

Article

Comparison of Efficiency-Based Optimal Load Distribution for Modular SSTs with Biologically Inspired Optimization Algorithms

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Abstract: The battle of currents between AC and DC reignited as a result of the development in the field of power electronics. The efficiency of DC distribution systems is highly dependent on the efficiency of distribution converter, which calls for optimized schemes for the efficiency enhancement of distribution converters. Modular solid-state transformers (SSTs) play a vital role in DC distribution networks and renewable energy systems (RES). This paper deals with efficiency-based load distribution for solid-state transformers (SSTs) in DC distribution networks. The aim is to achieve a set of minimum inputs that are consistent with the output while considering the constraints and efficiency. As the main feature of modularity is associated with a three-stage structure of SSTs, this modular structure is optimized using ant lion optimizer (ALO) and validated by applying it to the EIA (Energy Information Agency) DC distribution network which contains SSTs. In the DC distribution grid, modular SSTs provide the promising conversion of DC power from medium voltage to lower DC range (400 V). The proposed algorithm is simulated in MATLAB and also compared with two other metaheuristic algorithms. The obtained results prove that the proposed method can significantly reduce the input requirements for producing the same output while satisfying the specified constraints.

Keywords: solid-state transformer; direct current; renewable energy systems; ant lion optimizer

1. Introduction

The battle of currents between AC and DC dates back in the 19th century when the pioneers of electricity battled over their medium of power, with Tesla supporting AC and Edison supporting DC [1–3]. The first battle concluded in favor of Tesla, and AC began its rule over DC as medium of power transfer [2,4]. The victory of AC at the first place was predominantly due to the invention of transformers, which provided AC a mean of voltage level transformation, thereby reducing losses. However, this supremacy of AC was encountered by DC once again with the advancement of power electric converters, when DC achieved its means for transformation through power electronics-based DC transformers [5,6].

DC stroke back in full swing and started taking over all parts of the power system, i.e., generation (through solar and wind, as wind can be better optimized with DC); transmission (HVDC transmission) and utilization (DC load LEDs, energy-saving DC-inverter based air-conditioners, etc.) [7,8]. The distribution sector is still under research, and several research efforts have been published so far in the relevant field. The authors of current study have presented several studies encompassing the efficiency analyses of AC and DC distribution systems on comparative grounds [9–14]. It has been concluded in the efficiency analyses of DC distribution networks as well as in the comparative analyses between AC and DC distribution networks that the efficiency of the DC distribution system highly depends on the efficiency of the DC–DC distribution converter. An approach to achieve optimized results is through the use of the modular architecture of DC–DC converters, which is the basic aim of this paper.

Over the past few decades, the distribution grid has brought benefits of low-carbon and energy savings due to the soaring adoption of distributed energy resources (DERs). This modernization also requires new concepts, topologies, and control in some basic components of the distribution grid. The transformer is an essential component of the distribution network that performs functions of controlling, transferring, and handling power [15]. In order to maintain power quality, various devices, such as STATCOMs, FACTS, and others, are required. However, the latest developments in the smart grid demand a device that is capable enough to distribute power while maintaining power quality. The device is summed up as a solid-state transformer (SST) or an intelligent transformer [16].

Considering the efficiency of the traditional low-frequency transformer (LFT), it is initiated from 97% and varies up to 98.5% for liquid-immersed LFTs. However, it is evident from the present body of knowledge that SSTs have reached an efficiency of 98.25% in LV distribution networks [3]. SSTs have significant potential to replace the LFTs, as they provide other benefits such as smaller size and advanced control features. A comparison between the size and weight of SSTs and LFTs confirms that the SST structure provides remarkable volume savings, i.e., one-third of LFTs [17,18]. In contrast to traditional setups that are manufactured from copper and iron windings, SSTs have silicon carbide (SiC) windings which is a significant factor in reducing weight [19].

Different topologies for SSTs were explored in [17,18]; SSTs possess different classifications according to the stages, power levels, and applications. The authors [18,20] provided a comparison of one-, two-, and three-step topologies. The one- and two-step topologies have limitations of poor DC link fault tolerance and do not provide modularity. Figure 1 shows the three-stage SST topology, as this setup supports modularity in structure.

