DEPARTMENT OF ELECTRONIC & ELECTRICAL ENGINEERING

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Power Flow Laboratory

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1 Voltage levels, current flows, and losses in the passive distribution system

The operation of the network is permissible when the voltage, line current, and transformer ratings are within their respective limits. That is:

1. **Voltage (pu):** $0.9pu \leq V_J \leq 1.1pu$ for buses $J \in [A, B, C, D, S]$
2. **Current (A):** $I_{N,LINE} \leq I_{N,MAX}$ for lines $N \in [1,2,3,4,5]$
3. **Transformer rating (MVA):** $S_{TX} \leq S_{RTX}$ where $S_{RTX} = 30MVA$

Note, these conditions are to be respected for each simulation scenario. The method for performing these simulations included running a short time-domain simulation of 0.5s using the powergui tool's load flow analyser. The Bus Type, Voltage, Angle, Real power, and Reactive power values were given in the simulation results window, and these were used to populate the appropriate columns in Table 1. In Table 2, the line currents and their capacities were ascertained from the meter blocks on the network model diagram.

Table 1: Base case load flow solution – assuming a load power convention

Bus Name	Bus Type [PQ, PV, Swing]	Voltage [pu]	Angle θ [deg]	P [MW]	Q [MVAr]
Bus_A	-	0.9889	28.06	0	0
Bus_B	PQ	0.9393	24.36	1.5	0.7265
Bus_C	PQ	0.9114	20.69	0.8	0.2630
Bus_D	PQ	0.9097	18.32	5.7	0
Bus_S	Swing	1	0	-8.476	2.6601

Table 2: Base case current flows and losses

Line Name	Line capacity in [A] or transformer rating [MVA]	Line current in [A] or apparent power [MVA]	Real power losses [kW]
Line 1	500	170.2	85.18
Line 2	500	79.26	32.61
Line 3	1200	296.4	334.34
Line 4	500	34.31	8.11
Line 5	2200	0	0
Transformer	30 MVA	8.87 MVA	10.49
		Total network losses:	470.73

The real power losses in Table 2 were calculated by accessing the report summary on the powergui tool and subtracting the power measured from one bus to another and the power measured the opposite way (i.e. subtracting the real power from Bus A -> Bus B and Bus B -> A). The transformer losses was calculated by doing the same calculation with busses S and A. The transformer apparent power was calculated by taking the measured real and reactive power at the Bus S side and feeding them into (1)

$$S = \sqrt{P^2 + Q^2} \tag{1}$$

$$S = \sqrt{8.476^2 + 2.6601^2} \approx 8.87\text{MVA} \tag{2}$$

The network operation in this configuration is deemed acceptable since the line currents, voltages, and transformer ratings are within the stated limits.

Throughout the simulation, and for the future sections, it was assumed that phases were balanced such that the simulation grid model is stable and has maximised system capacity. Another assumption made was that the short transmission line model was adopted. Utilisation of another model would result in greater real power losses across the lines.

An example calculation for the real power losses of Line 1 is computed as follows:

$$P_{loss} = 3(I_{Line})^2 R_{line} \tag{3}$$

$$= 3 \times (170.2)^2 \times (0.1153 \times 8.5) = 85.17kW \tag{4}$$

which is similar to the simulated value of 85.18kW.

Using the conservation of energy, a sanity check can be conducted to ensure that the power values are reasonable (5,6,7).

$$P_{Bus_S} = P_{Bus_{A,B,C,D}} + P_{Losses} \tag{5}$$

Evaluating $P_{A,B,C,D}$:

$$\sum_{J=0}^{J=3} P_{Bus_J} = 8MW \tag{6}$$

From Table 2:

$$P_{Losses} = 470.3kW \tag{7}$$

Summing (6) and (7) yields $P_{Bus_S} = 8.4703\text{MW}$ which is very close to the measured value of 8.476MW as seen in Table 1. The slight deviation experienced can be explained by rounding errors.

2 Assessment of the impact of wind generation on network operation

Connecting the wind farm to Bus D, and applying the same method and assumptions as previously, the results shown in Tables 3 and 4, were obtained by varying the wind farm output in intervals of 5MW.

