



Center for Advanced Power Systems

FLORIDA STATE UNIVERSITY



Load Frequency Control Modeling and Simulation

A MATLAB/Simulink based Tool

March 2017

Version History

Personnel

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KS

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Introduction

This document provides the description of using the load frequency control (LFC) tool as developed within MATLAB/Simulink by CAPS/FSU. The provided MATLAB files and Simulink model are geared toward the use for a specific multi-area power system, but the data structure and model blocks can be easily extended and adapted to other systems and case studies of interest.

The following sections build on one of the example scripts provided, and show how to setup model data, execute a simulation, show plots of the simulation results, and post-process data to create tables of parameters and metrics.

The multi-area time domain model provided includes five areas with two instances of storage and wind power, one in Areas 3 and 5 each. Note: Simulink model name includes the MATLAB/Simulink version (2015b) as it may be required to convert models to other versions.

Simplified Australian Power System Model

First, a brief overview of the simulated power system model (see Figure 1 for the single-line diagram.) The model is based on information found in [1] and [2]. The power system represents a part of the south-eastern Australian power system at the transmission level. The model includes 14 aggregated power stations and reflects a 5-area system. For the LFC studies, each area is represented by a single generator with equivalent inertia and load-based damping. Area 1 has one generation unit, which is based on a hydro plant. Areas 2–5 have two types of generation units, which are based on steam-reheat and gas turbines. Tie power flows are considered and controlled, and all power quantities are scaled to area base power (i.e., sum of generation capacity online). The turbine-governor time constants, gains, and droop have been chosen to reflect typical values. The synchronization torque coefficients have been derived through simulation in another, more detailed environment, and are based on operating conditions for the medium-heavy case. Data are not tabulated here but can be found in the main system setup function, which returns the LFC-data structure to the workspace.

The Simulink model file for the Australian power system can be found in `'slx_lfc_AustralianFiveArea_2015b.slx'` and has been developed in MATLAB/Simulink 8.6.0 (R2015b).

The corresponding power system setup function is `'lfc_setup_AustralianFiveArea'`.

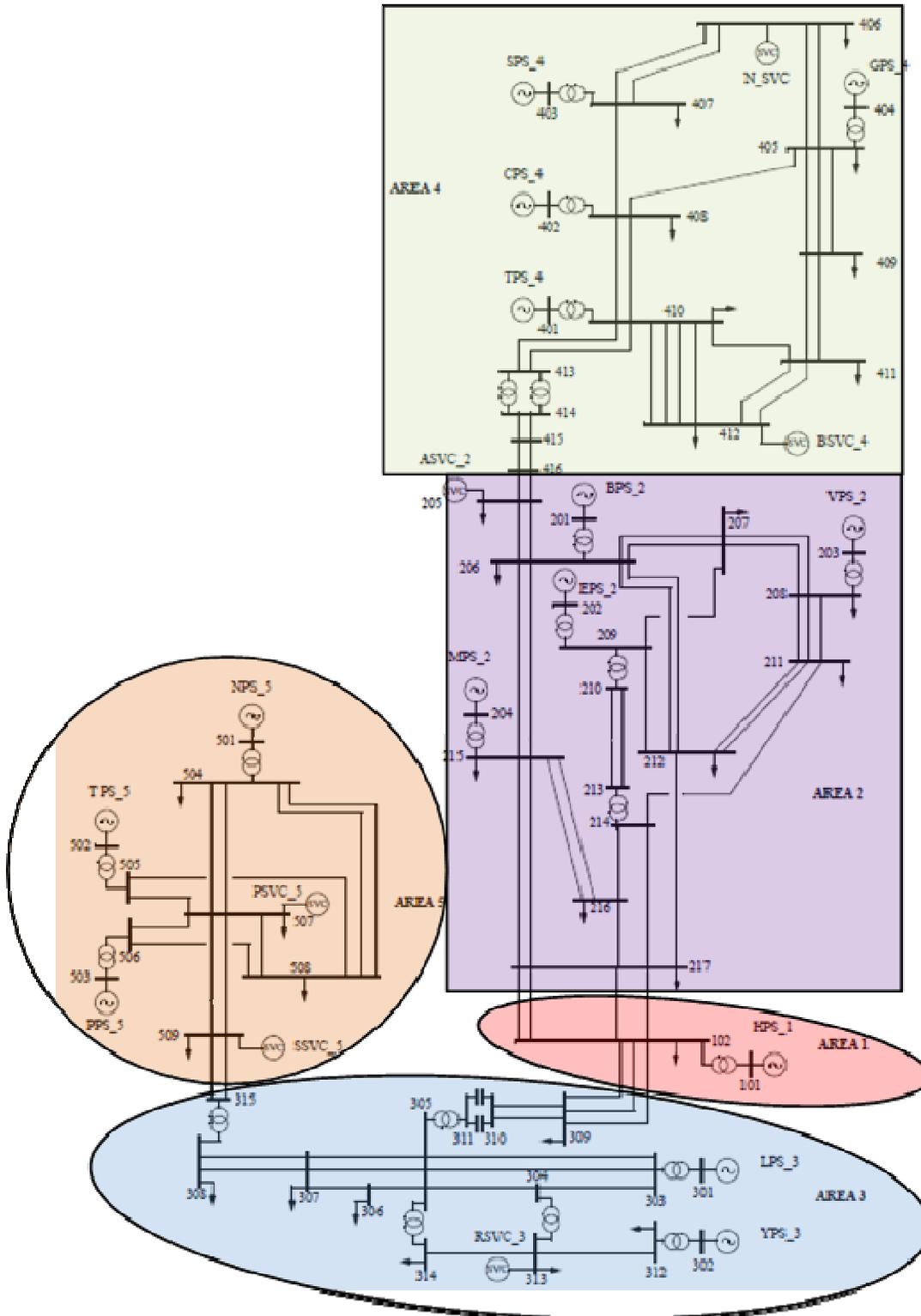


Figure 1 Single-line diagram of the simplified Australian power system (adapted from [2])

The Simulink model for the LFC studies is shown in Figure 2. As the model was used in studying possible storage sizing and response options to varying generation including wind power, subsystems for energy wind power and energy storage have been included. See Figure 3 and Figure 4 for the corresponding Simulink models. The area subsystem blocks encapsulate the inter-area dynamics as based on the generation types and load frequency controls. The area interaction is based on area angles and the synchronization torque coefficients. The corresponding signal linking is part of the “signal routing” subsystem.

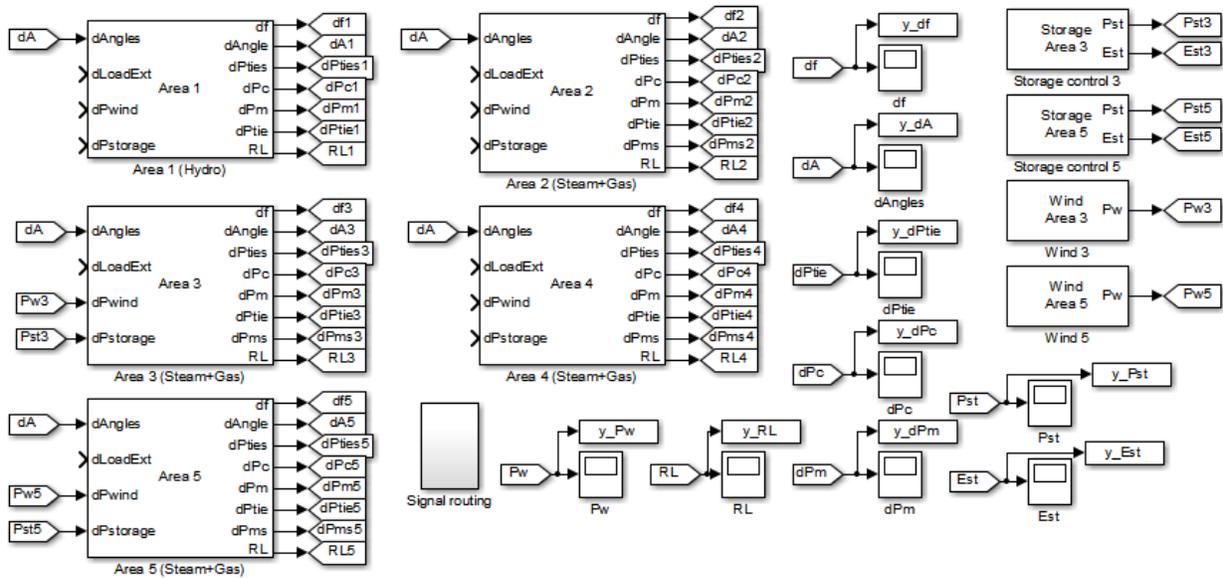


Figure 2 Simulink model of the 5-area system including storage and wind profile subsystems

