Cost Sustainability Analysis of an Enhanced Distribution Network

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Abstract—This study presents the cost sustainability analysis of an enhanced distribution network (DN). In the study, the enhancement of the DN was achieved through network reconfiguration (NR) and the introduction of distributed generation units (DGs) at some locations. When the DN was only reconfigured, the power losses in the network reduced by 23.39 % at 1.0 p.u. loading; whereas, the minimum voltage profile in the network improved by 1.79 %. When both reconfiguration and DG were engaged in losses minimization, power losses reduced by 61.94 % at full load, whereas the minimum voltages in the network improved by 7.66 %. When the DN was reconfigured and DGs were embedded at three different locations, the energy losses in the entire network reduced by 61.94 % and 58.37 % at 0.5 and 1.0 loadings respectively; whereas, the minimum voltages in the network improved by 1.21 % and 8.46 % at 0.5 p.u. and 1.0 p.u loadings respectively. The information obtained from the load flow analysis was used for the economic analysis of the DN when both reconfigured and three DGs were embedded at different locations of the network. The annual financial energy gains evaluated from the annual energy savings was about $125,000.00, when the DN operated at 100 % loading capacity all year round. The financial savings are sufficient to cover annual operational cost of solar PV DGs; as well as, recovering its capital investment with a payback period of 5 years.

Keywords— Network reconfiguration, distributed generation, solar PV, voltage profile, and payback period

1. INTRODUCTION

A distributed network (DN) is normally enhanced in order to reduce its energy losses during operation horizon, improve its energy efficiency and balance its load levels, and possibly increase the loadability of the entire network. To achieve all or some of the above mentioned gains, the DN must be reconfigured or additional distributed generation (DG) units embedded at optimal locations of the network. When a DN is reconfigured, the topology of the DN is changed by opening and closing of tie switches that sectionalized the network; whereas, addition of DGs is the injection of either renewable or non-renewable energy sources at optimal locations of the network.

Several methods have been utilized in solving the optimal NR problem, namely, heuristic algorithms (Koutsoukis et al., 2017; Lee et al., 2015; Shirmohammadi and Hong, 1989), simulated annealing (Lepuschitz, 2010), discrete mutant particle swarm optimization and binary particle swarm optimization (Soumitri and Chauhan, 2016; Jin et al., 2004; Dahalan and Mokhlis, 2012; Imran et al., 2014). In addition the reconfiguration problem has been considered with the simultaneous introduction of distributed generation. Tabu search algorithm, fire fly algorithm and ant colony optimization have been implemented successfully to yield results that significantly improve the voltage profiles and efficiency of distribution networks (Shamsudin et al., 2015; Dahalan, 2012, Rajaram, 2015, Rao, 2013). Review of literature revealed that research activities on economic sustainability, viability and realizability of an enhanced DN are very rare. Economic sustainability is a key consideration for developing economies with scarce financial resources to be allocated for many possible alternative projects to enhance power supply and reliable distribution.

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It is therefore, the objective of this study to analyze the financial sustainability of an enhanced DN using a 33-Bus Azare DN as case study. The rest of the paper is organized as follows: Section 2 of the paper presents methods adopted to achieve the goal of the study. In section 3, the simulations carried out using particle swarm algorithm in matpower environment in the matlab are reported. The voltage profiles and energy losses obtained during the simulation exercise are presented in section 4. In this section also, the results of simulations are used to evaluate the financial analysis of the case study. Section 5 concludes the paper.

2. METHODOLOGY

2.1 Objective Function of the Problem

The goal is to maximize power loss reduction in a DN viz:

\[
\text{max} \left( \Delta P_{\text{Loss}} + \Delta P_{\text{DG}} \right) \tag{1}
\]

Subject to:

\[
V_{\min} \leq |V_k| \leq V_{\max} \tag{2}
\]

\[
|I_{k,k+1}| \leq |I_{k,k+1,\text{max}}| \tag{3}
\]

\[
\sum_{k=1}^{n} P_{G_k} \leq \sum_{k=1}^{n} (P_k + P_{\text{Loss},k}) \tag{4}
\]

