Planning Algorithm for Single Wire Earth Return Distribution Networks

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***Abstract*—Power flow in earth return distribution systems typically depends on geographical location and specific earth properties. The planning of such systems has to take into account different operational and safety constraints from conventional distribution systems. This work presents the mathematical modeling and planning of Single Wire Earth Return (SWER) power distribution networks. The SWER load flow is modeled and formulated as an optimization problem. Then by using a heuristic iterative procedure, a planning algorithm is developed for the SWER system. The developed procedure includes optimal feeder routing and overhead conductor selection for both primary and lateral feeders with load growth over several time periods. A 30 node test network extracted from a rural area in Uganda is used to test the algorithm's practical application to give reasonable and consistent results. The model presented can be used in planning SWER networks for areas which have previously not been electrified as well as determining suitable upgrades for existing SWER distribution feeders. The algorithm's mathematical modeling and simulations were done using the General Algebraic Modeling System (GAMS).**

***Index Terms*--Optimal power flow, power distribution, power system modeling, power system planning.**

I. INTRODUCTION

Historically, rural electrification has been a huge challenge and remains so in many parts of the world [1]. The Single Wire Earth Return (SWER) distribution technology provides a cost-effective way to provide electricity to areas with scattered and sparse loads. The use of standard electrification technologies becomes unviable in rural areas due to the high cost of investment and the low load densities [2]. SWER systems use light-weight high-tensile conductors to supply power to rural areas from the main grid network using the earth as return path [2, 3]. This allows longer spans, lighter poles and fewer pole-top equipment to be used leading to considerable savings on initial investments compared to conventional two-wire single phase distribution systems. The planning of SWER systems must take into account specific operational, safety and earth resistivity constraints [4]. Stringent voltage and current limits must be maintained to prevent dangerous touch and step potentials to both man and beast. This can be done effectively by properly modeling an area's earth properties especially the average soil resistivity in different weather conditions and designing a suitable earthing scheme.

Extensive research has been undertaken on SWER systems [2-4, 10-13]. In [2], L. Mandeno presents the pioneering work on SWER in a paper published in 1947. Since then the technology has spread to various parts of the world allowing the economical electrification of otherwise remote rural areas. However, it is yet to be mainstreamed into the electrification of most developing countries the vast majority of whose rural areas lack access to electricity [5]. Many approaches for distribution system planning have been proposed [6, 15, 19, 21, 22]. A review of different power distribution planning models as well as their main strengths and weaknesses is given in [6]. However, most models presented do not consider the planning of earth return distribution networks.

The current work builds on the algorithm presented in [7].

A mathematical model of SWER distribution systems is presented. A load flow algorithm is subsequently formulated and a planning algorithm based on a heuristic iterative procedure is developed. The algorithm considers load growth over different time periods and consists of two parts. The first part determines the optimal feeder route configuration. The second part determines the optimal conductors for both the primary and the lateral feeders on the chosen route using performance indices based on the SWER load flow algorithm.

The planning procedure presented is suitable for areas which have previously not been electrified but can also be used when planning upgrades for existing feeders. A 30 node test network extracted from a rural area in Uganda's Mukono district is used to determine the practical application of the algorithm. All mathematical formulations and simulations were coded and run using GAMS on a 32-bit PC with Intel(R) Core(TM) 2 Duo CPU processor and 2 GB RAM.

II. MATHEMATICAL FORMULATION

A. SWER Line Model

The SWER line was modeled according to the Carson line model [8]. Carson's line models the impedances of overhead conductors with earth return. The total impedance, Z_{aa}, of an overhead line that has current return through the earth is given

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in (1). It includes the overhead conductor and ground self and mutual impedances which are derived in [8] and [9] and given by (2) to (4) respectively.

