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 efficiency enhancement of distribution converters. Modular solid-state transformers 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. Aim is to achieve a set of minimum inputs that are consistent with output while considering constraints and efficiency. As the main feature of modularity is associated with a three-stage structure of SSTs. This modular structure has been optimized using Ant Lion Optimizer (ALO) and validated by applying it EIA (Energy Information Agency) DC Distribution Network which contains SSTs. In the DC distribution grid, modular SSTs provide promising conversion of DC power from medium voltage to lower DC range (400V). 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 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 reduction in losses. However, this supremacy of AC was encountered by DC once again with the advancement of power electric converters, when DC got 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 loads-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 DC-DC distribution converter. An approach to achieve optimized results is through the use of 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-saving due to the soaring adoption of DERs (Distributed Energy Resources). 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]. To maintain power quality, different devices such as STATCOMs, FACTs, and other devices are required. However, the latest developments in the smart grid require a device that can distribute power while maintaining power quality. This device can be summed up as a solid-state transformer (SST) or an intelligent transformer [16].

Considering the efficiency of the traditional low-frequency transformer (LFT) which is greater than 97% and varies up to 98.5% for liquid immersed LFTs. However, it is evident from the literature 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. Comparison between the size and weight of SSTs and LFTs shows that SST's structure provides remarkable volume saving i.e., one-third of LFTs [17, 18]. As traditional setups have copper and iron windings, and SSTs have Silicon Carbide (SiC) windings which is a significant factor in reducing weight [19].

