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Voltage Profile Improvement using Switched Capacitors: Case of Single Wire Earth Return Distribution Network

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ABSTRACT: *Most rural areas in Africa are characterized by scattered villages with a very low demand in electricity. Due to improper planning and lack of knowledge on low cost technologies, the cost of extending the grid to supply these area is very high relative to the returns. Rural electrification by means of extending the main grid and distributing power using a single wire with earth return (SWER) has shown to be the least expensive rural electrification method in remote area where loads are light and scattered.This paper presents a developed model of Single wire earth return distribution network and a voltage profile of the network using backward and forward sweep method load flow algorithm. And finally presents the analysis of the effect of shunt capacitors on the voltage profile of the network using Maximum power saving method for the sizing and placement of the capacitor.*

Keywords: *SWER, switched capacitors, Maximum power saving, backward/Forward Sweep Method*

I. INTRODUCTION

Historically, rural electrification has been a huge challenge and remains so in many parts of the world. The use of standard electrification technologies becomes unviable in rural areas due to the high cost of investment and the low load densities [1]. As a result, Single Wire Earth Return (SWER) distribution technology has come to provide a cost-effective way of supplying electricity in rural area where loads are scattered and sparse. This technology, initially was proposed by Mandeno [2] and it has proven to be cost-effective in electrifying rural areas. SWER system has been in use since 1930 and it is still used in New Zealand, Australia, Namibia, South Africa and many other parts of the world. [3].

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 [3, 4]. 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.

In Single Wire Earth Return (SWER) power distribution network, the earth itself forms the return path for current of the single phase system. The ground used as return path presents technical and operational challenges as well as the dependency on earth conductivity to supply consumer loads. The common problem of continuous increase in electricity demand / consumption and the type of conductor used in SWER line cause the voltage drop to be high; thus require urgent attention in order to enhance system capacity and reliability.

This paper present the use of switched capacitor as one of the most effective and useful methods in reducing the power losses in distribution networks. After a load flow calculation using Backward/forward sweep method. The information provided by the load flow analysis consists of the active and reactive power flow in the each branch and the associated line losses, the magnitude and phase angles of voltages at each bus and the current in the various line section under steady state condition.

In this paper, the proposed backward and forward sweep method was used to calculate branch currents and nodal voltages using the Kirchhoff's law [5, 6, 7]. The validity of the method was tested on the 6-bus designed SWER radial distribution system. After the power flow is performed the voltage profile was determined and it has shown that there is a need to improve the voltage. A maximum power saving method was then used to determine the optimum placement and size of the capacitor.

II. CASE STUDY

In Rwanda, there is a strong ambition for electrical network expansion in rural area to provide electricity to the majority of the population which lacks access to electricity. A non-electrified sector from Muhanga district, in Southern Province Rwanda is selected to be supplied through SWER system. Rongi sector has 5 developed centers which are considered as major loads. The distance from the three phase transmission line to the first center is 10km and 60km to the last and the distance between these settlements ranges from 10 to 20km.

In this case study village, individual load are typically less than 5kW and overall demand of each settlement/center in the village ranges from 214 to 259kW. The pick demand occurring at 7PM is of 30.45kVA for first and last centers and 28.31kVA for middle centers. These pick demand are the one considered while sizing the distribution transformer and overall pick demand of 147.12kVA is taken into consideration for the size of isolation transformer. A 11/6.35 kV isolating transformer is used to connect two phases of a 11 kV feeder to a SWER feeder. This transformer prevents earth return currents from interacting with the 11kV feeder. Figure 1 shows a detailed schematic of a SWER feeder connection and associated customer load connections.

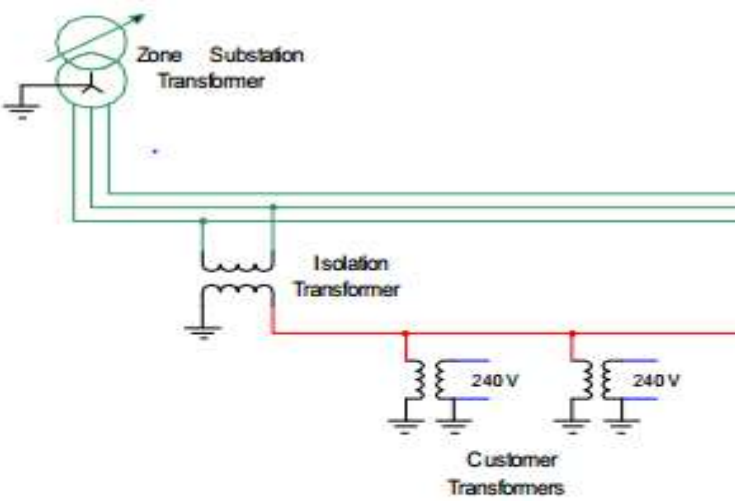

Figure 1. SWER feeder schematic

II.1. Network parameters consideration

Five load points are considered as mentioned above. The SWER line is to be extended from an 11kV grid. General network parameters were considered as follows:

f =50Hz,
Reference voltage at isolating transformer 6.35kV,
Base power 100kVA,
Demand factor 1 and
Power factor 0.9

