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Optimal Renewable Resources Mix for Energy Loss Minimization in Distribution Network-Case Study

This paper provides a case-study about an optimal mix of renewable energy sources in Mazoon Electricity Company (MZEC) network in Al Ashkharah-Oman.

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Abstract

This paper provides a case-study about an optimal mix of renewable energy sources in Mazoon Electricity Company (MZEC) network in Al Ashkharah-Oman. The system performance is analyzed in terms of voltage profile and power losses for various scenarios after building a power flow model using available network data. To reduce system power losses, candidate locations and their optimal sizes of distributed generation (DG) units are determined using the optimization toolbox offered by MATLAB©. The optimal renewable mix is obtained with the help of HOMER PRO© software.

1. Problem Statement

Natural gas is the primary source of electricity production in the Sultanate of Oman and the peak demand in the main interconnected system is growing. To satisfy the growth of power demand, eliminate the negative impacts of using non-renewable resources, and allow these resources to be used in other applications, the utilization of renewable energy resources to generate electricity should be increased. The objective of this paper is to design the optimal allocation of different types of DGs in the Mazoon Electricity Company (MZEC) distribution network in Al Ashkharah in such a way that the annual energy losses are minimized while considering all technical constraints, such as the voltage limits, the thermal limits of the feeder, the maximum investment capacity on each bus, the size of DG and the maximum penetration limit of the DG units.

2. Introduction

Nowadays, the use of fossil fuels such as oil, coal, and natural gas as resources to generate electric energy has increased significantly. The use of fossil fuels can cause many environmental impacts such as greenhouse emissions in addition to the concerns about depleting fossil fuel resources. It was found that more than 135 billion tons of oil are consumed annually to run vehicles and power stations in addition to other applications [1]. Furthermore, the demand for electric energy has increased significantly due to economic and population growth. Therefore, most countries, including the Sultanate of Oman, are heading towards renewable energy sources (RESs) to generate electricity and mitigate the environmental impacts, while meeting the increasing demand for electric energy [2]. One of the methods used to produce electricity from renewable energy is renewable-based Distributed Generation (DG) units that include solar photovoltaic (PV) systems and wind turbines [3]. According to IEEE, DG is an electric generation facility connected to an area electric power system (local grid) through a point of common coupling [4].

Natural gas is the primary source of electricity production in the Sultanate of Oman, providing around 97.5 % of total energy production [5]. Additionally, the peak demand in the main interconnected system is expected to grow at a rate of 5% [6]. To satisfy the growth of power demand, eliminate the negative impacts of using non-renewable resources, and allow these resources to be used in other applications, the utilization of renewable energy resources to generate electricity should be increased. Oman’s 2040 vision states that “Effective, Balanced and Resilient Ecosystems to Protect the Environment and Ensure Sustainability of Natural Resources to Support the National Economy” [7]. It aims to increase the natural energy consumption share ratio of total consumption to 20% by 2030 and 35-39% by 2040 [7].

Distribution systems may face several challenges due to the presence of DG such as changes in power flow, affecting technical losses and voltage profiles [3]. Therefore, renewable-based DG units must be optimally allocated in distribution systems to minimize annual power losses. In specific, allocating the optimal mix of DG depends on size and location (point of connection).

In the literature, various hybrid systems are discussed, including different combinations of PV systems, wind turbines, storage, and diesel engines and the suitable method to optimize the size and location. Reference [8] found that the PV-diesel-battery hybrid system is the most cost-effective of the three hybrid systems for supplying power demand. The suggested system uses 91 % renewable energy and has a cost of energy (CoE) of US$0.23/kWh. In reference [9], hybrid energy source PV/Biomass systems are optimized for off-grid application. The cost analysis results indicate that the combination of 10 kW PV systems, 8.0 kW biogas fueled generator, 32 storage batteries, and 12 kW converter was the optimal solution. This hybrid system offers electricity to consumers at a low cost compared to the cost of electricity from the grid. An optimal configuration of a hybrid renewable energy source consisting of a wind turbine and a solar system to meet the electrical needs of a medium-sized workshop in an industrial district in Ardabil, Iran, is investigated in [10]. The results demonstrate that, due to the windy climatic conditions in the study location, wind energy resources supply a significant portion of the generated energy. The integration of a 13kW diesel generator, a 1 kW PV array, 2 numbers of 3 kW wind turbines, a 6.13 kW converter, and 27 strings of 1 kW lead-acid battery storage bank is the optimum configuration that results in the lowest Levelized Cost of Energy (COE) of 0.462 $/kWh in the Ardabil area. Reference [11] investigated the techno-economic parameters of a hybrid diesel/PV/wind/battery power generation system for a major non-residential electricity customer in southern Iran. The HOMER Pro program was used to model the system's operation and to determine the best option based on comparative technical, economic, and environmental evaluations. Reference [12] presented an overview of the state-of-the-art research that uses HOMER for optimal Hybrid Renewable Energy Systems (HRESs) planning. HRESs have been modeled more in stand-alone mode than in grid-connected mode, and the most uncertain parameters mentioned in the articles are wind speed, solar radiation, fuel price, component cost, and primary load. Reference [13] focused on the design of hybrid systems based on PV-biomass gasifier-diesel and grid, as well as the optimization of system configuration for various load profiles. According to [13], the cost of energy for a grid-connected hybrid system is cheaper than for an off-grid hybrid system with similar load profiles. The simulation results suggest that the best option scenario for all scenarios is a biomass gasification system rather than a solar system. Reference [14] showed that using solar, wind, and fuel cells is the most practical technique to provide 100 percent electrical energy based on renewables for off-grid applications. The results of the research illustrated the feasibility and effectiveness of utilizing wind and solar resources for both hydrogen and energy production and also suggested that hydrogen is a more cost-effective long-term energy storage option than batteries.

