Fault Current Control for DC Microgrid Protection

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- DC Microgrid- Overview
- Type of Faults, Protection Methods & Challenges
- System Under Consideration
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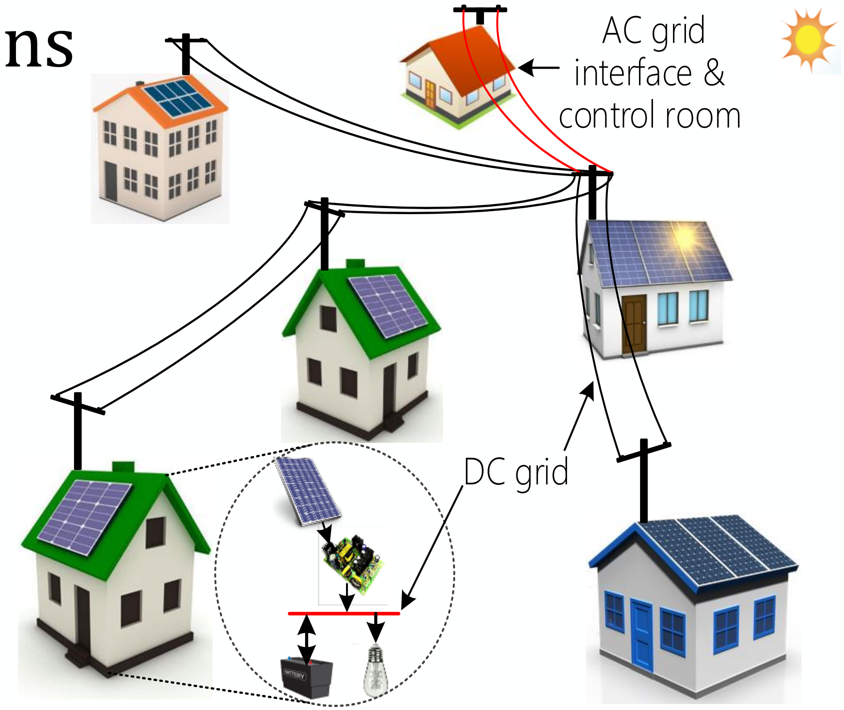
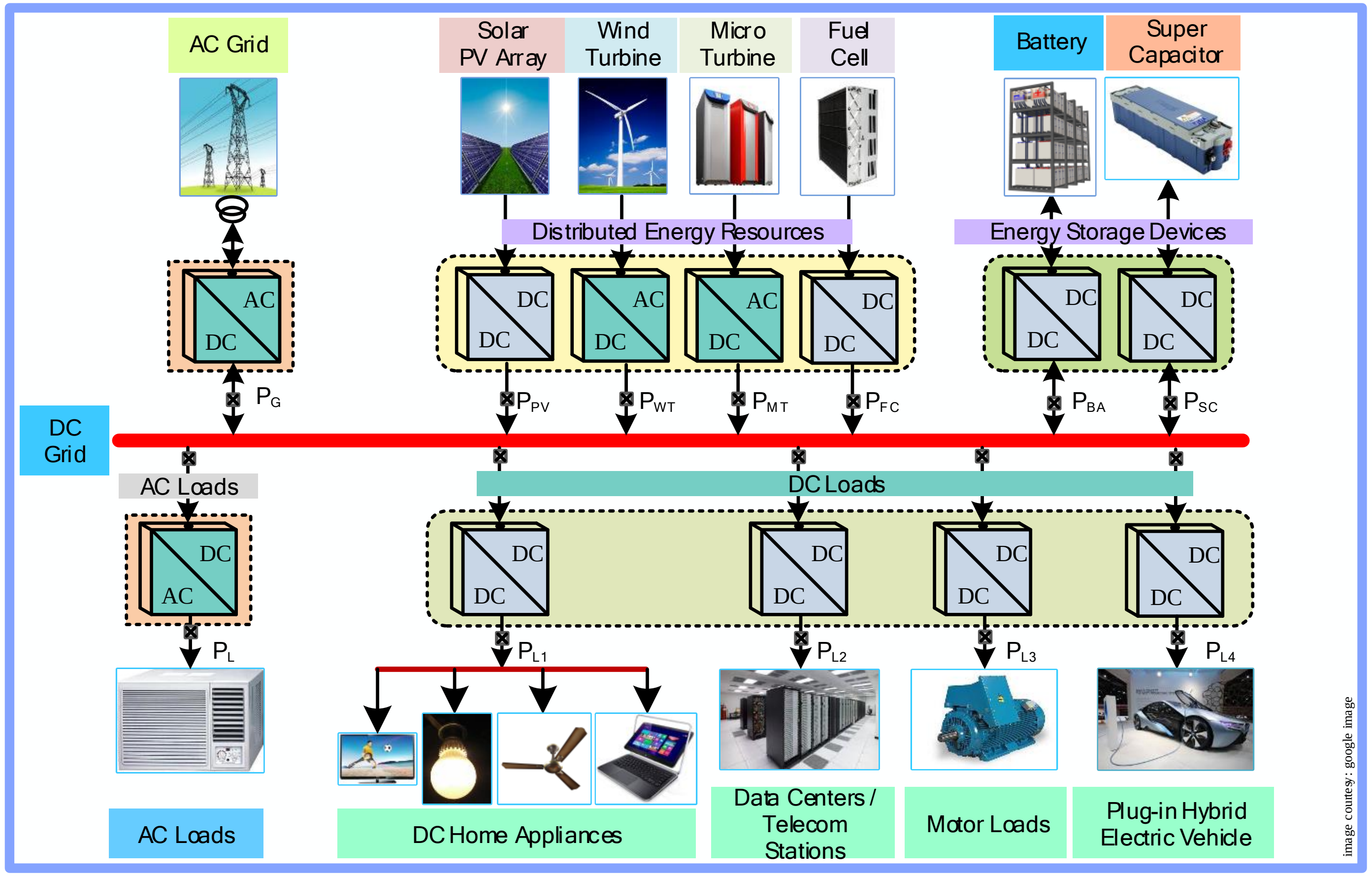
- Conclusions

