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A Cloud Based Model Symbiotic Organism Search Algorithm for Placement of Distributed Energy Resources in the Electrical Secondary Distribution Networks

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Abstract

The increased penetration of distributed energy resources (DERs) technologies to residential users has fostered the need for DERs integration and control methods in the secondary distribution networks (SDN). In order to reap the potential advantages of DERs and achieve their inclusion in the electrical power system while avoiding their negative impacts, the DERs should be optimally placed and sized. Considering the nature of electrical networks and DER operations, the DERs placement is a nondeterministic polynomial hard (NP-hard) optimization problem. Metaheuristic algorithms are efficient for solving DER placement problems. Metaheuristic algorithms for DER placement in SDN involve high computational effort, theoretical convergence assumptions that cannot be satisfied in the real world and dependence on parameter settings. Therefore, this study proposes a DER placement algorithm that employs a cloud-based model symbiotic organism search algorithm (CMSOS). The CMSOS is attributed to simple implementation and computation, good convergence, and parameter independence. The electrical network segment taken for Tanzania's electrical distribution network was used for testing the algorithms, considering power loss and voltage deviations. Results show that using DERs in the proposed locations reduces power loss by 89.3%. The convergence profile shows that the proposed CMSOS-based algorithm converges faster than the conventional symbiotic organism search algorithm (SOS).

Keywords: Metaheuristic Algorithms, Symbiotic Organism Search, DER Placements, Radial Distribution Network, Cloud-based model.

Introduction

The Electrical Power System (EPS) consists of generation plants, a transmission network, an electrical Primary Distribution Network (PDN), an electrical Secondary Distribution Network (SDN), and their associated control components (Schavemaker and Van der Sluis 2017). The SDN is sometimes called the Low Voltage (LV) network. It supplies power to individual customers from the service transformer at 0.4 kV (Zidan et al. 2017, Agbetuyi et al. 2021). Relative to other EPS parts, the SDN is more complex and dynamic and involves distinctive considerations and challenging scenarios. Unlike in PDN, in the SDN, there are no switches to simplify the reconfigurations. SDN involves short conductors with a large resistance-to-reactance (R/X) ratio, which is associated with more power losses and voltage violations than PDN (Zehir et al. 2017). The SDN is complex due to many possible arrangements and changing connections, unlike PDN, where the topology remains nearly settled and fewer parameters are considered (Avilés et al. 2020). The characteristics of SDN complicate the implementation of automated systems for protection, fault monitoring and control (Joseph and Mvungi 2014, Haes et al. 2019). In SDN, the reachability of backup feeders and laterals is difficult, leading to inefficient Service Restoration (SR) (Fan et al. 2021). Due to SDN characteristics and manual network operations for many developing countries, prolonged outages, power losses, voltage violations, and increased operational costs are very common (Kumar et al. 2006).

Distributed Energy Resources (DERs) involvement is among modern solutions for enhancing power system performances and significantly reducing outage time (Xu et al. 2017, Koutsoukis et al. 2019). The DERs are small generating units connected to the distribution networks near the point of use (Andrade et al. 2020). The DERs include renewable and non-renewable energy resources such as solar, small hydro, wind and gas turbines, and reciprocating engines (Khetrapal 2020). The DER units can locally support loads during the restoration process, minimize the number of switching operations, minimize restoration time, and provide opportunities to restore additional unrestored loads (Shen et al. 2019). In addressing power losses and system inefficiency in the distribution systems, the involvement of DERs has been more efficient than other techniques (Hussain et al. 2021). The ability of DERs to support grid operations has pushed many electric utilities worldwide to accommodate customers with generation capabilities (Hatziargyriou et al. 2016, Mahmoud et al. 2016).

Installation of DERs in power systems avoids many problems imposed by traditional power systems and offers several benefits to electric utilities and customers (Karimyan et al. 2014). However, the introduction of DER into the power system is challenging due to the intermittency of DER units and the structure of the power system infrastructure of most electric utility companies. The designs of existing power systems for most countries, including Tanzania, support one-way power flow and dependence on weather events for most DERs technologies hamper DERs penetration in the SDN (Mohammadi and Mehraeen 2016). Despite these challenges, the ability of DERs to provide green energy, the push for carbon-free power systems and the increased penetration of DERs technologies to residential users have fostered the need for establishing methods for DERs integration and control in the low voltage electrical networks (Alejandro 2015, Ma et al. 2019).