3. Existing System

Al Ashkharah is a town belonging to Wilayat of Jalan Bani Bu Ali in Al Sharqiyah South Governorate in the Sultanate of Oman. The primary substation (PSS) of Al Ashkharah consists of two transformers with a capacity of 20 MVA that are used to convert the voltage from 33 kV to 11.0 kV. Furthermore, in PSS capacitor banks are used to improve the power factor and hence stabilize the voltage from fluctuating. Several 11 kV feeders transfer energy through overhead power lines (OHL) or cables to feed different small regions. Figure 1 shows the data of a specific area supplied from (F26L5) which is feeder 26. Feeder 26 consists of 37 distribution transformers (11 kV/ 415 V) of different sizes (1000, 500, 315, 200, 100, 50 kVA). The values of per unit resistance (R) and reactance (X) are calculated for different transformers based on the X/R ratio and per unit impedance (Z). Table 1 presents the parameters of different types of conductors.

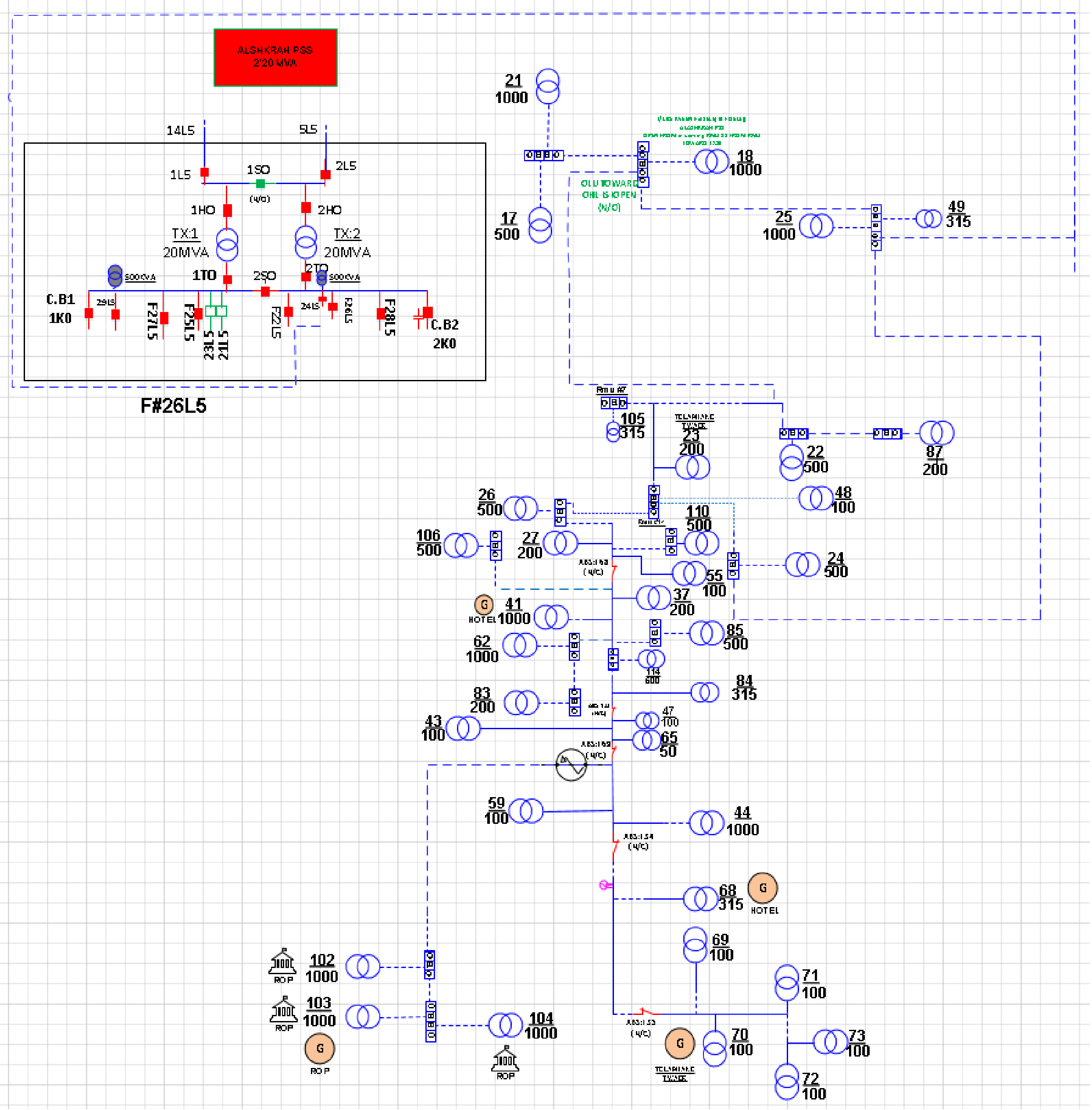


Figure 1:Feeder 26 of Al Ashkhara Network

Table 1: Conductor Data Used in the Al Ashkharah

Conductor Type	**Size (mm^2)**	**R (Ω /km)**	**X (Ω /km)**	**B (S /km)**
3/C XLPE Cable	50	0.494	0.115	0.0000817
3/C XLPE Cable	120	0.196	0.0988	0.0001147
3/C XLPE Cable	185	0.128	0.0931	0.0001351
3/C XLPE Cable	240	0.098	0.09	0.0001495
Wolf ACSR OHL	150	0.1828	0.221	0

4. Modeling of the Proposed System

The Electrical Transient Analysis Program (ETAP) was used to build the feeder 26 model. The feeder 26 consists of 90 buses. Then the remaining feeders (21, 22, 25, 28) were added as a lumped load to simulate the actual case. Figure 2 shows part of modeled feeder. Table 2 shows the simulation results of the power flow. The technical real power losses reached 418 kW. The voltage profile is presented in Figure 3. Most of the buses have voltage levels lower than the limit specified by the Omani Distribution Code, which is 94 % (0.94 Pu). Therefore, DG units can be used to improve the voltage profile. However, DG units must be optimally located and sized using an optimizing tool.

Table 2: Summary of ETAP Results

	P (MW)	**Q (MVAR)**
Generation	4.5	2.68
Load	4.112	2.667
Technical Losses	0.418	0.058

