



Effect of an Optimal Conductor Size Selection Scheme for Single Wire Earth Return Power Distribution Networks For Rural Electrification

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ABSTRACT

This research presents an improved optimal conductor size selection scheme for single wire earth return (SWER) in power distribution networks for rural electrification. The power distribution has become a challenge from grid extension for rural electrification due to high cost of electrification. Single wire earth return power distribution system is a cost effective means of rural electrification but is prone to high cost of power loss and cost of conductor due to improper size of conductor. The backward/forward sweep algorithm is used to determine the base case reactive power loss and active power loss while particle swarm optimization technique is used for optimal conductor size selection and cost of conductor in both primary and lateral of the network. The objective functions were formulated considering cost of conductor selection, power loss and voltage profile improvement. The developed method is implemented on extracted 13-bus of Namibia SWER distribution system and IEEE 13-bus system network in order to validate efficient of the proposed method via comparison to MINLP. The results show the effectiveness of this method in reducing power loss on the network and optimal selection of conductor size which results in reduction in the cost of conductor for the distribution network.

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INTRODUCTION

Access to safe, reliable and cost-effective energy is essential for a country to make the economic growth of the population. It is well known that electricity is a service and a key input into economic development and household activities. Electrification is generally accepted to add to the accomplishment of all economic state of any country in light of the assumption that sustainable access to power encourages economic and social advancement, and prompts improvement in the personal satisfaction (33). Up till now particularly in the rural areas in sub-Saharan Africa, electrification percentages are still low due to high cost of conventional method of electrification, where only 11% of the population use electricity in rural area (24). While in rural Sub-Saharan Africa, it is about 14.2% that has been able to have access to electricity. Hence, it is basic to give more consideration to country zap of the Sub-Saharan African region. The utilization of standard electrification advances ends up unviable in the provincial region because of the high expense of venture and the low burden's densities. Thus single

wire earth return (SWER) appropriation innovation was proposed to give a cost effective (for providing power in the rural areas and sub-urban region where loads are dispersed and scanty (31). SWER systems use lightweight high tensile conductors to supply power to rural areas from the main grid network using the earth as a return path (12). SWER uses longer spans, lighter poles, and fewer pole-top equipment to be used leading to a considerable saving on initial investment compared to conventional four wire three distribution systems(31). The technology initially proposed has turned out to be financially savvy in energizing rustic zones with little and dispersed loads in countries, for example, Namibia, Australia, Mozambique, and South Africa(43). Therefore, for these areas costs per connection and cost per kWh supplied would be considered high if conventional power supply system were to be utilized (35). Apart from that, the operation and maintenance of rural networks will be more problematic, and the quality of supply may also be lower (32). The investment of SWER system and operation have significant benefit in terms of cost-effective maintenance for electrification are

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always lower than the conventional system of electrification in rural and suburban areas due to followings the reasons:, lower cost of materials for establishing and expansion of the system, and maintenance (32). According to the study carried out by the International Energy Agency (IEA) in 2016, the number of people without electricity access was 1.2 billion or almost about 22% of the world's population while rural area has the highest percentage. Table 2.1 shows the world electricity access in 2016 collected from households, industry, national surveys, and international sources (39).

The objective of this research is to develop an improved optimal conductor size selection scheme for single wire earth return power distribution networks using particle swarm optimization (PSO) in order to reduce the cost of conductors and active powers loss on the network for rural electrification systems.

The rest of the paper is organized as follows. Second II discusses about the methodology incorporated to attained optimized conductor selection base on rural electrification system using particle swarm optimization. Section III elaborates the application of the proposed technique on the extracted 13 bus real-time SWER network in Namibia, IEEE 13-bus network system, the cost of conductor and both reactive and active power loss minimized was achieved.

The following steps were considered in ascertaining the optimal cost of conductor selection for rural electrification systems:

- Single wire earth return line model
- Analyses of SWER line power flow base on the forward/backward sweep technique with available data from SWER network.
- Choose an extracted of real-time rural electrification system and IEEE 13-bus system network.
- Mathematical method base on the objective function best suited cost of conductor from available sets of conductors.
- Adoption of an artificial intelligence base on the particle swarm optimization suitable for the best cost effective for both primary and lateral conductor of extracted rural network.

