Attachment 1 to Appendix A: Technical Specifications for" Medium-Voltage Direct Current (MV-DC) Filter "

April 13, 2026

1. BACKGROUND

A MV-DC source is a powerful tool in power electronics and energy systems research. NLR's CGI-2 is equipped with power electronics and software to enable that capability. This MV-DC Filter is a necessary piece to enable smooth voltage and low current ripples output.

2. OBJECTIVE

This project seeks to add a 4kA MV-DC Filter within the CGI-2 Yard. This filter will integrate with the existing 18MW 5kV DC output available in the CGI-2 E-House (ABB ACS6000). This setup will open a wide range of research opportunities, especially in the context of modern power systems and renewable energy integration. Key research areas include power quality improvement, grid-forming and grid-following control, advanced control algorithms, DC microgrid research, and hardware-in-the-loop simulations.

3. TECHNICAL REQUIREMENTS FOR THE MV-DC FILTER AND PROTECTION SYSTEM:

Summary of Technical Requirements:

Required Capabilities for the MV-DC Filter and Protection System:

- 3.1 Filter Topology – L-cmc-C
- 3.2 Filter Passives: 6x 2mH inductors
  - 3.2.1 2mH inductors
  - 3.2.2 DC resistance
- 3.3 Filter Passives: 2 windings common mode choke (2cmc)
- 3.4 Filter Passives: Mid-Point Grounding (R8, R9, C8, C9)
- 3.5 Ancillary Components
  - 3.5.1 DC Distribution
  - 3.5.2 DC Protection
    - 3.5.2.1 Fuse/breaker curve
    - 3.5.2.2 Filter capacitor branch protection
    - 3.5.2.3 LV OV Surge protection
  - 3.5.3 Sensing and Control
    - 3.5.3.1 Protection, Thermal, and Other System measurements
    - 3.5.3.2 Control integration with NLR's CGI
  - 3.5.4 Thermal management
- 3.6 System Layout and Electrical Interfaces
- 3.7 Environmental Conditions

REQUIRED CAPABILITIES

The CGI-2 E-House has two 9MVA Inverter units bundled into the ACS6000 Converter unit from ABB. The research team requires the MV-DC Filter to support 0-4kA / 0-5kV (0-18MW) capacity.

The Subcontractor shall enclose the MV-DC Filter system in a NEMA-4R or better container such that adequate protection from the environment is achieved. The package shall be delivered with minimum on-site assembly.

NLR will provide the installation of DC conductors via the existing conduit pathways within CGI-2 Yard. A precast concrete pad will be provided as a foundation (NLR scope).

Remote monitoring and power distribution capability shall be provided within the Filter. Commissioning will be provided by the Subcontractor to confirm operational functionality.

The design shall be for 4kA MV-DC filter and protection components as marked in red dashed box on Figure 1.