In achieving DER inclusion in the electrical power system, the DERs should be optimally placed and sized (Karunarathne et al. 2020). Studies have indicated that installing DER units at non-optimal places can result in negative impacts such as increasing system losses, reconfiguration of the protection scheme, voltage fluctuations and an increase in operation costs (Viral and Khatod 2012, Naik et al. 2014). The DER placement algorithms help the distribution system operators, such as Tanzania Electric Supply Company Limited (TANESCO), to determine the optimal locations and sizes of the DERs during system planning (Essallah et al. 2019). When the DERs are already in place, as the situation in the SDN with increased penetration of DERs technologies to residential users, the DERs placement algorithm can be used to suggest the optimal DERs sizes. Considering many possible locations for placing DERs in distribution networks and infinitely many possible sizes of DERs, getting optimal values is very challenging, making the DERs placement NP-hard optimization problem.

Several methods have been proposed for solving the DER placement problem, including the analytical, numerical and metaheuristic methods (Kola 2018). Analytical methods are formulated based on simplified assumptions leading to only indicative results. Numerical methods are slow and fail to converge for large-scale problems. Metaheuristic algorithms for DERs placement problems are trending and applied mostly in PDN (Dash et al. 2021). Considering the aforementioned characteristics of SDN, the DER placement problem is more difficult in SDN than in PDN. Therefore, methods designed for PDN may not work efficiently in SDN. Few studies reported the applications of metaheuristic algorithms in SDN for such purposes. Avilés et al. (2020) proposed an approach for network reconfigurations and optimal placement of transformers in SDN using Particle Swarm Optimization (PSO). Method for placement and sizing of Energy Storage Systems (ESS) in radial LV systems were reported (Giannitrapani et al. 2016, Jannesar et al. 2018, Mazza et al. 2020). However, such metaheuristic methods by authors in Giannitrapani et al. (2016), Jannesar et al. (2018), Mazza et al. (2020) and Avilés et al. (2020) include high computational effort theoretical convergence assumptions that cannot be satisfied in the real world and are dependent on parameter settings (Naik et al. 2021, Pereira et al. 2021).

The Symbiotic Organism Search (SOS) algorithm is among the metaheuristic algorithms with simple implementation, simple computation, good convergence, parameter independence, and excellent average central processing unit (CPU) time (Ezugwu and Prayogo 2019, Abdullahi et al. 2020). The SOS algorithms have been used for DER integration in PDN and other applications (Das et al. 2016, Abdullahi et al. 2020). However, according to the No-Free-Lunch theorem, finding an algorithm that can efficiently solve all problems is challenging (McDermott 2020). Therefore, the existing algorithms can be modified and used for different applications. One of the recently proposed versions of SOS is the cloud-based model SOS (CMSOS), which was proposed to improve the execution time and convergence speed of conventional SOS algorithms (Kawambwa et al. 2022). In that study, the CMSOS was used for DER placements in the PDN. Due to the characteristic differences between the PDN and SDN, and the fact that the SDN is much more complex than PDN, the applications of CMSOS algorithms can be extended to the SDN. Therefore, this study extends the application of the CMSOS metaheuristic algorithm from PDN to SDN.

In this study, the DERs placement algorithm was designed based on CMSOS and tested in the electrical network segment taken for Tanzania’s electrical distribution network considering power loss and voltage deviations. Results show that using DERs in the proposed locations reduces power loss by 89.3%. The convergence profile shows that the proposed CMSOS-based DER placement algorithm converges faster than the conventional symbiotic organism search algorithm (SOS). Also, results show that with increased load and network expansion, as the case for SDN, using the DERs improve the system stability and resiliency of the power system.

Materials and Methods

Testing electrical networks

The Tanzania Electric Supply Company (TANESCO) has constantly been working hard to ensure that faults and electrical network malfunctions are immediately addressed to reduce downtime. The implementation of the Supervisory Control and Data Acquisition (SCADA) and Distribution Management Systems using Remote Telemetry Units made it possible to monitor the transmission and primary distribution network. Due to the rapid expansion of the distribution network, the efficiency and reliable power supply are becoming a challenge to the Tanzania utility company. TANESCO needs to look at innovative ways, such as the inclusion of DERs, to meet the new demands of the electricity industry. Therefore, this study proposed the algorithm for placing DERs in the SDN and used electrical network segments taken from TANESCO to test the algorithm.