DC Microgrid - Overview

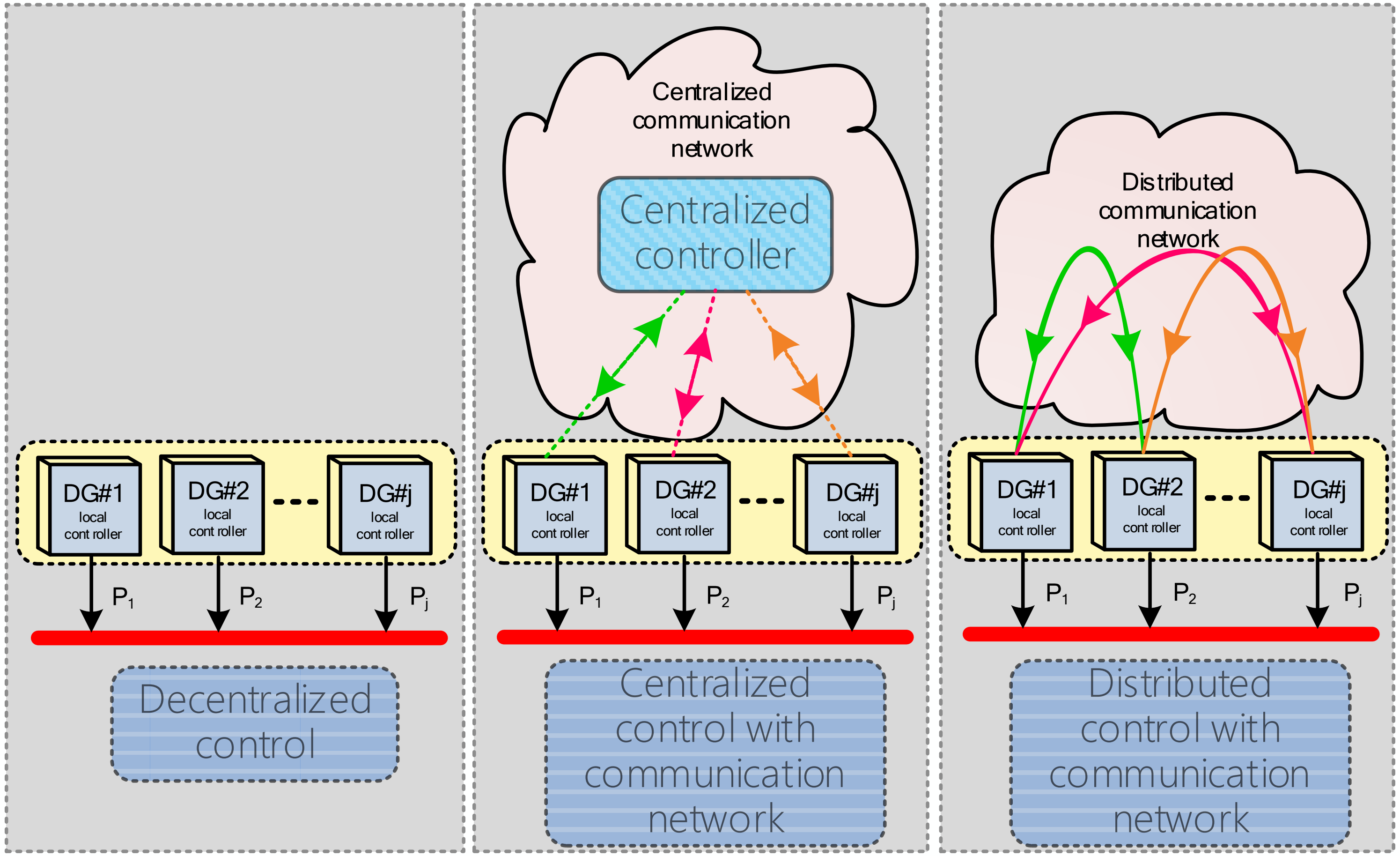
- Variety of sizes, technologies, and configurations
  - Single bus, multi-bus, radial, meshed, zonal etc.
- Energy efficiency
  - Reduced AC-DC conversion, generation sources closer to loads.
  - Economic benefits
- Simpler than AC
  - Reactive power, skin effect, etc. not an issue in DC power.



