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Loss Reduction in Isolated Rural Area Distribution Network Using Photovoltaic System

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Abstract: This paper investigates the utilization of photovoltaic (PV) systems in a rural area electricity network. The Rural Area Electricity Company of Oman is planning to install a 304 kW PV system at the powerhouse of the Almazyonah network. Based on the available network data, a power flow model of the system under study was built and the system's performance was studied. The location and installed capacity of the planned PV system were optimized based on loss reduction.

Keywords: Loss reduction, Rural area networks, Power flow, Photovoltaic systems.

تقليص الفاقد الكهربائي في شبكة توزيع ريفية معزولة باستخدام نظام الفولت ضوئي

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المستخلص: تبحث هذه الورقة الاستفادة من أنظمة الفولت الضوئية في شبكة توزيع كهرباء ريفية. حيث أن شركة كهرباء المنطقة الريفية تخطط من أجل تركيب نظام فولت ضوئي بسعة 304 كيلو واط في محطة توليد الطاقة الكهربائية لشبكة كهرباء المزيونة. استنادا إلى بيانات الشبكة المتوفرة، تم بناء نموذج تحليل تدفق الطاقة الكهربائية للنظام قيد الدراسة وتم دراسة آداء نظام الشبكة. وقد تم توخي اختيار الحلول المثلى للموقع والقدرة المركبة لنظام الفولت الضوئي المخطط له وذلك اعتماداً على تقليل الفاقد الكهربائي.

الكلمات المفتاحية: تقليل الفاقد الكهربائي، شبكات كهرباء المنطقة الريفية، تدفق الطاقة، أنظمة الفولت الضوئية

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1. Introduction

Natural gas-based generation facilities are used to generate electricity in the main interconnected system (MIS) of Oman. However, as Oman is a thinly populated country, connecting all remote rural areas to the MIS is not economical. Therefore, diesel generators are used to provide electricity for remote rural areas. This service is provided by the Rural Area Electricity Company SAOC (RAECO) under a license issued by the Authority for Electricity Regulation (AER) to generate, transmit, and distribute electricity in these remote rural areas. As of 2014, more than 45 such diesel-based isolated rural networks are in operation.

A renewable energy study published by the AER in June 2008 recommended the immediate implementation of renewable energy-based generation facilities in rural areas. Two years later, the AER announced six renewable energy pilot projects to be implemented within RAECO networks. Potential benefits from these projects include economic benefits in the form of avoided costs of diesel generation, the transfer of knowledge and experience to Oman, and capacity building within RAECO and other Omani companies (Authority for Electricity Regulation, 2015). By the end of 2012, the AER had issued new regulations to encourage the implementation of renewable energy projects in Oman's rural areas.

However, according to the AER, the implementation of renewable energy pilot projects has been delayed because of two significant barriers. The first barrier is the absence of a policy framework and policy instruments to encourage and support the economic deployment of renewable energy projects. The second barrier is the fossil fuel subsidies, which make renewable energy-based generation appear more expensive in comparison with fossil fuel-based electricity (Authority for Electricity Regulation, 2015).

One of the renewable energy pilot projects approved by the AER was a photovoltaic (PV) system in Almazyonah in the Dhofar Governorate. According to RAECO, the power purchase agreement of the 304-kW PV project was finalized in 2013 (Rural Areas Electric Company, 2015), and the first rural area PV system came online in May 2015.

Solar PV systems are classified as renewable energy-based distributed generation resources. Despite the benefits of PV systems and other renewable energy-based distributed generation (Al-Badi, Bourdoucen 2011; Elhadidy and Shaahid 2009), their presence in distribution systems alters the power flow. Consequently, the operation of PV systems may have technical and economic impacts on distribution systems. Therefore, it is important to optimize the location and size of any added PV system (Atwa and El-Saadany 2010; Abu-Mouti and El-Hawary 2011).

