IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received February 20, 2021, accepted March 1, 2021, date of publication March 4, 2021, date of current version March 15, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3063807

Optimal Design and Control of SSSCs for TLs Considering Technical and Economic Indices Using GA and SAMPE-JAYA Algorithms

AHMED E. ELGEBALY[1], IBRAHIM B. M. TAHA[2], AHMED M. AZMY[1], AND HOSSAM A. ABD EL-GHANY[1]

[1]Electrical Power and Machines Engineering Department, Faculty of Engineering, Tanta University, Tanta 31521, Egypt
[2]Electrical Engineering Department, College of Engineering, Taif University, Taif 21944, Saudi Arabia

Corresponding author: Hossam A. Abd El-Ghany (hossam.saleh@f-eng.tanta.edu.eg)

This work was supported in part by the Taif University Researchers, Taif University, Taif, Saudi Arabia, under Project TURSP-2020/61.

ABSTRACT Improving transmission lines (TL) steady-state stability limit can be achieved by Static Synchronous Series Compensators (SSSC) that work as a converter-based compensator. The modification of the SSSC function to inject both active and reactive power into the TL improves its performance according to different indices. The TL improvement indices include the reduction of TL losses, the enhancement of dynamic stability margin and the improvement of voltage profile along the TL. The economic index is considered a vital factor in the design of SSSC devices installed in TLs. This paper proposes an objective function to design and control SSSC devices by considering various technical and economical indices. The formulation of the objective function requires power flow analysis in the compensated transmission line under different loading conditions and compensation levels. The proposed multi-objective function includes the transmission line losses, the dynamic stability span, and the cost of SSSC device. The Genetic Algorithm (GA) and Self-adaptive Multi-population Elitist Jaya Algorithm (SAMPE-JAYA) are proposed as optimization techniques to obtain the minimized value of the multi-objective function. This paper proposes the installation of two SSSC devices in TL that leads to the improvement of the design and control indexes. The proposed objective function and the optimization techniques are applied for tie-line (400kV, 400km) that connects between two networks.

INDEX TERMS Dynamic stability, FACTS, genetic algorithm (GA), self-adaptive multi-population elitist (SAMPE) Jaya algorithm, static synchronous series compensator (SSSC).

I. INTRODUCTION

Nowadays the power demand rapidly increases in different power system stages: generation, transmission, and distribution [1]. Different abnormal operation conditions occur in electrical power systems such as faults, sudden load variations, voltage instability, harmonics and frequency changes that affect the power system stability. Some problems are carried out due to instability in electrical power systems, such as voltage and frequency instability which can cause failure in electrical power systems [1].

Flexible AC Transmission Systems (FACTS) are implemented and to improve power transfer capability, to reduce active power losses and address voltage instability problem in extra high voltage transmission lines (TLs) [2]. Many FACTS are used in electrical power systems such as Thyristor-Controlled Series Capacitor (TCSC), Static VAR Compensator (SVC), Thyristor-Controlled Series Phase Angle Reactor (TCPAR), Dynamic Voltage Restorer (DVR), Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow (UPF), ...etc. [1].

SSSC can be considered as a solid-state voltage source inverter connected in series with the overhead TL [3]. The SSSC inject a controlled voltage in a TL which is in quadrature with the TL current, that means the SSSC can be considered as a variable reactance compensator (capacitive or inductive) [3].

Some research works are discussing the constructions, performance, and control characteristics of SSSC

The associate editor coordinating the review of this manuscript and approving it for publication was Siqi Bu.

compensators [4]–[18]. In [4], the SSSC is used to inject controllable compensated voltage regardless the magnitude of the TL current. The SSSC supplied by the DC power supply is used to compensate the voltage drop through the overhead TL impedance. The X/R ratio is maintained with a high ratio during a high degree of series compensations. The implementation of SSSC using Electromagnetic Transient Program Simulation Software (EMTP) is carried out in [5]. Comparisons between SSSC and controllable series compensation (CSC) are carried out and implemented. In [6], comparisons are made based on theoretical considerations of power flow control of the overhead TL when applying SSSC and CSC. The results illustrate that the SSSC performance is more effective than CSC, especially with short TLs. However, the TL losses are not considered in these works, although the SSSC has a direct effect on them.

A frequency-domain model of the SSSC is implemented in [7], [8], considering the control devices. Different control strategies of SSSC are considered in the suggested model. The theoretical suggested model results are verified using PASCAD/EMTDC package. The dynamic performance comparisons between SSSC and STATCOM are presented in [9]. The dynamic performance of the SSSC is enhanced using the auxiliary regulator compared to that of the inherent Phase-Locked loop (PLL). Two characteristics types of SSSC controller are investigated in [10]. The first type depends on voltage regulations while the second depends on the impedance regulations. It is noted that the controller parameters affected the SSSC characteristics. The analytical model results are validated by those obtained from digital simulations. Nevertheless, the optimal value of the series injected voltage is not applied within the presented control systems.

The sizing of the SSSC controller in the transmission power system is considered as the main optimization challenge [11]. A main objective of the optimization problem is to decrease TL power losses of the network. The particle swarm optimization technique is used for the optimization process. The Newton-Raphson (NR) power flow model is modified to include the SSSC controller. The Power System Block (PSB) set and Simulink software are used for model validations. Comparisons between SSSC and STATCOM controllers' effect on TLs oscillation damping are introduced in [12]. The results illustrate that the SSSC is more valuable than the STATCOM controller on oscillation damping of the TL system. The SSSC effectiveness compared to STATCOM and UPF on damping the undesirable oscillations that occurred in the TL during abnormal conditions are introduced in [13]. Complete performance analysis of SSSC is implemented and carried out based on two radial distribution systems (12 and 69 bus) [14]. The model is used to enhance the power quality of the distributed network. The enhancement includes both bus voltages and TL losses. In the previous work, the objective function does not include any index for the stability margin of the TL especially when the TL resistance is considered.

In [15], the solutions for voltage instability, active and reactive losses, and heavily loaded transmission lines are studied and discussed. It used both SSSC and TCSC to solve these problems by reducing TL losses to enhance the voltage profile of the transmission network. The proposed model is validated based on MATLAB/PAT software. The results illustrate the effectiveness of SSSC compared to TCSC. Optimal control of SSSC is introduced in [15]. The objective of the suggested model is to reduce TL losses considering line voltage limits and maintaining the TL X/R ratio. The suggested model is validated based on MATLAB/Simulink based on 400kV, 400 km TL [16]. The main drawback of this model is the dependence on fixed X/R ratio after compensation as the only factor to maintain the system stability margin. In [17], a fuzzy controller is used for optimizing the SSSC controller system design. The fuzzy rules are used for tuning the SSSC parameters at different scenarios and different loads. The results illustrate the effectiveness of the proposed model for stability enhancement and fluctuations reductions. The suggested fuzzy-differential evaluation (FL-DE) model results are compared to that obtained from PSO, genetic, differential evaluation (GSA), and DE with the superiority of the suggested model. SSSC model is built to minimize power loss, enhance system reliability, and maximize the predictability of the system [18]. The model is built based on multi-objective biogeography-based optimization (MOBBO) considering operational constraints and uncertainty on the system. The optimal location and sizing of SSSC are studied and discussed based on the IEEE 57-bus system. Although the SSSC is designed and controlled upon multi-objective function with several technical indices, the cost of the SSSC device is not considered in combined with the required technical consideration.

The self-adaptive multi-population elitist Jaya algorithm SAMPE-JAYA is introduced in [19]. Generally, the performance of metaheuristic-based algorithms basically depends on the algorithmic-specific parameters. The suitable adjustment of the algorithm parameters is very essential. The inappropriate setting of these parameters may cause an increase in the computational cost or lead toward a local optimal solution. Consequently, some parameter-less algorithms such as the teaching-learning-based-optimization (TLBO) algorithm [20] and Jaya algorithm [21] have been developed to solve optimization problems. The Jaya algorithm is characterized by faster performance than TLBO algorithm.