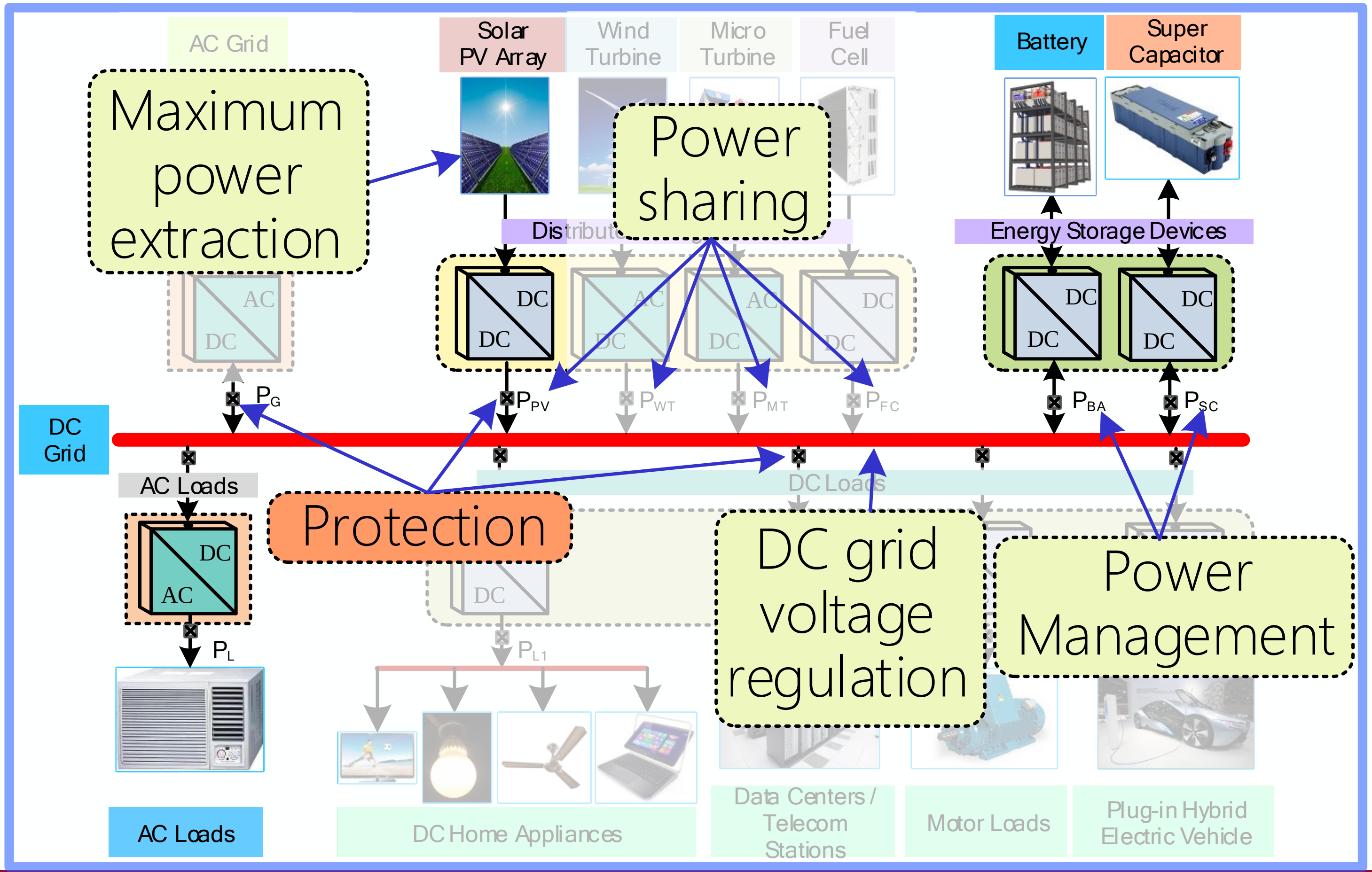
DC Microgrid Components



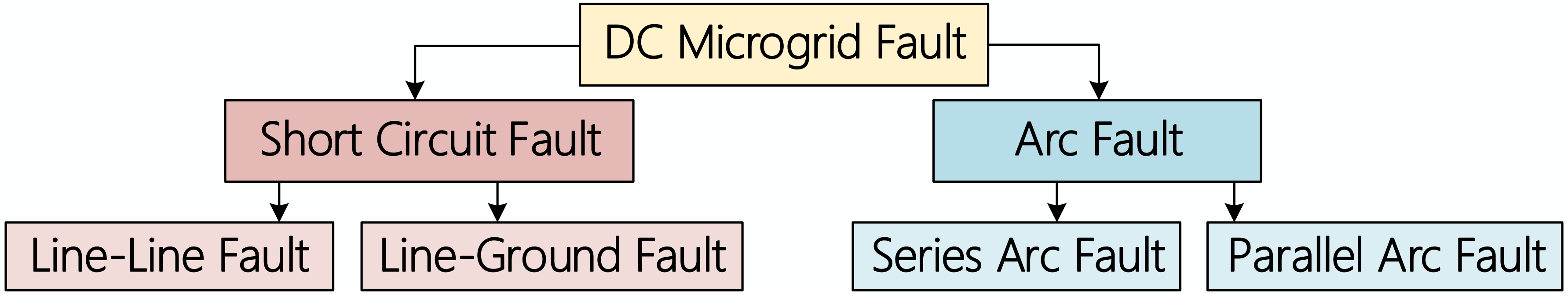
DC Microgrid Operating/Control Principles



