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EEEN30131 Power Flow Analysis and Power System Control

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Abstract

The management of power systems is complex due to the many variables involved in active power, reactive power, current, voltage, etc. Manually tuning these parameters and running power flow simulations in real time is challenging and requires human involvement increasing the risk of error. Therefore, in order to improve the management level of the power system, it is necessary to analyze the relationship between the parameters in the power system process and formulate effective control methods.

Keywords: power flow analyse, power system control

1. Introduction

A power system contains many variables, like active power, reactive power, current, voltage, etc. It is challenging to adjust these parameters manually and run power flow simulation in real time. In addition, when people are involved, it is easy to make mistake. To solve this, the report is mainly focus on to analyse the relationship of each parameter in power system flow, and the way to control these parameters.

2. Results and Discussion for Power Flow Analysis

In this section, bus 1 is modelled as a PV bus, so the voltage magnitude of bus 1 or synchronous generator 1 is set to 1.02 *p.u.*, and the active power is set manually. Bus 2 is modelled as a PQ bus and the bus 3 is slack bus. The voltage magnitude of bus 3 is set to 1 *p.u.* and angle of bus 3 is set to 0°.

2.1 A.1.3

Considering bus 1 is sending end and bus 3 is receiving end. Because the voltage magnitude of bus 1 and bus 3 and the angle of bus 3 are fixed, by increasing the active power (or system loading) of bus 1 from 3 *p.u.* to 6 *p.u.* (or from 40% to 100%), the angle of bus 1 is also increased from –3.6756° to –27.7436°. Equation (1) can show the relationship between active power and phase angle difference. In this power system, voltage magnitude of sending end (V_S), receiving end (V_R), angle of receiving end (θ_R) and impedance from sending end to receiving end (X_{SR}) is unchanged. If active power increases, the phase angle difference also increases, which means the angle of sending end increases.

$$P_S \cong \frac{V_S V_R}{X_{SR}}(\theta_S - \theta_R) \tag{1}$$

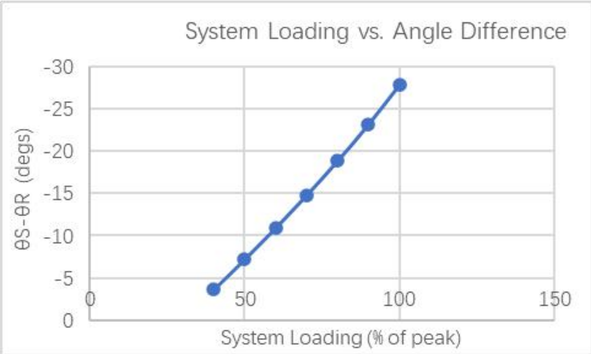

Figure 1. System Loading vs. Angle Difference

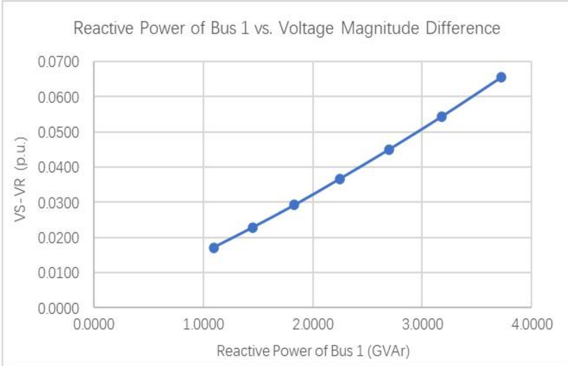

Figure 2. Reactive Power of Bus 1 vs. Voltage Magnitude Difference

Figure 1 shows the relationship between system load and angle difference between sending end and receiving end. When the system load increases, the angle difference also increases, which prove that the active power is mainly affected by phase angle difference.

Considering bus 1 is sending end and bus 2 is receiving end. It is obvious that when reactive power (or system loading) of bus 1 increases from 1.0932 *p.u.* to 3.7182 *p.u.* (or from 40% to 100%), the voltage magnitude of bus 2 decreases, from 1.0028 *p.u.* to 0.9545 *p.u.*. The relationship between reactive power and voltage magnitude difference can be described by equation (2). Voltage magnitude of sending end (V_S) and impedance from sending end to receiving end (X_{SR}) is unchanged. The voltage magnitude of receiving end must be decreased when reactive power of sending end increases.

$$Q_S \cong \frac{V_S}{X_{SR}}(V_S - V_R) \tag{2}$$

Figure 2 illustrates the relationship between reactive power of bus 1 and voltage magnitude difference between sending end and receiving end. The voltage magnitude difference will increase if reactive power of bus 1 increases, which prove that the reactive power is affected by the voltage magnitude difference.