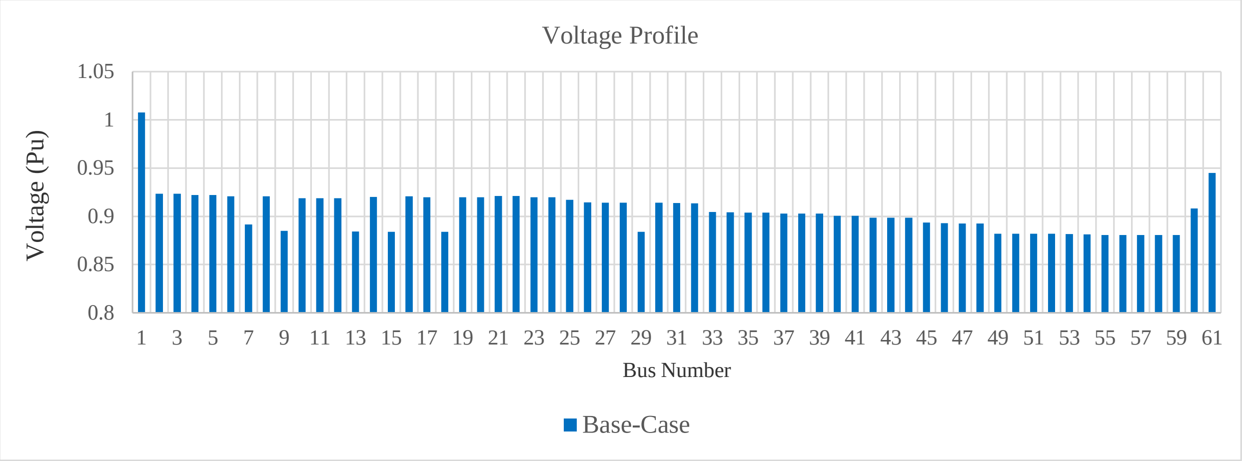


Figure 2: Voltage Profile of the Base-Case

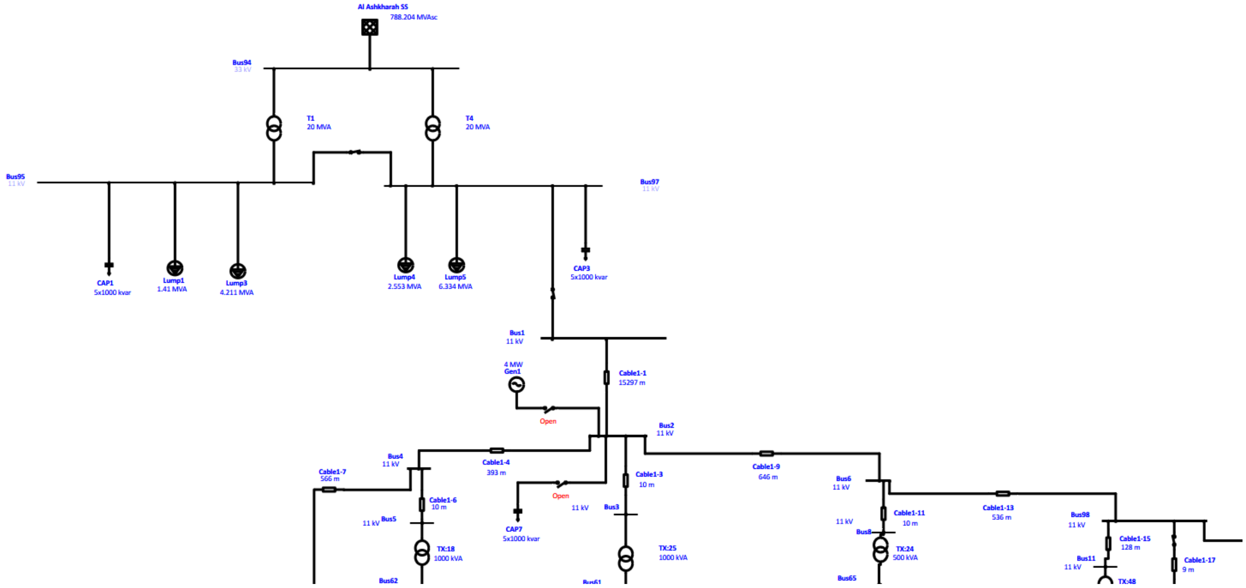


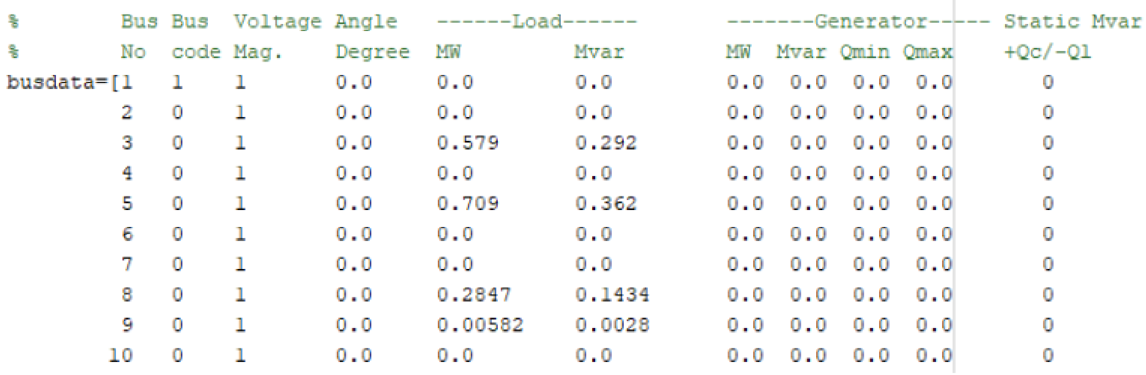
Figure 3: Part of modelled feeder in ETAP

4.1 Optimization Methods

Different techniques have been used to obtain the optimal mix of DGs in the distribution systems [15]. Classical optimization techniques, analytical techniques, hybrid techniques, and artificial intelligence techniques are examples of these methods. In recent years, artificial intelligence (AI) optimization methods have been widely applied. Methods based on artificial intelligence are conceptually distinct from those based on mathematical programming. AI methods are classified as modern optimization algorithms. AI algorithms include particle swarm optimization (PSO), genetic algorithms (GA), ant colony optimization (ACO), simulated annealing, and neural network-based approaches.

4.1.1 Preparation of the Power Flow Data

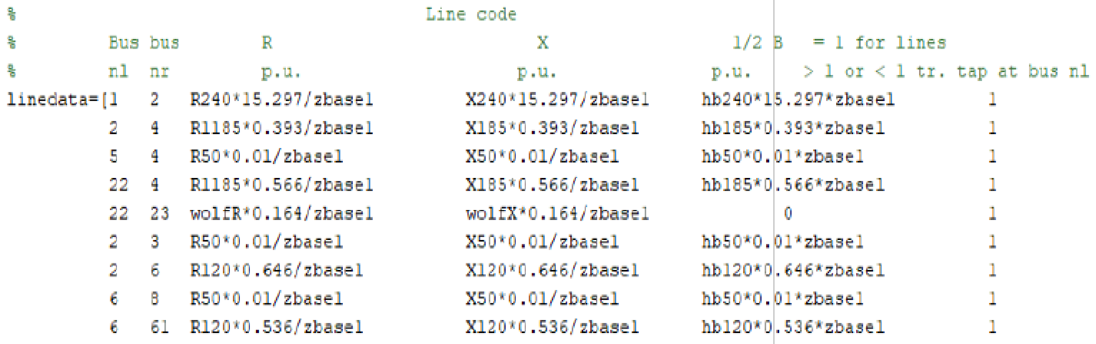
In this paper Genetic Algorithm (GA) method is selected which is used as a tool for optimization in MATLAB. Feeder 26 was modeled in MATLAB as a bus matrix. As seen in Figure 4, the first column shows the bus number, while the second column shows the bus type (Slack bus = 1, PV bus = 2, and load bus = 0). The next two columns are for voltage magnitude and