System Inductance for MVDC Circuit Breakers

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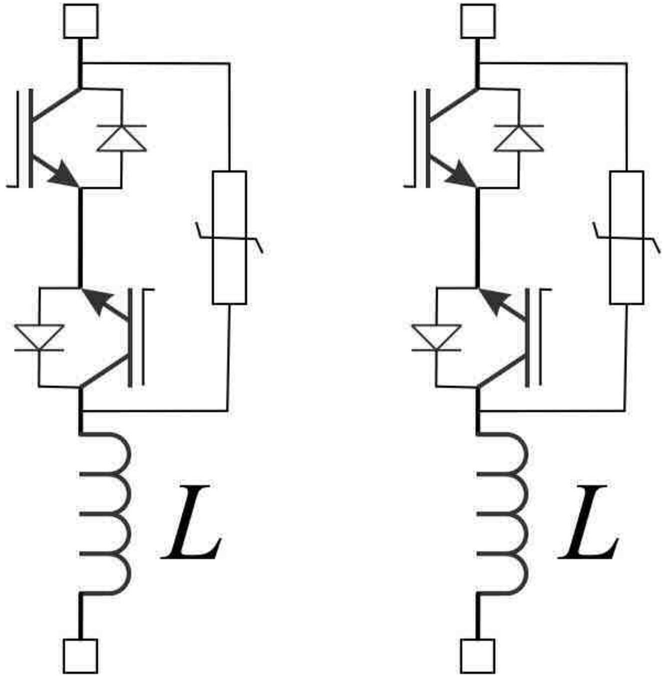
Introduction

- Medium Voltage Direct Current (MVDC) is a candidate for future naval electrical power systems
  - High Power and Pulsed loads
  - Fuel Efficiency
  - Power Density
- MVDC system characteristics
  - Regulated entirely by Power Electronic converters
  - All loads interact with MVDC bus via Power Electronic converters
  - Electrical Dynamics will be faster
  - Cable properties will likely be different from Medium Voltage Alternating Current (MVAC) cables
  - Traditional MVAC circuit breakers will not work due to lack of current zero crossing
- Solid State Circuit Breakers (SSCB) are one alternative for circuit protection
  - Typically have a series inductor (L) to limit current rise time
  - Inductance value depends on system inductance.



Is L needed?
If so, what should be its value?

Minimum System Inductance

- SSCB design characterized by:
  - Rated Current
  - Maximum Current Interruption Capability
  - Interruption time
    - Detect
    - Localize / Coordinate
    - Interrupt

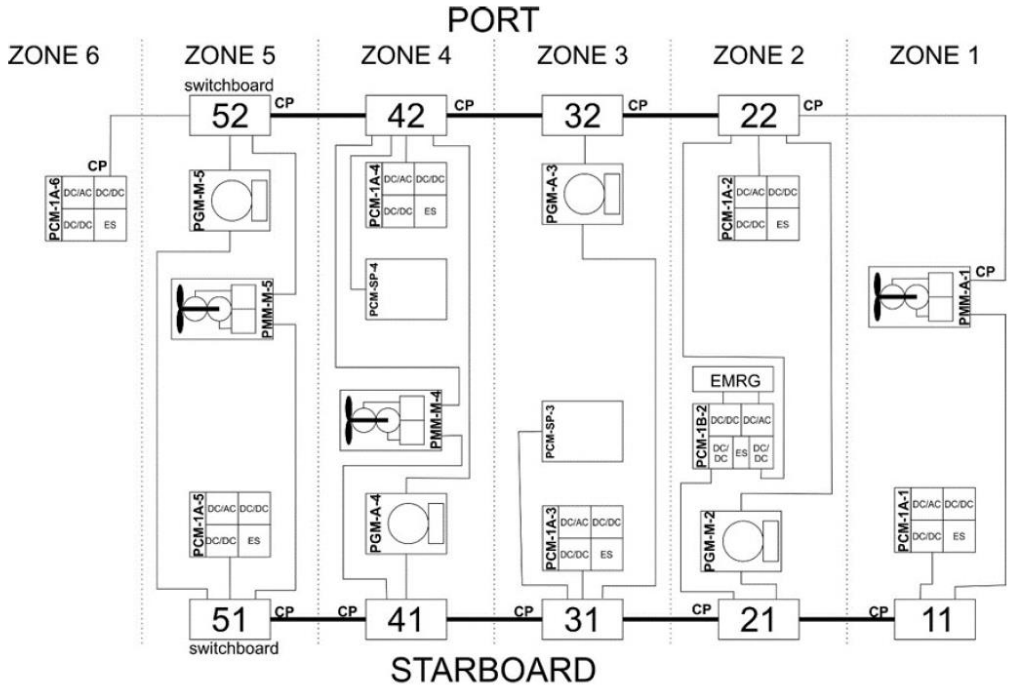
$$L_{sys\_min} = \frac{1000\, V_{sys}\, t_{int}}{(n_{SSCB\_int} - 1) I_{SSCB\_rate}} \quad (1)$$

