Some Control Theory Problems in Modern Energy Systems

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- Transient Stability of Power Systems Revisited
- Wind Speed Estimator for Windmill Systems
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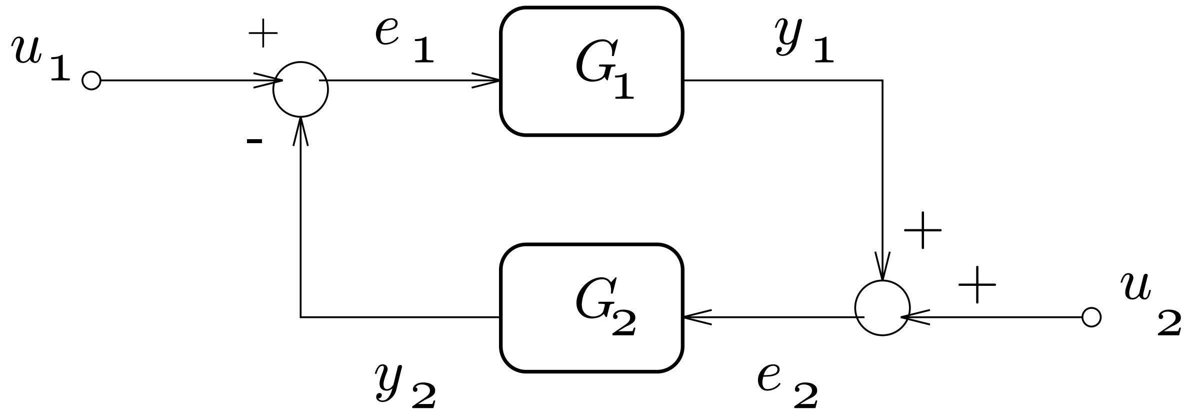
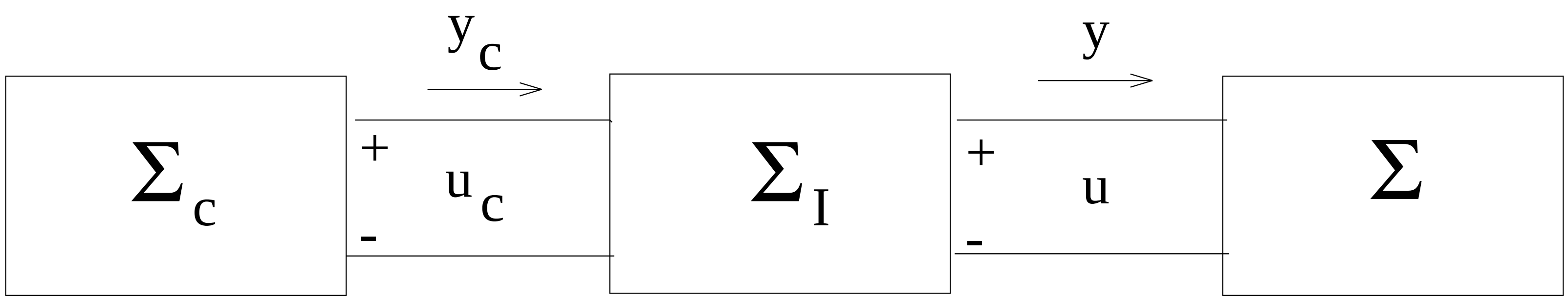
Main Message: Paradigm Shift for Controller Design

Classical formulation: Signal–processing viewpoint



- System model and controller are signal processors: $G_1 : e_1 \to y_1$, $G_2 : e_2 \to y_2$.
- Control specifications in terms of signals: tracking, disturbance attenuation, etc.
- Robustness represented via the "$\Sigma - \Delta$ paradigm", very successful for LTI systems: filtering reduces conservatism and easily computable.
- "Impossible" in nonlinear case:
  - nonlinear systems "mix" the frequencies,
  - far from obvious computations (NL filtering, Hamilton-Jacobi-Bellman PDE).

Basis of Passivity–based Control



- View plant as energy–transformation, as opposed to signal–transformation, device
- Consider systems that satisfy (generalized) energy–conservation:

  Stored energy = Supplied energy + Dissipation

- Control objective: preserve the energy–conservation property but with desired energy and dissipation functions

  Desired stored energy = New supplied energy + Desired dissipation

  In other words

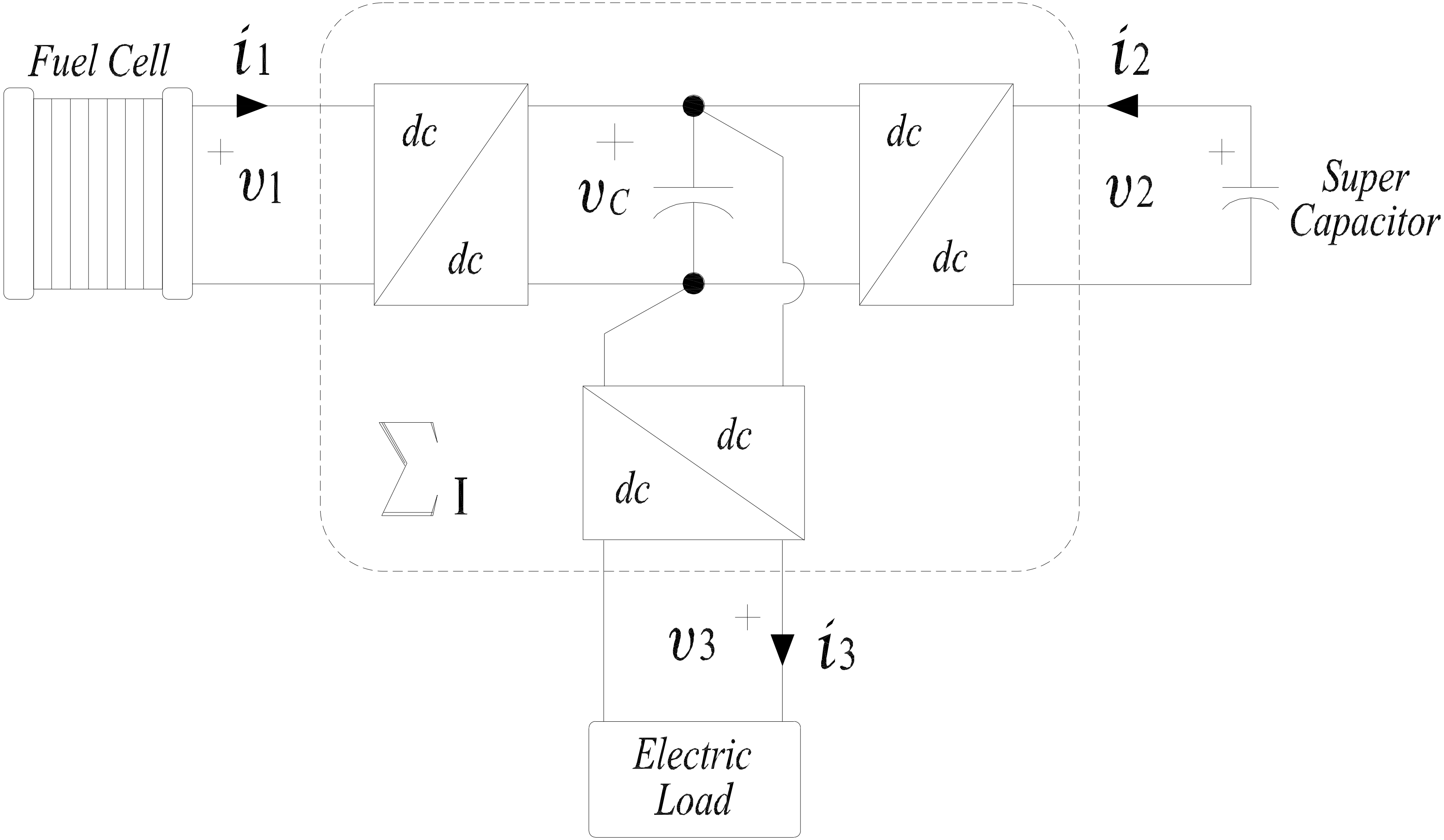
  PBC = Energy Shaping + Damping Assignment

- In many applications the natural viewpoint: active filters, FACTS, teleoperators, coordination/synchronization of large scale systems,...

