Impact of Delays on a Consensus-based Primary Frequency Control Scheme for AC Systems Connected by a Multi-Terminal HVDC Grid

J. Dai[1] Y. Phulpin[1] A. Sarlette[2] D. Ernst[2]

[1]Supélec, Paris, France

[2]FNRS and University of Liège, Belgium

IREP Symposium 2010

Outline

1. Problem addressed
2. Theoretical contributions
3. Empirical contributions
4. Conclusions

Outline

Outline

Outline

Problem addressed

Title: Impact of Delays on a Consensus-based Primary Frequency Control Scheme for AC Systems Connected by a Multi-Terminal HVDC Grid 4 elements:

1. Primary frequency control
2. Multi-terminal HVDC system
3. Consensus-based control scheme
4. Delays

Problem addressed

Title: Impact of Delays on a Consensus-based Primary Frequency Control Scheme for AC Systems Connected by a Multi-Terminal HVDC Grid 4 elements:

1. Primary frequency control
2. Multi-terminal HVDC system
3. Consensus-based control scheme
4. Delays

Problem addressed

Title: Impact of Delays on a Consensus-based Primary Frequency Control Scheme for AC Systems Connected by a Multi-Terminal HVDC Grid 4 elements:

1. Primary frequency control
2. Multi-terminal HVDC system
3. Consensus-based control scheme
4. Delays

Problem addressed

Title: Impact of Delays on a Consensus-based Primary Frequency Control Scheme for AC Systems Connected by a Multi-Terminal HVDC Grid 4 elements:

1. Primary frequency control
2. Multi-terminal HVDC system
3. Consensus-based control scheme
4. Delays

Problem addressed

Title: Impact of Delays on a Consensus-based Primary Frequency Control Scheme for AC Systems Connected by a Multi-Terminal HVDC Grid 4 elements:

1. Primary frequency control
2. Multi-terminal HVDC system
3. Consensus-based control scheme
4. Delays

Primary frequency control

- Frequency control: Limit frequency variations and restore balance between generation and load demand
- Primary frequency control:
  - Time scale: a few seconds
  - Local adjustment of generators' power output
  - Based on locally measured frequency
  - Primary reserves: generators' power output margin
- Larger synchronous area:
  - More generators participating in the primary control
  - Smaller frequency deviations

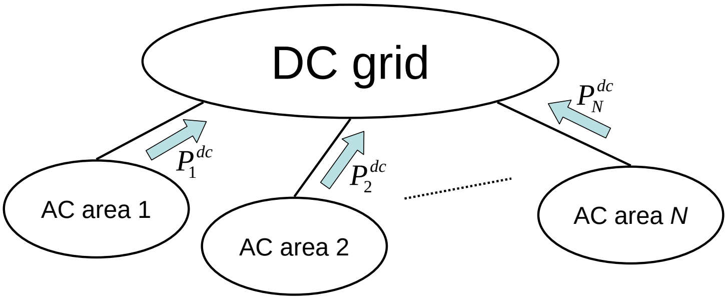
Primary frequency control

- Frequency control: Limit frequency variations and restore balance between generation and load demand
- Primary frequency control:
  - Time scale: a few seconds
  - Local adjustment of generators' power output
  - Based on locally measured frequency
  - Primary reserves: generators' power output margin
- Larger synchronous area:
  - More generators participating in the primary control
  - Smaller frequency deviations

Primary frequency control

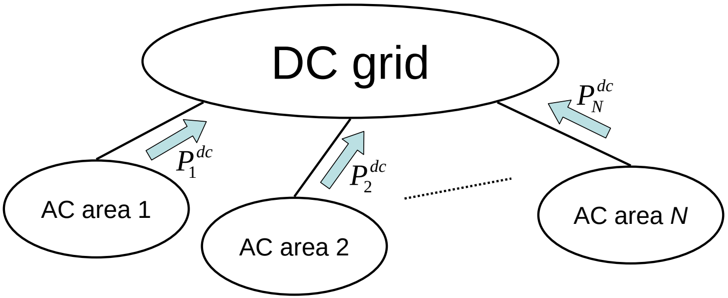
- Frequency control: Limit frequency variations and restore balance between generation and load demand
- Primary frequency control:
  - Time scale: a few seconds
  - Local adjustment of generators' power output
  - Based on locally measured frequency
  - Primary reserves: generators' power output margin
- Larger synchronous area:
  - More generators participating in the primary control
  - Smaller frequency deviations

Multi-terminal HVDC system



- Generally, P_i^{dc} are supposed to track pre-determined power settings.
- Frequencies are independent among AC areas.
  - Primary frequency control is independent from one area to another.

