Grid-Forming Control Strategy for Converter-Interfaced Wind Power Systems in Ethiopia

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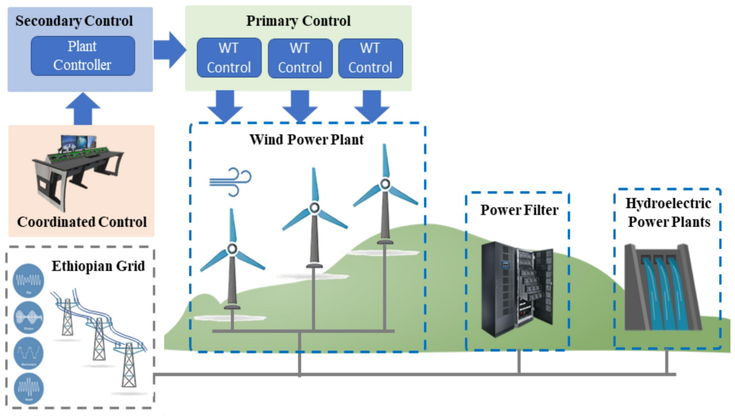
Project Description and Objectives

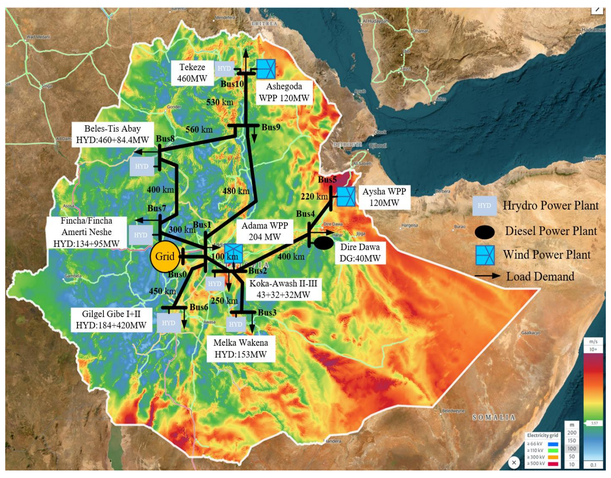
Ethiopia has vast renewable energy potential like hydro, wind, solar, and geothermal. Wind energy alone is estimated to be 1350 GW. Grid stability is affected due to major power outages in the dry season and dry years. Wind power become a good complement to hydropower, especially grid-forming wind power systems.



Project - **Large-Scale Integration of Wind Power Generation in Ethiopia (LastWind)** aims to propose innovative solutions for large-scale wind power integration into the Ethiopian grid.

- **Grid code recommendations** for the WPP integration in Ethiopia are proposed.
- **Planning tools** for the optimal sitting and sizing are developed.
- **Models and novel control strategies** are proposed for WPPs to handle grid-forming operation, hierarchical control, stability, harmonic, and resonance.
- **Coordinated control** for the wind/hydro hybrid power system will be investigated to achieve the power balance and flexible operation.

Planning Strategy of WPP



Simplified Ethiopian 230 kV transmission network

Capacities of Resources

Sources	HYD	WPP	DG
Count	6 clusters	3	1
Capacity	>2000 MW	444 MW	40 MW

1st - Investments

$$\min \quad F_1 = \sum_{i\in\Omega}\sum_{k\in\Omega_{WPP}} \xi_k \left(a_k C_k + b_k\right) X_{k,i}$$

$$\xi_k = \frac{r(1+r)^y}{(1+r)^y - 1}, \quad \forall k \in \Omega_{WPP}$$

$$\text{s.t.} \quad z_j \underline{X}_{k,i} \le X_{k,i} \le z_i \overline{X}_{k,i}, \forall k\Omega_{WPP}, \forall i \in \Omega$$

$$\sum_{i\in\Omega} z_i \le N_{WPP}$$

$$X_{k,i} \in \mathbb{Z}_+, z_i \in \{0,1\}, \quad \forall k \in \Omega_{WPP}, \forall i \in \Omega$$

