# Chapter 19: Transient Stabilization in Systems With Wind Power Using Fast Power-Electronically-Switched Storage

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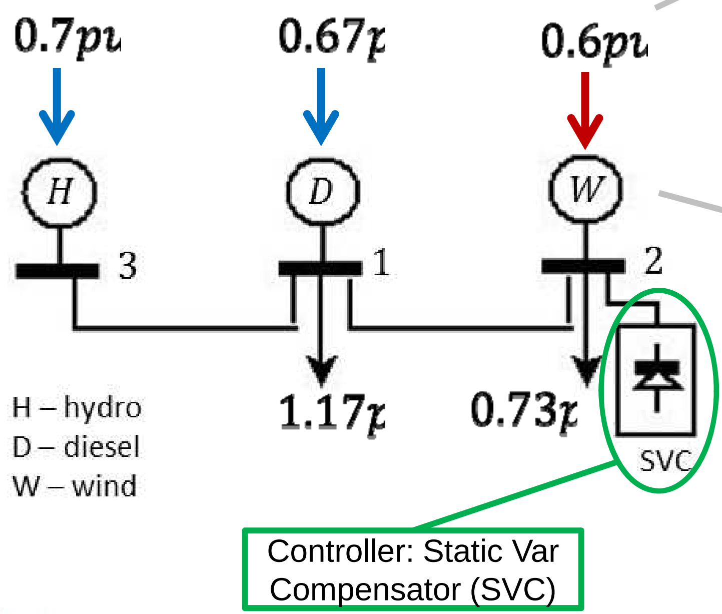
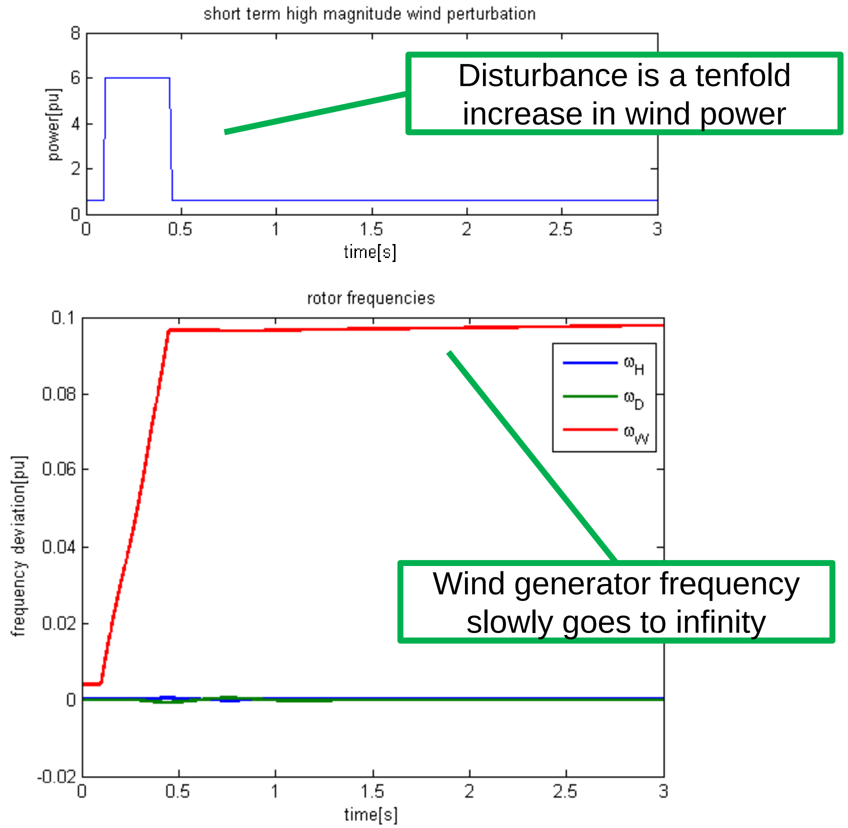
# Outline