Isolating transformer is rated at 150kVA while distribution transformer are at 30kVA.from [8] a choice of Steel Cored Aluminum Clad was made due to the fact that it has lower electrical resistance and provide better protection against corrosion, also it is light in weight [9**].**

Calculation of line impedance of SWER

The impedance of a SWER line Using Carson`s approach as explained in [10] is calculated using assumption below:

Choosing SC/AC conductor

$$\mathrm{GMR} = 0.7788 \times \sqrt{\frac{17.82}{3.14}}$$

$$=1.856 \qquad (1)$$

Assuming the height of the conductor above the earth in (m), of ha =10m and ρ the soil resistivity in Ωm at average soil which of about 250 Ωm

$$\bar{z}_{aa} = 5.75 + j4\pi * 10^{-4} 50 \ln\left(\frac{2*10}{1.856}\right) \qquad (2)$$

$\bar{z}_{aa}$= (5.75+j0.149) Ω/km

$$\bar{z}_{gg} = \pi^2 * 10^{-4} 50 - j0.0386 * 8\pi * 10^{-4} * 50 + j4\pi * 10^{-4} * 50 \ln\left(\frac{2}{5.6198 * 10^{-8}}\right) \qquad (3)$$

$\bar{z}_{gg}$= (0.0493+j 0.364) Ω/km,

$$\bar{z}_{ag} = j2\pi * 10^{-4} \ln\left(\frac{10}{\sqrt{\frac{250}{50}}}\right) \qquad (4)$$

$\bar{z}_{ag} = (j0.0004352)$ Ω/km,

The equation (1) is now

Zaa = 5.7992 + j0.512

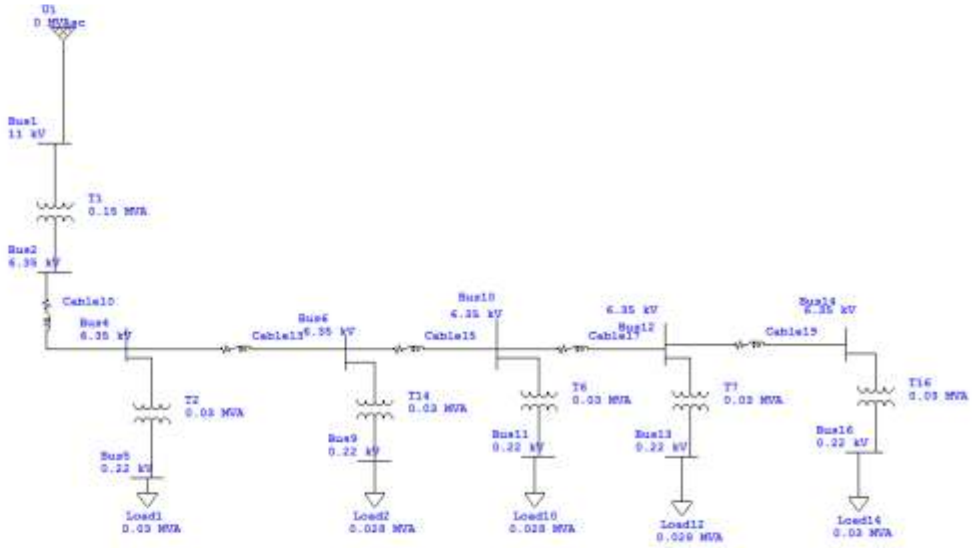

Figure.2 Single line diagram of the studied network**.**

Table I. load location and their maximum demand

Load location /section	Distance separation	Maximum demand	Impedance of line section	Total impedance of line section
B(AB) with A the isolating transformer location	10km	30.45kVA	(5.7992+j0.512)*10	58 + j5.12
C(BC)	20	28.31kVA	(5.7992+j0.512)*10	58 + j5.12
D(CD)	35	28.31kVA	(5.7992+j0.512)*15	69 + j7.68
E(DE)	45	28.31kVA	(5.7992+j0.512)*10	58 + j 5.12
F(EF)	60km	30.45kVA	(5.7992+j0.512)*15	69+ j7.68

III. LOAD FLOW CALCULATION

The SWER load flow formulation is based on the forward/backward sweep method presented in [10] for earth return networks. All nodal current injections due to loads and shunt elements are first computed based on initial voltage values for both the overhead conductor and ground return path.