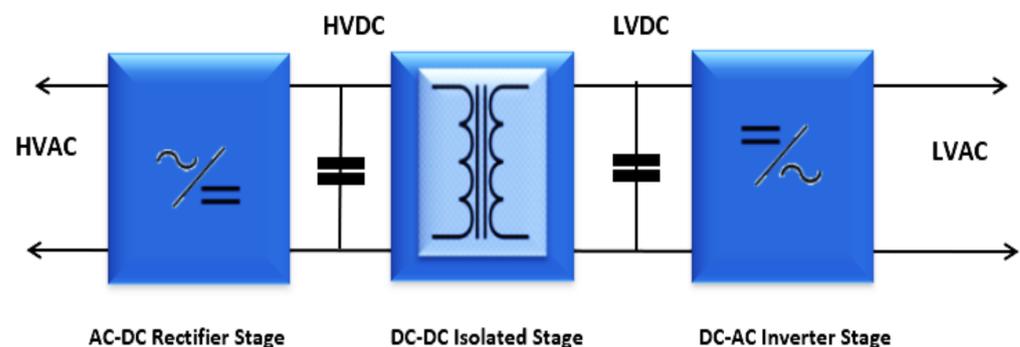


Figure 1. Three-stage SST topology.

Figure 2 illustrates the different compositions of solid-state transformers, such as module level, converter level, and system-level integrations. A modular SST possesses integrated power module (IPM) and provides different configurations, such as half bridge, multi-level converter and modular multi-level converters.

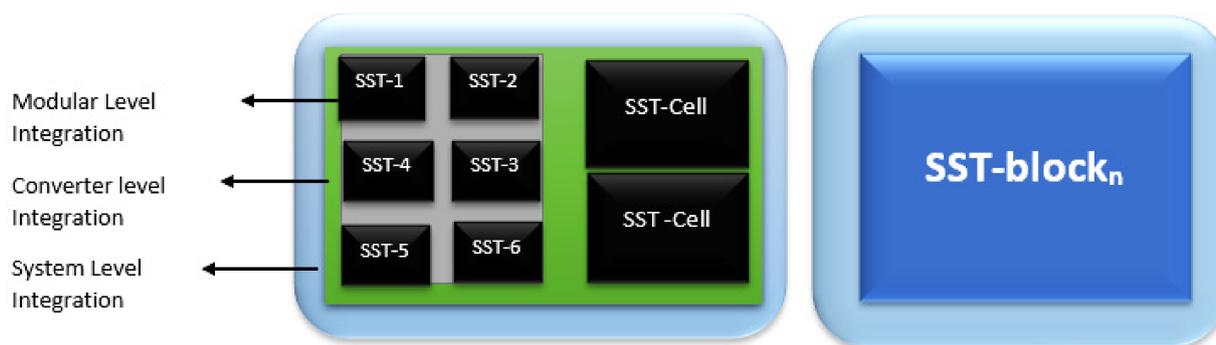


Figure 2. SST block with different modularity levels.

Modularity is an important feature that allows the same machine to be designed at a small level for multiple settings on a small scale at the same standard. The present body of knowledge proposes control strategies related to structural- and design-based optimization. The intelligence- or heuristic-based strategies for modular structure of SSTs are less explored throughout the literature. A basic control strategy was discussed for load division, which involves a simpler way to distribute load according to a specific bucket size scheme [21].

Economic load dispatch (ELD) or the optimal load distribution of generators has been explored by various researchers working in the field of power system operation and control. Many techniques, such as priority listing [22], LaGrange relaxation (LR), Linear Programming (LP), and dynamic programming (DP), have been implemented in research for ED problems [23–25]. However, all aforementioned techniques do not apply to non-smooth load curves. Therefore, in order to overcome this issue, metaheuristic algorithms, such as genetic algorithms (GAs), particle swarm optimization (PSO), artificial bee colony (ABC), and simulated annealing, are implemented for the solution of ED problems [26–29]. These algorithms provide fair efficiency values. Metaheuristic algorithms are optimization-based algorithms and categorized as: population-based and single point-based algorithms. Population-based algorithms prove valuable in searching several solutions at the same time [30–32]. The economic dispatch problem with scheduling of generators and renewable energy systems (RES) is addressed by various population-based techniques, such as ant lion optimization (ALO) [33], whale optimization (WOA) [34], grey wolf optimization (GWO), krill herd optimization [35], bat optimization algorithm (BOA) [36] and Salp swarm algorithm (SSA) [37].

In this paper, a novel technique is proposed which utilizes the efficiency parameter of SSTs along with load dispatch through the lambda iteration method. As the percentage loading capability/efficiency is an important consideration while optimizing load distribution in the DC distribution network, the proposed ALO algorithm is compared with the other two biologically inspired algorithms, which are GWO and WOA.

The rest of the paper is organized as follows. Sections 2 and 3 elaborate the problem formulation, which consists of two sub-sections: an overview for the ALO and an efficiency-based optimal load problem. The obtained results are discussed in Section 3. In the end, Section 4 concludes the work.