Dynamic Energy Router

Formulation of the Energy Transfer Problem

Energy management between storing, generating and load units interconnected through power electronic devices



Current Practice, Limitations and Objective

- Assume that system operates in steady state
- Translate power demand into current or voltage references
- Track references with PI controllers in the power converters
- Discriminate between fast and slow changing power demand via linear filtering

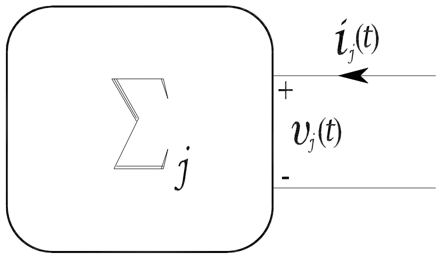
$\Rightarrow$ Behavior below par during transients and for fast changing demands

Our objective is to propose a Σ_I that

- Does not rely on steady–state considerations
- Allows to incorporate dynamic restrictions of the units

Mathematical Formulation of the Problem

- Units modeled as multiports Σ_j with port variables $v_j(t), i_j(t) \in \mathbb{R}^m$



- They verify the energy conservation law

$$H_j(t) - H_j(0) = \int_0^t v_j^\top(s) i_j(s) ds - d_j(t),$$

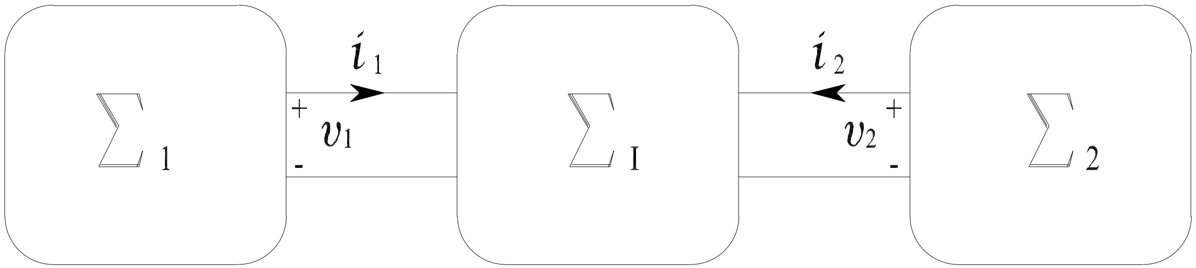
- $H_j(t)$ is the stored energy,
- The supplied energy is,

$$\int_0^t v_j^\top(s) i_j(s) ds.$$

- $d_j(t) \geq 0$ is the dissipation.

Duindam–Stramigioli Dynamic Energy Router

- DS–DER is a power–preserving interconnection Σ_I that transfer instantaneously the energy from one unit to the other. (Sanchez, *et al.*, IEEE–CSM'10)
- Assume, for simplicity, two ports



- Σ_I is power preserving selecting

$$\Sigma_I : \left\{ \begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} = \begin{bmatrix} 0 & \Gamma(t) \\ -\Gamma^\top(t) & 0 \end{bmatrix} \begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix} \right.$$

Indeed,

$$i_1^\top v_1 + i_2^\top v_2 = 0,$$

for any $\Gamma \in \mathbb{R}^{n\times n}$.

cont'd

- Now, neglecting dissipation,

$$\begin{aligned}\dot{H}_1 &= v_1^\top i_1 = v_1^\top \Gamma v_2 \\ \dot{H}_2 &= v_2^\top i_2 = -v_2^\top \Gamma^\top v_1.\end{aligned}$$

- How to select Γ? Take, for instance

$$\Gamma(t) = \alpha(t) v_1(t) v_2^\top(t), \quad \alpha(t) \in \mathbb{R}$$

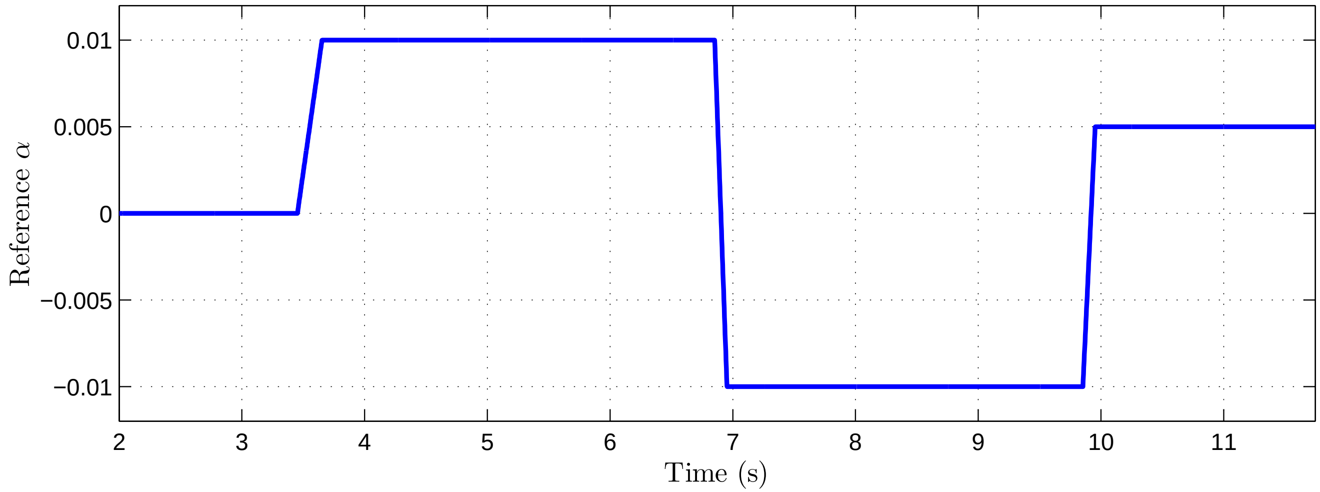
then

$$\begin{aligned}\dot{H}_1 &= \alpha |v_1|^2 |v_2|^2 \\ \dot{H}_2 &= -\alpha |v_1|^2 |v_2|^2.\end{aligned}$$

- $\alpha > 0$ transfers all energy from Σ_2 to Σ_1, ($\alpha < 0$, viceversa).
- Selecting the “shape" of $\alpha(t)$ we can regulate the energy transfer rate.

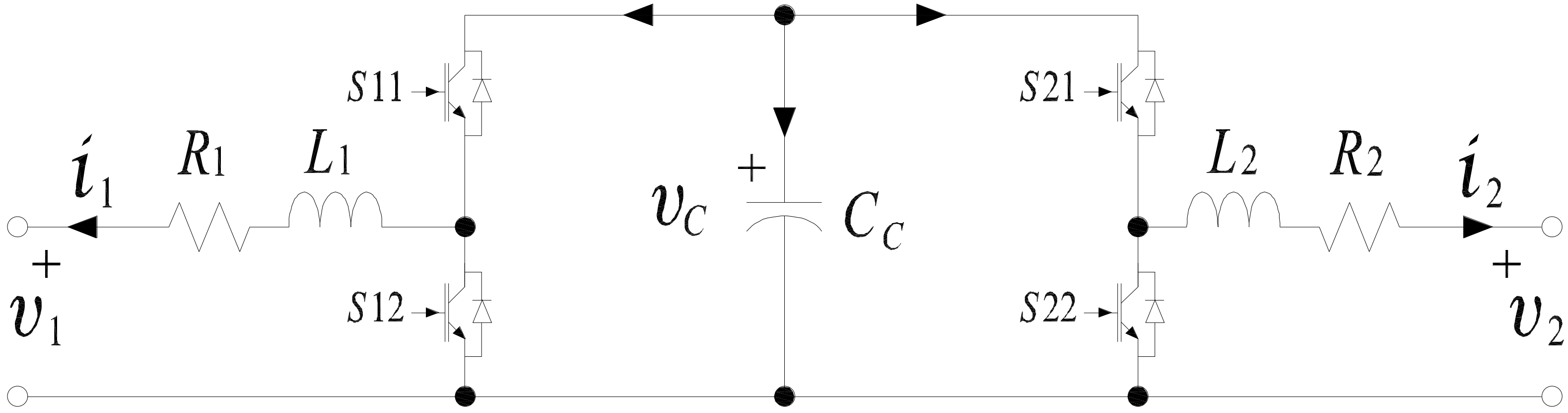
Experimental Results

- Σ_1, Σ_2 simple RC circuits.
- $\alpha(t)$ controls the direction and rate of change of energy flow.



- First, $\alpha(t)$ is positive and constant. Then, it decreases at a slow rate, until it achieves its lower value.
- Remains constant for some time and then increase at a faster rate.
- Finally, it reaches its maximum value and remains there until the end.