The single-line diagram for a small power system section to show a typical structure of a secondary distribution network in Tanzania is presented in Figure 1. The secondary distribution network mostly comprises a three-phases or single-phase low voltage (LV) network with a neutral conductor. Single distribution transformers serve loads for given areas.

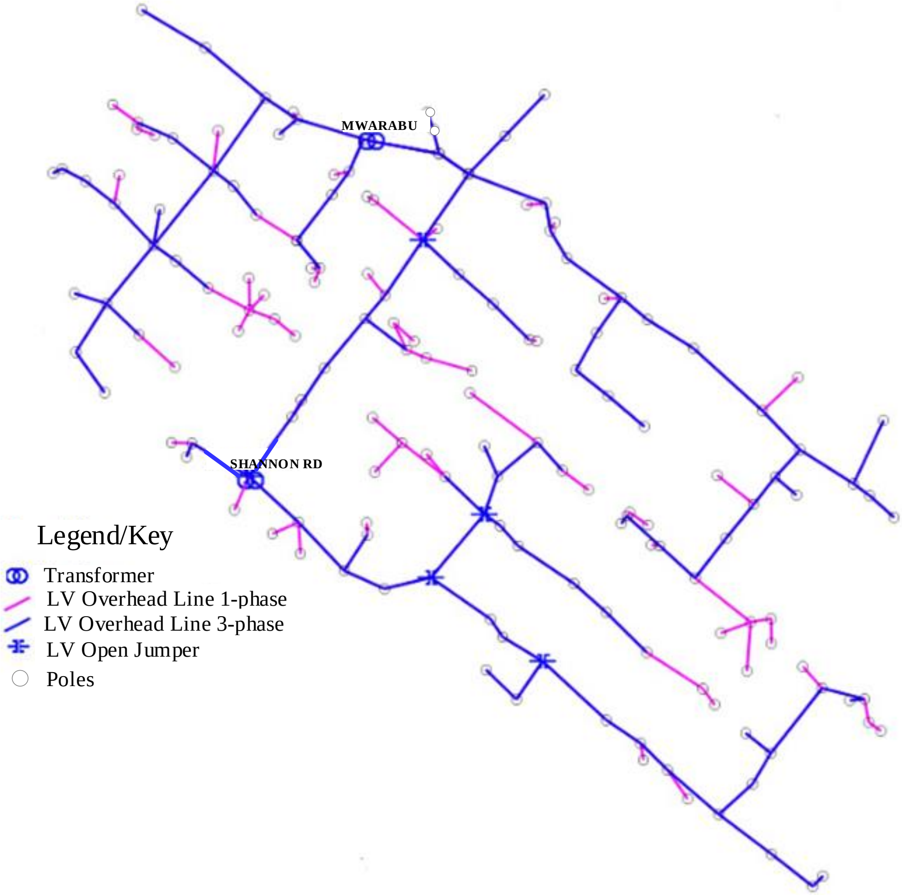

Figure 1: Tanzanian Secondary Distribution Networks (Kawambwa et al. 2021).

The network comprises LV jumpers to separate operating areas for transformers. The jumpers may also be used for load shedding and load shifting whenever needed. The poles are the major points for connecting customers in the secondary distribution network. The SDN is not static as it grows as new customers are connected to the network. According to Kawambwa et al. (2021), from January 2015 to September 2019, Tanzania's utility company observed a customer growth rate of 32% per year. This growth rate is significant for the distribution network as it is associated with changes in the topology and increased load demand, which impacts system performance. Therefore, ensuring power system efficiency in such a dynamic system may require the inclusion of DERs.

Mathematical problem formulation

The dynamic nature of SDN change operation parameters such as power loss, voltage profile, voltage deviation and operation costs. Active power loss is more influential in a radial distribution system than reactive power loss (Quadri et al. 2018). Therefore, in this study, the objective functions are active power loss, voltage deviations and Voltage Stability Index (VSI), as presented in (1), (2) and (4), respectively. The VSI is one of the important parameters that characterise the power system stability. The objective of the DER placement solution is to maximise the VSI. The VSI equation for optimisation problem minimisation can be presented as (4). The considered voltage constraints are presented in (5).