The main advantage of the SAMPE-JAYA technique is that it can decide the number of subpopulations adaptively. Moreover, compared with island-model GA [22], the latter uses only two groups (Master Island and Slave Islands) and it is very complicated. Moreover, multiple-population (multiple-deme, or parallel) GAs consist of several subpopulations that exchange individuals irregularly. The main drawback of this method is that the number of demes is to be adjusted for a better performance of the algorithm. The tuning of the number of subpopulations is a serious issue in the parallel evolutionary algorithm. Therefore, this issue is resolved by the proposed

SAMPE-JAYA algorithm, which adaptively determines the number of subpopulations. Accordingly, SAMPE-JAYA is preferred to be applied to solve the formulated optimization problem.

Most of the previous presented works to design and control the SSSC did not consider the cost of the device which is determined according to its rating. Moreover, the previous optimization techniques are time-consuming during the determination of the optimal control parameters. Therefore, the application of these techniques in fast response control systems may be limited. Moreover, the stability margin of the power system should be considered as the main factor to improve the system reliability during contingency conditions.

According to the research in [23], the concept of distributed SSSC installed in transmission line provides better dynamic performance, lower cost, and flexible investment process. The distributed SSSC enables to stage of the investment over a wider time frame. Therefore, in this paper, it is suggested to split the lumped SSSC device installed at the beginning of the transmission line to two SSSC devices at the two terminals of the TL. This enables to better handle the SSSC devices in two substations at TL ends. The distributed SSSC system requires complicated communication system between the control centers and each SSSC device. So, the installation of only two SSSC devices is analyzed in this study. Although the research in [23] explains the benefits of distributed SSSC concept, it did not include an optimization technique for the design or control of the installed devices.

In this paper, the main contribution is the optimal design and operation of two SSSC devices installed in a certain TL with objective related to minimum TL losses, maximum stability margin and minimum cost. The design is performed at the maximum transmitted power. Then, according to the optimization algorithm, the operation of the installed SSSCs is adjusted to transfer that power level with minimum losses and maximum stability margin. The research also discusses the differences between the effect of using single-objective functions to determine the optimal design and operation of two SSSC devices. The GA and SAMPE-JAYA algorithm are implemented to solve the optimization problem.

Section II discusses the principle of operation of SSSC to adjust the performance of TL. Section III discusses the objective function formulation to control the SSSC devices. Section IV introduces GA and SAMPE-JAYA algorithm as techniques to obtain the optimal solution. Section V is devoted to the simulation results and discussion. Finally, section VI provides conclusions.

II. THE SSSC PRINCIPLE OF OPERATION TO CONTROL T.L TRANSMITTED POWER

FIGURE 1 illustrates the two-machine model of a system under study with and without series compensation by SSSC. The two machines have terminal bus voltages of $V_i\angle\delta_i$ and $V_j\angle\delta_j$. The TL has a total resistance of R, a total inductive reactance of X_L and a midpoint voltage of V_{mid}. It can be observed that without any compensation the power angle ($\delta = \delta_i - \delta_j$) between the two bus voltages has a relatively high value which negatively affects the system stability margin. Moreover, the midpoint voltage has low value compared with

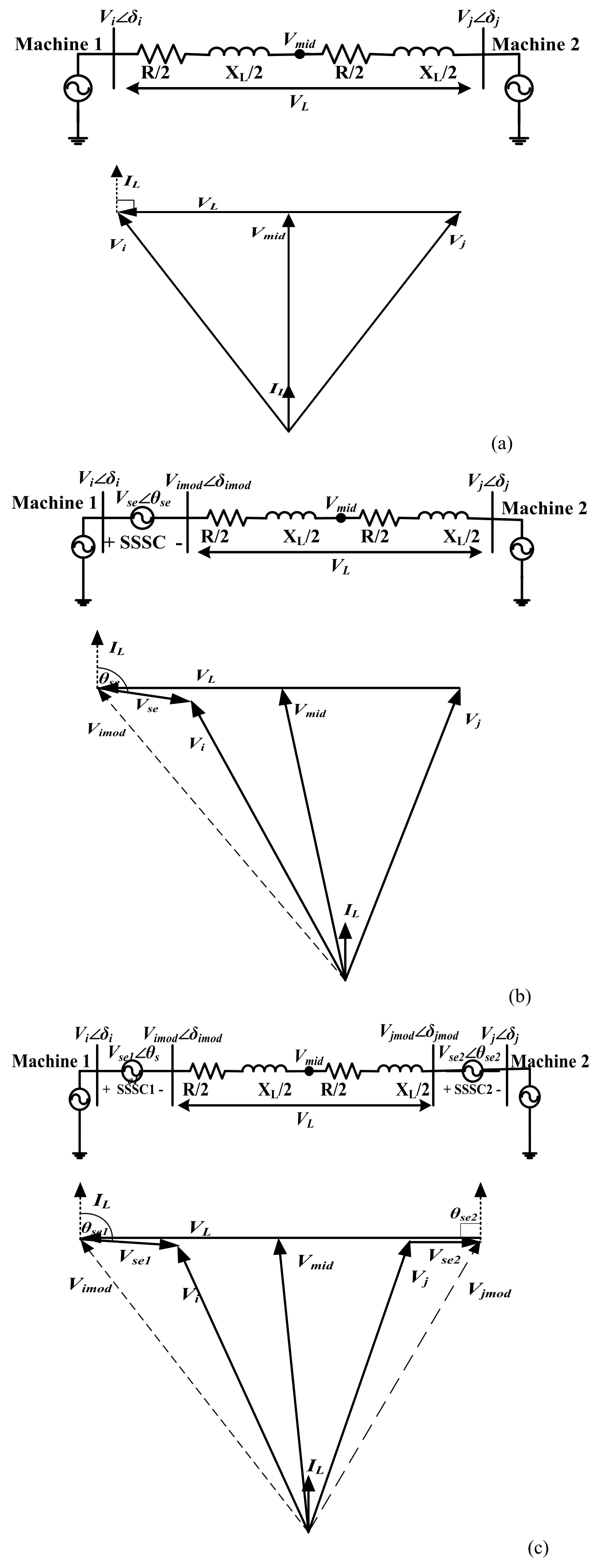

FIGURE 1. The two-machine model and corresponding phasor diagram (a) Without compensation (b) Compensation with one SSSC (c) Compensation with two SSSC.

the two machine bus voltages. The traditional series compensation depends on the added series reactance, whereas the associated voltage and reactive power depend on the Line current. On the other hand, the SSSC can inject compensated voltage which is independent of the TL current. The two-machine model and TL compensated by two SSSC devices are illustrated in FIGURE 1(b, c) while the compensation using one SSSC device is illustrated in FIGURE 1 (b). The series injected voltage $V_{se}\angle\theta_{se}$ is assumed to have flexible phase angle θ_{se} which may equal $-90°$ in case of capacitive reactive power compensation. and may be less than $-90°$. Therefore, the SSSC can inject both reactive and active powers into the system, where in this case, the SSSC should be equipped with energy storage system to inject active power into the system. The effect of series injected voltage is shown in FIGURE 1(b), where the phasor diagram illustrates that the phase angle between V_i and V_j is reduced, so that, the stability margin is improved, and the midpoint voltage is increased. The series compensation of the TL by two SSSC devices is proposed and carried out to enhance stability margin and reduce TL losses. As shown in FIGURE 1(c), the first SSSC device is used to inject both reactive and active powers into the TL while the second SSSC device is applied to inject only reactive power. The SSSC control function is used to inject this type of powers depending on the phase difference angle between the series voltage and the TL current. FIGURE 1(c) illustrates the improvement in the phase angle between the two-machine terminal bus voltages and the midpoint voltage. In general, it can be assumed that a series compensation voltage of $V_{se}\angle\theta_{se}$ is injected between the two machines. The series injected voltage can be produced by one device as in FIGURE 1 (a) or by two devices as in FIGURE 1(b). By assuming that the amplitude of both machine terminal bus voltages have the same value $|\bar{V}_i| = |\bar{V}_j| = V$, the TL is lossless and $\theta_{se} = \pm 90^o$. The transmitted power P_{ij} from *i to j* is as follows [24]:

$$P_{ij} = \frac{V^2}{X_L}\sin(\delta_i - \delta_j) + \frac{V}{X_L}V_{se}\cos\frac{(\delta_i - \delta_j)}{2} \tag{1}$$

where

$$\overline{V_{se}} = V_{se}\frac{\overline{I_L}}{|\overline{I_L}|}e^{\pm j\theta_{se}} \tag{2}$$

where I_L is the current of power line.