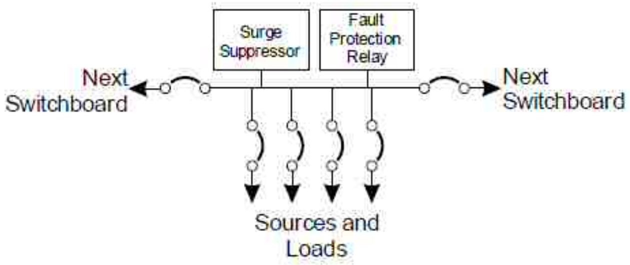
L_{sys_min}	minimum system inductance (μH)
V_{sys}	system voltage (kV)
t_{int}	time to peak current (μs)
n_{SSCB_int}	Multiple of steady-state rated current SSCB can interrupt
I_{SSCB_rate}	Steady-state rated current of SSCB (A)

System Voltage (kV)	SSCB current Rating (amps)	SSCB Interrupt Multiple	Interrupt Time (microseconds)	Minum System Inductance (uH)
12	250	2	2	96.0
12	250	5	2	24.0
12	250	10	2	10.7
12	250	2	5	240.0
12	250	5	5	60.0
12	250	10	5	26.7
12	250	2	10	480.0
12	250	5	10	120.0
12	250	10	10	53.3
12	2000	2	2	12.0
12	2000	5	2	3.0
12	2000	10	2	1.3
12	2000	2	5	30.0
12	2000	5	5	7.5
12	2000	10	5	3.3
12	2000	2	10	60.0
12	2000	5	10	15.0
12	2000	10	10	6.7
12	4000	2	2	6.0
12	4000	5	2	1.5
12	4000	10	2	0.7
12	4000	2	5	15.0
12	4000	5	5	3.8
12	4000	10	5	1.7
12	4000	2	10	30.0
12	4000	5	10	7.5
12	4000	10	10	3.3

Calculating System Inductance

- System inductance is the Thévenin equivalent calculated for each “side” of a SSCB.
  - Thévenin voltage approximated as nominal system voltage
  - If a “side” is only connected to loads, it is not a source of fault current and can be ignored.
- This system inductance is compared to the minimum system inductance to see if additional inductance must be added.
- Assumptions
  - Sources are stiff
  - Loads are not a source of fault current





Options to Lower Required System Inductance

- Clear Faults Faster
  - Detect and localize faults faster
  - Use devices that can turn off the fault current faster
- Increase the amount of current the SSCB can interrupt.
  - Use different devices
  - Use more devices in parallel
  - Use a SSCB rated for a higher steady-state current