The power factor in A.1.1 and A.1.2 is 0.95 lagging and 0.92 lagging, respectively. By analysing the equation (3) and (4), it is noticeable that if apparent power is unchanged and power factor increases, active power will increase and reactive power will decrease. In this power system, the active power is set manually, so the power factor only affects reactive power.

$$S^2 = P^2 + Q^2 \tag{3}$$

$$P = S \times Power\ Factor \tag{4}$$

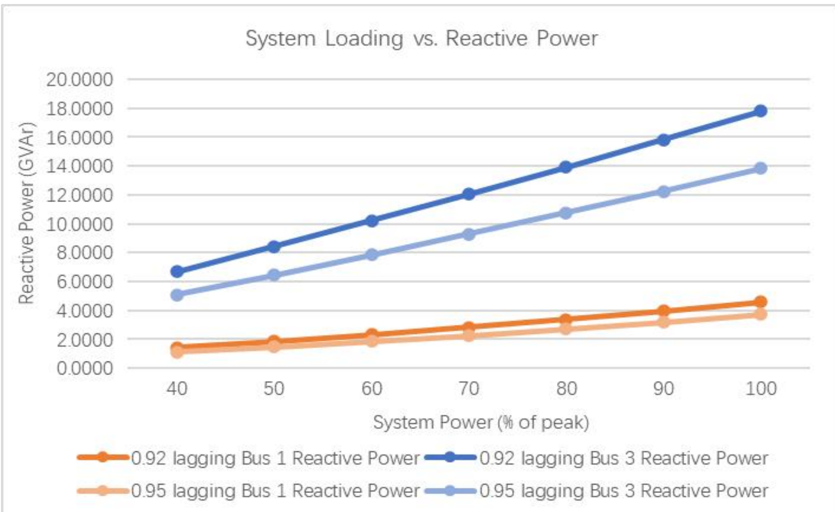

Figure 3. Reactive Power vs. System Loading

Figure 3 shows the reactive power of different buses with different power factor. For bus 1, the reactive power with 0.95 power factor is always smaller the reactive power with 0.92 power factor. Same pattern occurs in bus 3, the reactive power with 0.92 power factor is always greater than reactive power with 0.95 power factor.

2.2 A.2.1

Table 1. System Voltage Magnitude and Angles for Non-synchronous Generation

System loading	Bus 1		Bus 2		Bus 3	
Wind (GW)	V (pu)	θ (degs)	V (pu)	θ (degs)	V (pu)	θ (degs)
0	1.0200	-15.3718	0.9664	-18.5692	1.0000	0.0000
0.5	1.0200	-9.6948	0.9696	-13.7744	1.0000	0.0000
1	1.0200	-4.2182	0.9714	-9.1727	1.0000	0.0000
1.5	1.0200	1.1267	0.9717	-4.6996	1.0000	0.0000
2	1.0200	6.3953	0.9708	-0.3033	1.0000	0.0000
2.5	1.0200	11.6361	0.9687	4.0609	1.0000	0.0000
3	1.0200	16.8945	0.9653	8.4348	1.0000	0.0000
3.5	1.0200	22.2169	0.9606	12.8610	1.0000	0.0000
4	1.0200	27.6545	0.9546	17.3861	1.0000	0.0000
4.1	1.0200	28.7676	0.9532	18.3076	1.0000	0.0000
4.2	1.0200	29.8749	0.9518	19.2358	1.0000	0.0000
4.3	1.0200	30.9970	0.9502	20.1711	1.0000	0.0000

2.3 A.2.2

From Table 1, when the wind value is 4.3 *GW*, the voltage magnitude of bus 2 almost reach the statutory limits, which equals to 0.9502 *p.u.*. The statutory limits of the network will be exceeded, if the wind value is greater than 4.3 *GW*.

It is noticeable that the phase angle increases as the wind value increases. The equation (3) and equation (4) show that when the phase angle increases, reactive power also increases. In order to transmit more reactive power, larger voltage magnitude difference between sending end and receiving end is required, which is already shown in equation (2). When the voltage magnitude of receiving end is lower than the statutory limits of network, the system may unstable.

2.4 A.2.3

Table 1 shows that the active power of wind generator is increased by 0.5 *GW* each time before 4 *GW*. After 4 *GW*, the value is increased by 0.1 *GW* each time until it reaches the statutory limits of the network.

As mentioned earlier, reactive power is affected by the voltage magnitude difference. For equation (5), the power factor is always less or equal to 1, so if the active power increases, the reactive power will also be increased. Form equation (2), the voltage magnitude difference also will be increased.

$$\left(\frac{P}{PF}\right)^2 - P^2 = Q^2 \tag{5}$$

Before the wind power reaches 1.5 *GW*, both reactive power and voltage difference drop slightly. After 1.5 *GW*, both two values increase exponentially (transporting large reactive power requires large voltage drops). Figure 4 shows this pattern, and the wind power can only increase around to 4.3 *GW*, because beyond this point the voltage magnitude of bus 2 will exceed the statutory limits.

