Model predictive control of HVDC power flow to improve transient stability in power systems

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Motivation

- Raising interest in embedded HVDC-links
- Challenges in operating such systems :
  - Disable natural damping properties of AC systems
  - Impact power system stability
- Research has focused on advanced control schemes for converters to :
  - improve the system response w.r.t. sudden disturbances
  - particular focus on loss of synchronism phenomena

Loss of synchronism phenomena

- Follow a default creating a local imbalance
- Consist of increasing rotor phasor angle differences between interconnected generators
    - Can be characterized by a treshold in phasor angle difference
- The ability of a power system to remain in synchronism depends on
    - the initial state
    - the disturbance
    - the control actions
    - the fault clearing time
- Transmission system operators must define appropriate tuning for protections and operational devices

Approach

- Define emergency control strategies to :
  - avoid/delay loss of synchronism
  - counterbalance the negative effect of embedded HVDC transmission
- Rely on real-time information collected through WAMS
- Set power flow through HVDC-links using Model Predictive Control (MPC)

Problems addressed with MPC

- Time-variant finite-time control problems
- Problems usually characterized by dynamics
  $f : \mathbf{X} \times \mathbf{U} \times \{0, 1, \ldots, N-1\} \to \mathbf{X}$
  with :
  $$\mathbf{x}[n+1] = f(\mathbf{x}[n], \mathbf{u}[n], n)$$

Decision-making approach

- Process :
  - At instant n, identify a sequence of H successive actions that minimizes a cost function C
  - Apply the first control action
  - reproduces the same approach at $n+1$
- Motivation for $H << N$
  - Lower computation requirements
  - Longer-term dynamics are more difficult to predict

Decision-making approach

Identification of the optimal sequence over P^H possibilities :

- Exhaustive search - test P^H sequences
- A* algorithm :
  - Define a list of possibilities to explore (initially containing only the state at instant n).
  - At each step :
    - Pick the first element of the list
    - Explore the P possibilities from the associated state
    - Compute the additional costs with each possibility
    - increase the list with the new states and associated costs
    - Rank the elements of the list by increasing cost
  - when the first element of the list corresponds to time $n + H$, stop searching.

Application conditions

- The state variable corresponds to phasors and rotation speeds collected by WAMS
- The control variable is the power flows through embedded HVDC-links
    - Decision-space discretized and restricted to *values* by HVDC link
- function f represents power system dynamics
    - Approximation could be obtained by WAMS (with difficulties)

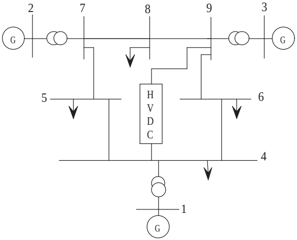
Computation of the costs

- Sum of instantaneous costs $c(\mathbf{x}[n])$

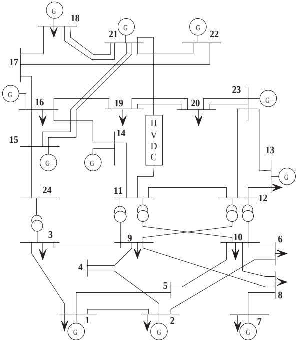
$$c(\mathbf{x}[n]) = \begin{cases} D(\mathbf{x}) - D_{min} & \text{if } \nexists i, j \in \{1, \ldots, N_G\} \\ & \text{such that} \| \delta_i[n] - \delta_j[n] \| \leq \delta_{max} \\ c_{pen} & \text{otherwise} \end{cases}$$

- Several formulations of instantaneous costs :
  - Power index
    $D_P(\mathbf{x}[n]) = \sum_{i=1}^{N_G} (w_i[n] - w_{COI}[n])(\theta_i[n] - \theta_{COI}[n])$
  - Coherency index $D_C(\mathbf{x}[n]) = \sum_{i=1}^{N_G} g_i(\mathbf{x}[n])(w_i[n] - w_{COI}[n])$
  - Energy index $D_E(\mathbf{x}[n]) = \sum_{i=1}^{N_G} (w_i[n] - w_{COI}[n])^2$

Benchmark systems



3 machine 9 bus system



IEEE 24 bus system

Simulation conditions

- System initially in steady-state operation
- 3-phase to ground fault initiated at n=0
- Simulation stops after two seconds or when synchronism is lost
- Considering only faults close to generators on the AC side
- A simulation step represents 10 ms, i.e. N=200.