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

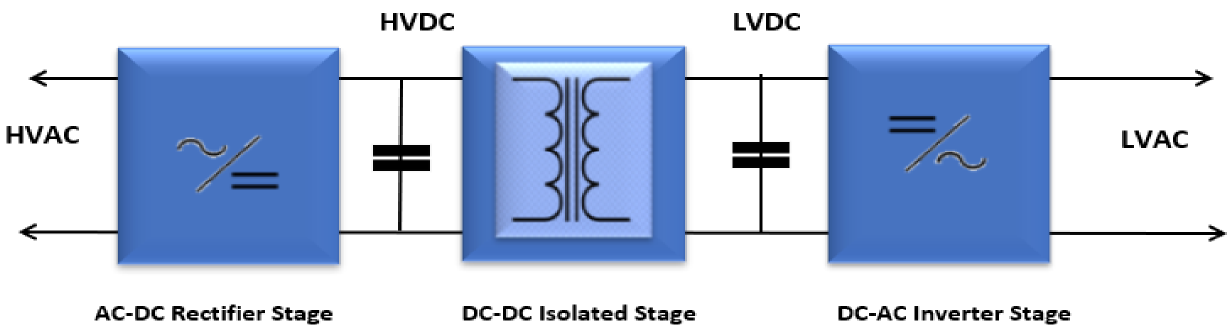

Figure 1. Three-stage SST Topology

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

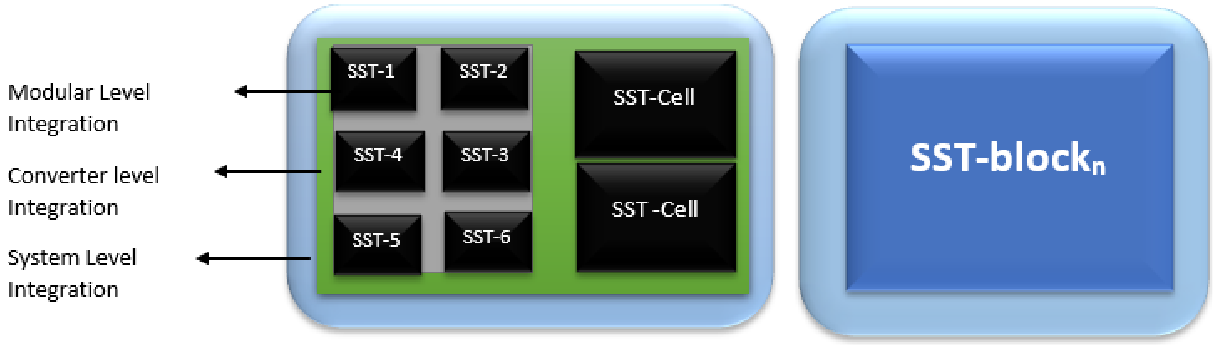

Figure 2. SST Block with Different Modularity Levels

As 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. In literature, mostly proposed control strategies are related to structural and design optimization. The intelligence or heuristic based strategies for modular structure of SSTs are less explored throughout literature. A basic control strategy has been 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 optimal load distribution of generators is a wieldy explored topic 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. So, to overcome this issue metaheuristic algorithms such as genetic algorithm (GAs) and particle swarm optimization (PSO), artificial bee colony (ABC), and simulated annealing have been implemented for the solution of ED problems [26-29]. These algorithms provide adequately good efficiency. Metaheuristic algorithms are optimization-based algorithms and categorized as: population-based and single point-based algorithms. Population-based algorithms work well in searching several solutions at same time [30-32]. For economic dispatch different 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] has been employed in literature for dispatch and scheduling of generators and Renewable Energy systems (RES).

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 percentage loading capability/efficiency is an important consideration while optimizing load distribution in the DC Distribution network. The proposed Ant Lion Algorithm is compared with the other two biologically inspired algorithms which are GWO and WOA.

The rest of the paper is organized as follows. Section 2 and Section 3 elaborates the problem formulation which consists of two sub-sections: an overview for the Ant Lion Optimizer (ALO) and an efficiency-based optimal load problem. The obtained results are discussed in Section 3 and section 4 concludes the work.

2. Problem Formulation

2.1 Ant Lion Optimizer

Ant lion optimizer is inspired by the hunting behavior of Ant lions as their name is derived from their unique hunting behavior. ALO algorithm mimics the hunting behavior of Ant lions in nature. An ant lion larva digs out coned shape pits in the sand by moving along a circular path and throwing sand out. After digging larva hide underneath the cone and wait for insects to come as edges are sharp enough that insects easily fall to the bottom

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of the trap. After consuming prey Antlions prepare traps for other insects. In the next sections, this meta-heuristic behavior will be modeled mathematically and the flowchart of this algorithm will explain working [38].

Operators for Ant Lion Optimization

Ant Lion Algorithm mimics interactions between antlions and ants in the trap. To mathematically model such behaviors, ants are required 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 ants' movement is provided as:

$$Y(t)= [0, cumSm(2r((t_1)-1, cumSm(2r((t_1)-1)..... cumSm(2r((t_n)-1)] \quad (2.1)$$

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:

$$r(t) = \begin{cases} 1 \ if \ rand > 0.5 \\ 0 \ if \ rand \leq 0.5 \end{cases} \quad (2.2)$$

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).

$$M_{Ant} = \begin{bmatrix} Ant\ 1{,}1 & Ant\ 1{,}2 & \cdots & Antn, 1 \\ Ant\ 2{,}1 & Ant\ 2{,}2 & \ldots & Antn, 2 \\ \vdots & \ldots. & \ddots & \vdots \\ Ant\ n, 1 & Ant\ n, 2 & \cdots & Ant\ n, n \end{bmatrix} \quad (2.3)$$

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

$$M_{OA} = \begin{bmatrix} Fobj(Ant1{,}1 & Ant1{,}2 & \cdots & Antn, 1) \\ Fobj(Ant2{,}1 & Ant2{,}2 & \ldots. & Antn, 2) \\ \vdots & \ldots & \ddots & \vdots \\ Fobj(Antn, 1 & Ant1{,}2 & \cdots & Antn, n) \end{bmatrix} \quad (2.4)$$

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 random walk with-in search space.

$$Y^n = R_i + \frac{(Y_i{}^t - P_i)*(Q_i - R_i{}^t)}{(Q_i{}^t - P_i)} \quad (2.5)$$

In above equation P_i and Q_i are a minimum and a maximum number of random walks in i[th] variable. R_i^t and P_i^t indicates maximum and minimum i[th] variable in t[th] iteration. As random walks are applied to all dimensions of ants so this above equation will be applied 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.

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$$Q_j^t = Antlion_j^t | Q^t \quad (2.6)$$
$$R_j^t = Antlion_j^t | R^t \quad (2.7)$$

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 in this algorithm to model the hunting capability of antlions. In the Ant lion Optimization algorithm, the roulette wheel operator is used to select antlions on basis of their fitness functions. This process provides better chances of selection for fittest antlions [39].