The two-machine model is tested under the injection of series voltage V_{se} with phase angle of $\pm 90^o$ and independent of TL current magnitude. As in FIGURE 2, the insertion of the series voltage lags the TL current (capacitive effect) that leads to increasing the steady state stability limit. On the other hand, the inductive voltage nature decreases the maximum transferred power.

Generally, the SSSC is installed in the TL to adjust its parameters by the series injected voltage $V_{se}\angle\theta_{se}$. The injected voltage affects the equivalent reactance of the TL when its phase is shifted by $\pm 90^o$ [4]. In [16], the adjustment of both equivalent reactance and resistance of TL is performed by providing the SSSC capability to injected active power. Therefore, the SSSC affects the power flow between the two machines i and j in FIGURE 1. The insertion of two SSSC devices improves the performance of the TL. With proper optimization technique, the design of the two devices can be optimized to get minimum installation cost with maximum operation indices. As shown in FIGURE 1(c), the insertion of the SSSC devices modifies the sending end i and receiving end j voltages as follows:

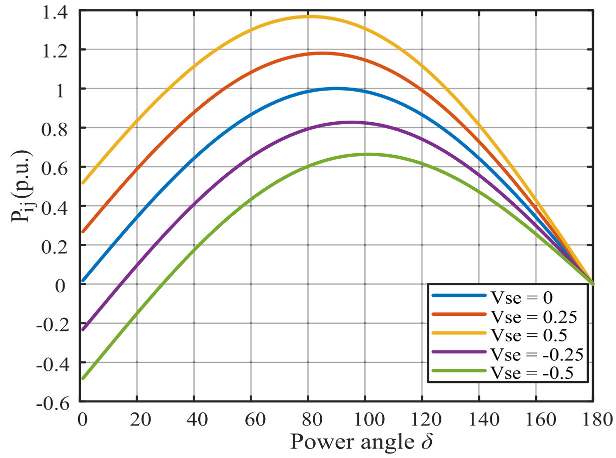

FIGURE 2. The transmitted power variation with the power angle at different levels of SSSC voltage.

$$V_{i(mod)}\angle\theta_{i(mod)} = V_i\angle\theta_i - V_{se1}\angle\theta_{se1} \tag{3}$$
$$V_{j(mod)}\angle\theta_{j(mod)} = V_j\angle\theta_j + V_{se2}\angle\theta_{se2} \tag{4}$$

where $V_{i(mod)}\angle\theta_{i(mod)}$ is the voltage at the sending end after SSSC1 insertion and $V_{j(mod)}\angle\theta_{j(mod)}$ is the voltage at the receiving end after SSSC2 insertion. According to the modified voltages and the parameters of the TL, the power flow through the TL can be calculated as follows [33]:

$$\begin{aligned} P_{ij} = & V_{i(mod)}^2 g_{ii} - V_{i(mod)}V_{j(mod)}\left(g_{ij}\cos\left(\delta_{i(mod)} - \delta_{j(mod)}\right)\right. \\ & \left. + b_{ij}\sin\left(\delta_{i(mod)} - \delta_{j(mod)}\right)\right) \end{aligned} \tag{5}$$

$$\begin{aligned} Q_{ij} = & -V_{i(mod)}^2 b_{ii} - V_{i(mod)}V_{j(mod)}\left(g_{ij}\sin\left(\delta_{i(mod)} - \delta_{j(mod)}\right)\right. \\ & \left. + b_{ij}\cos\left(\delta_i - \delta_j\right)\right) \end{aligned} \tag{6}$$

$$\begin{aligned} P_{ji} = & V_{j(mod)}^2 g_{jj} - V_{i(mod)}V_{j(mod)}\left(g_{ij}\cos\left(\delta_{j(mod)} - \delta_{i(mod)}\right)\right. \\ & \left. + b_{ij}\sin\left(\delta_{j(mod)} - \delta_{i(mod)}\right)\right) \end{aligned} \tag{7}$$

$$\begin{aligned} Q_{ji} = & -V_{j(mod)}^2 b_{ii} - V_{i(mod)}V_{j(mod)}\left(g_{ij}\sin\left(\delta_{j(mod)} - \delta_{i(mod)}\right)\right. \\ & \left. + b_{ij}\cos\left(\delta_{j(mod)} - \delta_{i(mod)}\right)\right) \end{aligned} \tag{8}$$

$$I_{(L)ji} = \frac{(P_{ji} + jQ_{ji})}{V_{j(mod)}\angle\theta_{j(mod)}} \tag{9}$$

$$I_{(L)ij} = \frac{(P_{ij} + jQ_{ij})}{V_{i(mod)}\angle\theta_{i(mod)}} \tag{10}$$

where g_{ii} and g_{jj} is the self-conductance of buses i and j respectively, g_{ij} is the transfer conductance between i and j, b_{ii} and b_{jj} is the self-susceptance of buses i and j respectively, b_{ij} is the transfer susceptance between i and j and $I_{(L)ij}$ and $I_{(L)ij}$ are the TL current at sending and receiving ends respectively. As in Equation (5), the transmitted power is

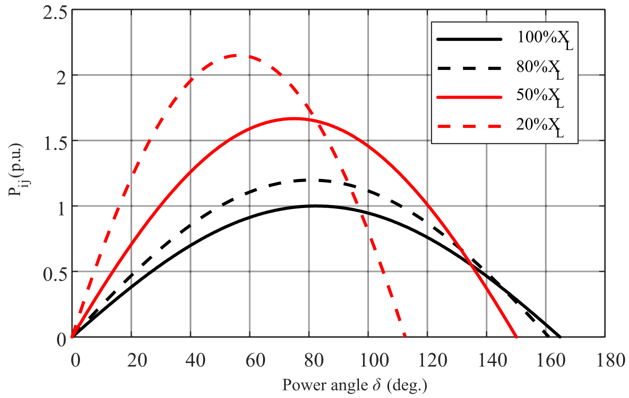

FIGURE 3. Relation between the transmitted power and the power angle at different equivalent T.L reactances.

mainly affected by the line reactance and it is also affected by the line resistance [2]. The TL resistance affects the angle at which the maximum power is transferred and the stability margin of the system. By assuming that, the SSSC devices affect only the equivalent reactance of the TL, and the ratio X_L/R equals 7.49 [16], the relation between power angle $\delta = \delta_{j(mod)} - \delta_{i(mod)}$ and the transmitted power can be deduced from Equation (5) as shown in FIGURE 3. Although the series compensation by a series capacitor reduces the equivalent reactance of the TL and increases the maximum possible transmitted power, the stability margin (maximum angle for power swing) is reduced as shown in FIGURE 3. [16] proposes fixing the X_L/R ratio to maintain the system stability margin. However, fixing X_L/R ratio is not the only factor to improve the stability margin because the stability margin may be improved by X_L/R ratio reduction.

The installation of the SSSC in TL has significant impact on the TL losses [2]. But the losses reduction contradicts with the cost of the SSSC. Moreover, the saving of system stability depends on the effective parameters of the compensated TL. Therefore, the following study is devoted to the optimal design of the SSSC devices by formulating multi-objective function considering the minimization of TL losses, minimization of cost and maximization of the system stability.