Power Electronics Implementation of DER



- Design a control law for the DER switches, which ensures that the currents track their desired references

$$\begin{bmatrix} i_1^\star(t) \\ i_2^\star(t) \end{bmatrix} = \begin{bmatrix} \alpha(t)v_1(t)v_2^2(t) \\ -\alpha(t)v_2(t)v_1^2(t) \end{bmatrix}.$$

- Fundamental problem: The energy of the DER verifies:

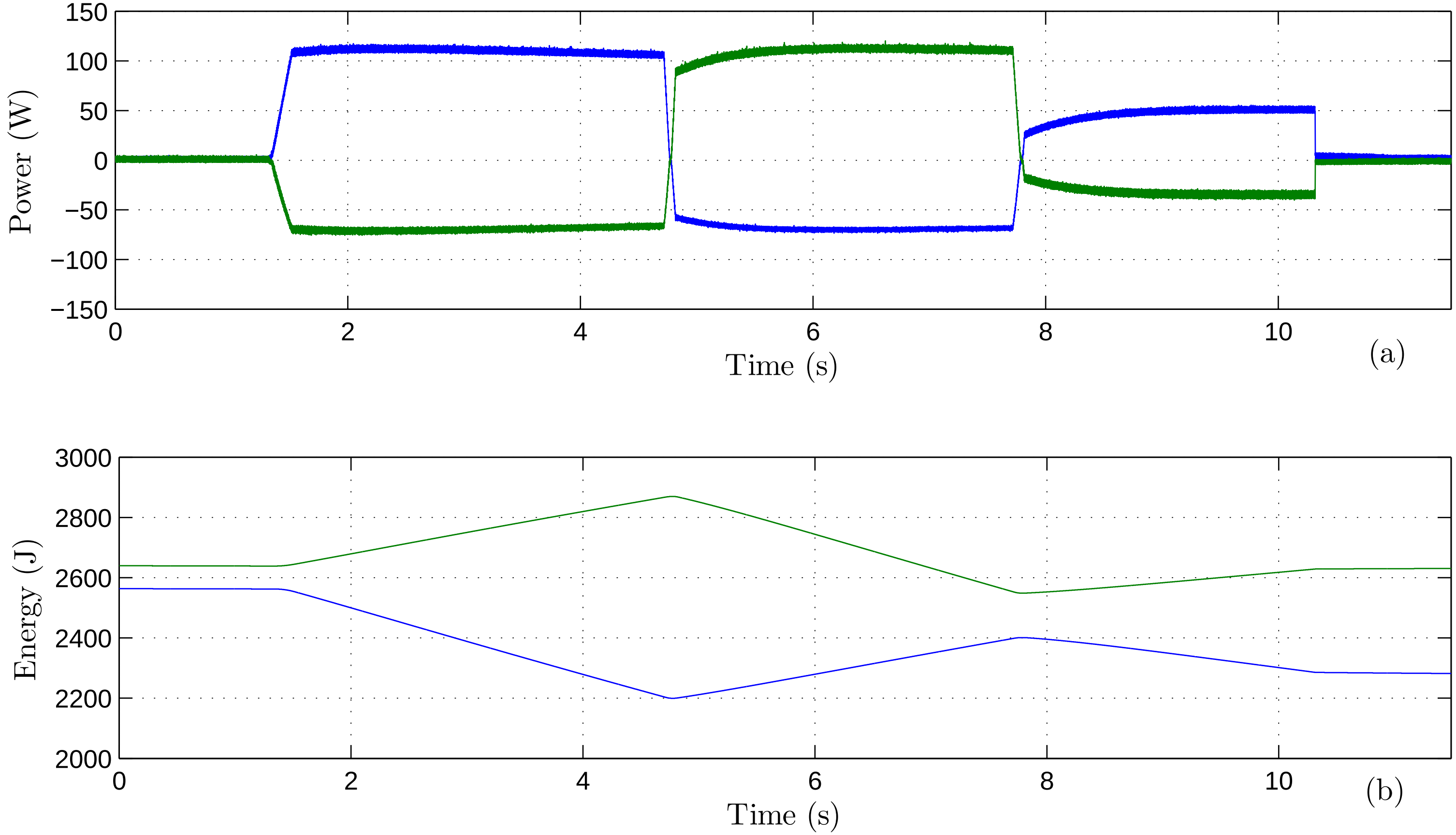
$$\dot{H}_I(t) = \underbrace{v_1(t)i_1(t) + v_2(t)i_2(t)}_{=0} - d_I(t) \leq 0,$$

and it becomes non-operational.

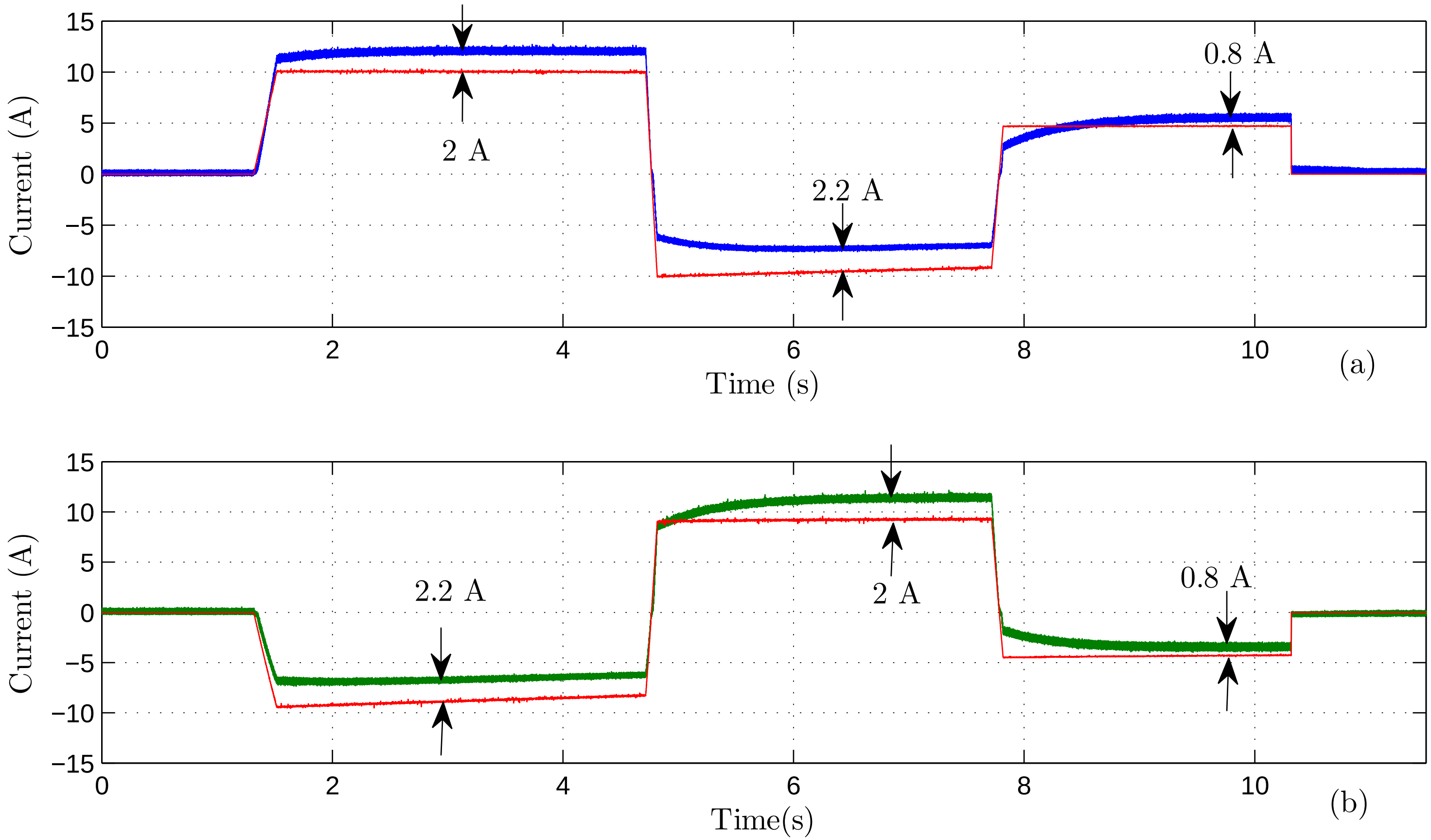
Compensating the Dissipation

- Adding outer–loop PI's to a feedback linearizing control to regulate the voltage $v_C(t)$:

$$w_j(t) = -k_p\widetilde{i}_j(t) - k_i\int_0^t \widetilde{i}_j(s)ds - k_{pv}\widetilde{v}_C(t) - k_{iv}\int_0^t \widetilde{v}_C(s)ds,\ j=1,2.$$