The branch currents are then calculated using Kirchoffs Current Law (KCL) for the line and ground respectively, where the loads are represented by their equivalent current injections. According to the KCL, the sum of all branch currents entering and leaving a node is equivalent to the load current at that node. Finally, nodal voltages for both overhead line and earth return are updated. This leads to an iterative procedure that ends when the difference between the specified and calculated current injections at each bus is minimum.
A detailed operation of the power flow using backward /forward sweep method is shown below.

III.1 Backward/forward sweep algorithm

Step 1: Read Bus data and line resistance and reactance data
Step 2: Read base MVA and base KV and calculate the per unit values of the data loaded.
Step 3: Backward walk from end node to source node to find all branch currents by using equation 3 and 4 while keeping constant flat initial voltages
Step 4: Forward walk from source node to the far end node, to find all voltages using equation 5 while updating the constant current values obtained in the previous iteration and check for convergence criterion.
Step 5: Check if the mismatch of the specified and calculated voltages at the substation is less than the convergence tolerance. If yes, go to next step. Otherwise, repeat step 3 and step 4.
Step 6: calculate the total active and reactive line losses using equations 1 and 2 with the currents and voltages obtained from the backward and forward sweep method.
Step 7: Print the result of all bus voltage and Total loss in the system
Step 8: Stop

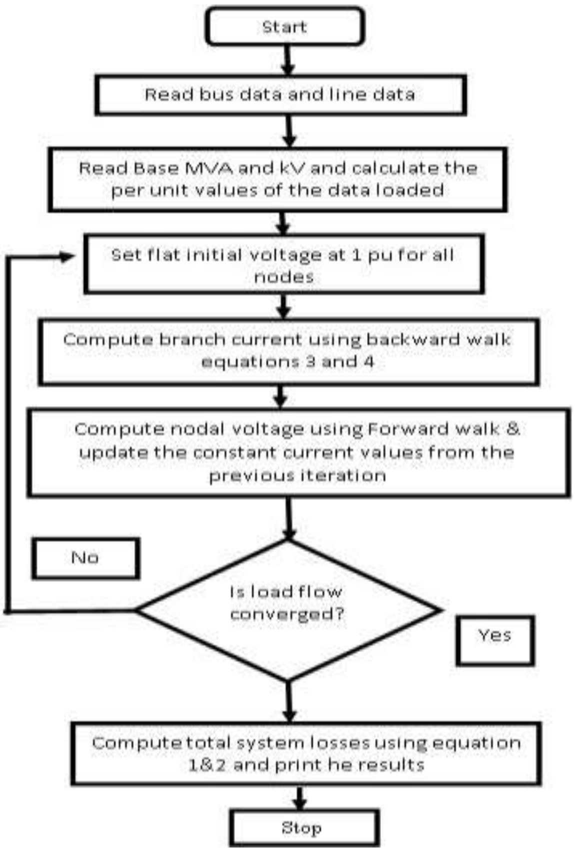

Figure.2 Flow chart for backward/forward sweep method

III.2 Maximum power saving method

To improve the voltage profile of the network, switched capacitor were proposed and maximum power saving method was used to determine the optimal placement and optimal size of the capacitor. Such method is based on branch current formula. It consists of reducing the line losses considering the current flowing in that line and considered that the current has real and imaginary component [11]. It uses imaginary component when it is to inject reactive power, which is the case for capacitors.

Mathematical expression

- Power loss

$$\mathbf{QTL} = \sum_{j=1}^{N} I_j^2 \times X_j \qquad (5)$$

Where *QTL* is the total reactive power loss in the system, I_j the branch current and X_j the reactance of the branch. The current I_j flowing has a real and imaginal part component, thus above can be rewritten with Ij= Iaj + Irj as:

$$\mathbf{QTL} = \sum_{j=1}^{N} I_{aj}^2 \times X_j + \sum_{j=1}^{N} I_{rj}^2 \times X_j \qquad (6)$$

- Bus voltage limit

The bus voltage should be within the tolerable range of ±5%.