- Transient stability problem in Flores Island power system
- Proposed solutions
  - Using FACTS as short-term energy storage
  - Using Flywheels as ‘longer-term’ energy storage
- Simulation results

# Transient Stability Problems Due to Large Disturbances

- Types of large disturbances causing transient instabilities
  - High wind surges in Flores Island
  - Failures of equipment and faults
- Frequency instability

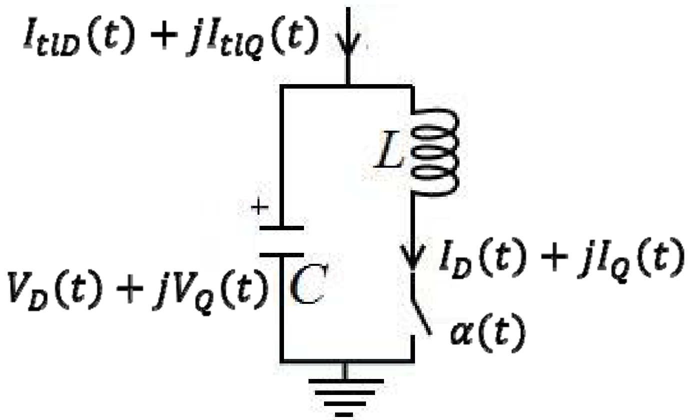


# Transient Stabilization using FACTS

- Establish a *nonlinear model* which is relevant for representing large disturbances
- *Time-varying phasors* are used to model dynamics of generators and FACTS devices
- Nonlinear control is *energy-based*; energy function is expressed using time-varying phasors
- Energy function has a physical interpretation of *incremental accumulated (stored) energy* in the system
- *Controller shifts* the incremental stored energy between generators and FACTS devices

# Time-Varying Phasor Model of FACTS (SVC)




$$\dot{V}_D(t) = \frac{1}{C}\left(I_{tlD}(t) - I_D(t)\right) + \omega V_Q(t)$$

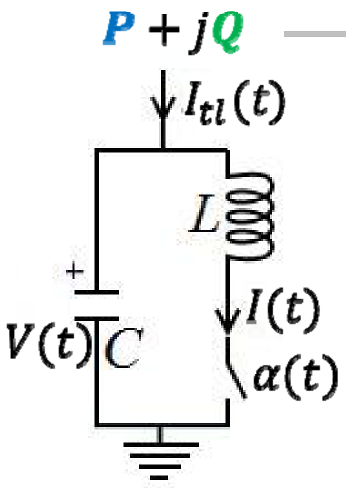
$$\dot{V}_Q(t) = \frac{1}{C}\left(I_{tlQ}(t) - I_Q(t)\right) - \omega V_D(t)$$

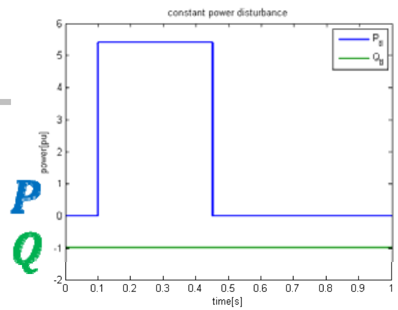
$$\dot{I}_D(t) = \frac{\alpha(t)}{L} V_D(t) + \omega I_Q(t)$$

$$\dot{I}_Q(t) = \frac{\alpha(t)}{L} V_Q(t) - \omega I_D(t)$$

- Time-varying phasors are used to model transmission lines and FACTS
  - Fast dynamics is captured
  - ODE model is established
- Assume fast thyristor switching – averaged switching model

