Evaluating the Effects of High Penetration of Roof-Top Wind Turbines on Secondary Distribution Circuits

Digital Object Identifier (DOI):
10.1109/TDCLA.2006.311476

Evaluating the Effects of High Penetrations of Roof-Top Wind Turbines on Secondary Distribution Circuits

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***Abstract*—Incentives for using wind power and the increasing price of energy might generate in a relatively short time a scenario where low voltage customers opt to install roof-top wind turbines. This paper focuses on evaluating the effects of such situation in terms of energy consumption, loss reduction, reverse power flow and voltage profiles. Various commercially-available roof-top wind turbines are installed in two secondary distribution circuits considering real-life wind speed data and seasonal load demand. Results are presented and discussed.**

***Index Terms*— distributed generation, roof-top wind turbines, distribution networks, power flow, line losses.**

I. Introduction

CURRENT energy policies are encouraging the connection of small-scale power generating plants to distribution networks, mainly in response to environmental concerns as well diversification of the energy mix. As such, Distributed Generation (DG) [1], electric power generation located within distribution networks or on the customer side of the network, is expected to play an increasingly important role in the power system infrastructure and market. On the other hand, given that distribution networks were not planned to support widespread insertion of power, various studies have reported that such integration may create technical and safety problems [2]-[6].

Considering the special attention given by governments to wind energy, currently the fastest growing technology, and a scenario where residential and commercial customers harness the benefits of on-site generation, this work is aimed at assessing the effects that a high level penetration of roof-top wind turbines may produce on secondary distribution, i.e. low voltage, circuits. Moreover, given the time-variant characteristics of wind generation it will be necessary to examine impacts over an extended time period.

Here, two secondary distribution circuits are analyzed considering seasonal daily demands. Wind power estimates are based on data for southern Scotland for the year 2003. Results are presented and discussed remarking the time-variant benefits and drawbacks of roof-top wind power generation taking into account critical scenarios of such generation.

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II. Technical Data

In this section the data required for performing the simulations of high penetrations of roof-top wind turbines in secondary distribution circuits is presented. This includes wind turbine power curves, wind speeds, load demand and secondary circuit details.

A. Wind Turbines and Wind Speed Data

In order to consider real-life roof-top wind turbines, five types that can easily be found in the market were chosen, as shown in Table I.

TABLE I
SELECTED COMMERCIAL WIND TURBINES

Type	Nominal Output (kW)	Type of Generator	Operational Wind Speed Range (m/s)
AIR-X [1]	0.4	Permanent magnet	3 – 20
Fortis Espada (FE) [2]	0.8	Permanent magnet	3 – 25
BWC XL1 [3]	1.0	Permanent magnet	3 – 20
SWIFT [4]	1.5	Permanent magnet	3 – 25
WES5 Tulipo (WES5) [5]	2.5	Induction generator	3 – 20

[1] Southwest Windpower [7], [2] Fortis Windenergy [8], [3] Bergey Windpower [9]
[4] Renewable Devices [10], [5] Wind Energy Solutions [11]

Since each wind turbine is manufactured by different companies their performances vary. Fig. 1 shows the corresponding power output curves which are required for a time-variant analysis given the changing nature of wind speeds.

Wind speed data used in this work corresponds to hourly measurements carried out by the UK Meteorological Office for central Scotland for 2003. Although there is a strong dependence between wind speed and geographical position, solely one anemometer was chosen for the distribution secondary circuits to be tested since they represent small areas. Average daily wind speeds of the selected anemometer are presented in Fig. 2.

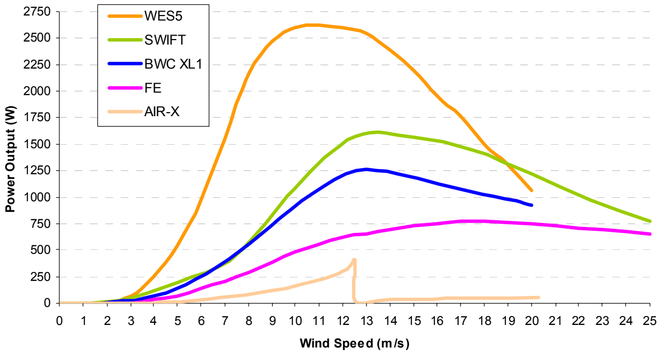

Fig. 1. Power output curves for the five selected wind turbines [7]-[11]