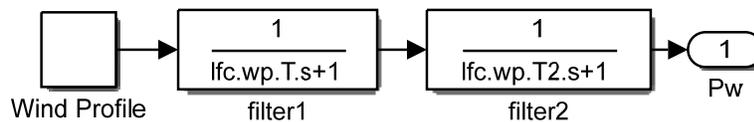


Figure 3 Simulink subsystem for wind generation based power profiles and filtering

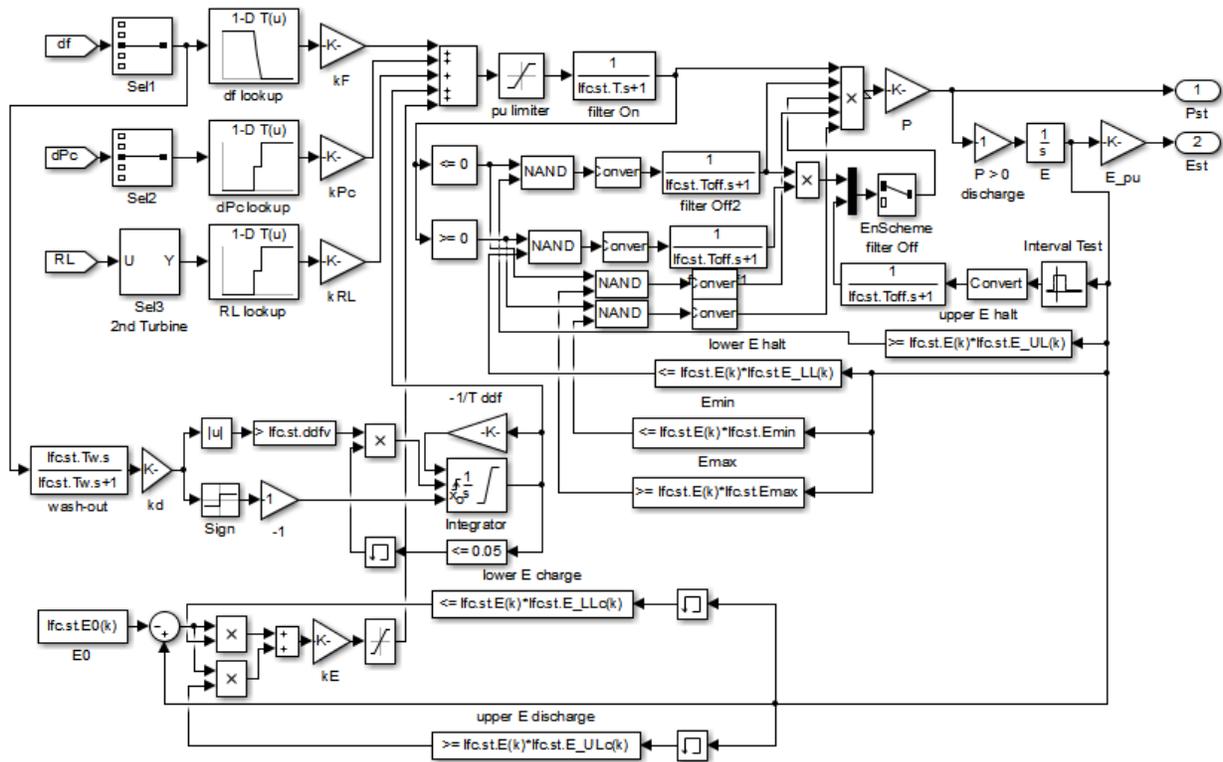


Figure 4 Simulink subsystem for energy storage and its controls

The energy storage subsystems provide a set of features that can be used and combined as needed. Features included are storage response triggers and controls as based on frequency deviations, area LFC-efforts, active turbine rate limits, and change in frequency. Additionally, controls for energy storage charge levels are provided for simulating options in energy limits and recharging.

One of the area subsystem models is depicted in Figure 5. It shows the two governor-turbines, tie-flows, and LFC setup. The area model was implemented with allowing to represent two types of generation. All corresponding blocks and transfer functions have been parameterized to support automated setups using MATLAB functions and scripts and the LFC data structure in the workspace.

The set of used and provided governors, turbines, reheater, and generation (i.e., rotating mass with load and damping) is depicted in Figure 6. These blocks show the underlying transfer functions and associated parameters. The blocks are combined to form individual generation types and areas. Note, blocks as shown are without the area based and generation type indexing for simplicity. An exception is the hydro governor as it requires more than one parameter (see the data setup function for additional documentation).

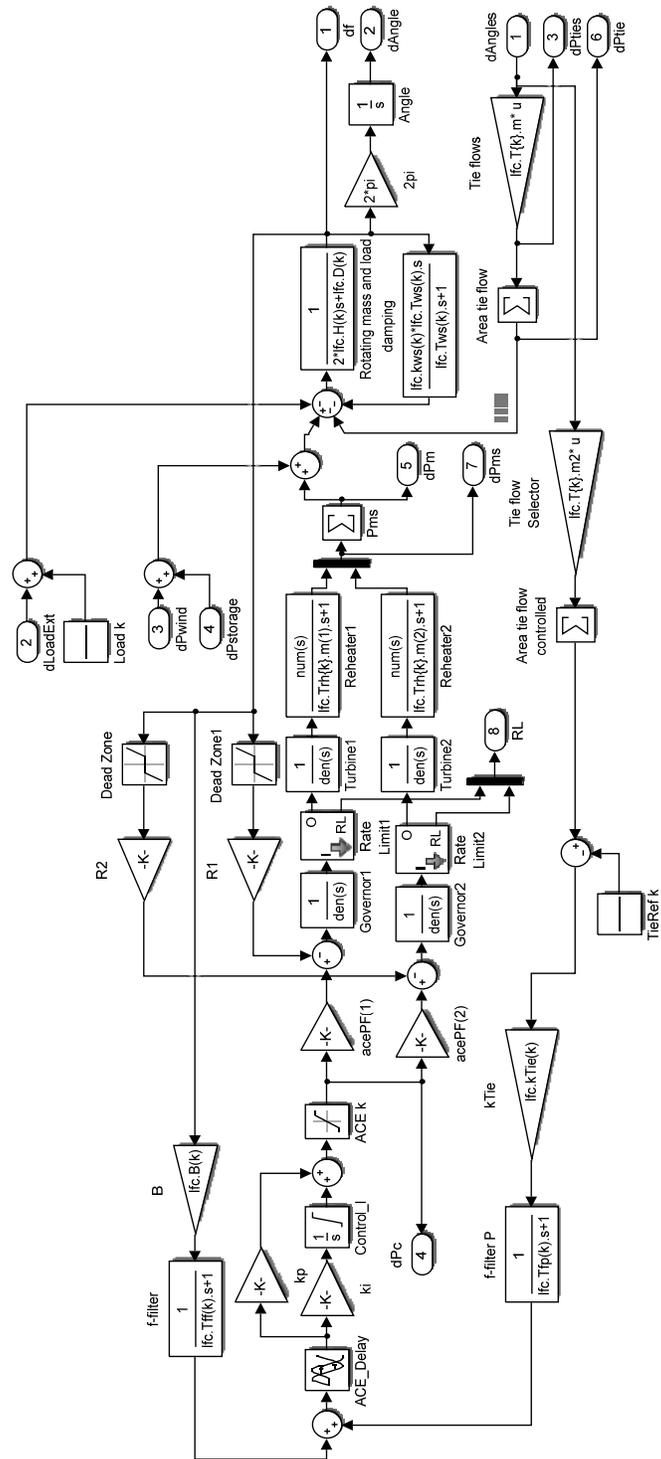


Figure 5 Simulink subsystem of an area with two types of generation

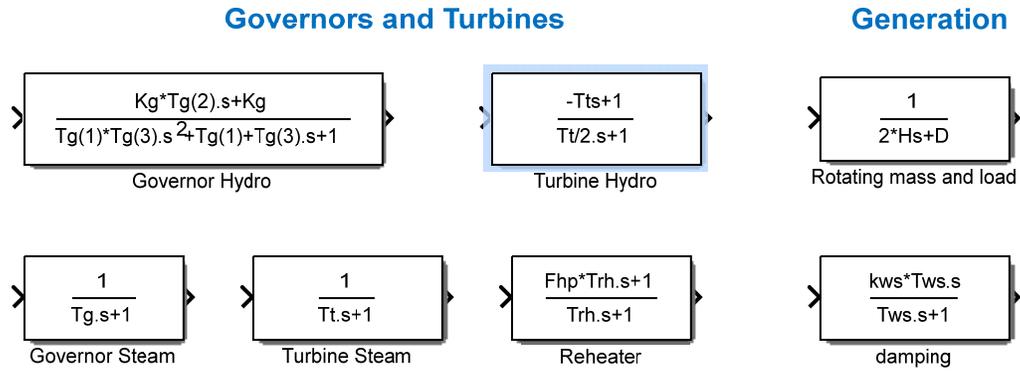


Figure 6 Transfer function blocks used to represent governors, turbines, rotating mass, and damping

The set of LFC Simulink subsystem blocks available through this tool is provided in a separate Simulink model file (slx_lfc_LibraryBlocks_2015b.slx), and its content is shown in Figure 7. All high-level subsystem blocks as shown have been masked and take two input arguments: the area number and LFC data structure name.

