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A Novel Partial Search Based Technique for Optimal Shunt Capacitors Placement and Sizing in Radial Distribution Systems

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***Abstract*—**This paper presents a new partial search based approach for solving the radial distribution systems' optimal shunt capacitors placement and sizing problem. The approach is based on a recent metaheuristic technique, the Multi-Verse Optimizer and the Modified Loss Sensitivity Factors. Just as in other existing approaches, the MLSFs are firstly used to generate the search space for optimal buses for shunt capacitors placement. Thereafter, the Multi-Verse Optimizer is used to determine most optimal buses from the generated search space as well as the corresponding optimal shunt capacitor sizes. To evaluate the effectiveness of the developed approach, simulations have been carried out on the 33 and 69 bus radial distribution systems. However, this paper only reports on simulation results for the 69 bus radial distribution system. These results show that the developed approach gives better results in terms of real and reactive power losses reduction as well as the overall cost of real power losses and shunt capacitors purchase. Additionally, the developed approach also helps in reducing the search space but then still gives accurate solutions just like the exhaustive search.

***Keywords*—**Capacitor Placement, Modified Loss Sensitivity Factors, Multi-Verse Optimizer, Radial Distribution Systems, Search Space Reduction.

I. INTRODUCTION

Quite a good number of researchers, [1-9], have utilized different partial search based approaches in identifying the most optimal bus(es) on which to install shunt capacitors in radial distribution systems. In the cited works, the objective functions being optimized were formulated so as to either minimize the total annual cost of shunt capacitor placement and real power losses, or to maximize the real power loss reduction and the net savings. After their installation, the shunt capacitors indeed resulted into meeting the objectives for which they were installed.

Contrary to the exhaustive search, in partial search based approaches, a search for the most optimal bus(es) is carried out in a fraction of the entire search space. Elsheikh *et al.* [1], and El-Fergany *et al.* [3] searched for the most optimal bus combinations in 9 out of the 34 buses that make up the 34 bus radial distribution system. Further, El-Fergany *et al.* [2], and Youssef *et al.* [9] searched for the most optimal bus combination in 9, and 12 out of the 69 buses that make up the 69 bus radial distribution system respectively. On the other hand, Abou El-Ela *et al.* [6] searched for the most optimal buses in a combination of 45 out of the 85 buses that make up the 85 bus radial distribution system. Before searching through a fraction of the search space (under partial search based approaches), the buses of a given system are first of all ranked according to a defined criteria. In [1] and [3], the Loss Sensitivity Factors (LSF) criteria was used in ranking the buses while in [2], the Power Loss Indices (PLI) criteria was used. For the foregoing, the first n candidate buses in the ranks were selected so as to form the partial search space.

In their preliminary study on optimal shunt capacitors placement and sizing in radial distribution systems, Mtonga *et al.* [10] compared three approaches that researchers have used in identifying optimal buses on which to install shunt capacitors with the intent of reducing the overall cost of real power losses and shunt capacitors purchase. The three approaches that the authors compared were the exhaustive search, the rank based and the partial search. Amongst the three, the exhaustive search stood out as the best approach in terms of accuracy. This was seconded by the partial search based approach. In the three approaches under comparison, the accuracy as well as the computation times were influenced by the search space size. Under the exhaustive search, the search space was not reduced hence resulting in the most accurate solution and also having relatively high computation time. For partial search based approaches however, the search space was partially reduced hence resulting into having the approaches returning sub optimal solutions at relatively less computation time. Lastly, the rank based approaches gave the least computation time since in this approach the search space was very much reduced.

In [11], Mtonga *et al.*, introduced the Modified Loss Sensitivity Factors (MLSF) (through modification of the conventional Loss Sensitivity Factors) and used it in developing a partial search based approach for optimal shunt capacitors placement in radial distribution systems. The developed approach was tested on the 33 bus radial distribution system and this helped in reducing the search space by 90.63 percent with no compromise in solution's accuracy. In this current study the authors aim to reduce the search space further by introducing a modification to the partial search based approaches given in [1-

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9] and [11]. After the modifications, the final search space reductions for the 33 and 69 bus radial distribution systems are expected to be around 99 and 99.56 percent. This reduction is not expected to result in any compromise in the solution's accuracy.

In the approach presented in [11] focus was only placed on the ranking of the top most bus. However, in the approach being put forth in this paper, the ranking of each and every candidate bus is considered. For example, assuming that based on the MLSF the 9 buses given in (1) are ranked as in (2).

$$\{2,3,4,5,6,7,8,9,10\} \tag{1}$$

$$\{5,6,10,7,3,9,8,4,2\} \tag{2}$$

Based on the concepts of the MLSF, bus number 5 is considered to be the critical bus since it tops up the rank given in (2). In the approach that was proposed in [11], the elements of vector (1) were firstly used in generating a search space and thereafter only the bus combinations containing the critical bus were considered to be the candidate solutions. To illustrate this further, consider a combination of 2 elements of vectors (1) and (2). The results of these combinations are indicated in (3) and (4) respectively.

