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Generator Response Following as a Primary Frequency Response Control Strategy for VSC-HVDC Connected Offshore Windfarms

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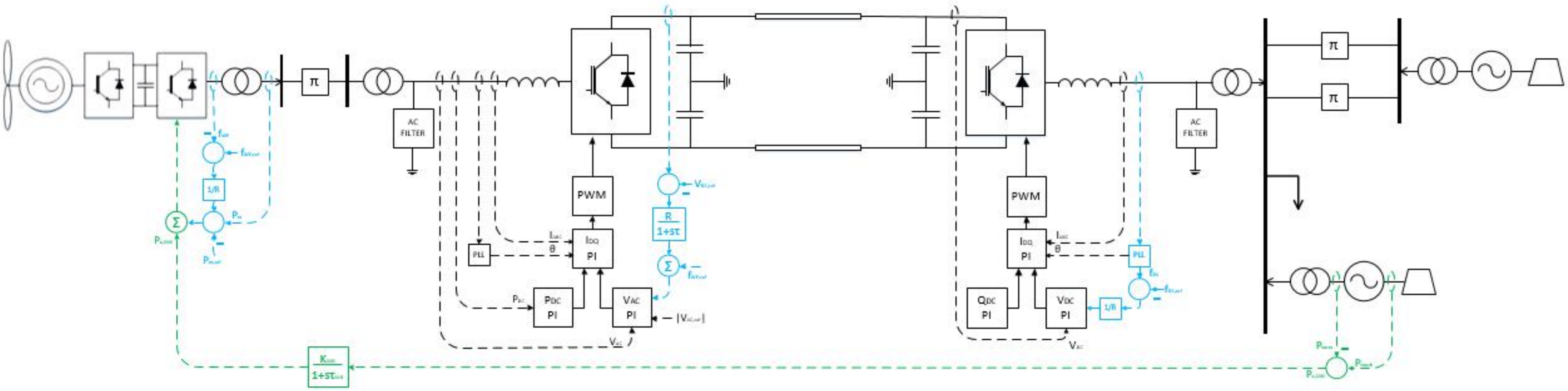
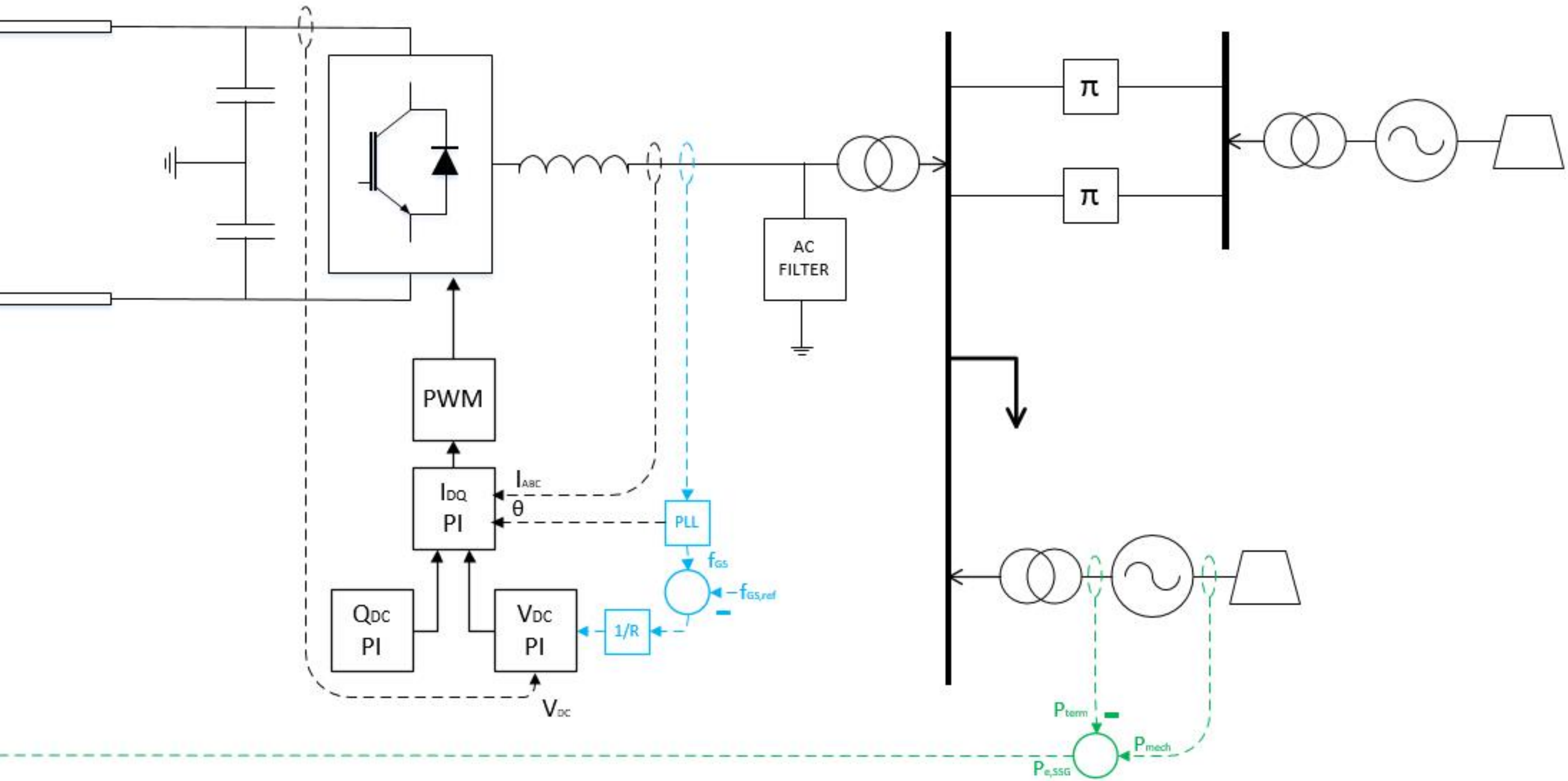
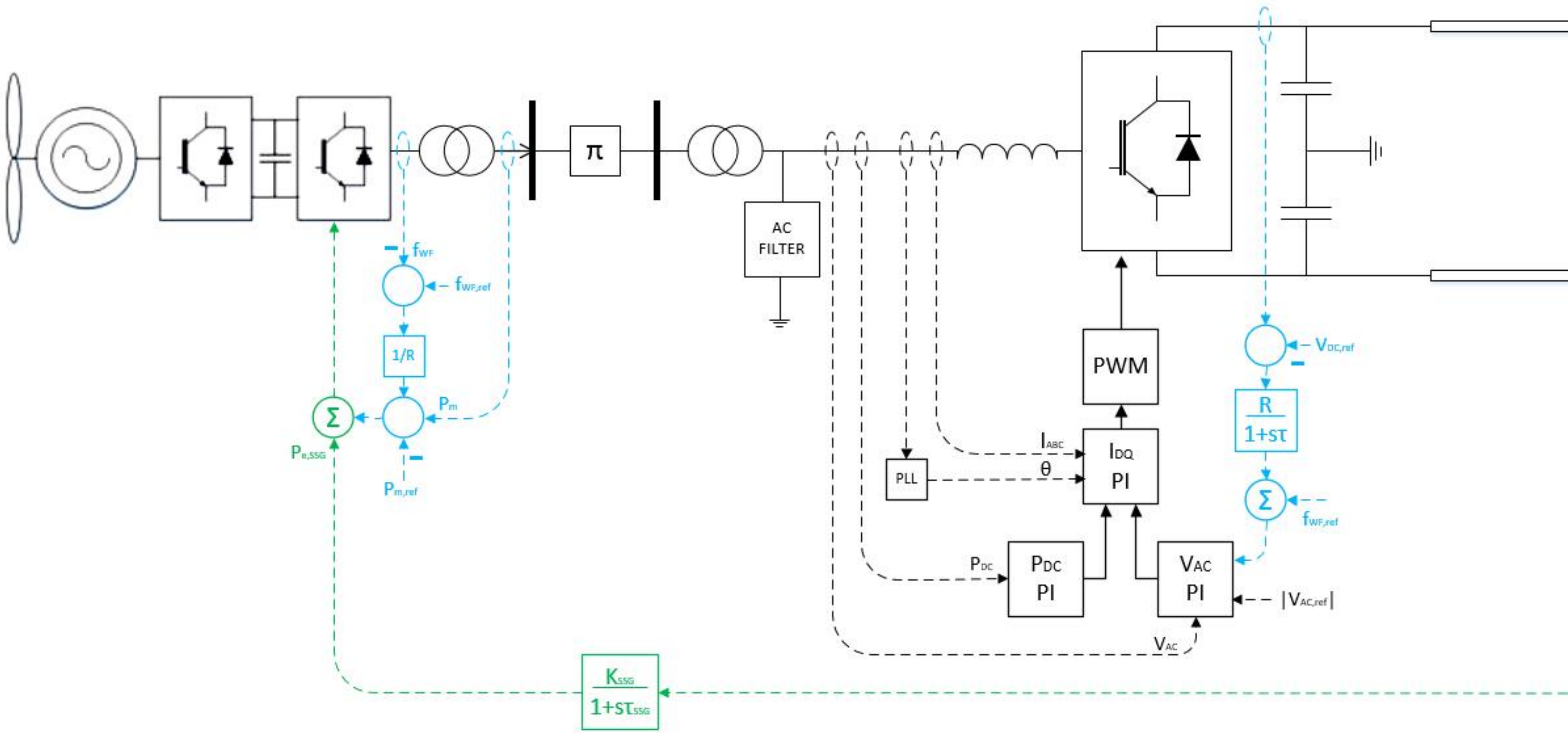
Full Theoretical System Model:



