DEPARTMENT OF ELECTRONIC & ELECTRICAL ENGINEERING

University of Strathclyde Engineering

EE467/EE867/EE967
Power Flow Laboratory

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Laboratory Manual

1 Introduction

In this laboratory you will gain experience in using the load flow analysis tool in Matlab/Simulink, to assess practical issues related to steady state operation of a typical distribution network with renewable energy sources. You will investigate how increasing penetration levels of renewable power generation affects voltage, current and power flow in the network. You will also try to apply some mitigating measures with the aim to improve operational parameters, overcome potential limits and maximise the utilisation of renewable generation.

2 Performing Load flow calculations in Simulink

2.1 Test Network model

In this lab exercise, a simple 5-bus 11kV network (developed in Matlab/Simulink) will be utilised. The network is energised from a 33 kV source through a 33kV/11kV transformer.

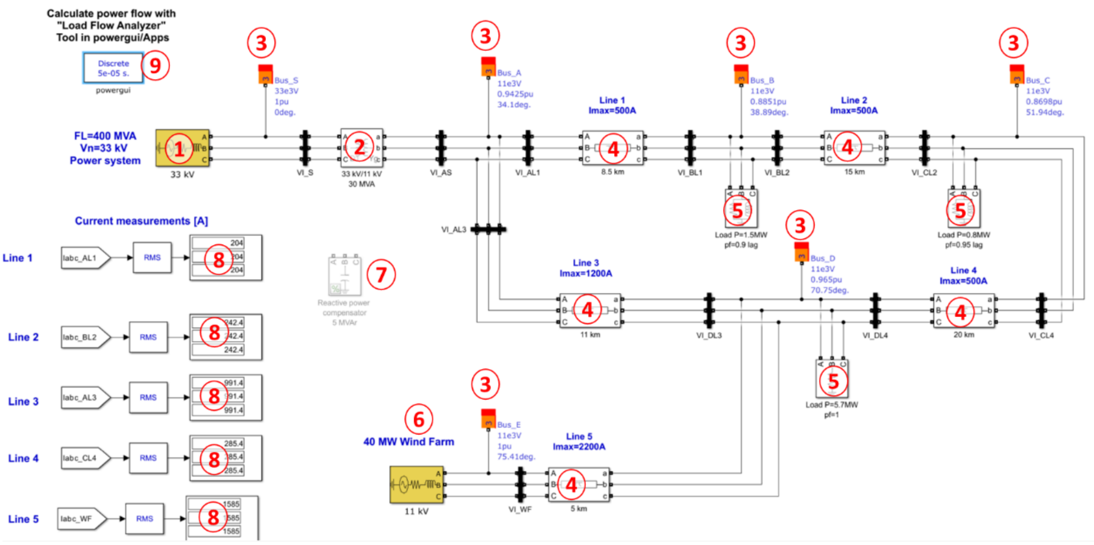


Figure 1. Test System in Matlab/Simulink

The key components of the test system (shown in Figure 1) include:

1. 33 kV supply network, modelled as a Three-Phase balanced voltage source with internal R-L impedance corresponding to the fault level of 400 MVA.
2. 30 MVA, 33 kV / 11 kV transformer supplying the 11 kV distribution network.
3. Load-flow busses which are used to set up target voltage for the PV and Swing (Slack) type busses, and to visualise the voltage phasors obtained from the load flow calculation.
4. 11 kV distribution lines modelled as three-phase lumped parameter Π sections.
5. Three-phase load blocks which consume specified amount of real and reactive power. Those blocks are configured as constant PQ components for the purposes of load flow analysis.