$$P_{loss} = \sum_{j=1}^{nb} I_i^2 \times R_i \tag{1}$$

$$V_d = \sum_{\mathrm{k=1}}^{n} \left(V_k - \mathrm{V_{rated}}\right)^2 \tag{2}$$

$$\mathrm{VSI_{k+1}} = |V_k|^4 - 4\left[P_{\mathrm{k+1}}X_j - \mathrm{Q_{k+1}}R_j\right]^2 - 4\left[P_{\mathrm{k+1}}R_j + \mathrm{Q_{k+1}}X_j\right]|V_k|^2 \tag{3}$$

$$VSI = \frac{1}{\mathrm{VSI_{min}}} \tag{4}$$

$$V_{min} < V_k < V_{max} \quad where\ \ k = 1,2,3,\dots,n \tag{5}$$

where P_{loss} is the total power loss, I_i is the current through the branch i, R_i is the resistance of branch i, and nb is the number of buses. V_d is the overall network voltage deviation. The VSI_k is the voltage stability index of the k^{th} bus, while R_j and X_j are the resistance and reactance of the j^{th} network branch connected between k^{th} and $(k+1)^{th}$ bus. The $P_{k+1}$and Q_{k+1} are the total active and reactive power demands at the bus $(k+1)^{th}$, respectively. The VSI_{min} is the minimum VSI of all buses. The V_k is the voltage magnitude of the k^{th} bus, expressed in p.u., and V_{rated} is the rated voltage of the network, which is 1 p.u. The V_{max} is the upper voltage limit and V_{min} is lower voltage limit. In this work, the minimum and maximum voltage limits are 0.9 p.u. and 1.1 p.u., respectively. The values of voltage limits are according to the Tanzania electrical power system grid code, which specifies a 10% tolerance for LV networks.

A **cloud-based model SOS algorithm**

The Symbiotic Organism Search algorithm is a metaheuristic algorithm inspired by the biological relationship among organisms in the ecosystem. The conventional SOS involves three major phases: mutualism, commensalism, and parasitism. The basic structure of SOS is presented in Algorithm 1, and more details of convention SOS can be found in Cheng and Prayogo (2014).

***Algorithm 1**: The basic structure of SOS (Cheng and Prayogo 2014).*

```
Initialization
while it < maxite do
Identify the best organism $X_{best}$ in an ecosystem
    for i=1: ecosize do
        Mutualism
        Commensalism
        Parasitism
    end
Checking termination criterion
end while
```

Since the cloud-based model SOS was developed based on the conventional SOS, it maintains the structure and number of phases presented in Algorithm 1. However, the CMSOS introduces a cloud model at the mutualism phase for improved performances, such as execution time and convergence speed. More details on CMSOS and its applications in primary distribution networks can be found in Kawambwa et al. (2022). In the mutualism phase, organisms X_i and X_j interact, the new candidate solutions X_{inew} and X_{jnew} is generated using (6) and (7).

$$X_{i\_new} = X_i + R \times (X_{best} - MV \times BF_i) \quad (6)$$

$$X_{j\_new} = X_j + R \times \left(X_{best} - MV \times BF_j\right) \quad (7)$$

where

$$R = \frac{k}{1+e^{-y}} \quad (8)$$

$$MV = \frac{X_i + X_j}{2}$$

The BFi and BFj are randomly selected as 1 or 2, which represent the benefit level for the organism X_i and X_j, respectively. The X_{best} represents the best organism in the ecosystem. The details on the values of k and y in (8) can be found in Kawambwa et al. (2022).

In the commensalism phase, organisms X_i and X_j interact such that X_i increases its chance of survival in the ecosystem by benefiting from X_j. The new candidate solution for X_i is given in (9).

$$X_{i\_new} = X_i + rand(-1,1) \times \left(X_{best} - X_j\right) \quad (9)$$

In the parasitism phase, two organisms X_i and X_j interact such that one organism benefits while another organism suffers from that relationship. The parasite for the randomly selected organism X_j called X_{j_par} is formed from a randomly selected organism X_i using (10).

$$X_{j\_par} = 2 \times X_i \quad (10)$$

$$X_{j\_new} = \begin{cases} X_j & \text{if } Obj(X_j) < Obj(X_{j\_par}) \\ X_{j\_par} & \text{if } Obj(X_j) \geq Obj(X_{j\_par}) \end{cases} \quad (11)$$

The X_{j_par} is the new organism that wants to invade the ecosystem. If X_{j_par} is better than X_j, then X_j is replaced by X_{j_par} otherwise X_j hold on as shown in (11) for function minimization problems. The $Obj(X_j)$ and $Obj(X_{j\_par})$ are the values of the objective functions for organisms X_j and X_{j_par}, respectively.

