Multi-terminal HVDC systems and ancillary services

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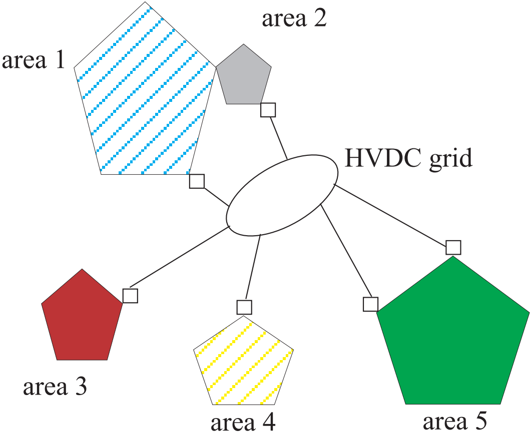
Multi-terminal HVDC systems

Multi-terminal HVDC systems: Become the solution of choice for connecting non-synchronous power systems and integrating offshore renewable energy sources.



Pros and cons of multi-terminal HVDC systems

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[1] Less active losses than the AC solution for the same voltage level; no need for reactive power compensation in submarine cable lines.
[2] Act as a firewall between different AC areas; (partial) decoupling of the dynamics between the zones.
[3] Control over the power transferred in the HVDC lines (eases the operation of the power system - may foster merchant investment).

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[1] Hardware technology not yet fully mature (e.g., problems with HVDC breakers)

[2] Still not yet understood how a multi-terminal HVDC should be operated, especially in real-time.

Operation of a multi-terminal HVDC grid in real-time

Main question: How to control the HVDC grid to offer ancillary services to the grid given various technological and regulatory constraints?

Why to care about ancillary services? Given the potential that these systems have to influence the dynamics of the system, it would be a missed opportunity not to care about.

What are the control variables? The amount of active P_i or reactive power Q_i that every area i 'injects' in the converters; voltages at both sides of the converters (dependencies between these variables). Possibility to change the value of these variables almost instantaneously.

Different types of ancillary services

Damping of small system oscillations. DC interconnections operated at constant power do not provide any damping torque. Slightly modulating the active power P_i may be a solution.

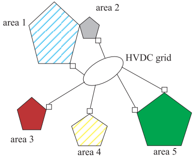
Prevention of loss of synchronism phenomena. Large variations of P_i may be a powerful mean to avoid loss of synchronism phenomena in area i in the aftermath of a large disturbance.

Voltage control. Tuning the settings of the Q_is may help optimizing the voltage profile in normal operating conditions. May also provide reactive power reserve in an emergency mode to avoid voltage collapses.

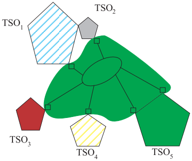
Frequency control. Appropriate modulation of the P_is may lead to a sharing of the primary frequency and secondary frequency reserves.

Ancillary services versus type of operation

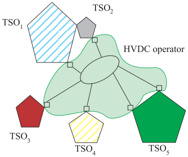
Consensus based (I)



Integrated (II)



Independent (III)
(and profit-based)



I: + Fair operation practices; potential for optimizing the global operation of the whole system.

- TSOs may never reach a consensus.

II: + Strong added value for the TSO operating the HVDC grid.

- May be unfavorable to other TSOs.

III: + Provide good incentives for offering ancillary services; may foster agreements for modulation of active power.

- Market power (e.g., for the control of the voltage).

Primary frequency regulation in an AC area

A hierarchy of control schemes exist to react to imbalances and drive the frequency back to its nominal value.

Primary frequency control acts at the shortest time scale (step response settling within a few seconds). Adjusts the power injections of some generation units as a function of measurements of the local frequency (frequency considered as the same everywhere in an AC system).

Available range of power injection variation around its nominal value is referred to as primary reserve.

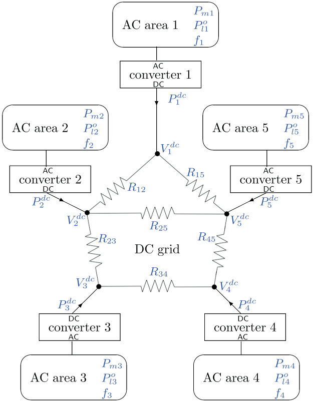
Costly: procurement costs in primary reserve markets in Germany totaled around €80 million in 2006 $\Rightarrow$ One of the initial motivation for interconnecting systems.