$$Z_{aa} = \bar{z}_{aa} + \bar{z}_{gg} - 2\bar{z}_{ag} \tag{1}$$

$$\bar{z}_{aa} = r_a + j4\pi \times 10^{-4} f \cdot \ln\left(\frac{2h_a}{GMR_a}\right) \tag{2}$$

$$\bar{z}_{gg} = \pi^2 \times 10^{-4} f - j0.0386 \cdot 8\pi \cdot 10^4 f + j4\pi \cdot 10^{-4} \cdot f \cdot \ln\left(\frac{2}{5.6198 \cdot 10^{-3}}\right) \tag{3}$$

$$\bar{z}_{ag} = j2\pi \cdot 10^{-4} \cdot \ln \frac{h_a}{\sqrt{\rho / f}} \tag{4}$$

Where, z_{aa}, z_{gg} are the self impedances of the overhead line and earth return respectively, z_{ag} is the mutual impedance between the overhead line and the earth return, r_a is the resistance of the phase conductor, f is the system frequency, h_a is the height of the overhead line above ground, GMR_a is the geometric mean radius of the overhead conductor and ρ is the resistivity of the earth. The overhead line shunt admittance was derived from the capacitive reactance which was calculated from the line capacitance, C, given by (5) [9, 7].

$$C = \frac{2\pi\varepsilon_o}{\ln\left(\frac{2h_a}{GMR_a}\right)} \tag{5}$$

The SWER lines can be connected directly to their energizing three phase feeders on the main grid network. However, an isolating transformer is often used to electrically isolate the SWER network from the energizing feeders. This allows earth fault protection to be used on the three phase system unlike in the former case where the SWER earth currents would be detected as a permanent earth fault [10]. The isolating transformer is considered in this study.

B. Load Model

Loads were modeled as constant power loads. The total load was distributed among distribution transformers and assumed to be proportional to the transformer sizes. Therefore, losses and voltage drops beyond the transformers to individual customer loads were ignored. Transformer losses and power factor variations due to the transformer inductance were considered to be part of the load [3, 7].

In SWER systems, the location of the load makes a big difference to the system's performance characteristics. Use of conventional load allocation methods for high diversity networks would create inaccuracies in SWER networks. This is because the latter networks have fewer customers spread over large distances leading to a low diversity factor [11]. Low load allocation at the end of a long SWER feeder leads to increased voltage levels towards the end of the network due to the Ferranti effect which is more pronounced in SWER systems. This effect, caused by line charging capacitance, would have to be mitigated using shunt reactors to keep the supply within regulated levels [12]. Load allocation towards the end of a SWER network may therefore need to be scaled up to model the network in a more demanding state [11].

C. Load Flow Algorithm

The SWER load flow algorithm was formulated as an optimization problem. The output terminals of the isolating transformer formed the infinite bus supplying power at 1 p.u. The constraints of the optimization formulation were based on the backward/forward sweep method for load flow calculation of radial networks [14] and are given by (6) to (8) [13].

$$\begin{bmatrix} I_{ia} \\ I_{ig} \end{bmatrix}^{(k)} = \begin{bmatrix} (S_{ia}/V_{ia}^{(k-1)})^* \\ -I_{ia}^{(k)} \end{bmatrix} - \begin{bmatrix} Y_{ia} \\ 0 \end{bmatrix} \begin{bmatrix} V_{ia} \\ V_{ig} \end{bmatrix}^{(k-1)} \tag{6}$$

$$\begin{bmatrix} J_{la} \\ J_{lg} \end{bmatrix}^{(k)} = -\begin{bmatrix} I_{ja} \\ I_{jg} \end{bmatrix}^{k} + \sum_{m \in M} \begin{bmatrix} J_{ma} \\ J_{mg} \end{bmatrix}^{k} \tag{7}$$

$$\begin{bmatrix} V_{ja} \\ V_{jg} \end{bmatrix}^{(k)} = \begin{bmatrix} V_{ia} \\ V_{ig} \end{bmatrix}^{k} - \begin{bmatrix} Z_{aa} & Z_{ag} \\ Z_{ag} & Z_{gg} \end{bmatrix} \begin{bmatrix} J_{la} \\ J_{lg} \end{bmatrix}^{k} \tag{8}$$

Where, I_{ia}, I_{ig} are the equivalent current injections at node i for the overhead line and earth return respectively, S_{ia} is the specified complex power load at node i, V_{ia}, V_{ig} are the complex voltages at node i for the overhead conductor and earth return respectively, Y_{ia} is the shunt admittance of the overhead line at node i, and k is the iteration index; j is the end node of branch l and M is the set of all branches connected downstream from node j; i and j are the incoming and outgoing nodes of branch l respectively. A branch-to-node matrix was formulated for all the branches and nodes connected downstream from any branch [7]. All the parameters and variables are complex quantities.