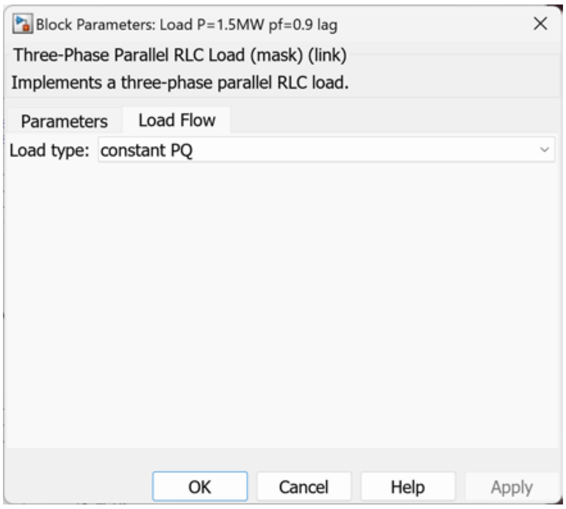


Figure 2. Load flow configuration of RLC type load

6. Three-phase AC voltage source which represents power output from the Wind Farm. This element is initially commented out to perform the calculations for the base case but should be enabled for latter studies. The wind farm is configured as a PV type node for load flow calculation purposes. Active power generation should be modified according to specific case study. Reactive power limits are fixed at ± 20 MVAr. It is assumed the windfarm is equipped with STATCOM device of 20 MVAr capacity.

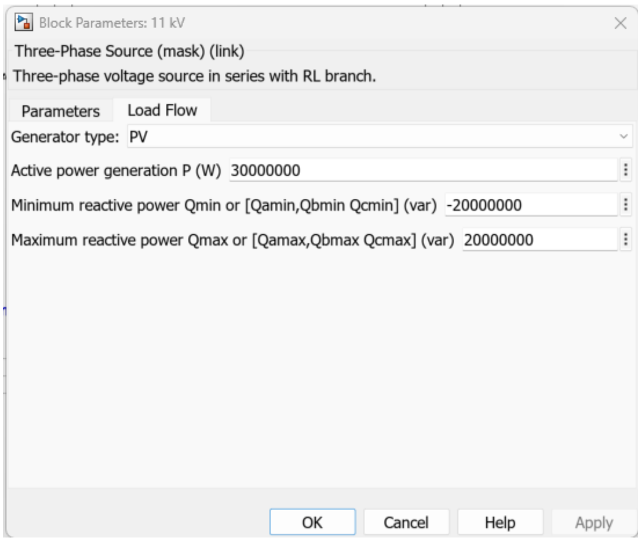


Figure 3. Load flow configuration of three-phase voltage source

7. Additional reactive power compensation device which can be configured and connected to any node, if deemed appropriate in specific cases.
8. Display blocks to visualise the RMS values of the currents flowing in the distribution lines.
9. Powergui block which is needed for configuring time-domain power system simulation parameters in Simulink (when using Simscape™ Electrical™ Specialized Power Systems Blocks), and to access a number of tools for steady-state analysis, including load flow.

2.2 Performing power flow calculation

A single power flow calculation in Simulink involves the following steps:

1. With Test System in Figure 1 open, double-click on "Powergui" component. In the Apps tab identify "Load Flow Analyzer"

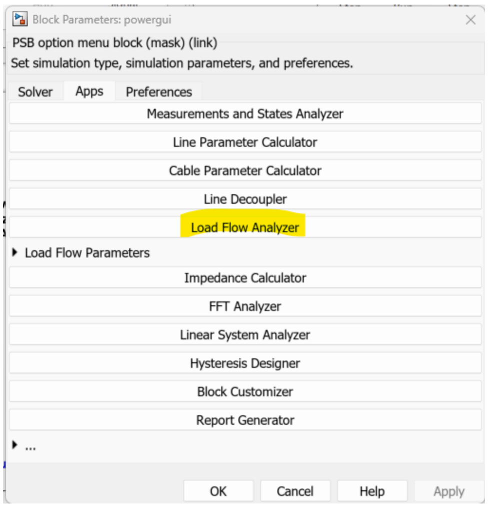
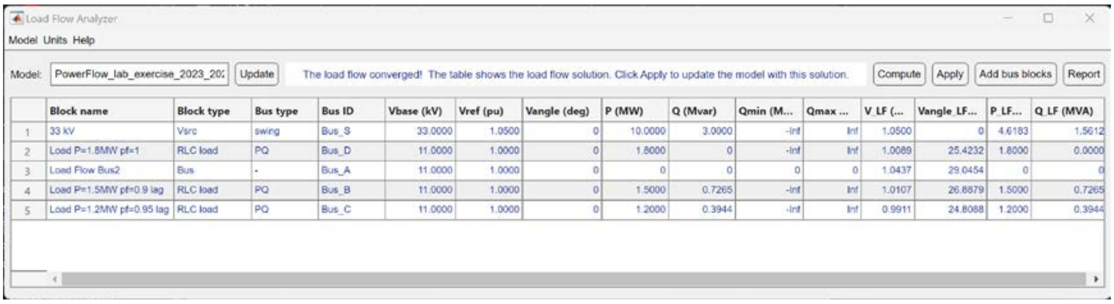


Figure 4. Available tools in Powergui block

2. In "Load Flow Analyzer" press *Compute* to start load flow iterations. If iterations converge, the result in terms of voltage amplitude and angle, as well as injected (or consumed) real and reactive power for each bus should appear in the four right hand side columns of the "Load Flow Analyzer" table. An example calculation is presented in Figure 5.