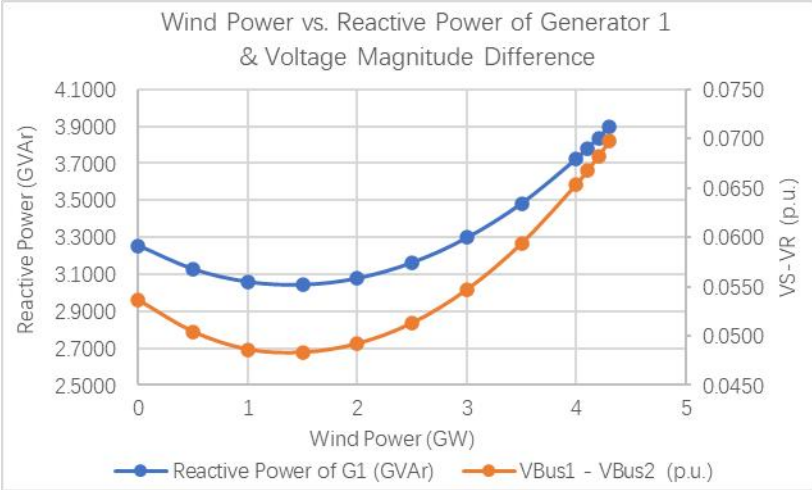

Figure 4. Wind Power vs. Reactive Power of Generator 1 & Voltage Magnitude Difference

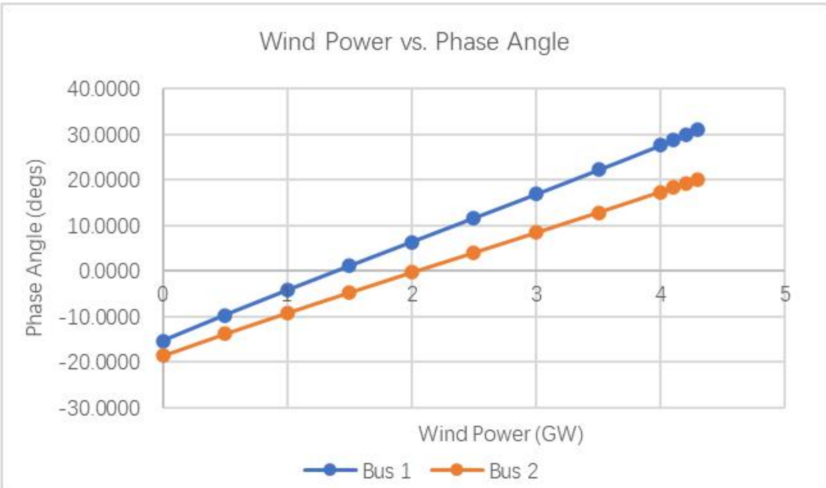

Figure 5. Wind Power vs. Phase Angle

For the active power, which is also mentioned earlier, it is mainly affected by phase angle difference. Figure 5 illustrates phase angle of bus 1 and bus 2. When the wind power increases, the phase angle of two buses increases proportionally and the difference between two phase angles increases slightly.

3. Results and Discussion for Power System Control

3.1 B.1.2

As conventional fossil fuel based synchronous generators are replaced by renewable energy sources (like wind turbines which are often non-synchronous generators), the inertia of the power system is expected to decrease. A power system has been designed to simulate the effects of reduced system inertia. There are two areas in this power system, by gradually reducing the angular momentum (M_1) and capacity of area 1, the inertia can be reduced. Nadir and settling frequency will be recorded if the frequency response of the system can be stabled within 30 seconds. All recorded data are shown in Figure 6.

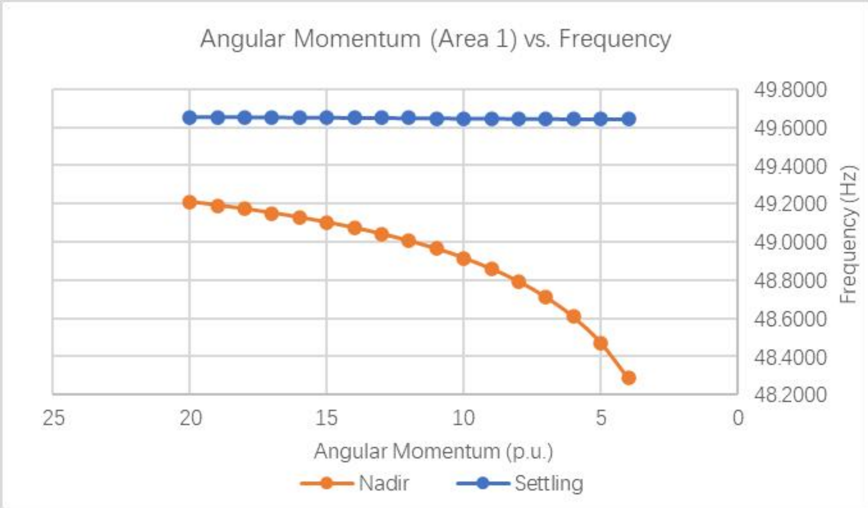

Figure 6. Angular Momentum (Area 1) vs. Frequency

According to Figure 6, the lowest angular momentum in area 1 that allows the system to reach a stable frequency equilibrium after 30 seconds is 4 *p.u.*, and the nadir and settling frequency is 48.2885 *Hz* and 49.6419 *Hz*, respectively.