The objective function minimizes the difference between the calculated and specified bus load powers from the backward/forward sweep iterations. This is illustrated in (9) and (10) for both overhead and earth return path respectively [13, 7]. A detailed account of power flow derivation in earth return distribution networks can be found in [13].

$$\Delta S_{ia}^{k} = V_{ia}^{k} (I_{ia}^{k})^* - Y_{ia}^{*} \left| V_{ia}^{k} \right|^2 - S_{ia} \tag{9}$$

$$\Delta S_{ig}^{k} = V_{ig}^{k} (I_{ig}^{k})^* \tag{10}$$

III. NETWORK PLANNING ALGORITHM

The SWER planning algorithm considers load growth over different time periods up to a horizon year. In the development of the algorithm, the following assumptions were made [15].

- That the location of the isolating transformer substation is known since it is often located close to the point of grid extension from the three phase MV network.
- Data on existing loads, their locations and the prevailing load growth rate are readily available.
- Interconnections between load centers have multiple route options. Multiple conductor options likewise exist for each interconnection.

- Information on all equipment options including unit costs, electrical characteristics, etc. is available.
- The present worth of all costs is considered for the different time periods.

A. Optimal Feeder Routing

The objective of feeder routing is to interconnect all load centers at minimum investment cost. The optimal feeder route was determined using the minimum spanning tree (MST) algorithm formulated as an optimization problem.

The input of the MST algorithm was considered to be an acyclic graph $G = (V, A, c)$, where V is the set of network nodes, A is the set of arcs or branches constituting all possible network routes and $c(i,j)$ is the weight of the arc (i,j) related to its length or cost. It is considered that there is only one directed arc from i to j and that there are no cycles of total negative weight [16].

The optimal route was determined by formulating the MST algorithm as a mixed integer linear programming (MILP) problem. The objective was to minimize the total feeder length subject to radiality constraints. By introducing the integer variable x_{ij}, the set $\boldsymbol{X}$ was created for all branches whereby $x_{ij} = 1$ denotes that the arc (i,j) is included in the feeder route whereas $x_{ij} = 0$ denotes otherwise [17]. The full optimization problem formulation is given by (11) to (17). The solution will be the optimal route layout with respect to line lengths.

Minimise:

$$z = \sum_{\substack{ij \in A \\ i \neq j}} c_{ij} x_{ij} \tag{11}$$

Subject to:

$$\sum_{\substack{i \in V \\ i \neq j}} x_{ij} \leq 2 \qquad \forall j \neq 1 \tag{12}$$

$$\sum_{\substack{j \in V \\ i \neq j}} x_{ij} \geq 1 \qquad \forall j \neq n \tag{13}$$

$$\sum_{i \in V} x_{i1} = 0 \tag{14}$$

$$\sum_{\substack{i \in V \\ i \neq n}} x_{in} = 1 \tag{15}$$

$$u_i - u_j + n x_{ij} \leq n - 1 \ , \qquad 1 \leq i \neq j \leq n \tag{16}$$

$$x_{ij} \in \{1, 0\} \qquad \forall (i,j) \in A \tag{17}$$

Where n is the total number of nodes and u_i and u_j are unrestricted variables. Constraints (12) to (15) are radiality constraints. Constraints (12) and (13) determine the number of branches attached to a particular node and (13) allows for multiple branches from a node while ensuring that there is no outgoing branch from the last node n. Constraints (14) and (15) ensure that no branch is incident on the source node and that only one branch is incident on the last node respectively.

The number of branches incident on a node is limited to a maximum of two in (12) instead of one to allow radiality. This is because the latter case would result in a network with one directed path from the source to the last node without branches as in the Travelling Salesman Problem (TSP) [18]. Constraint (16) eliminates local loops in the resultant network and ensures that all n odes are connected. It can be proven that there exist values for u_i and u_j in the inequalities of (16) which rule out disjoint cycles or sub-networks from the MST [18].