{2,3; 2,4; 2,5; 2,6; 2,7; 2,8; 2,9; 2,10; 3,4; 3,5; 3,6; 3,7; 3,8; 3,9; 3,10; 4,5; 4,6; 4,7; 4,8; 4,9; 4,10; 5,6; 5,7; 5,8; 5,9; 5,10; 6,7; 6,8; 6,9; 6,10; 7,8; 7,9; 7,10; 8,9; 8,10; 9,10} (3)

{5,6; 5,10; 5,7; 5,3; 5,9; 5,8; 5,4; 5,2; 6,10; 6,7; 6,3; 6,9; 6,8; 6,4; 6,2; 10,7; 10,3; 10,9; 10,8; 10,4; 10,2; 7,3; 7,9; 7,8; 7,4; 7,2; 3,9; 3,8; 3,4; 3,2; 9,8; 9,4; 9,2; 8,4; 8,2; 4,2} (4)

In [11], the search space was generated as in (3) (i.e. it was generated irrespective of the MLSF's ranking). On the other hand, in this paper, the search space will be generated as in (4) (i.e. the search space will be generated with consideration to the ranking of all the buses). Now if we only consider the bus combinations containing the assumed critical bus, then (3) and (4) reduces to (5) and (6).

$$\{2,5;\ 3,5;\ 4,5;\ 5,6;\ 5,7;\ 5,8;\ 5,9;\ 5,10\} \tag{5}$$

$$\{5,6;\ 5,10;\ 5,7;\ 5,3;\ 5,9;\ 5,8;\ 5,4;\ 5,2\} \tag{6}$$

In this study, the optimal bus combination is considered (as shall be shown in the results section of this paper) to be part of the combinations in the first rows of (6). Therefore, in picking out only a percentage of the bus combinations given in (6), one is guaranteed to pick the most optimal bus combination in the process.

In [11] as well as in this study, the original search space was reduced through the use of the MLSF and MATLAB's *any* and *ismember* commands. These commands are discussed in the Appendix section.

The rest of the paper is structured as follows: Section II briefly discusses the methodology that was used in this study. Afterwards, Section III presents and discusses the simulation results while Section IV gives a conclusion of the study.

II. Methodology

For this study, the results were generated through computer simulations which were carried out in MATLAB. The computer that was used in the simulations had the following specifications:

Processor type: Intel® Core™ i3-5005U
Processor speed: 2GHz
RAM size: 4GB

In the following subsections discussions about the 69 bus radial distribution system, the MLSF, the developed novel partial search based optimal shunt capacitors placement technique, the Multi-Verse Optimizer, the problem formulation and lastly, the evaluation criteria are presented.

A. Test Case: The 69 Bus Radial Distribution System

The developed approach was tested on the 69 bus radial distribution system which is made up of 69 buses and 68 branches. Its real and reactive power loads are equal to 3801.4 kW and 2693.6 kVAr respectively. The base case minimum voltage, real power losses and reactive power losses for the system are 0.9092 p.u., 224.8949 kW, and 102.1155 kVAr respectively. Details of the line and load data used in this study are adopted from [12].

B. Modified Loss Sensitivity Factors

Development of the Modified Loss Sensitivity Factors (MLSF) was carried out after noting a shortfall in the conventional Loss Sensitivity Factors (LSF) for cases where shunt capacitors were to be installed at a single bus within the 10, 33 and 69 bus radial distribution systems. For these systems, the bus which the LSF give out as the most optimal bus does not result in either the most minimal real power losses or the most minimal total cost of real power losses and shunt capacitors purchase when capacitors are installed on it. The MLSF counters this shortfall because for these factors the bus that is given out as the most optimal one does result in the most minimal real power losses as well as the most minimal total cost of real power losses and shunt capacitors purchase when capacitors are installed on it.

Unlike in the conventional LSF (in which the choice of optimal buses is dependent on the LSF value alone), for the MLSF, identification of the most optimal bus on which to install shunt capacitors within a given system is influenced by both the localized reactive power load at a given bus and its corresponding branches' loss sensitivity factor value [11]. With reference to Fig. 1, calculation of the MLSFs is achieved through the use of (7).