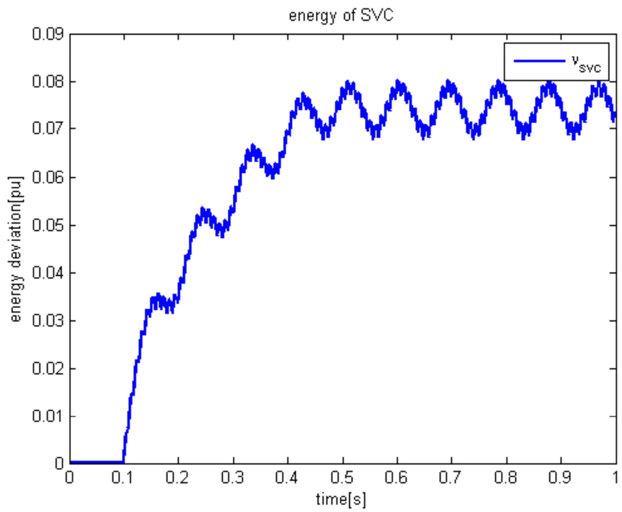
# Using FACTS Devices as Temporary Energy Storage



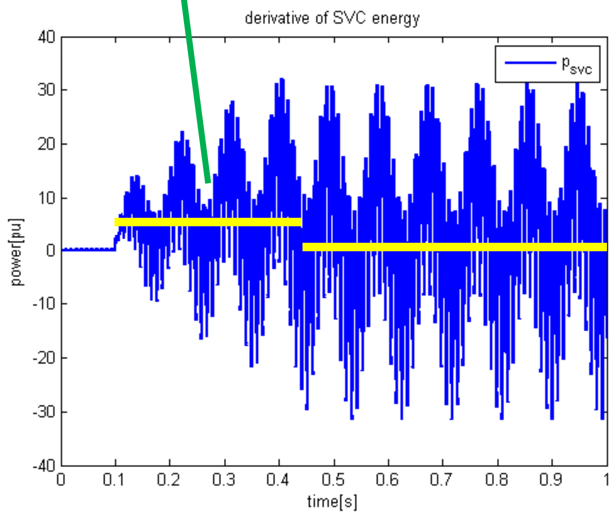




- Exploit the fact that reactive elements can accumulate active power during transients

Active power is different than zero on the average and it is equal to the size of the constant power disturbance $P$




$$v(t) = \frac{1}{2}L\tilde{I}^2(t) + \frac{1}{2}C\tilde{V}^2(t)$$




$$p(t) = \frac{dv(t)}{dt} = L\tilde{I}(t)\frac{d\tilde{I}(t)}{dt} + C\tilde{V}(t)\frac{d\tilde{V}(t)}{dt}$$