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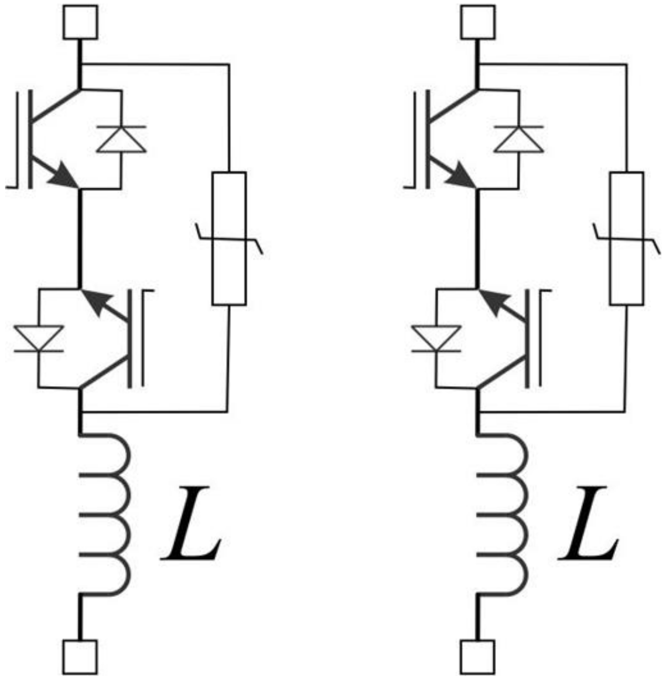
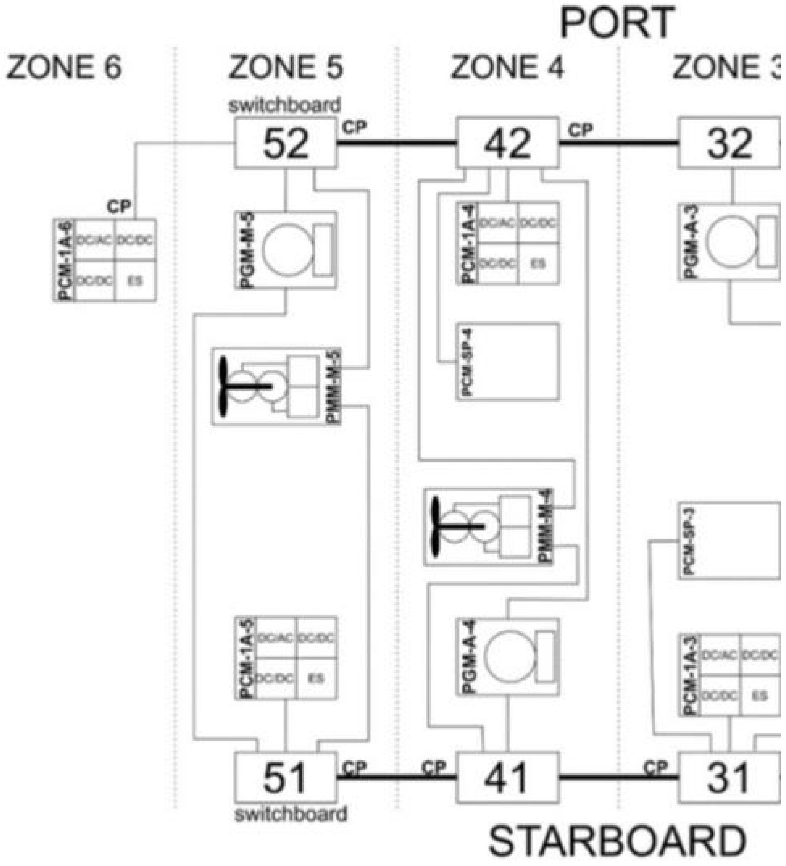
Options to Raise System Inductance

- Add inductance to each SSCB
  - Choose values such that the minimum system inductance is available for all configurations of the power system
- Add inductance to each source
  - Island each source upon detection of a fault
- Combination of the above



Fault Detection and Localization Implications

- SSCBs feeding only loads need not coordinate with other SSCBs; they can trip on overcurrent
- SSCBs connected to a source need not coordinate with other SSCBs upon detecting reverse current.
- All other conditions require coordination to ensure only the correct SSCBs trip
- Recommend combination of directional and differential protection



Stability Implications

- Increasing system inductance implies that the load capacitance must also increase to ensure stability
- Hence minimizing additional system inductance is desirable.