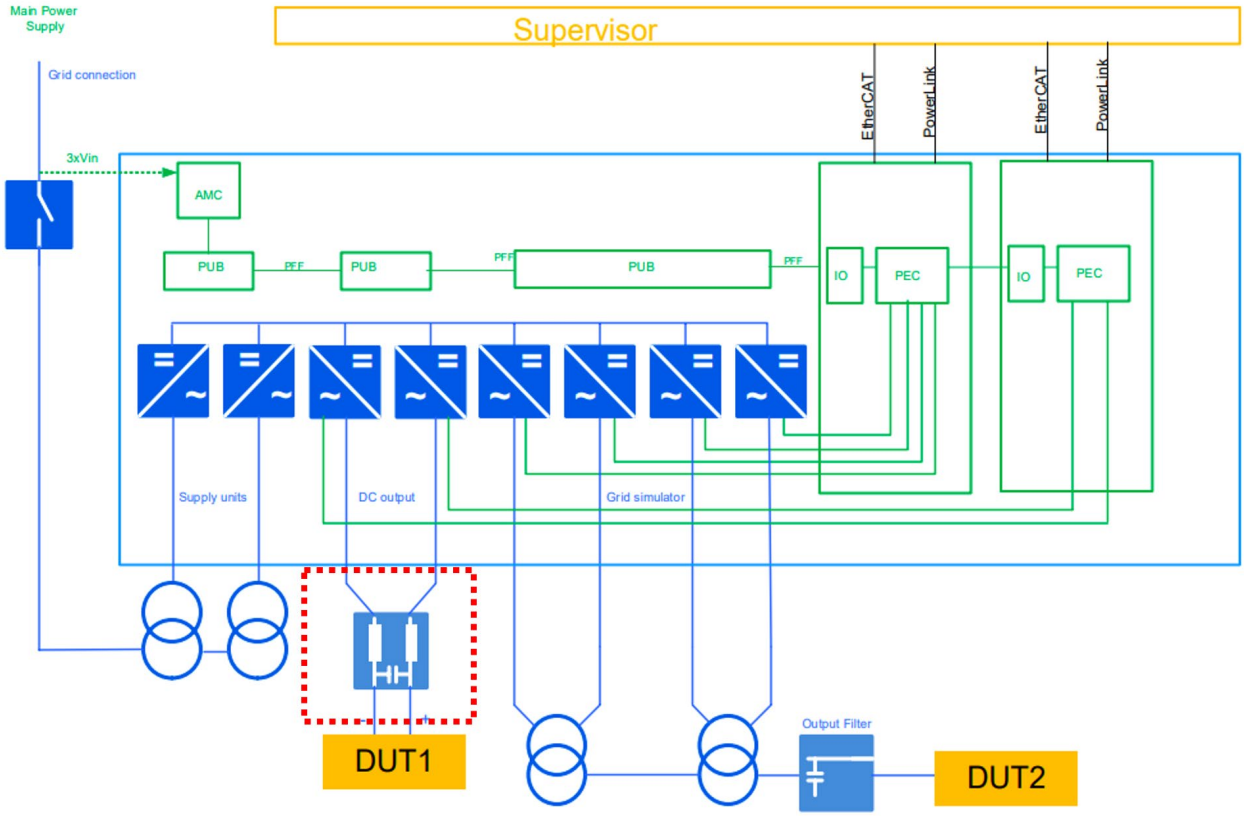


Figure 1: CGI-2 overview with MV-DC filter and protection marked using dashed rectangle

The design for the MV-DC filter shall be based on topology described in section 3.1 by integrating the passive filter components (described in sections 3.2, 3.3 and 3.4) into an environmental enclosure (described in section 3.6) with necessary cooling, protection, and telemetry (described in section 3.5.4).

3.1 Filter Topology – L-cmc-C

The MV-DC filter topology has been identified as shown below in Figure 2 and consists of the following:

- Six identical inductors connected in series that are used to minimize circulating currents between interleaved PWM switching inverter phases;
- Resistance in each branch that limits circulating DC current that can be either an internal inductor resistance or the sum of internal inductor resistance and discrete series resistors;
- Output capacitance with resistive damping that together with L1-L6 form LC low pass filter; and
- CMC – L7 – that reduces common-mode currents that flow back to inverter through mid-point grounding and NP filter.