Table 3: Impact of the wind farm generation on voltage levels

Wind farm output [MW]	Voltage amplitude (RMS) [pu]				
	Bus_A	Bus_B	Bus_C	Bus_D	Bus_E
15	0.9834	0.9501	0.9478	0.9885	1
20	0.9725	0.9344	0.9295	0.9829	1
25	0.9590	0.9131	0.9040	0.9752	1
30	0.9425	0.8851	0.8698	0.9650	1
35	0.9218	0.8481	0.8234	0.9515	1
40	0.8949	0.7965	0.7566	0.9330	1

Table 4: Impact of the wind farm generation on line currents, transformer apparent power and real power losses

Wind farm output [MW]	Line current (RMS) [A]					Transformer apparent power [MVA]	Total losses [kW]
	Line 1	Line 2	Line 3	Line 4	Line 5		
15	74.03	86.38	362.9	126.8	788.1	7.55	889.94
20	107.2	137.8	569.6	178.5	1050	12.457	1989.3
25	152.7	189.5	777.4	231	1314	17.419	3562
30	204	242.4	991.5	285.4	1585	22.536	5668.96
35	260.8	298.2	1219	343.8	1874	27.986	8454.42
40	326.7	360.5	1476	410.4	2199	34.155	12276.35

An example calculation of the transformer apparent power for the 15MW condition is

$$S = \sqrt{6.11^2 + 4.44^2} = 7.55\text{MVA} \quad (8)$$

The real and reactive power figures were taken from the Bus S side since these values will breach the transformer limit before Bus A. Total losses were given in the load flow analyser performance table.

The introduction of the wind farm increases the current drawn by each line as it adds more power to the network. Subsequently, since the resistance remains constant, the voltage would hence decrease as the power output of the wind farm generator increases. The relationship between wind farm output and bus voltages for each wind farm power interval is displayed in Figure 1 below.

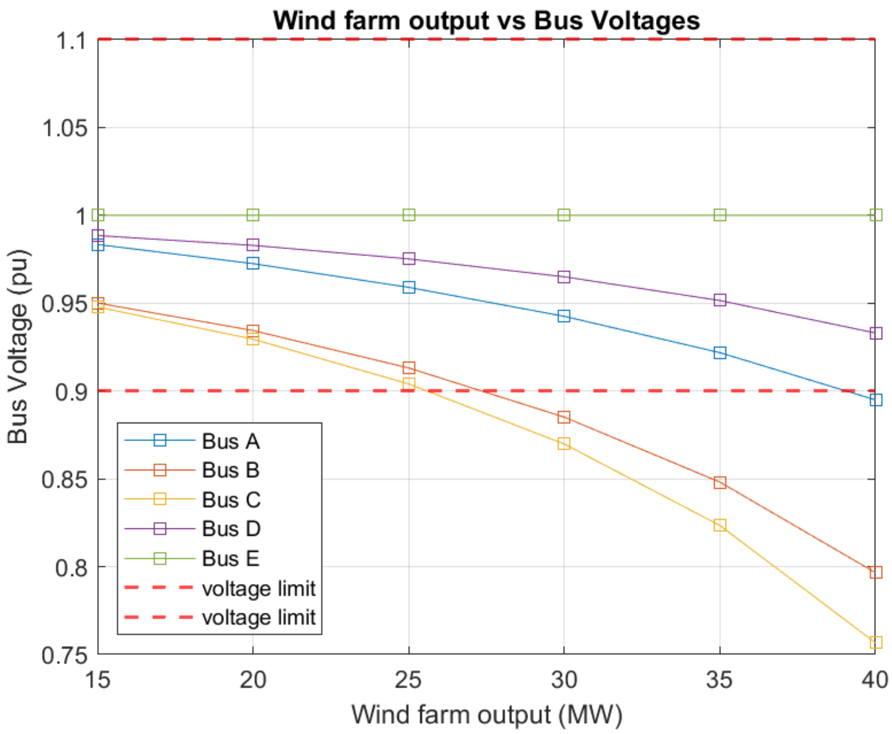

Figure 1 - Wind farm output vs Bus voltages for varying wind farm power outputs

Consideration of the network operating conditions, and analysis of the tables and figures listed above, enables the discovery of the maximum output of the windfarm. Figure 1 highlights that the voltage at Buses B and C breach these conditions as it falls out of the 0.9pu to 1.1pu boundary for 30MW and above. Likewise, by comparing the yielded values with the transformer and current ratings, it can be deducted that the maximum power output it limited to 25MW.

Furthermore, it is worth noting that the real power losses are greater than those obtained in Table 2. This is due to the increase in current and hence increase in I^2R losses.

3 Mitigating wind generation limits

Improving the maximum permissible output can be achieved by the addition of a reactive power compensator. This acts to increase the power factor and therefore increases the real power while decreasing the reactive power. The compensator was placed at Bus C since Table 3 shows that it is the lowest per unit and so it offers the most room for voltage compensation.

Conducting the same procedure as the previous sections yields the following output for Table 5, Table 6, and Figure 2.