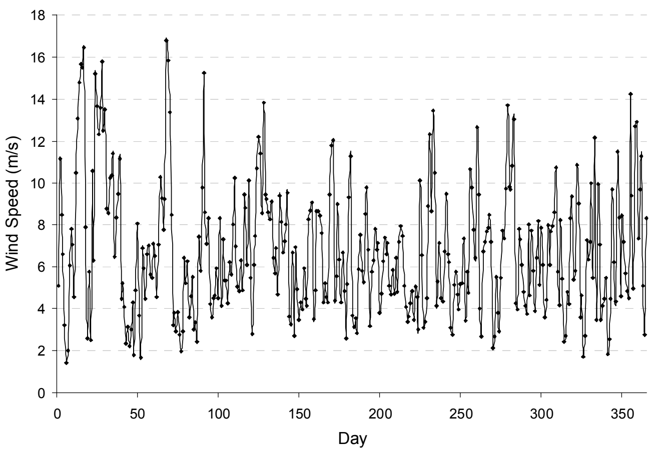

Fig. 2. Average daily wind speeds for 2003 – Central Scotland

Nonetheless, even being considered useful information average daily wind speeds just exhibit the wind power potential of a given geographic area. The impacts on the operational behavior of secondary circuits will be seen when analyzing critical scenarios such as the maximum daily generation which is obtained when, for a given wind turbine, "usable" wind speeds appeared throughout the day.

B. Test Network and Load Demand

Two low voltage distribution secondary circuits were used in order to evaluate the effects of high penetration of roof-top wind turbines. Both four-wire three-phase circuits possess a radial structure and line voltage of 240V. Line section and load data are presented in Appendix A. The 21-bus circuit which contains 16 residential loads accounting for a total maximum demand of 26.5 kW, mainly using ASC 2/0 conductors. The second circuit is composed by 29 buses, 12 of which are residential loads with a total maximum demand of 17.7 kW, using ACSR #2 conductors. Both secondary circuits will use the typical load profiles shown in Fig. 3, obtained after adjustment from the design values of peak demand to the actual average value of peak winter demand and minimum summer demand as reported by the Electricity Association in UK [12].

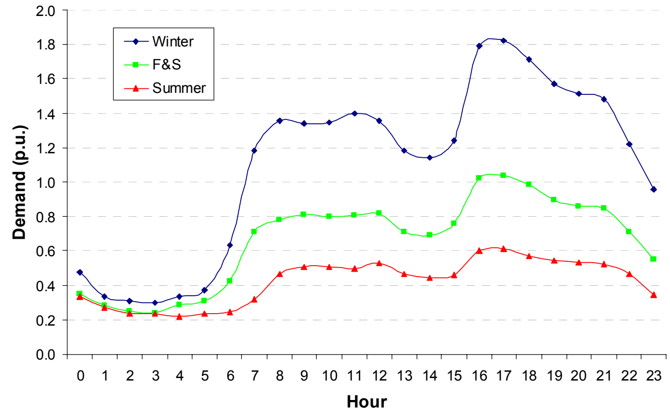

Fig. 3. Seasonal daily demand

III. Test and Results

The four-wire three-phase power flow algorithm based on the backward/forward current summation technique from [13] was adopted. Load was modeled as constant power with wind turbine generation considered as negative load (power factor equal to unity).

Since the purpose of this work is to evaluate the effects of a high penetration of wind turbines, simulations carried out assume that 10 residential consumers each have a specific model of roof-top wind turbine. For the 29-bus circuit, 63% of residential customers will have a roof-top wind turbine installed, whereas the figure is 83% for the 21-bus circuit. The following subsections will describe different approaches to evaluate the effects of those wind turbines on the secondary distribution circuits.

A. Energy

Given the three seasonal demand patterns presented in Fig. 3, i.e., summer, F&S (fall and spring) and winter, Figures 4 and 5 show the 24-hour energy consumption of the day during which the output of each model of wind turbine was at its seasonal maximum on each of the 21-bus and 29-bus circuits, respectively. With different power curves for each turbine, the days shown are not necessarily the same for each device, as Table II indicates. The first values of energy consumptions ("NO WT") correspond to the original secondary circuits, i.e., no wind turbine installed.