Stability Condition for
Constant Power Loads
And sources employing droop

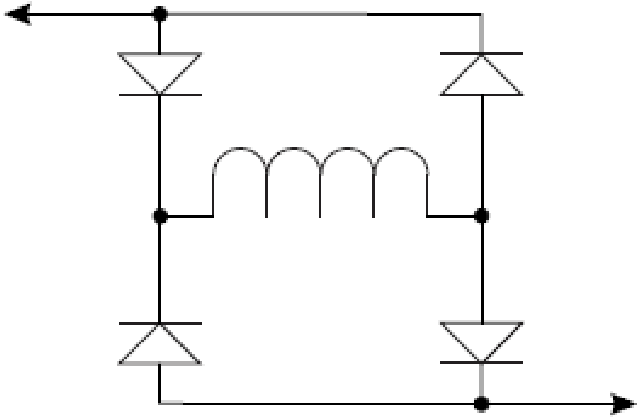
$$P_0^2 < \frac{V_B C V_{NL}^3 d(1-d)^2}{L}$$

Where

P_0	Rated Power
V_B	Nominal System Voltage
V_{NL}	No load voltage
d	droop coefficient
C	Load input capacitance
L	System inductance

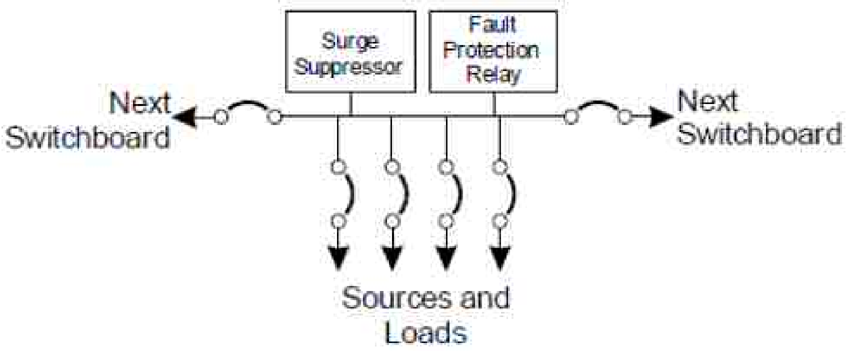
Pulsed Load Implications

- The current in a SSCB may have to reverse direction when supplying a pulse to a pulsed load.
- Current reversal through an inductor requires time.
- Keeping the current through the inductor unidirectional reduces time to increase the current.
- Unidirectional inductor can be designed to be lighter and smaller than a bi-directional inductor.
- Comes at the expense of power losses in the diodes.



Alternate Fault Detection, Localization, and Isolation Methods

- Replace SSCBs that do not connect directly to a source with a disconnect switch.
- Install minimum system inductance in the remaining SSCBs.
- Upon detection of a fault, all SSCBs open
- The fault current will likely require several milliseconds to decay before the disconnect switches can open
  - Use this time to localize the fault with differential or directional protection
  - Only command the appropriate disconnect switches to open or close
- Once disconnects are final position and the fault isolated, close the SSCBs to energize the bus.
- Once the bus is energized, loads can start drawing power.
- Overall power interruption time is anticipate to be less than 100 ms; critical loads must ride through this interruption.



Conclusions

- System Inductance of shipboard cables not likely to be sufficient for SSCB operation.
- If using only SSCBs, recommend locating additional inductance with the sources.
- If using SSCBs only with sources, recommend adding the minimum system inductance to each SSCB.