# MVDC System Stability

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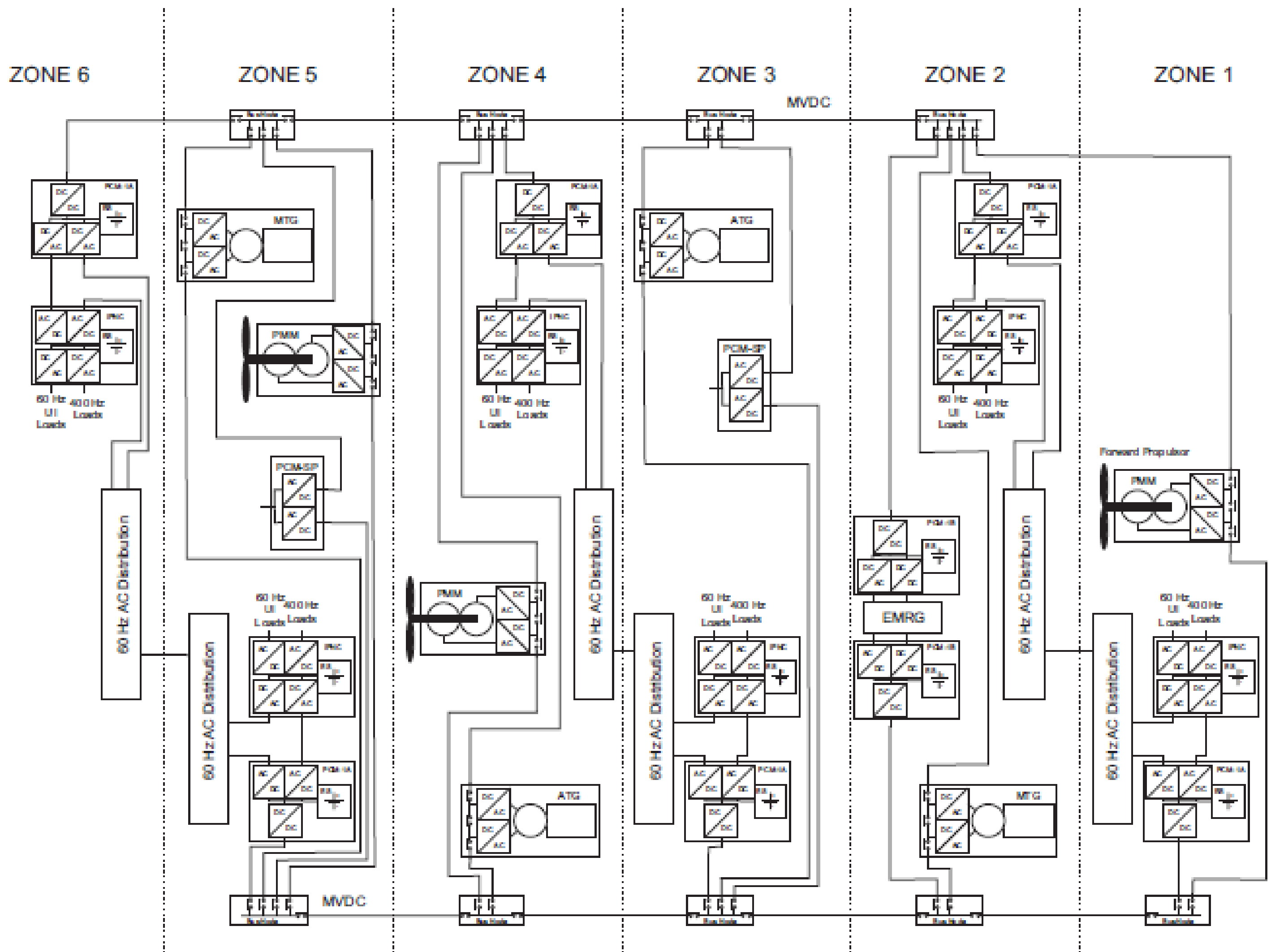
# Proposed MVDC Architecture 1.02



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# Properties of Proposed MVDC Architecture