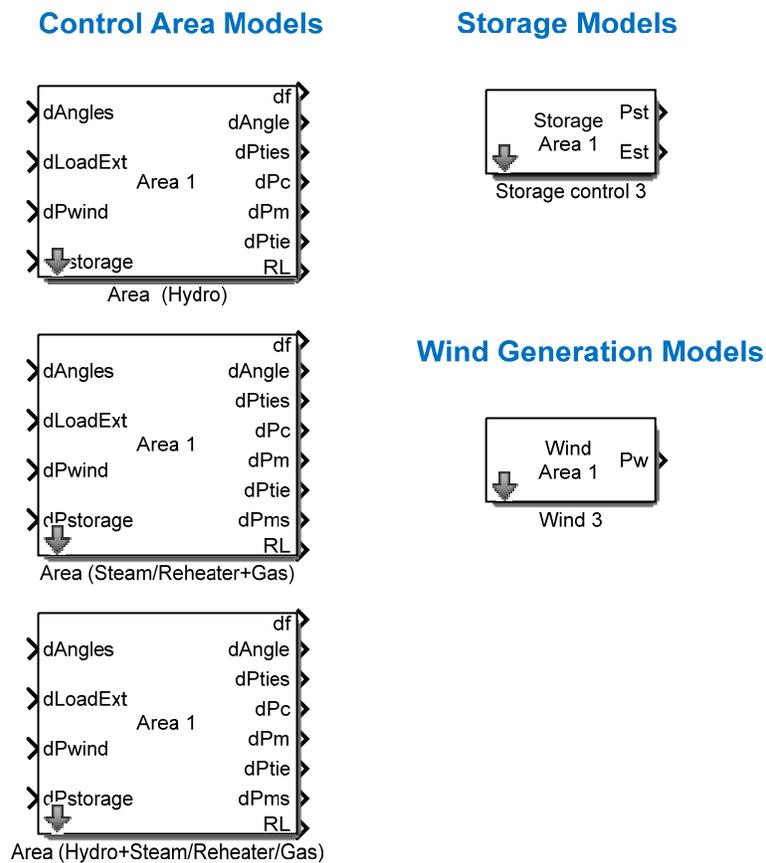


Figure 7 LFC Simulink subsystem block library

LFC Demo Examples

The following provides an overview of the three basic LFC examples provided.

Example 1: Load steps in areas

The first example applies load steps of various sizes in Areas 2–5, which all have active load frequency controls. The steps of 1%, 2%, 3% and 4% as based on area rating are implemented as 1 second ramps by default but can be changed by the user. The following code shows how studies can be setup and run using the provided data set and model. A few options are changed from the default settings here, namely the governor deadband is eliminated, and sampling is increased. Figure 8 shows the corresponding frequency response (i.e., deviation from the nominal 50 Hz) and turbine response (i.e., increase in power to match the area load changes).

```
s1xModelFile = 's1x_lfc_AustralianFiveArea_2015b';
lfc = lfc_setup_AustralianFiveArea('loadsteps',[0.00 0.01 0.02 0.03 0.04]);
lfc.gdb = 0; % set governor deadband to 0 (default is 15 mHz)
lfc.sim.Tss = 1/4; % set scope data sampling to 0.25 s (default is 1 s)
lfc.sim.Ts = 1/4; % set model workspace output sampling

open(s1xModelFile)
sim(s1xModelFile);
```

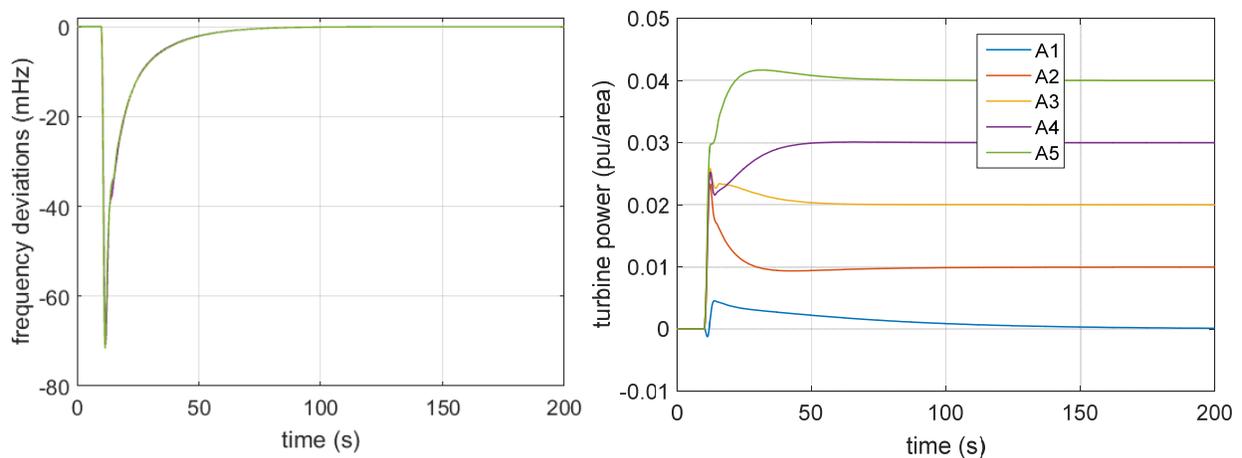


Figure 8 Example 1: Frequency and turbine responses in Areas 1–5 to step load increases