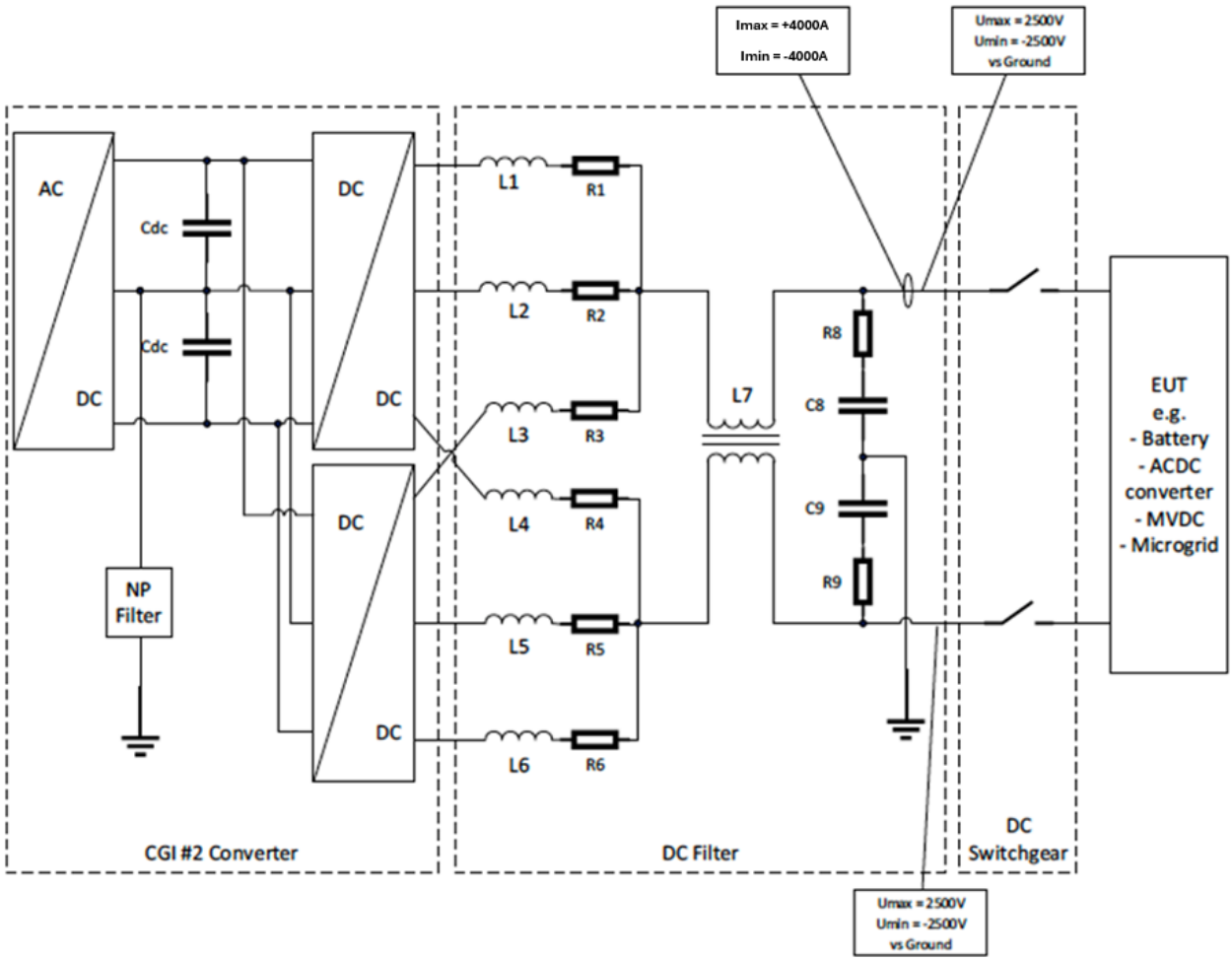


Figure 2: MV-DC Filter Topology

3.2 Filter Passives: 6x 2mH inductors

The design shall include 6x 2mH inductors as specified below:

3.2.1 2mH Inductors

	Min	**Typ**	**Max**
Inductance	1.9mH	2mH	2.1mH
Max voltage vs ground	-2.5kV		2.5kV
Max differential voltage (peak)	-2.5kV	-1.8kV to 1.8kV	2.5kV
DC current	-1333A		1333A
Current ripples frequency	350Hz	570Hz	700Hz
Current ripples magnitude (peak-peak) @285Hz		500A	
Current ripples magnitude (peak-peak) @200Hz		700A	
DC resistance			20mOhm

Expected inductor current harmonics:

Apart from nominal DC current, inductors shall be designed with margin allowing for switching frequency harmonics. It has been identified that for nominal switching frequency (Fs=570Hz) and filter parameter, highest ripple current observed is ca 500Apk-pk as shown in Figure 3.