Sliding ants towards antlion:

In the proposed mechanism, antlions build traps according to their fitness and ants move randomly over search space. Antlions shoot sand upward after sensing the presence of prey so ants cannot escape the pit. To model this behavior of hunters, the radius of ants' random walks hyper-sphere is decreased adaptively. The equations 6, and 7 are defined in this regard:

$$Q^t = \frac{Q^t}{I} \quad (2.8)$$
$$R^t = \frac{R^t}{I} \quad (2.9)$$

Catching prey and rebuilding pit:

The objective function is calculated in the final stage of the hunt. On basis of objective functions, ants are selected and their positions are updated. This updated position will be a position of the latest hunted ant and this will enhance chances of preying on new ants. Mathematical model is provided in the given equation

$$Antlion_j^t = Ant_i^t \quad if\ f(Ant_i^t) > f\left(Antlion_j^t\right) \quad (2.10)$$

Elitism:

Evolutionary algorithms involve an important feature of elitism that allows them to maintain the best solution at each stage throughout the optimization process. In this algorithm, in each iteration, every best antlion is saved and considered elite. Therefore, random walk around a selected antlion by roulette wheel and elite candidates are as follows.

$$Ant_i^t = \frac{W_A^t + W_E^t}{2} \quad (2.11)$$

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

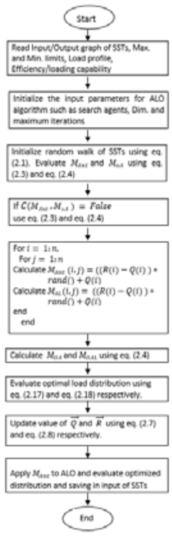

Figure 3. ALO Flow chart

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2.2 Objective function

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

$$P_{jn} = c + bP_{oj} + aP_{oj}^2 \quad (2.12)$$

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

$$P_{j-total} = \sum_{j=1}^{n} P_{jn} = c + bP_{oj} + aP_{oj}^2 \quad (2.13)$$

For this problem, load balance constraints and SST minimum and maximum constraints are utilized for the formulation of the objective function. Supply and demand balance constraint is

$$\sum_{j=1}^{n} P_{oj} - P_D = 0 \quad (2.14)$$

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

Solid-state transformers also observe some minimum and maximum output power limitations like distributed generators which can be stated as

$$P_{SST,j}^{min} \leq P_{SST,j} \leq P_{SST,j}^{max} \quad (2.15)$$

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

$$L = P_{jn-total} + \lambda(P_D - \sum_{j=1}^{n} P_{oj}) \quad (2.16)$$

For optimal values of SST, the efficiency of solid-state transformers is also considered as an important factor and employed as

$$P_{jn-total} = \frac{\sum_{j=1}^{n} P_{oj}}{\eta_{SST,j}} \quad (2.17)$$

$\eta_{SST,j}$ is an efficiency of SST and j is the number of solid-state transformers.

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

$$\eta_{SST,j} = \alpha + \beta L_{oj} + \gamma L_{oj}^2 \quad (2.18)$$

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

The primary focus of this is to achieve a systematic reduction of input on the modular structure of solid-state transformers using the ALO algorithm. This will provide an optimal distribution of load demand. The application of the Antlion Algorithm for modular solid-state transformers 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 here represented by the US in [9, 40, 41] by using data from EIA and DOE (Energy Efficiency Administration and Department of Energy). This 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

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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 these 16 SSTs, six are from the market in sets of three and the other ten are from the literature [42-46]. From [21] input/output equations and loading/efficiency curves for optimal load distribution of modular SSTs setup has been utilized.