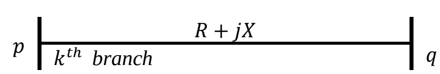

Fig. 1: A distribution branch between buses p and q

$$MLSF = \frac{\partial P_{loss_k}}{\partial Q_{pq}} \times Q_{Lq} = \frac{2Q_{pk}}{V_p^2} \times R_{pq} \times Q_{Lq} \tag{7}$$

where $\frac{\partial P_{loss_k}}{\partial Q_{pq}}$ is the kW per $kVAr$ change in real power losses;

Q_{pq} is the total reactive power flowing through the k^{th} branch (VArs); R_{pq} is the total resistance of the k^{th} branch (Ω); V_p is the voltage at bus p (volts) and lastly, Q_{Lq} is the reactive load at bus q.

After being ranked on the basis of the MLSF values, the sequence of compensation for the 69 bus radial distribution system is given as follows

{61, 49, 59, 12, 64, 7, 11, 8, 10, 55, 50, 54, 21, 48, 17, 65, 9, 6, 16, 13, 14, 53, 68, 62, 34, 24, 33, 45, 37, 51, 66, 26, 29, 39, 41, 18, 35, 27, 20, 36, 43, 28, 52, 22, 40, 69, 67, 46, 2, 3, 4, 5, 15, 19, 23, 25, 30, 31, 32, 38, 42, 44, 47, 56, 57, 58, 60, 63} (8)

C. The Developed Novel Search Space Reduction Technique

The developed search space reduction technique is based on the MLSF and MATLAB's *ismember* and *any* commands. However, the use of the MLSF is partial. In the developed approach, consideration is only given to the highly ranked bus within the MLSF bus rank vector. This bus is taken to be the critical bus and consequently, it is used in the initial reduction of the search space. After the initial search space reduction, a further reduction of the search space is achieved through the selection of a defined percentage of the already reduced search space. In this study, the chosen percentage has been determined based on the findings of El-Fergany *et al*. [2]. Accordinng to El-Fergany *et al*. [2], the selection of about 10 to 25 percent of the total number of buses ranked using Power Loss Indices (PLI) and then determining the most optimal solution from the selected list guarantees the attainment of absolute or sub optimal solutions.

This study first generates the search space and then picks out all the candidate solutions containing the critical bus. Afterwards, the search space is reduced further by picking about 10 to 25 percent of the combinations of the ranked candidate solutions. The following steps outline the processes involved in the developed novel search space reduction technique.

Step 1: Load the bus system under consideration and then calculate the MLSF. The 69 bus radial distribution system is loaded.

Step 2: Enter the number of buses at which one intends to have shunt capacitors installed. For this study the number is equal to 3.

Step 3: Using MATLAB's $nchoosek(A, r)$ command, generate the search space from which to search for the 3 most optimal buses for shunt capacitors placement. For the test system under consideration, matrix A is given by (8) and as given in step 2, r is equal to 3. Therefore, the search space is given as matrix B (9).

$$B = \begin{bmatrix} 61 & 49 & 59 \\ 61 & 49 & 12 \\ 61 & 49 & 64 \\ \vdots & \vdots & \vdots \\ 57 & 58 & 63 \\ 57 & 60 & 63 \\ 58 & 60 & 63 \end{bmatrix} \quad (9)$$

which is a (50116×3) matrix.

Step 4: Select the highly ranked bus in the MLSF bus rank vector given in (8) and make it a sole element of matrix C (10). It can be noted from (8) that bus 61 is the highly ranked bus. Therefore, matrix C is given as follows

$$C = [61] \quad (10)$$

Step 5: Use the $ismember$ command to check for the rows in matrix B which contain the sole element of matrix C, i.e. 61. Executing the command, $D = ismember(B, C)$ results into (11).

$$D = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (11)$$

From (11) it may be noted that there is a one for each location at which there was 61 while there are zeros for all other locations that did not contain the number 61.

Step 6: Create an all zeros matrix of the same dimension as the search space (i.e. matrix B (9) in this case). Designate this matrix as E (12).

$$E = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (12)$$

Step 7: Initialize i; where i represents the total number of rows in the search space (i.e. the total number of rows in matrix B for this case). For the considered example, i ranges from 1 to 50116 (as given in (9)).

Step 8: for i = 1:50116

(a) Select the i-th row from matrix B (9);

(b) Select the i-th row from matrix D (11);

(c) Determine the maximum value for the selected i-th row from matrix D by executing the MATLAB command $max(D(i,:))$;

(d) If $max(D(i,:))$ = = 1, replace the elements in the i-th row of matrix E by the elements in the i-th row of matrix B else maintain the zeros in the i-th row of matrix E and end;

Step 9: Print out the results from step 8. For this case the result is matrix E which is given in (13).

$$E = \begin{bmatrix} 61 & 49 & 59 \\ 61 & 49 & 12 \\ 61 & 49 & 64 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (13)$$

From (13) it can be noted that all other rows, except the ones which have the element 61, are made up of zeros.