LSG, SSG, Strong Grid, GS-VSC:



WTG, Weak Grid, WF-VSC:



Goals for this Presentation:

- **Provide Background Definitions and Motivation for the Project**
- The effects of inertia are relevant on a dynamic time scale, therefore:
  - Derive Linearized System Equations for Analysis of Synchronous Dynamics
  - Study a Small Signal Disturbance due to a Simple Asynchronous Load Change at the PCC
- **Develop the Theoretical System Model**
- **Describe signal flow of the VSC-HVDC “Communication-less” Method**
- **Describe signal flow of the Fiber Optic Communication Method**
- Time Domain Simulation in PSCAD
- Spectral Analysis of Time Domain Results for Comparison
- Laboratory Test

Outline:

- **Definitions Relevant to AC/DC System Interaction**
- Motivation for Generator Response Following
- Definitions Relevant to Synthetic Inertia and Mechanical Dynamics
- Theoretical System Model
- Practical Modifications
- Other Work

AC System Voltage Strength:

$$SCR_{DC} = \frac{AC\ System\ Short\ Circuit\ Power}{Power\ Rating\ of\ DC\ Link} = \frac{S_{SC,AC}}{P_{DC}} = \frac{E_{AC}^2}{P_{DC}\,Z_{AC}}$$

SCR_{DC}: Effective Short Circuit Ratio is a measure of AC System Short Circuit Strength relative to Capacity of the DC Link

- Strong Voltage AC System has low thevenin equivalent impedance and small voltage variations
- Weak Voltage AC System can result in Dynamic Overvoltage Problems and Harmonic Resonances

Recommended Voltage Strength for an HVDC Connection is:

$$SCR_{DC} \geq 10$$

AC System Frequency Strength:

$$H_{DC} = \frac{AC\ System\ Total\ Rotational\ Inertia}{Power\ Rating\ of\ DC\ Link} = \frac{KE_{LSG}+KE_{SSG}+KE_{WTG}}{P_{DC}}\ \left[\frac{MWs}{MVA}\right]$$