Currents of Σ_I and their References



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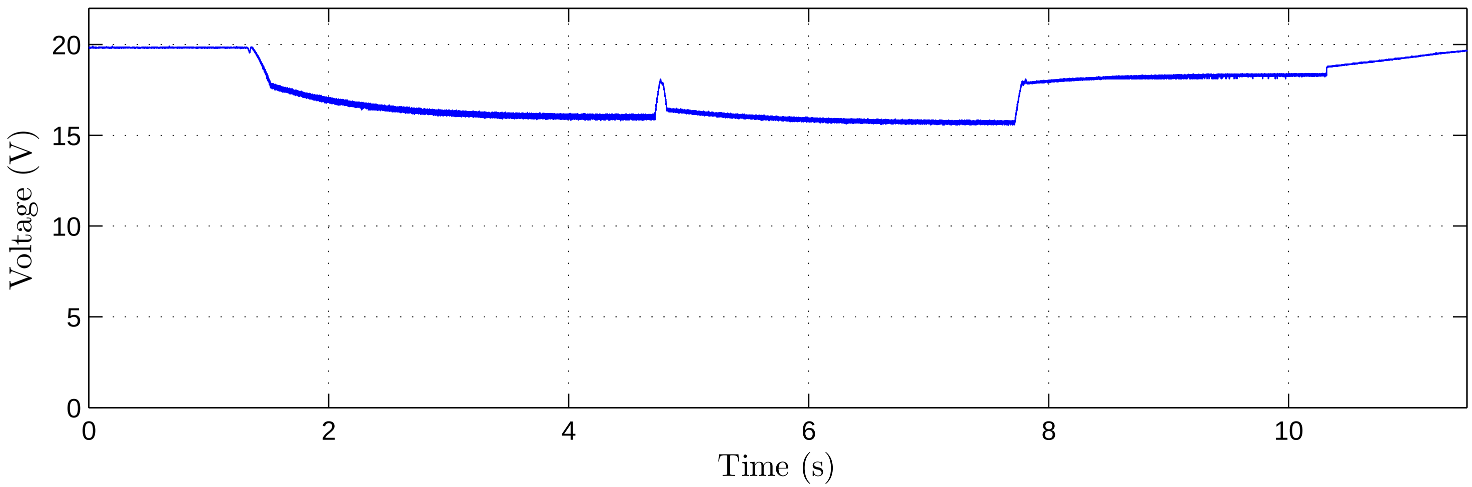
Voltage of DC Link



Proposed Solution: Abandon Power Preservation

- Define mappings $F_j(v)$ for the current references:

$$i_j^\star(t) = F_j(v(t)), \quad j \in \bar{N},$$

- Two different objectives:
  - Ensure the desired power dispatch, $P_j^\star(t) = v_j^\top(t) F_j(v(t))$.
  - Compensate dissipation, $\sum_{j=1}^N v_j^\top(t) F_j(v(t)) = d_I(t)$.
- Possible choice

$$F_j(v) = \delta_j \Pi_{k=1,k\neq j}^N |v_k|^2 v_j, \quad \sum_{j=1}^N \delta_j(t) = d_I(t).$$

- If $|v_j(t)| \geq \epsilon > 0$, fix

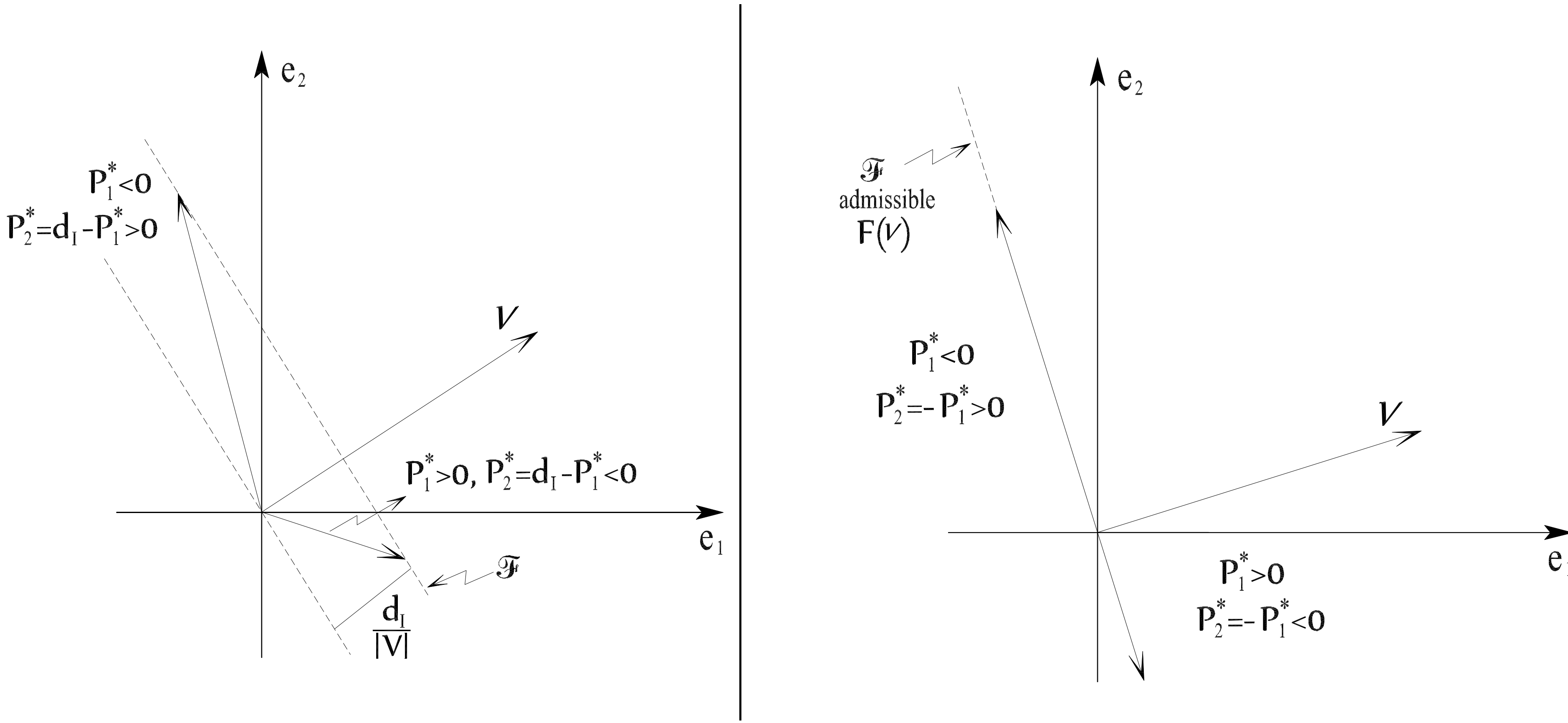
$$F_j(v_j(t)) = \frac{P_j^\star(t)}{|v_j(t)|^2} v_j(t),$$

with $\sum_{j=1}^N P_j^\star(t) = d_I(t)$.

Geometric Interpretation of the New DER and the DS–DER

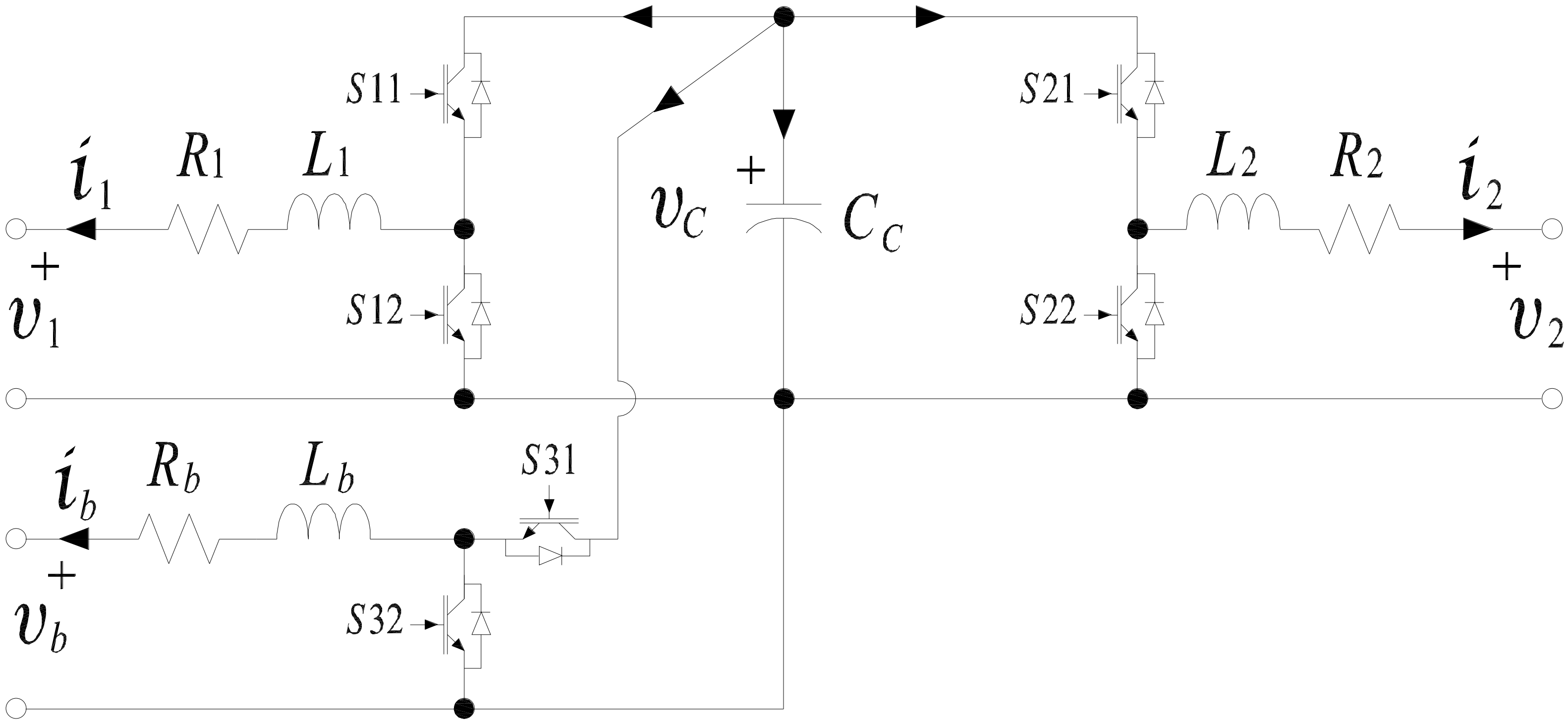
Given v and d_I, the set *F* defines the admissible vectors $F(v)$, that satisfy

$$\sum_{j=1}^{N} v_j^{\top}(t) F_j(v(t)) = d_I(t).$$



Simulation Results of the New DER

- A battery is added as a third port, to compensate the losses.