Performance Parameters

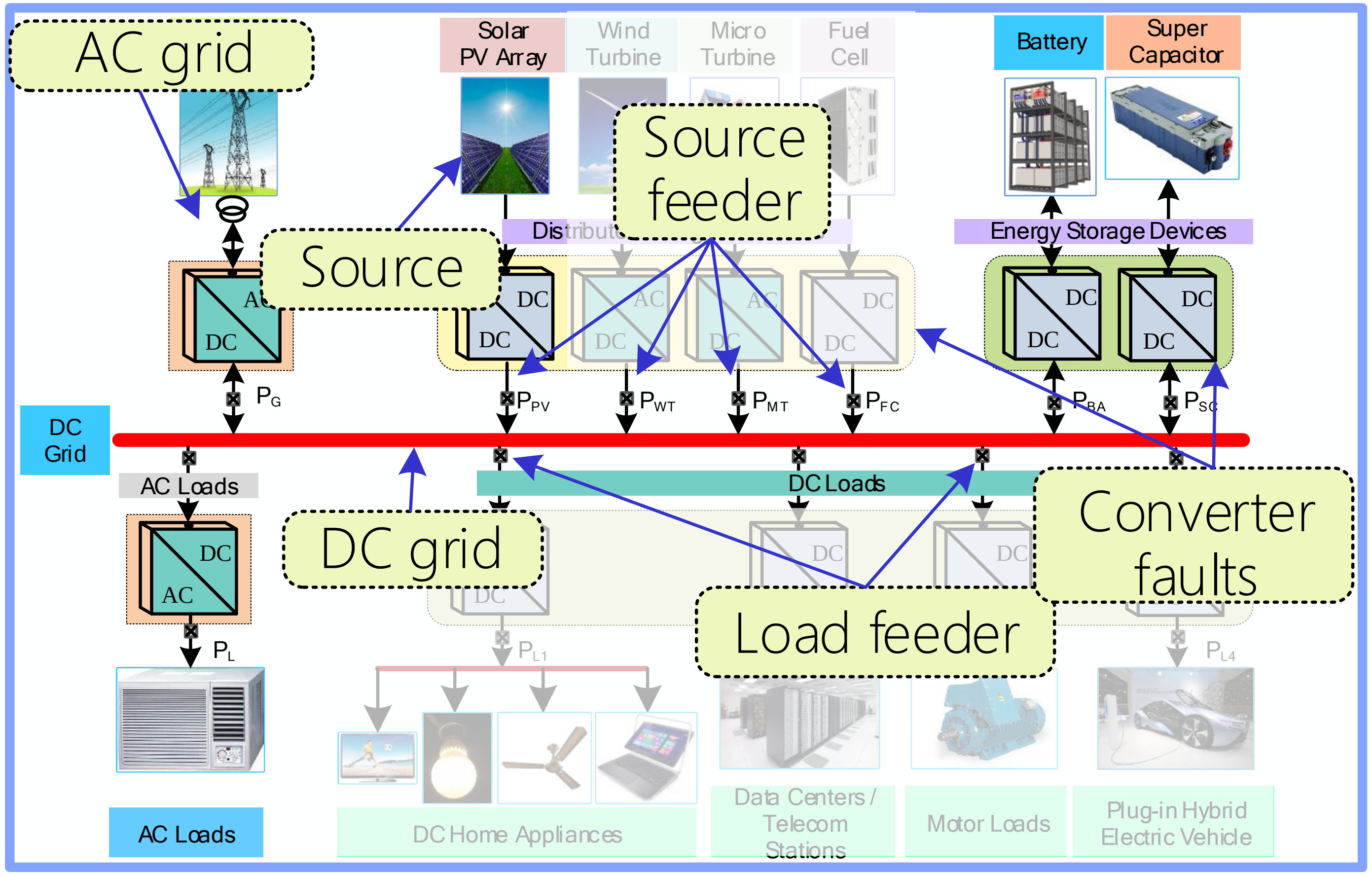


Types of Fault: Solar-PV based DC microgrid

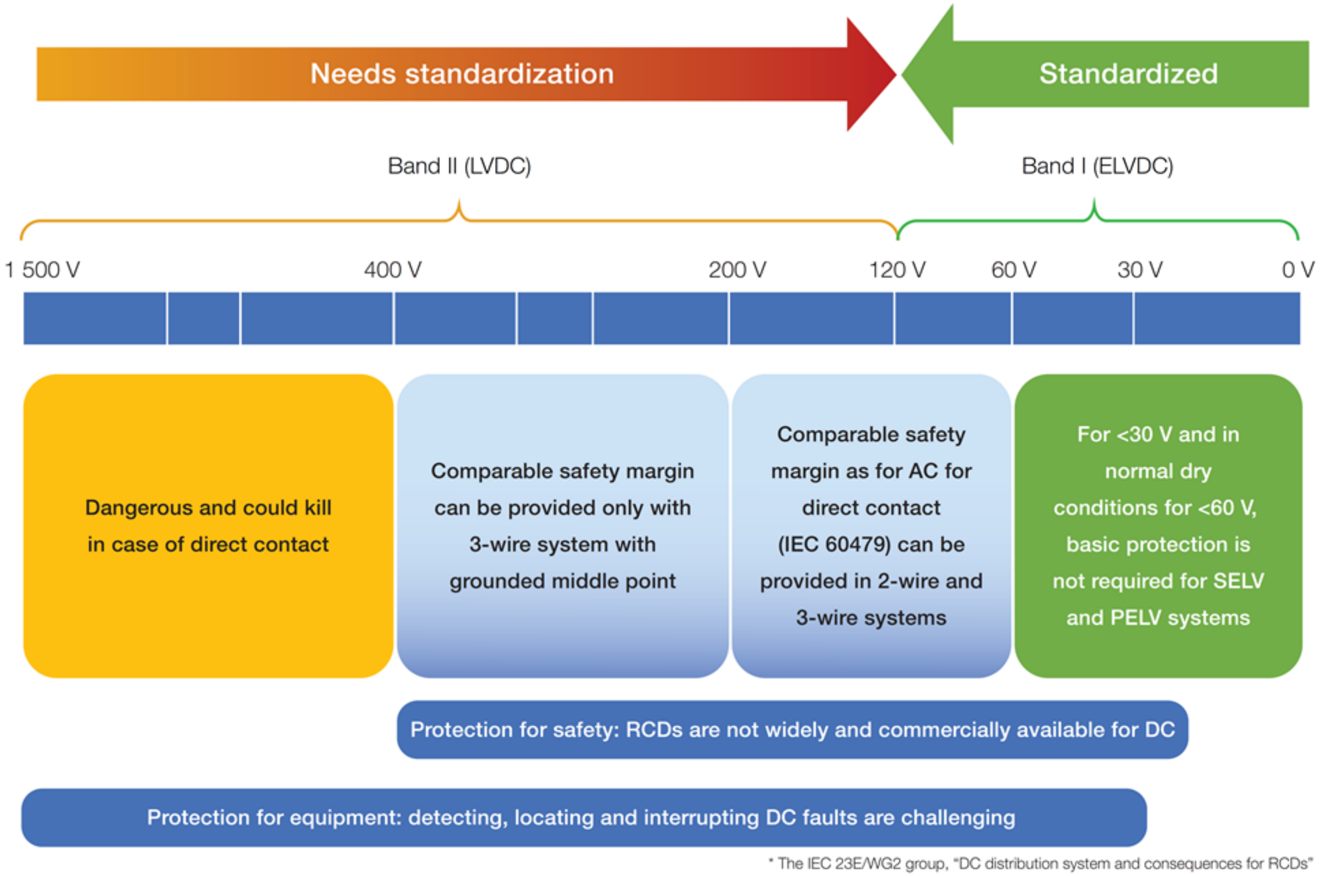


- Low Impedance Faults
- High Impedance Faults

Fault Locations



Standardization



Challenges of DC Protection

- No zero crossing
- Circuit breaker arcing
- Characterization of faults from disturbances/transients.
- Faster speed requirements
- Communication protocols
- Lack of guidelines and standards (IEEE P2030.10, IEEE 1547.4, IEC SEG4, IEEE PES IGCC DC@Home, NEC, REbus™, EMerge Alliance, etc.)

Protection Methods & Schemes

DC Microgrid Protection Methods

Unit Protection	Non-Unit Protection	Single Ended	Double Ended
Protect specific zones	Follow a threshold value to detect the various faults	Local measurement of voltage and current	Sensing devises at both ends & communication channels

DC Microgrid Fault Detection Schemes

- Magnitude of voltage
- Magnitude of current
- Impedance estimation method
- Power probe unit method
- Virtual Impedance method
- Differential current-based fault detection
- Transient-based fault protection
- Voltage derivative supervised current derivative protection
- Advanced fault detection techniques for PV arc, ground, and Line-Line faults

DC Protection Devices

DC Microgrid Protection Devices

Fuse
- Conventional

DC Circuit Breaker
- Molded Case
- Vacuum CBs
- Hybrid-solid/vacuum

Protective Relay
- DC power relays
- Digital relays

Arc Fault Interrupter
- Arc Fault Circuit Interrupter (AFI)
- Combination Arc-Fault Circuit Interrupter (CAFI)