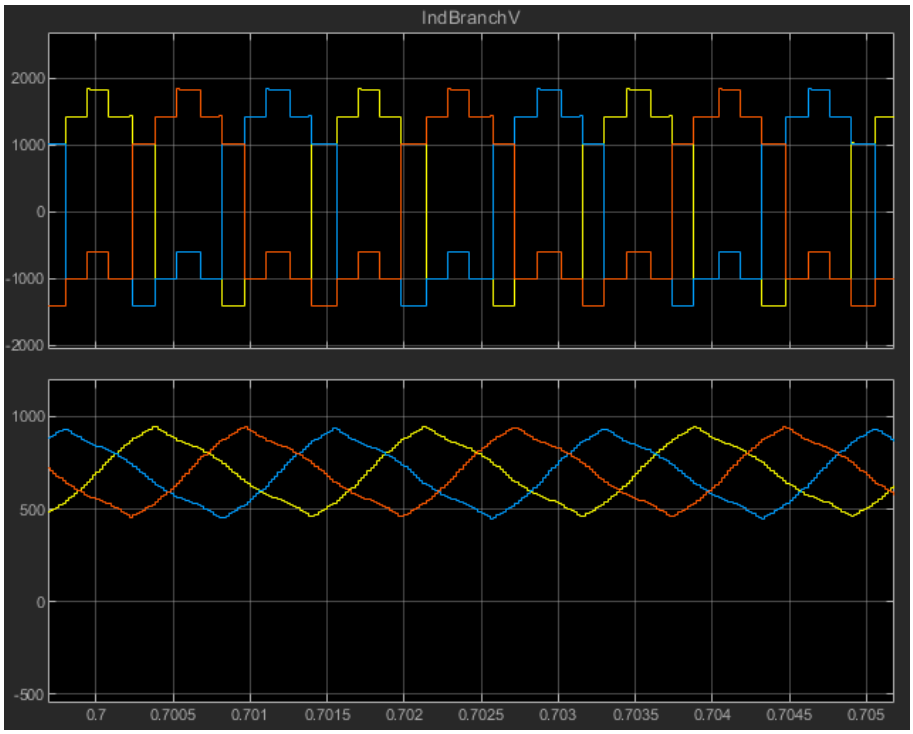


Figure 3: Inductors voltage (top) and current(bottom) at following conditions: 2100A load, 2mH, 2x2.8mF and 570Hz switching

For operation at nominal current of 4kA switching frequency will have to be reduced to 400Hz thus current ripples expected are higher. Chokes must be designed to operate continuously in that condition.

3.2.2 DC Resistance

The design shall include 20mOhm of resistance in each inductor branch to balance loads of inductors. If that could be achieved by DC winding resistance that would be beneficial since no additional resistance will have to be developed; otherwise, 6x discrete resistors shall be added so that series resistance reaches a combined minimum value of 20mOhm.

3.3 Filter Passives: 2 windings common mode choke (2cmc)

CGI-2 modulation is a source of considerable common mode voltage that without proper common-mode choke do not allow us to implement a middle center point referenced to ground. MV-DC filter topology consists of 2 winding common-mode choke (2cmc) that allows for implementation of middle point grounding between C8 and C9 as shown in Figure 2.

Common-mode choke will see full rated current of converter up to +- 4kA and very minimal ripples. The voltage on windings is also relatively small at 400V pk-pk. Necessary insulation

must be provided between positive and negative winding since the voltage between these may reach 5kV.