A cloud-based model SOS algorithm for DERs placement

The DER placement algorithm describes the steps used to implement the proposed CMSOS for solving the formulated mathematical problems. The DERs placement algorithm identified the optimal locations and sizes of DERs simultaneously. Each organism represents one solution set, and the function value of the organism represents its fitness. The organism's size depends on the number of DERs. The organism's structure presented in Figure 2 shows that each organism consists of two parts, DER locations and DER sizes. Each location is mapped to one size, that is, the location LDG_i is mapped to size SDG_i. To place DER in the network means to place the size SDG_i at the location LDG_i. The flowchart and pseudocode of the proposed CMSOS algorithm for DER placement are presented in Figure 3 and Algorithm 2.

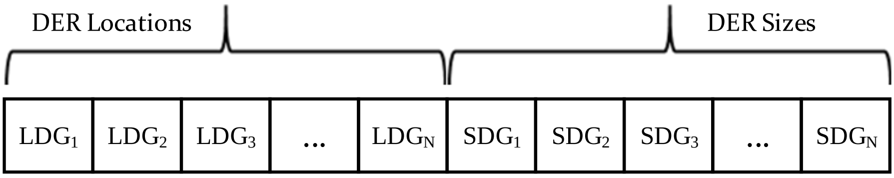

Figure 2: The structure of an Organism.

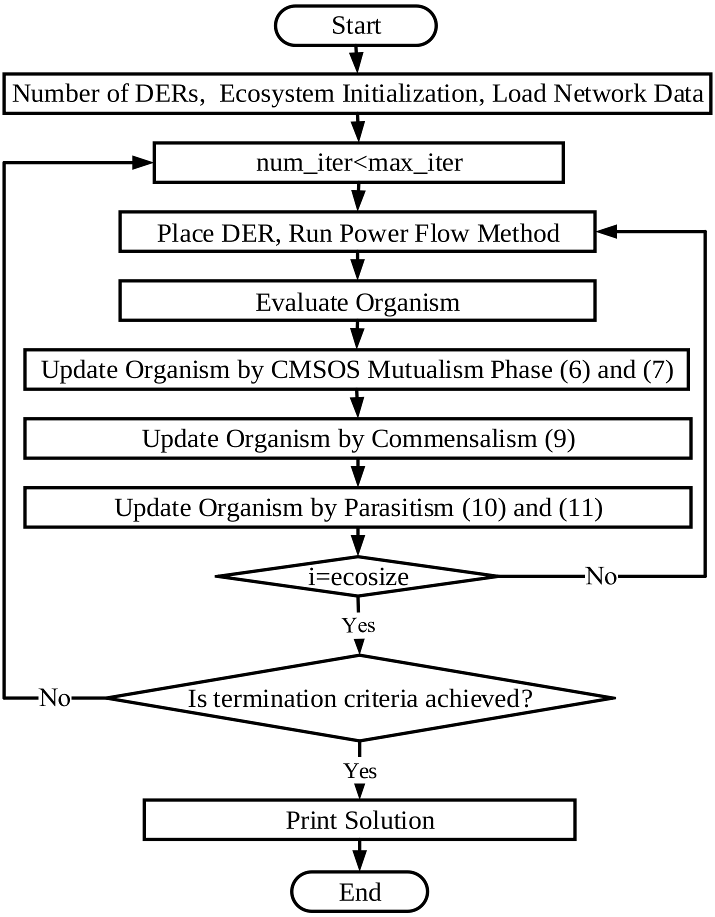

Figure 3: Flowchart of the proposed DER placement algorithm.

The DER placement algorithm starts by initializing the number of DERs to be placed, the size of the ecosystem, network line and load data, and random initialization of all organisms. Then, for a chosen organism i, its size is placed at its proposed location in the network, and the power flow of the network is run to obtain voltages on all nodes and currents on each branch. The power flow method involves some iterations; only a single iteration of power flow was applied to serve time. The direct load flow (DLF) method was used in this study for the DERs placement algorithm. Then the organism is evaluated to get its fitness value using the objective function mathematical formulations such as power loss, voltage deviations and voltage stability index. Then the organism goes through the three phases of CMSOS, mutualism, commensalism, and parasitism. Then, the new solution is accepted if it passes constraint violation tests. Penalty functions can discard or weaken the possibility of the organism being selected as an optimal solution when its solution set violates given constraints. These processes are repeated for all organisms until termination criteria are reached. The termination criteria can be the number of iterations or specific values of objective functions.