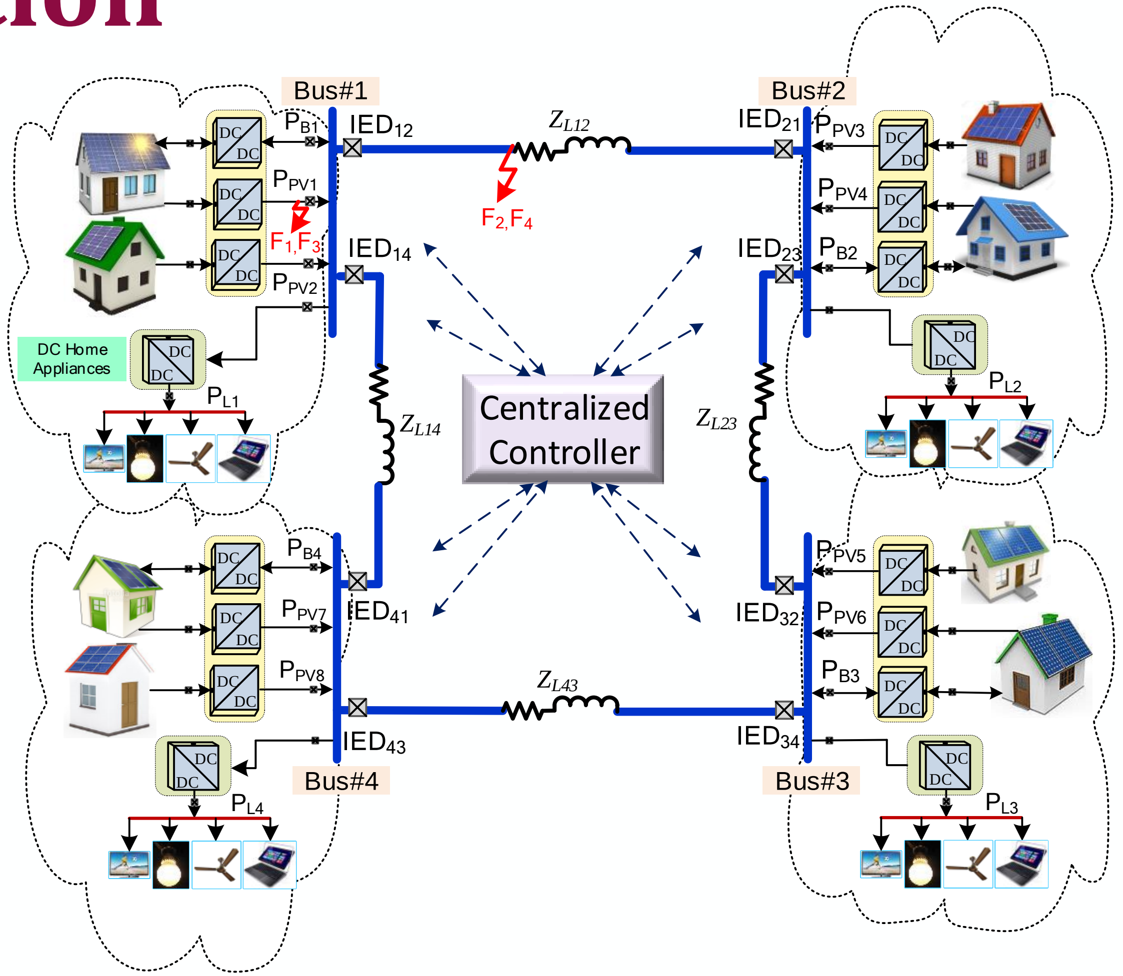
Solid State CB
- Gate turn off thyristor (GTO)
- Emitter turn-off (ETO) thyristor
- Insulated gate bipolar transistor (IGBT)
- Insulated gate commutated thyristor (IGCT)
- Coupled inductor SSCB

Hybrid CB
- Thyristor-based DC hybrid CB

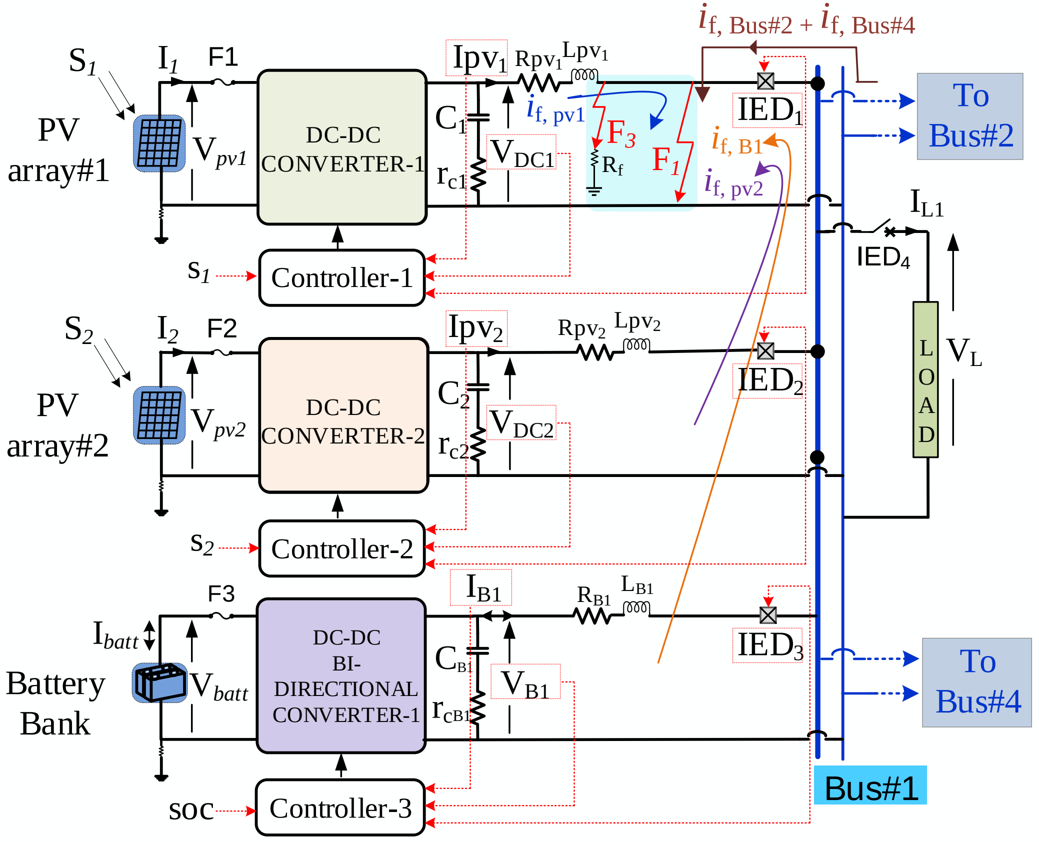
- High Switching speed
- Fully controllable
- High voltage blocking & current carrying capability
- Low on-state conduction loss
- Arcing is small

System Under Consideration

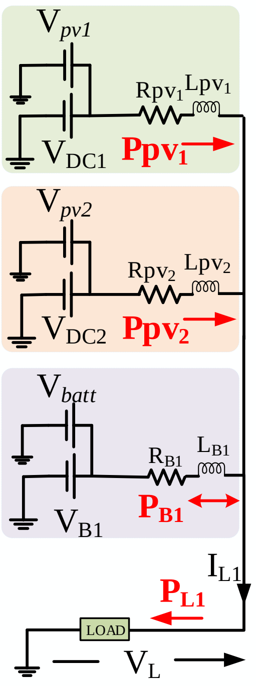
- A standalone 4-bus DC microgrid system.
- Each bus consists of two parallel connected solar-PV boost converters, one bidirectional converter for energy storage, and DC loads
- L-L (F_1 & F_2) or L-G (F_3 & F_4) fault created at converter-1 terminal and Feeder.