It follows, therefore, that the branch numbering in developing the MST has no relationship with the power flow in the network. Rather, once an optimal route is obtained, the nodes on the primary and lateral feeders should be re-labeled appropriately to calculate the power flow. It is important that the node n is located farthest from the source in the MST algorithm above.

B. Optimal Conductor Selection

With the optimal feeder route established, an iterative procedure was developed to determine the branch conductor that would best meet the network demand. The objective is to minimize the energy losses and line voltage drops while maintaining a reliable, secure and economical supply to the forecast load. The appropriate conductor for each branch will be that which minimizes the investment and real power loss costs while keeping nodal voltages within acceptable levels [19]. The conductor selection algorithm presented is based on that proposed in [7]. Conductor selection was done iteratively using the SWER load flow algorithm presented in section II part *C* to formulate appropriate network performance indices for each conductor option.

1) Network Performance Indices

Each conductor was placed onto the network in turn and its performance analyzed. Network performance for each scenario was obtained by running simulations of the SWER load flow algorithm for every time period. From the load flow results, performance indices were then formulated based on the system's voltage profile, real power losses and the utilization of conductors as a fraction of their thermal limits.

The voltage index, $I_{V,c}$, given by (18) is a measure of the average nodal voltage deviation per time period from the nominal 1 p.u (V_0) during a planning period of T years. The lower the voltage index, the better the network performance. The power loss index, $I_{L,c}$, given by (19) calculates the ratio of total power losses to total active power demand for all time periods. For good network performance, this index should be as low as possible. The utilization index, $I_{U,c}$, is given by (20) and is a measure of the average current through each conductors as a ratio of its total current capacity limit in each time period. It follows that the higher the conductor utilization without overload during the planning period, the better the performance since under-utilization incurs unnecessarily high investment costs.

$$I_{V,c} = \frac{\sum_{i=1}^{n}\sum_{t=1}^{T} \left| V_{i,t,c} - V_o \right|}{n \cdot T} \tag{18}$$

$$I_{L,c} = \frac{\sum_{l=1}^{nb}\sum_{t=1}^{T} (J_{l,t,c}^2 \cdot R_{l,c})}{\sum_{i=1}^{n}\sum_{t=1}^{T} P_{i,t}} \tag{19}$$

$$I_{U,c} = \frac{\sum_{l=1}^{nb}\sum_{t=1}^{T}(J_{l,t,c}/J_{max,c})}{nb \cdot T} \tag{20}$$

Where, T is the total number of time periods (years) considered; $V_{i,t,c}$ is the voltage at node i in period t for conductor c; $J_{l,t,c}$ is the current flowing through conductor c on branch l during period t; $R_{l,c}$ is the resistance of branch l conductor c; $P_{i,t}$ is the real power demand at node i during period t; $J_{max,c}$ is the current carrying limit of conductor c; and nb is the total number of branches.

The lateral feeders carry considerably lower current than the primary feeder. Therefore, a smaller lateral conductor should be chosen for improved utilization and lower investment costs. Two overall indices, $I_{P,c}$ and $I_{L,c}$, were thus formulated to determine optimal conductors for the primary and lateral feeders respectively. Both indices were based on the performance indices formulated in (18) to (20) and are given by (21) and (22).

$$I_{P,c} = \frac{I_{U,c}}{I_{V,c} \cdot I_{L,c} \cdot C_c^2} \tag{21}$$

$$I_{L,c} = \frac{I_{U,c}^2}{I_{V,c} \cdot I_{L,c} \cdot C_c^2} \tag{22}$$

Where C_c is the per unit conductor cost. The cost of the most expensive conductor was used as the base cost. Therefore, indices (21) and (22) are dimensionless.

The indices given by (21) and (22) reflect the proportional contributions of each performance index to the overall network performance for a given conductor. For example, in the primary feeder index, $I_{P,c}$,the conductor performance is directly proportional to its utilization since an under-utilized network wastes resources. Conversely, the performance is inversely proportional to the losses and voltage deviations. Hence, the directly proportional index, $I_{U,c}$, appears in the numerator whereas the inversely proportional indices $I_{L,c}$ and $I_{V,c}$ including investment costs are in the denominator of (21).