2. Problem Formulation

2.1. Ant Lion Optimizer

ALO is inspired by the hunting behavior of antlions. An ant lion larva moves in a circular path and digs out cone-shaped pits in the sand, consequently throwing the sand out. After digging, the larva hides underneath the cone and waits for the insects to come since the edges are sharp enough that insects easily fall to the bottom of the trap [38]. After consuming their prey, antlions prepare traps for other insects. In the next sections, this

meta-heuristic behavior is modeled mathematically, and the flowchart of this algorithm given in Figure 3 explains the workings.

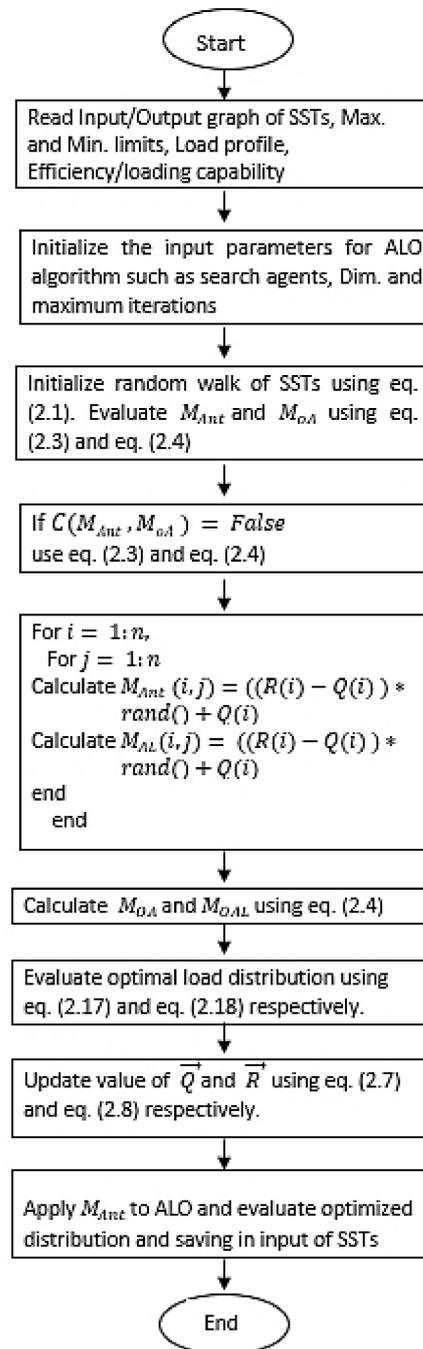


Figure 3. ALO flow chart.

2.1.1. Operators for ALO

ALO algorithm is derived from the interactions between antlions and the ants in the trap. The mathematical modeling of such a behavior requires the ants to move over search space as ants move stochastically and antlions hunt them. Naturally, ants move stochastically while searching for food; therefore, a random walk is selected for ant movement, stated as

$$Y(t) = [0, \text{cumSm}(2r((t_1) - 1), \text{cumSm}(2r((t_1) - 1) \dots \text{cumSm}(2r((t_n) - 1))] \quad (1)$$

where “cumSm” calculates the cumulative sum and “n” presents the maximum number of allowed iterations. $r(t)$ is a stochastic function and is defined as

$$r(t) = \begin{cases} 1 & \text{if rand} > 0.5 \\ 0 & \text{if rand} \leq 0.5 \end{cases} \tag{2}$$

where “t” defines the step of random walk (iteration in this study), and “rand” is a random number generated with uniform distribution in the interval of (0, 1).

$$M_{Ant} = \begin{bmatrix} Ant\ 1,1 & Ant\ 1,2 & \cdots & Antn,1 \\ Ant\ 2,1 & Ant\ 2,2 & \cdots & Antn,2 \\ \vdots & \dots & \ddots & \vdots \\ Ant\ n,1 & Ant\ n,2 & \cdots & Ant\ n,n \end{bmatrix} \tag{3}$$

This matrix M_{ant} refers to the parameters of each solution and saves the location of each ant. The ant objective function matrix is employed in the algorithm, which saves the fitness function of each candidate.

$$M_{OA} = \begin{bmatrix} Fobj(Ant1,1) & Ant1,2 & \cdots & Antn,1 \\ Fobj(Ant2,1) & Ant2,2 & \dots & Antn,2 \\ \vdots & \dots & \ddots & \vdots \\ Fobj(Antn,1) & Ant1,2 & \cdots & Antn,n \end{bmatrix} \tag{4}$$

Random Walks for Ants

Random walks are based on the cumulative sum equation. During each step of optimization, antlions update their position with a random walk. Following normalization, the equation is used to keep the random walk within the search space.

$$Y^n = R_i + \frac{(Y_i^t - P_i) * (Q_i - R_i^t)}{(Q_i^t - P_i)} \tag{5}$$

In the above equation, P_i and Q_i are the minimum and maximum number of random walks in the i th variable. R_i^t and P_i^t indicate the maximum and minimum i th variables in the t th iteration. Since random walks are solicited to all dimensions of ants, the above equation applies to all iterations due to limitations of search space.