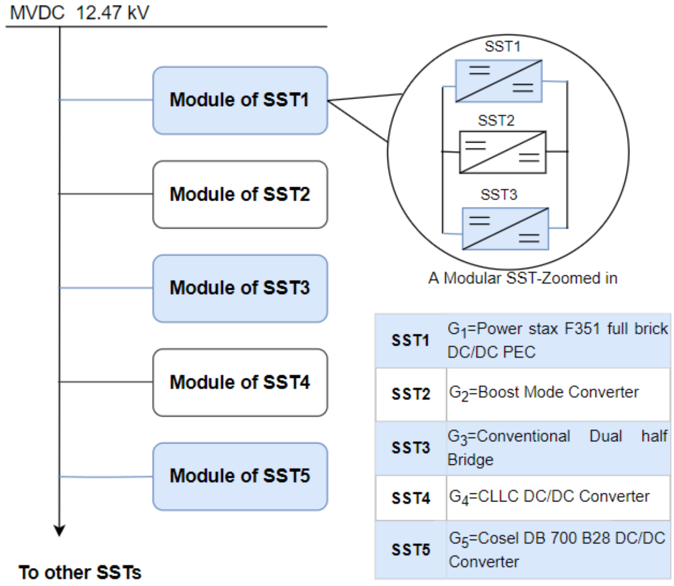

Figure 4. DC Distribution System with modular structure zoomed in

A problem has been formulated in such a way that firstly input/output equations from graphs [21] has been extracted using a curve fitting tool in MATLAB. All these five graphs in figure 5 provide a general quadratic equation with variable values if $(\alpha, \beta\ and\ \gamma)$.

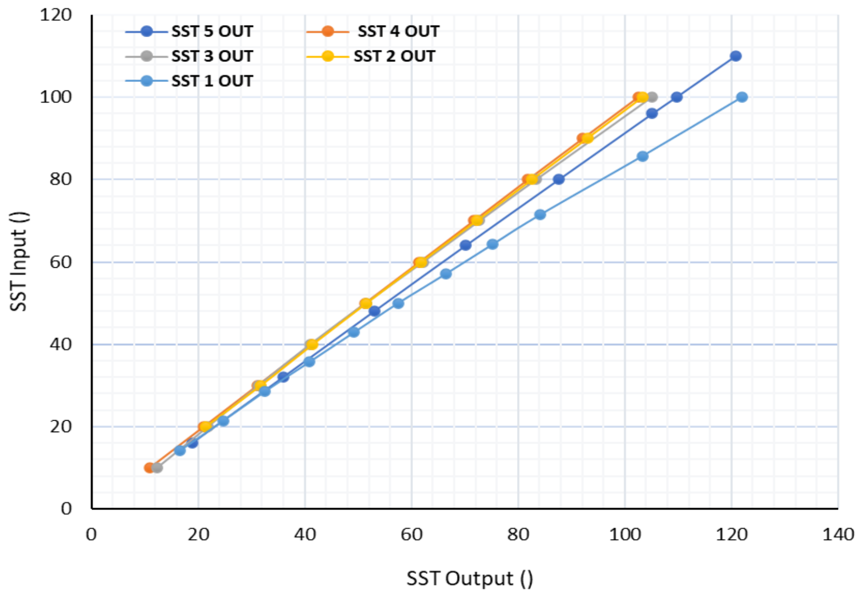

Figure 5. Output vs. Input characteristics of SSTs

Table 1 presents the SST equation parameters along with minimum and maximum power handling capabilities. As p_o is the output power of a single SST and p_{in} is the input power. Then for modular solid-state transformer structure containing 16 SSTs equation parameters are tabulated in Table 1 as 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 obatined from [21] and then by using MATLAB curve fitting tools quardatic equation constant parameters and efficiency of each SST at every loading point are obtained. Figure 6 is illustrating this efficiency vs. loading behaviour at each loading condition.

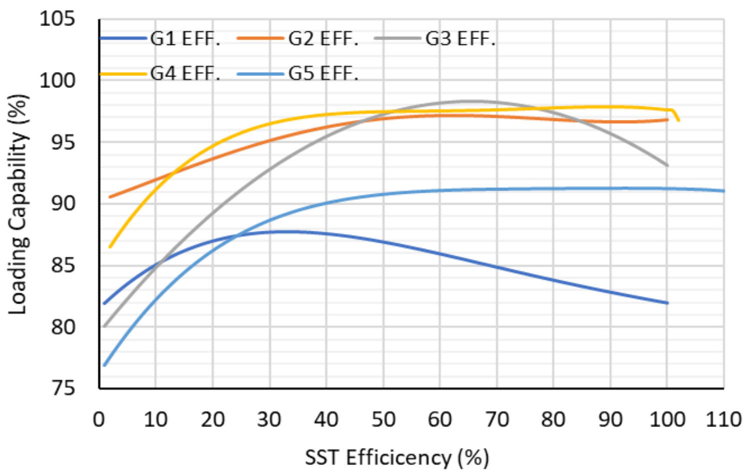

Figure 6. Efficiency vs. loading capability characteristics of SSTs

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

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A 24-h load profile from [9] has been used to optimally distribute load among SSTs in figure 7. Along this a 24-h percentage loading profile is obtained by dividing each hour load by its maximum value and presented in figure 8. Table 2 is providing loading vs. efficiency equation constants(a,b,c) which is used to find point to point data. This efficiency profile will help us to prioritize the most efficient generators to fulfill load requirements.

