DISTRIBUTED ELECTRICAL SYSTEMS LABORATORY

Prevention of Large-scale Blackouts in Modern Power Systems

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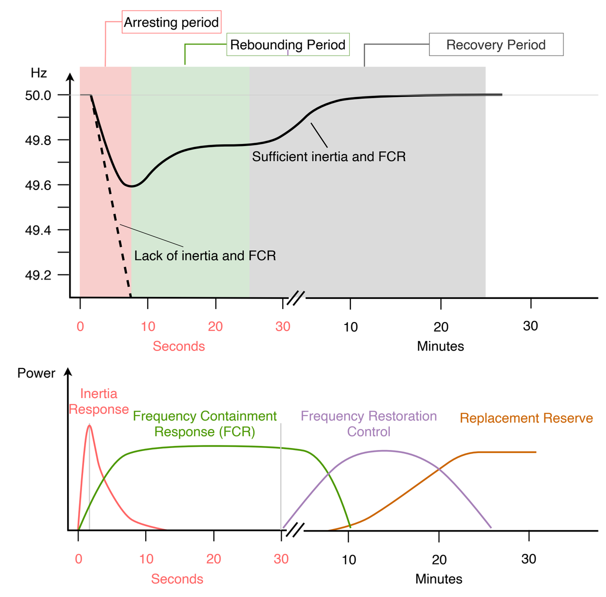
Context

Frequency Stability



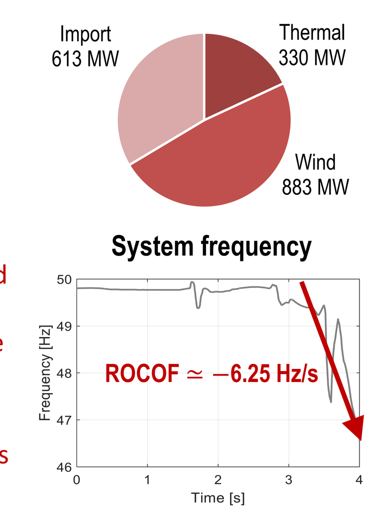
Blackout Event of September 28, 2016, Australia[1]

Tornadoes in South Australia (SA) tripped multiple 275 kV transmission circuits, and resulted in multiple faults in quick succession.

The voltage dips due to the faults triggered protection on several wind farms to runback about 456 MW of wind generation.

The reduction in wind farm output was compensated by an increase in power imported from Victoria. However, the import reached a level that tripped the interconnector on loss of synchronism protection.

Frequency falling so fast that load shedding schemes were unable to stop the fall, resulting in a blackout.