Step 10: Use the *any* command given by equation A11 (in the Appendix section) to only print out the non-all-zero rows of matrix E. Executing the command, (any(E,2),:), results in (14).

$$Reduced\ search\ space = \begin{bmatrix} 61 & 49 & 59 \\ 61 & 49 & 12 \\ 61 & 49 & 64 \\ \vdots & \vdots & \vdots \\ 61 & 58 & 60 \\ 61 & 58 & 63 \\ 61 & 60 & 63 \end{bmatrix} \quad (14)$$

From (14) it can be noted that it is only the rows which contain the critical bus (i.e. bus number 61) that have been printed. These are in the form of a (2211×3) matrix. Consequently, application of this approach has led to a reduction of the search space dimensions from (50116×3) to (2211×3).

Step 11: Reduce the search space further by selecting about 10 to 25 percent of the already reduced search space given in (14).

The percentage is dependent on the size of the test system being dealt with. For medium and large systems, a relatively smaller percentage is preferred. However, for smaller systems the opposite is true [2]. In selecting a defined percentage of the already reduced search space, priority is given to the top most rows. For this study, 10 percent of the already reduced search space was selected. This translates to the 221 rows (i.e. 10 percent of 2211 rows) which are illustrated in (15).

$$Reduced\ search\ space = \begin{bmatrix} 61 & 49 & 59 \\ 61 & 49 & 12 \\ 61 & 49 & 64 \\ \vdots & \vdots & \vdots \\ 61 & 64 & 37 \\ 61 & 64 & 51 \\ 61 & 64 & 66 \end{bmatrix} \quad (15)$$

Fig. 2 gives a flowchart for the developed search space reduction technique.

D. The Multi-Verse Optimizer

Mtonga *et al.* [15] demonstrated the superiority of the Multi-Verse Optimizer (MVO) against Chicken Swarm Optimization algorithm, Cultural Algorithm, Flower Pollination Algorithm, Gravitational Search Algorithm and Particle Swarm Optimization algorithm. This comparison served as a supplement to the already existing literature on power system optimization using MVO [16-19]. Consequently, due to its proved effectiveness in optimal shunt capacitors sizing (proved by Mtonga et al. [15]), this study used it in identifying the discrete optimal shunt capacitor sizes to be installed in the 69 bus radial distribution system.