2nd - Operation Cost

HYD & WPP & DG Operation costs | WPP & Load Curtailment costs | Utility Purchase costs | CO2 Emission costs

$$\min F_2 = \frac{365}{ND}\left(C_{mop,HYD} + C_{mop,DG} + C_{mop,WPP} + C_{CO2} + C_{ls} + C_{WPP,c} + C_{grid}\right)$$

$$C_{mop,HYD} = \sum_{i\in M}\sum_{k\in\Omega_{HYD}} \left(\alpha_i P_{k,i} + \beta_i\right),$$

$$C_{mop,DG} = \sum_{i\in M}\sum_{k\in\Omega_{DG}} \left(\alpha_i P_{k,i}^2 + \beta_i P_{k,i}\right)$$

$$C_{mop,WPP} = \sum_{i\in M}\sum_{k\in\Omega_{DG}} \left(\alpha_i P_{k,i} + \beta_i P_{k,i}\right),$$

$$C_{CO2} = \sum_{i\in M}\sum_{k\in\Omega_{DG}} \left(\gamma_{CO2,k} P_{k,i}\right),$$

$$C_{ls} = \sum_{i\in M}\sum_{k\in\Omega_{ls}} \left(\mu_i P_{Lc,i}\right),$$

$$C_{WPP,c} = \sum_{i\in M}\sum_{k\in\Omega_{WPP}} \left(\mu_i p_{wpp,i}\right),$$

$$C_{grid} = \gamma_{CO2,k} P_{grid} + \lambda P_{grid},$$

Investment Capacity Constraints | Power output Constraints | Power Flow Constraints | Ramping rate constraints

$$0 \le p_{k,i}(t) \le \overline{p}_k X_{k,i}, \quad \forall k \in \Omega_{WPP}, \forall i \in M, \forall t$$

$$\underline{p}_k \le p_{k,i}(t) \le \overline{p}_k, \quad \forall k \in \Omega_{DG\cup HYD}, \forall i \in M, \forall t$$

$$P_{ij}(t) - \sum_{h\in\Gamma_i} P_{ih}(t) = \begin{cases} -P_{INJ,i}(t), & \forall i \in M, \forall t \\ p_{l,i}(t), & \forall i \in \Omega/\mathrm{M}, \forall t \end{cases}$$

$$P_{INJ,i}(t) = P_{HYD,i}(t) + P_{WPP,i}(t) + P_{DG,i}(t) + p_{Lc,i}(t) - p_{l,i}(t) - P_{WPP,c,i}(t),$$

$$V_i^s(t) - V_j^s(t) = 2\left(lr_{ij} P_{ij}(t)\right), \forall (i,j) \in \Xi, \forall t$$

$$\underline{U} \le V_i(t) \le \overline{U}, \quad \forall i \in \Omega, \forall t$$

$$0 \le P_{ij}(t)^2 \le \overline{I}_{ij}^2, \quad \forall (i,j) \in \Xi, \forall t,$$

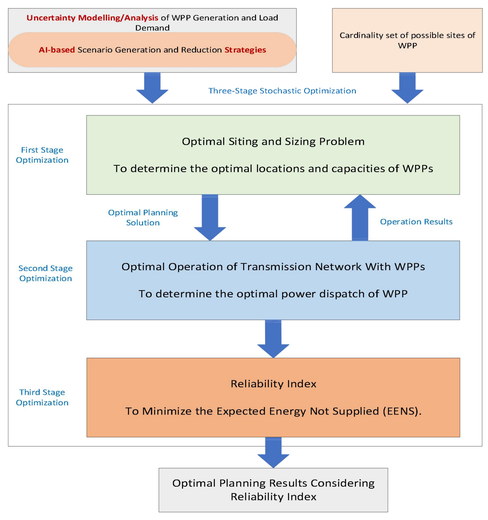
3rd - Reliability Index

Utility outages | Line/cable faults | Plant faults

$$\begin{cases} \min F_2 = (1) + F_3, \\ F_3 = \mu\left(\sum_{i\in\Omega}\sum_{t=1}^{T}\left(\left|\mathrm{LoLoss}_i(t)\right|\right)\right), \end{cases}$$

$$\begin{cases} \mathrm{LoLoss}_i(t) \ge 0, \quad \forall i \in \Omega, \forall t, \\ \sum_{t=1}^{T}\sum_{i\in\Omega} \mathrm{LoLoss}_i(t) <= T_{EENS}, \end{cases}$$