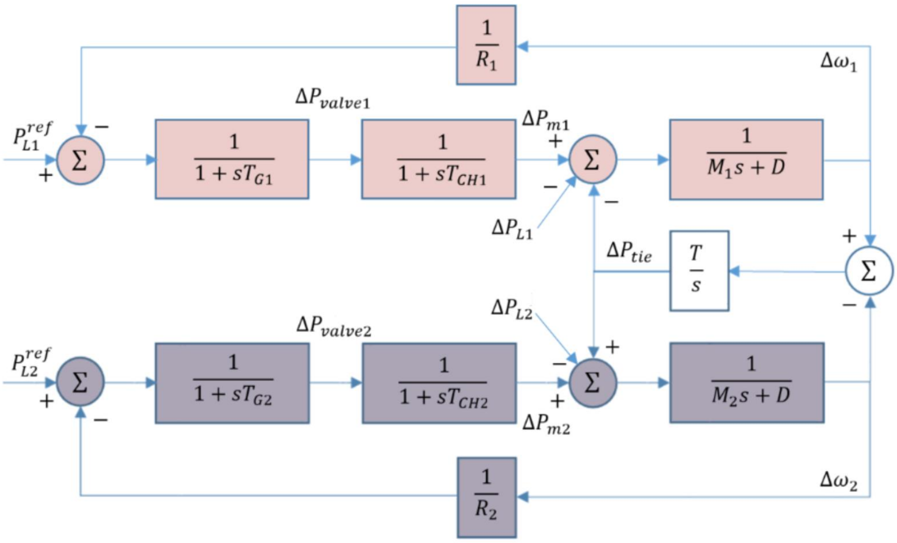

Figure 7. Two Interconnected Areas (D. M. Ceseña, n.d.)

Figure 7 shows the connection between area 1 and area 2, because the structure of two areas is identical, only area 1 (upper part) will be discussed. By analyzing the connection of each part, the relationship between Δω and other part can be expressed by equation (5). In equation (6), $\Delta P_{L1}(s)$ is non-frequency dependent load change, which is 0.3 *p.u.* in this system.

$\frac{1}{1+sT_{CH1}}$ is a part of the prime mover model, which can increase the mechanical power, and the $CH1$(0.5 *p.u.*) stands for the charging time.

The $\frac{1}{R_1}\left(\frac{1}{1+sT_{G1}}\right)$ is the feedback droop control, which can allow the machine respond to change in frequency and vary its power output to stabilize the system automatically. R_1 is 10%

and $T_{G1} = \frac{1}{K_{G1}R_1}$, where K_{G1}= 100 *p.u.*. *D* is the damping term, which is equal to 0.6 *p.u.* in area 1. $M_1 s$ is the angular momentum, and this value is controlled manually.

$$\Delta\omega(s) = \frac{-\frac{1}{M_1 s + D} \times \Delta P_{L1}(s)}{1 + \frac{1}{R_1}(\frac{1}{1 + sT_{G1}})(\frac{1}{1 + sT_{CH}})(\frac{1}{M_1 s + D})} \quad (6)$$

If the numerator and denominator are divided by $\frac{1}{M_1 s+D}$, equation (7) will be produced. It is noticeable that when $M_1 s$ become smaller, the $\Delta\omega(s)$ will increase, which means if the angular momentum is small, the system frequency will be more difficult to stabilize. Figure 6 also shows the same result. As the angular momentum decrease, the nadir frequency becomes lower, which means $\Delta\omega$ is larger.

$$\Delta\omega(s) = \frac{-\Delta P_{L1}(s)}{(M_1 s + D) + \frac{1}{R_1}(\frac{1}{1 + sT_{G1}})(\frac{1}{1 + sT_{CH1}})} \quad (7)$$

For the steady state, $\Delta\omega$ can be describe as equation (8), which is equals to $\frac{-0.3}{\frac{1}{0.1}+0.6} = -0.0283\ Hz$. Therefore, the steady state of this power system is 50−0.0283 = 49.9717 Hz, which close to the steady state frequency shown in Figure 6.

$$\Delta\omega = \lim_{s\to 0}[s\Delta\omega(s)] = \lim_{s\to 0}\left[\frac{-\frac{1}{M_1 s + D} \times \Delta P_{L1}(s)}{1 + \frac{1}{R_1}\left(\frac{1}{1 + sT_{G1}}\right)\left(\frac{1}{1 + sT_{CH1}}\right)\left(\frac{1}{M_1 s + D}\right)}\right] = \frac{-\Delta P_L}{\frac{1}{R} + D} \quad (8)$$

