Voltage Control in an HVDC System to Share Primary Frequency Control Reserves between Non-Synchronous Areas

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Power System Computation Conference (PSCC)
August 23, 2011

Outline

1. Background
2. DC-voltage-based control scheme for primary frequency control
3. Coordination with secondary frequency control
4. Conclusions

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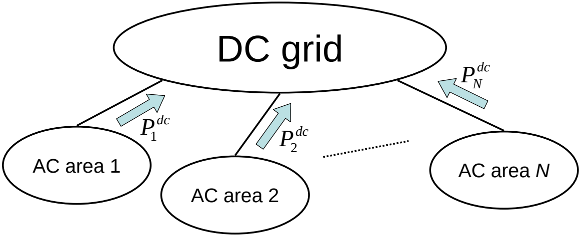
Primary frequency control

- Frequency control: Limit frequency variations and restore balance between generation and load demand.
- Primary frequency control:
  - Time scale: a few seconds.
  - Based on local frequency measurements.
  - Adjustment of power injections (mainly by generators).
  - Primary reserves: power margins deployable within a few seconds.
- Larger synchronous area:
  - More generators participating in primary frequency control.
  - Lower costs of reserves per MW.
  - Motivation to extend synchronous areas at a continental scale.

Multi-terminal HVDC system



- Generally, P_i^{dc} are supposed to track pre-determined power settings.
- Primary frequency control is independent from one area to another.
- Is it possible to share primary reserves among these AC areas as if they were connected by a large AC grid?

Previous work

- A simple control law:
  - Applied a two-terminal HVDC link.
  - To change the power exchanged via one converter in proportional to the frequency difference between both areas.
  - Generalized by the authors to a multi-terminal HVDC system.
- Problem: Dependency on remote information.
  - reliability
  - delays: potential instability

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Reference Operating Point

- The steady state, at which the system is expected to be operated in the absence of power imbalances. The values are denoted by a bar overhead.
- For each AC area:
  - Frequency: at its nominal value. $\bar{f} = f_{nom}$
  - Aggregated generator:
    - Constant rotational speed: $\bar{P}_e = \bar{P}_m$
    - Electrical output: $\bar{P}_e = \bar{P}_{load} + \bar{P}^{dc}$
    - Mechanical input: equal to its reference value given by the secondary frequency controller: $\bar{P}_m = P_m^o$
- DC grid: at a steady-state power flow.

DC-voltage-based control scheme for an HVDC grid

- Control objective: Sharing primary frequency reserves among non-synchronous areas by making the frequency deviations stay close to each other.
- Control variables: $V_1^{dc}, \ldots, V_N^{dc}$
- Subcontroller for area i controls V_i^{dc} such that

$$V_i^{dc} = \bar{V}_i^{dc} + \alpha_i (f_i - \bar{f}_i)$$

- where
  - $\bar{V}_i^{dc}$: Value of V_i^{dc} at the Reference Operating Point.
  - α_i: controller gain.
  - f_i: Frequency of area i.
  - $\bar{f}_i$: Value of f_i at the Reference Operating Point.

Features

$$V_i^{dc} = \bar{V}_i^{dc} + \alpha_i(f_i - \bar{f}_i)$$

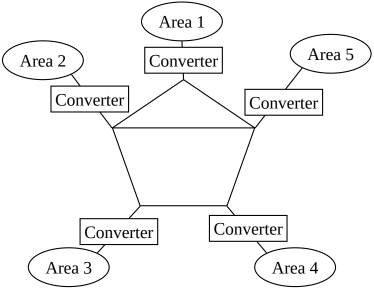
- Idea:
  1. A positive power imbalance (surplus) in area *i*: $f_i \uparrow$.
  2. The control law: $V_i^{dc} \uparrow$.
  3. The DC load flow equation: $P_i^{dc} \uparrow$.
  4. The positive power imbalance within area *i* is mitigated: $f_i \downarrow$.
- Decentralized: Each area acts only based on local information. Each area is controlled in the same way.
- The HVDC system functioning in non-conventional mode.

Theoretical results on system stability

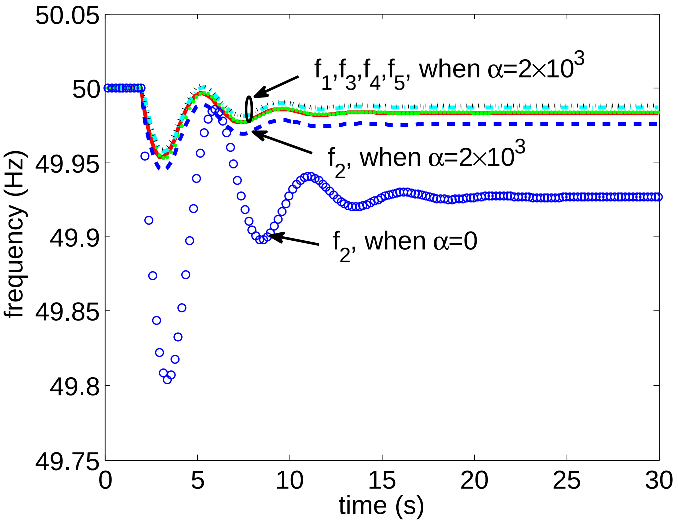
- Assumptions:
  - Linearized model.
  - Identical control gain for each converter.
  - DC power flow approximation.
- Expression of the unique equilibrium point: The frequency deviations are different from each other.
- For the special case of homogeneous AC areas:
  - Asymptotic stability proved: The system converges to the equilibrium point.
  - Effectiveness: By increasing the value of the controller gain α, the differences between the frequency deviations of the AC areas can be made arbitrarily small.