	Block name	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mvar)	Qmin (M...	Qmax ...	V_LF (...	Vangle_LF...	P_LF...	Q_LF (MVA)
1	33 kV	Vsrc	swing	Bus_S	33.0000	1.0500	0	10.0000	3.0000	-Inf	Inf	1.0500	0	4.6183	1.5612
2	Load P=1.8MW pf=1	RLC load	PQ	Bus_D	11.0000	1.0000	0	1.8000	0	-Inf	Inf	1.0089	25.4232	1.8000	0.0000
3	Load Flow Bus2	Bus	-	Bus_A	11.0000	1.0000	0	0	0	0	0	1.0437	29.0454	0	0
4	Load P=1.5MW pf=0.9 lag	RLC load	PQ	Bus_B	11.0000	1.0000	0	1.5000	0.7265	-Inf	Inf	1.0107	26.8879	1.5000	0.7265
5	Load P=1.2MW pf=0.95 lag	RLC load	PQ	Bus_C	11.0000	1.0000	0	1.2000	0.3944	-Inf	Inf	0.9911	24.8088	1.2000	0.3944

Figure 5. Example load flow solution

3. Press *Apply* to transfer the load flow result back to the network model. You should now see the correct voltages at each "Load Flow Bus" block on the network diagram.
4. The result can also be exported to Excel spreadsheet or Matlab report file using the *Report* button. This is particularly convenient when performing further analysis using the calculated voltages and power flows in the network (e.g., to assess power losses in the individual lines and/or transformers).
5. Further, to measure currents in the distribution lines (e.g., to compare the flowing current against the line thermal limit) a short simulation can be performed, and the RMS values of the measured currents should appear in the display boxes 8 (refer to Figure 1).

For further information refer to the Matlab help page for Load Flow Analyzer.

3 Programme of Power Flow studies

During the laboratory sessions you will perform a series of load flow calculations in order to analyse and mitigate specific challenges related to steady state operation of a small section of a distribution network with embedded wind generation.

When asked to assess if the network condition is permissible, consider the following three criteria:

1. **Voltage level:** The voltage amplitude must not deviate from the nominal value by more than $\pm 10\%$ at all busses.
2. **Line current:** The maximum thermal capacity (i.e., maximum current I_{max}) must not be exceeded for any of the lines in the network. The values of I_{max} for each line are shown on the network diagram in Figure 1.
3. **Transformer rating:** The apparent power flowing through the transformer must not exceed its rating.

3.1 Voltage levels, current flows, and losses in the passive distribution system (2 marks)

In this part you will perform a load flow calculation for a system without any additional/embedded generation (this is a base case you will use for initial assessment and comparison). The “45 MW Wind Farm” should be disabled (commented out). The solution should only include the existing loads (marked as 5 in Figure 1). Your report should include bus voltages, injected/consumed powers at each bus, the currents and real power losses in each line, the total real power losses in the grid and the apparent power flowing through the transformer. It is suggested to use Table 1 and Table 2 as a template for reporting your results.

Based on the result, comment whether the operation of the network in this condition is acceptable.

Table 1: Table for reporting on load flow solution

Bus Name	Bus Type [PQ, PV, Swing]	Voltage [pu]	Angle θ [deg]	P [MW]	Q [MVAr]
Bus_A					
Bus_B					
Bus_C					
Bus_D					
Bus_S					

Table 2: Table for reporting on current flows and losses

Line Name	Line capacity [A]	Line current [A]	Real power losses [kW]
Line 1			
Line 2			
Line 3			
Line 4			
Line 5			
		Total network losses:	

Note: There is more than one way of establishing the values of currents and power losses in the lines as those are not explicitly provided with the power flow solution. You utilise the detailed results from the Load Flow Analyzer report and/or by perform current measurements directly in the network diagram (blocks marked 8 in Figure 1) following a short time-domain simulation (e.g., 0.5s). Whichever way you perform your analysis, always explain your method, state your assumptions, and provide example calculations.