Trapping in Antlion Pits

Antlion traps affect the random walk of ants, to model this system mathematically Equations (3) and (4) are proposed.

$$Q_j^t = Antlion_j^t | Q^t \tag{6}$$

$$R_j^t = Antlion_j^t | R^t \tag{7}$$

These equations provide information of random walk-in hypersphere defined by vectors Q^t and R^t around antlions.

Building Traps

A roulette wheel operator is employed to the algorithm for modeling the hunting capability of antlions. In the ALO algorithm, the roulette wheel operator is utilized to select antlions on the basis of their fitness functions. This process provides a scenario of better chances for the selection of the fittest antlions [39].

Sliding Ants towards Antlion

The antlions build traps according to their fitness, whereas the ants move randomly over the search space. Antlions shoot the sand upward after sensing the presence of prey, thus trapping the ants and not letting them escape. In order to model this behavior of hunters, the radius of the ants' random walks' hyper-sphere is decreased adaptively. Equations (6) and (7) are defined in this regard:

$$Q^t = \frac{Q^t}{I} \tag{8}$$

$$R^t = \frac{R^t}{I} \tag{9}$$

Catching Prey and Rebuilding Pit

The final stage calculates the objective function of the hunt. On the basis of the objective functions, ants are selected, and their positions are updated. The updated position is a position of the latest hunted ant, thereby enhancing the chances of preying on new ants. A mathematical model is provided in the given equation:

$$\text{Antlion}_j^t = \text{Ant}_i^t \text{ if } f(\text{Ant}_i^t) > f(\text{Antlion}_j^t) \tag{10}$$

Elitism

Evolutionary algorithms make use of elitism to maintain the best solution at each stage. In each iteration, every best antlion is saved and considered elite. A random walk around a selected antlion by a roulette wheel and elite candidate is depicted as

$$\text{Ant}_i^t = \frac{W_A^t + W_E^t}{2} \tag{11}$$

W_A^t is a random walk around the antlion selected by the roulette wheel, and W_E^t is the random walk around the elite at the t th iteration.

2.2. Objective Function

The objective function is formulated to optimally distribute the load on modular SSTs considering load and SST constraints. The ALO algorithm is employed to find out the minimum optimal amount of input on each SST. This objective function finds the lowest input power for modular transformer configurations. For SST, input/output curves are utilized for constructing a generalized second-order equation.

$$P_{jn} = c + bP_{oj} + aP_{oj}^2 \tag{12}$$

P_{jn} is the input of SST and P_{oj} is the output of each SST. In the above equation, a , b and c are derived using the curve-fitting technique. These equations can be generalized as

$$P_{j\text{-total}} = \sum_{j=1}^n P_{jn} = c + bP_{oj} + aP_{oj}^2 \tag{13}$$

Load balance constraints and SST minimum and maximum constraints are utilized for the formulation of the objective function. Supply and demand balance constraint is

$$\sum_{j=1}^n P_{oj} - P_D = 0 \tag{14}$$

where P_D is the load demand, and the output of SST should be equal to the consumption of the load side demand in the DC distribution network.

SSTs also observe some minimum and maximum output power limitations, such as distributed generators, which can be stated as

$$P_{SST,j}^{\min} \leq P_{SST,j} \leq P_{SST,j}^{\max} \tag{15}$$

To find out the solution of this constrained optimization, the lambda iteration method is utilized, where λ is used for constrained optimization

$$L = P_{jn-total} + \lambda \left(P_D - \sum_{j=1}^n P_{oj} \right) \tag{16}$$

For optimal values of SST, the efficiency of SSTs is also considered an important factor and employed as

$$P_{jn-total} = \frac{\sum_{j=1}^n P_{oj}}{\eta_{SST,j}} \tag{17}$$

$\eta_{SST,j}$ is an efficiency of SST and j is the number of SSTs.