Illustrative case

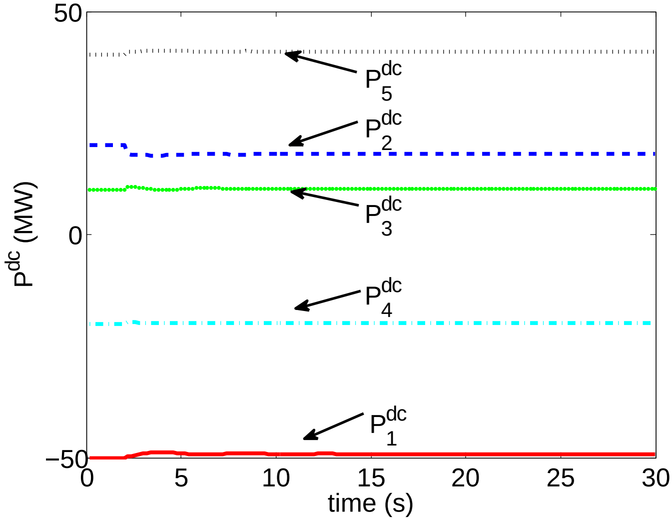
- An MT-HVDC system with 5 areas: Each area is modeled by an aggregated generator and an aggregated load.
- A nonlinear model: without simplifying assumptions made in the theoretical study.
- Power imbalance: a step increase by 5% in the load demand of area 2 at $t = 2$s.



Simulation result: Frequency



Simulation result: Power injections



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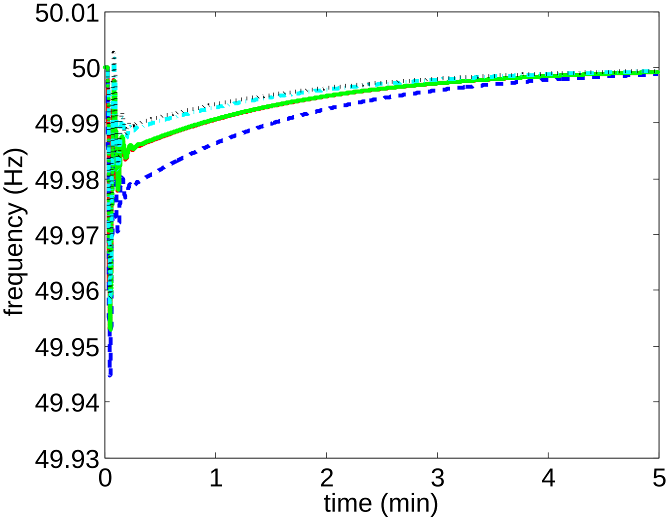
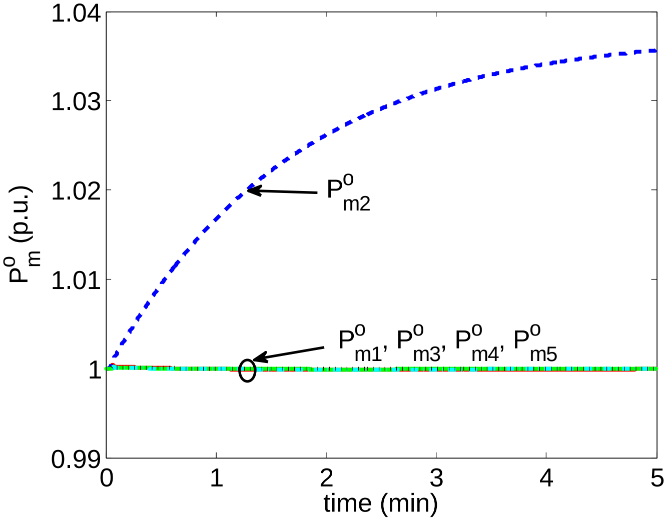
Secondary frequency control

- Objectives: To restore the frequency and the power exchanged between the control areas back to their nominal/schedule values.
- UCTE practice:
  - Network power frequency characteristic.
  - Area control error (ACE): allows locating the power imbalance.
  - P_m^o is adjusted by an integral controller.
- Direct generalization of the UCTE practice to the HVDC system applying the control scheme for primary frequency control.

Simulation result: Frequency



Simulation result: control variables P_m^o in p.u.



Conclusions

- A control scheme acting on HVDC converters' DC voltage.
- Theoretical results:
  - Expression of the unique equilibrium point.
  - Stability proved for the special case of homogeneous AC areas.
  - Effectiveness of the control scheme demonstrated.
- Simulation results:
  - Frequency deviation mitigated.
  - Use of a non-linear model confirms the theoretical results.
- Secondary frequency control scheme
- Perspectives:
  - Practice: Feasibility of HVDC system with each converter tracking a reference value for its DC voltage.
  - Economic benefits.
  - Integration of wind farms.