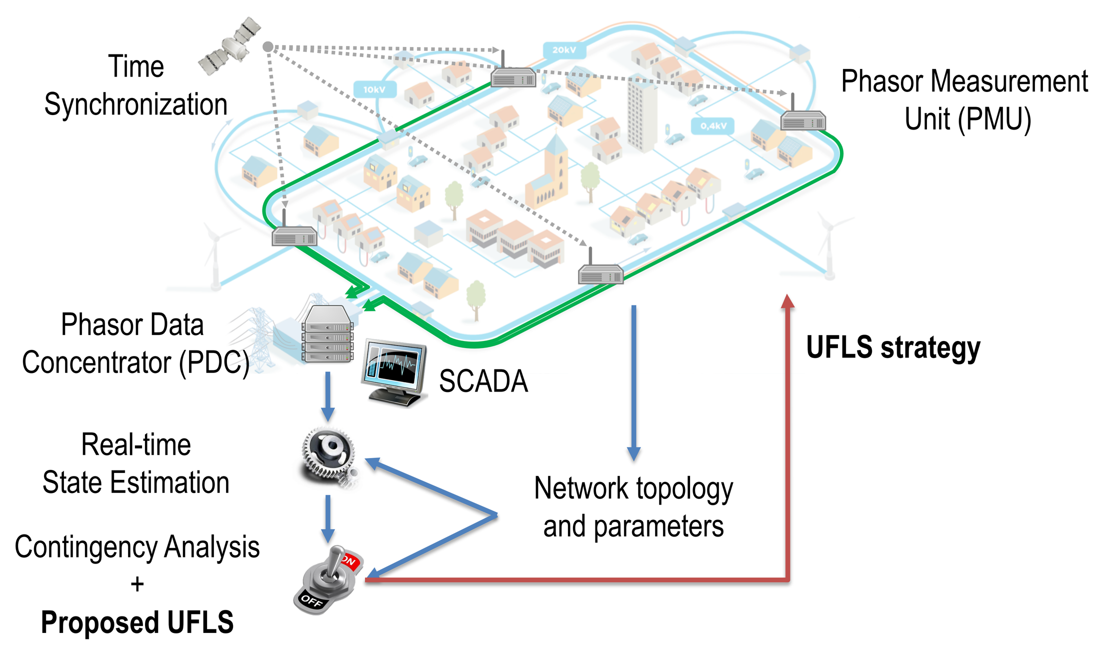


Aims and Contributions

- Apply the Optimal Power Flow (OPF)-driven Under-frequency Load Shedding (UFLS) scheme in low-inertia power grids with high shares of renewable resources.
- Minimize the amount of load shedding while ensuring a safe trajectory of the system frequency and preventing nodal voltages and branch currents from violating their feasible limits.
- Compare the proposed UFLS scheme with the one recommended by the European Network of Transmission System Operators (ENTSO-E).

OPF-driven UFLS Method

Enhance performance of emergency operational practice in TSOs' control room



Objective: Minimize the amount of load shedding $\sum_l^L \Delta P_{l,LS}$

Grid constraints

- **Frequency**

$$\begin{cases} f_{min}^{t\in[t_1,t_2]} \le f(t) \le f_{max}^{t\in[t_1,t_2]}, & \forall t \in [t_1,t_2] \\ f_{min}^{t\to\infty} \le f(t) \le f_{max}^{t\to\infty}, t \to \infty \end{cases}$$

- **Nodal voltage** $V_{i,min} \le V_i \le V_{i,max}$
- **Branch current** $I_{ij} \le I_{ij,max}$

- Dynamic OPF: frequency is tracked in time-domain.

Generators

$$\Delta P_g = \begin{cases} -\Delta f/R_g & if -\Delta f/R_g \le \Delta P_{g,max} \\ \Delta P_{g,max} & if -\Delta f/R_g > \Delta P_{g,max} \end{cases}$$

$$\Delta Q_g = \begin{cases} \beta \Delta P_g & if\ V_g > (Q_g - \beta P_g)/Q_{P=0} \\ \frac{Q_{g,n}}{P_{g,n}} \Delta P_g & if\ V_g \le (Q_g - \beta P_g)/Q_{P=0} \end{cases}$$

Loads

$$P_l = (P_{l,n} + \Delta P_{l,LS}) \left(\frac{V_l}{V_n}\right)^{k_{pv}} \left(1 + k_{pf}(f_l - f_n)\right)$$

$$Q_l = (Q_{l,n} + \Delta Q_{l,LS}) \left(\frac{V_l}{V_n}\right)^{k_{qv}} \left(1 + k_{qf}(f_l - f_n)\right)$$

$$\Rightarrow \quad \Delta P_l = \Delta P_{l,LS} + \frac{k_{pv} P_{l,n}}{V_n} \Delta V_l + P_{l,n} k_{pf} \Delta f$$

$$\Delta Q_l = \Delta Q_{l,LS} + \frac{k_{qv} Q_{l,n}}{V_n} \Delta V_l + Q_{l,n} k_{qf} \Delta f$$

Dynamic system frequency response

- **Equivalent single-machine swing equation**

$$\frac{d\Delta f(t)}{dt} = \frac{f_n}{2H}\left(\Delta P_{PFR}(t) - P_{LoG} + \sum_{l=1}^{L} \Delta P_{l,LS} - (D_s + D_{BESS})\Delta f(t)\right)$$

Calibration $D_s = D_{s,0} + \alpha \frac{\sum \Delta P_{l,LS}}{P_{LOG}}$

- **Frequency regulation of synchronous generators**

$$k_1 \frac{d^2 \Delta P_{PFR}(t)}{dt} + k_2 \frac{d\Delta P_{PFR}(t)}{dt} + k_3 \Delta P_{PFR} = -\frac{1}{R_{eq}}\left(k_4 \frac{d^2 \Delta P_{PFR}(t)}{dt} + k_5 \frac{d\Delta P_{PFR}(t)}{dt} - \Delta f(t)\right)$$