Multi-terminal HVDC system



- Generally, P_i^{dc} are supposed to track pre-determined power settings.
- Frequencies are independent among AC areas.
  - Primary frequency control is independent from one area to another.

A control scheme proposed in an earlier work

- Control objective: Sharing primary frequency reserves among non-synchronous areas by imposing that $\Delta f_1(t) = \ldots = \Delta f_N(t)$.
- Control variables: $P_i^{dc}, \ldots, P_{N-1}^{dc}$
-

$$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t) - \Delta f_k(t)) + \beta \sum_{k=1}^{N} b_{ik} \left(\frac{d\Delta f_i(t)}{dt} - \frac{d\Delta f_k(t)}{dt} \right)$$

- $i = 1, \ldots, N-1$, where
  - $\Delta f_i(t)$: Frequency deviation of area i from its nominal value.
  - α and β: integral and proportional control gain.
  - b_{ik}: coefficient representing the communication graph.

A control scheme proposed in an earlier work

- Control objective: Sharing primary frequency reserves among non-synchronous areas by imposing that $\Delta f_1(t) = \ldots = \Delta f_N(t)$.
- Control variables: $P_i^{dc}, \ldots, P_{N-1}^{dc}$
- $$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t) - \Delta f_k(t)) + \beta \sum_{k=1}^{N} b_{ik} \left(\frac{d\Delta f_i(t)}{dt} - \frac{d\Delta f_k(t)}{dt} \right)$$
- $i = 1, \ldots, N-1$, where
  - $\Delta f_i(t)$: Frequency deviation of area i from its nominal value.
  - α and β: integral and proportional control gain.
  - b_{ik}: coefficient representing the communication graph.

A control scheme proposed in an earlier work

- Control objective: Sharing primary frequency reserves among non-synchronous areas by imposing that $\Delta f_1(t) = \ldots = \Delta f_N(t)$.
- Control variables: $P_i^{dc}, \ldots, P_{N-1}^{dc}$
- $$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t) - \Delta f_k(t)) + \beta \sum_{k=1}^{N} b_{ik} \left(\frac{d\Delta f_i(t)}{dt} - \frac{d\Delta f_k(t)}{dt} \right)$$
- $i = 1, \ldots, N-1$, where
  - $\Delta f_i(t)$: Frequency deviation of area i from its nominal value.
  - α and β: integral and proportional control gain.
  - b_{ik}: coefficient representing the communication graph.

A control scheme proposed in an earlier work

- Control objective: Sharing primary frequency reserves among non-synchronous areas by imposing that $\Delta f_1(t) = \ldots = \Delta f_N(t)$.
- Control variables: $P_i^{dc}, \ldots, P_{N-1}^{dc}$
- $$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t) - \Delta f_k(t)) + \beta \sum_{k=1}^{N} b_{ik} \left(\frac{d\Delta f_i(t)}{dt} - \frac{d\Delta f_k(t)}{dt} \right)$$
- $i = 1, \ldots, N-1$, where
  - $\Delta f_i(t)$: Frequency deviation of area i from its nominal value.
  - α and β: integral and proportional control gain.
  - b_{ik}: coefficient representing the communication graph.

A control scheme proposed in an earlier work

- Control objective: Sharing primary frequency reserves among non-synchronous areas by imposing that $\Delta f_1(t) = \ldots = \Delta f_N(t)$.
- Control variables: $P_i^{dc}, \ldots, P_{N-1}^{dc}$
-

$$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t) - \Delta f_k(t)) + \beta \sum_{k=1}^{N} b_{ik} \left(\frac{d\Delta f_i(t)}{dt} - \frac{d\Delta f_k(t)}{dt} \right)$$

- $i = 1, \ldots, N-1$, where
  - $\Delta f_i(t)$: Frequency deviation of area i from its nominal value.
  - α and β: integral and proportional control gain.
  - b_{ik}: coefficient representing the communication graph.

A control scheme proposed in an earlier work

- Control objective: Sharing primary frequency reserves among non-synchronous areas by imposing that $\Delta f_1(t) = \ldots = \Delta f_N(t)$.
- Control variables: $P_i^{dc}, \ldots, P_{N-1}^{dc}$
- $$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t) - \Delta f_k(t)) + \beta \sum_{k=1}^{N} b_{ik} \left(\frac{d\Delta f_i(t)}{dt} - \frac{d\Delta f_k(t)}{dt} \right)$$
- $i = 1, \ldots, N-1$, where
  - $\Delta f_i(t)$: Frequency deviation of area i from its nominal value.
  - α and β: integral and proportional control gain.
  - b_{ik}: coefficient representing the communication graph.