For finding the values of η_{SST} , efficiency and loading capability curves are used for extracting the generalized equations for SSTs.

$$\eta_{SST,j} = \alpha + \beta L_{oj} + \gamma L_{oj}^2 \tag{18}$$

α , β and γ are coefficients for efficiency and loading graph. L_{oj} is the loading capability of the graph at each point.

For the procedure outlined above, the objective function values are updated in each iteration with a better solution. This iterative process continue until the termination criterion is satisfied.

The primary focus is to achieve a systematic reduction of input on the modular structure of SSTs using the ALO algorithm. This will provide an optimal distribution of load demand. The application of the ALO algorithm for modular SSTs has not been explored yet, and this is motivation to implement ALO for optimal load distribution of SSTs in the DC distribution system.

3. Simulation and Results

A residential load model of a typical US building is considered as in [9,40,41]. Data from EIA and DOE (Energy Efficiency Administration and Department of Energy) are utilized. The load profile contains AC native, DC native, and independent loads (A, D, and I type). In this problem, a set of 16 SSTs is utilized to form a modular architecture instead of employing a single non-modular SST. Figure 4 represents the modular structure for SSTs installed in the DC distribution system. Out of the 16 SSTs, 6 are from the market in sets of three and the other 10 are from the literature [42–46]. From [21], the input/output equations and loading/efficiency curves for optimal load distribution of modular SSTs setup are utilized.

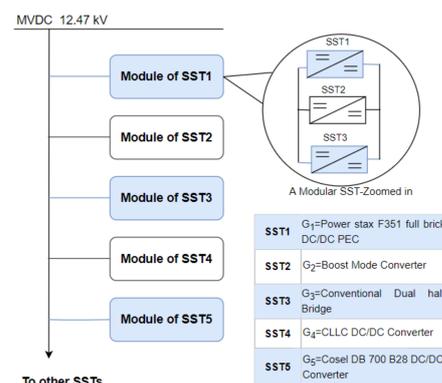


Figure 4. DC distribution system with modular structure zoomed in.

The problem is formulated in such a way that initially, the input/output equations from the graphs [21] are extracted using a curve-fitting tool in MATLAB. All these five graphs in Figure 5 provide a general quadratic equation with variable values if (α , β and γ).

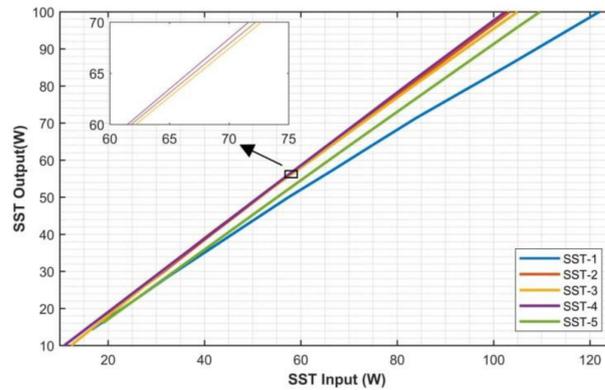


Figure 5. Output vs. input characteristics of SSTs.

Table 1 presents the SST equation parameters along with minimum and maximum power handling capabilities. p_o is the output power of a single SST and p_{in} is the input power. The data for modular SST structure comprising 16 SSTs are tabulated in Table 1, with corresponding SST configuration parameters with upper and lower operating limits.

Table 1. SST equation parameters.

SST Configuration Input/Output	α	β	γ	P_{min}	P_{max}
SST1-set of 3	0.0017	1.0409	1.4481	14.28	100
SST2-set of 3	0.003	0.9845	1.5944	20	100
SST3-set of 3	0.0010	0.9268	2.8204	10	100
SST4-set of 3	0.0002	0.9991	0.9542	10	100
SST5-set of 4	0.003	1.0438	2.1322	16	110

Efficiency and loading capability graphs are obtained from [21] and then by using MATLAB curve-fitting tools, quadratic equation constant parameters and the efficiency of each SST at every loading point are obtained. Figure 6 illustrates this efficiency vs. loading behavior at each loading condition.

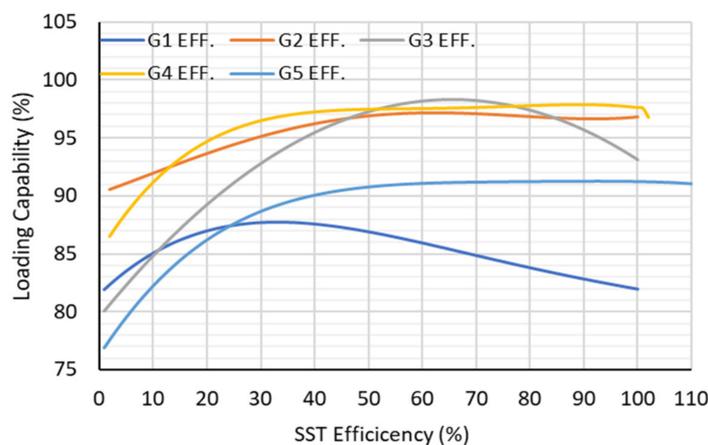


Figure 6. Efficiency vs. loading capability characteristics of SSTs.