In the lateral conductor selection index, $I_{L,c}$, the utilization index is squared to emphasize the importance of utilization in the lower current carrying laterals. The implementation of the above involved the creation of two sets containing the primary and lateral branches respectively. The above procedure is summarized in figure 1 [7].

The following conditions must be fulfilled for each scenario of the iterative procedure.

a) All nodal voltages should be within specified limits.
b) Kirchoff's current law should be satisfied at all nodes.
c) All conductor currents should be within their current carrying limits to prevent system overload.

All indices were calculated only for scenarios that met the above criteria.

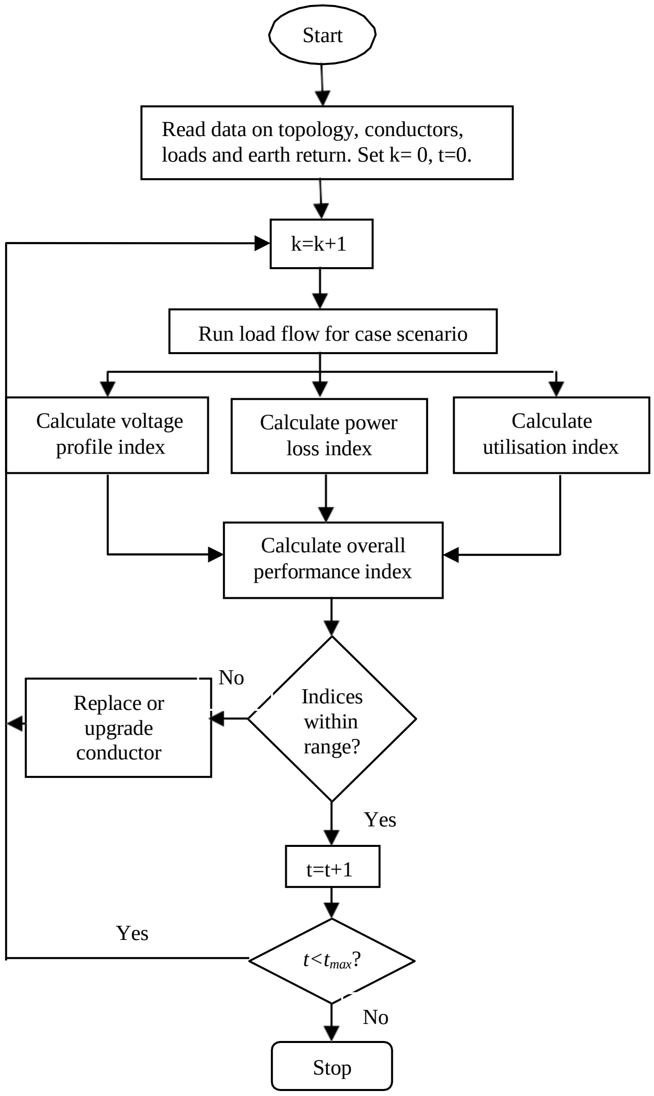

Figure 1. Flow diagram of conductor selection algorithm

IV. APPLICATION

A. The Test Network

Thirty load points were considered in the case study extracted from a rural area in Mukono district, central Uganda. The SWER line was to be extended from a 33 kV grid. Load data in a previously un-electrified rural area were obtained from field surveys and the local power distribution company. The load data are given in table I whereas figure 2 shows the relative load locations.