Example 2: Storage response in Area 3

The second example compares the frequency response to a step load (2% in Area 3) without and with energy storage. The storage is located in Area 3 and sized to 0.001 pu power and 0.01 pu-s energy as based on Area 3 rating. In this case, the load step triggers frequency oscillations as the 15 mHz governor deadband is active. The storage controls are set to respond to frequency deviations (the only available responds option used here) and limit oscillations to smaller magnitudes. The following provides the code to setup and run the two cases. In addition, code to collect simulation results, move it into the LFC-data structure and save the resulting data is provided with the example. Putting the model and simulation data into one unified data structure simplifies post-processing later. For example, computing response metrics for a larger set of simulated scenarios can be done and is provided with the tool (see below).

```
lfc = lfc_setup_AustralianFiveArea('loadsteps',[0 0 0.02 0 0]);
lfc.sim.Tss = 1/4; % set scope data sampling to 0.25 s (default is 1 s)
lfc.sim.Ts = 1/4; % set model workspace output sampling
% Storage setup
% Choices in power and energy
lfc.st.P = [0 0 0.001 0 0]; % power pu-Area rating
lfc.st.E = lfc.st.P .* 10; % energy rating (pu-s)
lfc.st.E0 = lfc.st.E * 0.5; % initial condition SOC of 50%
% Additionally required setup (can be left unchanged)
lfc.st.kEpu = 1./lfc.st.E; % gain for 'state-of-charge' per unit computation
idx = isinf(lfc.st.kEpu); % set gain to zero if no storage in area
lfc.st.kEpu(idx) = 0;

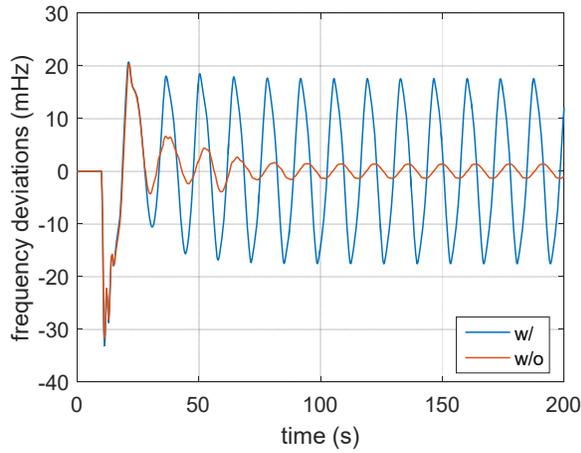
% Simulate w/o
% Results are saved in the following to allow post-processing later.
open(slxModelFile)
sim(slxModelFile);
% Collect simulation result data in structure and save
y1 = struct('y_df',y_df,'y_dPm',y_dPm,'y_dPtie',y_dPtie,'y_dPc',y_dPc,...
    'y_Pst',y_Pst,'y_Est',y_Est,'y_RL',y_RL);

lfc.y = y1;
flag = lfc_fct_saveDataFile('dir','Example2','file','NoStorage','type','mat','data',lfc);

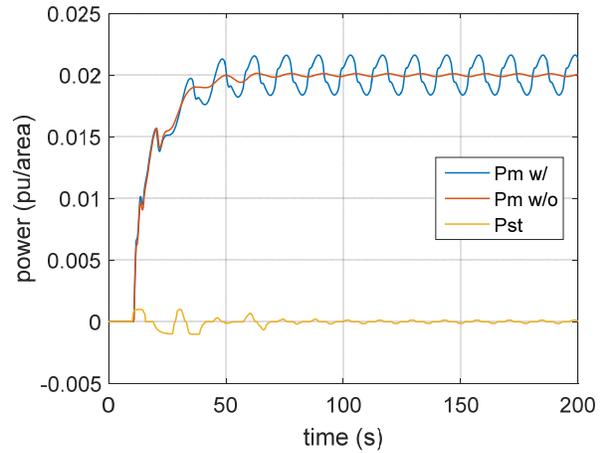
% Turn on storage (i.e., gain on frequency deviation)
lfc.st.kF = [0 0 20 0 0]; % enable/gain on frequency

sim(slxModelFile);

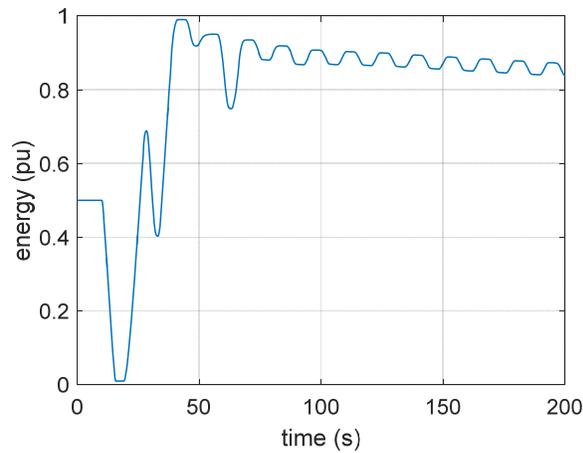
y2 = struct('y_df',y_df,'y_dPm',y_dPm,'y_dPtie',y_dPtie,'y_dPc',y_dPc,...
    'y_Pst',y_Pst,'y_Est',y_Est,'y_RL',y_RL);
lfc.y = y2;
flag = lfc_fct_saveDataFile('dir','Example2','file','WithStorage','type','mat','data',lfc);
```



(a) Frequency deviation



(b) Turbine (Pm) and storage (Pst) power response



(c) Storage energy level

Figure 9 Example 2: Response to a step load change without and with storage in Area 3

Figure 9 shows results concerning frequency deviations, turbine and storage power responses, and energy storage level. After the initial transient, which is beyond the storage capabilities, the storage limits oscillations to smaller magnitudes, and the load frequency controlling unit only needs to respond to the average demand.

Example 3: Using wind profiles and storage

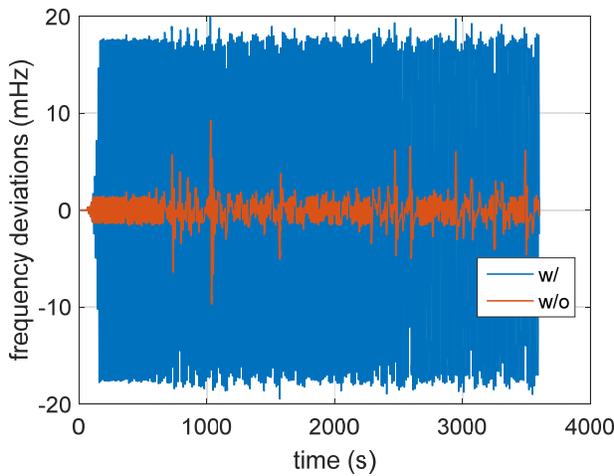
The third example simulates the load frequency response for varying wind generation as based on a profile (the provided profile and setup varies wind generation power in Areas 3 and 5). Again, two cases are run: without and with storage in Area 3. Part of the code is given below, and includes the call to adding the wind profile information to the LFC data structure. The profile is for one day but the simulation is shortened to one hour. Additionally, the function provided to compute power up- and down-ramping information is used to compute power and timing (i.e., duration) aspects for the storage in Area 3.

```
lfc = lfc_setup_AustralianFiveArea('loadsteps',[0 0 0 0 0]);
lfc.sim.Tss = 1/4; % set scope data sampling to 0.25 s (default is 1 s)
lfc.sim.Ts = 1/4; % set model workspace output sampling
% Storage setup
% Choices in power and energy
lfc.st.P = [0 0 0.001 0 0]; % power pu-Area rating
lfc.st.E = lfc.st.P .* 10; % energy rating (pu-s)
lfc.st.E0 = lfc.st.E * 0.5; % initial condition SOC of 50%
% Additionally required setup (can be left unchanged)
lfc.st.kEpu = 1./lfc.st.E; % gain for 'state-of-charge' per unit computation
idx = isinf(lfc.st.kEpu); % set gain to zero if no storage in area
lfc.st.kEpu(idx) = 0;
% Wind profile (one day, minute-by-minute)
lfc = lfc_setup_AustralianFiveArea_windProfileDay(lfc);
% Shorten simulation time to the first hour for the demo here
lfc.sim.Tend = 60*60; % simulation stop time (s)

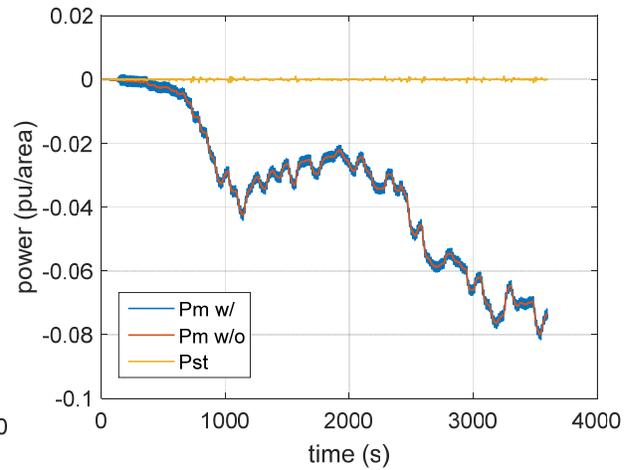
% Simulate w/o
open(slxModelFile)
sim(slxModelFile);
% Collect simulation result data in structure
y3 = struct('y_df',y_df,'y_dPm',y_dPm,'y_dPtie',y_dPtie,'y_dPc',y_dPc,...
    'y_Pst',y_Pst,'y_Est',y_Est,'y_RL',y_RL);
lfc.y = y3;
flag = lfc_fct_saveDataFile('dir','Example3','file','NoStorage','type','mat','data',lfc);

% Turn on storage (i.e., gain on frequency deviation) and simulate again
lfc.st.kF = [0 0 20 0 0]; % enable/gain on frequency
sim(slxModelFile);
y4 = struct('y_df',y_df,'y_dPm',y_dPm,'y_dPtie',y_dPtie,'y_dPc',y_dPc,...
    'y_Pst',y_Pst,'y_Est',y_Est,'y_Pw',y_Pw,'y_RL',y_RL);
lfc.y = y4;
flag = lfc_fct_saveDataFile('dir','Example3','file','WithStorage','type','mat','data',lfc);

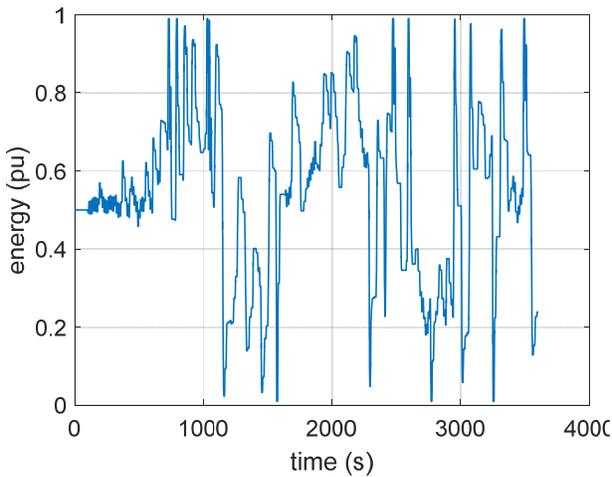
% Compute storage power ramping information (scaled w.r.t. storage power)
[y4.PstRamps,y4.PstDiffs,y4.PstTdiffs] = lfc_fct_getPowerRamps(y_Pst.Data(:,3)/lfc.st.P(3));
```