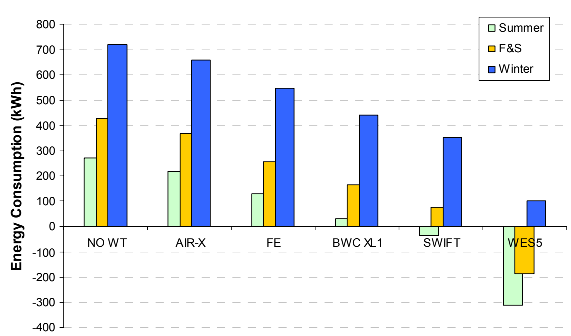

Fig. 4. Seasonal daily energy consumption for the maximum energy production day of the analyzed wind turbine considering the 21-bus circuit

Fig. 5. Seasonal daily energy consumption for the maximum energy production day of the analyzed wind turbine considering the 29-bus circuit

TABLE II
DATE FOR THE MAXIMUM DAILY ENERGY PRODUCTION FOR 2003

	Summer	F&S	Winter
AIR-X	01-Jul	06-May	02-Jan
FE	21-Aug	10-Mar	15-Jan
BWC XL1	01-Jul	06-May	21-Dec
SWIFT	01-Jul	10-Mar	21-Dec
WES5	01-Jul	06-May	02-Feb

As expected, the more the nominal capacity insertion of wind turbines, the less the energy consumed by the circuits. Moreover, in some cases the wind power generation exceed the circuit demand, leading to a scenario were energy is exported. In this way, it can be seen in Fig. 5 that the insertion of 10 WES5 wind turbines (total nominal capacity of 25 kW) is able to fully supply the 29-bus circuit demand and even export energy when considering the maximum daily energy production. Given that, in some cases, reverse power flow may disrupt the operation of distribution transformers, regular export of energy may not be desirable. In this way, 10 BWC XL1 wind turbines (total nominal capacity of 10 kW) may be suitable for the 21-bus circuit, whereas for the 29-bus solely 8 kW of total nominal capacity (10 FE wind turbines) may be installed.

Certainly, the insertion of wind turbines will relieve the load demand leading to a reduction of power losses. However, this statement is limited to a given generation capacity since losses may also increase, as shown in Fig. 6.

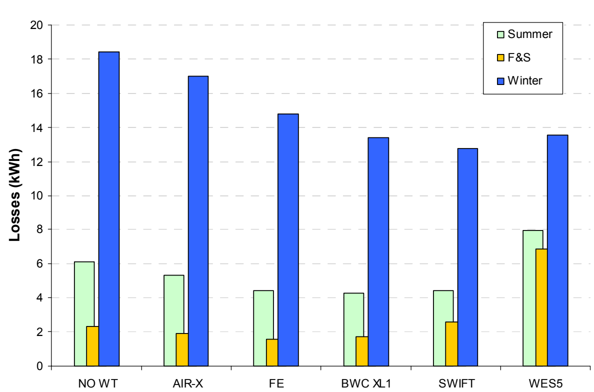

Fig. 6. Seasonal daily losses for the maximum energy production day of the analyzed wind turbine considering the 21-bus circuit

B. Total Power Flow Through the Distribution Transformer

Even analyzing the total energy consumption, as presented in Fig. 4 and Fig. 5, some results may be masked due to the time-variant characteristic of both the demand and wind power generation. Therefore, an hourly analysis becomes a useful tool for observing the behavior of the total power flow through the distribution transformer.

Figures 7 to 9 present hourly power flows at the head of the circuit of those configurations where installed wind turbines did not produce negative daily energy consumption for the 21-bus circuit (Fig. 4), considering summer, F&S and winter seasons, respectively. Clearly, while some configurations remain demanding power from the distribution transformer throughout the day, some wind turbines do produce reverse power flows, confirming the importance of such a detailed approach. Consequently, for this secondary circuit it may be appropriate to install no more than 10 FE wind turbines (total nominal capacity of 8 kW, i.e., 30% capacity penetration), although small reverse power flows appear as it can be verified in Fig. 8.