- Same energy pattern for the supercapacitors as before, i.e. $P_1^\star(t) = -P_2^\star(t)$, but

$$P_3^\star(t) = d_I(t) = R_1 i_1^2(t) + R_2 i_2^2(t) + R_3 i_3^2(t).$$

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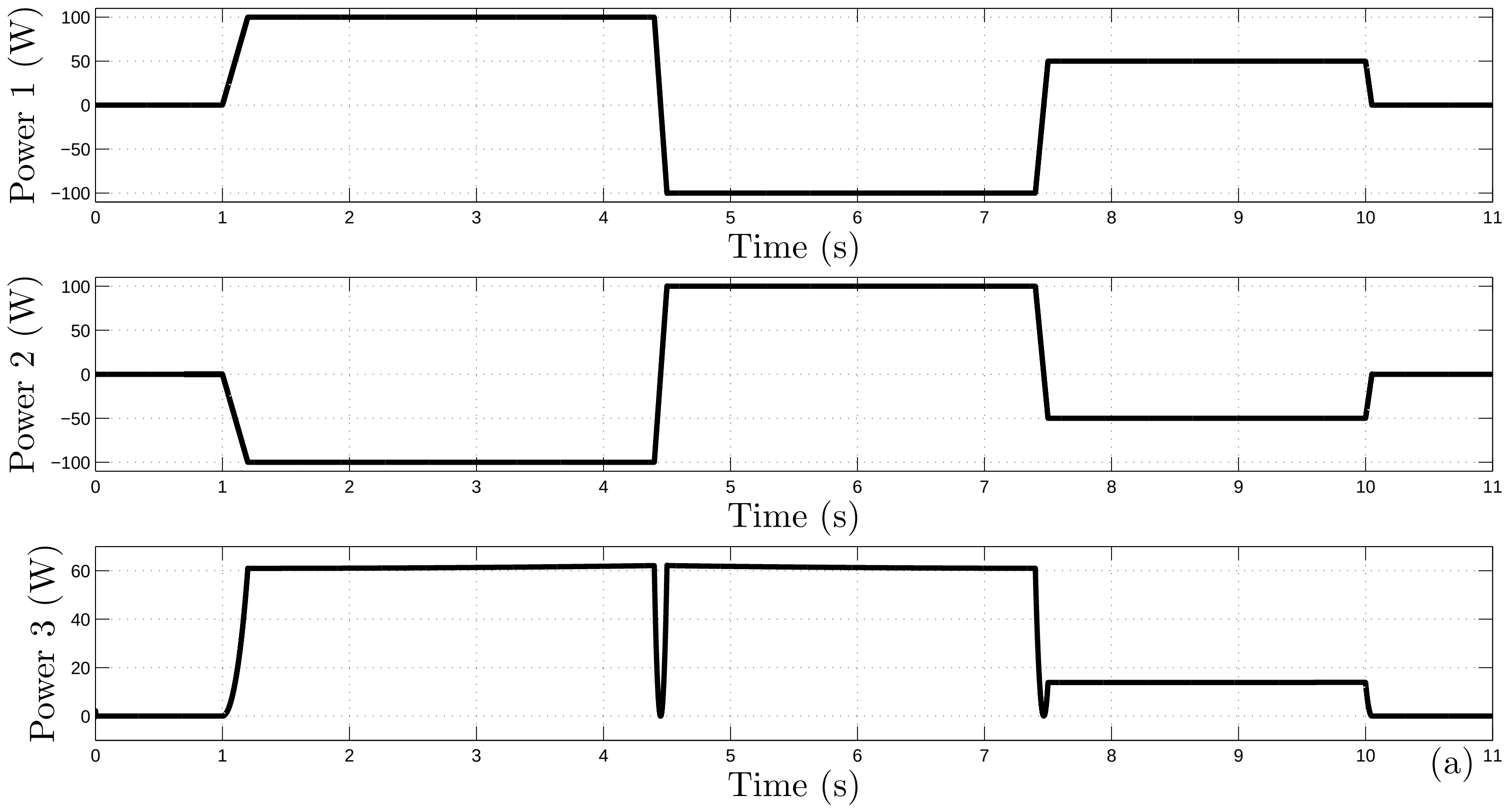
Power of Multiports



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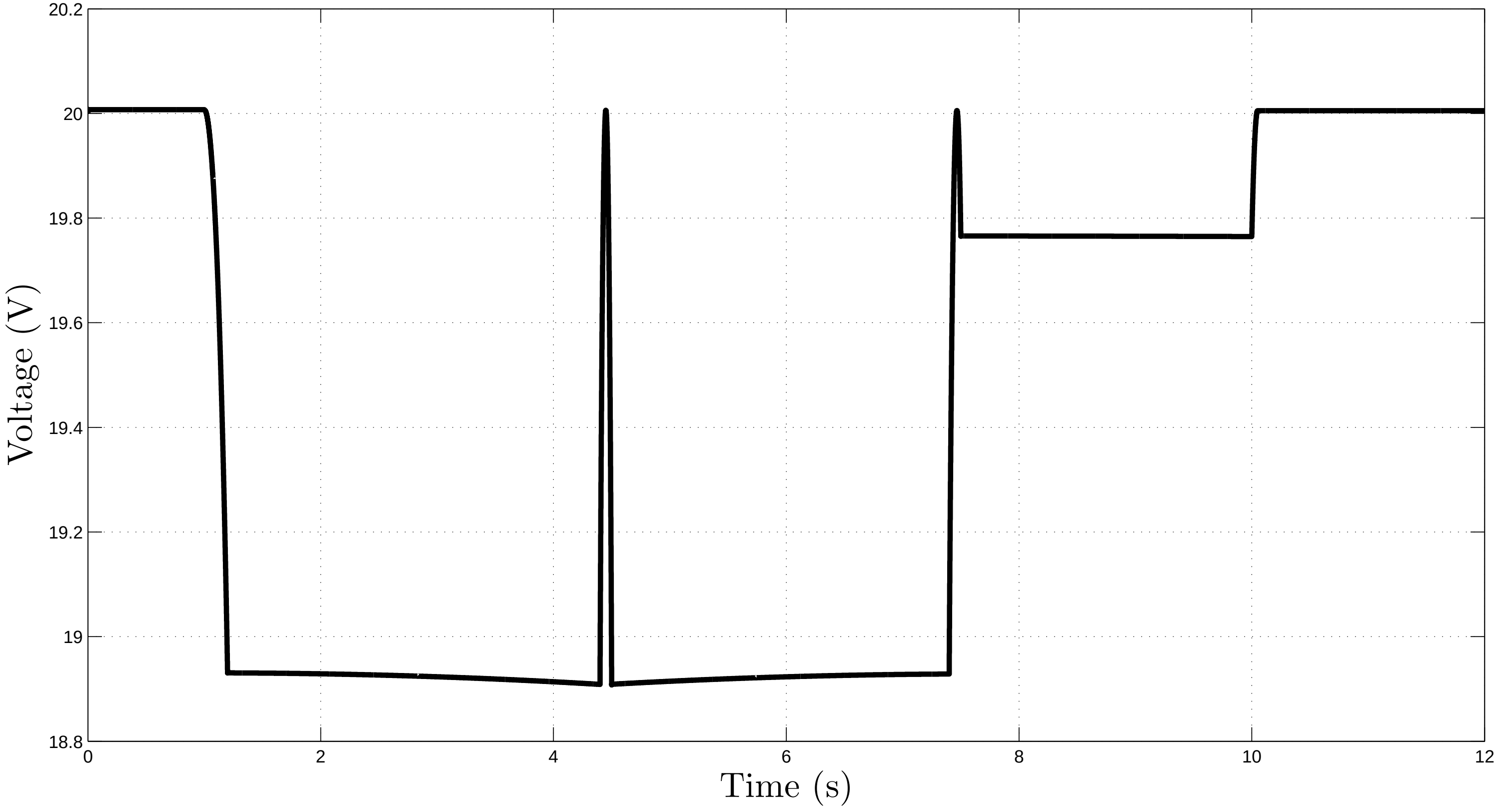
Voltage of DC Link