- **Frequency regulation of Battery Energy Storage System (BESS)**

$$\Delta P_{BESS} = k_{BESS} \Delta f \ \rightarrow D_{BESS} = k_{BESS}/S_b$$

Nodal voltages and branch currents

Obtained using **sensitivity coefficients**[2] computed as a function of the system state and the system admittance matrix.

$$\mathbb{1}_{\{i=k\}} = \frac{\partial \underline{V}_i}{\partial P_k} \sum_{j=1}^{N} \overline{Y}_{ij} \overline{V}_j + \underline{V}_i \sum_{j=1}^{N} \overline{Y}_{ij} \frac{\partial \overline{V}_j}{\partial P_k} \qquad \frac{\partial |\overline{V}_i|}{\partial P_k} = \frac{1}{|\overline{V}_i|} \mathrm{Re}\left\{\underline{V}_i \frac{\partial \overline{V}_i}{\partial P_k}\right\}$$

$$-\mathbb{1}_{\{i=k\}} = \frac{\partial \underline{V}_i}{\partial Q_k} \sum_{j=1}^{N} \overline{Y}_{ij} \overline{V}_j + \underline{V}_i \sum_{j=1}^{N} \overline{Y}_{ij} \frac{\partial \overline{V}_j}{\partial Q_k} \qquad \frac{\partial |\overline{V}_i|}{\partial Q_k} = \frac{1}{|\overline{V}_i|} \mathrm{Re}\left\{\underline{V}_i \frac{\partial \overline{V}_i}{\partial Q_k}\right\}$$

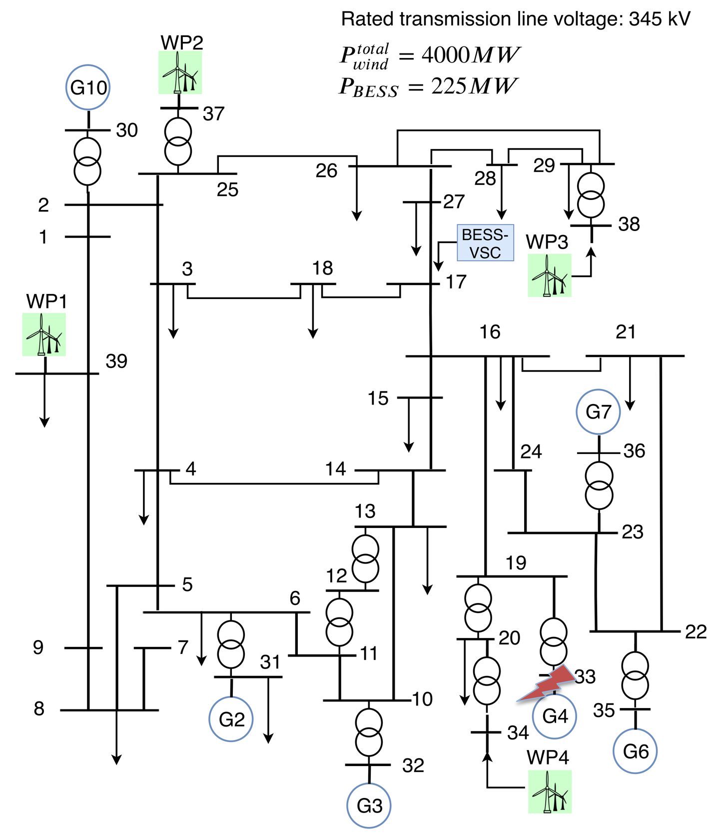
$$\Rightarrow \quad |\Delta \overline{V}_i| \cong \frac{\partial |\overline{V}_i|}{\partial P_k} \Delta P_k + \frac{\partial |\overline{V}_i|}{\partial Q_k} \Delta Q_k$$

$$|\Delta \overline{I}_{ij}| \cong \frac{\partial |\overline{I}_{ij}|}{\partial P_k} \Delta P_k + \frac{\partial |\overline{I}_{ij}|}{\partial Q_k} \Delta Q_k$$