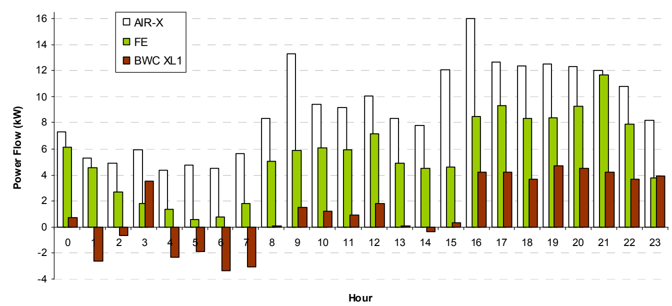

Fig. 7. Hourly power flows for the maximum energy production summer day of the analyzed wind turbine considering the 21-bus circuit

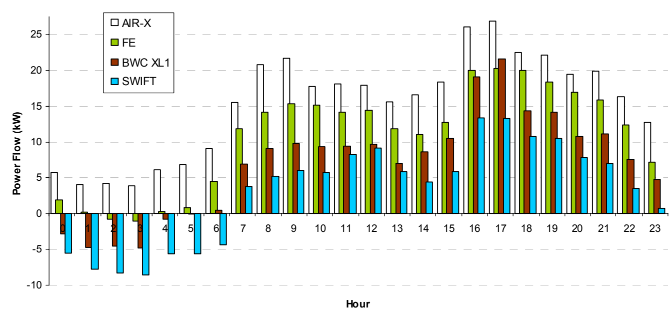

Fig. 8. Hourly power flows for the maximum energy production F&S day of the analyzed wind turbine considering the 21-bus circuit

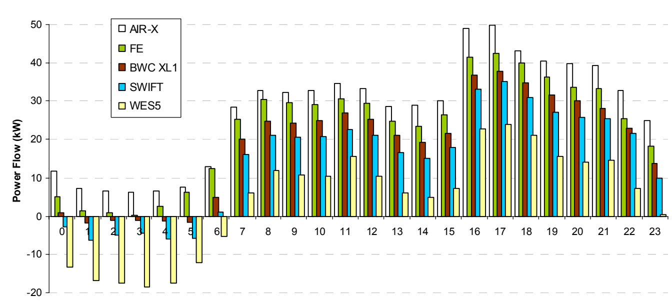

Fig. 9. Hourly power flows for the maximum energy production winter day of the analyzed wind turbine considering the 21-bus circuit

C. Three-phase Power Flow Through the Transformer

It is well known that distribution systems present unsymmetrical line segments and unbalanced loads, i.e., unbalance is a common-day problem face by utilities. Consequently, the total power flow at the head of the circuit can be split into its three-phase components in order to gain a deeper insight.

Fig. 10 presents the hourly three-phase power flows for the maximum energy production summer day considering ten AIR-X wind turbines installed in the 21-bus circuit. Although Fig. 7 exhibits that there is no reverse total power flow, when having a per phase analysis one can find out that during some hours reverse power flow do take place for phases *b* and *c*. It is important to remark that the 21-bus circuit is particularly unbalanced, with most loads in phase *a*. Consequently, since the wind power injection is assumed balanced among the three phases, the least loaded phases are more affected.

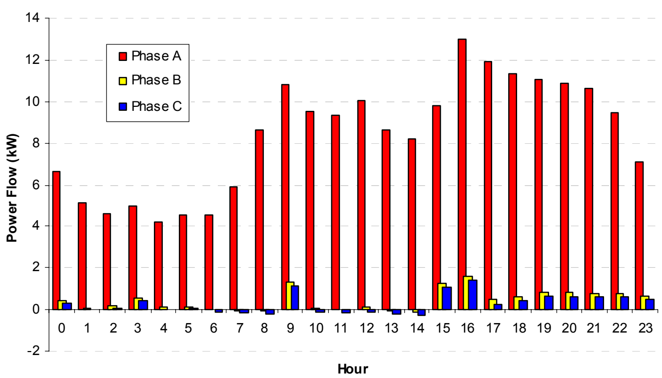

Fig. 10. Hourly three-phase power flows for the maximum energy production summer day for ten AIR-X wind turbines considering the 21-bus circuit

D. Voltage Profile

Decrease of losses and reverse power flows directly affect the voltage profile of the secondary circuit. Certainly, due to power quality issues the maintenance of voltages within specified limits is very important.