III. PROBLEM FORMULATION FOR SSSC DEVICES OPTIMAL CONTROL

SSSC devices are used for optimal control of power transfer through tie-line as well as enhancement of transient stability under certain constraints. In this model, two SSSC devices are installed with the following assumptions. Both SSSC devices can inject or absorb active and reactive power. In this study, the two SSSC are considered as independent sources. It is necessary to involve an active power source in this type of SSSC [26]–[29]. The SSSC system can be integrated with energy storage (ES) system [26], [27]. The integration of energy storage system enables to control the SSSC in the four power quadrant planes [28]. Therefore, it is essential to integrate active power sources at the SSSC-DC bus such as battery, SMES, fuel cell etc. The DC bus may be fed by a DC controlled rectifier connected to the AC system [29]. Due to the insertion of SSSC devices, some important parameters may affect the power loss, voltage profile and X/R ratio. The multi-objective function of the problem combines terms of different nature, as to minimize the tie-line power loss, minimize total cost of the installed SSSC devices and maximize of transient stability span angle. In addition, the power balance equation, limit of midpoint voltage and X_L/R ratio are taken as constraints. The control variables are represented by the voltage injected by the SSSC devices as magnitude and phase. The design is performed by assuming that the TL transfers the maximum allowable power. During the operation of the system, the optimization is applied only for minimization of TL losses and maximization of span angle.

A. MULTI-OBJECTIVE FUNCTION

The proposed three parts of the multi-objective function (F) are the power loss (F_1) of the tie-line, the total cost of the installed SSSC devices (F_2) and the transient stability span angle (F_3). F_3 has to be maximized while F_1 and F_2 have to be minimized. The adopted multi-objective function has three terms which are given in the following form and it is described in the following sections:

$$min.(F) = min.\left(W_1.F_1 + W_2.F_2 + W_3.\frac{1}{F_3}\right) \tag{11}$$

where, W_1, W_2 and W_3 are weighting factors. The total power losses of the tie-line (F_1) is described by the following equation:

$$F_1 = P_{loss}\left(V_{se1}, \theta_{se1}, V_{se2}, \theta_{se2}, \delta_j\right) = P_{ij} - P_{ji} \tag{12}$$

where P_{loss} is the total active power loss of tie-line. The total cost of installing SSSC devices (F_2) is given by the following equations:

$$F_2 = \mathrm{C_{SSSC}} \times \mathrm{S_{SSSC}} \tag{13}$$

$$\mathrm{S_{SSSC}} = |\mathrm{S_{SSSC1}}| + |\mathrm{S_{SSSC2}}| = \left|3 \times V_{se1}\angle\theta_{se1} \times I^*_{(L)ij}\right| + \left|3 \times V_{se2}\angle\theta_{se2} \times I^*_{(L)ji}\right| \tag{14}$$

where $\mathrm{C_{SSSC}}$ is the capital cost of the installed of SSSC calculated per kVA ($/kVA) and $\mathrm{S_{SSSC}}$ is the SSSCs installation capacity (kVA).

The transient stability of a certain power system is related to maintaining of system operating case or the transferring to very close state after a certain sudden disturbance. This disturbance may be a sudden change of loads, sudden outage of generator or TL or faults. The importance of improving transient stability is the determination of system capability to resist the transient state succeeding the significant disturbances. The equal area criterion is used to evaluate the transient stability study of the studied SSSC compensated system. The system is assumed to be subjected to a solidly three-phase fault at the sending end terminal while the TL transfers a certain power P_{ij}. Then, the SSSC devices act to

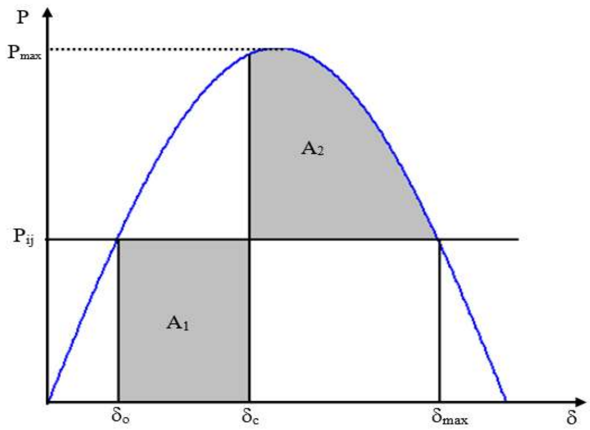

FIGURE 4. Equal area criterion for critical clearing angle.

maximize the critical clearing angle to improve the system transient stability. The critical clearing time can be increased (increasing the duration of the disturbances without loss of system synchronism) by increasing the critical clearing angle δ_c. FIGURE 4 illustrates the equal areas describing the studied case. The transient stability span angle (F_3) is given by the following equations:

$$F_3 = \delta_c - \delta_o \tag{15}$$

The critical clearing angle can evaluate as:

$$\int_{\delta_o}^{\delta_c} P_{ij} d\delta = \int_{\delta_c}^{\delta_{max}} (P_{max} \sin\delta - P_{ij}) d\delta \tag{16}$$

Integrating both sides, we get:

$$P_{ij}(\delta_c - \delta_o) = P_{max}(\cos\delta_c - \cos\delta_{max}) - P_{ij}(\delta_{max} - \delta_c) \tag{17}$$

Solving for δ_c, we get:

$$\cos\delta_c = \frac{P_{ij}}{P_{max}}(\delta_{max} - \delta_c) + \cos\delta_{max} \tag{18}$$

where δ_c is the critical clearing angle; δ_o is the original power angle; δ_{max} is the maximum angle that the system will reach after clearing a certain disturbance. δ_{max} is equal to $\pi - \delta_o$ for critical clearing and P_{max} is the maximum transferable power. The SSSC control affects P_{max} as in FIGURE 3 and therefore the value of δ_c.

B. SYSTEM CONSTRAINTS

The four constraints of the proposed optimization problem include active power balance equation, midpoint voltage, X/R ratio and SSSC active power output constraints. The balance of the active power equation in the suggested method is represented as equality constraint. Equality constraint can be constructed as follows:

$$P_i + P_{se1} - P_{loss} - P_j + P_{se2} = 0 \tag{19}$$

where, P_i is the sending-end active power generated and P_j is the received active power. As $P_i + P_{se1} = P_{ij}$ and $-P_j + P_{se2} = P_{ji}$, substituting P_{ij}, P_{ji} and P_{loss} from Equations (5) and (7) respectively, yields:

$$V_{j(mod)}^2 g_{jj} - V_{i(mod)} V_{j(mod)} \left(g_{ij}\cos\left(\delta_{j(mod)} - \delta_{i(mod)}\right) + b_{ij}\sin\left(\delta_{j(mod)} - \delta_{i(mod)}\right)\right) - P_{ji} = 0 \tag{20}$$

The transmission line power flow and the power generation at the transmission line sending end are conditioned by:

$$\begin{cases} \left|S_{ij}\right| \le SF_{max} \\ P_{i,min} \le P_i \le P_{i,max} \end{cases} \tag{21}$$

where, $\left|S_{ij}\right|$ is the magnitude value of the sending-end apparent power, SF_{max} is the maximum TL power flow; $P_{i,max}$ and $P_{i,min}$ are the maximum and minimum generation limits at bus i.

As in FIGURE 1, the minimum voltage over the TL occurs at the middle point [16]. The limit on midpoint voltage (V_{mid}) is considered as the third constraint which is an inequality constraint:

$$|V_{min}| \le |V_{mid}| \le |V_{max}| \tag{22}$$

where, $|V_{max}|$ and $|V_{min}|$ are the maximum and minimum phase voltage magnitudes, which equal $\pm$ 5% of rated voltage [16], respectively. V_{mid} can be extracted as:

$$V_{mid} = V_j + \frac{1}{2}V_L \tag{23}$$

$$V_L = V_i - V_j - V_{se1} - V_{se2} \tag{24}$$

where, V_L is the tie-line voltage drop.