And the power flow in the network is calculated by

\[
P_{k+1} = P_k - P_{\text{Loss},k} - P_{L,k+1} = P_k - \frac{\delta_k}{|V_k|^2}(P_k^2 + (Q_k + Y_k|V_k|^2)^2) - P_{L,k+1} \tag{5}
\]

\[
Q_{k+1} = Q_k - Q_{\text{Loss},k} - Q_{L,k+1} = Q_k - \frac{x_k}{|V_k|^2}(P_k^2 + (Q_k + Y_k|V_k|^2)^2) - Y_{k+1}|V_{k+1}|^2 - Q_{L,k+1} \tag{6}
\]
\[ |V_{k+1}^2| = |V_k^2| + \frac{B_k^2 + X_k^2}{|V_k|^2} \left( P_k^2 + Q_k^2 \right) - 2( R_k P_k + X_k Q_k ) \]

\[ |V_{k+1}^2| = |V_k^2| + \frac{B_k^2 + X_k^2}{|V_k|^2} \left( P_k^2 + Q_k^2 \right) - (Q_k + Y_k |V_k|^2) - 2( R_k P_k + X_k Q_k + X_k^2 |V_k|^4) \]

(6)

where, \( P_k \) = real power flowing out of bus \( k \), \( Q_k \) = reactive power flowing out of bus \( k \), \( P'_k \) = real power flowing out of bus \( k \) after reconfiguration, \( Q'_k \) = reactive power flowing out of bus \( k \) after reconfiguration, \( P_{load} \) = real load power at bus \( k+1 \), \( Q_{load} \) = reactive power flowing out of bus \( k \), \( Y_k \) = shunt admittance at any bus \( k \), \( R_k \) = resistance of the line section between buses \( k \) and \( k+1 \), \( X_k \) = reactance of the line section between buses \( k \) and \( k+1 \).

The power loss in a line linking buses \( k \) and \( k+1 \) is:

\[ P_{\text{Loss}}(k, k+1) = R_k \left( \frac{P_k^2 + Q_k^2}{|V_k|^2} \right) \]

(7)

Hence, total line losses in the entire DN sums to:

\[ P_{\text{T Loss}} = \sum_{k=1}^{N} P_{\text{Loss}}(k, k+1) \]

(8)

After embedding DGs, power loss is:

\[ P_{\text{DG Loss}} = \frac{R_k}{|V_k|^2}\left(P_k^2 + Q_k^2\right) + \frac{R_k}{|V_k|^2}(P^2 - 2P_k P_G - 2Q_k Q_G - 2P_k P_{DG} - 2Q_k Q_{DG}) \]

(9)

So that the net change in power loss after the introduction of DGs is given as:

\[ \Delta P_{\text{DG Loss}} = \frac{R_k}{|V_k|^2}\left(P_k^2 + Q_k^2 - 2P_k P_G - 2Q_k Q_G\right) \left(\frac{G}{L}\right) \]

(10)

where, \( V_{\text{min}} \) = minimum bus voltage, \( V_{\text{max}} \) = maximum bus voltage, \( R_k \) = resistance at bus \( k \), \( X_k \) = reactance at bus \( k \), \( P_{\text{T Loss}} \) = total power loss in all feeders, \( P_{\text{DG Loss}} \) = total real power loss reduction due to reconfiguration, \( \Delta P_{\text{DG Loss}} \) = total real power loss reduction due to connection of DGU, \( L \) = distance from source to the DG location in \( k \), \( G \) = total length of the feeder from source to bus \( k \) in km

2.2 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is an example of a meta-heuristic algorithm that employs advanced techniques to search for the optimal solution to an optimization problem. Kennedy and Eberhart were inspired to develop it by observing the social characteristics of schools of fish and swarms of birds. It is simple, stable and can be enhanced by augmenting it with other optimization techniques.