Fig. 11 shows the voltage profiles of the longest path in the 29-bus circuit considering three different sets of wind turbines during the hour of peak demand (17:00 – 18:00) of the maximum generation summer day. Phase *a* was considered for analysis since the 29-bus circuit is reasonably well balanced. As expected, the original voltage profile ("NO WT") is improved by adding sets of ten AIR-X, SWIFT or BWC XL1 wind turbines. Nonetheless, the latter, due to the reverse power flow (see Fig. 5), exhibits voltages above that of the distribution transformer (node 1). On the other hand, if we are to consider voltage limits, for instance, ±5%, the largest voltage exceeds the reference voltage by 0.4%.

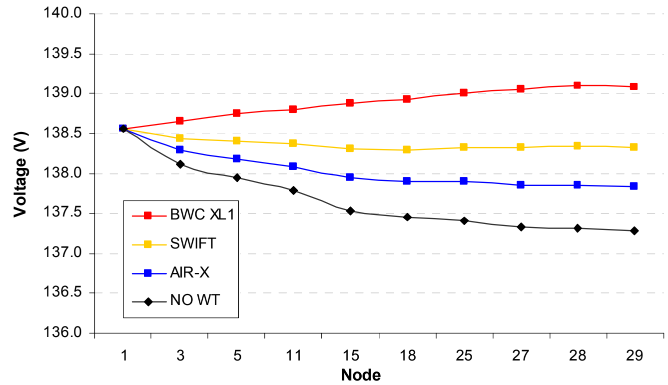

Fig. 11. Phase-*a* voltage profiles of the longest path in the 29-bus circuit during the most loaded hour (17:00 – 18:00) of maximum energy production summer day

IV. Conclusions

This work presents an evaluation of the effects of high penetrations of roof-top wind turbines on secondary (low voltage) distribution circuits. Energy consumption, loss reduction, reverse power flows and voltage profile were analyzed considering sets of different commercially-available roof-top wind turbines.

As expected, results suggest that the higher the penetration the greater the reduction in losses in the secondary circuit. Nonetheless, when total demand is exceeded reverse power flows appear which may disrupt transformer operation. It was also shown that, due to load unbalance, which is common in distribution systems, a per phase analysis is needed. Voltage profiles are also improved by higher penetrations and given the relatively modest turbine capacities there is limited risk of breaching voltage limits.

Reverse power flow and voltage control strategies, as well as protection schemes should be also analyzed in scenarios with high penetration of wind turbines, considering both technical and economic aspects.

Finally, it is important to note that this study considered the maximum energy production day of each season, so the effects of the wind power generation are most significant. In practice, in order to investigate the impacts of wind turbines insertion in distribution networks it is critical the availability of wind speed forecasting for a given horizon, considering a longer period of time, as well as the uncertainties associated.

V. Appendix A

Table A-1a and Table A-1b present the corresponding line section data, self and mutual impedances, in ohms for the 21-bus circuit. Corresponding load demand (representing 1.0 p.u.) is shown in Table A-2, where solely those nodes with load are included.

Table A-3 presents the corresponding line section data for the 29-bus circuit. Three-phase impedance matrices Z_1, Z_2 and Z_2, are required to compute all self and mutual impedance in ohms. Table A-4 shows the respective load demand (representing 1.0 p.u.).

TABLE A-1A
LINE SECTION DATA (Ω) – 21-BUS CIRCUIT

Line Section	Raa	Xaa	Rab	Xab	Rac	Xac
1 - 2	0.0243	0.0246	0.0001	0.0062	0.0001	0.0052
1 - 3	0.0237	0.0240	0.0001	0.0060	0.0001	0.0050
2 - 4	0.0218	0.0221	0.0001	0.0055	0.0001	0.0046
3 - 5	0.0241	0.0244	0.0001	0.0061	0.0001	0.0051
3 - 6	0.0290	0.0293	0.0001	0.0074	0.0001	0.0062
4 - 7	0.0213	0.0216	0.0001	0.0054	0.0001	0.0045
4 - 8	0.0204	0.0206	0.0000	0.0052	0.0000	0.0043
5 - 9	0.0239	0.0242	0.0001	0.0061	0.0001	0.0051
6 - 10	0.0282	0.0285	0.0001	0.0071	0.0001	0.0060
7 - 11	0.0171	0.0173	0.0000	0.0043	0.0000	0.0036
8 - 12	0.0219	0.0222	0.0001	0.0056	0.0001	0.0047
10 - 13	0.0232	0.0235	0.0001	0.0059	0.0001	0.0049
10 - 14	0.0262	0.0265	0.0001	0.0067	0.0001	0.0056
11 - 15	0.0176	0.0178	0.0000	0.0045	0.0000	0.0037
11 - 16	0.0241	0.0243	0.0001	0.0061	0.0001	0.0051
12 - 17	0.0220	0.0223	0.0001	0.0056	0.0001	0.0047
13 - 18	0.0223	0.0226	0.0001	0.0057	0.0001	0.0047
14 - 19	0.0281	0.0285	0.0001	0.0071	0.0001	0.0060
16 - 20	0.0249	0.0252	0.0001	0.0063	0.0001	0.0053