H_{DC}: Effective Inertia Constant is a measure of AC System Rotational Inertia relative to Capacity of the DC Link

- Strong Frequency AC System has High Mechanical Inertia. It can absorb dynamic power imbalances leading to shallow frequency gradients and slow frequency variations
- Weak Frequency AC System is unable to absorb power imbalances leading to sharp frequency gradients and faster frequency variations

Recommended Frequency Strength for an HVDC Connection is:

$$H_{DC}\ > 3\ sec$$

AC System X/R Ratio:

Inductive AC System has a high amount of inductance relative to resistance. Therefore:

- exhibits strong dependency between Frequency and Active Power (ie: changes in active power will create changes in frequency)
- exhibits strong dependency between Voltage and Reactive Power (ie: changes in reactive power will create changes in voltage magnitude)

Typical X/R Ratio for 230 kV AC Transmission System:

$$X/R = 10$$

AC System Stiffness:

$$\beta = \Sigma \frac{1}{R_i} + D \quad \text{where} \quad \Delta f_{ss} = -\Delta P_L / \beta$$

β: Composite Frequency Response Characteristic: A Measure of System Frequency Sensitivity to Changes in Load (sometimes referred to as stiffness)

$\frac{1}{R_i}$: Individual f-P Regulation Constants: Typical value is 20 to 25

D: Steady state damping effect of all frequency dependant AC loads. Typical value is 1 to 2

- A Stiff AC System has small Steady State Frequency Changes
- β also contributes to Primary Response

AC System Dynamic Stability:

$$\Delta T_e = K_S \Delta\delta + K_D \Delta\omega$$

K_S: Synchronizing Power (Synchronizing Torque) Coefficient:
Component of Electrical Power in phase with rotor angle deviation, positive value prevents aperiodic drift of rotor angle

K_D: Damping Power (Damping Torque) Coefficient: Component of Electrical Power in phase with speed deviation, positive value prevents oscillatory instability

HVDC Power Connections do not naturally have these small signal synchronizing or damping components.

Synchronous vs. Asynchronous:

Synchronous Component:

- Inherent to the component and/or contains synchronizing controls
- Contains a Synchronous Power Coefficient for Dynamic Stability
- Example: Synchronous Generator

Frequency Dependent Asynchronous Component:

- Source/Load Changes as a function of frequency
- Example: Simple inductor/capacitor, Induction Machine

Frequency Independent Asynchronous Component:

- Component functions independently of frequency
- Example: Simple resistor, power electronics

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Motivation for Generator Response Following:

Historical Perspective:

- A traditional solution to the problem of low Effective Inertia Constant H_{DC} is to add synchronous condensers to the AC system, increasing the amount of mechanical inertia

- Synchronous Condensers also supply the reactive power requirement of Traditional Load Commutated Converters

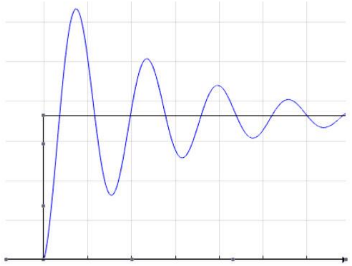
Contribution:

- Similarly, this project studies the Mechanical Inertia Response (Electromechanical Power) of a Small Synchronous Generator (SSG) connected at the point of common coupling (PCC)

- A P_e measurement at the SSG can be amplified and superimposed onto the inertia-less Aggregated Wind Turbine Generator (WTG)

- The result is an amplified synchronous dynamic response from the VSC-HVDC Connected Offshore Wind Farm (OWF) at the PCC

Mechanical vs. Synthetic Inertia:



The Swing Equation for Inertial Response:

$$\mathrm{M}\frac{df}{dt} = P_m - P_e$$ [quantities in pu]

Inertia Constant in the Per Unit System ($M = 2H$):

$$\mathrm{H} = \frac{KE}{S_{RATED}}, units \left[\frac{MWs}{MVA}\right]$$

Kinetic Energy Associated with Mechanical Inertia:

$KE = \int J\omega \, d\omega = \frac{1}{2}J\omega^2$ and quantifies P_e injection

Global Frequency Gradient of Strong AC Grid determined by Composite Inertia Constant:

$$H_{eq} = \frac{KE_{LSG} + KE_{SSG} + KE_{OWF}}{S_{LSG} + S_{SSG} + S_{OWF}}$$

KE_{LSG}, KE_{SSG}: Mechanical Inertia from the SSG and the Aggregated Large Synchronous Generator (LSG) at PCC

KE_{OWF}: Synthetic Inertia from the Power Reserve of the Offshore Windfarm (eg: Turbine Rapid Braking Action, Sub-Optimal MPPT)

Generator Response Following and Synthetic Inertia:

Without Generator Response Following (GRF):

$$H_{OWF} = \frac{KE_{OWF}}{S_{OWF}} \cong \frac{0}{S_{OWF}}$$

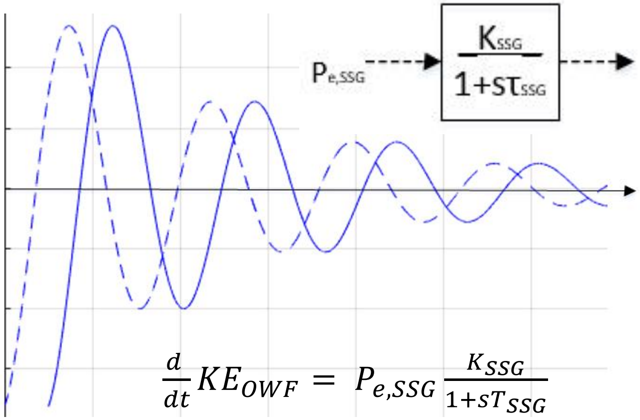
With Generator Response Following (GRF) and gain of one:

$$H_{OWF} = H_{SSG}$$

$$\frac{KE_{OWF}}{S_{OWF}} = \frac{KE_{SSG}}{S_{SSG}}$$

$$KE_{OWF} = KE_{SSG}\frac{S_{OWF}}{S_{SSG}}$$ therefore $$H_{eq,GRF} > H_{eq}$$

Instantaneous Power Reserve of OWF must also be designed for power injection at all points in time:



$$P_{Reserve}(t) \geq \frac{d}{dt}KE_{OWF}$$ where $$\frac{d}{dt}KE_{OWF} = P_{e,SSG}\frac{K_{SSG}}{1+sT_{SSG}}$$

Communication Channels:

Fiber Optic Communication: Information transmitted via fiber optic cable.