Transient Stability of Power Systems

Model of the Power System

- We consider a large–scale power system consisting of n generators interconnected through a transmission network which we assume is lossy.
- The dynamics of the i-th machine with excitation is represented by the classical three–dimensional flux decay model

$$\begin{aligned}
\dot{\delta}_i &= \omega_i \\
\dot{\omega}_i &= -D_i\omega_i + P_i - G_{ii}E_i^2 - E_i \sum_{j=1, j\neq i}^{n} E_j Y_{ij} \sin(\delta_i - \delta_j + \alpha_{ij}) \\
\dot{E}_i &= -a_i E_i + b_i \sum_{j=1, j\neq i}^{n} E_j \cos(\delta_i - \delta_j + \alpha_{ij}) + E_{fi} + u_i
\end{aligned}$$

- δ_i, ω_{Mi}: rotor angle and speed, E'_{qi}: the quadrature axis internal voltage, u_{fi}: the field excitation signal, $G_{Mij} = G_{Mji}$, $B_{Mij} = B_{Mji}$ and G_{Mii}: conductance, susceptance and self-conductance of the generator i, E_{fsi}: constant component of the field voltage, P_{mi}: constant mechanical power, $x_{di}, x'_{di}, \omega_{i0}$ and D_{Mi}: direct-axis—synchronous and transient—reactances, synchronous speed and damping coefficient

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Problem Formulation and Solution

- Assume the model with $u_i = 0$ has a stable equilibrium point at $[\delta_{i*}, 0, E_{i*}]$, with $E_{i*} > 0$. Find a control law u_i such that in closed–loop
  - an operating equilibrium is preserved,
  - a Lyapunov function for it is given and,
  - it is asymptotically stable with a well–defined domain of attraction.
- Two additional requirements are that the domain of attraction of the equilibrium is enlarged by the controller and that the Lyapunov function has an energy–like interpretation.
- For lossless lines we can assign

$$H_d(\delta, \omega, E) = \psi(\delta) + \frac{1}{2}|\omega|^2 + \frac{1}{2}(E - E_*)^\top \Gamma (E - E_*),$$

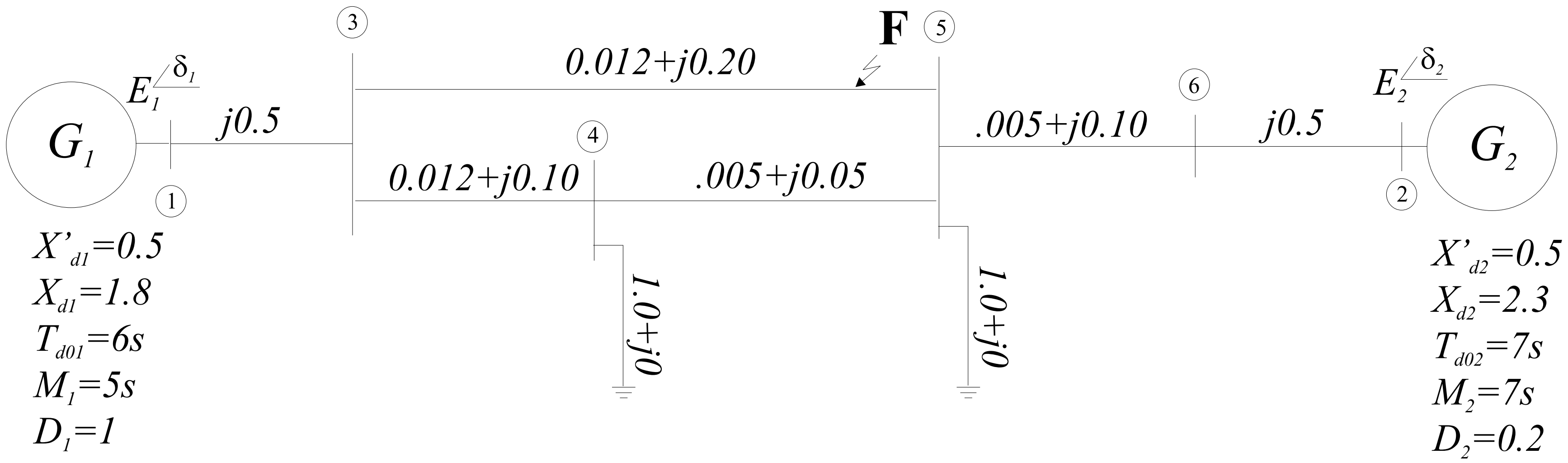
- If the lines are lossy we have to introduce a cross-term in the energy function.

$$H_d(\delta, \omega, E) = \psi(\delta) + \frac{1}{2}|\omega|^2 + \frac{1}{2}[E - \lambda(\delta)E_*]^\top \Gamma [E - \lambda(\delta)E_*].$$

- (Ortega, *et al.*, TAC'08)

Simulations

- Consider the two machines system



- The disturbance is a three-phase fault in the transmission line that connects buses 3 and 5, cleared by isolating the faulted circuit simultaneously at both ends.
- This modifies the topology of the network an consequently induces a change in the equilibrium point.
- Without control the system is highly sensitive to the fault and the critical clearing time is almost zero.

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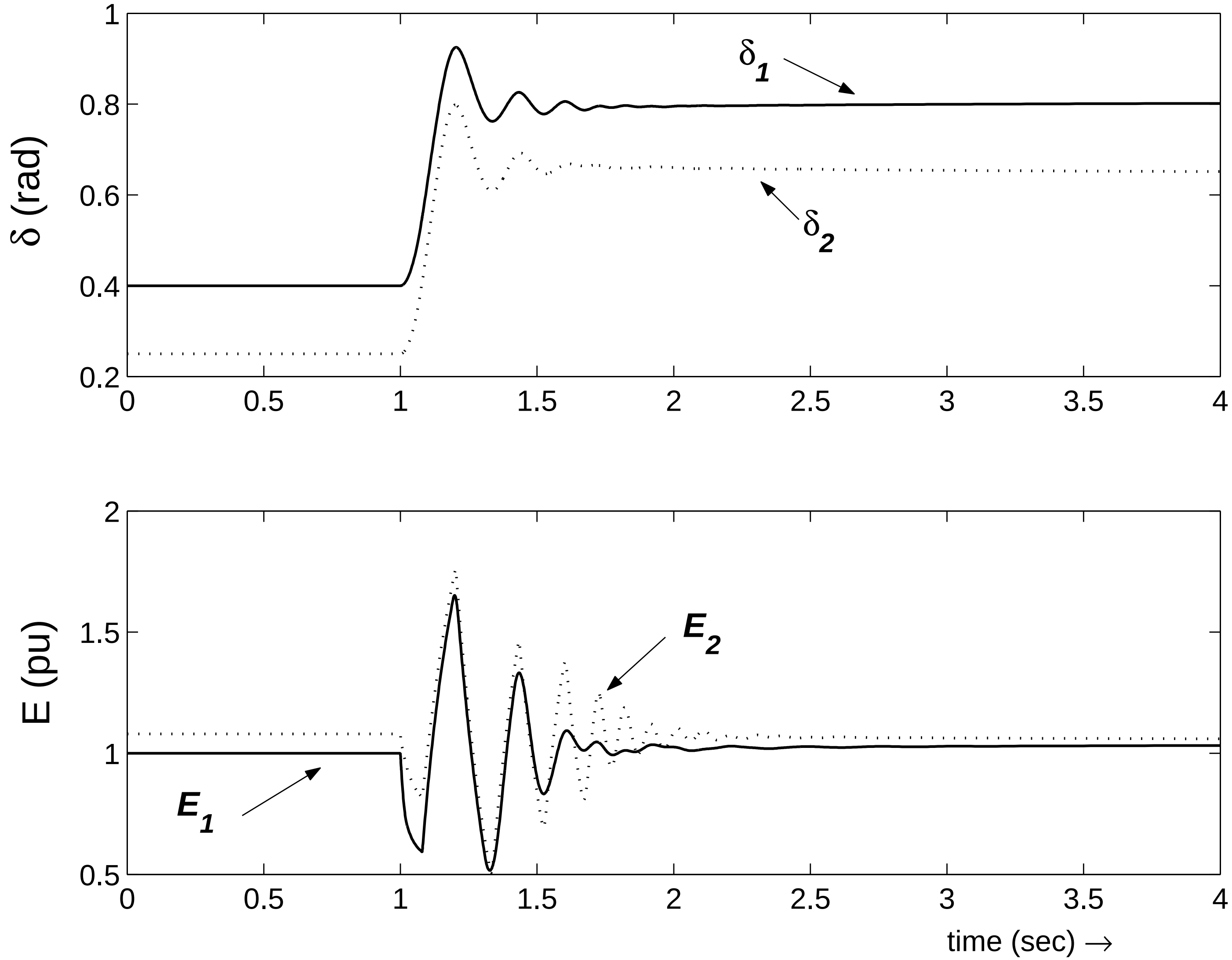
Load Angle and Internal Voltage, $t_{cl} = 80\ m\sec$



Other Results and Open Questions

- Considered also actuation via flexible AC transmission systems, (Manjarekar, *et al.*, Electrical Power Systems Research'10, EJC'11).
- Structure preserving models
  - Cyclo-dissipativity properties have been established and a linear controller proposed – leads to an LMI test, (Guisto, *et al.*, CDC'08).
  - "Full solution" using Lyapunov–based designs (Dib, *et al.*, TAC'10), (Casagrande, *et al.*, CDC'11).
- Alternative formulation as a synchronization, not stabilization, problem, (Dib, *et al.*, ACC'11).
  - Immersing a pendular dynamics.
  - Existence solution for n machines.