***Algorithm 2**: Pseudocode of the proposed DER placement algorithm*

```
Initialization
Initialization of the number of DERs to be placed
Initialization of SOS ecosystem
Load network data
Identify the best organism $X_{best}$ in an ecosystem
while $num\_iter < max\_iter$ do
    for i=1: $ecosize$ do
        Place DER the DER on specified locations
        Run power flow method
        Evaluate organism
        Identify the best organism $X_{best}$ in an ecosystem
        Update organism by CMSOS mutualism phase
        Update organism by CMSOS commensalism phase
        Update organism by CMSOS parasitism phase
    end
    Update the best organism $X_{best}$ in an ecosystem
Checking termination criterion
end while
```

Results and Discussion

The proposed algorithm was implemented in the TANESCO network with 79 nodes and 37 branches. The total active load demands without any DER was 60.3175 kW. The rated voltage and system base powers are 0.4 kV and 315 kVA, respectively. The total active power loss of the network was 13.0357 kW. Without any DER connected (base case), voltage deviation and voltage stability index were 0.4715 and 0.5121, respectively. The network and load data of considered distribution network can be found in Kawambwa et al. (2021). This study considered the placement of four DERs that deliver only active power (DER type-I).

Results for optimal number of DERs in the Tanzanian power system

A study was done to show the effects of the number of DERs on the performance of the power system. The CMSOS was used to find the optimal location and size of DER for each considered case. The voltage profiles for different numbers of DERs are presented in Figure 4. It was observed that without DER, the profile shows a significant deviation from the required value of 1 p.u. With the increased number of DERs, the voltage profile improves. As the number of DERs increases, a point is reached where there is no significant difference in the profile, as observed for the placement of four and five DERs. Therefore, for the study area TANESCO power system, four DERs can be considered optimal for other analyses.

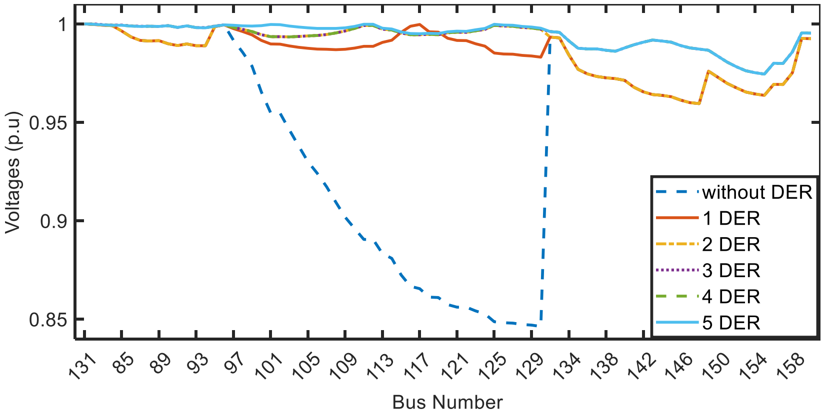

Figure 4: Study area voltage profile for different numbers of DERs placement.

Results for DER placement in the Tanzanian power system

This study investigated the inclusion of DERs in the Tanzanian power system. The results for power loss minimization considering the placement of four DERs are presented in Table 1. Results show that both CMSOS and SOS found the same DER locations (90, 111, 125 and 143) and the same DER sizes (5.44 kW, 10.60 kW, 8.89 kW and 9.48 kW). The presentation of the study area power system with DERs located is shown in Figure 5. The voltage deviation (V_d) and voltage stability index (VSI) are 0.0068 and 0.9016, respectively. Power loss was reduced from 13.0357 kW to 1.3989 kW, equivalent to 89.3% power loss reduction for SOS and CMSOS. The power loss reduction was calculated using (12).

$$\text{Loss Reduction (LR)} = \frac{Ploss_{base} - Ploss_{calculated}}{Ploss_{base}} \times 100\% \qquad (12)$$

Where $Ploss_{base}$ is power loss of the electrical network before DER placement and $Ploss_{calculated}$ is the power loss of the network after placement of DERs.