Power losses are proportional to the resistance of the power path and the loading of the line. Unlike central plants, distributed generation (DG) is located near consumers; therefore, the resistance in the current path is much lower than that between central plants and electricity consumers. Moreover, on-site DG can reduce the loading of transmission lines and relieve heavily loaded lines, leading to more reduction in power loss. In Kai *et al.* (2012), a distribution system expansion planning strategy encompassing renewable DG systems with schedulable and intermittent power generation patterns is presented. In Chen and Duan (2014), the proposed cost function of the optimization problem included two cost components: operation and investment. A strategy for DG allocation in radial distribution networks under uncertainties of load and generation using an adaptive genetic algorithm (GA) was presented by Ganguly and Samajpati (2015). It has been demonstrated that loss reduction depends on DG penetration level, location, and reactive power control capability (Albadi and El-Saadany 2008; Attwa *et al*. 2009).

In this work, the location and size of the PV system was optimized to minimize losses using GA for the first PV pilot project installed in RAECO networks.

After this introduction, the paper proceeds with presenting network data from the Almazyonah site. The model of that network is presented in section 3. The simulation results of the network performance with and without the PV system are presented and discussed in section 4. Finally, a summary of the main conclusions is presented in section 5.

2. System Data

The Almazyonah network consists of nine diesel generators (3× 2-MW, 3 × 1-MW, and 3 × 1-MW mobile engines) and 51 transformers [Table 1]. There are five sizes of 11 kV/415 V transformers [Table 2]. Detailed loading on these transformers and per unit line data are presented in the Appendices A and B, and a single-line diagram is presented in Fig. 1.

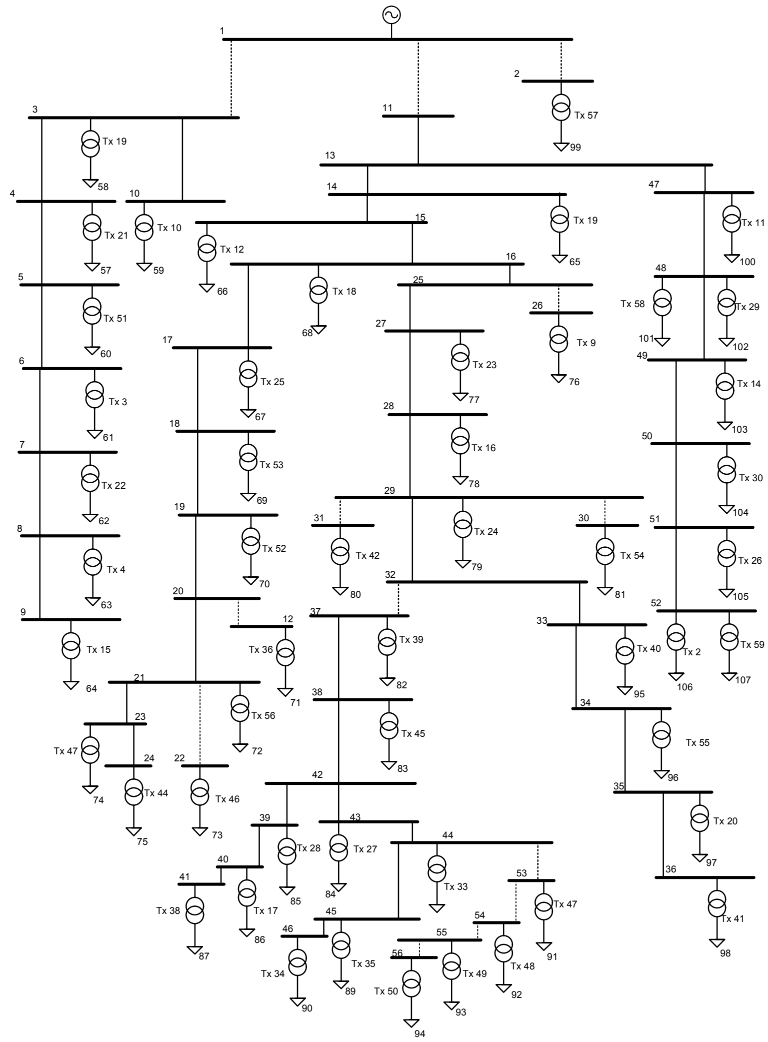

Figure 1. Almazyonah single-line diagram.