- **Advantage:** Relevant for future development of MTDC networks where direct communication with multiple onshore AC networks may be required
- **Disadvantage:** performance and reliability concerns such as: time delay, reduced data rate, loss of connection

VSC-HVDC Communication-less: V-f proportional cascade used to synthetically couple the strong onshore AC grid to the weak offshore AC grid. Theoretical System Model will elaborate on the signal flow.

- **Advantage:** fast, reliable
- **Disadvantage:** Fiber Optic Communication may be required later as the system grows more complex

Frequency Response:

Inertial Frequency Response:

- Associated with P_e in the swing equation
- Stored energy compensates for temporary power imbalance after load change
- Communicated to OWF via fiber optic channel

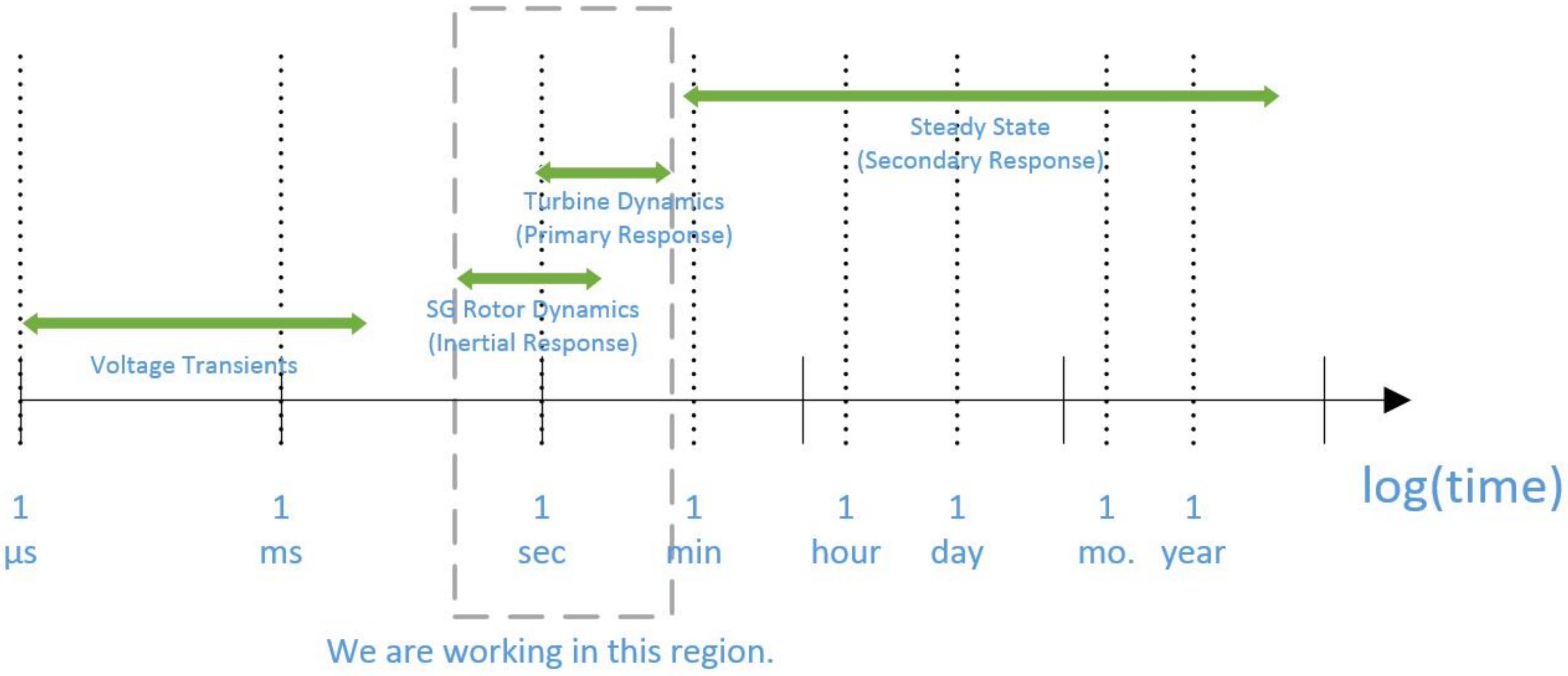
Primary Frequency Response:

- Associated with P_m in the swing equation
- Turbine adjusts to meet new demand of load change
- Communicated to OWF via VSC-HVDC communication-less channel