Table 5: Impact of the wind farm generation on voltage levels (with additional reactive compensation)

Wind farm output [MW]	Voltage amplitude (RMS) [pu]				
	Bus_A	Bus_B	Bus_C	Bus_D	Bus_E
15	0.9924	1.01	1.092	0.9953	1
20	0.9823	0.9968	1.077	0.99	1
25	0.9698	0.9788	1.057	0.9828	1
30	0.9546	0.9555	1.03	0.9734	1
35	0.9361	0.9254	0.9941	0.9612	1
40	0.913	0.8855	0.9463	0.9452	1

Table 6: Impact of the wind farm generation on line currents, transformer apparent power and real power losses (with additional reactive compensation)

Wind farm output [MW]	Line current (RMS) [A]					Transformer apparent power [MVA]	Total losses [kW]
	Line 1	Line 2	Line 3	Line 4	Line 5		
15	38.86	111.3	345.8	188.8	804.7	6.378	1000.25
20	52.9	140.2	544.8	234.1	1059	11.142	2024.25
25	96.65	178.7	744.2	281.7	1315	15.912	3481.62
30	146	222.5	947.5	331.9	1575	20.773	5413.61
35	198.7	270.5	1160	385.8	1847	25.851	7915.88
40	256.2	323.7	1391	445.9	2142	31.364	11196.16

An example calculation of the transformer apparent power for the 15MW condition is

$$S = \sqrt{6^2 + 2.01^2} \approx 6.378\text{MVA} \quad (9)$$

The same method was used to gain real and reactive powers for the calculation above.

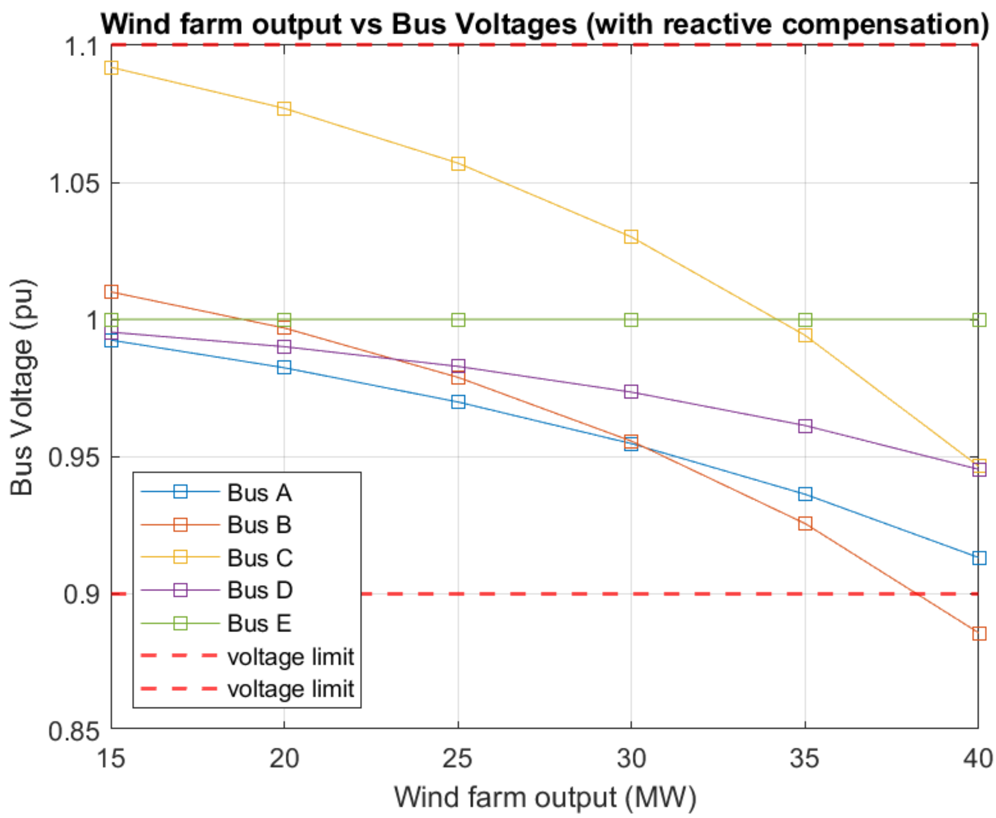

Figure 2 - Wind farm output vs Bus voltages with reactive compensator

Figure 2 shows that the current, voltage, and transformer ratings are permissible for 35MW – a 10MW increase compared to not having a compensator. This can be regarded as beneficial for the owner since revenue is paid per MWh of electricity generation.