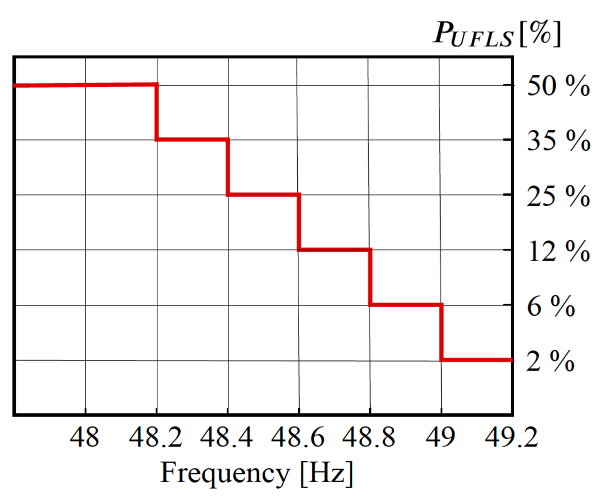
Performance Assessment

IEEE 39-bus low-inertia power grid time-domain full-replica dynamic model

- **4 type-III wind power plants** replace 4 synchronous generators in IEEE 39-bus benchmark power system[2].
- A 225 MW/175 MWh **BESS**
- **A simulated PMU for each bus**
- **Time-domain dynamic models are open sourced:** https://github.com/DESL-EPFL/
- Execute on Opal-RT eMEGAsim **Real Time Simulator**



Compare with the UFLS scheme recommended by ENTSOE[3] (standard UFLS)



Contingency: tripping of G4

- 485 MW generation power tripped
- Causes several nodal voltage and branch currents limits be violated if no UFLS is applied.

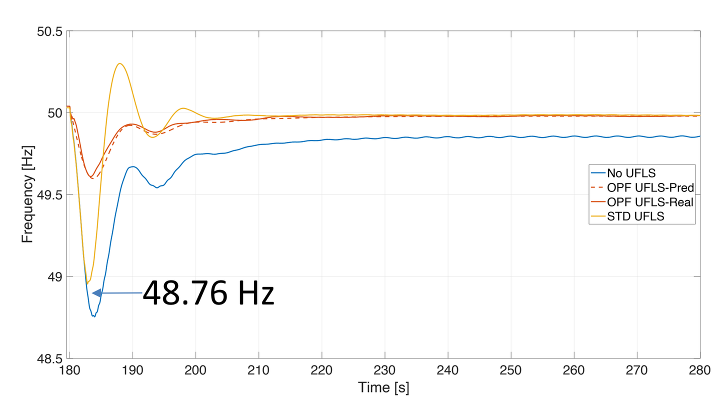
Metric: Expected Energy Not Served (EENS)

$$EENS = \sum_{t=t_0}^{t_s} \sum_{l=1}^{L} \Delta P_{l,LS} \Delta t$$

- t_0 is the time when the contingency happened
- t_s is equal to t_0+100 s
- L is the total number of load buses.