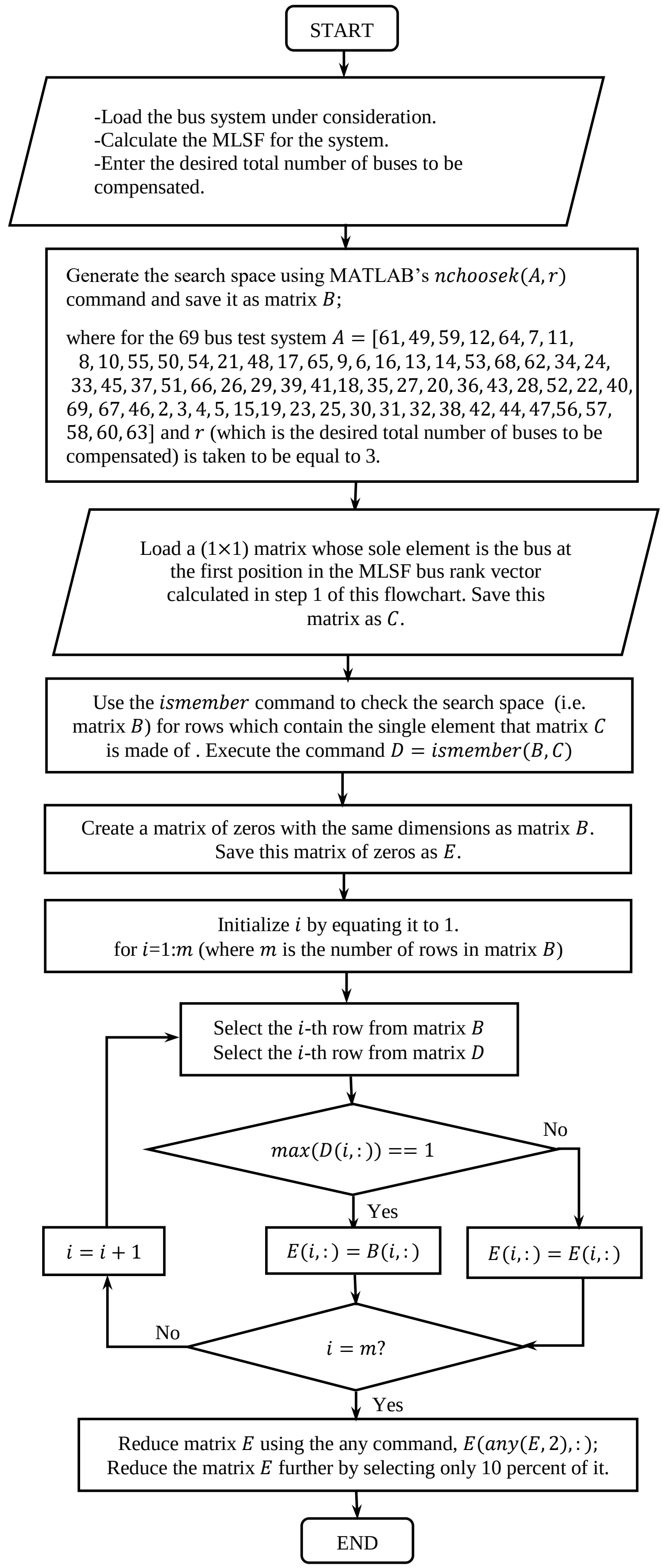

Fig. 2: Flowchart for the developed search space reduction technique

MVO, which belong to a family of nature inspired metaheuristic optimization algorithms, was released in 2015 by S. Mirjalili, S.M. Mirjalili and A. Hatamlou. The algorithm is based on the concepts of the black hole, the white hole and the worm hole. In the MVO, a candidate solution is termed universe and its fitness function value is termed inflation rate. For minimization problems, universes with lower inflation rates are considered to have a higher probability of having white holes while universes with higher inflation rates are considered to have higher probability of having black holes and the opposite is true for maximization problems. Now in an attempt to determine the desired inflation rate, universes with lower inflation rates tend to send objects (decision variables) to universes with high inflation rates through white holes. On the other hand, universes with high inflation rates tend to receive objects through black holes. The black/white hole mechanism is responsible for the search space exploration and its formula is given by equation (16) [20].

$$x_i^j = \begin{cases} x_k^j & r1 < NI(U_i) \\ x_i^j & r1 \geq NI(U_i) \end{cases} \tag{16}$$

In equation (31) x_i^j, U_i and $NI(U_i)$ denotes the j-th parameter of the i-th universe, the i-th universe and the normalized inflation rate of the i-th universe respectively. Lastly, $r1$ denotes a random number (between 0 and 1).

Contrary to the foregoing, the exploitation phase of the MVO is not influenced by the universes' inflation rates. However, at a given iteration, each and every universe undergoes the exploitation phase through the worm hole computational mechanism given by equation (17).

$$x_i^j = \begin{cases} \left.\begin{cases} X_j + \text{TDR} \times \left((ub_j - lb_j) \times r4 + lb_j \right) & r3 < 0.5 \\ X_j - \text{TDR} \times \left((ub_j - lb_j) \times r4 + lb_j \right) & r3 \geq 0.5 \end{cases}\right\} & r2 < \text{WEP} \\ x_i^j & r2 \geq \text{WEP} \end{cases} \tag{17}$$

where X_j denotes the j-th parameter of current best universe formed, TDR (Travelling Distance Rate) and WEP (Wormhole Existence Probability) are coefficients, lb_j and ub_j denote the lower and upper bounds of j-th variable, x_i^j indicates the j-th parameter of i-th universe while $r2, r3, r4$ are random numbers (between 0 and 1) generated using MATLAB's rand command. WEP is adaptive and decreases over iterations. Its formula is given by equation (18) [20].

$$\text{WEP} = \min + l \times \left(\frac{\max - \min}{L} \right) \tag{18}$$

In equation (18), min and max denotes minimum and maximum values respectively. Just as in [20], the values of min and max that this study has used are 0.2 and 1 respectively. Lastly, l and L correspondingly denote the current and maximum iterations.

On the other hand, TDR which defines the distance rate (variation) by which an object can be teleported around the best universe obtained so far is given by equation (19) [20]:

$$\text{TDR} = 1 - \frac{l^{1/p}}{L^{1/p}} \tag{19}$$

where p defines the exploitation accuracy over the iterations. In this study its value was set to 6 [20]. Further, in order to have more precise exploitation/local search around the best universe obtained, TDR is increased over the iterations. Fig. 3 gives the general flowchart for the MVO [15].