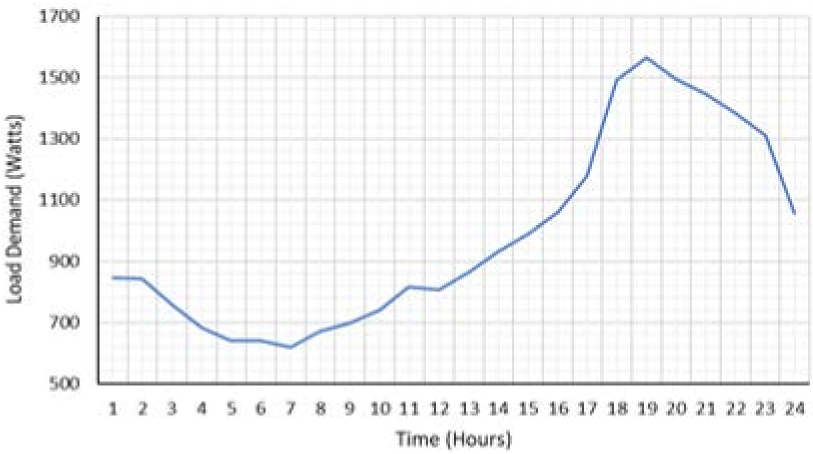

Figure 7. 24-h load profile of DC Distribution network [9]

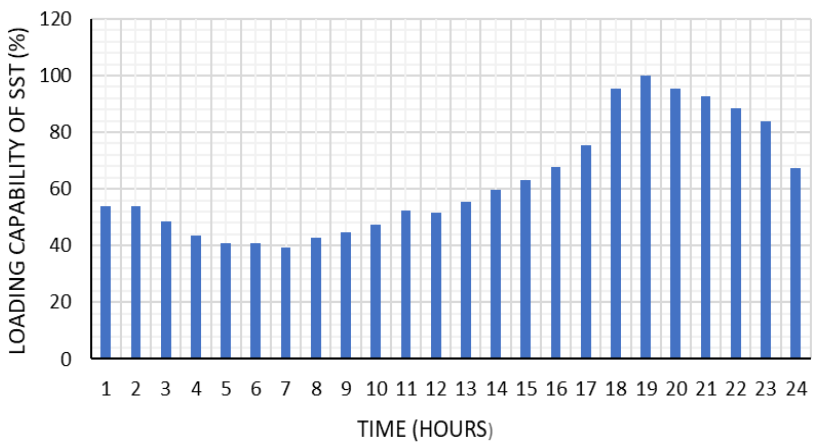

Figure 8. 24-h percentage loading Capability profile

To highlight the efficiency of the proposed algorithm, a test case scenario has been simulated. ALO algorithm has been 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 Ant Lion algorithm. In the test case I, all solid-state transformers are utilized irrespective of their efficiency priorities. during the simulation and optimal load, distribution is executed in MATLAB. Figure 9 is presenting test case I , which is unscheduled SST incident and optimized with ALO algorithm.

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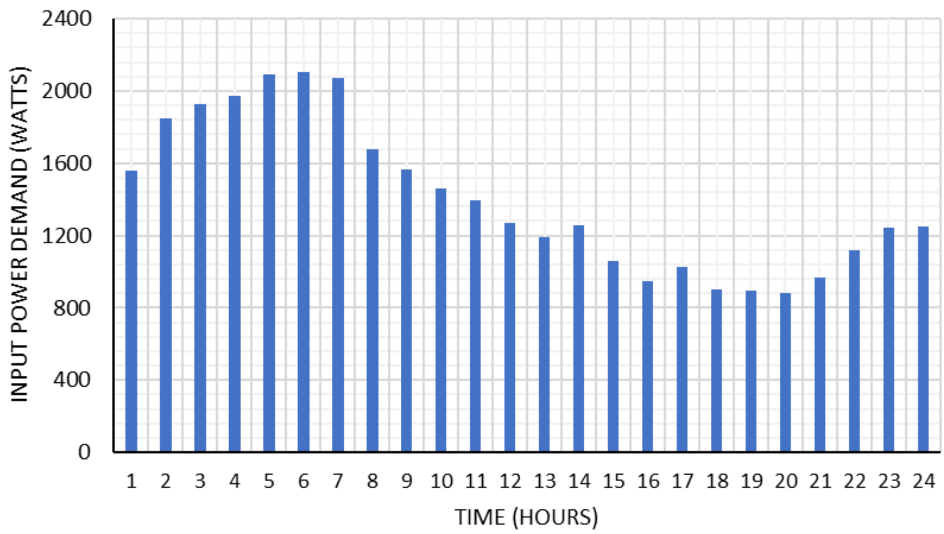