A load profile from [9] is utilized for the optimal distribution of the load among SSTs in Figure 7. Moreover, a 24 h percentage loading profile is obtained by dividing each hour load by its maximum value and is presented in Figure 8. Table 2 provides the loading

vs. efficiency equation constants (a, b, c), which are used to find point-to-point data. This efficiency profile will help us to prioritize the most efficient generators to fulfill the load requirements.

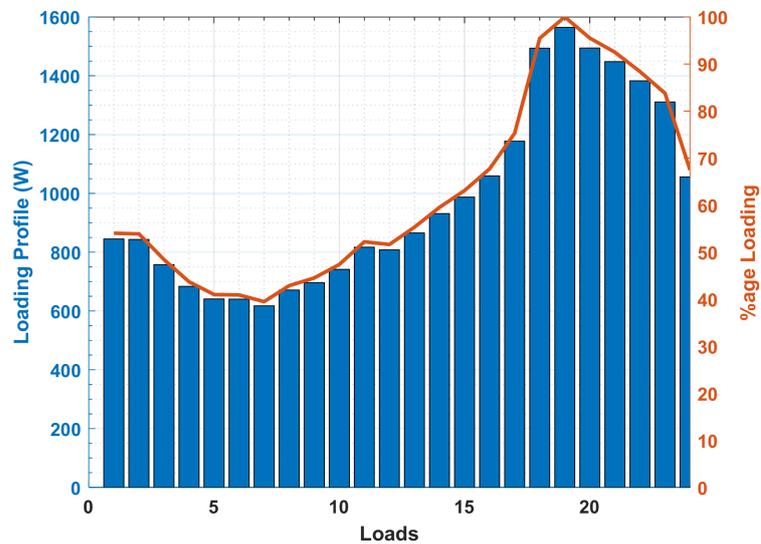


Figure 7. Load profile of DC distribution network [9].

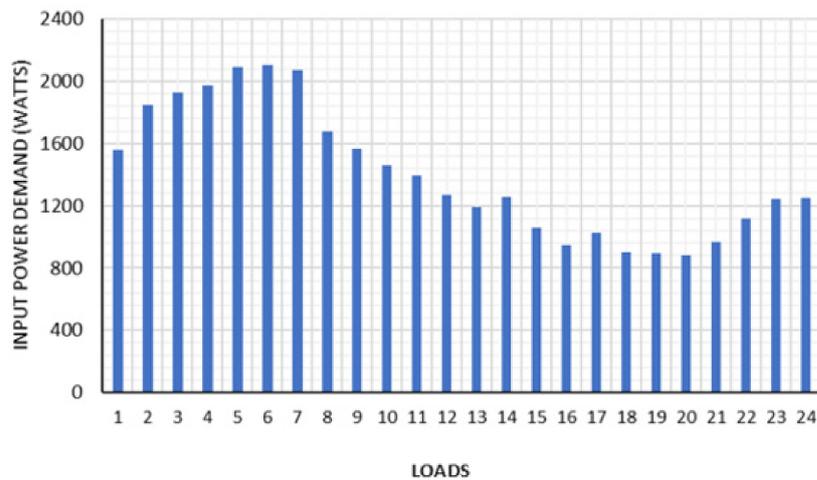


Figure 8. Load optimization using ALO without scheduling of SSTs.

Table 2. Efficiency vs. loading capability equation configuration parameters.

Loading/Efficiency	a	b	c
SST1	−0.0012	0.0780	85.9195
SST2	−0.0015	0.2206	89.5267
SST3	−0.0044	0.5768	79.4532
SST4	−0.0015	0.2108	90.6773
SST5	−0.0015	0.2444	81.9398

A test case scenario is simulated to highlight the efficiency of the proposed algorithm. ALO is implemented on modular solid-state structure with and without unit commitment. In this case, unit commitment is scheduled on basis of the efficiency of SSTs.

Scenario I: All 16 SSTs are ON and working while a load is optimally distributed using the ALO. In the test case I, all SSTs are utilized irrespective of their efficiency priorities during the simulation and optimal load distribution is executed in MATLAB. Figure 8 presents test case I, which is unscheduled SST incident and optimized with the ALO algorithm.