3.2 B.2.2

Assuming a power system has three areas, and they are connected by tie-line. The demand of area 3 is suddenly greater than generation by 300 MW. The primary control will start in 2 seconds and fully deployed by 10 seconds. In this stage, both area 1 and area 2 are delivered power to area 3. The frequency drop caused by contingency is −0.004 $p.u.$. Therefore, the power contribution of the generators in this power system can be calculated.

$$G_1: \Delta P_{m1} = -\frac{\Delta\omega_1}{R_1} = -\frac{-0.004}{0.05} = 0.08\ p.u. \text{ and } G_2: \Delta P_{m2} = -\frac{\Delta\omega_2}{R_2} = -\frac{-0.004}{0.025} = 0.16\ p.u.$$

However, the total power contribution of the generators is 0.08 + 0.16 = 0.24 $p.u.$, which is not enough. In this case, the load in area 1 and area 2 are also injected power into the power system, which can be calculated as following:

$$Load\ 1: D_1\Delta\omega = 5 \times (-0.004) = -0.02\ p.u.$$

$$Load\ 2: D_2\Delta\omega = 10 \times (-0.004) = -0.04\ p.u.$$

So, the total power contribution from area 1 and area 2 equals to 0.08+0.16−(−0.02)−(−0.04) = 0.3 $p.u.$, which is enough to solve the contingency.

The $\Delta\omega$ can be also calculated by using equation (9), which is also equal to −0.004 $p.u.$. The relationship between $\Delta\omega$ and damping constants (D_1 and D_2) can also be expressed by equation (9). As the damping constants increase, $\Delta\omega$ becomes small.

$$\Delta\omega = \frac{-\Delta P_{L1}}{\frac{1}{R_1} + \frac{1}{R_2} + D_1 + D_2} \quad (9)$$

3.3 B.3.2

It is possible to manage the voltage across the grid by injecting reactive power at specific locations, for example, using generator, synchronous condensers, capacitor banks, etc. To explore the effect if reactive power injection on voltage, the synchronous condenser connects to Bus 3 (shown in Figure 8). By changing the output of the synchronous condenser, the result can be found.

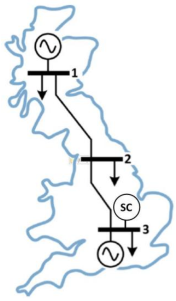

Figure 8. Simplified GB System with Added Synchronous Condenser (D. M. Ceseña, n.d.)

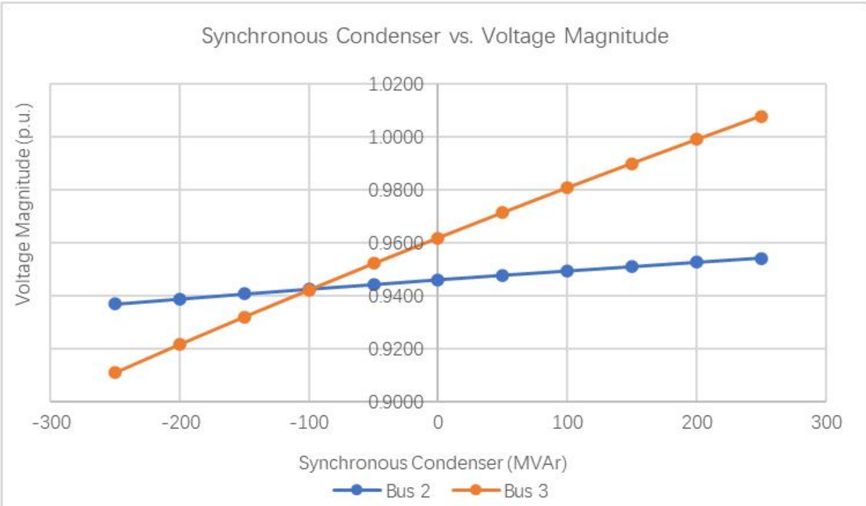

Figure 9. Synchronous Condenser vs. Voltage Magnitude

The reactive power is influenced by the voltage magnitude difference. When the reactive power is injected into the power system from bus 3, apparently, the voltage magnitude will be changed. As the reactive power becomes larger, the voltage magnitude becomes also larger. However, because the synchronous condenser connects to bus 3, the voltage magnitude changes more rapidly in bus 3, which is shown in Figure 9. It is noticeable that when the synchronous condenser increases to $-100MVAr$, the voltage different between bus 2 and bus 3 is minimized (0.0004 $p.u.$), which means the line 2 and 3 has minimum voltage drop. After this point, the voltage magnitude difference becomes larger as the reactive power increases.