3.2 Assessment of the impact of wind generation on network operation (3 marks)

With the wind farm connected to "Bus_D" (elements 3, 4, and 6 enabled in the network model) establish experimentally the impact of varying power output from the "45 MW Wind Farm" on voltage levels, line currents and total real power losses.

To record your results, use the tables suggested below (Tables 3 and 4). You can also present the results graphically as this can be effective in illustrating certain trends not immediately obvious from the numerical values included in the tables.

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
20					
25					
30					
35					
40					
45					

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]	Network losses [kW]
	Line 1	Line 2	Line 3	Line 4	Line 5		
20							
25							
30							
35							
40							
45							

Using the results obtained in this part determine the operational limit (i.e., maximum output of the wind farm) which would be acceptable from the network steady state operation standpoint. Consider voltage level, current flows and transformer apparent power.

Comment on the total power losses in the network compared to the result obtained in 3.1.

3.3 Mitigating wind generation limits (3 marks)

In this section you are asked to investigate the impact of adding a reactive power compensating device in an attempt to reduce the wind farm curtailment (i.e., to increase the maximum permissible output) and thus to maximise the utilisation of this renewable energy resource.

1. By looking at the results from section 3.2 select the most suitable Bus to which the reactive power compensating capacitor (marked as 7 in Figure 1) should be connected.
2. With the device 7 connected, repeat the load flow analysis at increasing wind generation output from 20 MW to 45 MW, and record the results in tables (and graphs), similar to those in section 3.2.
3. Establish maximum permissible wind farm generation output and compare it to that obtained in 3.2. Comment on the outcome.

3.4 Assessment of the wind farm daily revenue (2 marks)

In this part, based on the findings from section 3.2 and 3.3 you are asked to make an assessment of the wind farm expected daily revenue from generating electrical power, potential revenue loss resulting from the network related constraints, and finally the benefits of reactive power compensation. In your calculation assume that the wind farm can sell electrical energy at £450/MWh. The available wind energy resource, i.e. the unconstrained wind generation daily profile, is presented in Figure 6.

1. Calculate how much revenue (in £) the windfarm owner could generate each day if there was no generation curtailment, and the whole available wind resource could be utilised.
2. How much would the owner lose weekly (compared to unconstrained generation) if the generation limit established in section 3.2 was imposed.
3. Using the outcome of section 3.3 calculate how much income loss can be recovered by connecting 5 MVAr reactive power compensating device in this network.
4. Comment what else could be done in practice (in addition to reactive compensation) to allow this wind farm to operate at its full capacity, i.e. to overcome all network related constraints.

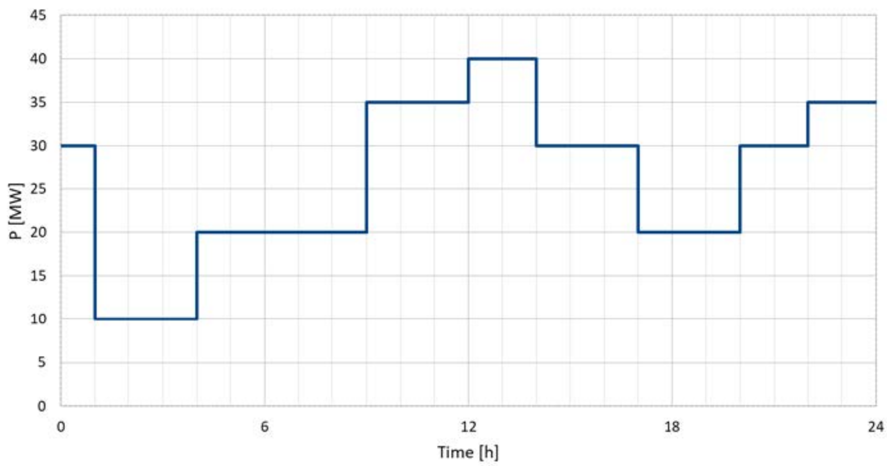


Figure 6. Unconstrained daily generation profile of the Wind Farm