TABLE I
DISTRIBUTION SYSTEM LOAD DATA

Bus	X coordinate	Y coordinate	Demand (kVA)	Bus	X coordinate	Y coordinate	Demand (kVA)	Bus	X coordinate	Y coordinate	Demand (kVA)
0	1.0	1.0	0	11	2.5	6.0	16	22	6.0	11.3	25
1	0.7	2.3	25	12	1.7	6.3	25	23	10.0	6.0	16
2	2.3	2.3	32	13	1.0	5.0	16	24	11.3	6.3	16
3	3.0	4.7	16	14	4.3	7.3	16	25	10.3	7.7	32
4	4.5	4.7	16	15	5.0	9.0	32	26	9.0	7.3	16
5	6.0	6.0	25	16	4.3	10.0	32	27	8.0	9.0	25
6	7.0	4.7	16	17	3.0	10.3	16	28	7.0	7.7	16
7	8.7	5.0	25	18	2.0	10.3	25	29	7.3	2.3	25
8	9.3	3.3	25	19	1.3	11.7	25	30	9.0	1.0	32
9	11.0	3.7	16	20	3.3	8.3	16	Total load (kVA)			682
10	12.7	4.7	32	21	2.0	8.7	32	Total length (km)			49.6

Other general network parameters considered were: f=50 Hz, ρ = 400 Ωm, Z_{gg} = (0.0493 + j0.3643) Ω/km, reference voltage at isolating transformer 19.1 kV, base power 100 kVA, demand factor 1 and power factor 0.8. The mutual impedance between line and earth return was considered to be negligible.

B. Overhead Conductors

In order to allow for the long spans of SWER feeders in practice, lightweight and high tensile strength conductors were chosen. Nine options were considered and their electrical characteristics are given in table II. The unit costs were assumed to be directly proportional to the conductor sizes and hence current carrying limits. The properties given in table II are specified for 75°C with overhead line clearance 6.5 m.

TABLE II
CONDUCTOR ELECTRICAL PROPERTIES

Conductor code		R (Ω/km)	X (Ω/km)	Current rating (A)
1	Bantam	5.26	1.02	69
2	Mole	3.30	1.03	98
3	Magpie	3.31	0.99	92
4	Shrike	2.08	0.96	122
5	Squirrel	1.67	0.99	148
6	Snipe	1.31	0.93	162
7	Loon	1.04	0.92	186
8	Grouse	0.86	0.94	195
9	Petrel	0.69	0.91	232
10	Minorca	0.63	0.91	244

C. Results and Discussion

1) Optimal Feeder Route

The optimal feeder route was determined using the optimization formulation in section III part *A*. For simplicity, the feeder investment costs were considered to be proportional only to the distance between load points. Costs related to terrain, right of way, etc. were not considered. The algorithm was solved as a MILP problem in GAMS. The MST route obtained was re-labeled to allow calculation of the network load flow.

The resultant network is shown in figure 2 with the primary feeder highlighted. The node and branch numbering scheme used was based on that proposed in [21]. All nodes on the primary feeder were numbered first with 0 as the source node. Then those on the laterals starting with the one closest to the source and its sub-laterals were numbered. Branches were numbered the same as their receiving nodes such that branch 1 was that connecting node 0 to 1.

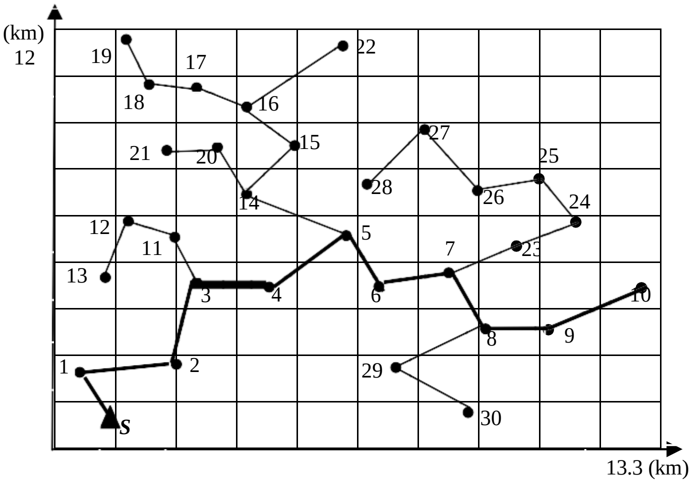

Figure 2. Optimal feeder route and locations of system load points

TABLE III
OVERALL PERFORMANCE INDICES FOR 5% ANNUAL LOAD GROWTH OVER 10 YEARS

	Primary ($I_{P,c}$)	Lateral ($I_{L,c}$)
Bantam	0.117	0.060
Magpie	0.424	0.077
Mole	0.288	0.049
Shrike	1.191	**0.171**
Squirrel	0.958	0.112
Snipe	1.140	0.120
Loon	1.078	0.098
Grouse	**1.219**	0.105
Petrel	1.005	0.073
Minorca	0.976	0.067