Table 1: Power loss minimization results in TANESCO for SOS and CMSOS

	SOS		**CMSOS**	
	Location	Size (kW)	Location	Size (kW)
	90	17.1423	90	17.1423
	111	28.0039	111	28.0039
	125	29.8740	125	29.8740
	143	33.3915	143	33.3915
Power loss	1.3989		1.3989	
V_d (p.u)	0.0068		0.0068	
VSI^{-1}	1.1092		1.1092	
VSI (p.u.)	0.9016		0.9016	

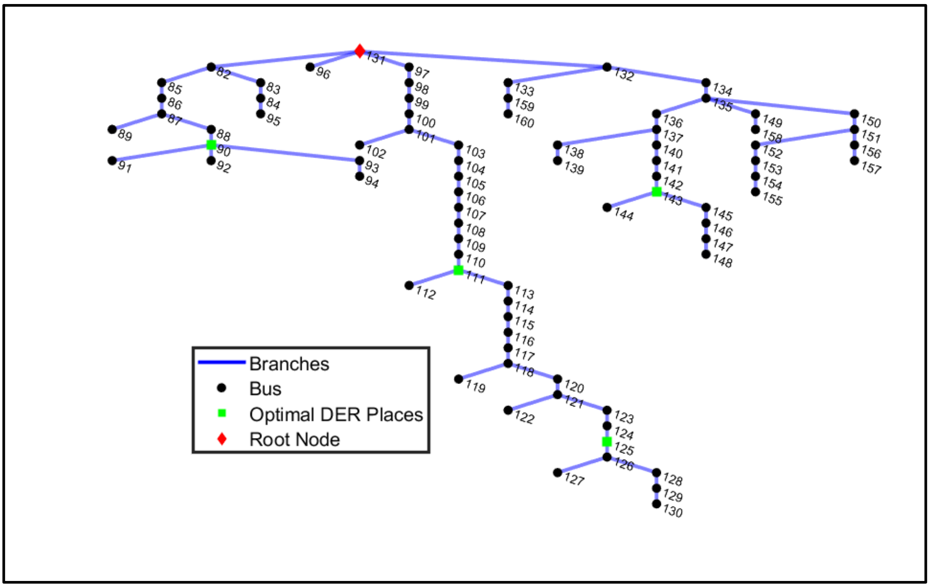

Figure 5: The TANESCO power system with proposed optimal DERs locations.

A fast converging metaheuristic algorithm is necessary for efficient power system optimization. The proposed CMSOS and the conventional SOS were compared, considering the convergence profiles. The comparative convergence plot for CMSOS and SOS for the TANESCO system is presented in Figure 6. Also, the acceleration rate (AR) presented in (13) was used to measure the convergence speed of the algorithms. Results show that the proposed CMSOS converge faster than SOS. The AR value considering power loss minimization was 2.9048, implying that the proposed DER placement algorithm based on CMSOS is more than twice as much faster than the SOS-based placement algorithm. Therefore, it can be stated that the proposed CMSOS is efficient for DERs placement and optimization in the tested power system.

$$\mathrm{AR} = \frac{\mathrm{NFFE}_{\mathrm{SOS}}}{\mathrm{NFFE}_{\mathrm{CMSOS}}} \tag{13}$$

Where $\mathrm{NFFE}_{\mathrm{SOS}}$ is number finite function evaluation (NFFE) for conventional SOS algorithm and $\mathrm{NFFE}_{\mathrm{CMSOS}}$ is the NFFE for CMSOS.

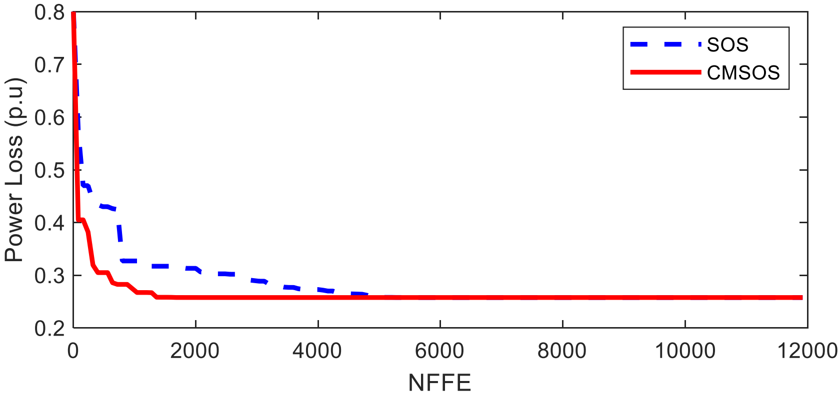

Figure 6: Convergence between SOS and CMSOS.