Results

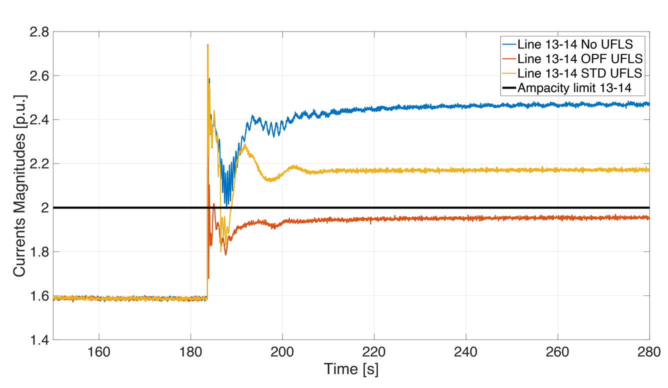
System Frequency



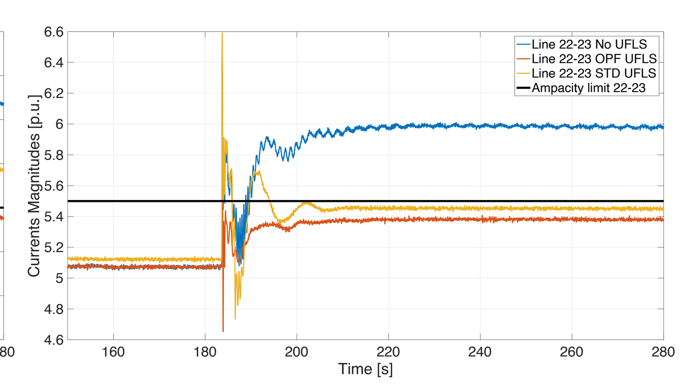
Frequency Nadir

- **48.95 Hz** for Standard UFLS (+200mHz)
- **49.61 Hz** for OPF-UFLS (+800mHz)

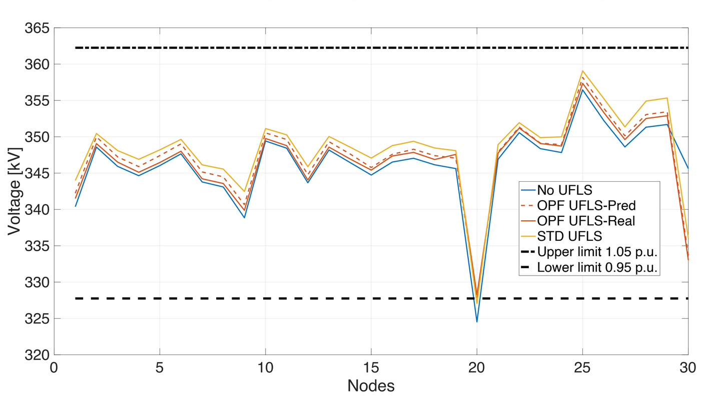
Line 13-14



Line 22-23



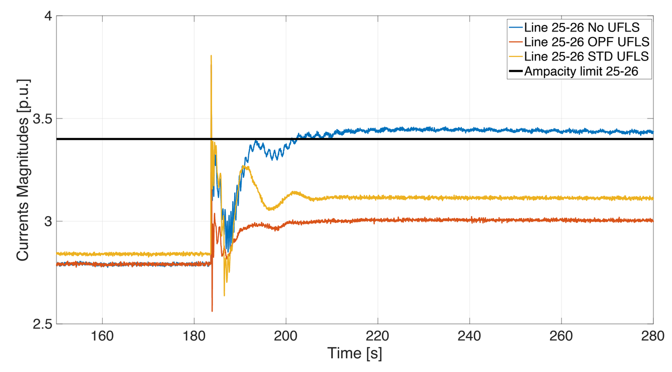
Post-contingency Nodal Voltages



Nodal voltage constraints

- Standard UFLS: **violated**
- Proposed UFLS: **respected**

Line 25-26



Line ampacity constraints

- Standard UFLS: violated
- Proposed UFLS: respected

Low-inertia 39-bus with BESS vs without BESS

		Voltage and current limits violated	EENS [MWh]
Config. II	No UFLS	Nodes 20 Line 13-14 Line 22-23 Line 25-26	-*
	Standard UFLS	Nodes 20 Line 13-14	10.54*
	OPF-driven UFLS	No violation	12.54
Config. III	No UFLS	Nodes 20 Line 13-14 Line 22-23 Line 25-26	-*
	Standard UFLS	Nodes 20 Line 13-14	10.54*
	OPF-driven UFLS	No violation	9.66

* This value does not consider the EENS caused by the line tripping due to the ampacity and voltage limits violations.

[1] AEMO, "Renewable integration study: Stage 1 report - enabling secure operation of the nem with very high penetrations of renewable energy," Australian Energy Market Operator, Tech. Rep., April 2020.
[2] R. Ramos, I. Hiskens et al., "Benchmark systems for small-signal stability analysis and control," IEEE Power and Energy Society, Tech. Rep. PES-TR18, August 2015.
[3] ENTSO-E, "Technical background and recommendations for defence plans in the continental europe synchronous area," Tech. Rep., 2010.