Table 1. Network data.

Component	Quantity
Diesel generators	9
Transformers	51
Busses	107
OH Lines	43
Cables	14
Measured peak (kW)	1,823
Measured peak (kVAR)	1,136

Table 2. Transformers' data.

KVA	Quantity	X/R %	Z%
1,000	9	5.57	4.75
500	5	5.1	4.75
315	9	3.97	4.75
200	13	3.37	4.75
100	15	2.32	4.75

In this study, the proposed PV plant is modelled as load bus with a negative output. The output of the PV system coincides with the system peak load at which the power flow analysis was conducted. In this study, a 3% derating of the PV system output is assumed to consider the inverter efficiency and dust effect, and the output at peak load is assumed to be 295 kW. Different derating factors for a 5 MW plant are discussed in Al-Badi *et al.* (2011). In the current study, for the purpose of testing the actual PV system performance in local weather conditions, two types of PV technologies were used: thin film and crystalline technologies.

3. System Modeling

3.1 Power Flow Model

Power flow analysis is widely used in power system operation and planning. The power flow model of the system can be built using relevant networks, loads, and generation data. Outputs of the power flow model include voltages at different busses and line flows in the network. These outputs are obtained by solving power balance equations as follows:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j), \quad (1)$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j), \quad (2)$$

where, $|V_i|$ and $|V_j|$ are the magnitudes of the voltage at bus i and j, respectively; δ_i and δ_j are the associated angles; $|Y_{ij}|$ is the magnitude of the Y-bus element between the two busses; and θ_{ij} is the corresponding angle.

These power balance equations are nonlinear; therefore, iterative techniques such as the Newton-Raphson, Gauss-Seidel, and fast-decoupled methods are commonly used (Al-Badi *et al.* 2011). In this work, the network model was built using the MATLAB load flow toolbox (Mathworks, Natick, Massachusetts, USA). Input data consisted of two input matrices: a bus data matrix that shows each type of bus, voltage magnitude of voltage controlled busses, and generation and load data; and a branch data matrix that gives information on all connections between busses, including branch impedances.

The system losses can be calculated once the power flow problem is iteratively solved. For example, the losses in line *i-j* are the algebraic sum of the power flow as below:

$$S_{L\,ij} = S_{ij} + S_{ji} \quad (3)$$

where, $S_{ij} = V_i\, I_{ij}^*$ and $S_{ji} = V_j\, I_{ji}^*$

The genetic algorithm (GA) toolbox in MATLAB was used to study the effect of installing the PV system on the total system losses (Al-Badi *et al.* 2011).

3.2 Genetic Algorithms (GAs)

GAs are global search heuristics that are based on the mechanics of natural genetics (Al-Badi *et al.* 2011; Albadi and El-Saadany 2008) and use techniques inspired by evolutionary biology. Examples of these techniques are inheritance, mutation, selection, and crossover. GA maintains a population of individuals that represent the candidate solutions to the given problem and has been used to obtain high-quality solutions for many optimization problems in science and technology.

The GA process starts with an initial solution from a population of randomly generated individuals [Fig. 2].

Each individual represents a candidate solution to the optimization problem. The fitness of every individual in the population is evaluated in each generation. The reproduction operator is the first to be applied, which follows Darwinian theory. Selecting an individual in the new population depends on its fitness value, which in turn depends on the fitness function, which is problem specific. In this study, the total power loss in the system is defined as the fitness function. The survival of the fittest process encourages the propagation of strong individuals. However, this does not necessarily produce better individuals. To find stronger ones, the crossover procedure is used. This is achieved by mating reproduced individuals, therefore combining their features. Mutation is used to improve the population diversity and can help in cases where an individual representing a suboptimal solution dominates the population. In such cases, mutation is used to converge to a suboptimal solution by changing the values of the binary digits at random. It is worth mentioning that mutation rates should be kept low to prevent damaging good solutions. AG can be terminated when the fitness level is satisfactory or the limit of the maximum number of generations is reached.