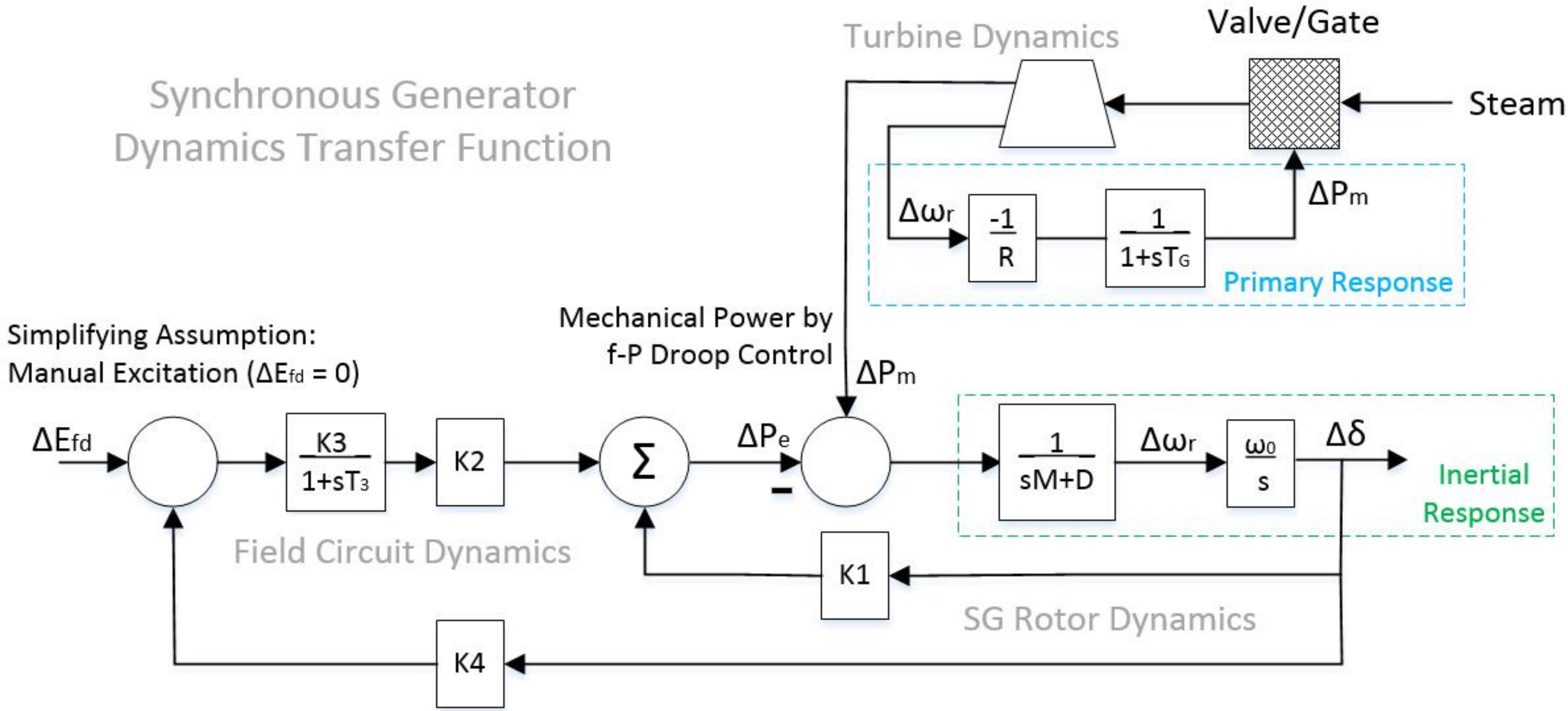
Secondary Frequency Response: System renormalization after primary response steady state has been reached:

- Associated with Power Setpoint or Reference
- Examples: Dynamic Deloading of Wind Turbines, Traditional "Supplementary Control" such as load shedding, etc

Relevant Timescale:



LSG, SSG Small Signal Transfer Function:



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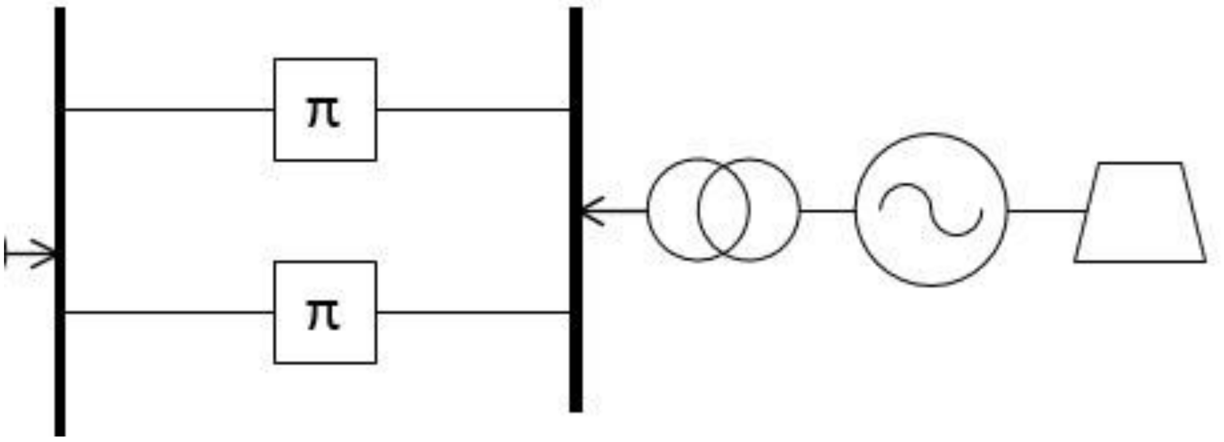
Aggregated Large Synchronous Generator (LSG) and Strong Grid:

- Equivalent pi model with Lumped Parameters
- Strong AC Grid (SCR_{DC} > 10) for Constant Voltage