The dual winding common mode choke inductors for the filter system are specified below:

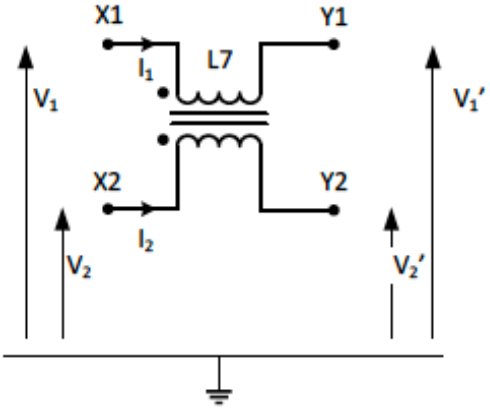
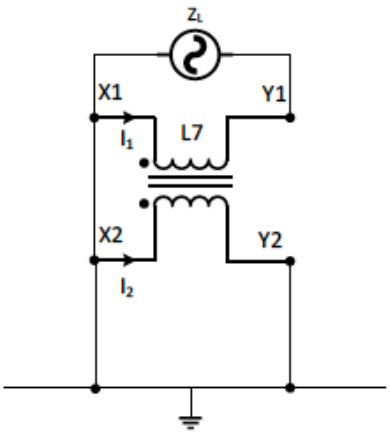


Figure 4: Common Mode Choke

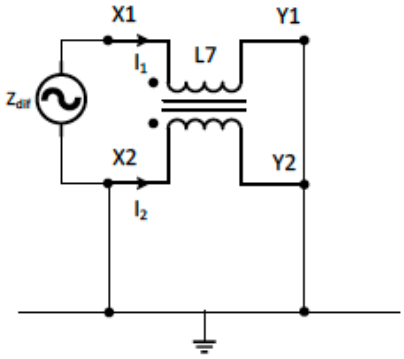
	Min	**Typ**	**Max**
X1-Y1 – positive voltage winding			
V_1 & V_1'- instantaneous	0		2.5kV (could go higher during transient tbd)
$V_{11} = V_1 - V_1$'	-500V		500V
X2-Y2 – negative voltage winding			
V_2 & V_2'- instantaneous	-2.5kV		0
$V_{11} = V_1 - V_1$'	-500V		500V
Currents			
I_1 & I_2	-4kA		4kA
$I_{dif} = (I_1 - I_2)/2$	-4kA		4kA
$I_{cm} = (I_1 + I_2)$			1Arms
Impedances			
L_{cm} @<1700Hz*	20mH	more is better	
R_{cm} @<1700Hz*	0.1 Ω	more is better	
$L_L = L_{dif}$		less is better	0.2mH
$R_L = R_{dif}$		less is better	10mΩ

**Note: @<1700Hz – _requires impedance to be within min/max for all frequencies between 0 and 1700Hz*

- Measurement of leakage impedance – $Z_L = R_L + i\omega L_L$ (as in standard transformer definition)

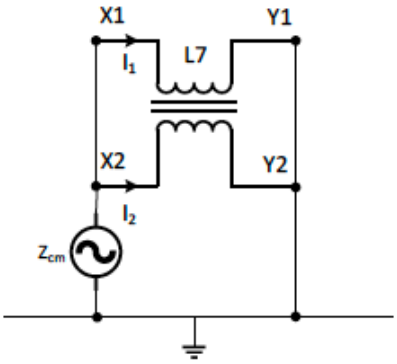


- Measurement of differential impedance – $Z_{dif} = R_{dif} + i\omega L_{dif}$



Differential impedance is same as leakage. Measurement circuits are electrically the same – just drawn differently.

- Measurement of common mode impedance – $Z_{cm} = R_{cm} + i\omega L_{cm}$



- Typical voltage and current waveforms:
  The top graph shows V1 (blue) and V1' (red). The second graph shows V2 (blue) and V2' (red). The third graph is differential current and the fourth graph is of common mode current with Lcm=100mH.