The improvement of system stability after compensation is achieved by saving the X_L/R ratio less than the original ratio without compensation. This inequality constraint can be formulated as a function of control variables.

$$\frac{X_{eff}}{R_{eff}} \le \frac{X_L}{R} \tag{25}$$

where, R_{eff} and X_{eff} are the effective resistance and reactance of the TL after SSSC devices compensation, respectively.

$$\frac{X_{eff}}{R_{eff}} = \frac{X_L - imag(Z_{SSSC1} - Z_{SSSC2})}{R - Re(Z_{SSSC1})} \tag{26}$$

where, Z_{SSSC1} and Z_{SSSC2} are the series impedance of the SSSC devices. These values can be extracted as a function of control variables as follows:

$$Z_{SSSC1} = \frac{V_{se1}\angle\theta_{se1}}{I_{(L)ij}} \tag{27}$$

$$Z_{SSSC2} = \frac{V_{se2}\angle\theta_{se2}}{I_{(L)ji}} \tag{28}$$

From the previous analysis and assumptions, the control variables to be determined are V_{se1}, θ_{se1}, V_{se2}, θ_{se2} and δ_2. The optimization techniques should test the search space to get the minimum objective function according to the specified constraints. The following section proposes several optimization techniques that can solve the formulated objective function and determine the optimal parameters.

IV. SOLUTION OF THE OPTIMIZATION PROBLEM

The multi-objective function formulated in the previous section is minimized by proposing two optimization techniques. These techniques are genetic algorithm (GA) [30], JAYA algorithm and Self-adaptive Multi-population Elitist (SAMPE-JAYA) algorithm [21]. The following subsections are discussing these techniques.

A. GENETIC ALGORITHM (GA)

The GA is considered as one of the meta-heuristic techniques which relies on the genetics and natural selection laws. For optimization problems, the GA provides the best solutions within the search space [30]. GA explores the solution in a parallel manner to get the optimal solution from population of points. Therefore, GA can avoid the local optimal solution problem. Real-Coded GA [30] consists of four essential phases which are initial population, evaluation function, selection, and genetic operators (mutation and crossover). GA algorithm guides the population into convergence to obtain the global optimal solution. Primarily, the initial population or chromosome population is created. Depending on genetic operators, new chromosomes are created. The new generated chromosomes by the selection operators create a new population with improved fitness of the objective function. This procedure is repeated till the improvement is stopped. It can be accomplished after a certain number of iterations.

Regardless the SSSCs operation procedure, this work focuses on the optimization technique that solves the SSSCs operation problem (voltage injected by SSSC devices), where three objective functions are implemented. The GA is applied to determine the global minimum solutions of the multi-objective function. The solution procedure begins with random injection of both the magnitude and angle of SSSCs voltages to start the chromosome population. Thus, power flow solutions are performed, and several study system parameters are calculated. Consequently, the multi-objective function is estimated using Equation (11). Then, the parent is chosen from the population. Therefore, the new chromosomes are generated from the recombination processes. The population is regenerated for all iterations till achieving a satisfactory termination criterion and then, the corresponding results are provided.

B. JAYA AND SAMPE-JAYA AS OPTIMIZATION TECHNIQUES

Venkata Rao firstly developed the Jaya algorithm [21]. This algorithm is characterized by simplicity and implementation without special algorithms for tuning. According to the lower and upper bounds of the required variables, the Jaya algorithm randomly creates the initial solution (P). Then, each variable is stochastically updated as in Equation (29). Assuming that (F) is the objective function to be minimized. F has two basic values $f(worst)$ and $f(best)$ which represent the worst and best objective values, respectively.

$$\begin{aligned} A(m+1, n, k) = {} & A(m, n, k) + r(m, n, 1) \\ & - (A(m, n, b) \ |A(m, n, k)|) - r(m, n, 2) \\ & (A(m, n, w) - |A(m, n, k)|) \end{aligned} \tag{29}$$

where w and b are the indexes of the worst and best solutions within the current population respectively; m is the iteration index; n is the variable index [1: d] where d is the number of design variables; k is the candidate solution index. $A(m, n, k)$ refers to the n^{th} variable of k^{th} candidate solution in m^{th} iteration. $r(m, n, 1)$ and $r(m, n, 2)$ represent random numbers belongs in the range [0], [1]. These random numbers are considered as scaling factors which confirm the best diversification [31].

The JAYA algorithm is enhanced using splitting technique. The entire population of search domain is split into subpopulations to enhance the search diversity. The allocation of these subpopulations throughout the search space enables to effectively detection of the changes. Therefore, JAYA algorithm is improved by the splitting technique to provide SAMPE-JAYA algorithm [21], [31], [32].

The algorithm creates the subpopulation adaptively according to the following two assumptions:

The first assumption supposes that the SAMPE-JAYA creates a number of subpopulations depending on the quality of the solutions, i.e., fitness function value. Also, this algorithm is improved by the replacement of the worst solutions in the group having poor fitness values with the best solutions in the group that has high fitness values. This process is called elitism. This splitting optimization technique enables to spread the search over the search space rather than focusing on a specific area. Consequently, SAMPE-JAYA can monitor the problem landscape variations to obtain the optimal solution. **The second assumption** supposes that throughout the search process, SAMPE-JAYA adjusts the number of subpopulations depending on the changing strength of the problem. Therefore, the number of subpopulations could be increased or reduced depending on the solution quality, i.e., enhancement in the fitness value. The number of subpopulations is increased or decreased according to the deterioration or improvement of the solution, respectively. Additionally, the identical solutions are replaced by the newly created solutions for keeping the diversity and enhancing the exploration process.

FIGURE 5 illustrates the of procedures of the SAMPE-JAYA algorithm. The following steps should be carried out to apply the proposed technique:

Step 1: The algorithm needs the determination of the design variable numbers (d), P and a termination criterion which may be a certain number of iterations or specific required accuracy.

Step 2: According to the distinct fitness function, the initial solution can be calculated.

Step 3: Split the entire population into several subpopulation group u according to the required solution quality.