3.3 Identification of Candidate Connection Busses

To find out the optimum location or the point of connection of the PV system in the Almazyonah network, a total of 107 network buses are available. These include both the medium (11 kV) and low voltage (415 V) nodes. Because of the size of the PV system, it is connected to the 11 kV network. As a result, 56 medium-voltage nodes remain as candidate connection busses after excluding the low voltage busses.

Looking at the voltage profile of the system before connecting a new DG, the PV system, in this case, busses that are far away from the source (the power house), has a low-voltage profile compared with the upstream ones. Therefore, considering the voltage profile resulted in reducing the number of candidate locations to 10.

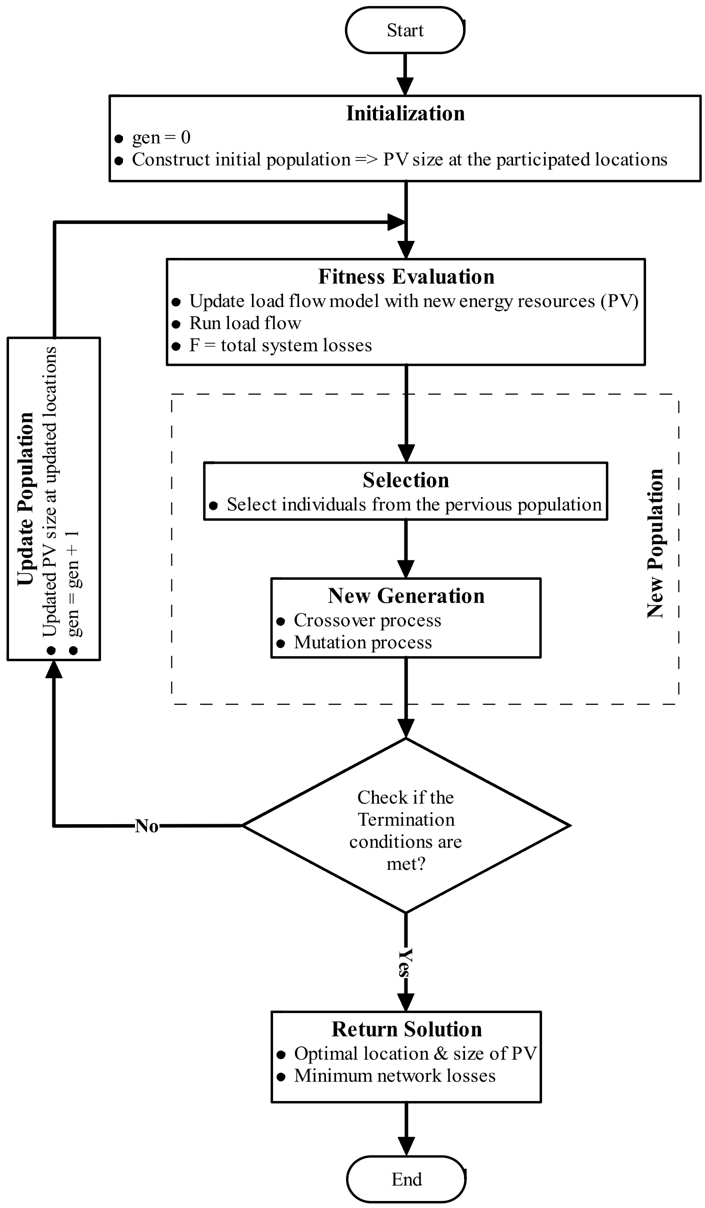

Figure 2. Genetic algorithm (GA) flow chart.

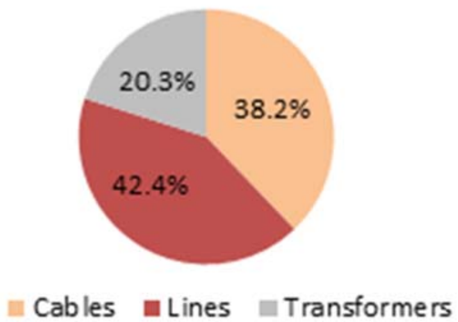

Figure 3. Distribution of power losses in the system.