TABLE A-1B
LINE SECTION DATA (Ω) – 21-BUS CIRCUIT

Line Section	Rbb	Xbb	Rbc	Xbc	Rcc	Xcc
1 - 2	0.0243	0.0246	0.0001	0.0082	0.0243	0.0246
1 - 3	0.0237	0.0240	0.0001	0.0080	0.0237	0.0240
2 - 4	0.0218	0.0221	0.0001	0.0073	0.0218	0.0221
3 - 5	0.0241	0.0244	0.0001	0.0081	0.0241	0.0244
3 - 6	0.0290	0.0293	0.0001	0.0097	0.0290	0.0293
4 - 7	0.0213	0.0216	0.0001	0.0072	0.0213	0.0216
4 - 8	0.0204	0.0206	0.0000	0.0068	0.0204	0.0206
5 - 9	0.0239	0.0242	0.0001	0.0080	0.0239	0.0242
6 - 10	0.0282	0.0285	0.0001	0.0095	0.0282	0.0285
7 - 11	0.0171	0.0173	0.0000	0.0058	0.0171	0.0173
8 - 12	0.0219	0.0222	0.0001	0.0074	0.0219	0.0222
10 - 13	0.0232	0.0235	0.0001	0.0078	0.0232	0.0235
10 - 14	0.0262	0.0265	0.0001	0.0088	0.0262	0.0265
11 - 15	0.0176	0.0178	0.0000	0.0059	0.0176	0.0178
11 - 16	0.0241	0.0243	0.0001	0.0081	0.0241	0.0243
12 - 17	0.0220	0.0223	0.0001	0.0074	0.0220	0.0223
13 - 18	0.0223	0.0226	0.0001	0.0075	0.0223	0.0226
14 - 19	0.0281	0.0285	0.0001	0.0094	0.0281	0.0285
16 - 20	0.0249	0.0252	0.0001	0.0084	0.0249	0.0252

TABLE A-2
THREE-PHASE LOAD – 21-BUS CIRCUIT

	Phase *a*		Phase *b*		Phase *c*	
Node	W	Var	W	Var	W	Var
1	2209.7	941.3	255.4	108.8	0.0	0.0
2	1425.9	607.4	0.0	0.0	219.5	93.5
3	2223.9	947.4	231.9	98.8	231.9	98.8
4	3440.4	1465.6	228.0	97.1	228.0	97.1
5	2742.4	1168.2	0.0	0.0	0.0	0.0
7	0.0	0.0	201.3	85.7	500.4	213.2
9	1251.4	533.1	566.1	241.2	201.3	85.7
10	775.9	330.5	822.1	350.2	0.0	0.0
11	885.3	377.2	0.0	0.0	0.0	0.0
12	1584.6	675.0	0.0	0.0	306.5	130.6
13	681.0	290.1	0.0	0.0	442.7	188.6
14	131.3	56.0	131.3	56.0	0.0	0.0
15	627.5	267.3	276.7	117.9	276.7	117.9
17	912.1	388.6	0.0	0.0	0.0	0.0
18	1090.9	464.7	0.0	0.0	0.0	0.0
19	793.5	338.0	73.6	31.3	0.0	0.0
20	541.2	230.5	0.0	0.0	0.0	0.0