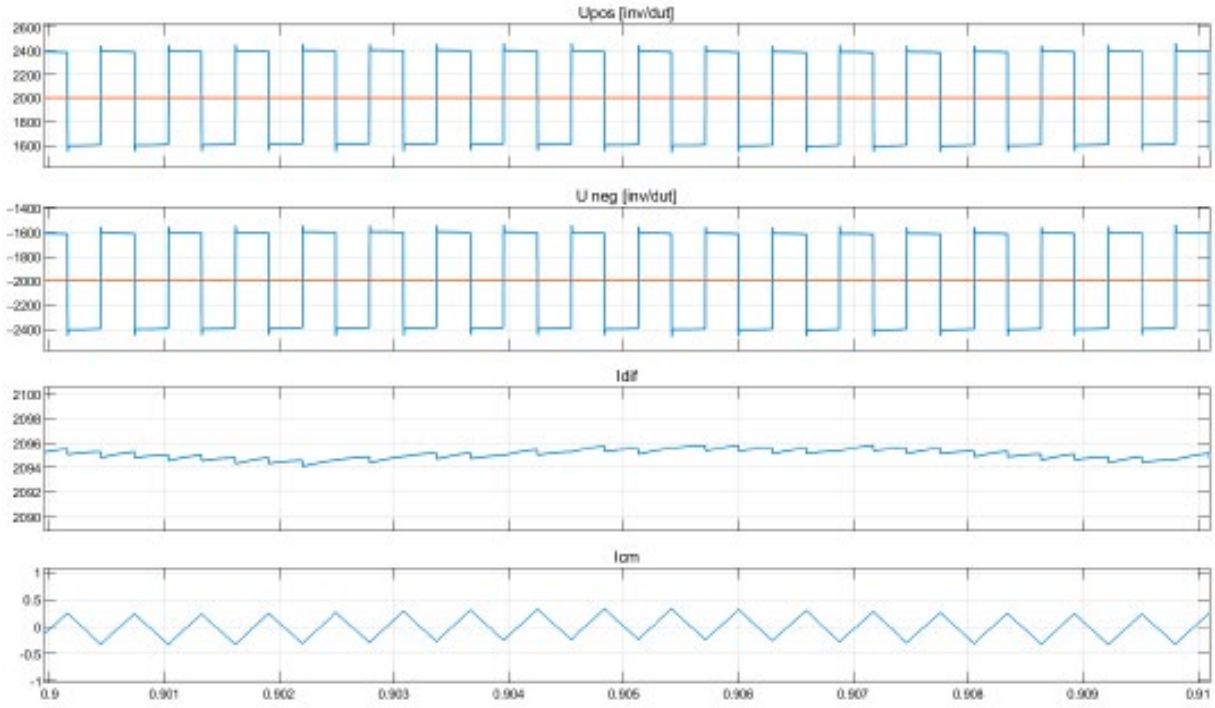
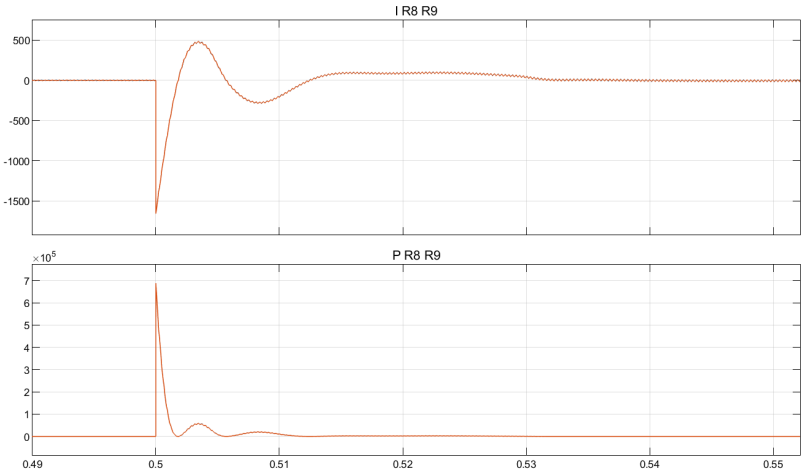


Figure 5: Typical Voltage and Current for Common Mode Choke

3.4 Filter Passives: Mid-Point Grounding (R8, R9, C8, C9)

Ideally in steady state resistors R8 & R9 will not consume much power however the power rating of these resistors has to be considered. Simulations show that in steady state these resistors are going to see a very low power likely below <200W each. However, these shall be designed to be able to withstand various dynamic conditions. Specifically, the two scenarios shown below:

Start of 8MW load would cause a voltage dip. Initially current will be supplied from capacitors thus it will flow through resistors. A waveform is shown with current spiking to 1500A for a very short period of time. Resistor, capacitor and respective fuses shall be designed to be able to withstand that current. See below for current and power waveforms at resistors:



Output voltage ramp from 0 to 4000V in 0.5s causes consumption lower < 400W.