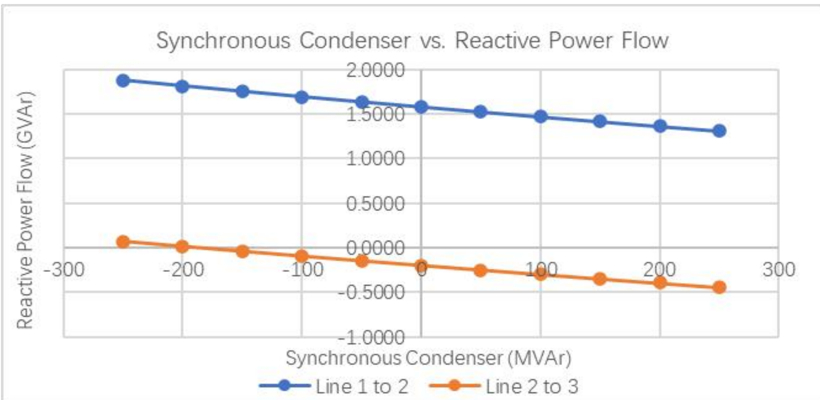

Figure 10. Synchronous Condenser vs. Reactive Power Flow

The original reactive power in the power system can be cancelled with the reactive power which is injected by the synchronous condenser. As the synchronous condenser injects more reactive power to the power system, the reactive power in the power system is smaller, which is shown in Figure 10.

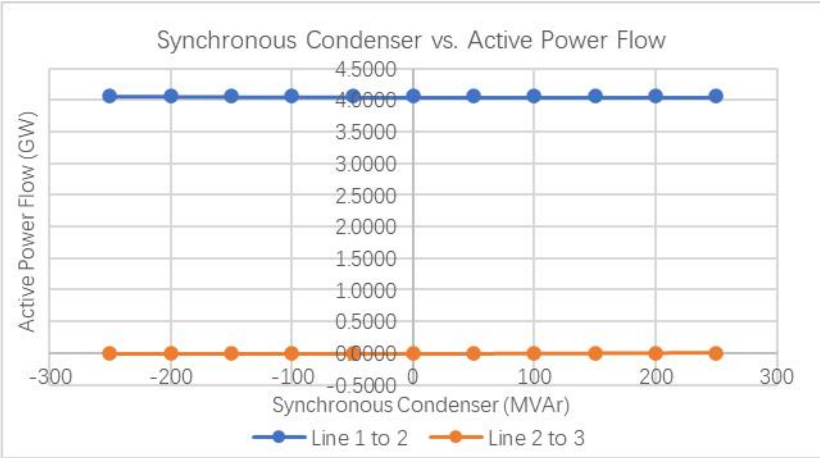

Figure 11. Synchronous Condenser vs. Active Power Flow

Figure 11 shows that as the reactive power increases, the active power does not change, which means the active will not be affected by reactive power.

4. Conclusion

By analysing the equivalent model of the GB power system, the relationship of parameters in the formula which are covered in the lecture can be proved. In part A, power flow of the steady state behaviour of the GB power system model will be discussed. For part B, the frequency stability of the system will be analysed, and discuss the way to control the power system.

Declaration

I hereby confirm that this report and the associated excel template include my own work, I have not shared my results, and I have not viewed someone else's results. I am also aware that both the report and excel template will be reviewed for similarities with the documents submitted by other students.

References

D. M. Ceseña, (n.d.). Power Flow Analysis & Power System Control Coursework.

Appendix

A.1.3

Report:
(A.1.3) Discuss the results you have obtained **[10 marks]**.

You might want to include some of the following in your discussion:
- *Descriptions and explanations about how the results change with varying loading.*
- *Comparisons about the results with different load power factors.*
- *Data visualisation that supports your discussion.*
- *Information from the lectures or literature that supports your discussion.*

A.2.1, A.2.2, A.2.3

Report:
(A.2.1) Record the system voltage magnitudes and angles as the non-synchronous generation in Scotland increases from an initial output of 0 GW. Record these values in a table. Use your judgement to decide the number of results to include in the table (you need enough results to support your discussion).

Stop increasing the generation once the voltage limits are violated. Remember, the voltage magnitudes in the system must be kept between 0.95 pu and 1.05 pu at all times.

Include the table of data you produced for Task A.2.1 in your report. This is not included in the excel file like the other system data tasks. **[7 marks]**

(A.2.2) Determine the maximum value of Scottish non-synchronous generation (to the nearest 100 MW) that can be accommodated by the system before the system voltage limits are violated.

Make sure you clearly state the maximum allowable value of Scottish non-synchronous generation in your report. **[3 marks]**

(A.2.3) Discuss the results you have obtained. **[10 marks]**

You might want to include some of the following in your discussion:
- *Descriptions and explanations about how the system parameters change with varying loading.*
- *Make sure you consider the different parameters in the test system that vary.*
- *Data visualisation that supports your discussion.*

B.1.2

Report:
(B.1.2) Discuss the results you have obtained **[10 marks]**.

You might want to include some of the following in your discussion:
- *Description of the study.*
- *The lowest angular momentum in area 1 (M_1) that allows the system to reach a stable frequency equilibrium after 30 seconds.*
- *Descriptions and explanations about how the frequency stability metrics (nadir and settling frequency) change as the angular momentum varies.*
- *Data visualisation that supports your discussion.*

B.2.2

Report:
(B.2.2) Discuss the results you have obtained **[5 marks]**.