Results for load growth in the Tanzanian power system

The proposed CMOS algorithm was used to study the effect of load growth and DERs placement in the Tanzanian power system. The load growth of the power system can be modelled as per (14) (Satyanarayana et al. 2007). From collected data and requirement analysis, the percentage increase of the TANESCO load per year was 32%. Therefore, the influence of load growth on the power system's performance considering the case without DERs and with DERs, was studied. For the cases where DERs were considered, the proposed algorithm was used to find the optimal placement and sizes of the DERs. In this analysis, the system's capacity and network size in terms of the number of nodes were assumed constant.

$$\mathrm{L} = \mathrm{L}_0\left(1+\frac{r}{100}\right)^{n} \tag{14}$$

where L_0 is the base-case load of the system, L is the estimated load after n years, and r is the load growth rate.

The study was done to investigate the estimated voltage profile for the next three years. The base case loading was estimated to increase by 32% each following year. The voltage profiles for the considered years are presented in Figure 7. The results for the next three years with DER and without DERs placement are shown in Table 2. The power losses, voltage profile (voltage deviation) improvements, voltage stability index and minimum voltages were considered. It is observed from Figure 7 and Table 2 that as the load increases, the voltage deviation (V_d), VSI and power loss increase and minimum voltage decrease, signifying the worsening of the system stability that may lead to collapsing of the system. Also, for each particular year, all considered parameters are better with DERs than without DERs.

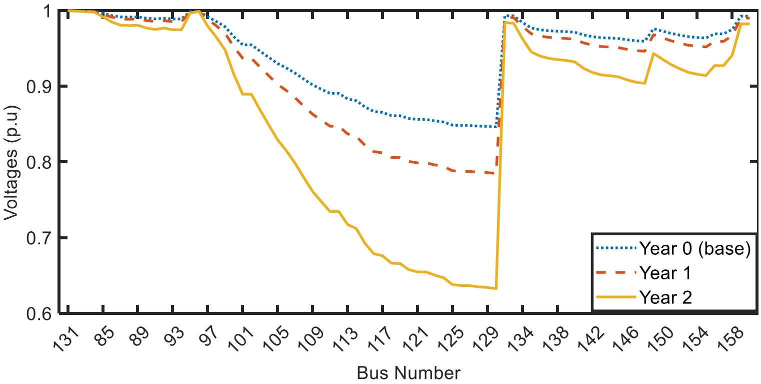

Figure 7: Node voltage profiles for three years.

Table 2: Estimated results for three years with DER and without DER

		Power loss	V_d	VSI	Minimum voltage
Year 0 (Base)	No DER	13.0356	0.4715	1.9528	0.8463
	With DER	1.3989	0.0068	0.9016	0.9745
Year 1	No DER	24.5732	0.9159	2.6414	0.7849
	With DER	3.7260	0.0584	0.8288	0.9545
Year 2	No DER	83.0240	2.7250	6.2843	0.6326
	With DER	28.8682	0.8855	0.3980	0.7951

Conclusion

This paper extends the applications of the CMSOS metaheuristic algorithm from PDN to SDN. The DER placement algorithm based on the CMSOS metaheuristic method has been designed for SDN applications. The electrical network segment taken for Tanzania's electrical distribution network was used for testing the algorithms, considering power loss, voltage deviations and VSI. Firstly, the experiment was conducted to find the optimal number of DERs that can be accommodated in the given distribution network. For the test case electrical network, four DERs were optimal. Then the proposed DER placement algorithm was applied to provide optimal locations and sizes of four DERs. Results show that using DERs in the proposed locations reduces power loss by 89.3%. The convergence profile shows that the proposed CMSOS-based algorithm converges faster than the conventional SOS algorithm, which shows the improved performance of the proposed algorithm. Since SDN is characterized by load growth and network expansions, the proposed algorithm was tested for load growth cases for three consecutive years. Results show that using the DERs improves the power system's stability and resiliency.

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