LC of filter form a resonant circuit at 116Hz. Oscillation at this frequency will cause maximum power dissipation on resistors R8&R9. At 150Vrms perturbation level from CGI inverter both resistors will see 40kW of load – 20kW each and 282A rms. RC branch shall be able to operate continuously at this condition.

Requirements for R8&R9 shall be set based on above scenarios thus:

R8 & R9:

- Max power dissipation = 20kW
- Max current – 282Arms
- Max peak current – 2000A (without breaking fuse)

C8 & C9

- Max current 282Arms
- Peak current – 2000A (without breaking fuse)
- Withstand voltage – 2800 V

Additionally, C&R must be able to withstand short to ground or line to line fault. These will cause at least an initial spike of 10 kA (5000V/0.5Ohm). This can be achieved with support of fuse blowing if needed.

3.5 Ancillary Components

3.5.1 DC Distribution

The filter system shall include connection equipment for field connection of input wiring from the CGI-2 and for output wiring to the broader system at the site.

3.5.2 DC Protection

The output shall allow for disconnection via a DC switchgear, as indicated in Figure 2, with protection for the filter and CGI system as indicated below. This protection can be through a DC breaker and/or fusing depending on the Subcontractor's design .

3.5.2.1 Fuse/breaker Curve

The following table summarizes requirements for a breaker tripping time in case of fault on DUT side. For given fault current the breaker/fuse should ensure opening in less than T_{Brk}.

$I(T_{CGI})$ [kA]	**T_{Brk} [ms]**
54.6	7.9
52.9	8.2
48.9	8.9
40.5	11.1
25	22.3

DC breaker can either detect the short itself by using di/dt or instantaneous threshold or similar or can use CGI-2 trip signal.

3.5.2.2 Filter Capacitor Branch Protection

Protection of the filter capacitors on the mid-point ground shall be considered for high currents introduced from transient and short circuit conditions .

- Subcontractor shall identify required protection based on withstand ratings for selected passive components within the mid-point ground filter.
- Subcontractor shall provide a fuse or other protection concept to protect filter capacitor (C8/C9) and damping resistance R8/R9 from e.g. unexpected HF oscillations.
- Subcontractor shall provide discharge resistors for capacitors.

Note, NLR intends to monitor R/C currents and will implement a protection that will stop CGI before fuse operation to reduce the occurrence of such events though response time is a limiting factor.

3.5.2.3 LV OV (Over-voltage) Surge Protection

Even though the MV-DC filter allows operation up to 5kV, it is mostly going to be used for LV operation with equipment rated below 1500V. Transients during LV operation

may result with large OV swings thus surge protection is necessary. This equipment may need to be disconnected from the circuit for operation at higher voltages.

3.5.3 Sensing and Control

3.5.3.1 Protection, Thermal, and Other System measurements

The MV-DC filter and protection system shall include all sensing and measurement required for the operation of the System. This may include but is not limited to voltage and current measurement for the DC switchgear for the supplied breaker/fuse solution and temperature measurements for thermal management of system. Switchgear operation shall consider normal conditions for opening and closing the breaker/switch, maintenance, and fault conditions.

3.5.3.2 Control Integration with NLR's CGI

Operation of the MV-DC filter with the CGI will require the following voltage and current measurement points within the filter:

Current measurement *(Subcontractor provided current transducers)*

- 2x closed-loop with DC – 100 kHz with 0.1 to 0.2% full scale accuracy using a dedicated external precision burden resistor on output (switch)
- 2x closed-loop with DC – 100 kHz with 0.1 to 0.2% full scale accuracy using a dedicated external precision burden resistor on C8 & C9 branch smaller rating

Voltage measurements *(NLR will procure and install on Subcontractor-provided voltage taps)*

- Positive pole to ground output
- Negative pole to ground output

The design shall include a control compartment to allow for installation of instrumentation. Current measurements shall be terminated in this compartment.