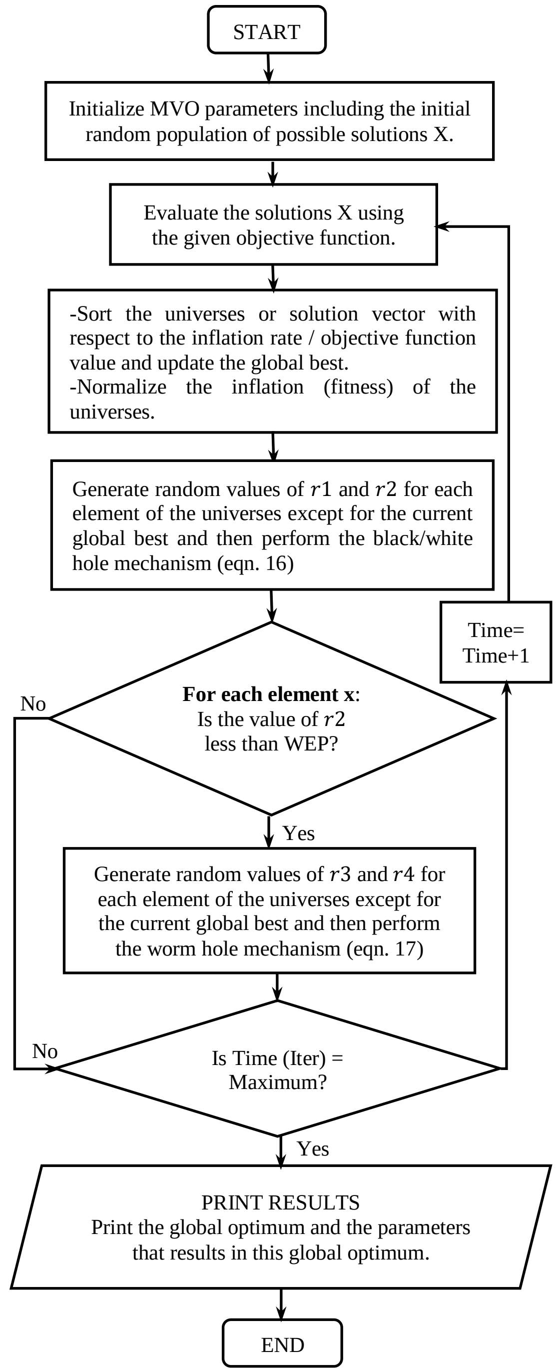

Fig. 3: Flowchart for the Multi-Verse Optimizer.

E. *Problem Formulation*

The objective function that was being minimized in this study is given in (20). Its minimization was guided by the constraints given in (21) and (22).

minimize{Total Real Power Losses Cost + Shunt Capacitors Purchase Cost}

$$minimize\left\{ K_e \sum_{j=1}^{nb} T_j \, P_j + \sum_{i=1}^{ncap} K_c Q_{ci} \right\} \tag{20}$$

$$V_{n,min} \leq |V_n| \leq V_{n,max} \tag{21}$$

$$Q_{cn,min} \leq Q_{cn} \leq Q_{cn,max} \quad (22)$$

In (20), K_e, which was taken to be 168$/kW-Year [21], denotes the average electrical power losses cost. On the other hand, nb denotes the total number of branches within a given electrical network while T_j denotes the duration of the load level under consideration (Years). P_j denotes the kW electric power loss in branch j and then K_c denotes the purchase cost of a given capacitor size per kVAr [21]. Q_{ci} is the size (kVAr) of the shunt capacitor installed at bus i and $ncap$ is the total number of buses with shunt capacitors installed. In this study, $ncap$ is equal to three. Further, V_n denotes the voltage magnitude at the n-th bus while $V_{n,min}$ and $V_{n,max}$ denotes the allowable minimum and maximum voltage limits at the n-th bus. Q_{cn} denotes the reactive power injection at the n-th bus while $Q_{cn,min}$ and $Q_{cn,max}$ denotes the allowable minimum and maximum reactive power injection at the n-th bus. In this work, $Q_{cn,min}$ and $Q_{cn,max}$ were set to 150 and 4050 kVArs while $V_{n,min}$ and $V_{n,max}$ were set to 0.9 and 1.1 p.u respectively.

Lastly, in minimizing the objective function, the MVO parameters such as the maximum iteration and the number of search agents were set to 50 and 30 respectively. The other variables like WEP_Min and WEP_Max were respectively set to 1 and 2.

F. Evaluation Criteria

The effectiveness of the developed approach was assessed through its application in solving the optimal shunt capacitors placement and sizing problem in the 69 bus radial distribution system. The solution attained by the proposed approach was evaluated by comparing it with those obtained by other approaches. The parameters forming a basis for comparison were the total yearly cost, the real power losses and finally, the reactive power losses.