BUS#1- Converter Cable Fault (F_1)

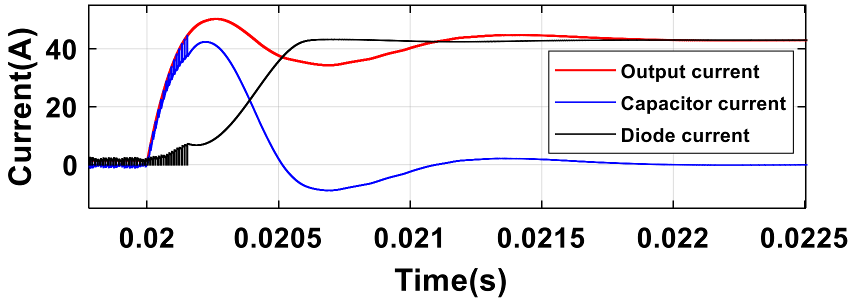


(a)



(b)

$$i_f = i_{f,pv1} + i_{f,pv2} + i_{f,B1} + i_{f,Bus\#2} + i_{f,Bus\#4}$$



(c)

- Converter-1's contribution to the fault current can be divided into two components:
  - (i) The fault current component from the DC power source (PV), and
  - (ii) The current from the DC bus capacitor.

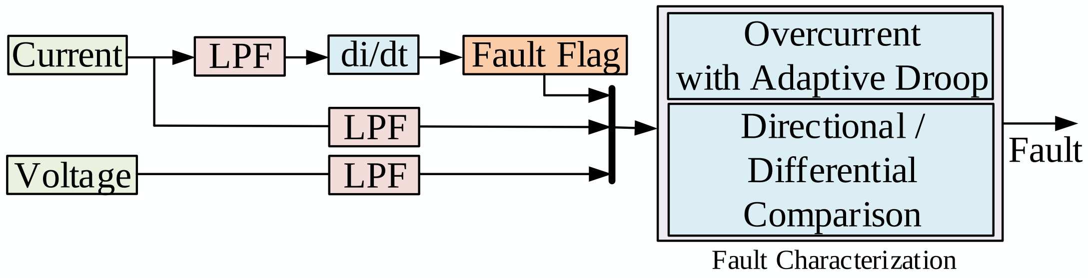
Proposed Droop Algorithm -Objectives

- Power sharing
- Maximum power point tracking (MPPT)
- Energy management
- **Protection**: Control the reference voltage of each converter by using an adaptive virtual Resistance, called R_{droop}.

Sijo Augustine, Mahesh K. Mishra, and N. Lakshminarasamma,, **A Unified Control Scheme for a Standalone Solar - PV Based LVDC Microgrid System with HESS**" in IEEE Journal of Emerging and Selected Topics in Power Electronics. doi: 10.1109/JESTPE.2019.2916421

Sijo Augustine, M. J. Reno, S. M. Brahma and O. Lavrova, "**Fault Current Control and Protection in a Standalone DC Microgrid Using Adaptive Droop and Current Derivative**," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, doi: 10.1109/JESTPE.2020.2984609.

Current Derivative + Adaptive Droop



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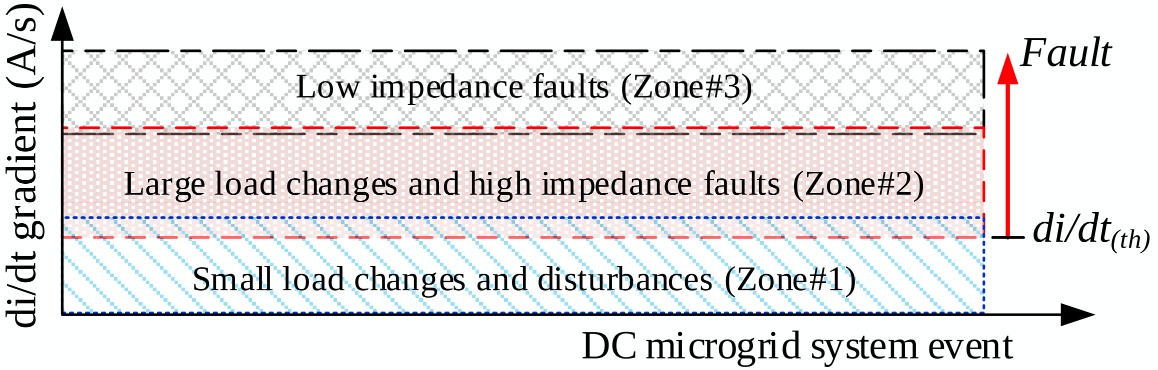