$$P = \frac{1}{T}\int_0^T p(t)dt$$

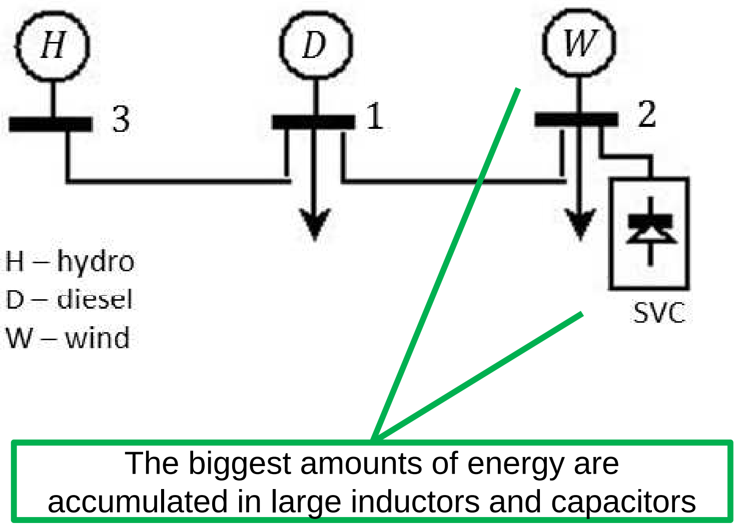
# Energy-based Control Law

$$v(t) = \sum_i v_{Ci}(t) + \sum_i v_{Li}(t)$$

$$\dot{v}(t) = \dot{v}_{diss}(t) + \dot{v}_{exch}(t) + \dot{v}_{acc}(t)$$

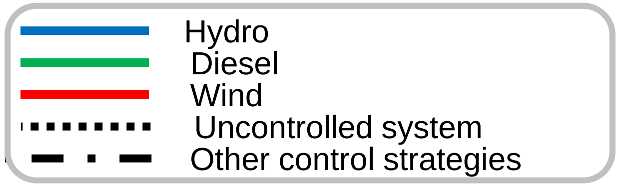
$$e(t) = \dot{v}^{ref}(t) - \dot{v}_{acc}(t) = P^{ref}(t) - \dot{v}_{acc}(t)$$

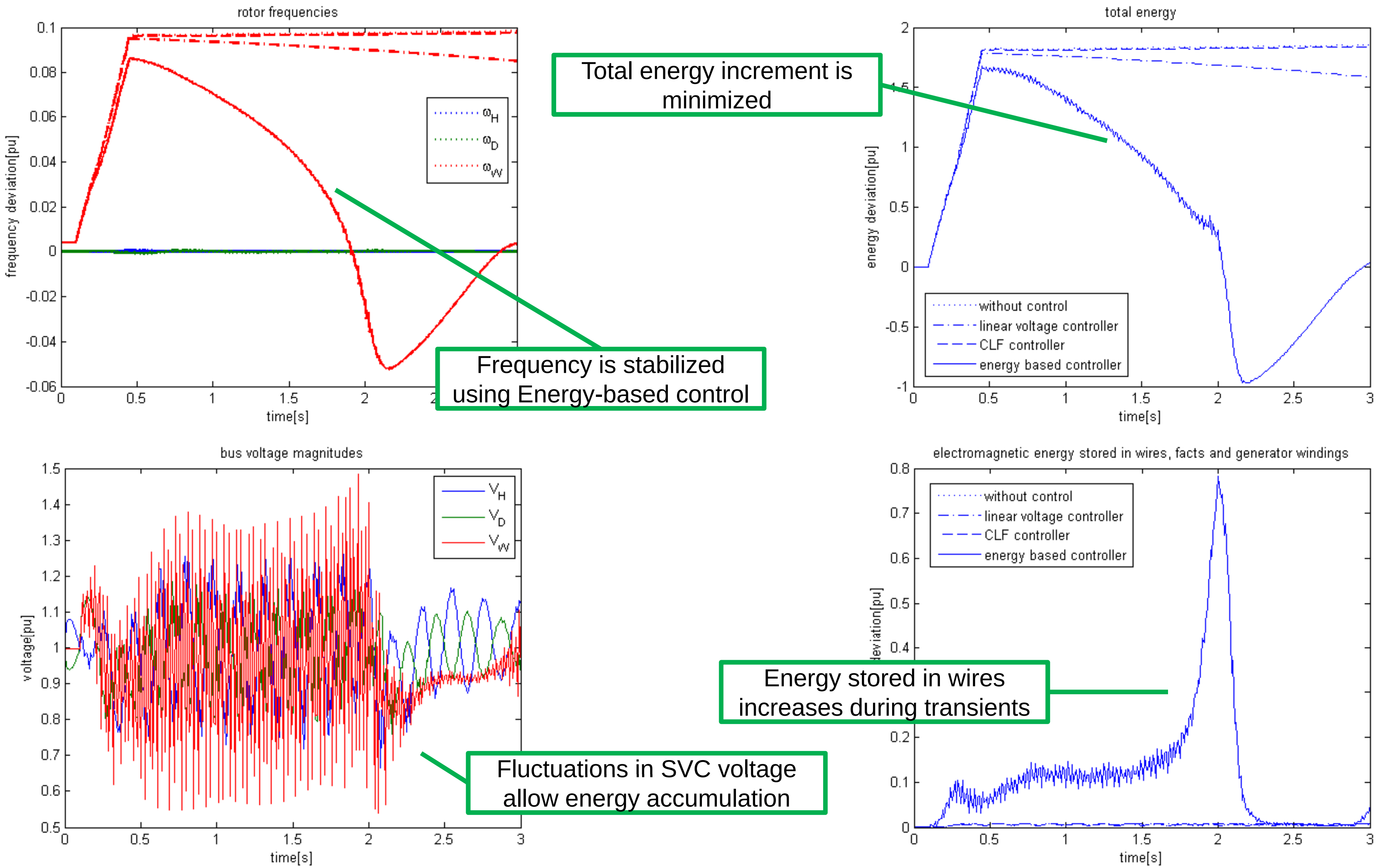
$$\alpha(t) = K_P e(t) + K_I \int_0^t e(\tau)d\tau$$