2) *Conductor Selection*

A 10 year planning period was considered in the base case and the annual rural load growth rate estimated to be 5%. The SWER load flow was obtained for each time period and the performance indices calculated. Table III summarizes the overall index results for each conductor given 5% annual load growth over 10 years.Simulation results in table III show that ‘grouse’ was the best choice for the primary feeder whereas ‘shrike’ was the conductor of choice for the laterals in the base case. The total real power losses throughout the planning period on the primary feeder with grouse for this scenario were 373 kW and the largest p.u voltage deviation was 0.069. The total real power losses throughout the planning period on the lateral feeders with shrike were 34 kW and the largest p.u voltage deviation was 0.124.

D. Sensitivity Analysis

A sensitivity analysis was done to observe the choice of conductor made using the above procedure in different operating scenarios. This involved varying the annual load growth rate and the length of the planning period.

1) *Lower load growth and shorter planning period*

The annual load growth rate was reduced to 2% to consider the network performance under slow load growth conditions. The planning period was likewise reduced from 10 to 7 years. The performance indices for this scenario are given in table IV.

The simulation results show that ‘magpie’ is the best choice conductor for the lower demand network for both the primary and lateral feeders. This choice makes sense since a smaller conductor is required for the lower demand network and the smaller ‘bantam’ conductor on the laterals would give unacceptable voltage deviation of 0.193 p.u. The total real power losses throughout the planning period on the primary feeder with magpie conductor were 752 kW and the largest p.u voltage deviation was 0.119. The total real power losses throughout the planning period on the lateral feeders with magpie conductor were 27 kW and the largest p.u voltage deviation was 0.123.

2) *Higher load growth over the same planning period*

In this scenario, a higher annual load growth of 8% and the same planning period of 10 years were considered. This puts the network in a higher demand state. The overall index results for this scenario are given in table IV.

The best conductor choice for this scenario was ‘grouse’ for the primary feeder and ‘snipe’ for the laterals according to results in table IV. The primary feeder choice conductor remained the same as that in the base case. However, the larger snipe conductor replaced shrike as the best choice for the lateral feeder to reflect the higher demand network. The total real power losses throughout the planning period on the primary feeder with grouse were 545 kW and the largest p.u voltage deviation was 0.094. The total real power losses throughout the planning period on the lateral feeders with snipe were 30 kW and the largest p.u voltage deviation was 0.122.

TABLE IV
SENSITIVITY ANALYSIS RESULTS FOR CONDUCTOR SELECTION

	2% growth, 7 years		8% growth, 10 years	
	($I_{P,c}$)	($I_{L,c}$)	($I_{P,c}$)	($I_{L,c}$)
Bantam	0.284	0.056	0.045	0.060
Magpie	**1.847**	**0.297**	0.174	0.063
Mole	1.250	0.188	0.133	0.040
Shrike	1.530	0.179	0.376	0.061
Squirrel	1.222	0.117	0.479	0.064
Snipe	1.444	0.125	0.904	**0.114**
Loon	1.360	0.102	0.860	0.093
Grouse	1.535	0.109	**0.976**	0.100
Petrel	1.263	0.075	0.807	0.069
Minorca	1.225	0.069	0.785	0.064

V. CONCLUSION

The study presents an algorithm for planning of Single Wire Earth Return power distribution networks. The planning procedure involves the determination of the optimal radial feeder route using a minimum spanning tree algorithm formulated as an optimization problem. A heuristic iterative procedure is then used to select suitable conductors for both the primary and lateral feeders. This is implemented with a SWER load flow algorithm which is used to formulate appropriate indices for optimal conductor selection in different time periods with load growth. Application to a test network showed that the planning algorithm gave logical and consistent results. The proposed procedure can be applied to power distribution planning in both previously un-electrified areas and those where an upgrade of existing distribution systems is required.

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