You might want to address the following questions in your discussion:
- *What is the combined response of the synchronous generators and demands?*
- *How would the frequency response of the loads vary with different damping constraints?*

B.3.2

Report:
(B.3.2) Discuss the results you have obtained **[5 marks]**.

You might want to include some of the following in your discussion:
- *Description of the study.*
- *Visualization of the results*
- *The impacts of reactive injections at the receiving end of a line (Bus 3).*

A.1.1

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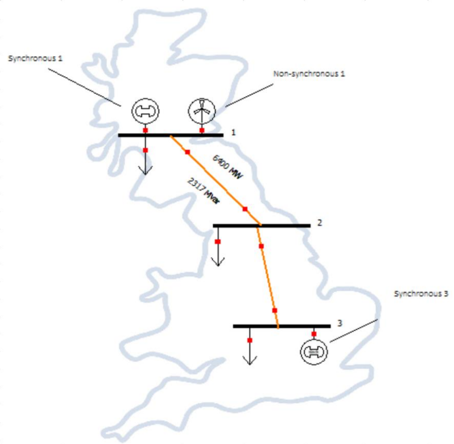
Student number: 10725319

A.1.1 Voltage magnitude and angle for a power factor of: 0.95 lagging

System loading	Bus 1		Bus 2		Bus 3	
(% of peak)	V (pu)	θ (degs)	V (pu)	θ (degs)	V (pu)	θ (degs)
40	1.0200	-3.6756	1.0028	-5.2725	1.0000	0.0000
50	1.0200	-7.2553	0.9971	-8.8288	1.0000	0.0000
60	1.0200	-10.9477	0.9907	-12.4942	1.0000	0.0000
70	1.0200	-14.7876	0.9833	-16.3030	1.0000	0.0000
80	1.0200	-18.8205	0.9750	-20.3000	1.0000	0.0000
90	1.0200	-23.1088	0.9655	-24.5464	1.0000	0.0000
100	1.0200	-27.7436	0.9545	-29.1319	1.0000	0.0000

A.1.1 Active and reactive power outputs for a power factor of: 0.95 lagging

System loading	Synchronous 1		Non-synchronous 1		Synchronous 3	
(% of peak)	P (GW)	Q(GVAr)	P (GW)	Q(GVAr)	P (GW)	Q(GVAr)
40	3.0000	1.0932	-	-	16.6092	5.0976
50	3.5000	1.4502	-	-	21.0199	6.4597
60	4.0000	1.8336	-	-	25.4363	7.8535
70	4.5000	2.2464	-	-	29.8591	9.2820
80	5.0000	2.6933	-	-	34.2892	10.7494
90	5.5000	3.1808	-	-	38.7278	12.2617
100	6.0000	3.7182	-	-	43.1768	13.8281



A.1.2

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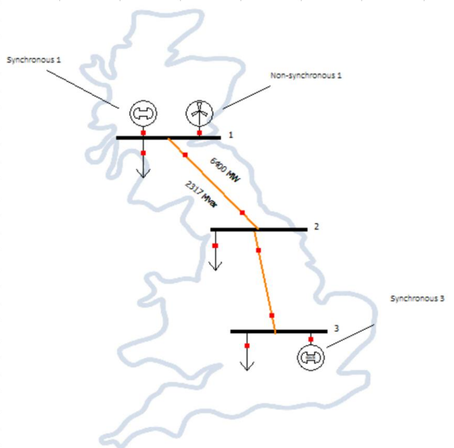
A.1.2 Voltage magnitude and angle for a power factor of: 0.92 lagging

System loading	Bus 1		Bus 2		Bus 3	
(% of peak)	V (pu)	θ (degs)	V (pu)	θ (degs)	V (pu)	θ (degs)
40	1.0200	-3.6938	0.9988	-5.2744	1.0000	0.0000
50	1.0200	-7.2992	0.9921	-8.8516	1.0000	0.0000
60	1.0200	-11.0286	0.9845	-12.5491	1.0000	0.0000
70	1.0200	-14.9199	0.9760	-16.4038	1.0000	0.0000
80	1.0200	-19.0230	0.9664	-20.4650	1.0000	0.0000
90	1.0200	-23.4080	0.9556	-24.8012	1.0000	0.0000
100	1.0200	-28.1793	0.9430	-29.5150	1.0000	0.0000

A.1.2 Active and reactive power outputs for a power factor of: 0.92 lagging

System loading	Synchronous 1		Non-synchronous 1		Synchronous 3	
(% of peak)	P (GW)	Q(GVAr)	P (GW)	Q(GVAr)	P (GW)	Q(GVAr)
40	3.0000	1.4227	-	-	16.6096	6.6811
50	3.5000	1.8644	-	-	21.0207	8.4395
60	4.0000	2.3339	-	-	25.4377	10.2303
70	4.5000	2.8350	-	-	29.8614	12.0566
80	5.0000	3.3729	-	-	34.2928	13.9230
90	5.5000	3.9550	-	-	38.7333	15.8364
100	6.0000	4.5930	-	-	43.1850	17.8070