4 Assessment of the daily revenue loss resulting from the wind generation curtailment

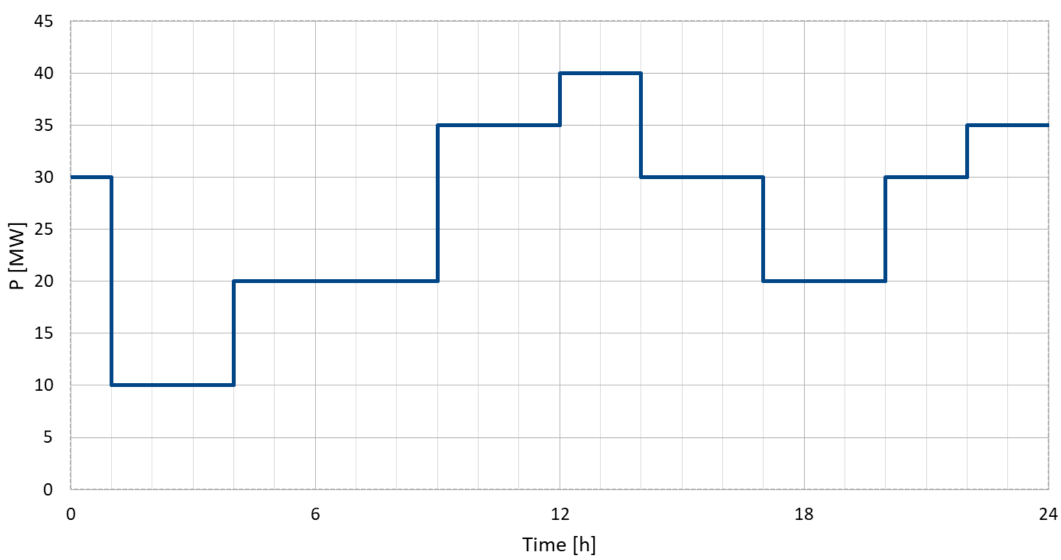

Figure 3. Unconstrained daily generation profile of the Wind Farm

4.1

By summing the product of the power output every hour and the cost per MWh, the revenue for the unconstrained generation of the wind farm was calculated to be £281,250 per day and £1,968,750 per week.

$$450\left(\frac{£}{MWh}\right)\times\int_0^{24} f(h)dh \;\; (MWh) = £281{,}250 \tag{10}$$

$$£281{,}250 \times 7 = £1{,}968{,}750 \tag{11}$$

4.2

Imposing the model from section 3.2, the generating farm would be capped at 25MW since this is the greatest power condition that does not breach the current, voltage, or transformer limits. Note, generation at 30MW is not viable since it causes the voltage at Bus B to exceed the limit since 0.8851pu < 0.9pu .

This constrained generation at 25MW means that the owner makes £231,750 a day and £1,622,250 per week. Calculating the difference between the constrained generation at 25MW and unconstrained generation indicates that the owner loses out on £346,500 per week.

$$450\left(\frac{£}{MWh}\right)\times\int_0^{24} f^*(h)dh \;\; (MWh) = £231{,}750 \tag{12}$$

$$£231{,}750 \times 7 = £1{,}622{,}250 \tag{13}$$

$$£1{,}968{,}750 - £1{,}622{,}250 = £346{,}500 \tag{14}$$

4.3

Addition of a reactive compensator improves network performance and now enables the wind farm to generate 35MW without breaching the network conditions. With this addition, the owner now makes £276,750 a day and £1,937,250 a week. The income recovered is calculated as £45,000 per day.

$$450\left(\frac{£}{MWh}\right)\times\int_0^{24} f^{**}(h)dh \;\; (MWh) = £276{,}750 \tag{15}$$

$$£276{,}750 \times 7 = £1{,}937{,}250 \tag{16}$$

$$£276{,}750 - £231{,}750 = £45{,}000 \tag{17}$$

4.4

In practice, implementation of a Battery Energy Storage Supply (BESS) would aid in mitigating the generation curtailment, and hence contribute to the wind farm operating at full capacity.

This is because for scenarios in sections 2 and 3 where the generation is curtailed due to the limitations of the network architecture, the owner of the wind farm would lose out on generation to the grid, and hence money. The BESS operates to capture the excess generation above the curtailment limit. This provides a clean solution to the issues that lie with the intermittency of wind generation as the stored energy can be later used to smoothen demand peaks while simultaneously maximising the profitability for the owner.

A more costly method to enable the wind farm full operation capacity is to upgrade the network infrastructure such that the thermal current limits, voltage limits, and transformer ratings will have a greater threshold. Such a solution is not feasible, in comparison to the BESS implementation, since it will be highly costly and result in downtimes on sections of the network which can heavily affect customers.