angle. The following two columns indicate the real and reactive power of the load. After that, the generator column consists of the real and reactive power of the generators well as the reactive power limits. Finally, the static Mvar column indicates the injected reactive power. However, the injected reactive power is fixed as 0 in this model.



```
%         Bus Bus  Voltage Angle   ------Load------      -------Generator----- Static Mvar
%         No  code Mag.    Degree  MW         Mvar       MW   Mvar Qmin Qmax    +Qc/-Ql
busdata=[1    1    1       0.0     0.0        0.0        0.0  0.0  0.0  0.0       0
         2    0    1       0.0     0.0        0.0        0.0  0.0  0.0  0.0       0
         3    0    1       0.0     0.579      0.292      0.0  0.0  0.0  0.0       0
         4    0    1       0.0     0.0        0.0        0.0  0.0  0.0  0.0       0
         5    0    1       0.0     0.709      0.362      0.0  0.0  0.0  0.0       0
         6    0    1       0.0     0.0        0.0        0.0  0.0  0.0  0.0       0
         7    0    1       0.0     0.0        0.0        0.0  0.0  0.0  0.0       0
         8    0    1       0.0     0.2847     0.1434     0.0  0.0  0.0  0.0       0
         9    0    1       0.0     0.00582    0.0028     0.0  0.0  0.0  0.0       0
        10    0    1       0.0     0.0        0.0        0.0  0.0  0.0  0.0       0
```