- All sources, loads, and energy storage interact only with the MVDC bus via power electronics
- Sources and large loads (> 1 MW) simultaneously interact with both MVDC buses
- MVDC bus voltage
  - 6 kV, **12 kV**, or 18 kV
  - Grounding scheme undetermined at this time
- Fault Detection, Localization, and Isolation method undetermined at this time
- Recoverability method following damage undetermined at this time


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# Stability

1. Unique **Steady State Solution** Must Exist
   – AKA system equilibrium state
   – Must be an “acceptable” steady state solution
2. That steady state solution must be **small-signal stable**
   – Linear stability criteria applies
   – AKA static stability
3. System response to perturbations must also be acceptable via **transient-stability**
   – AKA large-signal stable
   – AKA dynamic stability


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# Stability Specification

- Must be able to specify properties of power systems equipment such that they can be tested in the factory prior to integration into the ship while still minimizing probability of integration problems once installed on the ship.
- Can employ supervisory control managed set-points.
- System should be inherently stable upon loss of controls communication
  - Current ramp rates may be limited


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# Steady State Solutions

- Use controls to drive the steady state behavior of Generator sets (PGMs) / Power Conversion (PCMs) / and loads.
- Design the desired steady state behavior to achieve power sharing, power quality, and energy storage charging and discharging.
  - PGMS:
    - Voltage droop on current until power limit reached, then …
    - Constant power until low voltage limit reached, then …
    - Constant current (abnormal condition)


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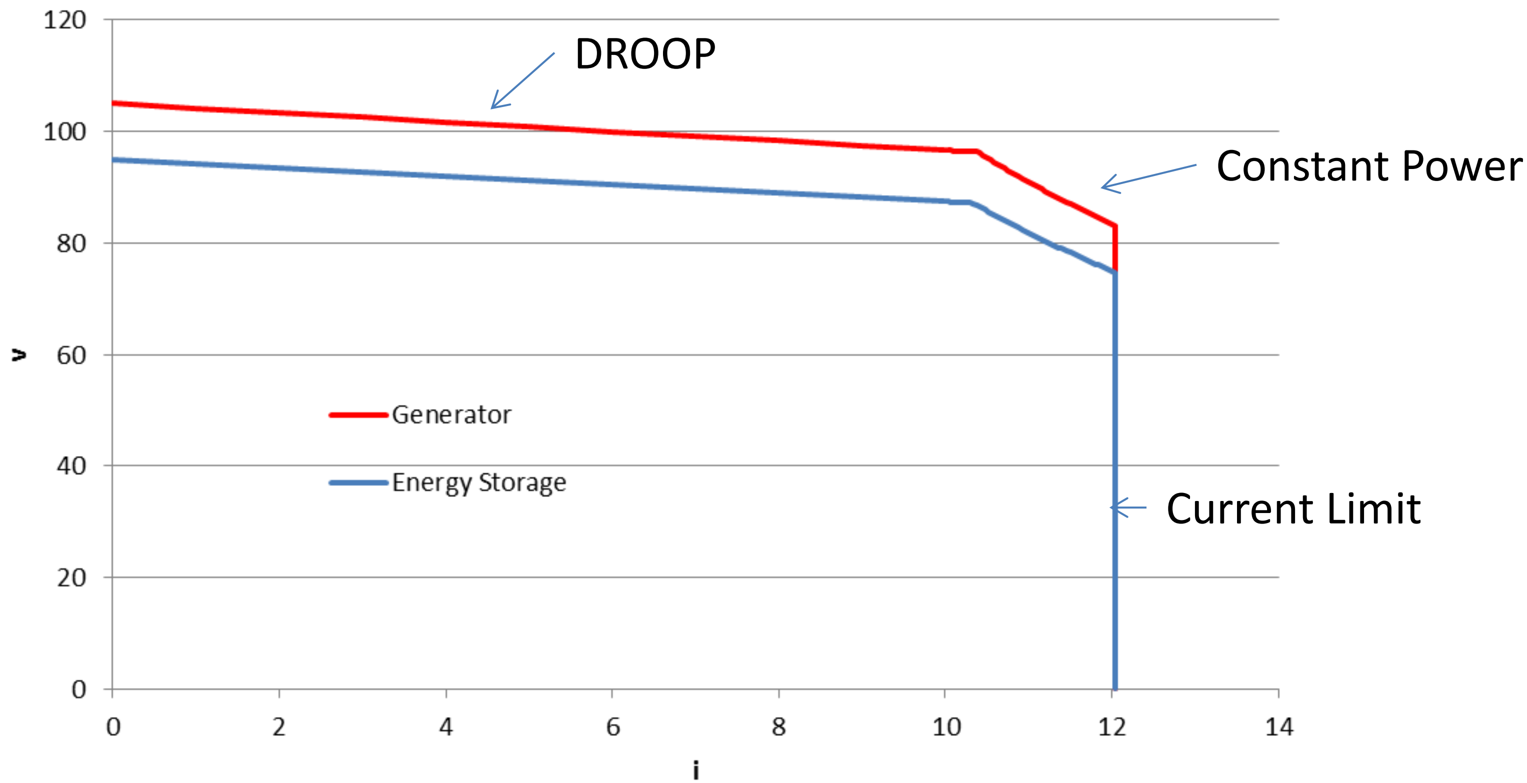
# PGM and Energy Storage Steady State characteristic