- Temporarily accumulates energy of a disturbance in FACTS devices [6].

# Simulation Results



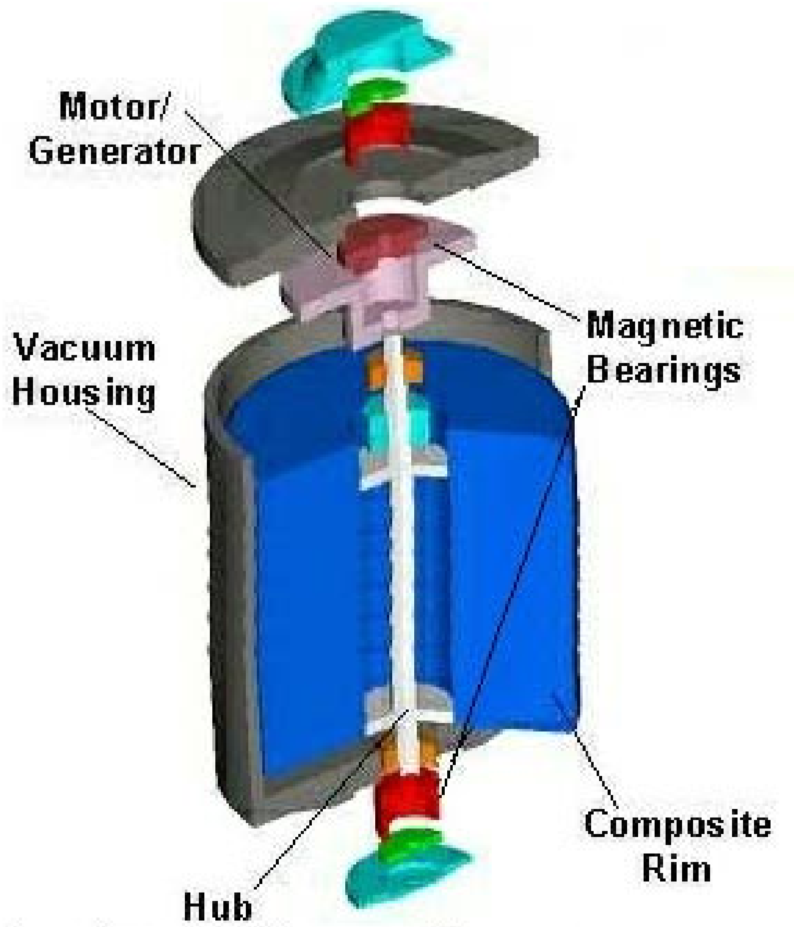



# Transient Stabilization using Flywheels

- Introduce flywheels and their applications
- Sliding mode control
- Use flywheels in response to large wind disturbances when
  - Modeling the rest of the system as a disturbance
  - Modeling the dynamics of the rest of the system