In PSO, the coordinates of each particle represent a possible solution associated with two vectors: the position (\( S_i \)) and velocity (\( V_i \)) vectors. Each particle updates its position based on its own best exploration; best swarm overall experience, and its previous velocity vector according to the following model:

\[ v_{i}^{k+1} = w v_{i}^{k} + c_1 \cdot \text{rand} \cdot \left( p_{\text{best}i} - s_{i}^{k} \right) + c_2 \cdot \text{rand} \cdot \left( g_{\text{best}i} - s_{i}^{k} \right) \]

(11)

\[ s_{i}^{k+1} = s_{i}^{k} + v_{i}^{k+1} \cdot \Delta t \]

(12)

where, \( v_i^k \) = \( i^{th} \) velocity component at iteration \( k \), \( \text{rand} () \) = random number between 0 and 1, \( s_i^k \) = current position of particle in the \( i^{th} \) dimension, \( c_1, c_2 \) = acceleration coefficients, that are usually set 2.0, \( p_{\text{best}i} \) = personal best position in the \( i^{th} \) dimension, \( g_{\text{best}i} \) = global best position in the \( i^{th} \) dimension, \( \Delta t \) = time step, \( w \) = inertia weight.

For the value of inertia weight(\( w \)), it is assumed to decrease linearly during the course of the simulation from 0.9 to 0.2 according to:

\[ w(i) = \left( \frac{w_{\text{min}} - w_{\text{max}}}{\text{iter}_{\text{max}} - 1} \right) (i - 1) + w_{\text{max}} \]

(13)

where, \( w(i) \) = the inertia weight at iteration \( i \), \( w_{\text{min}} \) = the minimum inertia weight (final), default = 0.2, \( w_{\text{max}} \) = the maximum inertia weight (initial), default = 0.9 and \( \text{iter}_{\text{max}} \) = iteration by which inertia weight should be at final value, default = 1500.

The PSO algorithm applicable to the problem on hand is described as follows:

- Input data and initialize parameters. For each particle, the position and velocity vectors will be randomly initialized with the same size as the problem dimension.
- Measure the fitness (power loss) of each particle (\( p_{\text{best}} \)) and store the particle with the best fitness (\( g_{\text{best}} \)) value by running the load flow program.
- Update velocity and position vectors according to (7) and (8) for each particle.
- Check for violation of constraints.
- Decrease the inertia weight (\( w \)) linearly with (9).
- Repeat steps 2–5 until a termination criterion is satisfied.

2.3 Economic Analysis of an Enhanced Distribution Network

The injection of DGs into an existing DN is an investment which requires through economic analysis so as to establish its economic viability. The economic viability and sustainability of any investment is a function of its payback period (\( P_r \)); which is defined as

\[ P_r = \frac{\text{Total cost of the New Investment } (C_{NI})}{\text{Total Annual Savings } (C_{AS})} \]

(14)

In (14), \( C_{AS} = C_{AS}^{W} - C_{AS}^{W+I} \)

(15)
where, $C_{AS}^{W_{0}}$ and $C_{AS}^{W_{I}}$ are financial annual losses incurred from a project without and with injection of new investment into the existing project respectively.

If the cost of electricity, annual total energy losses without and with injection of new investment into the existing project in order to enhance its performance are: $a$($/kWh), $E_{AL}^{W_{0}}$ (kWh) and $E_{AL}^{W_{I}}$ (kWh) respectively; therefore:

$$C_{AS}^{W_{0}} = aE_{AL}^{W_{0}}$$

(16)

$$C_{AS}^{W_{I}} = aE_{AL}^{W_{I}}$$

(17)

As such the payback period for enhancing the performance of existing project with injection of new investment into the old project is therefore

$$P_{p} = \frac{E_{AL}^{W_{I}}}{E_{AL}^{W_{0}} - E_{AL}^{W_{I}}} = \frac{C_{ki}/a}{E_{AL}^{W_{I}}}$$

(18)

In (18), $E_{AL}^{W_{I}}$ = Annual Energy saving (kWh)

3. MODELLING AND SIMULATION

For the purpose of determining economic analysis of a DN, in this study, a 33-Bus Azare DN was used as a case study. The one line diagram of this network is shown in Fig. 1.