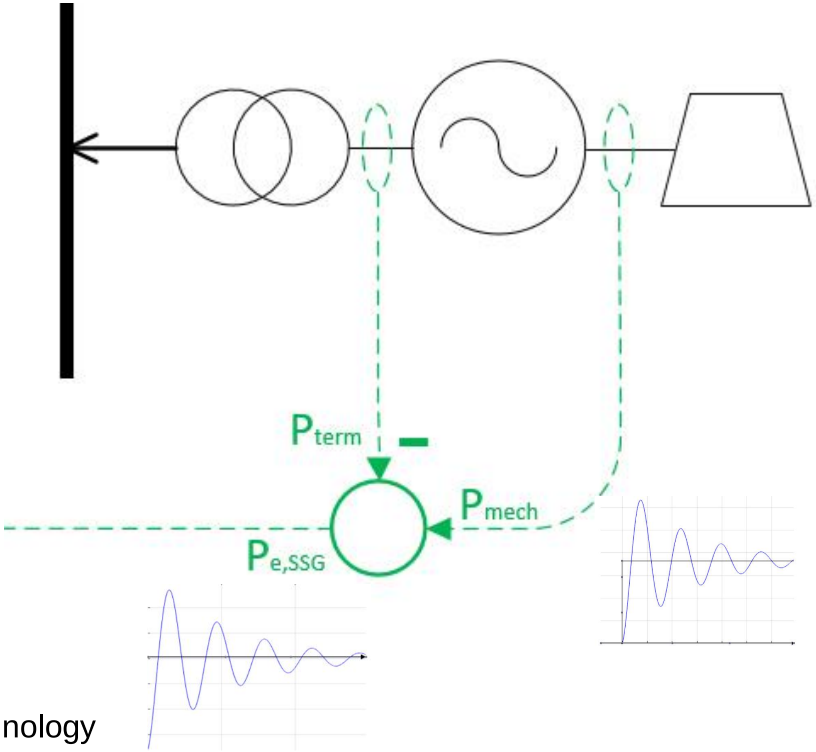
- Strong AC Grid (H_{DC} > 3) for Constant Frequency
- Inductive AC Grid: X/R = 10 (typical) for f-P Load Sharing
- Contribution to Steady State Stiffness: $\beta_{LSG} = 4\ x\ \frac{1}{0.04}$ = 100
- Inertia Constant: $H_{LSG} = 3.0$
- Simplifying Assumption: Manual Excitation

Small Synchronous Generator (SSG):

- Connected at PCC
- Required Power Rating: roughly 5% of HVDC Link
- Contribution to Steady State Stiffness: $\beta_{SSG} = \frac{1}{0.04} = 25$
- Inertia Constant: $H_{SSG} = 3.0$
- Simplifying Assumption: Manual Excitation

P_e: shaft power minus terminal power. Measurement is sent to OWF via **fiber optic channel**

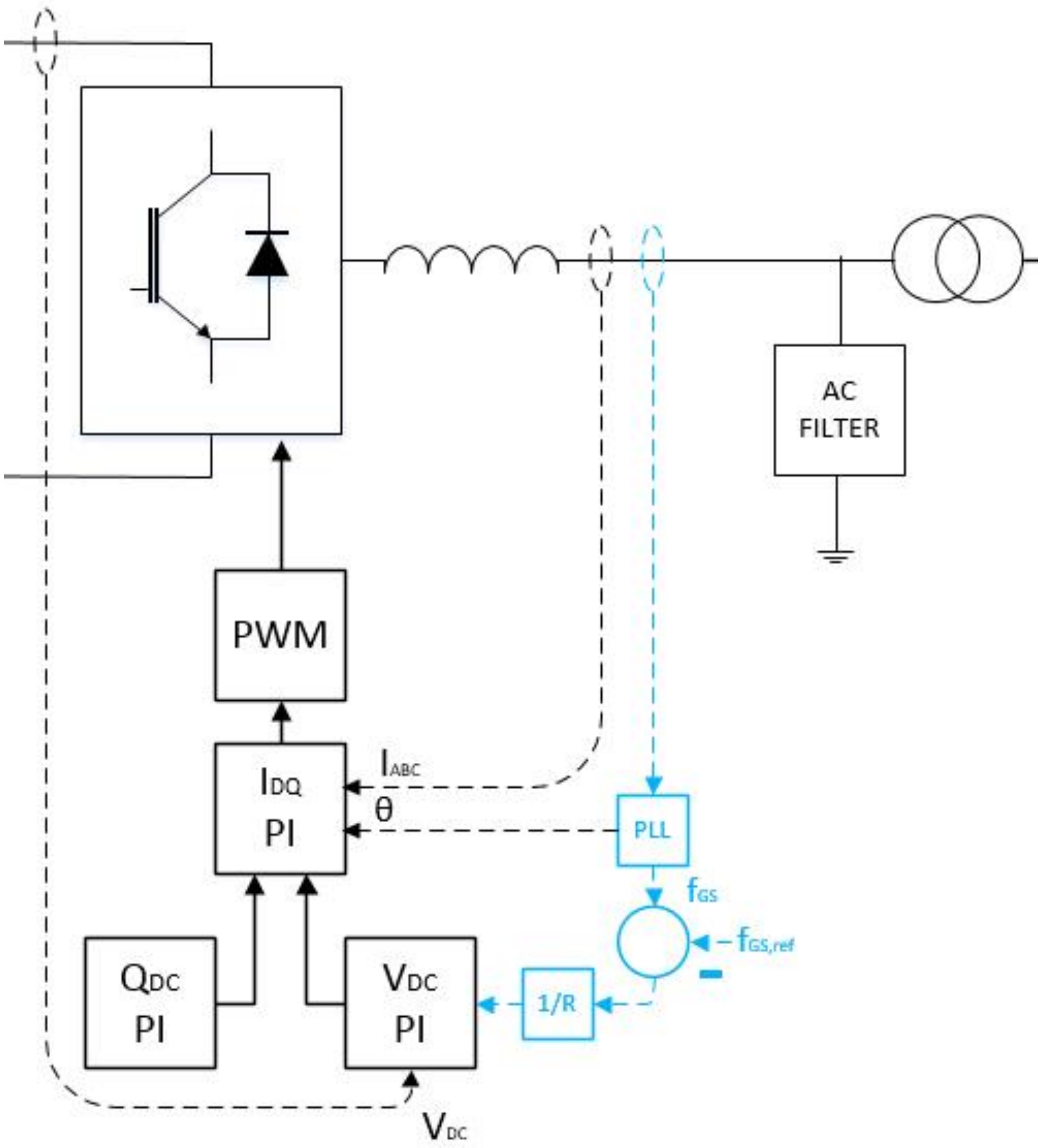
P_m: measured at the shaft



Grid Side VSC (GS-VSC):