TABLE A-3
LINE SECTION DATA – 29-BUS CIRCUIT

Line Section	Length (km)	3ϕ Impedance Matrix	Line Section	Length (km)	3ϕ Impedance Matrix
1 - 2	0.017	Z_1	13 - 16	0.030	Z_2
1 - 3	0.023	Z_1	14 - 17	0.020	Z_3
2 - 4	0.015	Z_1	15 - 18	0.011	Z_3
3 - 5	0.011	Z_1	16 - 19	0.031	Z_2
4 - 6	0.022	Z_2	17 - 20	0.007	Z_2
4 - 7	0.008	Z_1	17 - 21	0.010	Z_3
4 - 8	0.008	Z_2	17 - 22	0.032	Z_2
5 - 9	0.010	Z_3	18 - 23	0.005	Z_2
5 - 10	0.015	Z_1	18 - 24	0.019	Z_3
5 - 11	0.019	Z_3	18 - 25	0.013	Z_2
6 - 12	0.019	Z_2	23 - 26	0.028	Z_2
8 - 13	0.029	Z_2	25 - 27	0.019	Z_2
9 - 14	0.028	Z_3	27 - 28	0.020	Z_2
11 - 15	0.031	Z_3	28 - 29	0.023	Z_2

$$Z_1 = \begin{bmatrix} 1.1756 + j0.7207 & 0.2123 + j0.4138 & 0.2031 + j0.3721 \\ 0.2123 + j0.4138 & 1.1457 + j0.7552 & 0.1897 + j0.4401 \\ 0.2031 + j0.3721 & 0.1897 + j0.4401 & 1.1295 + j0.7741 \end{bmatrix} \Omega/\text{km}$$

$$Z_2 = \begin{bmatrix} 1.2697 + j0.7982 & 0.2046 + j0.4330 & 0.1959 + j0.3903 \\ 0.2046 + j0.4330 & 1.2414 + j0.8295 & 0.1832 + j0.4569 \\ 0.1959 + j0.3903 & 0.1832 + j0.4569 & 1.2261 + j0.8467 \end{bmatrix} \Omega/\text{km}$$

$$Z_3 = \begin{bmatrix} 0.9154 + j0.7936 & 0.2046 + j0.4330 & 0.1959 + j0.3903 \\ 0.2046 + j0.4330 & 0.8871 + j0.8249 & 0.1832 + j0.4569 \\ 0.1959 + j0.3903 & 0.1832 + j0.4569 & 0.8718 + j0.8421 \end{bmatrix} \Omega/\text{km}$$

TABLE A-4
THREE-PHASE LOAD – 29-BUS CIRCUIT

	Phase *a*		Phase *b*		Phase *c*	
Node	W	Var	W	Var	W	Var
3	451.4	148.4	209.7	68.9	0.0	0.0
6	0.0	0.0	18.1	5.9	329.2	108.2
8	641.7	210.9	397.9	130.8	504.9	166.0
9	188.2	61.9	268.8	88.4	0.0	0.0
10	166.0	54.6	97.2	31.9	349.3	114.8
12	262.5	86.3	142.4	46.8	120.1	39.5
13	326.4	107.3	441.0	144.9	331.3	108.9
14	147.2	48.4	310.4	102.0	127.1	41.8
15	377.1	123.9	348.6	114.6	403.5	132.6
16	1044.4	343.3	185.4	389.6	20.1	335.3
19	330.6	108.7	562.5	184.9	754.2	247.9
20	0.0	0.0	236.8	77.8	216.0	71.0
21	311.1	102.3	544.4	178.9	234.7	77.1
22	294.4	96.8	59.7	19.6	0.0	0.0
23	112.5	37.0	112.5	37.0	0.0	0.0
24	113.9	37.4	0.0	0.0	0.0	0.0
25	0.0	0.0	170.8	56.1	170.8	56.1
26	570.8	187.6	273.6	89.9	0.0	0.0
27	507.6	166.8	291.0	95.6	343.1	112.8
28	144.4	47.5	366.7	120.5	569.4	187.2
29	118.1	38.8	118.1	38.8	0.0	0.0

VI. ACKNOWLEDGMENT

The authors would like to express their gratitude to Prof. Janusz Bialek for his assistance in and support.

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VIII. Biographies

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Gareth P. Harrison (M'02) is a Lecturer in Energy Systems in the School of Engineering and Electronics, University of Edinburgh. In addition to his work on integrating distributed generation into electricity networks, he is involved in analysing the impact of climate change on the electricity industry with emphasis on hydropower, marine energy and electricity demand. Dr. Harrison is a member of the Institution of Electrical Engineers, UK and a Chartered Engineer.

Accepted Paper