Figure 2: Bus Data Matrix in MATLAB

The second step in MATLAB was to construct the line matrix. Each column has specific data. The first and second columns show the bus numbers that connect the line from the first to the second bus. The next three columns are for the impedance data (R, X, and B/2), in per unit, of the OHL and cables between every two buses as shown in Figure 5. The last column represents the transformer tapping for any line that consists of a transformer. However, the transformer tapping is fixed as 1 in this model.



```
%                                      Line code
%         Bus bus        R                            X                  1/2 B    = 1 for lines
%         nl  nr         p.u.                         p.u.               p.u.     > 1 or < 1 tr. tap at bus nl
linedata=[1   2   R240*15.297/zbase1        X240*15.297/zbase1     hb240*15.297*zbase1         1
          2   4   R1185*0.393/zbase1        X185*0.393/zbase1      hb185*0.393*zbase1          1
          5   4   R50*0.01/zbase1           X50*0.01/zbase1        hb50*0.01*zbase1            1
          22  4   R1185*0.566/zbase1        X185*0.566/zbase1      hb185*0.566*zbase1          1
          22  23  wolfR*0.164/zbase1        wolfX*0.164/zbase1              0                  1
          2   3   R50*0.01/zbase1           X50*0.01/zbase1        hb50*0.01*zbase1            1
          2   6   R120*0.646/zbase1         X120*0.646/zbase1      hb120*0.646*zbase1          1
          6   8   R50*0.01/zbase1           X50*0.01/zbase1        hb50*0.01*zbase1            1
          6   61  R120*0.536/zbase1         X120*0.536/zbase1      hb120*0.536*zbase1          1
```

Figure 3: Line Data Matrix

4.1.2 Power Flow Result from MATLAB

Table 3 shows the simulation results of the power flow. The technical real power losses in feeder 26 reached 392 kW.

Table 3: Summary of MATLAB Results

	P (MW)	**Q (MVAR)**
Generation	4.509	2.694
Load	4.122	2.666
Technical Losses	0.39204	0.05272

There is a small difference between MATLAB© and ETAP© results due to ignoring transformers losses MATLAB model.

4.1.3 Optimal Location and Size

To classify the optimal locations of DGs, all buses are considered candidate buses. Then, the number of candidate buses was decreased by eliminating the bus with the lowest DG capacity. In the end, four buses have been chosen to be the best locations. The buses are 4, 36, 12, and 3. GA is applied to the four candidate buses to find the best size of Distributed Generation. The upper bound was chosen to be 4.7 MW based on the ampacity of the cable.

The system performance of different scenarios was then tracked by comparing the total power losses. The impact of connecting different PV systems on power losses is described in Table 4.

Table 4: System Performance with PV size (MW) and location

Scenario	PV size-Bus 4	PV size-Bus 36	PV size-Bus 12	PV size-Bus 3	Total size (MW)	PLoss (MW)	Reduction in PLoss (%)
4 DG	0.866	1.534	1.106	0.756	4.252	0.0093	97.63
3 DG	1.479	1.525	1.226	0.0	4.23	0.0094	97.60
2 DG	2.46	1.76	0.0	0.0	4.22	0.011	97.19
1 DG	4.231	0.0	0.0	0.0	4.231	0.0321	91.81

The last stage to do with MATLAB© is to see the effect of connecting the DG (PV or wind) on the voltage profile for all buses in the system. Figure 6 indicates the voltage profile for the current system, with the presence of one DG in the system and the profile based on the Omani distribution code.