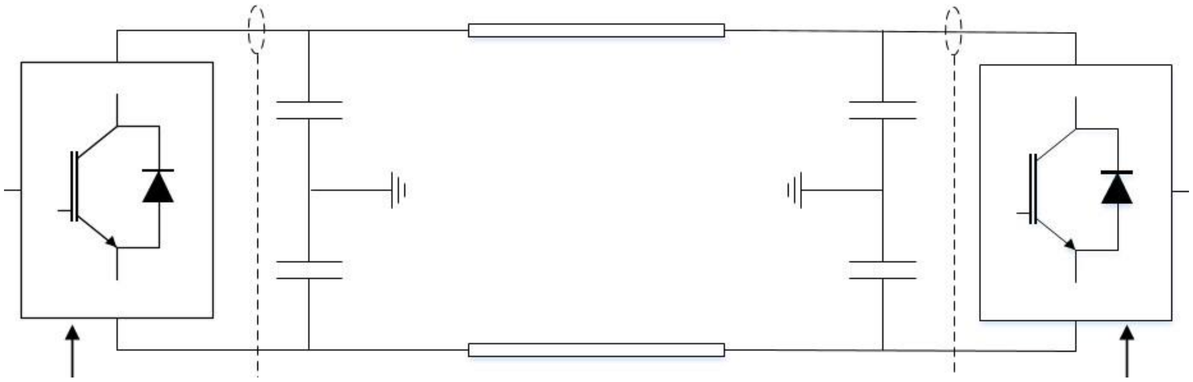
- Average Model for mechanical dynamics
- Constant Reactive Power Control
- Constant V_{DC} Control modified with Frequency-V_{DC} Droop (**communication-less channel**)

GS-VSC operates independently of Active Power



VSC-HVDC Link:

Simplifying Assumptions:



- Uni-Directional Power Flow from OWF to Onshore AC Grid

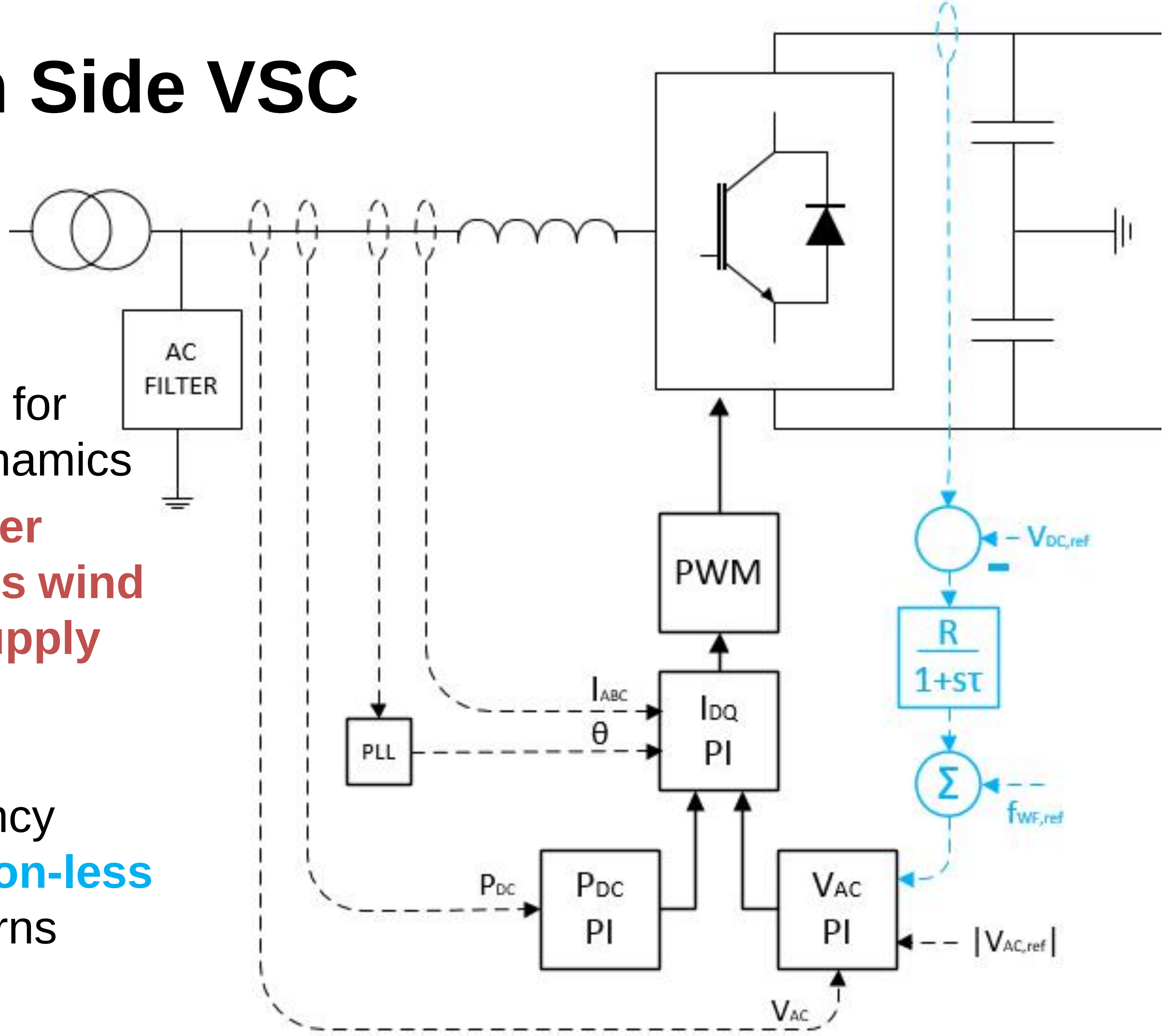
- No Converter Losses: $P_{AC} = P_{DC}$