2.1 SWER line modelled using Carson's model

The SWER line was modelled according to Carson's model. Fig. 1 shows a typical line of

SWER. Carson's line models the impedance of overhead conductors with earth return (18). The overall impedance, Z_{aa} of overhead line that current return through the earth is given in equation 1

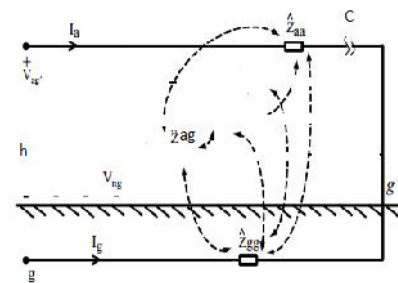
Figure 1 Typical model line of SWER

$$Z_{aa} = Z_{aa}^- + Z_{gg}^- - 2Z_{ag}^- \Omega \quad (1)$$

Where

Z_{aa} is self-impedance's of overhead line, Z_{gg} is fictitious impedance of earth return.

Z_{ag} is mutual impedance between the overhead line and earth return.



The SWER load flow formulation

This is based on the forward/backward sweep technique presented in equation (2) for earth return networks (Hesamzadeh *et al.*, 2015). The line currents are then calculated using Kirchhoff's Current Law (KCL) in equation (3) and (4) for the line and ground respectively, where the loads are represented by their equivalent current injections. According to the KCL, the entirety of all node currents incoming and exit a bus is conforming to the load current at that node

$$\begin{bmatrix} I_{ia,t} \\ I_{rig,t} \end{bmatrix} = \begin{bmatrix} (S_{ia,t}/V_{ia,t}) \\ -I_{ia,t} \end{bmatrix} - \begin{bmatrix} Y_{ia} \\ \mathbf{0} \end{bmatrix} \cdot \begin{bmatrix} V_{ia,t} \\ V_{ig,t} \end{bmatrix}$$

$$\forall i \in N, t \in T \quad (2)$$

All nodal current injections due to loads and shunt elements are first calculated and centred on initial voltage values for both the overhead conductor and ground return path using (2)

$$\sum_{i \in N} J_{ija,t} - \sum_{i \neq j} J_{ija,t} = I_{ja,t} \quad \forall i \neq 1, t \in T$$

$$(3)$$

$$\sum_{i \in N} J_{ijg,t} - \sum_{i \neq j} J_{ijg,t} = I_{jg,t} \quad \forall i \neq 1, t \in T$$

$$(4)$$

Nodal voltages for both overhead line and earth return are updated using (5). This leads to an iteration procedure that ends when the difference between the specified and calculated current

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injections at each node is lowest. $I_{j,a,t}$ is current injections at bus i for the overhead in period t $I_{j,g,t}$ is the for the earth return in period t

$S_{i,a,t}$ is complex power at node i

$$\begin{bmatrix} V_{i,a,t} \\ V_{i,g,t} \end{bmatrix} = \begin{bmatrix} V_{i,a,t} \\ V_{i,g,t} \end{bmatrix} - \begin{bmatrix} Z_{aa} & Z_{ag} \\ Z_{ag} & Z_{gg} \end{bmatrix} \begin{bmatrix} I_{i,a,t} \\ I_{i,g,t} \end{bmatrix} \quad \forall i \in M, t \in T \quad (5)$$

$V_{i,a,t}$ is complex voltage at node i for the overhead in period, $V_{i,g,t}$ is complex voltage at node i for the earth return

Case study

The case study was separated from a rural electrification plot in Opuwo, northern Namibia. The SWER line was worked to source rural loads utilizing a 200 kVA detaching transformer reticulated at 19.1 kV from a 33 kV three-phase support network. Fig. 2 shows the extracted line diagram of the SWER test network. The objective was to analyse the performance of the optimal conductors selected for both primary and branches of the conductor using the proposed optimization tools in different operating system scenarios, in relation to the existing conductors of the test network (8).