A control scheme proposed in an earlier work

- Control objective: Sharing primary frequency reserves among non-synchronous areas by imposing that $\Delta f_1(t) = \ldots = \Delta f_N(t)$.
- Control variables: $P_i^{dc}, \ldots, P_{N-1}^{dc}$
-

$$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t) - \Delta f_k(t)) + \beta \sum_{k=1}^{N} b_{ik} \left(\frac{d\Delta f_i(t)}{dt} - \frac{d\Delta f_k(t)}{dt} \right)$$

- $i = 1, \ldots, N-1$, where
  - $\Delta f_i(t)$: Frequency deviation of area i from its nominal value.
  - α and β: integral and proportional control gain.
  - b_{ik}: coefficient representing the communication graph.

Delay modeling

- Sources of delays: measurement, transmission, computation, application
- Assumption: identical regardless of AC areas and communication links
- Dynamics of the effective power injections

$$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t-\tau) - \Delta f_k(t-\tau)) + \beta \sum_{k=1}^{N} b_{ik}\left(\frac{d\Delta f_i(t-\tau)}{dt} - \frac{d\Delta f_k(t-\tau)}{dt}\right)$$

- where τ: Delay between AC areas.

Delay modeling

- Sources of delays: measurement, transmission, computation, application
- Assumption: identical regardless of AC areas and communication links
- Dynamics of the effective power injections

$$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t-\tau) - \Delta f_k(t-\tau)) + \beta \sum_{k=1}^{N} b_{ik} \left(\frac{d\Delta f_i(t-\tau)}{dt} - \frac{d\Delta f_k(t-\tau)}{dt} \right)$$

- where τ: Delay between AC areas.

Delay modeling

- Sources of delays: measurement, transmission, computation, application
- Assumption: identical regardless of AC areas and communication links
- Dynamics of the effective power injections

$$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t-\tau) - \Delta f_k(t-\tau)) + \beta \sum_{k=1}^{N} b_{ik}\left(\frac{d\Delta f_i(t-\tau)}{dt} - \frac{d\Delta f_k(t-\tau)}{dt}\right)$$

- where τ: Delay between AC areas.

Delay modeling

- Sources of delays: measurement, transmission, computation, application
- Assumption: identical regardless of AC areas and communication links
- Dynamics of the effective power injections

$$\frac{dP_i^{dc}(t)}{dt} = \alpha \sum_{k=1}^{N} b_{ik}(\Delta f_i(t-\tau) - \Delta f_k(t-\tau)) + \beta \sum_{k=1}^{N} b_{ik} \left(\frac{d\Delta f_i(t-\tau)}{dt} - \frac{d\Delta f_k(t-\tau)}{dt} \right)$$

- where τ: Delay between AC areas.

Theoretical results on system stability

- Assumptions:
  - Constant losses within the DC grid
  - Communication graph of the frequency information access among AC areas: connected, undirected, constant in time.
  - Linearized model
- Stability results on the impacts of the delays:
  - Unique equilibrium point:
    Following a step change in the load of one of the AC areas, there is a unique equilibrium point: $\Delta f_1 = \Delta f_2 = \ldots = \Delta f_N$.
  - Nyquist criterion for the special case where all the AC areas have identical parameters.

Theoretical results on system stability

- Assumptions:
  - Constant losses within the DC grid
  - Communication graph of the frequency information access among AC areas: connected, undirected, constant in time.
  - Linearized model
- Stability results on the impacts of the delays:
  - Unique equilibrium point: Following a step change in the load of one of the AC areas, there is a unique equilibrium point: $\Delta f_1 = \Delta f_2 = \ldots = \Delta f_N$.
  - Nyquist criterion for the special case where all the AC areas have identical parameters.

Theoretical results on system stability

- Assumptions:
  - Constant losses within the DC grid
  - Communication graph of the frequency information access among AC areas: connected, undirected, constant in time.
  - Linearized model
- Stability results on the impacts of the delays:
  - Unique equilibrium point:
    Following a step change in the load of one of the AC areas, there is a unique equilibrium point: $\Delta f_1 = \Delta f_2 = \ldots = \Delta f_N$.
  - Nyquist criterion for the special case where all the AC areas have identical parameters.