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Wind Speed Estimation in Windmill Systems

Model of the Windmill System

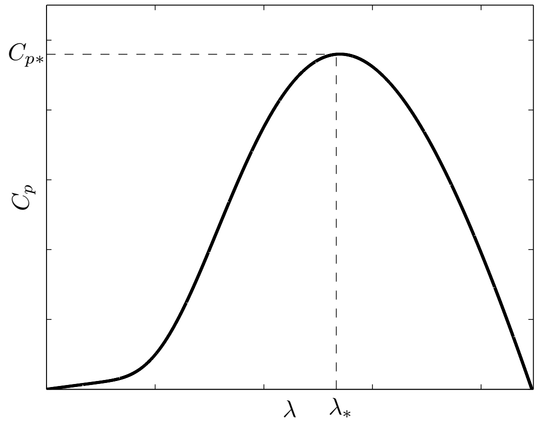
- System is a wind turbine and a generator. The mechanical dynamics

$$(SM) \quad J\dot{\omega}_m = \frac{P_w}{\omega_m} - T_e.$$

- The mechanical power at the windmill shaft

$$P_w = \frac{1}{2}\rho A C_p(\lambda) v_w^3, \quad \lambda := \frac{r\omega_m}{v_w}.$$

- The power coefficient $C_p(\lambda)$



Wind Speed Estimation Problem

Problem Formulation Given the system, verifying:

- Assumption 1 The power coefficient is a known, smooth, function $C_p : [0, \lambda_M] \to \mathbb{R}_+$, which verifies

$$C_p'(\lambda) \begin{cases} > 0 & \text{for} \quad \lambda \in [0, \lambda^\star) \\ = 0 & \text{for} \quad \lambda = \lambda^\star \\ < 0 & \text{for} \quad \lambda \in (\lambda^\star, \lambda_M], \end{cases}$$

  where $\lambda^\star := \arg\max C_p(\lambda)$.
- Assumption 2 The wind speed v_w is an unknown positive constant.
- Assumption 3 The electrical torque T_e and the motor speed w_m are measurable.
- Assumption 4 For all $\lambda \in (0, \lambda^\star)$, the power coefficient verifies

$$\frac{3}{\lambda} C_p(\lambda) > C_p'(\lambda).$$

Design an on–line estimate of the wind speed, $\hat{v}_w$, such that

$$\lim_{t \to \infty} \hat{v}_w(t) = v_w.$$

Some Remarks

- $C_p(\lambda)$ can be easily obtained from experimental data, and the algorithm implemented from a table look–up.
- Constant wind speed assumption only needed for the theory. An on–line estimator is able to track slowly–varying parameters, assumption justified by the time scale separation between the wind dynamics and the mechanical and electrical signals.
- On–line estimators average the noise—in contrast with differentiator–based or extended Kalman filter schemes currently used.
- Measuring w_m and T_e is standard practice in windmill systems.
- Theory applicable also if blade pitch β is included, i.e., $C_p(\lambda, \beta)$, or for more complete descriptions of the mechanical dynamics. For instance

$$
(FM) \qquad
\begin{aligned}
I_r \dot{\omega}_r &= \frac{P_w}{\omega_m} - K_\theta \theta - B_\theta \dot{\theta} - B_r \omega_r \\
I_g \dot{\omega}_g &= -T_e + \frac{K_\theta}{N}\theta + \frac{B_\theta}{N}\dot{\theta} - B_g \omega_g \\
\dot{\theta} &= \omega_r - \frac{\omega_g}{N} \\
P_e &= T_e \omega_g .
\end{aligned}
$$

Main Estimation Result

Proposition (Ortega, *et al.*, IJACSP'11) Consider the system (SM), verifying Assumptions 1–4. The estimator

$$\begin{aligned} \dot{\hat{v}}_w^I &= \gamma\left[T_e - \frac{\rho A}{2}\frac{(\hat{v}_w^I+\gamma\omega_m)^3}{\omega_m}C_p\left(\frac{r\omega_m}{\hat{v}_w^I+\gamma\omega_m}\right)\right] \\ \hat{v}_w &= \hat{v}_w^I + \gamma\omega_m, \end{aligned}$$

where $\gamma > 0$, is an adaptation gain, is asymptotically consistent, that is,

$$\lim_{t\to\infty} \hat{v}_w(t) = v_w.$$

Remark Assumption 4 is satisfied in the range where the torque coefficient has negative slope. Indeed,

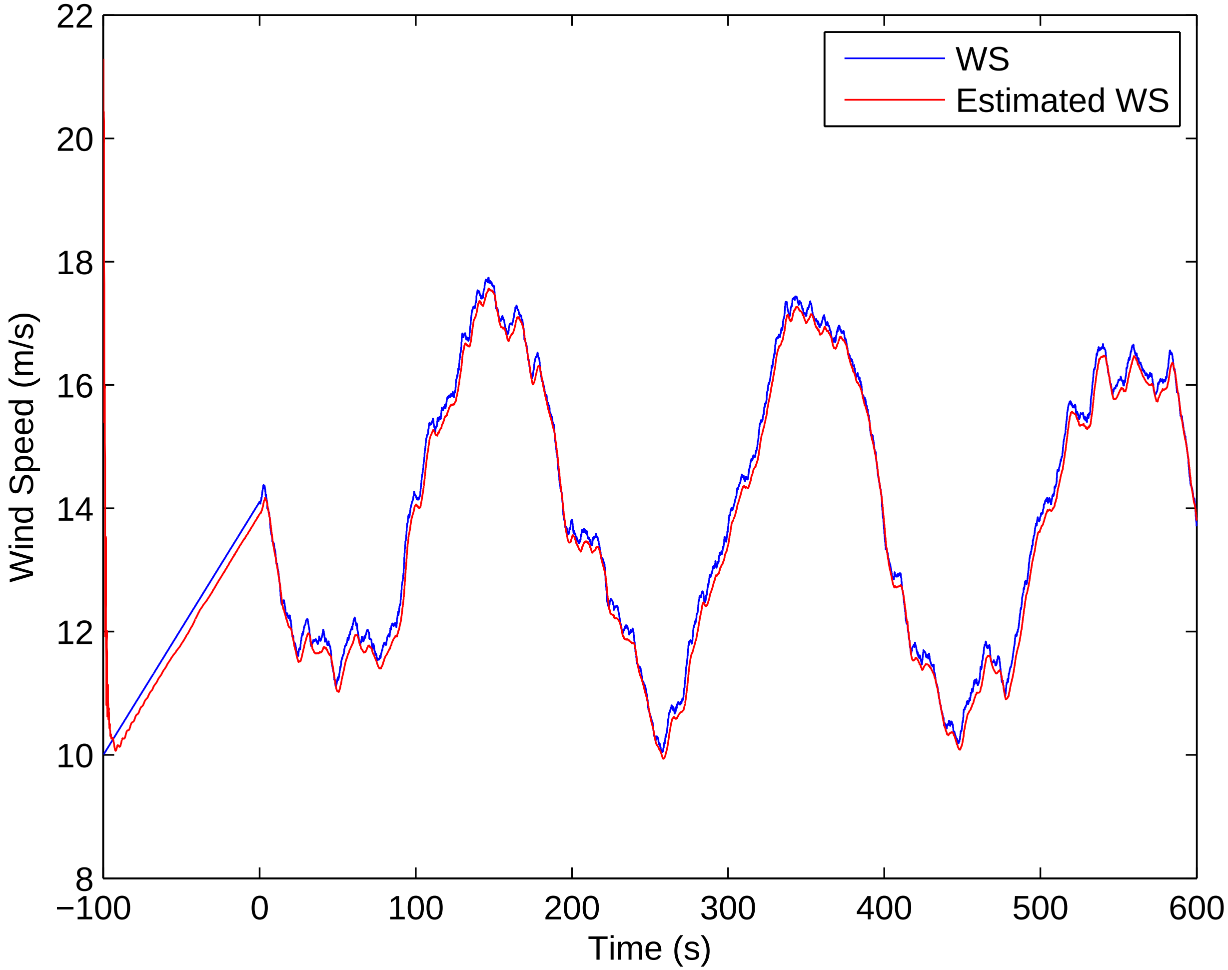
$$C_T(\lambda) := \frac{1}{\lambda}C_p(\lambda),$$

satisfies

$$C_T'(\lambda) \le 0 \;\Rightarrow\; \text{Assumption 4.}$$

Simulation Results: Periodic Wind

Done in Vestas professional software, with the full model (FM) and real wind data.