Energy Storage Droop characteristic
Occurs during PGM Constant Power Mode

Graph is notional



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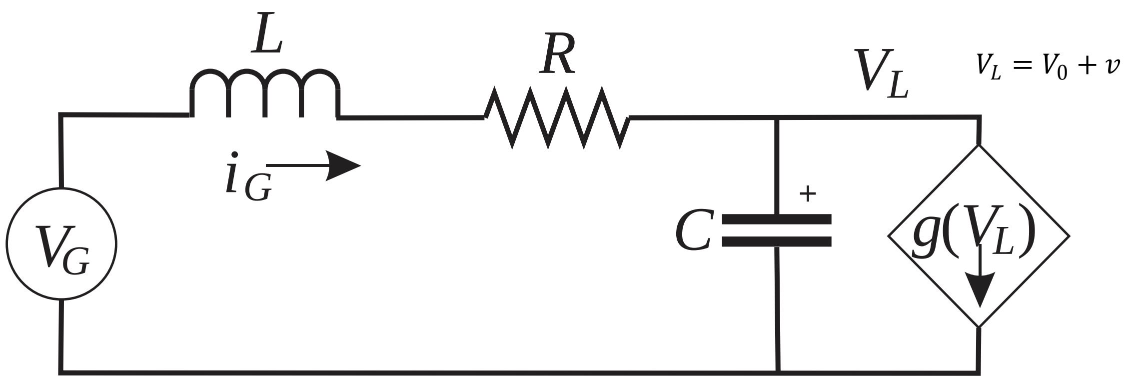
# Small signal / static stability




$$0 = \left(1 + R\frac{dg(V_0)}{dV_0}\right)v + \left(RC + L\frac{dg(V_0)}{dV_0}\right)\frac{dv}{dt} + LC\frac{d^2v}{dt^2}$$

- For stability, all the coefficients have to have the same sign
- If $\frac{dg(V_0)}{dV_0}$ is positive, then always small signal stable
- If the load is a constant power load, then additional criteria must be satisfied to assure small signal stability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# Small signal stability – Negative slope $i$ vs. $v$

$$0 = \left(1 + R\frac{dg(V_0)}{dV_0}\right)v + \left(RC + L\frac{dg(V_0)}{dV_0}\right)\frac{dv}{dt} + LC\frac{d^2v}{dt^2}$$

To ensure small signal stability, following conditions must apply:

$$1 + R\frac{dg\,(V_0)}{dV_0} > 0$$

$$RC + L\frac{dg(V_0)}{dV_0} > 0$$


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# Constant Power Loads: Small Signal Stability

Assume:

$$g(V_L) = \frac{P}{V_L} + hV_L$$

Condition 1

$$1 + Rh - R\frac{P}{V_0^2} > 0$$

Condition 2

$$RC + Lh - L\frac{P}{V_0^2} > 0$$

- If Stability satisfied for $h = 0$, then satisfied for any positive $h$.
- For realistic systems with a droop characteristic much less than 1 and a load voltage much larger than 1, Condition 1 is always met
- With the source regulated with a droop characteristic ( $R$, $V_0$ a function of $V_{NL}$ and $d$) Condition 2 can be restated to …

$$P_0^2 < \frac{V_B C V_{NL}^3 d(1-d)^2}{L}$$

- If C and L are chosen such that the static stability condition holds for the rating of the generator, than the system will be static stable for all combinations of constant power loads and resistive loads equal to or less than the rating of the generator