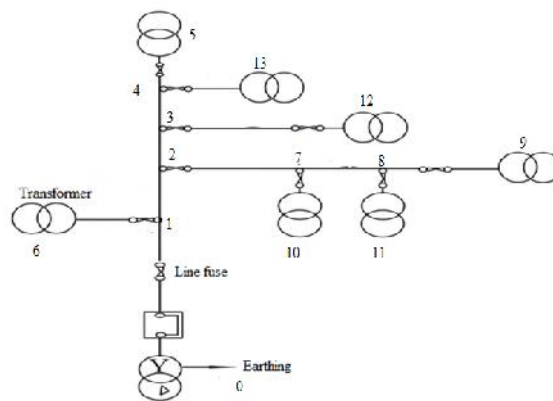


Fig. 2 Extracted 13-Bus SWER networks system case study of Namibia

The extracted Namibia 13-Bus SWER network system consists of seven isolated distribution transformer situated at bus 5, 6, 9, 10, 11, 12 and 13 with the slack bus at the reference point of the network where i and j are number of buses at the particular point in network. Table 2 shows the network load data for the case study.

Mathematical Model of Objective Function

In an optimal conductor selection problem, the purpose is to select the conductor size and type from a set of available conductors such that the total cost is minimized while satisfying nonlinear constraints on voltage limits of the SWER system buses and maximum ampacities of the conductors. The cost consists of the both the cost of conductor at the primary and lateral of the SWER system ($C_{j,c}$) and the capital investment cost of the conductor $CC_{(j,c)}$. It can be formulated for a branch j with type c conductor as shown in equation 2.8 as follows:

$$Cost(j,c) = C_{(j,c)} + CC_{(j,c)} \quad (6)$$

The annual cost of the power loss in branch j with c type conductor (PL) is given as:

$$P_L(j,c) = P_{a\text{loss}}(j,c) \times [k_p + (k_g \times LSF \times T)] \quad (7)$$

$$P_L(j,c) = P_{r\text{loss}}(j,c) \times [k_p + (k_g \times LSF \times T)] \quad (8)$$

Both $P_{a\text{loss}}(j,c)$ and $P_{r\text{loss}}(j,c)$ are active and reactive power loss of the j th branch with the conductor under peak load conditions, k_p is the cost of peak demand power loss (\$/kWh), k_g is the cost of power losses (\$//kWh), T is the number of hours per year, and LSF is the loss factor which is defined as the ratio of power loss in the system during a given period to the power loss that could result if the system peak loss had persisted throughout that period. LSF is expressed in terms of the load factor (LF), the average load to the peak demand in a given period, as follows:

$$LSF = 0.2(LF) + 0.8(LF)^2 \quad (9)$$

Thus, the total yearly cost of power loss (PL^{total}) can be expressed as follows:

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$$PL^{total} = \sum_j^b \cdot \sum_c^n \{P_{loss}(j,c) + P_{rloss}(j,c)\} \times [k_p + (k_e \times LSF \times T)] \quad (10)$$

where b is the total number of branches in the system and n is the number of the available conductors' types. The capital investment cost of the conductor (CC) is defined in terms of the annual depreciation of the capital cost of the jth branch with the cth conductor, thus:

$$CC_{(j,c)} = IDF \times l(j) \times IC(c) \quad (11)$$

So that,

$$IDF = \frac{i(1+i)^Y}{(1+i)^Y - 1} \quad (12)$$

where IDF is the interest and depreciation factor, i is the interest rate value, Y is the planned lifetime (years), l(j) is the length of branch j(km), and IC(c) is the investment cost of the c type conductor per unit area per unit length

Thus, the objective function (OF) for the optimal selection of types and sizes of the conductors can be expressed as:

$$Obj = \min(PL^{total} + CC^{total}) \quad (13)$$

Where CC^{total} is the total capital investment cost of both primary and branches conductor.

Subject to constraints

The subject considered constraints can be expressed, as follows:

Bus voltage of SWER system constraint

$$V_{min}(m) \leq |V(m,c)| \leq V_{max}(m) \quad \forall (m \in k, c \in n) \quad (14)$$

where m is the bus number, k is the total number of buses in the system. $V_{min}(m)$ and $V_{max}(m)$ are the minimum and maximum voltage at bus m, respectively. They are considered as 0.8 p.u. and 1.2 p.u., respectively.