4. Results and Discussion

4.1. System Performance without PV System

The calculated real power losses in all transformers' and lines' resistive elements represent 2% of the total power generated by the diesel generators (23 kW). The contribution of different network components in the losses is shown in Fig. 3. It is worth noting that the pilot PV project (304 kW) was connected to the distribution system at the powerhouse according to the current plan. Installing the PV system at the generation station would not alter the power flow; therefore, the value of losses will not be altered either. In this case, the benefits of the PV system are limited to emission and fuel consumption reduction.

4.2. Optimal Location of Current Proposed Size

Using GA, the optimum location of the proposed-sized PV system is bus 54 (transformer Tx 50). The total losses were reduced to 17.31 kW, yielding a ~25% reduction. In addition, installing the PV system at this location improves the voltage profile at different busses [Fig. 4].

4.3. Optimum Location and Size of PV System

The impact of increasing the size of the PV system at different locations was investigated [Fig. 5]. On the basis of the results, the optimum location of the PV system was determined to be at bus 39 (transformer Tx 28), with a size of 1,200 kW.

This connection would reduce the real power losses from 23 to 12 kW yielding a ~50% reduction. Losses could be reduced further by considering more than one location. However, the objective of the study was to determine one location for the PV project. The voltage profile of the system was improved [Fig. 4].

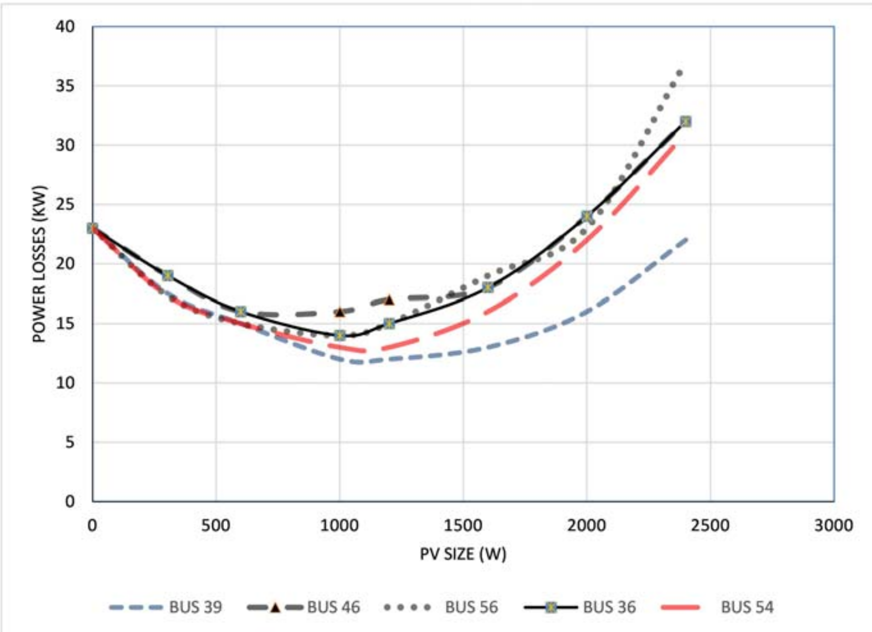

Figure 4. Voltage profile at different scenarios.

5. Conclusions

This study considered the impact of the first PV pilot project in Oman on system losses via a system model, which was built according to measured data provided by the Rural Area Electricity Company, and system losses were obtained. It was found that optimal sizing and siting of PV systems in distribution networks helps in maximizing their benefits. This is because the presence of PV systems in distribution networks alters the classical downstream power flow; therefore, the presence of PV systems may have technical and economic impacts on the system. Installing the PV system at the powerhouse will not change the power flow; therefore, it will not