Three-stage planning strategy of WPP



Faults

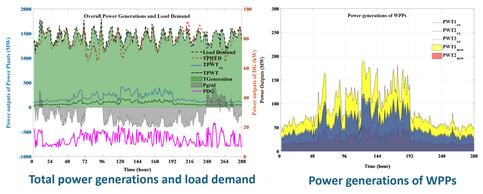
Utility outages: Day 4 for 24 hours,
Hydropower at bus 3: On Day 11 for 24 hours

New Planned WPP Capacity

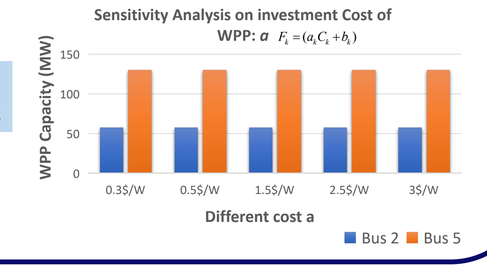
BUS2: 57.5 MW (max:120 MW)	BUS 5: 130 MW (max:300 MW)

Economic Costs

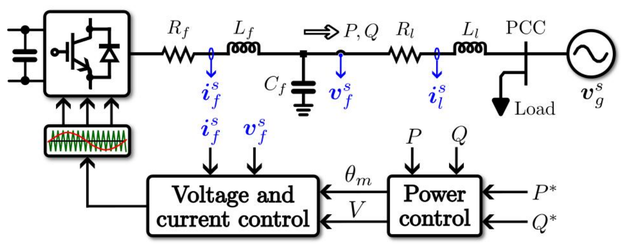
Investment Costs	$5.59 million
CO2 Emission Costs	-$5.04 million
EENS costs	$0
Operation Costs	$81 million
Curtailment Costs	$0.38 million
Total Costs	$81.5 million



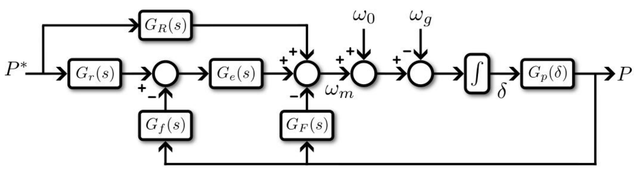
Total power generations and load demand | Power generations of WPPs



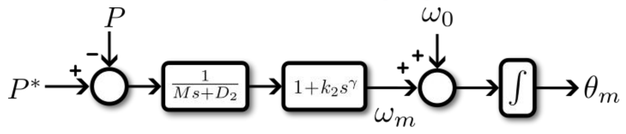
Grid-Forming Control Strategy



A Generic Active-Damping Control:



A Fractional-Order Active-Damping Control:



Reference tracking

$$G_T(s) \triangleq \frac{G_p s^{-1}\left[G_r(s)G_e(s) + G_R(s)\right]}{1 + G_p s^{-1} G_S(s)}$$

Inertial response

$$G_S(s) \triangleq G_f(s)G_e(s) + G_F(s)$$

Disturbance damping: frequency dips

$$G_D(s) \triangleq \frac{G_p s^{-1}}{1 + G_p s^{-1} G_S(s)}$$

Controller Design: Method I

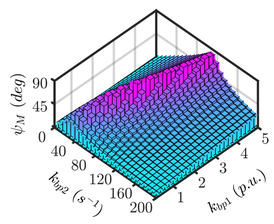
$$G_S(s) = \frac{1}{Ms + D_p} + \frac{k_{hp1} s}{s + k_{hp2}}$$

Controller Design: Method II

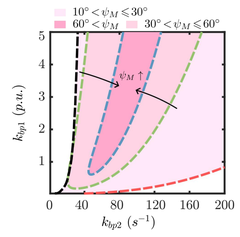
$$G_S(s) = \frac{1}{Ms + D_p} + \frac{k_{bp1} s}{(s + k_{bp2})^2}$$

Controller design

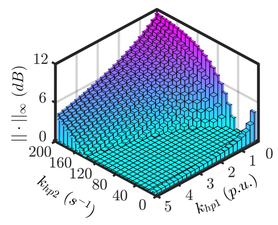
Tuning of the Generic Active-Damping Control:



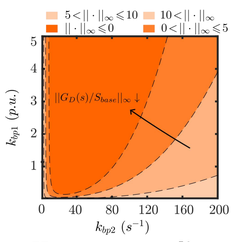
Phase margin



PM contour lines

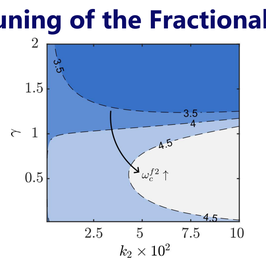


H_∞ (disturbance)

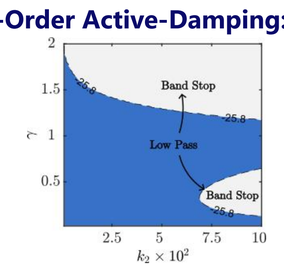


H_∞ contour lines

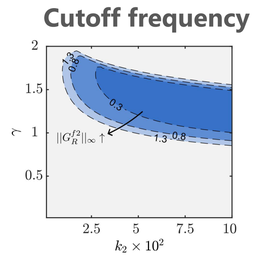
Tuning of the Fractional-Order Active-Damping:



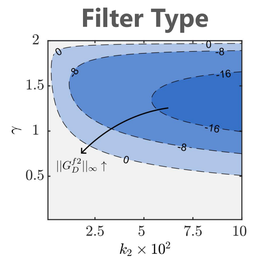
Cutoff frequency



Filter Type



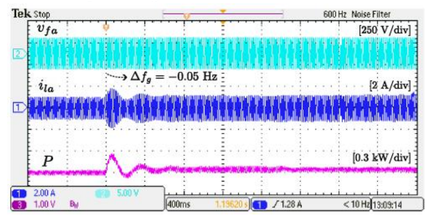
H_∞ (reference)



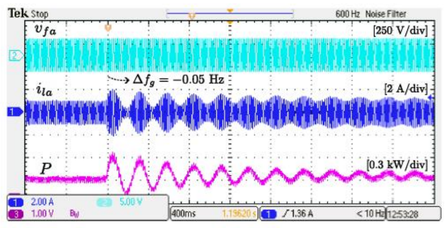
H_∞ (disturbance)

Comparative Experimental Results with a grid frequency deviation

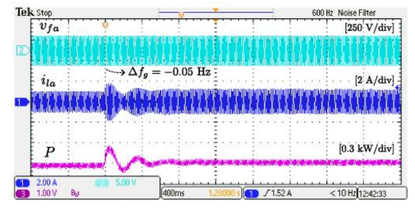
- A fractional order controller based active damping strategy for grid-forming inverters.
- Reference tracking, disturbance damping, and inertial response can be quantitatively evaluated in sequence.
- Under -0.05Hz grid-frequency deviation disturbances, the transient power oscillations can be effectively reduced from 2.8 s to 0.4 s.



Proposed APC designed using method I



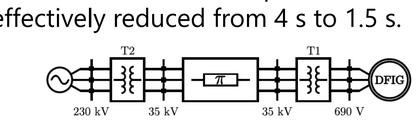
Conventional APC

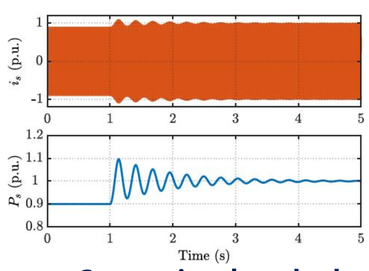


Proposed APC designed using method II

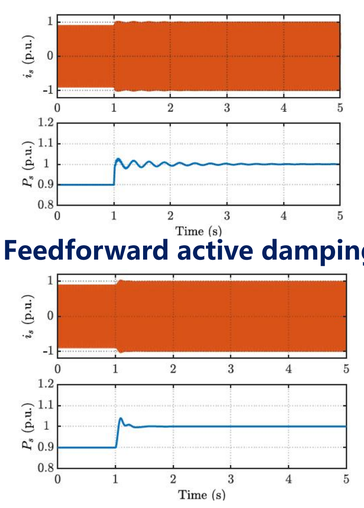
Comparative Simulation Results with a DFIG under frequency reference changes

- An active damping strategy based on a band-pass filter and the swing equation for DFIGs.
- Under -0.1p.u. power reference deviation disturbances, the transient power oscillations can be effectively reduced from 4 s to 1.5 s.





Conventional method



Feedforward active damping | **Proposed active damping**

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