Theoretical results on system stability

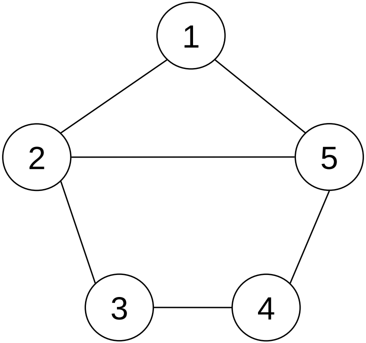
- Assumptions:
  - Constant losses within the DC grid
  - Communication graph of the frequency information access among AC areas: connected, undirected, constant in time.
  - Linearized model
- Stability results on the impacts of the delays:
  - Unique equilibrium point:
    Following a step change in the load of one of the AC areas, there is a unique equilibrium point: $\Delta f_1 = \Delta f_2 = \ldots = \Delta f_N$.
  - Nyquist criterion for the special case where all the AC areas have identical parameters.

Theoretical results on system stability

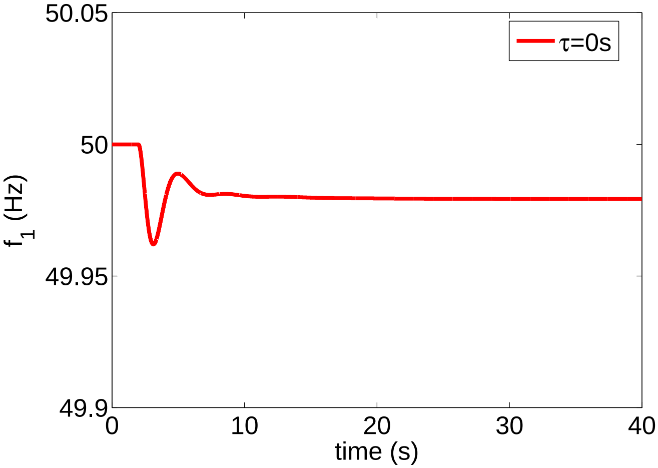
- Assumptions:
  - Constant losses within the DC grid
  - Communication graph of the frequency information access among AC areas: connected, undirected, constant in time.
  - Linearized model
- Stability results on the impacts of the delays:
  - Unique equilibrium point:
    Following a step change in the load of one of the AC areas, there is a unique equilibrium point: $\Delta f_1 = \Delta f_2 = \ldots = \Delta f_N$.
  - Nyquist criterion for the special case where all the AC areas have identical parameters.

Benchmark system

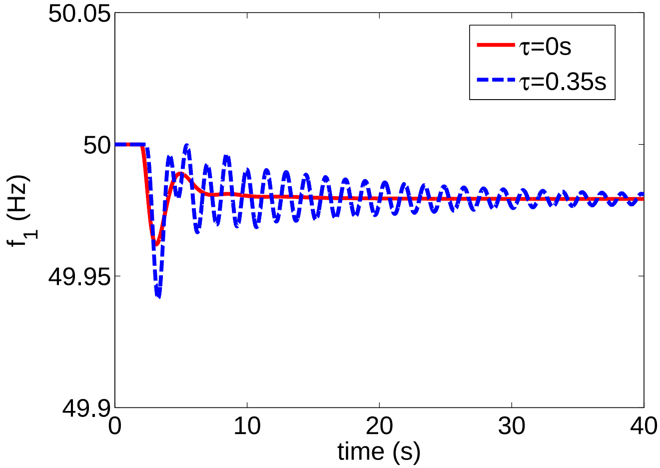
- An MT HVDC system with 5 areas: Each area is modeled by an aggregated generator and a load.
- Communication graph:
  - A circle: an area
  - An edge: a communication channel between the two areas