$|V_{jmin}| \le |V_j| \le |V_{jmax}|$

- Power flow

The Power flow in each branch must be equal or less than maximum vapacity rating in order to respect the thermal capacity limit of the line.

$|I_j| \le I_{jmax}$, j=1, 2, 3…….N

The total reactive power injected (Q_{jCap}) must be equal to the sum of total reactive power loss(Q_{Loss}) and the total load(Q_{jLoad}).

$$\sum Q_{jCap} = Q_{Loss} + \sum Q_{jLoads} \qquad \textbf{(7)}$$

If the capacitor current is injected at bus k, the current flow from the source to the bus k is affected by the current injected but beyond the node k, the flow remains the same, and the mathematical expression is given below:

$$\mathbf{QTLcapk} = \sum_{j=1}^{N}\left(I_{aj} + I_{Capk}\right)^2 \times X_j + \sum_{j=k+1}^{N} I_{aj}^2 \times X_j + \sum_{j=1}^{N}\left(I_{rj} + a_k\, I_{Capk}\right)^2 \times X_j + \sum_{j=k+1}^{N} I_{rj}^2 \times X_j \qquad \textbf{(15)}$$

Where QLTcapk is the total active power loss with the capacitor cuurent injected at node k, Iaj and Irj is the real and imaginary components of the current flowing from the base load flow, Icapk is the capacitor current injected at node k and Xj is the line reactance. a_k= (sign) tan ($\cos^{-1}$(PF cap)), sign =+1 if capacitor is injecting the reactive power and sign= -1 if it is consuming the reactive power from the network.

Now the saving at each node is calculated by subtracting the total power loss with capacitor from the total based loss without the capacitor as shown below:

Saving (SS) = QTL – QTLcapk (8)

The maximum value of power saving is found by equating to zero the derivative of the power saving with respect to its equivalent capacitor current injected at node k and considering only the imaginary component of the current flowing for reactive power injection[12].

$$\mathbf{SS} = -2 I_{capk} \sum_{j=1}^{k} I_{rj} \times X_j - I_{Capk}^2 \sum_{k=1}^{k} X_j \qquad \textbf{(9)}$$

$$\frac{\partial ss}{\partial I_{Capk}} = 0 \cong -2 \sum_{j-1}^{k} I_{rj} \times X_j - 2 I_{Capk} \sum_{j=1}^{k} X_j \qquad \textbf{(10)}$$

From the derivative equation, the value of the current injected at each node can be evaluated respectively and these computed current values are replaced in the maximum saving equation for all the nodes, then the node with higher power saving is identified and selected as candidate for capacitor placement. The expression for the capacitor current at each node is given below:

$$I_{Capk} = -\frac{\sum_{j-1}^{k} I_{rj} \times X_j}{\sum_{j=1}^{k} X_j} \qquad \textbf{(11)}$$

The optimal size of capacitor at selected node k is calculated using the capacitor current injected at optimal branch and its corresponding voltage magnitude[11].

$$Q_{Capk} = I_{Capk} \times |V_k| = |V_k| \frac{\sum_{j=1}^{k} I_{rj} \times X_j}{\sum_{j=1}^{k} X_j} \qquad (12)$$