The Azare DN serves the town of Azare in Bauchi state, northern Nigeria. The town is majorly residential and is served by the Jos Electricity Distribution Company Plc (JEDC Plc). Feeders supplying the community come from a nearby substation that supplies power at 11 kV to the residential area. Fig. 1 highlights the network case study. In order to evaluate necessary electrical parameters of the case study, a matlab script was developed using particle swarm algorithm. Matpower was used to carry out load flow analysis. Matpower is a package of matlab M-files developed at Cornell University’s Power Systems Engineering Research Center, for solving power flow problems (Zimmerman, Murillo-Sanchez and Thomas, 2011). The information of the case study served as input data for the developed script.

For load flow studies, the limits of the parameters used in the test bed were set at base MVA of 100 MVA, and between 0.9 and 1.0 p.u for the minimum and maximum value of the voltage. For the financial analysis in this study, the following assumptions have been applied: All energy users are being charged the residential tariff; energy tariff is taken as N29.81/kWh or $0.00994/kWh (based on 2017 residential rate of Jos Electricity Distribution Power Company Plc., where the case study belongs); and exchange rate is taken as N300/$ (at time of the research).

4 RESULTS AND DISCUSSION

4.1 Network Reconfiguration

Fig. 2 illustrates the voltage profile of the network at a loading of 1.0 p.u. There is an improvement of the overall voltage profile at most of the buses in the distribution network. The base network has a minimum voltage of 0.9052 at bus 15. The tie switches that opened in the base network were 33, 34, 35, 36 and 37 (where $L_{1}$, $L_{2}$, $L_{3}$ and $L_{4}$ stand for 34, 35, 36 and 37 respectively).

However, after the optimal reconfiguration of the entire network, the tie switches that opened to give minimum power losses were 4, 10, 19 and 25. In addition, the voltage profile of the network after reconfiguration was generally improved than the base network scenario. The resulting minimum voltage improved by 1.8% as shown in Fig. 2.
Table 1. Results of 33-Bus Azare Distribution Network

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Load Level</th>
<th>Power Loss (kW)</th>
<th>Minimum Voltage (p.u)</th>
<th>% Loss Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>0.50</td>
<td>80.0153</td>
<td>0.9496</td>
<td>0.96106</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>223.2188</td>
<td>0.9052</td>
<td>0.9745</td>
</tr>
<tr>
<td>Only Reconfiguration</td>
<td>0.50</td>
<td>64.1861</td>
<td>0.9611</td>
<td>0.92139</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>164.28</td>
<td>0.9611</td>
<td>0.92139</td>
</tr>
<tr>
<td>Reconfiguration + DG Installation</td>
<td>0.50</td>
<td>33.6064</td>
<td>0.9496</td>
<td>0.9745</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>80.0153</td>
<td>0.9052</td>
<td>0.9745</td>
</tr>
</tbody>
</table>

Fig. 3 shows the voltage profile of the network at a loading of 0.5 p.u. There is an improvement of the overall voltage profile at most of the buses in the distribution network after reconfiguration. The base network has a minimum voltage of 0.9496 at bus 15. The tie switches that opened at 0.5 loading in the base network were 33, 34, 35, 36 and 37 (where L1, L2, L3 and L4 stand for 34, 35, 36 and 37 respectively). However, after the optimal reconfiguration of the entire network, the tie switches that gave minimum power losses were 4, 10, 19 and 25. In addition, the voltage profile of the network after reconfiguration was generally improved than the base network scenario. The resulting minimum voltage improved by 1.2% as shown in Fig. 3.

Fig. 4 depicts the voltage profiles of the network at a loading of 1.0 p.u with an optimal inclusion of DGs of 0.1 MW, 0.3 MW and 0.2 MW at buses 12, 13 and 18 respectively. These buses were chosen because out of all other buses where DGs could be placed, these three buses gave the lowest power losses with the use of DGs. L2, L3 and L4 stand for 34, 35, 36 and 37 respectively.

However, after the optimal reconfiguration of the entire network, the voltage profile of the network after reconfiguration was generally improved than the base network scenario. The resulting minimum voltage improved by 0.4% as shown in Fig. 4.