# Flywheel Energy Storage System

- Stores energy by accelerating a rotor to a very high speed
- Tensile strength of rotor material determines maximum capable stored energy
- Flywheel is connected to electric machine to control its rotational speed
- To decrease energy losses
  - Flywheel is operated in a vacuum
  - Magnetic bearings are used to levitate rotor [2],[3],[4]



# Potential Applications for Flywheels

- Flywheels have small time constants (compared to generators and alternative types of storage)
- Can be used for uninterruptible power supply, frequency stabilization, frequency regulation
- While FACTS devices can store active power only during transients, flywheels can store active power in steady state also
- Therefore, flywheels are more appropriate to use for prolonged disturbances

# Dynamic Model of Flywheel

- When flywheel is connected to permanent magnet synchronous machine:
  - 3 state variables: $\omega_f$, $i_{qs}$, $i_{ds}$
  - 2 input variables: $v_{qs}$, $v_{ds}$

$$\frac{N}{2}\lambda_m i_{qs} = T_e = J\frac{d\omega_f}{dt} + D\omega_f$$

$$v_{qs} = r_s i_{qs} + L\frac{di_{qs}}{dt} + \omega_f L i_{ds} + \omega_f \lambda_m$$ [5]

$$v_{ds} = r_s i_{ds} + L\frac{di_{ds}}{dt} - \omega_f L i_{qs}$$

# Sliding Mode Control

- Drive $i_{qs}$ and $i_{ds}$ to desired values by fast switching of $v_{qs}$ and $v_{ds}$

***Switching Function***

$$S_{ds} = i_{ds}^* - i_{ds}$$
$$S_{qs} = i_{qs}^* - i_{qs}$$

***Voltage Input***

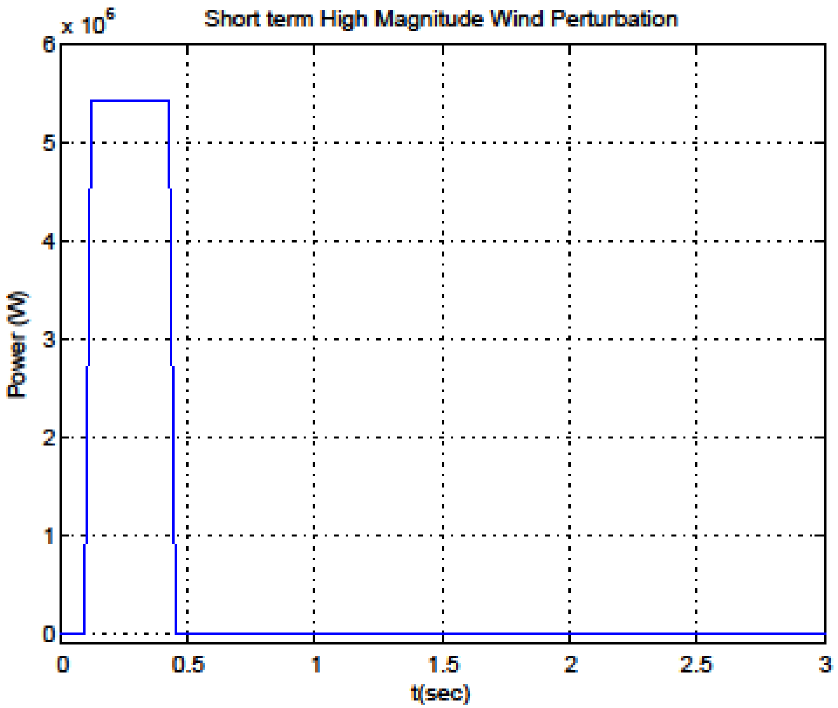
$$v_{ds} = V_0 sign\{S_{ds}\}$$
$$v_{qs} = V_0 sign\{S_{qs}\}$$