Conductor current carrying capacity of system constraint

$$|I(j,c)| \leq I_{max}(c) \quad \forall (m \in k, c \in n) \quad (15)$$

Where I (j,c) is the current flowing in conductor j of type c, and $I_{max}(c)$ is the maximum current carrying capacity of the cth type conductor

Particle Swarm Optimization for Conductor Selection

Several techniques of metaheuristic approach and conventional method has been used in the selection appropriate conductor for SWER distribution system using conventional or analytical method genetic algorithm, developed algorithm, but in this work swarm intelligence technique base on particle swarm optimization (PSO) is proposed to be used due to its simplicity and generating better solution within short period of time, fast convergence with quality solutions and correctness of the algorithm. Particle Swarm Optimization (PSO) is an optimization technique introduced by Kennedy and Eberhart in 1995 (54), it uses a modest mechanism that mimics swarm behaviour in birds flocking and fish schooling to guide the particles to search for global optimal solutions. Particle swarm optimization described with three simple behaviours of separation, alignment, and cohesion (63). Separation is the behaviour of avoiding the crowded local flock mates while alignment is the behaviour of moving towards the average direction of local flock mates. Cohesion is the behaviour of moving towards the average position of local flock mates. The formulas of the PSO algorithm are as follows (54; 63) This is a vector whose members are determined by evaluating a velocity update equation (15).

$$v_{jk}^{t+1} = v_{jk}^t + c_1 \cdot r \quad \text{and} \quad (0,1) \cdot (X_{pbest}^t - x_{jk}^t) + c_2 \cdot \text{rand}(0,1) \cdot (X_{gbest}^t - x_{jk}^t)$$

Once the velocity is determined, the position vector is updated using the following equation

$$x_{jk}^{t+1} = x_{jk}^t + v_{jk}^{t+1} \quad (2.8)$$

where v_{jk}^t and x_{jk}^t are particle velocity and particle position respectively. f is the dimension in the search space, f is the particle index, and t is the iteration number.

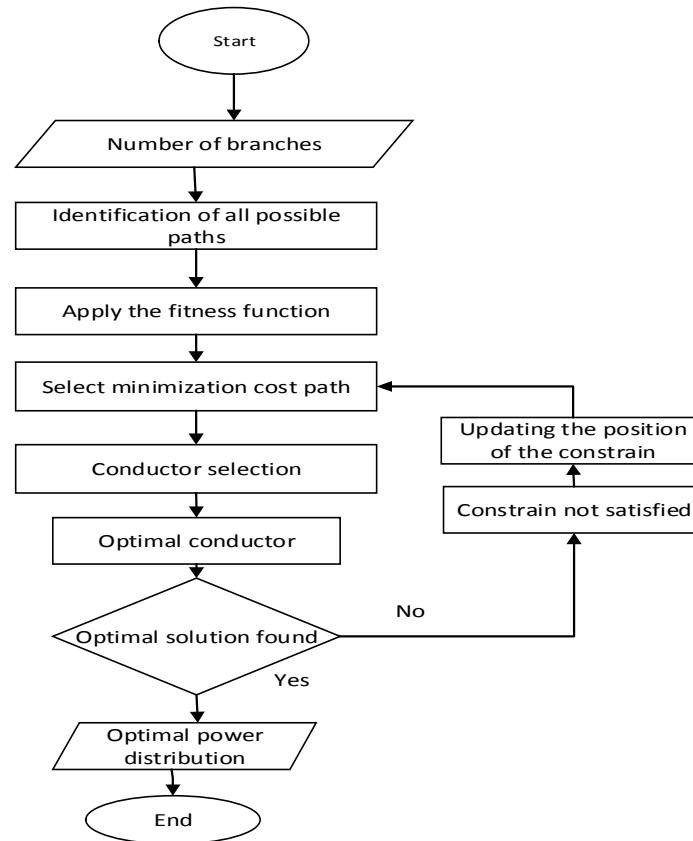


Figure 3: Flowchart of the proposed optimal conductor selection.

Conductor Selection Properties and its Specification

An ongoing conductors' library is utilized. One can see that the proposed set of conductors investigated a more extensive pursuit space and prevailing with regards to finding the most ideal arrangement of conductors that fulfil the target

capacities while obeying with the arrangement of imperatives with high yearly burden development situations (35) Table 3.3 shows the types of conductors with its electrical properties while table the electrical properties of ACSR specification conductors used in this work.