Fig. 5 illustrates the voltage profile of the network at a loading of 0.5 p.u with an optimal inclusion of DGs of 0.1 MW, 0.3 MW and 0.2 MW at buses 13, 29 and 30 respectively. There is an improvement of the overall voltage profile at most of the buses in the DN after reconfiguration. The base network has a minimum voltage of 0.9496 at bus 15. The tie switches that opened in the base network were 33, 34, 35, 36 and 37 (where L1, L2, L3 and L4 stand for 34, 35, 36 and 37 respectively). However, after the optimal reconfiguration of the entire network, the tie switches that gave minimum power loss were 4, 10, 19 and 25. In addition, the voltage profile of the network after reconfiguration was generally improved than the base network scenario. The resulting minimum voltage improved by 1.2% as shown in Fig. 5.

![Fig. 4: Voltage profile of test network with Distributed Generation at 1.0 p.u loading](image)

The final state of the network after reconfiguration and the application of embedded distribution generation units is presented in Fig. 6.

![Fig. 6: Test network after reconfiguration](image)
Table 1 displays the power loss reduction observed in two situations: when configuration only was applied and then when reconfiguration and DG installation are applied. After reconfiguration only, power losses in the DN decreased by 19.18 % from 80.02 kW to 64.19 kW at 0.5 p.u. loading off the network. A 26.39 % loss reduction occurred at 1.0 loading; from 223.22 kW to 164.28 kW. For the case when DG installation was applied with network reconfiguration, the reduction in power losses improved significantly to 58.37 % and 61.94 % at 100 % and 50 % loads respectively.

4.2 Cost Analysis

Table 2. Financial Analysis of DG-Based Energy Gains

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Load Level</th>
<th>Power Loss (kW)</th>
<th>Monthly Energy Loss (kWh)</th>
<th>Monthly Financial Loss (N)</th>
<th>Annual Energy Loss (kWh)</th>
<th>Annual Financial Loss (N)</th>
<th>Annual Financial Loss ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>0.50</td>
<td>80.0153</td>
<td>57.6102</td>
<td>1,717,384.39</td>
<td>700,934.03</td>
<td>20,894,843.37</td>
<td>69,649.48</td>
</tr>
<tr>
<td>Only Reconfiguration</td>
<td>1.00</td>
<td>223.2188</td>
<td>160,717.54</td>
<td>4,790,899.75</td>
<td>1,955,396.69</td>
<td>58,290,375.27</td>
<td>194,301.25</td>
</tr>
<tr>
<td>Reconfiguration + DG Installation</td>
<td>0.50</td>
<td>80.0153</td>
<td>57.6102</td>
<td>1,717,384.39</td>
<td>700,934.03</td>
<td>20,894,843.37</td>
<td>69,649.48</td>
</tr>
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<td></td>
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<td>1,955,396.69</td>
<td>58,290,375.27</td>
<td>194,301.25</td>
</tr>
</tbody>
</table>

For the financial analysis shown in Table 2, the following assumptions have been applied:

- All energy users are being charged the residential tariff.
- Energy tariff = ₦29.81/kWh or $0.10/kWh (the 2017 residential rate of Jos Electricity Distribution Power Company Plc which oversees the test network).

Table 2 gives a breakdown of the financial analysis of the cost involved in operating the test DN with the status quo, with reconfiguration only and with a combination of both reconfiguration and distributed generation. The base annual energy losses in the DN due to electrical power losses stand at 1,955.4 MWh at 100 % load and 700.9 MWh at 50 % load. These annual energy losses translate to ₦58.29 million at 100 % loading and at ₦20.89 million at 50 % loading of the network. However, when the DN is reconfigured to minimize power losses, the annual energy savings are 91.25 MWh and 138.6 MWh with 100 % load and 50 % load respectively.