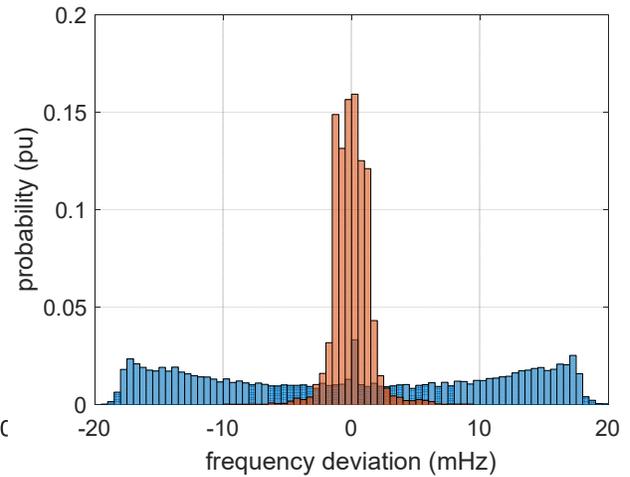
(a) Frequency deviations



(b) Turbine (Pm) and storage (Pst) power response



(c) Storage energy level



(d) Frequency deviation histogram

Figure 10 Example 3: Response to varying wind generation without and with storage in Area 3

Figure 10 shows results concerning frequency deviations, turbine and storage power responses, energy storage level, and probability of frequency deviations (histogram with 1 mHz bins). Looking at the mechanical power (Pm) once storage is available, it reflects the wind power with opposite sign. Also, the LFC study begins initialized at the “no deviations” state. The energy storage level is controlled to stay within absolute bounds (1% and 99%), and limited efforts go toward keeping within 30-70%.

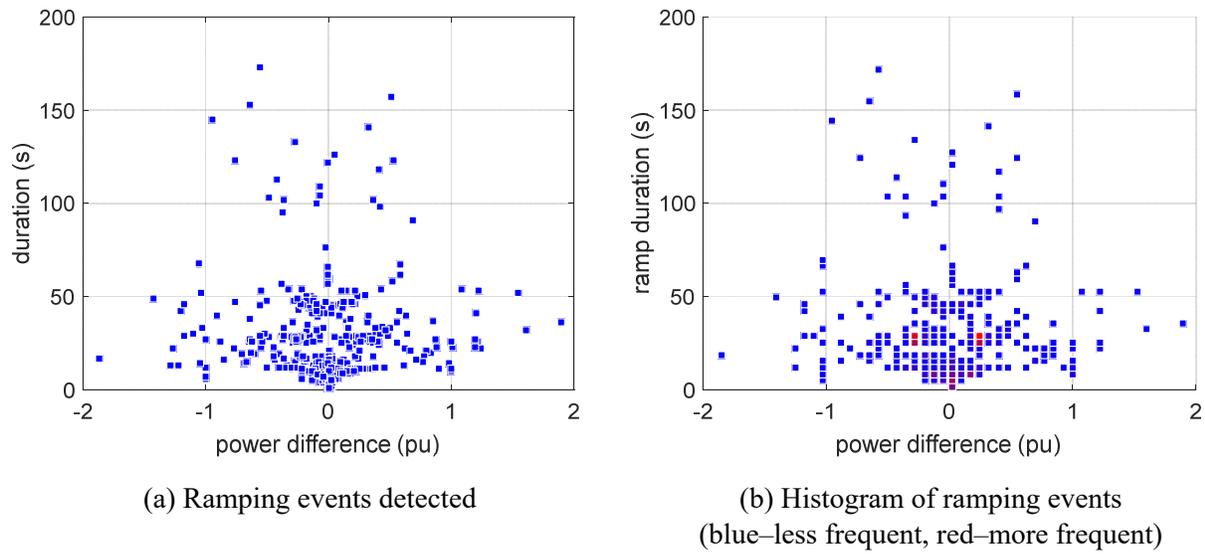


Figure 11 Example 3: Characteristics of storage power ramps:
power differences between extrema and ramping duration

Figure 11 shows the computing storage power ramping information. In the figure on the left, every power ramp and duration data point is shown. In the figure on the right, probability information is included as a third information item: the color information designates the likelihood of ramps occurring (i.e., blue—lower, red—higher). As an example, picking one of the data point shown close to 2 pu and 40 s: the wind variations caused the storage to change from absorbing to providing power, almost moving through the full capability range in the 40 seconds.

Simulating Larger Case Studies

The three examples described above show how to use the tool in basic LFC problems. To facilitate larger case studies that evaluate many combinations of parameter settings and conditions, dedicated simulation functions are included. Two example scripts are provided in using the simulation functions to study sets of scenarios (`script_lfc_AustralianFiveArea_StorageStudy_Steps.m` and `script_lfc_AustralianFiveArea_StorageStudy_WindProfiles.m`), and the following summarizes the functional relationships and calling sequence.

Larger case studies require the following process and fundamental steps:

1. Develop the corresponding **Simulink model**.
2. Implement function to set model (default) parameters using the **LFC data structure**.
3. Implementation of a helper function to be used in setting **scenario parameters**.
4. Implementation of a helper function to be used in post-processing of results while evaluating data and computing **response metrics**.
5. Implement case study script

- a. Define **“global” parameters** that are required for the study including the Simulink model name, result data folder, scenario helper function, choice of executing as a single process or in parallel.
- b. Determine the **scenario parameter matrix** that provides the data to be used in individual simulation runs; examples: storage ratings and size, control parameters, etc.
- c. Call main **simulation** function (lfc_fct_RunSimulations) that facilitates simulation setups (single or parallel processing and distribution of parameter sets). The main function incorporates calls to a provided simulation helper function (lfc_fct_RunSimulation) that loops over either the full or part of the scenarios and saves corresponding simulation results.
- d. Call to main **evaluation** function that processes simulation results with the help of the user defined helper evaluation function.

The described process of developing a case study is depicted in Figure 12. As a result, case scenario data and metrics tables are created. Examples of computing metrics are given below.