Evaluation criteria

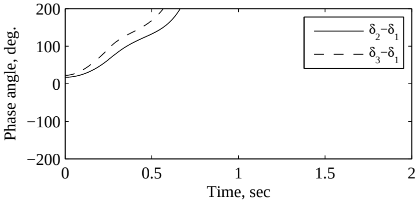
- Criteria : time to instability (TTI)
- Comparison with alternative control schemes :
    - No specific control : constant current setting (CC)
    - Control sequence that maximizes of the TTI (Optimal)
    - PI control considering phasor angle deviations (PI)

Modeling

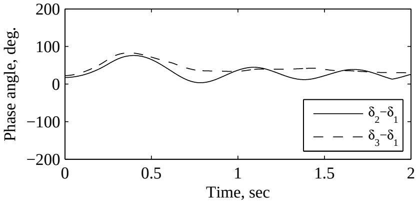
- Simplified generator model :
    - No advanced excitation control for generators
    - Governor actions are not considered
- Simplified HVDC model :
    - LCC-converters
    - HVDC line is modeled by a resistance
    - HVDC converters are assumed to apply settings within less than 10 ms
    - One converter maintains the voltage while the other adjusts the current to match the power setting
    - Limitations are considered for both voltage and current

Results 1/4 - Illustrative example

Fault at bus 5 in the 3 machine 9 bus system
(cleared at t=250ms)



CC



MPC-D_E

Results 2/4 - Impact of H

TTI obtained with different values of the MPC time horizon

H	Control strategy		
	D_P	D_C	D_E
1	343	353	350
3	361	361	356
5	361	361	360
10	361	361	361
15	361	361	361

Fault at bus 3 of the
3 machine 9 bus system

H	Control strategy		
	D_P	D_C	D_E
1	463	456	465
3	477	475	475
5	480	475	477
10	480	477	479
15	480	477	479

Fault at bus 22 of the
IEEE 24 bus system

Results 3/4 - Evaluation of the control strategies

TTI obtained on the 9 bus system with different control strategies

Fault	Control strategy					
	CC	*PI*	D_P	D_C	D_E	Optimal
1*-4	330	373	693	693	691	693
2*-7	357	364	426	430	427	437
3*-9	205	206	361	361	356	361
4*-5	299	299	299	299	299	299
4-5*	392	468	448	754	748	754
6*-4	309	340	850	358	824	856
7*-8	288	312	445	448	442	448
7-8*	260	271	799	798	807	812
6-9*	203	203	203	203	203	203

Results 4/4 - Evaluation of the control strategies

TTI obtained on the 24 bus system with different control strategies

Fault	Control strategy					
	CC	PI	D_P	D_C	D_E	Optimal
21-22*	321	323	477	475	475	482
15-21*	361	361	361	361	361	361
15*-21	476	498	752	758	754	788
17-18*	379	380	809	782	783	809
13*-23	443	488	460	463	447	468
16*-17	477	504	701	713	709	713
17*-18	462	483	866	860	847	868

Conclusion

- Contributions of the paper :
  - Using WAMS information can lead to significant benefits in terms of power system stability
  - MPC is a promising alternative for HVDC control even with a restricted time horizon
  - Instantaneous transient stability index are relevant and useful
- Further works :
  - Apply the MPC-based strategy in more detailed dynamic simulations
  - Consideration of time delays
  - Consideration of the lack of accuracy in state/dynamics estimation