In carrying out simulations for this study, the MVO was used in determining the optimal shunt capacitor sizes for four different cases. In the first case, the search space for optimal buses on which to install shunt capacitors was generated using the approach proposed in this paper. In the second and third cases, the search spaces for the buses were generated using the first 12 and 9 elements of the LSF and PLI bus rank vectors given in (23) and (24) respectively.

$$\{57,58,61,60,59,64,17,65,16,21,19,63\} \quad (23)$$

$$\{61, 64, 59, 65, 62, 57, 58, 60, 63\} \quad (24)$$

With 3 as the desired total number of buses on which to install shunt capacitors, the search spaces for the vectors in (23) and (24) would be 220×3 (i.e. $nCr = 12C3$) and 84×3 (i.e. $nCr = 9C3$) respectively. This same procedure was applicable to the fourth case. For this case the ranking for the buses combined the LSF that is based on the change of real power losses with respect to a change in the reactive power flow $\left(\frac{\partial P_{loss_k}}{\partial Q_{pq}}\right)$ and the one which is based on the change of real power losses with respect to a change in voltage $\left(\frac{\partial P_{loss_k}}{\partial |V_p|}\right)$ [9]. The ranking of the buses for this case is given in (25).

$$\{57,58,61,60,59,64,17,16,63,62,21,19\} \quad (25)$$

Futher, to sum up the assessment, results of the developed approach were also compared with those obtained by Teaching and Learning Based Optimization (TLBO) algorithm [23] and Flower Pollination Algorithm (FPA) [24].

III. Results and Discussion

Table I gives a tabulation of the results for this study. It is evident from the table that both the approach that this paper proposes and the one in [11] gives the best results in terms of the total yearly cost and the power losses (both real and reactive). These approaches result in a corresponding 34.33 and 35.37 percent reduction in the total yearly cost of real power losses and shunt capacitors purchase, and the hourly real power losses. On the other hand, in terms of the minimum voltage, these approaches slightly fall behind the rest of the approaches.

However, the approach proposed in this paper is a better one because it results in a reduction of the search space from 50116 to 221 (i.e. 99.56% reduction) while the method in [11] reduces this search space from 50116 to 2211 (i.e. 95.59% reduction). Consequently, it can be concluded that the approach presented in this paper is better than the one presented in [11].

Table I: Comparison of the simulation results for the 69 bus radial distribution system

Parameters	Uncompensated	Compensated						
		TLBO [23]	FPA [24]	MVO				
				Combined [9]	PLI [23]	LSF [23]	Method in [11]	**Proposed**
Year		2014	2018	2020	2020	2020	2020	**2020**
Total cost/year ($)	37,782.34	25,027.71	24,963.20	24,946.49	25,746.80	24,946.49	24,811.09	**24,811.09**
Cost reduction/year (%)	-	33.76	33.93	33.97	31.85	33.97	34.33	**34.33**
Net savings/year($)	-	12,754.63	12,819.14	12,835.85	12,035.54	12,835.85	12,971.25	**12,971.25**
Real power losses/hour (kW)	224.8949	146.3173	145.803	146.2053	151.2030	146.2053	145.3466	**145.3466**
Loss reduction/hour (%)	-	34.94	35.17	34.99	32.77	34.99	35.37	**35.37**
Reactive power losses/hour (kVAr)	102.1155	68.0291	67.907	68.141	70.1176	68.141	67.7536	**67.7536**
Loss reduction/hour (%)	-	33.38	33.50	33.27	31.34	33.27	33.65	**33.65**
Optimal buses and capacitor sizes in kVAr	-	12 600 61 1050 64 150	11 450 22 150 61 1350	17 300 57 150 61 1200	57 150 61 900 64 300	17 300 57 150 61 1200	12 450 21 150 61 1200	**12 450** **21 150** **61 1200**
Total kVAr	-	1800		1650	1350	1650	1800	**1800**
V_{min}	0.9092	0.9313	0.93304	0.9313	0.9313	0.9313	0.9308	**0.9308**
Search space size		-	-	(220×3)	(84×3)	(220×3)	(2211×3)	**(221×3)**
Computation time (s)		-	-	10759.19	3602.71	10759.19	113,223.33	**11,320.93**

After implementing the proposed approach and then using MVO to search for the most optimal bus combination (while at the same time searching for the most optimal shunt capacitor sizes for each given bus combination) from the reduced search space, the algorithm returns 12, 21 and 61 as the most optimal bus combinations. For the uncompensated case these buses register 0.9682, 0.9569, and 0.9123 p.u. as bus voltages. Now when using the PLI approach, buses 12 and 21 are discarded as candidate solutions due to them having voltages of not less than 0.9500 p.u.. Consequently, due to this, the PLI approach fails to determine the most optimal bus combination, i.e. 12, 21, 61 and then settles for 57,61, 64. In a similar manner, when using the LSF and the combined approach, bus number 12 is discarded as a candidate solution because its normalized voltage level is not less than 1.01. Therefore, despite having the other two buses (21 and 61) in the 12 element bus rank vector (23), these approaches also fail to determine the most optimal bus combination (i.e. 12, 21, 61).