Table 3: Electrical properties of ACSR Specification Conductors used in this work

Conductor code	R (Ω)	X (Ω /km)	Current Rating (A)	A(mm^2)	IC(\$/km)
Bantam	5.26	1.02	69	12.90	150
Mole	3.30	1.03	98	15.91	204
Magpie	3.31	0.99	92	25.81	138
Shrike	2.08	0.96	122	42.01	250
Squirrel	1.67	0.99	148	48.39	118

SIMULATION RESULT AND ANALYSIS

A reactive power loss analysis at the extracted 13-bus SWER network of Namibia. The total reactive power loss, voltage profile, and PSO obtained from the proposed method compared with the result from the mixed integer non-linear programming (MINLP). The total reactive power loss at the base case of MINLP is 4.698kVAR which reduced to 0.464kVAR. It suffices to say that 90.12%

reactive power loss reduction on the base case of MINLP compared to on apply the proposed method. The lowest bus voltage of the proposed method is 0.9960 per unit. The lowest bus voltage of MINLP is 0.964 per unit. The cost of conductor selection before and after selection is \$ 40826 and \$1838. The best conductor selection on both primary and lateral line of the section of extraction Namibia SWER system distribution network topology with PSO

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shows low power loss than that of the MINLP. Figure 4 shows, reactive power loss profile of both the proposed method and the MINLP while Figure 4 shows voltage profile for both the proposed method and the MINLP

It can be seen that the active power loss at the line branch of , 10, 11 and 13 has same power losses reduction before and after of branch number 7-10, 8-11, 6-1

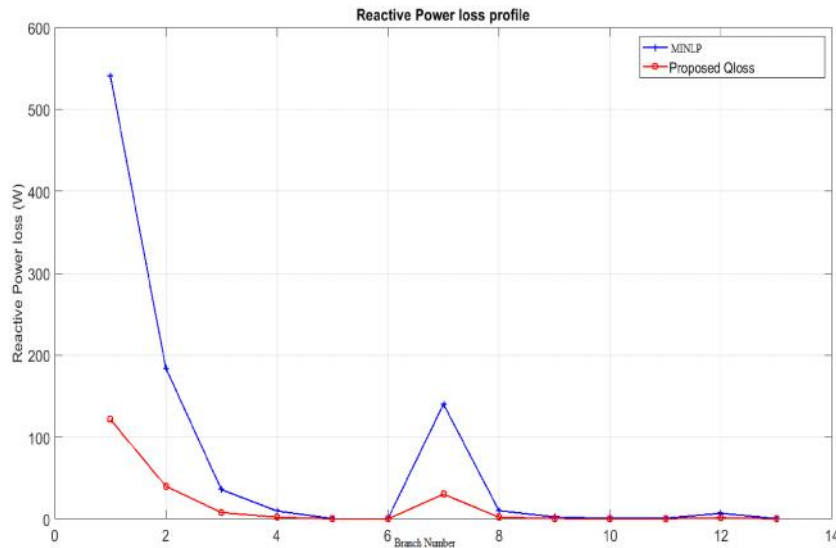


Figure 4: Reactive power loss for the proposed method and MINLP

It can be seen that the reactive power loss at the line branch of 5, 6 and 10 has same power losses reduction before and after of branch number 13-4, 12-3, 7-10, 8-11 and 6-1 all most have the same reactive power losses. Table 3 shows the details of reactive power loss at the line.

Active Power Loss Analysis at the Extracted 13-Bus Swer Network of Namibia

The total active power loss, voltage profile, and PSO obtained from the proposed method compared with the result from the mixed integer non-linear programming (MINLP). The total active power loss at the base case of MINLP is 4.132kW which reduced to 0.5180kW. It suffices to say that

87.46% active power loss reduction on the base case of MINLP compared to on applied the proposed method. The lowest bus voltage of the proposed method is 0.9960 per unit. The lowest bus voltage of MINLP is 0.964 per unit. The cost of conductor selection before and after selection is \$ 40826 and \$1838. The best conductor selection on both primary and lateral line of the section of extraction Namibia SWER system distribution network topology with PSO shows low power loss than that of the MINLP. Figure 5 shows, active power loss profile of both the proposed method and the MINLP while Figure 4 shows voltage profile for both the proposed method and the MINLP