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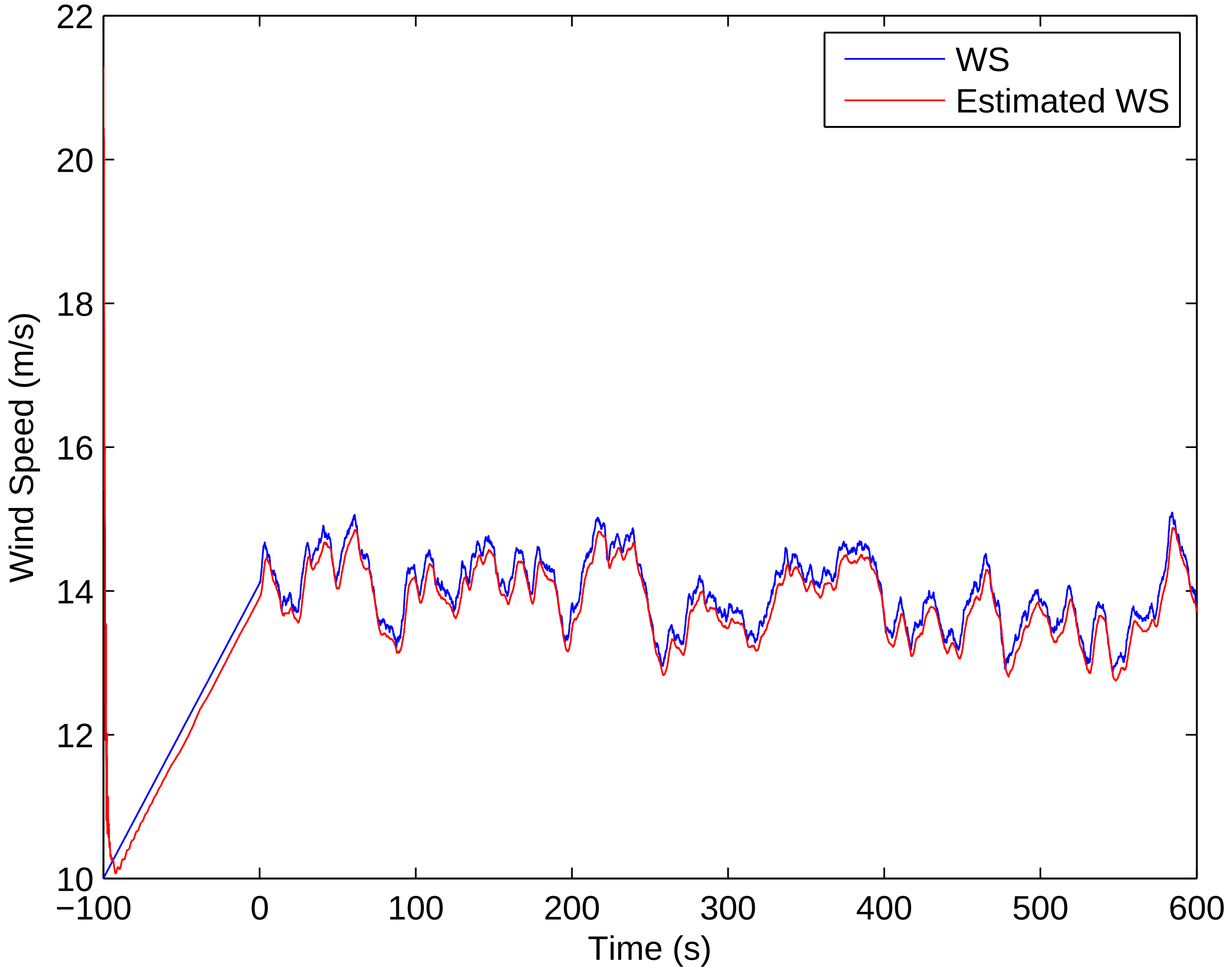
Simulation Results: Turbulent Wind



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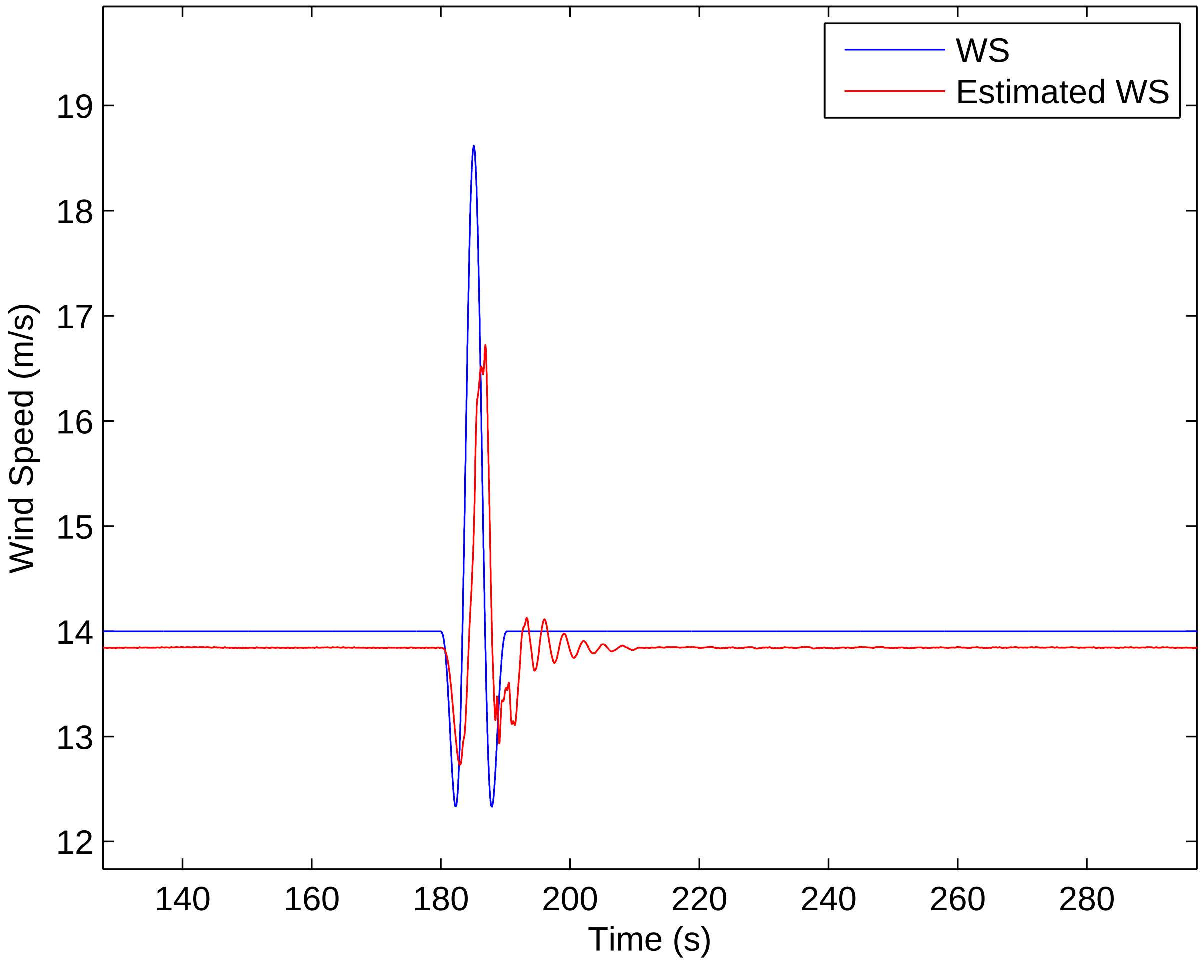
Simulation Results: Gust



Some Additional Results

- Energy quality
  - Power factor compensation is equivalent to cyclo–dissipasivation: The nonlinear non–sinusoidal case, (Garcia, *et al.*, IEEE-CSM'07).
  - Passivity and robust PI control of the air supply system of a PEM fuel cell model, (Talj and Ortega, Automatica'11).
- Power converters
  - An adaptive PBC for a unity power factor rectifier, (Escobar, *et al.*, IEEE TCST'01).
  - Experimental comparison of several PWM controllers for a single-phase ac-dc converter, (Karagiannis, *et al.*, IEEE-TCST'03).
  - An adaptive controller for the shunt active filter considering a dynamic load and the line impedance, (Valdez, *et al.*, IEEE-TCST'09).
- Drives
  - Sensorless control of PMSM with guaranteed stability properties, (Shah, *et al.*, IFAC'11).
  - PBC of doubly–fed induction machines, (Battle, *et al.*, EJC'07).