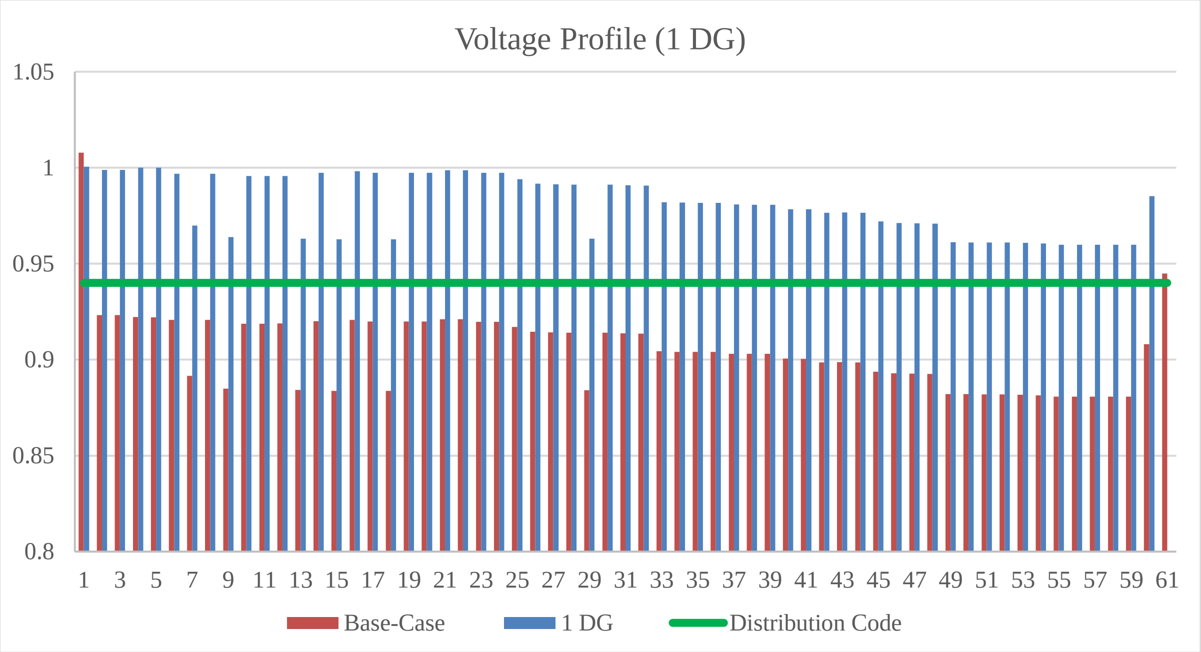


Figure 6: Voltage profile with DG Compared with Base-Case

4.1.4 Effect of DG size in power losses

At bus 60, a case study of system power loss as a function of PV size is conducted. According to GA, 1.52 MW is the optimal PV size that can be installed in bus 60. Any change in DG size by increasing or decreasing the size beyond 1.52 MW will lead to larger losses in the network as shown in Figure 7.

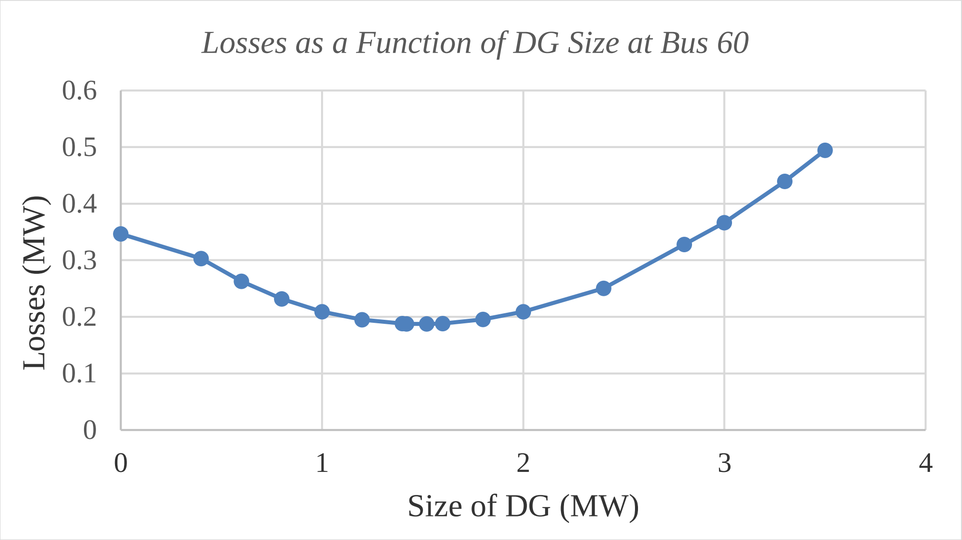


Figure 7: Losses as a Function of DG Size at Bus

4.1.5 HOMER PRO©

The purpose of this section is to model feeder 26 of the existing system using HOMER PRO© software and investigate multiple scenarios of power systems (Grid, PV solar panels, and Wind turbines) to reach the optimal mix. The real load profile, solar radiation, and wind speed of Al Ashkharah are used as input for the model. The schematic diagram for the proposed model is presented in Figure 8 and the load profile is shown in Figure 9. There are three main factors that will be considered to decide the best mix which are the Net Present Cost (NPC), cost of energy, and operation and maintenance (O&M) cost. HOMER PRO software is used to conduct an economic analysis and seek to minimize the Net Present Cost (NPC) in determining the best system configuration. Table 5 shows the technical data of the PV panels, wind turbines, battery storage, and the converter. Table 6 presents a comparison between the existing system and the proposed system (with renewable energy). For the base (existing) system, the levelized cost of energy is \$0.117/kWh. For the proposed system the levelized cost of energy is \$0.0289/kWh. The other advantage for the proposed system is the reduction of emissions.