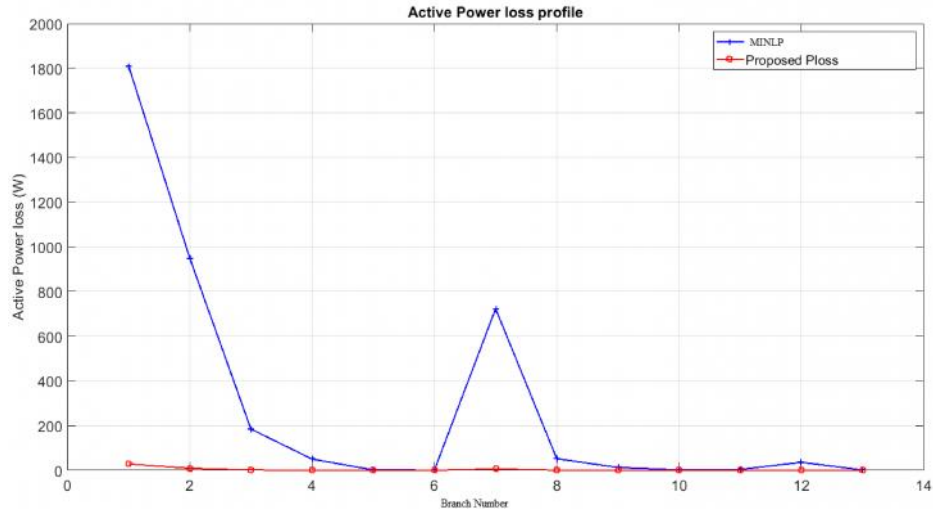


Figure: 5 shows active power loss for the proposed method and MINLP.

It can be seen that the active power loss at the line branch of , 10, 11 and 13 has same power losses reduction before and after of branch number

7-10, 8-11, 6-1. Figure 6: Voltage profile of the both the developed method and MINLP for the extraction of Namibia SWER system

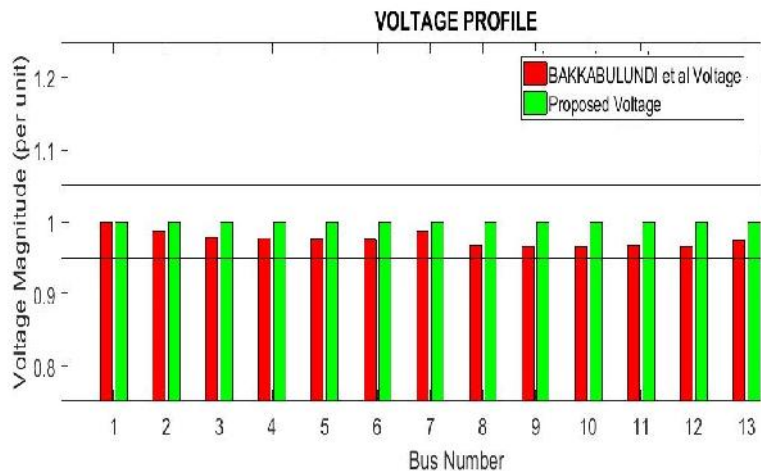


Figure 6: Voltage profile of the both the proposed method and MINLP for the extraction of Namibia SWER system.

The generated profile values that were obtained from the developed code with line and load data ran in Matlab interface. The voltage size in per unit was plotted against the number of bus of 13-bus network of extraction Namibia SWER

distribution system. It can be seen from the profile at bus 1 voltage profile remain the same before and after applying the developed method, while buses 9, 10, 11, and 12 have the same voltage magnitude on the developed method of 1.2 pu.

Table 4: Summary results of both the proposed method and the MINLP

Parameters Description	MINLP	Proposed Method
Active Power Loss (kW)	4.132	0.518
Reactive Power Loss (VAr)	4.698	0.464
Minimum voltage (up)	0.964	0.996
Power loss percentage reduction %	NA	87.46 and 90.12
Optimal Cost of Conductor (\$)	4826	1838
Percentage Cost of Reduction (%)	NA	62.16



CONCLUSION

This research was to present a developed optimal size of conductor selection scheme for single wire earth return (SWER) in simultaneously using PSO for optimum conductor size selection and cost of overall power distribution networks in use in rural electrification of an extracted 13-bus real network of Namibia SWER system and validation via comparison using IEEE 13-bus network system. The BFS algorithm was used to determine the base case and after applied technique of both reactive and active power loss. The results obtained indicate that the proposed method was effective and efficient in terms of cost effectiveness of optimal conductor size selection which significantly improved the voltage profile of the network compared to when using MINLP for conductor selection. The test results were concluded that by using this optimization method, about 62.16% cost reduction, and 90.12% and 87.46% of reactive and active power loss reduction in network were achieved.

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