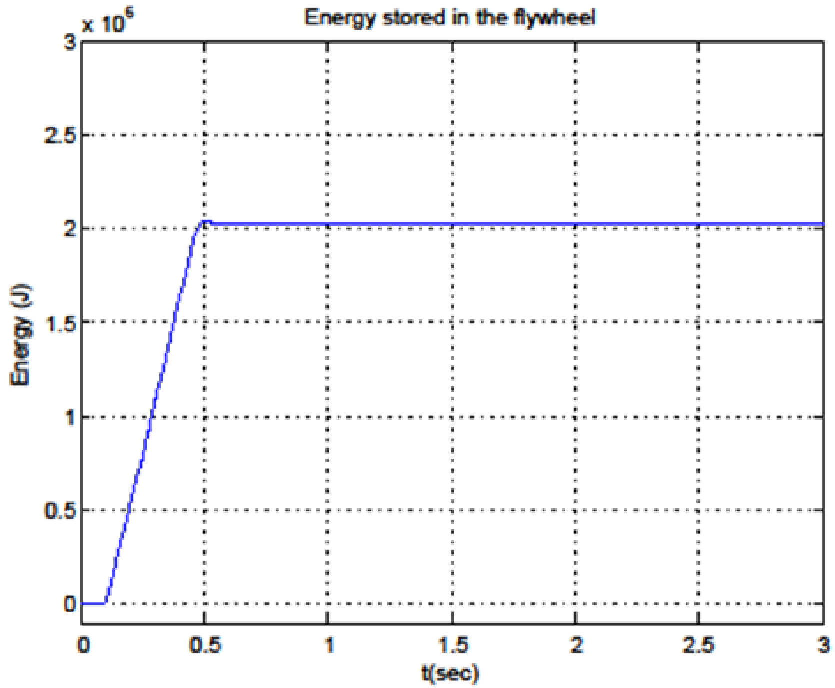
***Flywheel Power***

$$P_f = T_e \omega_f$$
$$P_f = \frac{N}{2} \lambda_m i_{qs} \omega_f$$

# Response to Wind Disturbance

- Treat the rest of the system as a disturbance
- Set $i_{qs}^{*} = \dfrac{2\Delta P_{wind}}{N\lambda_m\omega_f}$ , so flywheel absorbs wind disturbance