Scenario II: All 16 SSTs are working when 100% load is demanded, otherwise there will be SST scheduling according to the efficiency of SSTs. In this case, a unit commitment strategy is employed on the basis of the efficiency priorities of SSTs. When a load is less than maximum, only the most efficient SSTs are selected for operation. Figure 9 shows a visual illustration of the improvements achieved by using the scheduling of SSTs along with ALO, except the regions where all SSTs are ON, presenting the maximum demands in load profiles. For comparison, Scenarios I and II are utilized to investigate the scheduling effects on SSTs while using the ALO algorithm. This provides a visibly reduced amount of 1417.71539 W input, approximately 1.4 KW for the same amount of load.

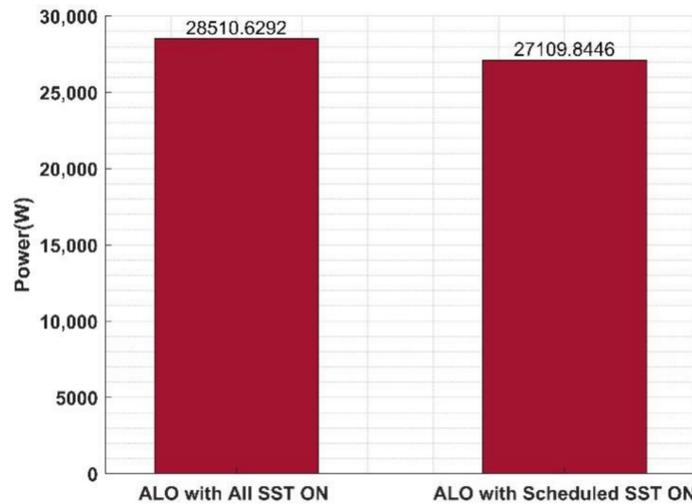


Figure 9. Comparison of ALO for scheduled and unscheduled SST scheme.

Scenario III: The test cases presented above are compared with other metaheuristic techniques, such as whale optimization and grey wolf optimization which is presented in Figure 10. Moreover, the results of Scenarios I and II are compared with Scenario III, where two different metaheuristic techniques (whale optimization algorithm (WOA) and grey wolf (GWO) optimization) are employed. This comparison provides superior results produced by ALO for load distribution when scheduling is considered. As shown in Figure 11, improvement achieved by ALO is 4.21 percent and followed by WOA (i.e., 0.9 percent); lastly, GWO does not provide any significant results.

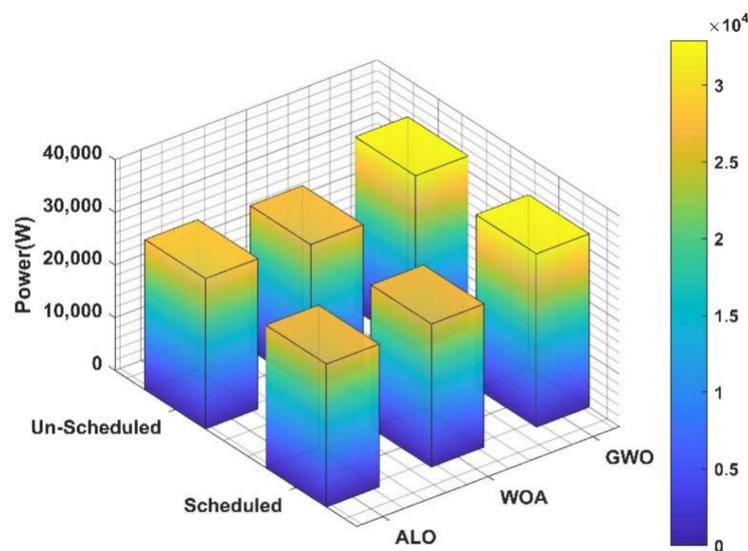


Figure 10. Comparison of ALO, GWO, and WOA for input reduction.

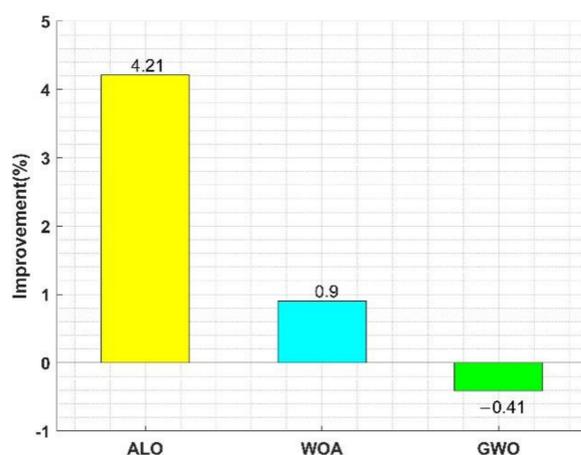


Figure 11. Efficiency improvement of ALO, GWO, and WOA with respect to unscheduled SSTs.