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# Source stability design approach

- Set $V_G$ and $R$ based on steady-state characteristic (droop)
  - A "slow" outer loop controller may vary these to achieve better load sharing, power quality, etc.
- Set $L$ to keep the $R/L$ ratio constant
  - ratio set by system controller based on dynamic stability and capability of source controller.
- Set $C$ to ensure static stability for a constant power load equal to the power rating of the source.
  - Add a margin to the value of C (say double it)


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# Implementation

- $V_G$, $R$, $R/L$, and $C$ are set points for the source controller to regulate the behavior of the electrical interface.
  - The physical system must have the “control authority” to accurately regulate to these values
  - The control algorithms for these regulators will impact the “dynamic stability”
- Can easily show that a composite system composed of multiple paralleled sources and constant power loads will be statically stable if ….
  - Each source is statically stable with a constant power load equal to its power rating
  - All the sources are regulating to the same $R/L$ ratio
    - This may be very conservative.


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# Source Controller

- Regulate to 4 set-points: $V_G$, $R$, $R/L$, and $C$
  - $V_G$ and $R$ establish the desired steady state condition
  - $L$ and $C$ ensure static stability
    - Implemented via Hamiltonian Surface Shaping
- Generator Set
  - Have ability to control:
    - Prime Mover Power / shaft speed
    - Generator Field (unless Permanent Magnet)
    - Power Electronics gate signals
  - Is this sufficient?
- Energy Storage
  - Have ability to control:
    - Power Electronics gate signals
  - Is this sufficient?
- Interaction of controllers
  - Need to ensure higher order dynamics of loads and sources do not result in an instability
  - Do we use typical gain and phase margins?


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# Dynamic Stability

- System will eventually achieve and remain at its desired steady state condition without intervention when placed in a state other than its desired steady state condition
- AKA Transient Stability or Large-signal Stability
- Subtraction or Addition of large loads will initially cause the power system to deviate substantially from the new desired steady-state condition.
- Implemented via Power Flow Control
  – Shapes the trajectory to the desired steady-state condition.


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# Power Flow Control

- During a transient, power will
  - Be generated
  - Be dissipated
  - Increase stored energy in an energy storage element
  - Decrease stored energy in an energy storage element
- Can involve PCM-1As and loads in addition to PGMs
  - Load management
  - Stored energy in PCM-1As and Loads
- Need to ensure the trajectory to the steady-state operating point does not:
  - Damage equipment
  - Cause equipment to malfunction
  - Cause unintended state changes (i.e. equipment tripping off line)



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# Dynamic Stability Strategy

- Control the PGM to maximize Transient Performance
  - follow the droop characteristic to the extent possible
  - Prevent damage to PGM equipment
  - Take advantage of inherent energy storage and controllability
- Use PCM-1A Energy Storage as next stage
  - Follow the Energy Storage droop characteristic to the extent possible
  - Will probably be power limited
  - Should have faster transient performance than PGM
  - Ability to rapidly change power flow across ship may be limited by bus impedance
  - Provide served pulse loads with current characteristics required
- Use PCM-1B Energy Storage to provide power and energy capacity not provided elsewhere to very large pulse loads
  - Ensure MVDC bus remains within Power Quality standards
  - Provide served pulse loads with current characteristics required
- Use Supervisory Controls to pre-arrange performance of all power system elements
  - Active communication during a pulse event among power system elements should be minimized or eliminated
- Implemented via control algorithms for $V_G, R, C, L, PCMs$ and loads



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# Stability Summary

- Have an approach for ensuring stability of an MVDC bus
  - Much work remains to prove that it will work
- Steady-state operating points determined by droop characteristics of sources: $V_G$ and $R$
- Small-signal (static) stability ensured by regulating $C$ and $L$
- Large-signal (dynamic) stability through the regulator algorithms for $V_G, R, C, L$ and loads


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