- No DC Cable Resistive Losses:

$V_{DC,GS} = V_{DC,WF}$ and therefore $f_{GS} = f_{WF}$

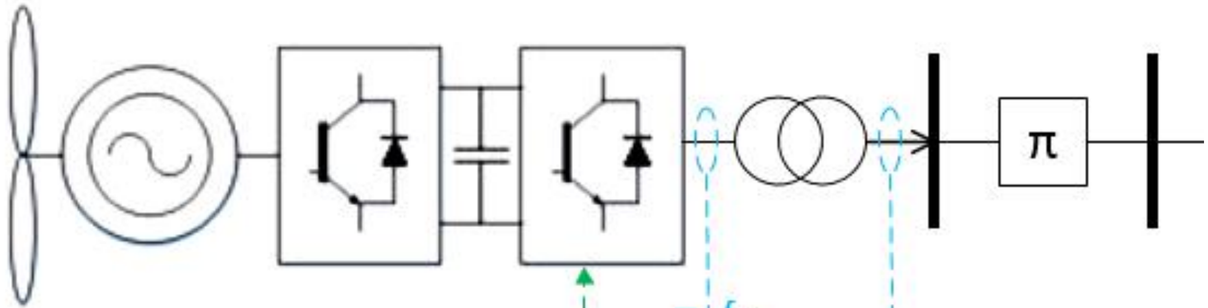
Grid side frequency same as Wind Farm Side Frequency (ie: synthetically coupled) with a time delay.

Wind Farm Side VSC (WF-VSC):

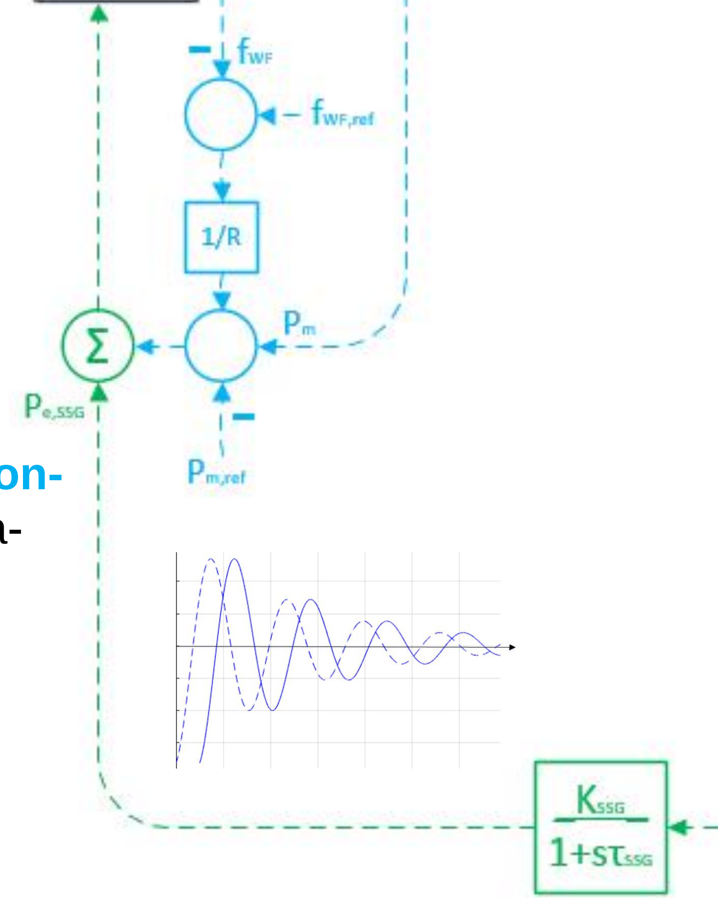


- Average Model for mechanical dynamics
- **Constant Power Control follows wind farm power supply**
- Constant V_{AC} magnitude with varying frequency (**communication-less channel**) governs weak AC grid frequency

Aggregated Wind Turbine Generator (WTG) and Weak Grid:



- Equivalent pi model with Lumped Parameters
- Weak AC Collection Grid follows WF-VSC V_{AC} controller amplitude and frequency
  - SCR = 2 (typical)
  - H = 0 (no mechanical inertia)
  - **Low X/R Ratio (decouples f from P)**



P_m: received by frequency variation (**communication-less channel**) and f-P droop converts to inertia-less primary response

$P_{e,SSG}$: measurement received by **fiber optic channel** and superimposes a synthetic inertia response

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Practical Modifications:

In general, redundancy of communication channels will increase reliability. Below are some other possible communication schemes. System design with a first priority option as well as a second priority option may be desirable.

- Option #1:
  - Small Synchronous Condenser
  - Inertial Response → Pe measurement sent via fiber optic channel
  - Primary Response → Performed by communication-less method
- Option #2:
  - Small Synchronous Condenser
  - Inertial Response → Pe measurement sent via communication-less channel
  - Primary Response → Performed by communication-less method
- Option #3:
  - Nearby Generator/Turbine Installation
  - Inertial & Primary Response → Pe & Pm measurement sent via fiber optic channel
- Option #4:
  - Nearby Generator/Turbine Installation
  - Inertial & Primary Response → Pe & Pm measurement sent via communication-less channel

Other Work:

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References:

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- Kim, “HVDC Transmission Power Conversion Applications in Power Systems”
- Temesgen, “Control, Dynamics and Operation of Multi-Terminal VSC-HVDC Transmission Systems”
- Watson, “Power Systems Electromagnetic Transients Simulation”
- Moreira, “Participation of Multi-Terminal HVDC Grids in Frequency Regulation Services”
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