In contrast to the effectiveness, there are certain limitations to the use of these techniques. For example, ALO cannot produce fruitful results if the load profile is constant. Moreover, higher processing time is required to find a suitable search space

4. Conclusions and Future Recommendations

Various metaheuristic approaches play a paramount role in economic scheduling and dispatch. The present body of knowledge contains various approaches for improving the performance of power systems by economic load management. The trend is, however, shifting from conventional techniques to metaheuristic approaches. The ALO method is proposed to solve the optimal load distribution of modular SSTs. In this research, 16 SSTs of five different types are used in the DC distribution network. An objective function is formulated which considers the input/output behaviors of the SSTs and their minimum and maximum power handling capability. Three test cases are employed: S-I—all SSTs ON; S-II—only scheduled SSTs ON; and S-III—comparison with other metaheuristic methods. ALO provides better results for SST scheduling based on efficiency as compared to the other two methods (whale and grey wolf optimizer).

The most effective utilization of a scenario or available circumstances/resources is a stitch in time, considering the current energy situation. Many studies are presented and are under consideration dealing with the optimization of diverse scenarios, from all walks of life [47–50]. The current study may form a base for comparative efficiency analysis of AC and DC distribution systems with the DC system incorporating the suggested scheme of modular architecture. The battle of currents between AC and DC is still waiting for a definite verdict at distribution scale i–e as to whether DC is better than AC or not [51,52]. The proposed architecture possesses the tendency to lift the efficiency of DC at distribution scale as compared to AC, thereby assisting the researchers to reach a definite verdict in favor of DC. Therefore, a future study can be devised to incorporate the proposed scheme and employ it in a DC distribution network to present an efficiency comparison against AC distribution.

The escalating augmentation in the utilization of DC as medium of power transmission and distribution accompanied with sophisticated control has brought ease from the sustainability perspective and, on the other hand, complexity from the technical design perspective. The control of power coming from major renewable energy resources in smart grids demands the placement of SSTs rather than LFTs, leading to better efficiency, control and quality [53]. There is no doubt in the technical soundness of SSTs over LFTs; however, cost is the barrier hindering the path of adoption of SSTs. SSTs may not be suitable for conventional AC systems; however, SSTs do possess the tendency of providing better economics considering the efficiency analysis [54]. Passive devices installed in the SST are the major cost concern, speculations exist the mass production of SSTs may reduce the cost. Yet again, efficiency is the factor that once wiped DC out the power system in the

nineteenth century and it is the same factor based on which DC is striking back. Efficiency, or, more specifically, the operational efficiencies of any device, are definitely linked to its economics in terms of payback period, lifetime and sustainability when compared against any other device [55]. The current study presents the analysis in terms of the technical efficiency and paves the way for a future cost analysis. A futuristic analysis in this regard can be a study that furnishes the comparative analyses on techno-economic grounds that presents a compromise of technology over cost and vice versa.

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Abbreviations

DER	Distributed energy resources
LFT	Low frequency transformer
cumSm	Cumulative sum
$r(t)$	Stochastic function
t	Step of random walk
Rand	Random number generator
M_{ant}	Parameters of each solution
P_i	Minimum of random walks in i th variable
Q_i	Maximum of random walks in i th variable
R_i^t	Maximum i th variable in t th iteration.
P_i^t	Minimum i th variable in t th iteration.
W_A^t	Random walk around the antlion selected by the roulette wheel
W_E^t	Random walk around elite at the t th iteration
P_{jn}	Input of SST
P_{oj}	Output of each SST
(a, b & c)	Constants from Input/output quadratic equation
P_D	Load demand
$P_{SST,j}^{\min}$	Minimum and maximum output power limitations
$P_{SST,j}^{\max}$	Maximum output power limitations.
λ	Lagrangian constant
$P_{jn-total}$	Total input power of all SSTs
η_{SST}	Efficiency of j th SST
(α, β & γ)	Coefficients for efficiency and loading graph
L_{oj}	Loading capability of the graph
P_{in}	Input power of SST
P_{min}	Minimum power handling capability of SST.
P_{max}	Maximum power handling capability of SST.
HFT	High frequency transformer
DER	Distributed energy resources
LFT	Low frequency transformer

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