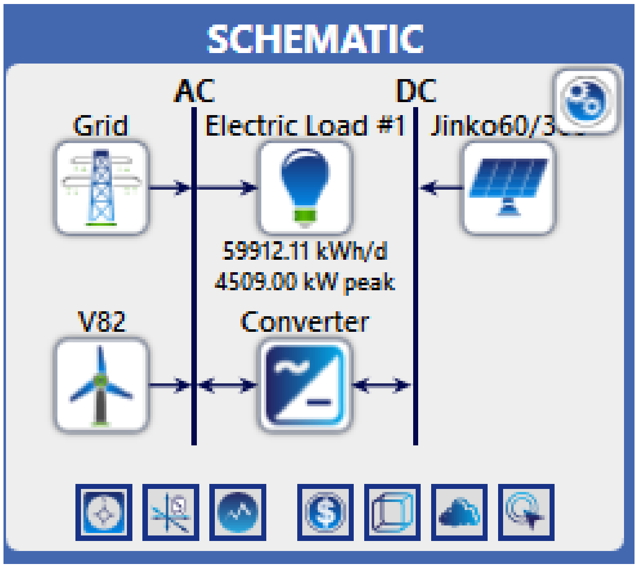
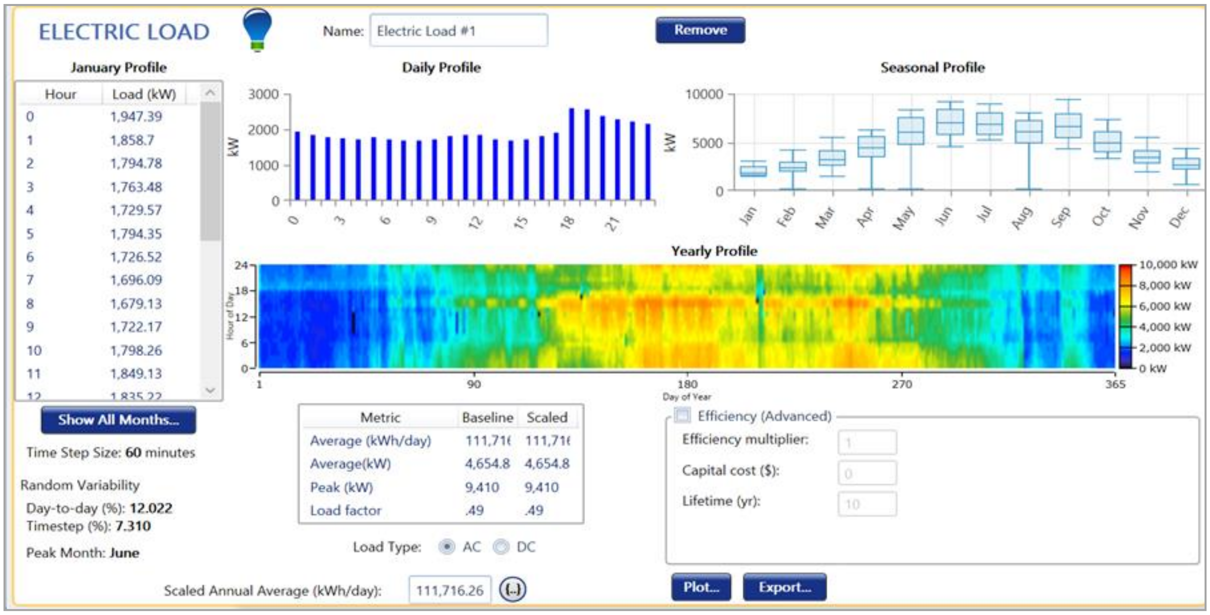


Figure 8: The Proposed System Model



ELECTRIC LOAD

Name: Electric Load #1

January Profile

Hour	Load (kW)
0	1,947.39
1	1,858.7
2	1,794.78
3	1,763.48
4	1,729.57
5	1,794.35
6	1,726.52
7	1,696.09
8	1,679.13
9	1,722.17
10	1,798.26
11	1,849.13
12	1,835.22

Time Step Size: **60** minutes

Random Variability

Day-to-day (%): **12.022**

Timestep (%): **7.310**

Peak Month: **June**

Metric	Baseline	Scaled
Average (kWh/day)	111,71(	111,71(
Average(kW)	4,654.8	4,654.8
Peak (kW)	9,410	9,410
Load factor	.49	.49

Load Type: ● AC ○ DC

Scaled Annual Average (kWh/day): 111,716.26

☐ Efficiency (Advanced)