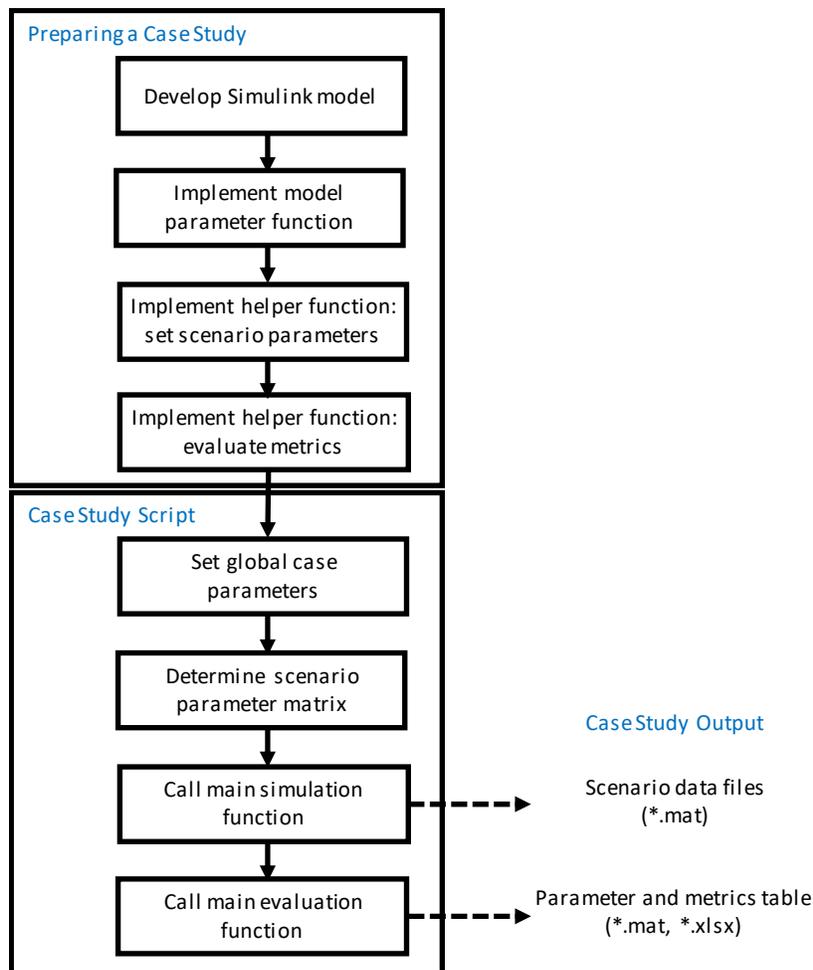


Figure 12 LFC development and application process

Computing Metrics

To allow more comprehensive studies, additional functions are needed to post-process simulation results with respect to salient response characteristics. An evaluation function is provided, which calls a user-provided case-specific helper function, to compute data for parameter and metrics tables. The main and helper functions automate handling of larger case studies by reading saved simulation data and creating a data table. The table is stored as MATLAB data file and Excel spreadsheet. The following shows the main function call and part of the results as computed for the two case studies, Examples 2 and 3, above.

```
% for Example 2: compute metrics for the step disturbance
lfc_fct_Evaluation('dir','Example2','fct',@lfc_fct_Evaluation_Steps,'header',1);

% for Example 3: compute metrics for the wind profile based disturbance
lfc_fct_Evaluation('dir','Example3','fct',@lfc_fct_Evaluation_Profile,'header',1);
```

Table 1 Example 2: Parameters and metrics computed

Load step		Storage size				Frequency dev. (mHz)				Ramp limit active		Storage power		Stor. max. ramp		Stor. rise time		Min.stor. level	
A3	A5	A3	A5	A3	A5	A3	A3	A3	A5	A3	A5	A3	A5	A3	A5	A3	A5	A3	A5
(pu)	(pu)	(pu)	(pu)	(s)	(s)	min	max	p-p	p-p	(s)	(s)	(%)	(%)	pu/s	pu/s	(s)	(s)	(%)	(%)
0.02	0	0	0	0	0	-33	21	35	35	1.25	1.25	0	0	0	0	0	0	0	0
0.02	0	0.001	0	10	0	-32	20	3	3	1.25	1	100	0	2.370	0	0.75	0	1	0

Table 2 Example 3: Parameters and metrics computed

Storage		Frequ.set	Frequ.deviations (mHz)				Frequ. 3xSD		Max. dACE/dt		Stor. change SD		Stor. change max.		Est.storage	
A3	A5	point	A3	A5	A3	A5	A3	A5	A3	A5	A3	A5	A3	A5	A3	A5
pu	pu	(mHz)	min	max	min	max	mHz	mHz	pu/min	pu/min	pu/min	pu/min	pu/min	pu/min	s	s
0	0	50	-19	20	-19	20	35	35	0.22	0.33	0	0	0	0	0	0
0.001	0	50	-10	9	-10	9	4	4	0.09	0.19	5.64	0	132.87	0	20	0

Notes: The tables are included here to provide examples of possible metrics and features supported in analyzing simulation results. The column entries are specific to the examples provided, and corresponding computations should be adapted in the user provided evaluation helper function to fit a study’s needs.

- A3 and A5 designate Area 3 and 5, respectively.
- Ramp limits active represents the time turbines were at the limits.
- Maximum storage ramp is based on instantaneous values (as sampled).
- Storage rise time is the time from event start until 90% of the deployed storage power is reached.
- SD means standard deviation.
- Estimated storage in seconds is based on the maximum energy difference experienced, maximum power deployed, and a multiplying factor of 2: $T = E_{max} / P_{max} * 2$.

Remarks

This document describes a tool developed for load frequency control studies. The tool includes several functions to run simulations and process results, a set of Simulink blocks to model LFC problems, and several setup and example files for the five area Australian power system model. Three basic examples illustrate setting up studies, simulating scenarios, and post-processing data. Two additional, larger case studies for step power changes and wind profiles are provided but not further described herein. Nevertheless, these two examples are meant to demonstrate the use of the tool in the context of larger case studies.

The LFC tool is easily extendable and provides the means to study other power system models and case scenarios. The tool has been structured to limit required user adaptations to the Simulink mode, corresponding model data structure, and two helper functions (i.e., one for setting scenario parameters and one for evaluating response metrics). Any custom modifications and extensions by users are welcome.

References

The following two references provide the core transmission system information as used in the five-area example studies.

- [1] L. Lima, "Report on the 14-generator system (Australian Reduced Model)," IEEE PES Task Force on Benchmark Systems for Stability Controls, 2013.
- [2] M. Gibbard and D. Vowles, "Simplified 14-Generator Model of the SE Australian Power System," The University of Adelaide, Adelaide, South Australia, 2010.

Appendix

As an overview to the tool, the following provides the function prototypes, help information, and the scripts for the two larger case studies.

lfc_readme

```

%% lfc_readme.m
%
% This set of MATLAB/Simulink files provides a basis for simulating load
% frequency control problems. The Simulink model provides the time domain
% subsystems for turbine-governors, generators, inter-area flows, and area
% control error (ACE) controls. As provided, the m-files include everything
% required to study LFC-based problems of the simplified Australian transmission
% system model (see [1] and [2] for documentation). The only additional data
% required are the choices in turbine-governors (and their respective
% parameters settings, see below) and synchronization torque coefficients
% (these have been derived from simulation results within another, more
% detailed simulation environment, also below).
%
% The setup as provided here is for up to two types of turbine-governors per area.
% Both the Simulink model(s) and the MATLAB data structure can be extended to
% accommodate additional features.
%
% Getting started:
%
% Run the provided example MATLAB-scripts to see how studies are set up, simulated,
% and post-processed to compute metrics of interest. Three simple cases are
% given in 'script_lfc_AustralianFiveArea_Examples.' The examples call the
% various helper function to setup studies, run the simulation, and compute
% and save metrics. Several plots are created to provide examples for use
% in other studies.
%
% The core and linking component is the MATLAB data structure named 'lfc'.
% All simulation parameters as stored within lfc. The Simulink
% model uses parameters stored in this structure. Also, the simulation
% results are moved as fields into the structure (within lfc.y) for ease of
% collecting model and simulation data.
%
% Note: The lfc-folder may be added to MATLAB's path to simplify use in
% custom cases within other folders. As provide, the examples do not
% require this step and can be simply run from within the folder.
%
% List of files:
%
% lfc_data_WindProfile_Day.mat      ... data file with wind profiles for Area 3 and 5
%                                  (note: the two profiles have been aggregated
%                                  from several individual profiles
%                                  for units in the respective
%                                  areas.)
% lfc_fct_Evaluation.m             ... main function for evaluating simulation results
% lfc_fct_Evaluation_Profile.m     ... evaluation helper function,
%                                  specific to the wind profile studies
% lfc_fct_Evaluation_Steps.m       ... evaluation helper function,
%                                  specific to the power step studies
% lfc_fct_RunSimulation.m          ... simulates a set of scenarios
% lfc_fct_RunSimulations.m         ... sets up simulation of scenarios
%                                  (single process or parallel)
% lfc_fct_SetParameters_StepStudy_... helper function, sets
%                                  scenario parameters in the power step study