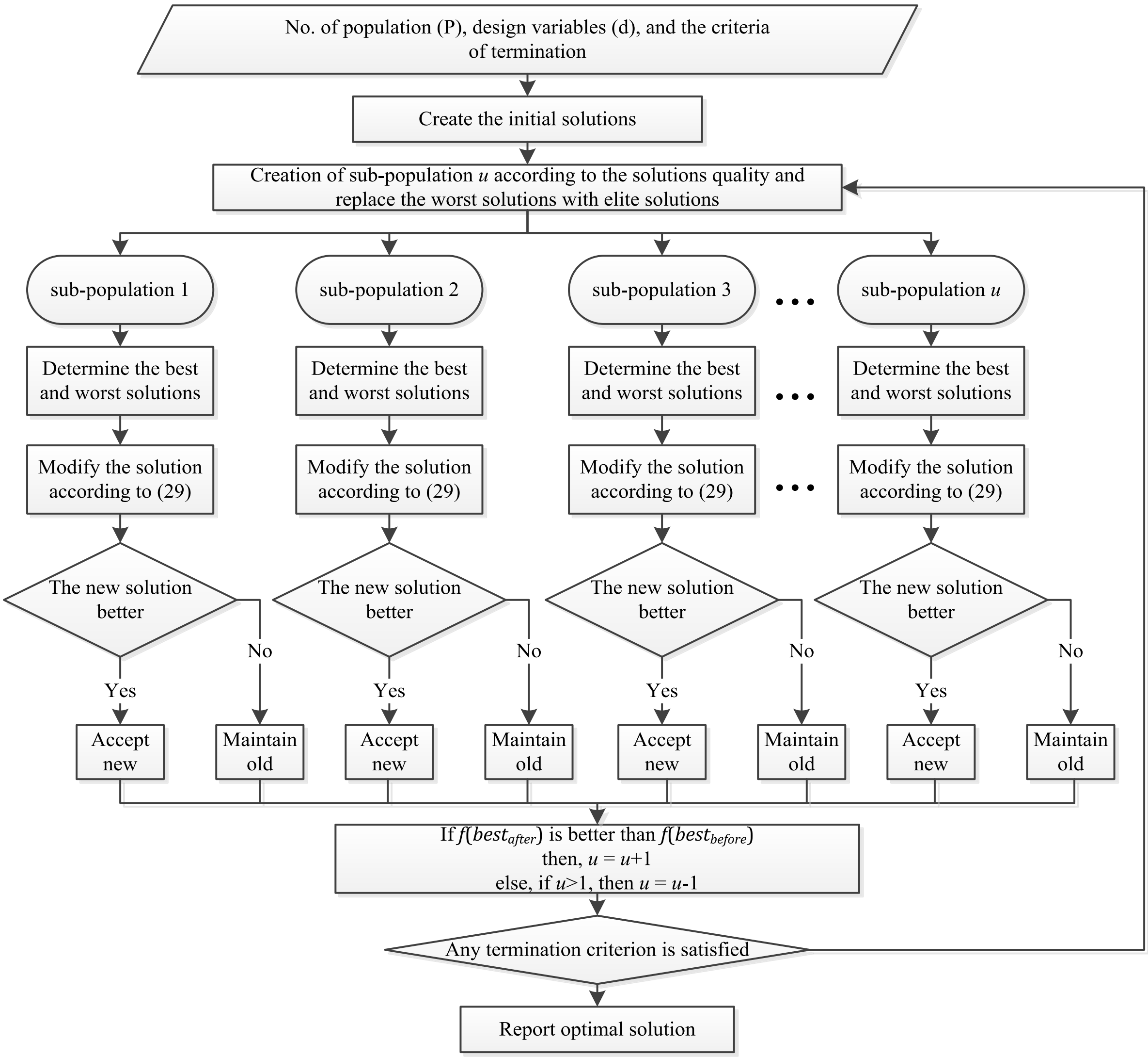

FIGURE 5. Flowchart of the proposed SAMPE-JAYA algorithm.

TABLE 1. Comparison of GA and SAMPE-JAYA with ref. [16] for one SSSC device and single-objective function (tie-line power losses).

Tie line power (MW)			1000				850				650	
Algorithm	Without	[16]	GA	SAMPE-JAYA	Without	[16]	GA	SAMPE-JAYA	Without	[16]	GA	SAMPE-JAYA
Losses (MW)	145.9	112	102.3	100.6	93	82	75.7	71.56	48	43	41.21	41.14
Span of dynamic stability (deg.)	6.4	42	37.5	37.68	18.8	42	42.67	49.3	42	63.75	96.13	67.62
Cost (M$)	-	14.61	11.01	10.89	-	7.5	5.64	7.8	-	7.2	7.86	4.7
V_{mid} (%)	89.25	97.6	104.65	104.7	93	96.9	101.5	104.8	96	97.5	104.23	104.7
X/R	7.49	7.49	4.5	2.89	7.49	7.49	3.9	2.89	7.49	7.49	5.06	2.69
V_{se1} (kV)	-	63	49.65	49.5	-	37.5	29.69	42.06	-	21.99	55.99	33.46
θ_{se1} (deg.)	-	-105	-178	-180	-	-105	-172	-180	-	-159	-118	-180
δ_j (deg.)	-52.8	-30	-38	-38	-42	-30	-34	-32.3	-30.5	-24.8	-14	-24.63
P_{se1} (MW)	-	39	193	194	-	20	100	142	-	52	49	87
Q_{se1}(MVAR)	-	289	106	99	-	148	53	65	-	36	149	35
S_{ij} (MVA)	1181	1133	1120	1118	960	946	938	932	704	698	696	696

Replace the worst solutions in the inferior subpopulation with solutions in the superior subpopulation (elitism process).

Step 4: The basic Jaya algorithm is applied on each subpopulation to independently adapt the solutions in each group. The adapted solutions are only accepted if these solutions are better than the previous one.

Step 5: The entire subpopulations are combined again. Check which is the better solution $f(best_{before})$ or $f(best_{after})$, where $f(best_{before})$ and $f(best_{after})$ are the earlier and current best solution, respectively, of the whole population. The value of u is decreased or increased according to the deterioration or improvement of the solution, respectively. The aim of u updating is keeping of algorithm exploration or exploitation. Moreover, SAMPE-JAYA replaces the worst solutions in the inferior subpopulation with solutions in the superior subpopulation (elitism process).

Step 6: The termination criterion is checked to report the optimum solution. Else, (a) the randomly generated solutions replace the duplicated solutions and (b) the population is divided again as in step 3 and the succeeding steps are repeated.

V. SIMULATION RESULTS AND DISCUSSION

The parameters of the test system are provided in APPENDIX. The optimization study is applied when the tie-line transfers three levels of power 650, 850, 1000 MW.

The following subsections discuss various topics related to the optimization of the formulated problem. The first subsection compares between the proposed optimization techniques (GA and JAYA) with Sequential Quadratic Programming SQP that is presented in [16] when solving single-objective function. The second subsection is interested in the determination of weighting factors for the formulated multi-objective function in (11). This is for obtaining the global optimal solution [30]. After weighting factors determination, the third subsection is devoted to the application of different optimization techniques on the multi-objective function to obtain the optimal variables of SSSC. All the previous steps are applied when one SSSC device is inserted at the terminal i of the two-machine model. Finally, the optimal design and control of two SSSC devices are discussed when the proposed optimization techniques are applied.

A. COMPARISON OF DIFFERENT OPTIMIZATION TECHNIQUES USING SINGLE-OBJECTIVE FUNCTION (TL POWER LOSSES)

Firstly, the proposed optimization techniques are applied when one SSSC device is installed at bus i. To compare the effectiveness of the proposed optimization techniques with the technique used in [16], only a single objective function (the TL losses F_1) is applied. The number of design variables in this case $d = 3$ are $(V_{se1}, \theta_{se1}, \delta_j)$. Table 1 illustrates the results of the two proposed techniques compared with [16] to obtain minimum TL losses. It can be noticed that the insertion of one SSSC device with optimal control leads to TL losses reduction compared with the system without SSSC under any transmitted power level by 23, 30 and 31% for SQP, GA and SAMPE-JAYA, respectively. The cost of the device is determined by the multiplication of kVA cost by the kVA capacity of the device; for example, the cost of the device when the power transmitted to the load equals 1000MW according to SAMPE-JAYA optimization $50\$ \times \sqrt{194000^2 + 99000^2} = 50\$/\text{kVA} \times 2178000\text{kVA} = 10.89$ M\$. The estimated cost is calculated related to each transmitted power level i.e., the cost of the device is increased when the required transmitted power is increased. For GA and SAMPE-JAYA, it can be noticed that the constraints are not violated under any condition. However, applying the proposed algorithms leads to the reduction of the sending-end apparent power through the TL, which leads to the improvement of system capacity. The SAMPE-JAYA little bit (around 4%) provides better results than GA under the studied three cases. Results of Table 1 illustrate the effectiveness of the proposed optimization techniques compared with the previous applied technique in [16] in the case of applying the single objective.

B. MULTI-OBJECTIVE FUNCTION WEIGHTING FACTORS SELECTION

The application of the multi-objective optimization of Equation (11) requires the selection of the weighting factors and the determination of the base values to normalize the three terms of this equation. The GA is applied to the system to find the optimal parameters when only one SSSC device is inserted at the sending end. The GA is applied when the TL transfers the maximum power of 1000 MW.

Table 2 illustrates the results when the GA is applied to solve the multi-objective function under different weighting factors. The first three cases are considered as single-objective functions (F_1, F_2 and F_3) for each term of the multi-objective function F. The three optimum values of F_1, F_2 and F_3 from the three columns of cases 1, 2 and 3, respectively, are selected as a base value for normalization. Then, the three terms of the objective function (11) are divided by 102 MW, 42.65° and 10.9 M\$, respectively. W_1, W_2 and W_3 are positive constant factors for minimization problem, where the summation of these factors equals one. According to Table 2, several weighting values are tested to select the most suitable ones for a global optimal solution. It should be noticed that all constraints are not violated. From the (Sum. of all normalized single objectives), the minimum objective is obtained when the weighting factors of equation (11) W_1, W_2 and W_3 have the same value (0.333). These factors are applied for the following optimization cases. This table just shows a sample of results. When it is required to consider only a certain term in the objective function, the corresponding weighting factor, i.e., W_1, W_2 or W_3, is set to one. However, when it is required to equally consider all terms in the objective function, the corresponding weighting factors, i.e., W_1, W_2 and W_3, are set to 0.333. Weights are selected considering the three terms of the multi-objective function with the same value, while the operator has the freedom of choice to determine the weights. Moreover, the experience of the operator may control the selection of weights according to his point of view or according to the priority of certain indices more than the other factors.