B.1.1

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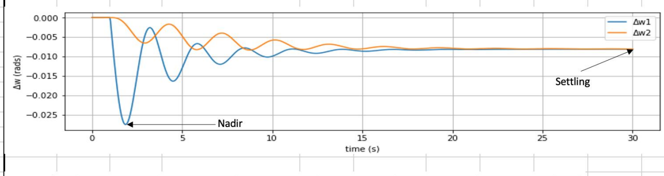
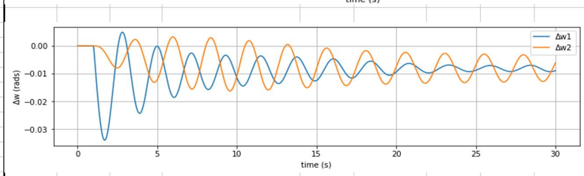
B.1.1 Primary frequency response

Angular momentum	Capacity1	Nadir		Settling	
M (pu)	(MW)	(pu)	(Hz)	(pu)	(Hz)
20	2000	0.9842	49.2085	0.9931	49.6546
19	1990	0.9838	49.1908	0.9931	49.6538
18	1980	0.9834	49.1716	0.9931	49.6530
17	1970	0.9830	49.1506	0.9930	49.6522
16	1960	0.9825	49.1274	0.9930	49.6514
15	1950	0.9820	49.1019	0.9930	49.6506
14	1940	0.9815	49.0734	0.9930	49.6498
13	1930	0.9808	49.0415	0.9930	49.6490
12	1920	0.9801	49.0053	0.9930	49.6482
11	1910	0.9793	48.9640	0.9929	49.6474
10	1900	0.9783	48.9163	0.9929	49.6466
9	1890	0.9772	48.8600	0.9929	49.6458
8	1880	0.9759	48.7930	0.9929	49.6449
7	1870	0.9742	48.7111	0.9929	49.6441
6	1860	0.9722	48.6082	0.9929	49.6432
5	1850	0.9695	48.4735	0.9928	49.6424
4	1840	0.9658	48.2885	0.9928	49.6419
3	1830	-	-	-	-
2	1820	-	-	-	-
1	1810	-	-	-	-
0	1800	-	-	-	-





B.2.1

Coursework Only the inputs in green can be edited

B.2.1 Calculate the primary frequency response

	ΔPm and DΔω	
	(pu)	(MW)
G1	0.0800	80.0000
G2	0.1600	160.0000
Load1	-0.0200	-20.0000
Load2	-0.0400	-40.0000
TOTAL:	0.3000	300.0000

B.3.1

Coursework Only the inputs in green can be edited

B.3.1 Voltage control - Voltage magnitued and angles 0.95 lagging

Condenser	Bus 1		Bus 2		Bus 3	
(MVAr)	V (pu)	θ (degs)	V (pu)	θ (degs)	V (pu)	θ (degs)
-250	1.0000	0.0000	0.9369	-7.1135	0.9108	-6.9536
-200	1.0000	0.0000	0.9388	-7.1088	0.9215	-7.0030
-150	1.0000	0.0000	0.9407	-7.1046	0.9319	-7.0512
-100	1.0000	0.0000	0.9425	-7.1006	0.9421	-7.0983
-50	1.0000	0.0000	0.9442	-7.0970	0.9521	-7.1445
0	1.0000	0.0000	0.9460	-7.0936	0.9618	-7.1897
50	1.0000	0.0000	0.9477	-7.0905	0.9714	-7.2341
100	1.0000	0.0000	0.9493	-7.0877	0.9808	-7.2777
150	1.0000	0.0000	0.9509	-7.0851	0.9900	-7.3205
200	1.0000	0.0000	0.9525	-7.0827	0.9990	-7.3625
250	1.0000	0.0000	0.9541	-7.0806	1.0079	-7.4039

B.3.1 Voltage control - Flows across lines 0.95 lagging

Condenser	Line 1-2		Line 2-3	
(MVAr)	P (GW)	Q(GVAr)	P (GW)	Q(GVAr)
-250	4.0612	1.8760	0.0005	0.0667
-200	4.0602	1.8133	0.0002	0.0116
-150	4.0593	1.7522	0.0001	-0.0423
-100	4.0586	1.6924	0.0000	-0.0953
-50	4.0581	1.6340	0.0000	-0.1474
0	4.0576	1.5768	0.0002	-0.1985
50	4.0573	1.5208	0.0004	-0.2488
100	4.0570	1.4659	0.0007	-0.2983
150	4.0569	1.4121	0.0010	-0.3471
200	4.0569	1.3593	0.0014	-0.3952
250	4.0569	1.3074	0.0019	-0.4425