In determining the most optimal buses, the three approaches (LSF, PLI and the combined approach) segregate candidate buses based on their voltages and from the presented results it can be seen that this is improper because it inhibits an algorithms ability to identify the most optimal candidate bus combination. On the other hand, the methods in [11] and the one presented in this paper do not segregate candidate buses based on voltage hence their ability to determine the most optimal candidate bus combination.

IV. Conclusion

This study has introduced a new partial search based approach for optimal shunt capacitors placement and sizing. For optimal placement, the approach ranks the candidate buses based on MLSF and then generates a search space from which the optimal buses are to be determined. Unlike in a number of existing approaches (LSF, PLI, Combined approach), the developed approach does not segregate candidate buses based on voltage. For this approach, all the system buses (except the slack bus) qualify as possible candidate buses for the installation of shunt capacitors. However, the candidate buses' corresponding MLSF has an influence on the chance of the buses being picked and evaluated when a fraction/percentage of the search space is selected.

The partial search based shunt capacitors placement and sizing approach developed in this paper has proved its effectiveness by being able to attain the least objective function value (i.e. the total cost per year) within relatively short computation times. Additionally, the approach has also proved its effectiveness by being able to give the best values in terms of the real and reactive power losses.

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APPENDIX

MATLAB's *ismember* and *any* commands

According to [13], $Lia = ismember(A, B)$ returns an array containing 1 (true) where the data in A is found in B and elsewhere it returns 0 (false). For example, when given matrices, A and B (shown in (A1) and (A2) respectively)

$$A = \begin{bmatrix} 2 & 3 & 4 & 5 \\ 4 & 6 & 7 & 9 \\ 2 & 1 & 7 & 8 \\ 5 & 3 & 8 & 7 \end{bmatrix} \quad (A1)$$

$$B = [5] \quad (A2)$$

Executing the command, $Lia = ismember(A, B)$ results into (A3)

$$Lia = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \quad (A3)$$

From (A3) it may be noted that the last element in the first row and the first element in the last row are ones while the rest are zeros. That is, there is a one for each location at which there was a five while there are zeros for all other locations that did not contain the number five. This trait of the *ismember* command greatly helped in the development of the search space reduction technique.

On the other hand, [14] states that the *any* command determines if any array elements are non-zeros such that if A is a vector, then $B = any(A)$ returns logical 1 (true) if any of the elements of A is a non-zero number or logical 1, and returns logical 0 (false) if all the elements are zero. For example, for matrix A (as shown in (A4))

$$A = \begin{bmatrix} 6 & 8 & 1 & 2 \\ 3 & 9 & 5 & 4 \end{bmatrix} \quad (A4)$$

Executing the command, $B = any(A)$ results into (A5)

$$B = any(A) = [1 \quad 1 \quad 1 \quad 1] \quad (A5)$$

In (16), the any command checks every column of matrix A and since none of the columns is made up of all zeros, the command $any(A)$ returns a (1×4) row matrix made up of all ones.

On the other hand, executing the command, $C = any(A, 2)$ results into (A6)

$$C = any(A, 2) = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad (A6)$$

In (A6), the any command checks every row of matrix A and since none of the rows is made up of all zeros, the command any(A,2) returns a (2×1) column matrix made up of all ones.

Furthermore, for matrix D (as shown in (A7))

$$D = \begin{bmatrix} 1 & 9 & 11 \\ 0 & 0 & 0 \\ 18 & 8 & 3 \end{bmatrix} \quad (A7)$$

Executing the command, E = any(A) results into (A8)

$$E = any(A) = [1 \quad 1 \quad 1] \quad (A8)$$

In (A9), the any command checks every column of matrix D and since none of the columns is made up of all zeros, the command any(D) returns a (1×3) row matrix made up of all ones.

On the other hand, executing the command, F = any(A,2) results into (20)

$$F = any(A, 2) = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \quad (A9)$$

In (20), the any command checks every row of matrix A and since row number 2 is made up of all zeros, the command any(A,2) returns a (3×1) column matrix whose rows, except the second, are made up of ones.

Taking a look at another matrix A (given in (A10))

$$A = \begin{bmatrix} 5 & 9 \\ 0 & 0 \\ 7 & 3 \end{bmatrix} \quad (A10)$$

For this matrix, executing the command B=(any(A,2),:) results into (A11)

$$B = A(any(A, 2), :) = \begin{bmatrix} 5 & 9 \\ 7 & 3 \end{bmatrix} \quad (A11)$$

That is, the command deletes the rows in (A10) that are made up of all zeros. Additionally, the command C = (~any(A,2),:) results into (A12)

$$C = A(\sim any(A, 2), :) = [0 \quad 0] \quad (A12)$$

That is, the command prints out the rows in (A10) that are made up of all zeros.