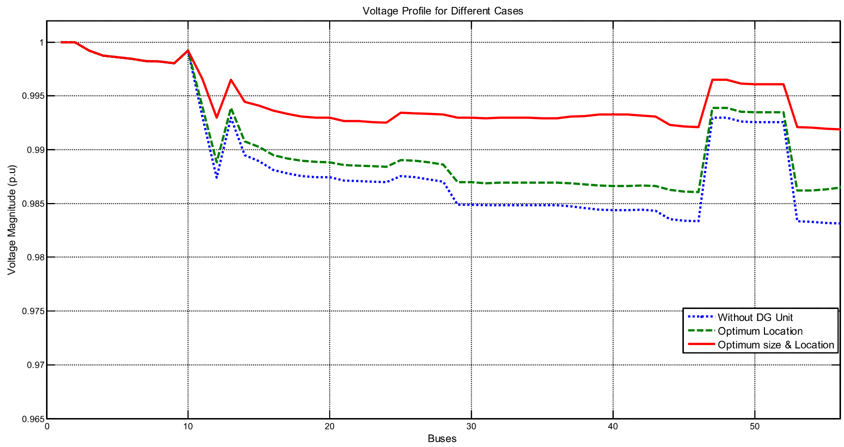

Figure 5. Impact of increasing the PV system on losses.

affect the value of losses. On the basis of loss minimization, the optimal location of the proposed PV system was determined using GA. Installing the PV system at the optimal location reduced system losses by approximately 25% and voltage profile was improved.

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Appendix A. The per unit line data.

From	To	R	X	B/2
1	2	0.0026	0.0029	3.87E-06
1	3	0.2613	0.2286	0.000202
1	11	0.2824	0.2471	0.000218
2	99	6.7564	22.7700	0
3	10	0.0106	0.0171	1.90E-07
3	4	0.1481	0.2397	2.66E-06
3	58	18.8000	43.6200	0
4	5	0.0597	0.0966	1.07E-06
4	57	18.8000	43.6200	0
5	6	0.0597	0.0966	1.07E-06
5	60	18.8000	43.6200	0
6	7	0.1511	0.2446	2.71E-06
6	61	0.8394	4.6753	0
7	8	0.0529	0.0856	9.50E-07
7	62	18.8000	43.6200	0
8	9	0.9306	1.5069	1.67E-05
8	63	1.8280	9.3220	0
9	64	3.6825	14.6222	0
10	59	18.8000	43.6200	0
11	13	0.0045	0.0073	8.14E-08
12	71	18.8000	43.6200	0
13	14	0.1163	0.1884	2.09E-06
13	47	0.0053	0.0086	9.50E-08
14	15	0.0181	0.0294	3.26E-07
14	65	1.8280	9.3220	0
15	16	0.0295	0.0477	5.29E-07
15	66	3.6825	14.6222	0
16	17	0.0302	0.0489	5.43E-07
16	25	0.0295	0.0477	5.29E-07
16	68	18.8000	43.6200	0
17	18	0.0287	0.0465	5.16E-07
17	67	3.6825	14.6222	0
18	19	0.0242	0.0391	4.34E-07
18	69	0.8394	4.6753	0
19	20	0.0091	0.0147	1.63E-07
19	70	0.8394	4.6753	0
20	21	0.1051	0.1703	1.89E-06
20	12	0.2842	0.0794	3.44E-05
21	22	0.0232	0.0088	4.64E-06
21	23	0.1058	0.1712	1.90E-06
21	72	6.7564	22.7700	0
22	73	0.8394	4.6753	0
23	24	0.1461	0.2366	2.62E-06
23	74	18.8000	43.6200	0
24	75	18.8000	43.6200	0
25	26	0.0653	0.0182	7.91E-06
25	27	0.0166	0.0269	2.98E-07
26	76	1.8280	9.3220	0
27	28	0.0121	0.0196	2.17E-07
27	77	6.7564	22.7700	0
28	29	0.1511	0.2446	2.71E-06
28	78	3.6825	14.6222	0
29	30	0.0085	0.0074	6.54E-06
29	31	0.0373	0.0414	4.16E-05
29	32	0.0032	0.0051	5.70E-08
29	79	3.6825	14.6222	0
30	81	0.8394	4.6753	0
31	80	0.8394	4.6753	0
32	33	0.0106	0.0171	1.90E-07
32	37	0.0158	0.0138	1.22E-05
33	34	0.0136	0.0220	2.44E-07
33	95	3.6825	14.6222	0
34	35	0.0136	0.0220	2.44E-07
34	96	6.7564	22.7700	0
35	36	0.1934	0.3131	3.47E-06
35	97	6.7564	22.7700	0
36	98	3.6825	14.6222	0
37	38	0.0166	0.0269	2.98E-07
37	82	3.6825	14.6222	0
38	42	0.0181	0.0294	3.26E-07
38	83	3.6825	14.6222	0
42	39	0.0121	0.0196	2.17E-07
42	43	0.0166	0.0269	2.98E-07
39	40	0.0091	0.0147	1.63E-07
39	85	18.8000	43.6200	0
40	41	0.0486	0.0293	2.08E-05
40	86	3.6825	14.6222	0
41	87	1.8280	9.3220	0
43	44	0.1284	0.2079	2.31E-06
43	84	3.6825	14.6222	0
44	45	0.2160	0.3498	3.88E-06
44	53	0.0609	0.0533	4.71E-05
44	88	18.8000	43.6200	0
45	46	0.0816	0.1321	1.47E-06
45	89	18.8000	43.6200	0
46	90	18.8000	43.6200	0
47	48	0.0015	0.0024	2.71E-08
47	100	6.7564	22.7700	0
48	49	0.3067	0.4966	5.51E-06
48	101	3.6825	14.6222	0
48	102	18.8000	43.6200	0
49	50	0.0831	0.1345	1.49E-06
49	103	6.7564	22.7700	0
50	51	0.2795	0.4526	5.02E-06
50	104	3.6825	14.6222	0
51	52	0.0967	0.1566	1.74E-06
51	105	18.8000	43.6200	0
52	106	6.7564	22.7700	0
52	107	6.7564	22.7700	0
53	54	0.0224	0.0196	1.73E-05
53	91	0.8394	4.6753	0
54	55	0.0504	0.0441	3.89E-05
54	92	1.8280	9.3220	0
55	56	0.0757	0.0663	5.85E-05
55	93	0.8394	4.6753	0
56	94	0.8394	4.6753	0