```

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```
% lfc_fct_SetParameters_WindProfileStudy.m ... helper function, sets
%                                     scenario parameters in the wind profile study
% lfc_fct_getPowerRamps.m             ... function to compute up- and down-ramp characteristics
% lfc_fct_saveDataFile.m             ... function to save simulation
%                                     results (structures and tables, *.mat and *.xlsx)
%
% lfc_readme.m                       ... this file
%
% lfc_setup_AustralianFiveArea.m     ... core data file in the studies included here:
%                                     derived from the simplified 5-area 14-generator system
% lfc_setup_AustralianFiveArea_WindProfileDay.m ... function to add wind
%                                     profile data to the lfc-structure, data is specific to
%                                     the 5-area case as provided here
%
% script_lfc_AustralianFiveArea_Examples.m ... example script: using the LFC
tool
% script_lfc_AustralianFiveArea_StorageStudy_Steps.m ... larger case study: generation
loss and storage
% script_lfc_AustralianFiveArea_StorageStudy_WindProfiles.m ... larger case study: wind profiles
and storage
%
% slx_lfc_AustralianFiveArea_2015b.slx ... the Simulink model used in all
%                                     time domain simulations, requires model data to be
%                                     available in a workspace data structure named 'lfc'
%                                     (can be changed in the respective block mask
%                                     setting); mask also requires to specify the area number.
%
% slx_lfc_LibraryBlocks_2015b.slx ... LFC tool Simulink subsystem block library
%
% Referenes:
%
% [1] M. Gibbard and D. Vowles, "Simplified 14-Generator Model of the SE Australian
%     Power System," The University of Adelaide, Adelaide, South Australia, 2010.
%
% [2] L. Lima, "Report on the 14-generator system (Australian Reduced Model),"
%     IEEE PES Task Force on Benchmark Systems for Stability Controls, 2013.
%
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```

lfc_setup_AustralianFiveArea()

```

%% function lfc = lfc_setup_AustralianFiveArea()
% Load frequency control (LFC) setup for the Australian system.
% Parameters are derived from the Australian power system model,
% medium-heavy loading conditions. Each of the five LFC-areas has its own
% base power.
%
% Setups as used here are for up to two types of generation per area. Can be
% extended by adding data to the structure defined here and modifying the
% Simulink model accordingly.
%
% Allows to set load and tie line reference step changes (pu/area steps),
% default is zero. Wind and storage structure/parameters are defined here but
% set to zero (i.e., no wind power profile or storage used).
%
% Input options (and defaults):
%     'LoadSteps',[0 0 0 0 0] ... pu/area-load steps in areas 1-5
%     'LoadStepTime',10      ... load step time (s)
%     'loadramptime',1      ... load ramp time (s)
%     'TieSteps',[0 0 0 0 0] ... pu/area-load steps in areas 1-5
%     'TieStepTime',[10]    ... tie reference step time (s)
%     'tieramptime',1       ... tie ramp time (s)
%
% Output: lfc ... LFC data structure
%
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```

lfc_setup_AustralianFiveArea_WindProfileDay()

```

%% function lfc = lfc_setup_AustralianFiveArea_WindProfileDay([lfc])
% One-day wind profile data for load frequency control (LFC) setup of
% the Australian system. Profiles are for Areas 3 and 5, expecting
% vectors WP_LFC_3 and WP_LFC_5 of wind power in MW with one data point
% every minute to be provided in the *.mat-data file.
%
% Input: lfc ... LFC data structure
%     [WindDataFileName] ... optional, data file name; default:
%     'LFC_WindProfile_Day.mat'
%
% Output: lfc. ... LFC data structure
%     .scen.PowerSeries{k}.v ... Area k wind power (pu)
%     .scen.TimeWind ... time vector (s)
%     .w.T and .w.T2 ... filter time constants (s)
%     .sim.Tend ... simulation end time (s)
%
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```

lfc_fct_saveDataFile()

```
%% function flag =  
lfc_fct_saveDataFile('dir',DirName,'file',FileName,'type',FileType,'new',newFlag,'data',data)  
% Save data file: supports *.mat and *.xlsx as generated in the LFC  
% studies.  
%  
% Input:  
% 'dir',DirName ... directory name (will be created if necessary)  
% 'file',FileName ... data file name  
% 'type',FileType ... file type: 'mat' (default) or 'xls' or 'xlsx'  
% 'new',newFlag ... new (overwrite, write header) or replace data only (for *.xls)  
% 'data',data ... data variable to be saved (e.g., LFC-structure)  
% 'range',xlsRange .. spreadsheet data range  
%  
% Output: flag ... success flag (0/1)  
%  
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%  
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```

lfc_fct_getPowerRamps()

```
% function [Pramps,[Pdiffs,Tdiffs]] = lfc_fct_getPowerRamps()  
%  
% Finds power ramps, power differences, and corresponding time intervals.  
% Assumes fixed sampling time and time difference is based on data point  
% indices.  
%  
% input: x ... power profile  
%  
% output: Pramps ... power ramps (change/time between extrema)  
% [Pdiffs] ... optional, P-difference between extrema  
% [Tdiffs] ... optional, time-difference between extrema  
%  
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%  
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```

lfc_fct_RunSimulation()

```

%% function lfc_fct_RunSimulation(lfc)
% Function to run one set of simulation scenarios. Received model setup, information
% on scenario specific data, and executes one run. Saves data for post-processing.
%
% Inputs:
%   lfc                ... LFC data structure
%   'slx',slxModelFile ... Simulink model to be run
%   'dir',slxDataFolder ... folder for simulation data (saving
%                       LFC-structure including time domain traces in lfc.y)
%   'fct',@SetParameters ... function to call to set scenario specific
%                       parameters
%   'ScenIdx',ScenIdx   ... Index into lfc.scen.SimSet of scenario(s) to run
%
% Outputs:
%
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```

lfc_fct_RunSimulations()

```

%% function lfc_fct_RunSimulations(lfc)
% Function to run one set of simulation scenarios either in a single process
% or in parallel. The function uses model information (i.e., lfc-data structure)
% and options to setup simulation runs by calling helper functions.
%
% Inputs and options:
%   lfc                ... LFC data structure
%   'slx',slxModelFile ... Simulink model to be run
%   'dir',slxDataFolder ... folder for simulation data (saving
%                       LFC-structure including time domain traces in lfc.y)
%   'fct',@SetParameters ... function to call to set scenario specific
%                       parameters
%   'ParSim',ParSim     ... 0/1, parallel execution = 1, default: 0
%   'worker','Worker'   ... String to use in worker' Simulink model
%                       names, default: 'Worker'
%
% Outputs:
%
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```

lfc_fct_SetParameters_StepStudy()

```
%% function lfc = lfc_fct_SetParameters_StepStudy (lfc)
% Function to setup wind profile based studies of the Australian
% 5-area system. Sets parameters for one of the scenarios.
%
% Inputs and options:
%     lfc           ... LFC data structure with simulation results
%     'ScenIdx',ScenIdx ... index in cases to run (row of lfc.scen.SimSet)
%
% Outputs:
%     lfc ... updated data structure
%
% Note: This file can be used as a prototype for other case studies.
%
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```

lfc_fct_SetParameters_WindProfileStudy()

```
%% function lfc = lfc_fct_SetParameters_WindProfileStudy(lfc)
% Function to setup wind profile based studies of the Australian
% 5-area system. Sets parameters for one of the scenarios.
%
% Inputs and options:
%     lfc           ... LFC data structure with simulation results
%     'ScenIdx',ScenIdx ... index in cases to run (row of lfc.scen.SimSet)
%
% Outputs:
%     lfc ... updated data structure
%
% Note: This file can be used as a prototype for other case studies.
%
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```

lfc_fct_Evaluations()

```
%% function lfc_fct_Evaluations(options)
% Function to evaluate all simulation results with respect to a set of metrics
% as of interest in studies of step changes in generation and load.
% All found data files (*.mat) within the specified folder are processed: expecting the
% LFC data structure with simulation results in lfc.y.
% A table of parameters and metrics is created and saved in *.mat and
% spreadsheet (*.xlsx) formats.
%
% Inputs:
%     'dir',DirName           ... directory name (to be scanned for data)
%     'dirTable',DirNameTable ... directory name for resulting metrics
%                             table files (default: data folder)
%     'table',TableName     ... name used for metrics table files
%                             (default: 'MetricsTable')
%     'new',flag            ... new (write variable names as table
%                             heading) or only numeric data
%     'fct',fctHandle       ... function handle to function used in evaluating metrics
%     'header',0/1         ... option to write custom spreadsheet
%                             header with three rows, default: 0
%
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```

lfc_fct_Evaluation_Steps()