Efficiency multiplier: 1

Capital cost ($): 0

Lifetime (yr): 10

Figure 9: The Load Profile for 1 year of Al Ashkharah

Table 5: Technical Data of the Components

	Name	**Capital Cost ($)**	**Operation and maintenance Cost ($/Year)**	**Lifetime (Years)**	**Rated Capacity (kW)**	**Hight (m)**
PV	Jinko Eagle PERC60 300W	1000 (For 1 kW)	10 (For 1 kW)	25	4000	-
Wind Turbines	Vestas V82 [1.65MW]	2,145,000 (1 unit)	9 (1 unit)	25	1650	80
Converter	System Converter	300 (For 1 kW)	0 (For 1 kW)	15	-	-

Table 6: Comparison between the Base System and the Recommended Mix

Scenarios	**Components**	**Cost of Energy ($/kWh)**
Base System	100 % of Grid purchases	0.117

Recommended Mix	50.2 % of Wind turbine 24.0 % of PV 25.7 % of Grid purchases	0.0289

4.1.6 Comparison between options

Three different options were compared in terms of total power losses for five years. An excel program (owned by Mazoon Electricity Company) was used to compare between the different options. The inputs to the program are loss load factor, cost of energy (OMR/MWh), losses in a year (MW), and the expected losses for the next four years. The output is the 5-year Cumulative Cost of Losses. The summary of this study is shown in Figure 10. It is obvious that option 3 (DGs) is more effective in reducing the cost of losses.

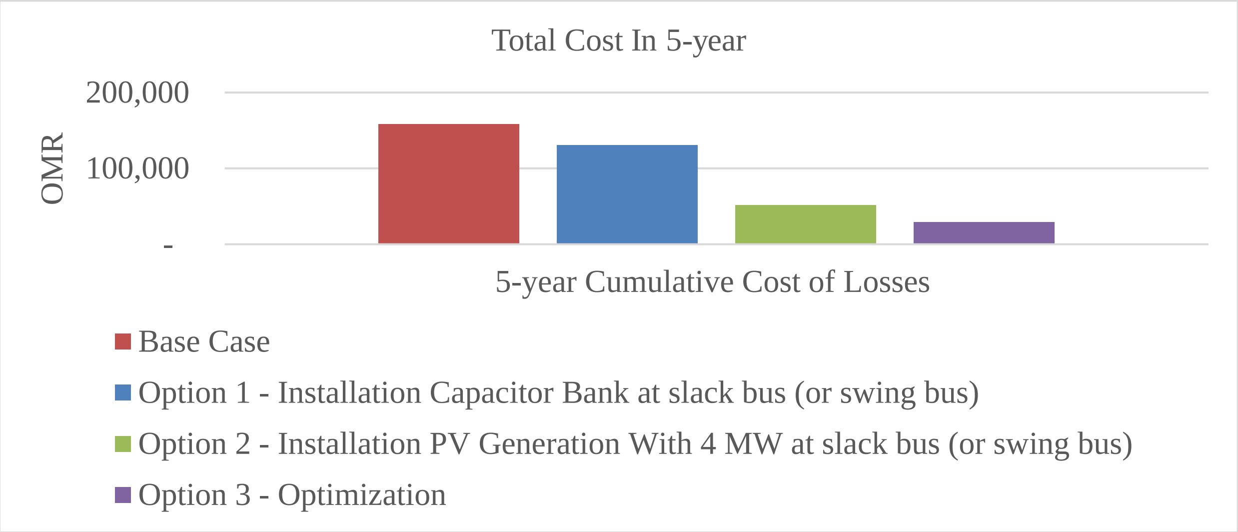


Figure 10: Five-year Cumulative Cost of Losses

5. Summary

The aim of this paper is to determine the optimal allocation of different kinds of renewable-based DG units in the Mazon Electricity Company distribution network so that annual energy losses are minimized based on technical constraints and engineering requirements. The study models and simulates the performance of the feeder 26 of Al Ashkharh distribution system and optimally allocates the capacity of renewable energy in the network using genetic algorithms (GA) to reduce the losses. The system model was built using ETAP© and MATLAB© load flow toolbox. Simulation results reveal that technical power losses represent 8.7% of the total load and that the voltage limits are violated at several buses. Four buses are optimally chosen as candidates to be used as points of connection for PV and wind systems. GA is used to find the optimal size of renewable energy systems. The performance of the system after installing PV and wind systems was simulated using the power flow model. Simulation results demonstrate that the optimal allocation of renewable systems at 4 buses can reduce losses by 97.63%. With the optimally sized PV system installed at only 1 bus, losses can be reduced by 91.81%. Furthermore, HOMER PRO© software was utilized to model feeder 26 of the real system and determine the optimal mix based on levelized cost of energy. Real load profile, wind speed, and solar radiation together with initial and maintenance costs of each item were used in the model. Different scenarios were obtained to determine the optimal solution. The best scenario is to install a mix of wind and PV, 50.2% and 24.0% respectively and the rest of required energy (25.7%) will be provided by the grid. The optimal scenario had levelized energy cost of $0.0289/kWh, versus an energy cost of $0.117/kWh for the current system.

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