Controlling the multi-terminal HVDC to share primary reserves

The different AC areas do not share the same frequency $\Rightarrow$ no sharing of the primary reserve.

We suppose that the different AC areas agree to control the multi-terminal HVDC system so as to share primary reserves such as if they were interconnected by AC links $\Rightarrow$ the active power injected into the HVDC grid should be modulated so as to ensure a same frequency everywhere.

Question: How to design such control strategies?



Frequencies (f_i) and power produced by every area i (P_{mi}) are state variables. V_i^{dc} and P_i^{dc} are control variables. P_{li}^0 is the power consumed by the load at the nominal frequency. If P_{li}^0 increases (decreases), f_i drops if P_i^{dc} is kept at its reference value (which is determined by a market clearing mechanism).

Power-injection-based control scheme

Control scheme composed of $N - 1$ subcontrollers, one for each HVDC converter except converter N which maintains the voltage of the DC grid. Modifies P_i^{dc} such that:

$$\frac{dP_i^{dc}}{dt} = \alpha \sum_{j=1}^{N} b_{ij}(\Delta f_i - \Delta f_j) + \beta \sum_{j=1}^{N} b_{ij} \left(\frac{df_i}{dt} - \frac{df_j}{dt} \right)$$

- $\Delta f_i = f_i - f_{nom,i}$ is the frequency deviation of area i
- α and β are control gains
- b_{ij}'s are the coefficients representing the communication graph between the AC areas. The value of b_{ij} equals 1 if subcontroller i receives frequency information of area j, and 0 otherwise.

Model for the AC areas and the HVDC grid

AC area i, for $i = 1, 2, ..., N$, is modeled by

$$\begin{aligned} J_i \tfrac{d}{dt} f_i &= \frac{P_{mi} - P_{li} - P_i^{dc}}{4\pi^2 f_i} - D_{gi}(f_i - f_{nom,i}) \\ T_{smi} \tfrac{d}{dt} P_{mi} &= P_{mi}^0 - P_{mi} - \frac{P_{nom,i}}{\sigma_i} \frac{f_i - f_{nom,i}}{f_{nom,i}} \\ P_{li} &= P_{li}^0 \cdot (1 + D_{li}(f_i - f_{nom,i})) \ . \end{aligned}$$

Power flows in the DC grid:

$$P_i^{dc} = V_i^{dc} \sum_{k=1}^{N} \frac{(V_i^{dc} - V_k^{dc})}{R_{ik}} \ .$$

Equations valid only until limits are hit. J_i is the moment of inertia of the aggregated generator of area i and D_{gi} its damping factor; σ_i is the generator droop, $P_{nom,i}$ its rated mechanical power, T_{smi} the time constant for local power-adjustment control. The reference power P_{mi}^0 is determined by a market clearing mechanism as well as secondary frequency control.

Theoretical analysis

Assumption 1. The graph representing frequency deviations communication among the subcontrollers is (i) constant in time (ii) undirected and (iii) connected.

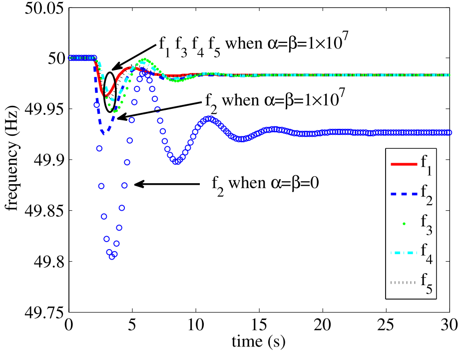
Assumption 2. The variation of the net overall power flow injected into the DC grid can be neglected.

Theorem 1. Consider that the power system, initially operating at its nominal equilibrium, is suddenly subjected to a step change in the load demand in one or several of its AC areas. Then, under Assumptions 1 and 2 the (linearized) HVDC system has a unique equilibrium point, at which the frequency deviations of all AC areas are equal.

Theorem 2. The linearized system is exponentially stable for any $\alpha > 0$ and $\beta \geq 0$.

Results

Variations of the f_is after a 5 % load increase in area 2:

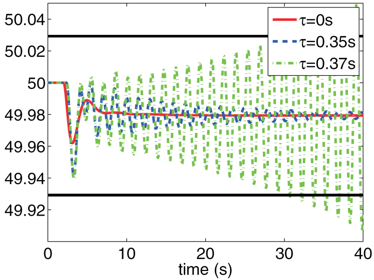


Notes: (i) Frequency deviations in area 2 are much smaller in the presence of the control scheme. (ii) All the frequencies converge towards the same value under the control scheme. (iii) Voltage excursions in the DC grid are small (less than 1%).