Appendix B. Transformer loading data.

Name	Rating (kVA)	P (kW)	Q (kVAR)
Tx 2	200	0	0
Tx 3	1000	74.96	46.74
Tx 4	500	53.35	33.27
Tx 5	500	30.71	19.15
Tx 9	500	77.25	48.17
Tx 10	100	0.00	0.00
Tx 11	200	14.30	8.92
Tx 12	315	12.16	7.58
Tx 14	200	28.97	18.06
Tx 15	315	10.10	6.30
Tx 16	315	119.99	74.82
Tx 17	315	69.06	43.06
Tx 18	100	0.00	0.00
Tx 19	100	46.88	29.23
Tx 20	200	44.31	27.63
Tx 21	100	20.27	12.64
Tx 22	100	0.00	0.00
Tx 23	200	35.15	21.92
Tx 24	315	73.74	45.98
Tx 25	315	123.99	77.31
Tx 26	100	0.00	0.00
Tx 27	315	14.16	8.83
Tx 28	100	18.79	11.71
Tx 29	100	0.00	0.00
Tx 30	315	31.89	19.89
Tx 33	100	25.22	15.73
Tx 34	100	29.75	18.55
Tx 35	100	5.24	3.27
Tx 36	100	3.85	2.40
Tx 38	500	28.00	17.46
Tx 39	315	26.69	16.64
Tx 40	315	8.64	5.38
Tx 41	315	0.00	0.00
Tx 42	1000	103.75	64.69
Tx 43	100	21.44	13.37
Tx 44	100	17.03	10.62
Tx 45	315	12.73	7.94
Tx 46	1000	85.52	53.32
Tx 47	1000	79.25	49.42
Tx 48	500	86.57	53.98
Tx 49	1000	33.31	20.77
Tx 50	1000	57.34	35.75
Tx 51	100	0.91	0.57
Tx 52	1000	85.54	53.34
Tx 53	1000	154.38	96.26
Tx 54	1000	12.45	7.76
Tx 55	200	2.90	1.81
Tx 56	200	14.46	9.02
Tx 57	200	28.36	17.68
Tx 58	315	0.00	0.00
Tx 59	200	0.00	0.00
Total		1823.36	1136.92