TABLE 2. Multi-objective function and different weighting factors using GA at one SSSC device (1000 MW tie-line power).

Case	1	2	3	**4**	5	6	7	8	9
W1	1	0	0	**0.33**	0.5	0	0.5	0.25	0.4
W2	0	1	0	**0.33**	0.5	0.5	0	0.5	0.4
W3	0	0	1	**0.33**	0	0.5	0.5	0.25	0.2
Sum. of all normalized single objectives	**1.052**	**1.026**	**1.041**	**1.00371**	**1.0057**	**1.0042**	**1.0411**	**1.0041**	**1.00378**
Losses (MW)	**102.3**	105.4	103.5	**102.5**	102.65	103.33	101.7	102.96	102.61
Span of dynamic stability F_3 (deg.)	37.5	**42.65**	38.9	**42.62**	43.32	42.6	37.45	43.25	43.08
Cost (M$)	11.01	11.32	**10.9**	**10.98**	11.22	10.95	10.79	11.11	11.1
V_{mid} (%)	104.75	102.83	104.3	**103.56**	103.49	103.04	104.48	103.31	103.54
X/R	2.95	4.06	3.18	**3.71**	3.8	3.87	2.97	3.87	3.76
V_{se1} (kV)	49.66	50.32	49.15	**49.47**	50.11	49.09	48.78	49.97	49.9
θ_{se1} (deg.)	-178	-146	-170	**-154**	-151	-150	-178	-150	-152
δ_j (deg.)	-38	-34	-37	**-34.5**	-34	-34	-38	-34	-34
P_{se1} (MW)	193	134	179	**148**	143	140	189	141	145
Q_{se1}(MVAR)	106	182	126	**162**	170	168	103	172	167
S_{ij} (MVA)	1120	1125	1122	**1121**	1121	1122	1120	1121	1121

TABLE 3. Comparison of GA and SAMPE-JAYA with ref. [16] for one SSSC device and multi-objective function.

Tie line power (MW)	1000				850				650			
Algorithm	Without	[16]	GA	SAMPE-JAYA	Without	[16]	GA	SAMPE-JAYA	Without	[16]	GA	SAMPE-JAYA
Losses (MW)	145.9	112	102.5	100.91	93	82	75.7	74.1	48	43	41.88	42.7
Span of dynamic stability F_3 (deg.)	6.4	42.37	42.62	43.65	18.8	42	42.6	50.58	42	63	64.16	63.78
Cost (M$)	-	14.61	10.98	10.92	-	7.5	3.5	6.8	-	7.2	3.2	2.98
F	-	1.1666	1.00371	0.9884	-	0.8348	0.7531	0.7308	-	0.4588	0.458	0.453
V_{mid} (%)	89.25	97.6	103.56	103.61	93	96.9	101.55	102	96	97.5	102.18	101
X/R	7.49	7.49	3.18	3.73	7.49	7.49	3.52	3.97	7.49	7.49	3.45	4.16
V_{se1} (kV)	-	63	49.47	49.57	-	37.5	29.7	36.07	-	21.99	23.14	20.85
θ_{se1} (deg.)	-	-105	-154	-153	-	105	-172	-149.4	-	-159	-168	-150
δ_j (deg.)	-52.8	-30	-34.5	-34	-42	30	-34	-30.24	-30.5	-24	-25	-24.4
P_{se1} (MW)	-	39	179	145	-	20	100	91	-	52	58	44
Q_{se1}(MVAR)	-	289	126	162	-	148	52	101	-	36	31	40
S_{ij} (MVA)	1181	1133	1121	1119	960	946	938	935	704	698	697	698

C. COMPARISON OF DIFFERENT OPTIMIZATION TECHNIQUES USING MULTI-OBJECTIVE FUNCTION FOR OPTIMAL DESIGN AND CONTROL OF ONE SSSC DEVICE

The multi-objective function (11) is solved by several optimization techniques when the previous selected weighting factors are used. In this section, only one SSSC device is assumed to be designed and installed at the sending end. Table 3 illustrates the results of the optimization for three levels of transferred power when three optimization approaches are applied. In this study, it is assumed that each transferred power requires a certain SSSC device. Therefore, each device has its own cost as in Table 3. The optimal value of the multi-objective function (F) illustrates that the proposed optimization techniques provide less objective value compared with SQP by 24.8% to 25.2% for GA and SAMPE-JAYA, respectively. The other advantage of SAMPE-JAYA is the simplicity of programing and the lower execution time [21]. The two optimization methods are adjusted to have the same population size of 200 and the same number of generations of 200. For the same number of generations, the GA requires 449 s while SAMPE-JAYA requires only 21.58 s. FIGURE 6 illustrates the progress of the minimum fitness value with the generation number. It can be observed that the SAMPE-JAYA reaches the steady optimal value faster than GA under the same essential parameters15 and 20 generations, respectively.

D. IMPROVING TL PERFORMANCE BY INSTALLING TWO OPTIMIZED SSSC DEVICES

The installation of two SSSC improves the performance of the tie-line according to the proposed indexes. Here the number of design variable $d = 5$ are ($V_{se1}, \theta_{se1}, V_{se2}, \theta_{se2}, \delta_j$). The following study explains the effectiveness of the two devices compared with one device. Table 4 demonstrates the results of the optimization problem using GA and SAMPE-JAYA. From the minimum values of the objective function F, it can be noticed that the minimum objectives are less than the objective when one SSSC device is applied by 0.22% to 0.13%, respectively. Therefore, it is recommended to install two devices in the tie line.

According to Table 3, at transferred power of 1000 MW, the SAMPE-JAYA optimizes the operation parameters of one device only. It can be noticed that the transmission line power losses equal 100.9 MW but the span of dynamic stability equals 43.65°. In the case of utilizing two devices (at the two ends of the transmission line) with the same ratings, while the summation of their ratings is the same as one device, the power losses in the transmission line is the same as in the previous case but the span of dynamic stability will be worse with a value of 41.9°. The illustration of these results aims at highlighting the importance of developing the parameters of each SSSC device individually. Therefore, each device

TABLE 4. Two SSSC devices using GA and SAMPE-JAYA.

Tie line power (MW)	1000			850			650		
Algorithm	Without	GA	SAMPE-JAYA	Without	GA	SAMPE-JAYA	Without	GA	SAMPE-JAYA
Losses (MW)	145.9	101.9	100.89	93	75.5	73.88	48	41.11	41.07
Span of dynamic stability F_3 (deg.)	6.4	44.6	43.9	18.8	42.49	49.35	42	156.23	156.27
Cost (M$)	-	11.4	10.917	-	5.51	6.57	-	5.5	5.5
F	-	1.0015	0.9871	-	0.74929	0.72994	-	0.3736	0.3734
V_{mid} (%)	89.25	103.48	103.18	93	100.9	102.19	96	104.2	104.2
X/R	7.49	3.74	3.73	7.49	3.83	3.7	7.49	2.6	4.87
V_{se1} (kV)	-	49.740	47.669	-	26.791	34.569	-	33.741	33.74
θ_{se1} (deg.)	-	-152.54	-153.82	-	-174	-155.45	-	-179.9	-180
δ_j (deg.)	-52.8	-33.63	-34	-42	-34	-30.95	-30.5	-23.392	-23.39
V_{se2} (kV)	-	2.025	2.035	-	2.153	3.339	-	5.41	5.4
θ_{se2} (deg.)	-	-133.25	-133.3	-	-115	-123	-	-149.7	-150
P_{se1} (MW)	-	145	142	-	92	96	-	87	87
Q_{se1}(MVA)	-	166	155	-	43	88	-	38	3
P_{se2} (MW)	-	3.4	3.3	-	0.86	0.3	-	9	9
Q_{se2}(MVAR)	-	8.4	8.2	-	8.1	1.2	-	12.3	12
S_{ij}(MVA)	1181	1115	1114	960	936	935	704	688	686

TABLE 5. Devices of SSSC are designed at 1000 MW and operating at different loading conditions using GA and SAMPE-JAYA.