This translates to financial savings of N2.72 million and ₦4.13 million respectively. When both network reconfiguration and distributed generation are employed simultaneously to minimize energy losses in the distribution network, the annual energy savings increase to 1,211.15 MWh and 406.54 MWh respectively for 100 % and 50 % loading of the network capacity. The resulting annual financial gains from the energy savings in this scenario are valued at ₦36.10 million ($120,347.65) and ₦12.12 million ($40,396.72) respectively for 100 % and 50 % network load. If we assume that the network is loaded at a minimum of 100% of the capacity all year round, the annual financial gains from the application of network reconfiguration and DG can cover the capital and recurrent cost of operating the generators installed at buses 13, 29 and 30 (0.1MW, 0.3MW and 0.2MW respectively as derived in earlier stated results). Levelized capital, fixed and variable operational and maintenance (O & M) costs were derived from U.S. Energy Information Administration, (2017). These costs are levelized costs for new generation resources for plants entering service in 2019.

Table 3 reveals that the DG type with the lowest capital cost and highest recurrent costs is the natural gas-fired power plant. However, for environmental safety, since DGs are best situated close to the users of electrical power, cleaner sources of energy are better; consequently, out of these generation sources in Table 3, wind onshore, solar PV and solar thermal are the most suitable considering carbon emission.

The test bed is located in the northern part of Nigeria, where there is no nearby ocean, but there is a clear sky and arid weather most of the year; therefore, solar PV generation would be the self-sustaining option of the
solar-based technologies. The DG chosen, according to Table 3, has total annual operational and maintenance (O & M) cost of $50,000.00; and with reference to Table 2, the reconfiguration and injection of DGs into the DN would result to the annual financial savings of $120,347.65. This indicates that with the solar PV as DGs option, there would be the annual financial savings of $70,347.65; and the payback period for the capital investment of $300,000.00 (Table 3) on solar PV generators supplying 0.6 MW at each of buses 13, 29 and 30 would be four years and three months. Even, when other additional costs are factored into the analysis, a payback period that is less than 10 years would still be obtained.

4.3 Applications to a Developing Economy
For the foregoing analysis, the annual energy savings from engaging in network reconfiguration of the DN is as high as 1.2 GWh; and the corresponding annual financial gain is $36.1 million. In a developing nation like Nigeria, about 48% of the population is without access to electricity (Ministry of Power, 2016). The factors responsible for this border on lack in investment in energy infrastructure for more than two decades, mismanagement, poor maintenance of the existing infrastructure and weak political will to improve the energy sector. Knowing that the existing energy infrastructure is far below the capacity to meet the country’s energy needs, it will be wise to extract as much energy as possible with minimal energy losses. Thus, there is an urgent need to improve on electrical power supply efficiencies in order to make energy available to a broader spectrum of the population. The funds available to the energy sector are paucity; therefore, there is need to opt for low cost and sustainable options. Modifications of the DN by optimal reconfiguration by DGs placement represents one option that local distribution companies can take advantage of to increase earnings and better satisfy teeming customers.

5 Conclusion
The results of the NR and DG applied to the Azare DN have been presented. The base network has a total power loss of 80.0153 kW and 223.2188 kW at 0.5 p.u and 1.0 p.u loads respectively. It also has a minimum voltage profile of 0.9496 and 0.9052 at 0.5 p.u and 1.0 p.u loads respectively. When only NR was applied to the DN, in order to minimize losses, the power losses in the network were reduced by 19.78% and 23.39% at 0.5 p.u and 1.0 p.u respectively. In addition, the minimum voltage profile in the DN improved from 0.9496 and 0.9052 to 0.9611 and 0.9214 respectively at 0.5 and 1.0 loads. When both NR and DGs were engaged in the DN, power losses were reduced by 58.37% and 61.94% at 0.5 and 1.0 load respectively; and the minimum voltages in the network improved to 0.9611 and 0.9745 at 0.5 and 1.0 loads.

When both NR and DG were employed to minimize energy losses in the DN, the annual energy savings amounted to 1,211.15 MWh and 406.54 MWh respectively for 100% and 50% loading of the network capacity. The resulting annual financial gains from the energy savings in this scenario turned out as $36.1 million and $12.12 million respectively for 100% and 50% network load. When the network is operated at 100% capacity all year round, the financial savings are sufficient to cover annual operational cost of solar PV DGs as well as the recovering of the capital investment in DGs with a payback period of less than five years.

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