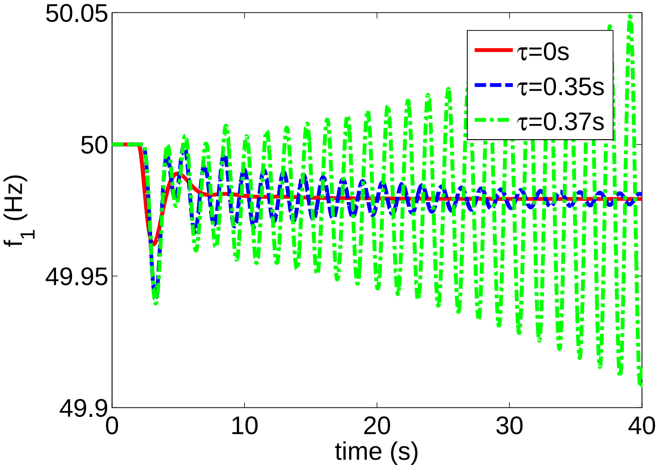
Simulation result: No delays



Simulation result: $\tau = 0.35$s



Simulation result: $\tau = 0.37$s



Stability criterion

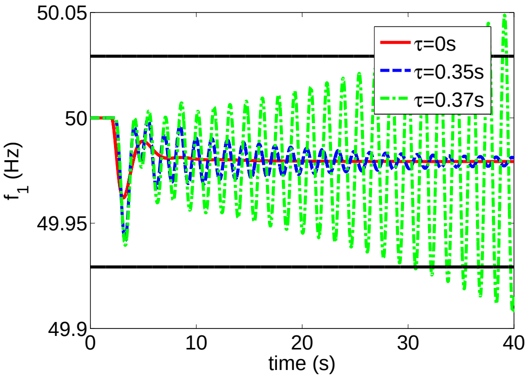
We define the following stability criterion:
The system is classified as stable if, 20 seconds after the step change in the load, all the AC areas' frequency deviations remain within $\pm$50mHz around f^e, i.e.,

$$|\Delta f_i(t) - \Delta f^e| \leq 50\text{mHz}, \forall i \text{ and } \forall t > 22\text{s}$$

where f^e is the common value to which the frequency deviations of all AC areas converge when no delays is considered.

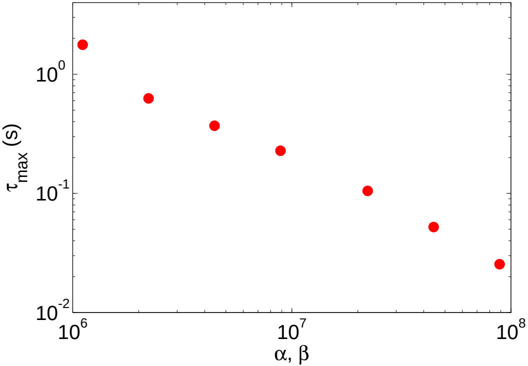
Stability criterion

- The $\pm$50mHz band around f^e is represented by the two horizontal lines.
- Unstable when $\tau = 0.37$s.

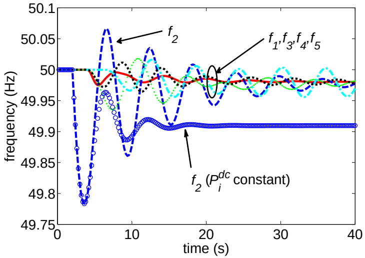


Maximum acceptable delay

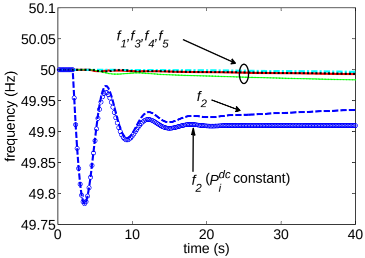
- For certain α, β, there exists a maximum acceptable delay, denoted by $\tau_{\max}$, beyond which the system is unstable.
- Evolutiona of $\tau_{\max}$ as a function of the controller gains (assuming that $\alpha = \beta$):



Oscillations of frequencies when $\tau = 2$s



$\alpha = \beta = 1 \times 10^6$



$\alpha = \beta = 1 \times 10^5$

Conclusions

- Practical issue (impact of delays) in the implementation of a previously proposed control scheme.
- Theoretical results:
  - Unique equilibrium point for the general case
  - Nyquist criterion for a special case
- Simulation results:
  - Frequency oscillations in the presence of delays
  - Relation between the maximum acceptable delay and the controller gains
- Perspectives:
  - Theoretical: extention to the general case
  - Practice: benchmark system with more details

Conclusions

- Practical issue (impact of delays) in the implementation of a previously proposed control scheme.
- Theoretical results:
  - Unique equilibrium point for the general case
  - Nyquist criterion for a special case
- Simulation results:
  - Frequency oscillations in the presence of delays
  - Relation between the maximum acceptable delay and the controller gains
- Perspectives:
  - Theoretical: extention to the general case
  - Practice: benchmark system with more details

Conclusions

- Practical issue (impact of delays) in the implementation of a previously proposed control scheme.
- Theoretical results:
  - Unique equilibrium point for the general case
  - Nyquist criterion for a special case
- Simulation results:
  - Frequency oscillations in the presence of delays
  - Relation between the maximum acceptable delay and the controller gains
- Perspectives:
  - Theoretical: extention to the general case
  - Practice: benchmark system with more details

Conclusions

- Practical issue (impact of delays) in the implementation of a previously proposed control scheme.
- Theoretical results:
  - Unique equilibrium point for the general case
  - Nyquist criterion for a special case
- Simulation results:
  - Frequency oscillations in the presence of delays
  - Relation between the maximum acceptable delay and the controller gains
- Perspectives:
  - Theoretical: extention to the general case
  - Practice: benchmark system with more details