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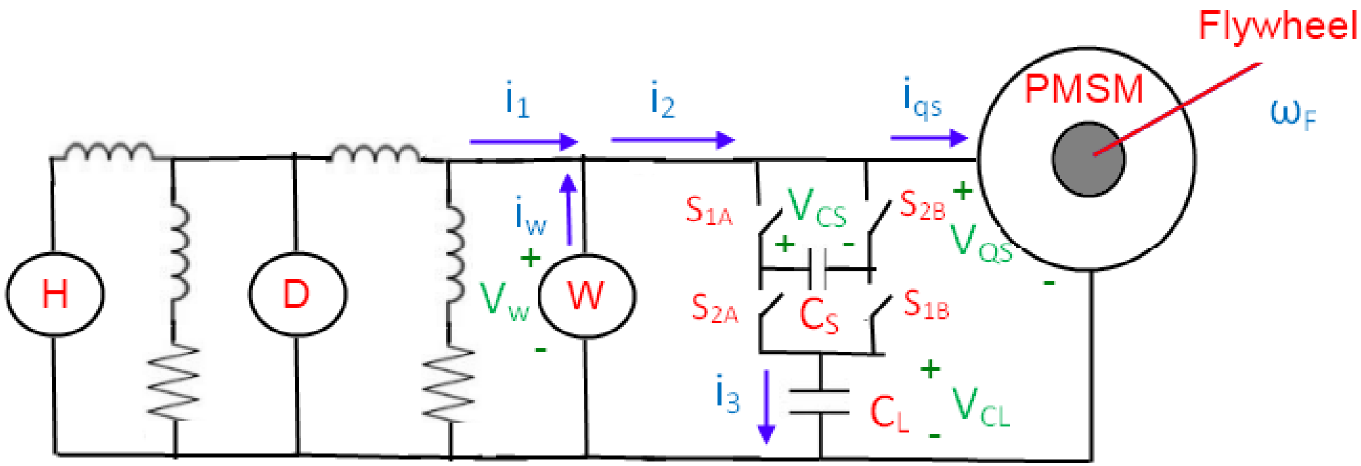
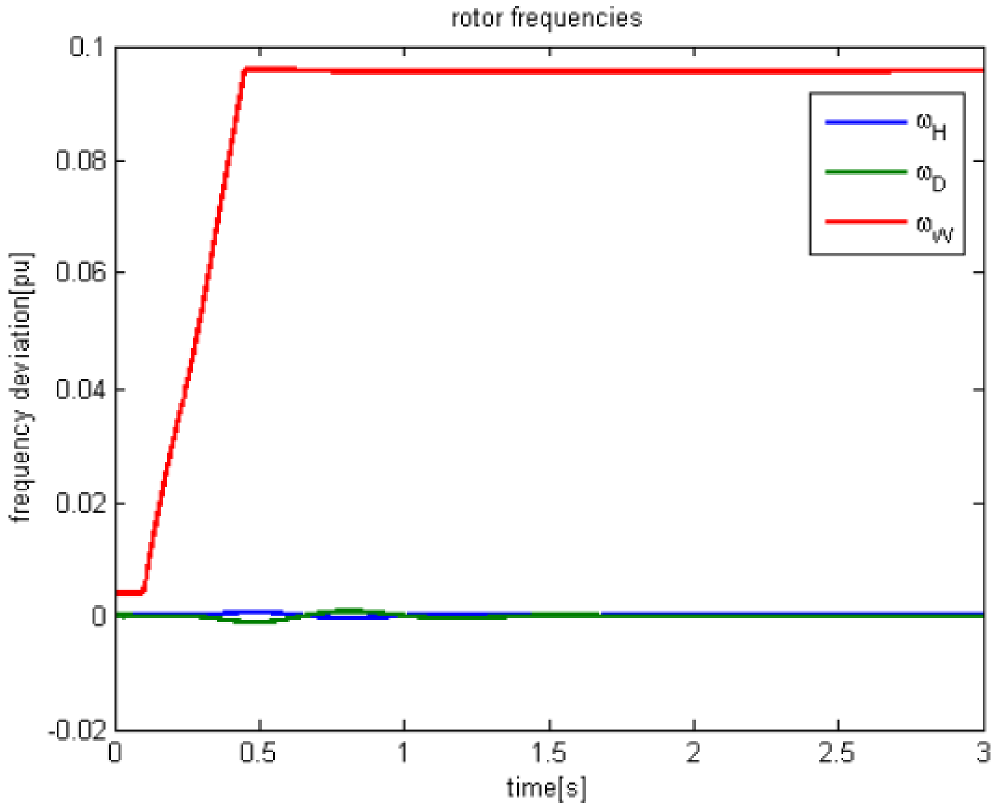
# Dynamic Model of Flores Island Power System




- Switches open and close at very high frequency relative to rest of the grid
- Large capacitor ($C_L$) serves to keep the voltage across the wind generator nearly constant
- The polarity of the small capacitor ($C_s$) changes to control $i_{qs}$

# Use Flywheel for Frequency Stabilization

- Include dynamics of the entire system
- Set $i_{qs}^{*}$=0A in order to stabilize the disturbance





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# Conclusions

- Transient stability of Flores island has been improved using smart control on FACTS and flywheels
- While FACTS can store active power only for short time intervals, flywheels can be used for prolonged disturbances

# Open Questions / Future Work

- Determining FACTS parameters based on stability requirements
- Larger power system with multiple flywheels
  - Multiple Input / Multiple Output Control
  - Decentralized or Cooperative Control?

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*Available at the request of the author