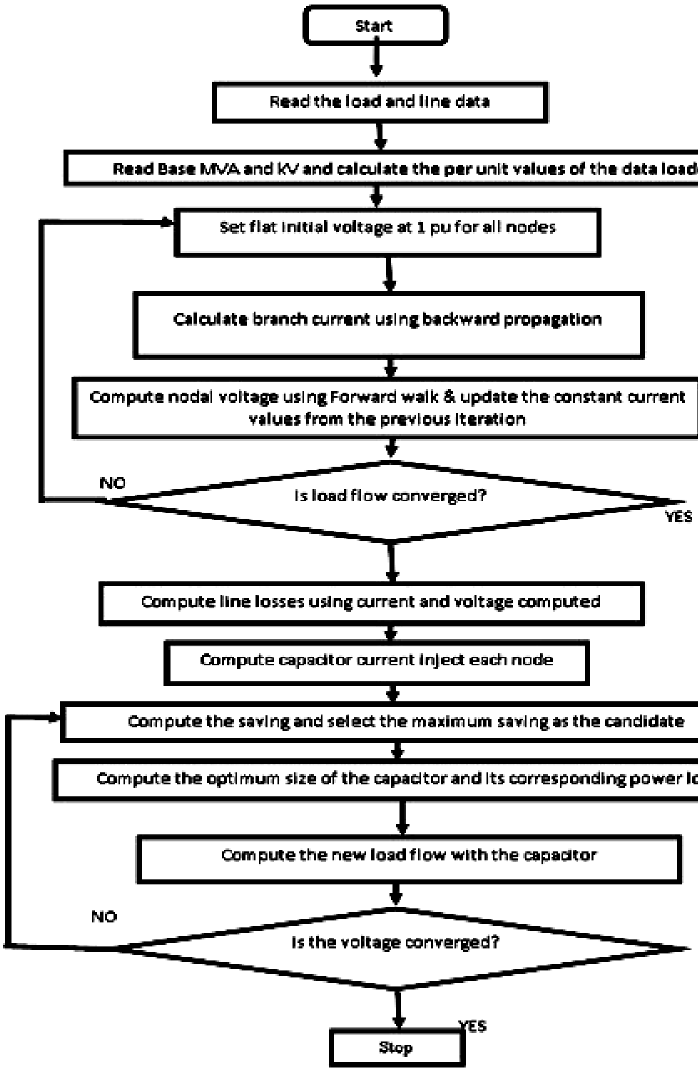

Figure.3 Flow chart for Maximum power saving method

IV. RESULT AND DISCUSSION

The effectiveness of the proposed method validity and performance was tested with the 6bus SWER RDN develop previously, the study was done under Matlab R2013a and the based load flow losses and the voltage using the BFSM load flow analysis method is shown in table II and figure.4 below respectively.

The characteristics of the systems is given below:
Total number of nodes: 6,
Total number of branches: 5,
KV base: 6.35 KV,
KVA base 100kVA,
From the results we noticed that there is a need to improve the voltage profile.

Table II. Based case result of the test systems

buses	**6**
Total load(KVA)	145.85kVA
Total reactive power loss(kVar)	8.4456

Maximum Voltage(pu)	1.0000
Minimum Voltage(pu)	0.8493

Fig.4. voltage profile

Applying the maximum power saving formula in the based load flow results above, the node 3 was identified for the optimal placement of the capacitor with the saving of 6.24kVar. It was then selected for the maximum reactive power loss reduction and the optimal size of the capacitor is calculated before another load flow is carried out with the capacitor injected to get the new system line loss and the new voltage profile. The results are presented in the table III and figure 5 below.

Table III. Simulation results with capacitor in the systems

Number of buses	**6**
Optimum siting	Node 3
Optimal size	55kVar
Total reactive power loss with capacitor injected	0.12kVar
Minimum Voltage(pu)	0.9512

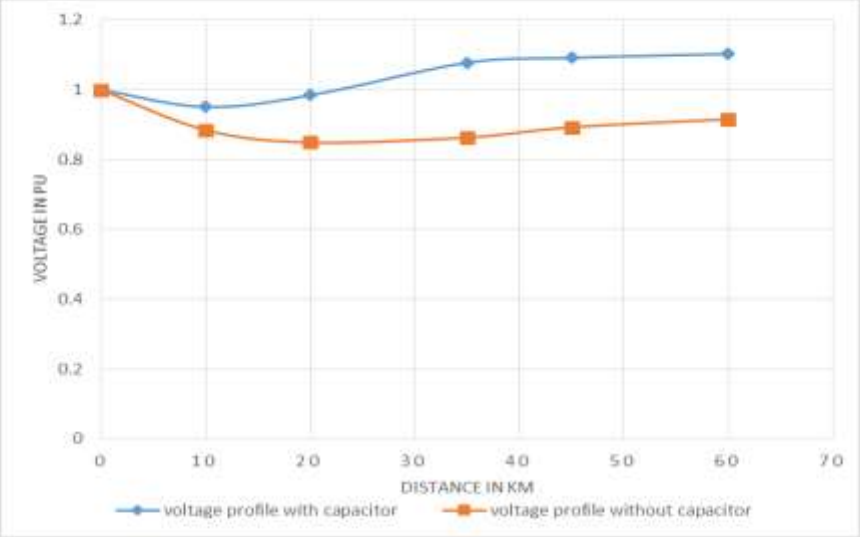

Figure 5. Voltage profile with capacitor injected

V. CONCLUSION

In this paper, the backward/forward sweep method was used for the analysis of the radial distribution systems and the maximum power saving method helped in the siting and sizing of the capacitor. The integration of the capacitor in the system has reduced the reactive power loss and the voltage profile has increased. The integration of capacitor in the distribution system has a positive impact by significantly reducing the losses and improving the voltage profile. In further studies, the network reconfiguration with the capacitor integrated for the maximum loss reduction can be considered and cost of the capacitor.

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