Figure 9. Load Optimization using ALO without scheduling of SSTs

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 basis of efficiency priorities of SSTs, when a load is less than maximum only the most efficient SSTs will be selected for operation. Figure 10 is visual illustration of improvements achieved by using 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 scheduling effects on SSTs while using the ALO algorithm. This provides a visibly reduced amount of 1417.71539W input approximately 1.4KW for the same amount of load.

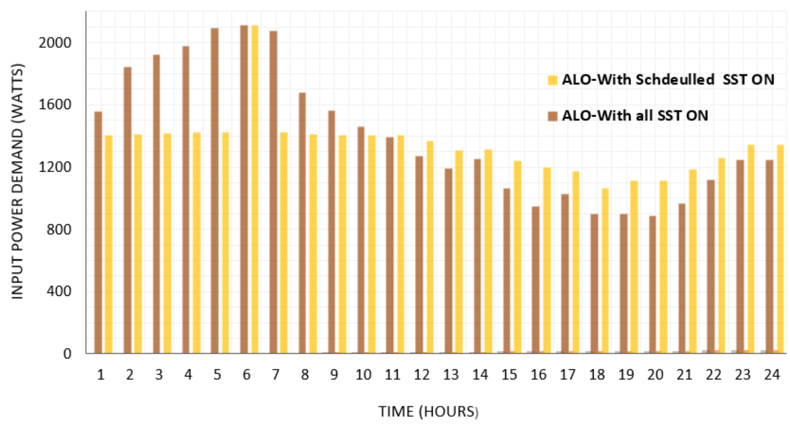

Figure 10. Comparison of ALO for scheduled and unscheduled SST scheme

Scenario III: Both above test cases has been compared with other metaheuristic techniques such as whale optimization and grey wolf optimization which is presented in figure 11. Moreover, the results of Scenarios I and II are compared with Scenario III where two other metaheuristic techniques whale optimization algorithm (WOA) and grey wolf (GWO) optimization have been employed. This comparison provides superior results produced by ALO for load distribution when scheduling is considered.

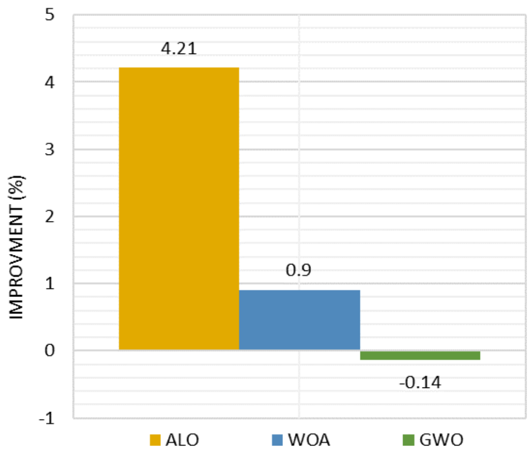

Figure 11. Comparison of ALO, GWO, and WOA for input reduction on SSTs

4 Conclusion

Different metaheuristic approaches play a vital role in economic scheduling and dispatch. Many researchers have been implemented different approaches for improving the performance of power systems by economic load management. To simulate the latest techniques, the ALO method is proposed to solve the optimal load distribution of modular SSTs. In this research sixteen SSTs of five different types are used in the DC distribution network. An objective function is formulated which considers input/output behaviors of 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 .The proposed method ALO provides better quality results for SST's scheduling on basis of efficiency as compared to the other two methods (Whale and Grey Wolf Optimizer).

The current study may form 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 whether DC is better than AC or not [47, 48]. 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 in a DC distribution network to present an efficiency comparison against AC distribution.

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