Two major shortcomings of this scheme

[1] In case of a dysfunction in the multi-terminal HVDC system, load imbalances will be created in the areas and the areas will lose the possibility to rely on primary reserves from other areas.

[2] If time for communicating the frequency information (τ on the figure) between the areas is too large, instabilities may occur !



DC-voltage-based control scheme

Control scheme composed of N subcontrollers. Modifies the V_i^{dc} such that:

$$V_i^{dc} - \overline{V}_i^{dc} = \gamma(f_i - f_{nom,i}) \quad \forall i \in \{1, \ldots, N\}$$

where $\overline{V}_i^{dc}$ is the voltage of the DC grid at node i at the reference operating point and $\gamma > 0$ is a gain.

Main rationale behind the control scheme: by decreasing its voltage on the DC side of its converter when its frequency decreases, an area will send less power to the DC grid.

Theoretical results

The analysis is much more technical than for the power-injection-based control scheme !

A “rough summary” of some of the results obtained:

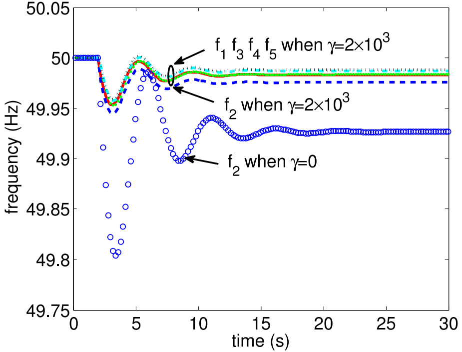
[1] If γ is small enough, then a load increase in area *i* leads to a new equilibrium point where the differences between the frequencies deviations are smaller. This shows that the control scheme leads to a sharing of the primary frequency reserve.

[2] If γ is small enough, then this new equilibrium is asymptotically stable.

Note: The detailed analysis can be found in : "*Cooperative control of a multi-terminal high-voltage DC network*". J. Dai, Y. Phulpin, A. Sarlette and D. Ernst. Submitted.

Simulation results

Variations of the f_i after a 5 % load increase in area 2:



Notes: (i) Frequency deviations in area 2 are much smaller in the presence of the control scheme. (ii) The frequencies do not converge to the same value (iii) Voltage excursions in the DC grid are small (less than 1%).

Final word: A long road ahead for researchers in power system dynamics and control...

Previously. Power systems could be seen as a two-layer network. A transmission network making the top-layer and distribution networks making the bottom layer. Advanced control algorithms were required only for the top-layer.

Nowadays. Migration towards a network with three layers. Top layer: a supergrid made of (multi-terminal) HVDC links. Middle layer: transmission networks. Bottom layer: distribution networks with renewables and demand side management. Every layer needs advanced control strategies.

Challenges for designing well-performing control strategies and make them work together are **immense**.

Presentation based on

”*Cooperative frequency control with a multi-terminal high-voltage DC network*”. J. Dai, Y. Phulpin, A. Sarlette and D. Ernst. Automatica, Volume 48, Issue 12, December 2012, Pages 3128-3134.

”*Voltage control in an HVDC system to share primary frequency reserves between non-synchronous areas*”. J. Dai, Y. Phulpin, A. Sarlette and D. Ernst. In Proceedings of the 17th Power Systems Computation Conference (PSCC-11), Stockholm, Sweden, August 22-26, 2011. (8 pages).

”*Impact of delays on a consensus-based primary frequency control scheme for AC systems connected by a multi-terminal HVDC grid*”. J. Dai, Y. Phulpin, A. Sarlette and D. Ernst. In Proceedings of the 2010 IREP Symposium - Bulk Power Systems Dynamics and Control - VIII, Buzios, Rio de Janeiro, Brazil, 1-6 August 2010. (9 pages).

”*Coordinated primary frequency control among nonsynchronous systems connected by a multi-terminal HVDC grid*”. J. Dai, Y. Phulpin, A. Sarlette and D. Ernst. IET Generation, Transmission & Distribution, February 2012, Volume 6, Issue 2, p.99-108.

”*Ancillary services and operation of multi-terminal HVDC systems*”. Y. Phulpin and D. Ernst. In Proceedings of the 10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Farms, Aarhus, Denmark, October 25-26, 2011. (6 pages).