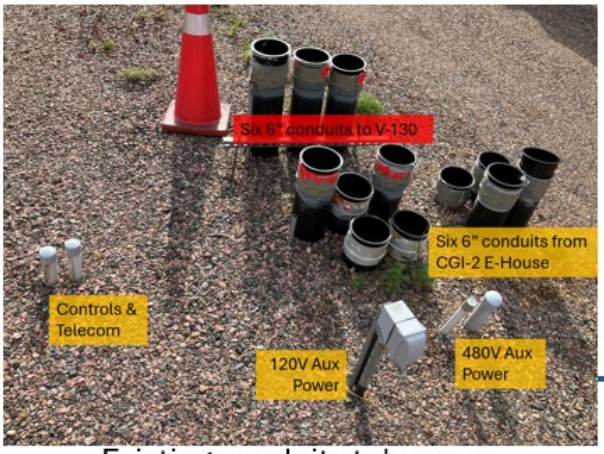
3.5.4 Thermal Management

The filter system shall include equipment to allow for continuous operation of the filter within the environmental conditions identified below. Passive component parameter variation across this temperature range should be identified, as well as any cooling equipment needs, if required.

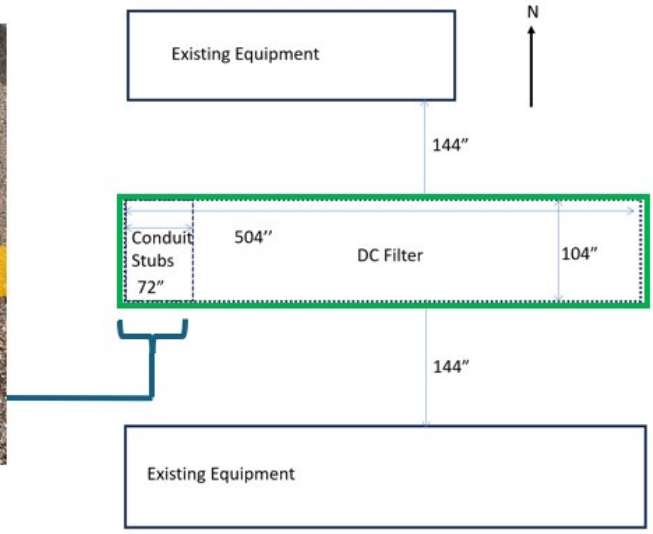
3.6 System Layout and Electrical Interfaces

- System shall be compliant with Nationally Recognized Testing Laboratory (NRTL) or equivalent.
- The dimensions of the MV-DC Filter enclosure shall not exceed 504"L x 104"W.

- The existing site has been designed with the following electrical interfaces which are contained in a “Conduit Stubs” area 72”L x 104”W. The DC Filter enclosure shall include compartment(s) to accommodate bottom feed access to these stub-ups.
- CGI-2 side DC power connections will be bottom fed through six 6” conduits (NLR scope). These shall be accessible for connections in a MV electrical compartment.
- Control and communication interfaces will be bottom fed through two 2” conduits (NLR scope). These shall be accessible for connections in a LV/control compartment.
- Auxiliary power interface (120V and 60A 480V 3-phase) will be bottom fed through separate 2” conduit (NLR scope). These shall be accessible for connections in a LV/control compartment.



Existing conduit stub up area



Proposed footprint (green) of DC Filter

3.7 Environmental Conditions

The MV-DC Filter will be outdoor-rated for the following Environmental Conditions:

- Ambient temperatures: -20-110F
- Humidity: full-range, Arvada, Colorado
- Elevation: 6000 ft above sea level
- Winds: 155 mph basic wind speed
- Enclosure: NEMA-4 or higher