Tie line power (MW)	1000		850		650	
Algorithm	GA	SAMPE-JAYA	GA	SAMPE-JAYA	GA	SAMPE-JAYA
Losses (MW)	101.9	100.89	72.2	71.55	41.25	41.15
Span of dynamic stability F_3 (deg.)	44.6	43.9	50.9	61.17	69.19	71.9
Cost (M$)	11.4	10.917	-	-	-	-
V_{mid} (%)	103.48	103.18	103.97	104.5	104.7	104.98
X/R	3.74	3.73	3.15	3.8	2.7	3.4
V_{se1} (kV)	49.740	47.669	38.8	47.38	33.74	34.101
θ_{se1} (deg.)	-152.54	-153.82	-171.6	-147.68	-177	-170.4
δ_j (deg.)	-33.63	-34	-31.27	-26.67	-24	-23
V_{se2} (kV)	2.025	2.035	1.88	1.565	0.917	1.731
θ_{se2} (deg.)	-133.25	-133.3	-112.98	-128.02	-145	-90
P_{se1} (MW)	145	142	124	109	86	83
Q_{se1}(MVA)	166	155	73	137	40	47
P_{se2} (MW)	3.4	3.3	0.1	1.9	1.4	-1.7
Q_{se2}(MVAR)	8.4	8.2	7	5.5	2.2	4.5
S_{ij} (MVA)	1115	1114	932	929	694	697

has its own parameters according to the adjustment of the optimization technique. Accordingly, Table 4 illustrates that the SAMPE-JAYA technique could adjust the parameters of each SSSC device, while the TL loss equals 100.89 MW which is less than the case of one device only. Moreover, the span of dynamic stability is improved to equal 43.9°. It can be noticed that the cost in the case of using two-SSSC devices (10.917 M$) is approximately the same as the cost of two equally split SSSC devices with a cost of (10.92 M$). Moreover, the optimized two-SSSC leads to the reduction of the sending-end apparent power from 1119 to 1114 MVA. In Tables 3 and 4 in the case of applying GA with 1000 MW transferred power, it can be noticed that the cost of the two-SSSC topology is a little bit higher than one-SSSC device but the overall objective function F is improved from 1.00371 to 1.0015.

Practically, the SSSC devices are designed when the transferred power is maximum. Therefore, the two SSSC devices are designed at 1000 MW transmitted power. The cost of the device and the value of series injected voltage are determined when applying the objective function with all suggested

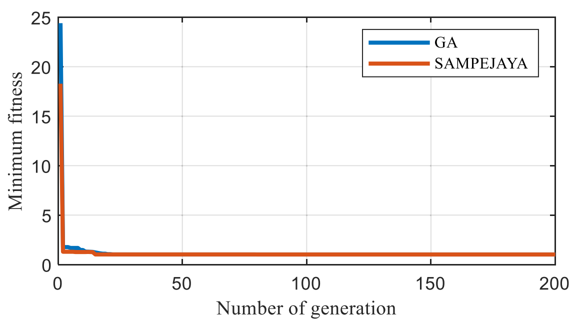

FIGURE 6. The relation between number of generation and minimum fitness for GA and SAMPE-JAYA.

terms. Then, at any less transmitted power, the optimization is applied only to obtain minimum losses and maximum span of dynamic stability. This is accomplished by setting W_1, W_2 and W_3 at 0.5, 0.5 and 0, respectively. Table 5 provides the results of SSSC devices when they are designed at 1000 MW transferred power. Then, the voltages of the two SSSC devices are set as an additional constraint because they are the maximum voltages. The voltages during control should be less than the maximum voltages. Both predetermined constraints and the new constraint are not violated.

VI. CONCLUSION

The enhancement of TL transfer capability has been achieved by the effective implementation of SSSC. In this paper, the design and control of one and two SSSC devices have been achieved according to specific multi-objective function. This multi-objective function includes the minimization of TL losses, the maximization of dynamic stability limit and minimization of cost. The proposed optimization techniques GA and SAMPE-JAYA have provided SSSC control variables that reduce the TL losses by 8.7% up to 10.2% compared with the SQP technique. Compared with the uncompensated TL, the TL losses can be reduced by 24.8% up to 25.2% for one SSSC using GA and SAMPE-JAYA respectively. The installation of two SSSC devices has improved the overall objective function by 0.13% and 0.22% by using GA and SAMPE-JAYA, respectively compared with the installation of one SSSC device. The proposed objective has been used to determine the rating and the cost of the two devices at maximum allowable transmitted power. Then, the objective function has been modified to include searching for minimum losses and maximum dynamic stability span. Searching for the optimized variable has been successfully achieved using the two proposed optimization technique.

APPENDIX

The parameters of test system (two-machine model) are as the following:

Each machine has line voltage of 400 kV.

The tie line distance is 400 km.

The tie-line inductance equals 0.93 mH/km.

The resistance equals 0.039 Ω/km.

The capacitance equals 0.13 nF/km.

The cost of kVA unit of SSSC approximately equals 50$ [33]. The equivalent X_L/R ratio of the line without compensation equals 7.49.

The maximum generated power $P_{i,max}$ equals 1200 MW.

The minimum generated power $P_{i,min}$ equals 250 MW.

The maximum transmitted power SF_{max} equals 1200 MVA.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support received from Taif University Researchers Supporting Project Number (TURSP-2020/61), Taif University, Taif, Saudi Arabia.

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AHMED E. ELGEBALY was born in Egypt, in 1983. He received the B.Sc. and M.Sc. degrees in electrical power and machines engineering from Tanta University, Egypt, in 2006 and 2012, respectively, and the Ph.D. degree from the Industrial Electronics Department, Moscow Power Engineering Institute, Russia, in 2018. He is currently working as a Lecturer with the Faculty of Engineering, Tanta University. He is also a Specialist in power electronics, power engineering, and machine control and design.

IBRAHIM B. M. TAHA received the B.Sc. degree from the Faculty of Engineering, Tanta University, Egypt, in 1995, the M.Sc. degree from the Faculty of Engineering, Mansoura University, Egypt, in 1999, and the Ph.D. degree in electrical power and machines from the Faculty of Engineering, Tanta University, in 2007. Since 1996, he has been teaching with the Faculty of Engineering, Tanta University. He joined Taif University as an Assistant Professor at the Electrical Engineering Department, Faculty of Engineering. He has also been an Associate Professor with the Electrical Power and Machine Department, Faculty of Engineering, Tanta University, since December 2016. His research interests include steady state and transient stability of HVDC systems, FACTS, multilevel inverters, power transformers fault detection based on dissolved gas analysis, partial discharge detection, nano technology applications on high voltage systems, applications of machine learning methods, and AI technique applications.

AHMED M. AZMY was born in El-Menoufya, Egypt. He received the B.Sc. and M.Sc. degrees in electrical engineering from El-Menoufya University, Egypt, in 1991 and 1996, respectively, and the Ph.D. degree in electrical engineering from University Duisburg-Essen, Germany, in 2005. He was the Head of the Department of Electrical Power and Machines Engineering, Tanta University, the Director of the Quality Assurance Unit, and the Executive Director of the Continuous Improvement and Qualification for Accreditation Program. He was also the Vice Dean for Community Service and Environment Development. He is currently the Director of the Automated Library Project, Tanta University, and again the Head of the Department of Electrical Power and Machines Engineering, Tanta University. His research interests include the intelligent techniques, dynamic simulation, smart grids, distributed generating units, and renewable energy resources. He had been awarded Tanta University Incentive Awards in 2010 and Prizes for international publishing from 2010 till 2020.

HOSSAM A. ABD EL-GHANY was born in El-Beheira, Egypt. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical power and machines engineering from Tanta University, Egypt, in 2004, 2008, and 2015, respectively. He has been an Associate Professor with the Electrical Power and Machine Department, Faculty of Engineering, Tanta University, since December 2020. His research interests include the allocation of DG, power system protection, fault location, and smart grid.