```
%% function MT = lfc_fct_Evaluation_Steps(lfc)
% Function to evaluate metrics in step change based studies of the Australian
% 5-area system, and specifically, response quantities for selected disturbances
% and storage solutions in Areas 3 and 5.
%
% Inputs:
%     lfc ... LFC data structure with simulation results
% Options:
%     'header',0/1 ... return table header instead of metrics table,
%                     default: 0
% Outputs:
%     MT ... metrics table (one row) or custom table header for
%           *.xls (default: metrics table)
%
% Note: This file can be used as a prototype for other case studies.
%
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```

lfc_fct_Evaluation_Profile()

```
%% function MT = lfc_fct_Evaluation_Profile(lfc)
% Function to evaluate metrics in power profile based studies of the Australian
% 5-area system, and specifically, response quantities for selected disturbances
% and storage solutions in Areas 3 and 5.
%
% Inputs:
%   lfc ... LFC data structure with simulation results
% Options:
%   'header',0/1 ... return table header instead of metrics table,
%                   default: 0
% Outputs:
%   MT ... metrics table (one row) or custom table header for
%         *.xlsx (default: metrics table)
%
% Note: This file can be used as a prototype for other case studies.
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%
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```

Large scale study script: Loss of generation and storage

```

%% script: script_lfc_AustralianFiveArea_StorageStudy_Steps.m
% This script runs a simulation study to analyze options of using
% storage to mitigate impact of loss of generation on load frequency control.
% The storage is used to counteract the rapid frequency decline and help support
% frequency recovery.
%
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%% Parameters
% Base multi-area time domain model provided includes five areas with
% two instances of storage and wind power, one in Areas 3 and 5 each.
% note: Simulink model name includes the MATLAB/Simulink version (2015b) as
% it may be required to convert models to other versions.
slxModelFile = 'slx_lfc_AustralianFiveArea_2015b'; % Simulink model
slxDataFolder = 'Storage_Steps'; % result folder
fct_SetParameters = @lfc_fct_SetParameters_StepStudy; % helper function to set specific scenario
parameters
ParSim = 1; % using parfor (toolbox)
slxWorkerName = 'WorkerStep'; % name string to use in workers' copy of Simulink model

%% Profile study: Using a wind profile and several storage setups
% Simulate part of the provided wind profile w/o and with storage responding
% to frequency deviations.
lfc = lfc_setup_AustralianFiveArea('loadsteps',[0 0 0 0 0]);
lfc.sim.Ts = 0.25; % set model workspace output sampling

%% Custom setup: Prepare storage and control combinations to be studied
% Simulating the following energy ratings in areas(s) (one at a time)
lfc.scen.EstSets = ...
    [0 0 20 0 20;
     0 0 40 0 40;
     0 0 60 0 60;
     0 0 80 0 60;
     0 0 90 0 70];
slxDataFolderBase = slxDataFolder;
for runs = 1:size(lfc.scen.EstSets,1)
    % Probing for combinations of
    lfc.scen.PstSet = [0:0.02:0.1]; % power ratings in Areas 3 and 5 (pu)
    lfc.scen.LoadSet = [0 0.10]; % load steps (pu)
    lfc.scen.EstSet = lfc.scen.EstSets(runs,:); % note: only this size,
    % i.e., not combinations thereof
    slxDataFolder = [slxDataFolderBase '_' num2str(max(lfc.scen.LoadSet)*100,'%0f') ...
        'p_' num2str(lfc.scen.EstSet(3),'%0f') 's_' num2str(lfc.scen.EstSet(5),'%0f') 's'];

    % Compute simulation set based on columns for [Pstep-A3 Pstep-A5 Pst-A3 Pst-A5]
    % note: helper function for this example case builds on this data
    % matrix to set parameters in individual simulation runs
    %

```

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```
% Scenario permutation list
nPset = length(lfc.scen.PstSet);
nLSet = length(lfc.scen.LoadSet);
lfc.scen.SimSet = zeros(nPset^2*nLSet^2,4);
idx = 0;
for ii = lfc.scen.LoadSet
    for jj = lfc.scen.LoadSet
        for kk = lfc.scen.PstSet
            for ll = lfc.scen.PstSet
                idx = idx + 1;
                lfc.scen.SimSet(idx,:) = [ii jj kk ll];
            end
        end
    end
end
% Eliminate duplicate 'no load step' entries
idx = flip(find(lfc.scen.SimSet(:,1)==0 & lfc.scen.SimSet(:,2)==0))';
for ii = idx
    lfc.scen.SimSet = lfc.scen.SimSet([1:ii-1,ii+1:end],:);
end
lfc.scen.Scenarios = 1:size(lfc.scen.SimSet,1);
% Restrict storage sizing to same power ratings
idx = flip(find(lfc.scen.SimSet(:,3)~=lfc.scen.SimSet(:,4) & ...
    lfc.scen.SimSet(:,3)~=0 & lfc.scen.SimSet(:,4)~=0))';
for ii = idx
    lfc.scen.SimSet = lfc.scen.SimSet([1:ii-1,ii+1:end],:);
end
lfc.scen.Scenarios = 1:size(lfc.scen.SimSet,1);

%% Simulate all scenarios
lfc_fct_RunSimulations(lfc,'ParSim',ParSim,'Worker',slxWorkerName,'slx',slxModelFile,...
    'dir',slxDataFolder,'fct',fct_SetParameters);

%% Post-processing: creating tables of parameters and metrics
lfc_fct_Evaluation('dir',slxDataFolder,'fct',@lfc_fct_Evaluation_Steps,'header',1);

end
```

Large scale study script: Wind profiles and storage

```
%% script: script_lfc_AustralianFiveArea_StorageStudy_WindProfiles.m
% This script runs a simulation study to analyze options of sizing
% storage to mitigate the impact of changing wind power on load frequency control.
% More specifically, the storage is used to counteract frequency disturbances
% as caused by wind generation and reduce the need for conventional generation units
% to respond.
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%
% CAPS/FSU (March 2017)
```

CAPS/FSU Load Frequency Control Tool

```
%% Parameters
% Base multi-area time domain model provided includes five areas with
% two instances of storage and wind power, one in Areas 3 and 5 each.
% note: Simulink model name includes the MATLAB/Simulink version (2015b) as
% it may be required to convert models to other versions.
slxModelFile = 'slx_LFC_AustralianFiveArea_2015b';           % Simulink model
slxDataFolder = 'Storage_WindProfiles';                     % result folder
fct_SetParameters = @lfc_fct_SetParameters_WindProfileStudy; % helper function to set specific
scenario parameters
ParSim = 1;                                                % using parfor (toolbox)
slxWorkerName = 'WorkerProfile'; % name string to use in workers' copy of Simulink model

%% Profile study: Using a wind profile and several storage setups
% Simulate part of the provided wind profile w/o and with storage responding
% to frequency deviations.
lfc = lfc_setup_AustralianFiveArea('loadsteps',[0 0 0 0 0]);
lfc.sim.Tss = 1; % set scope data sampling (default is 1 s)
lfc.sim.Ts = 1; % set model workspace output sampling
% Wind profile (one day, minute-by-minute)
lfc = lfc_setup_AustralianFiveArea_WindProfileDay(lfc);

%% Custom setup: Prepare storage and control combinations to be studied
% Probing for combinations of
lfc.scen.PstSet = [0 0.01 0.025 0.05]; % these power ratings in Areas 3 and 5 (pu)
lfc.scen.fstSet = [5 10 15 20]*1e-3; % and these frequency corner points (Hz)

%% Compute simulation set based on columns for [Pst-Area3 Pst-Area5 f-setpoint]
% Scenario permutation list
nPset = length(lfc.scen.PstSet);
nfSet = length(lfc.scen.fstSet);
lfc.scen.SimSet = zeros(nPset^2*nfSet,3);
idx = 0;
for ii = lfc.scen.fstSet
    for jj = lfc.scen.PstSet
        for kk = lfc.scen.PstSet
            idx = idx + 1;
            lfc.scen.SimSet(idx,:) = [jj kk ii];
        end
    end
end
end
% Eliminate duplicate 'no storage' entries
idx = flip(find(lfc.scen.SimSet(:,1)==0 & lfc.scen.SimSet(:,2)==0));
for ii = idx
    lfc.scen.SimSet = lfc.scen.SimSet([1:ii-1,ii+1:end],:);
end
lfc.scen.Scenarios = 1:size(lfc.scen.SimSet,1);

%% Simulate all scenarios
lfc_fct_RunSimulations(lfc,'ParSim',ParSim,'Worker',slxWorkerName,'slx',slxModelFile,...
    'dir',slxDataFolder,'fct',fct_SetParameters);

%% Post-processing: creating tables of parameters and metrics
lfc_fct_Evaluation('dir',slxDataFolder,'fct',@lfc_fct_Evaluation_Profile,'header',1);
```