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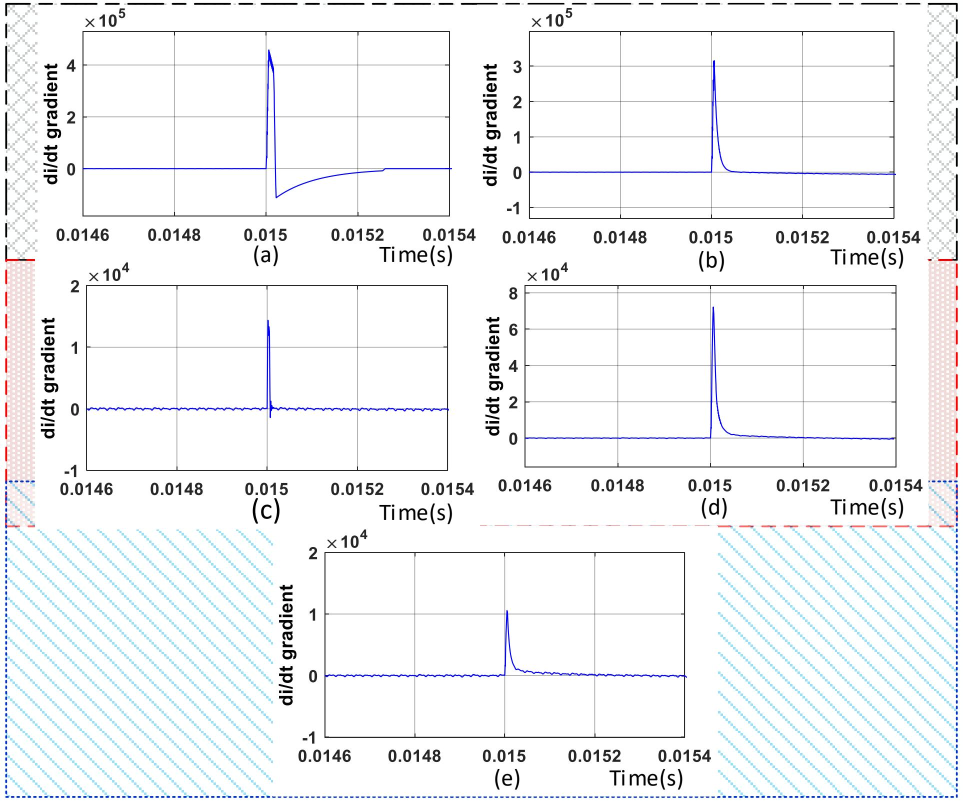
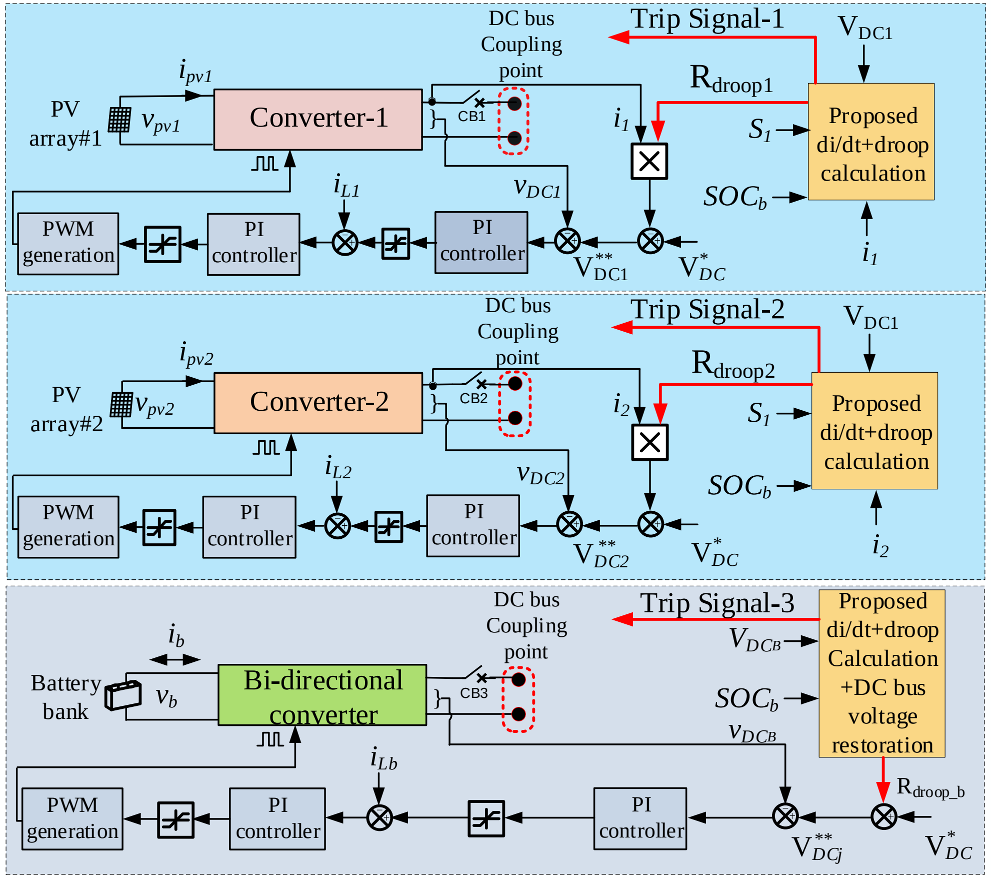
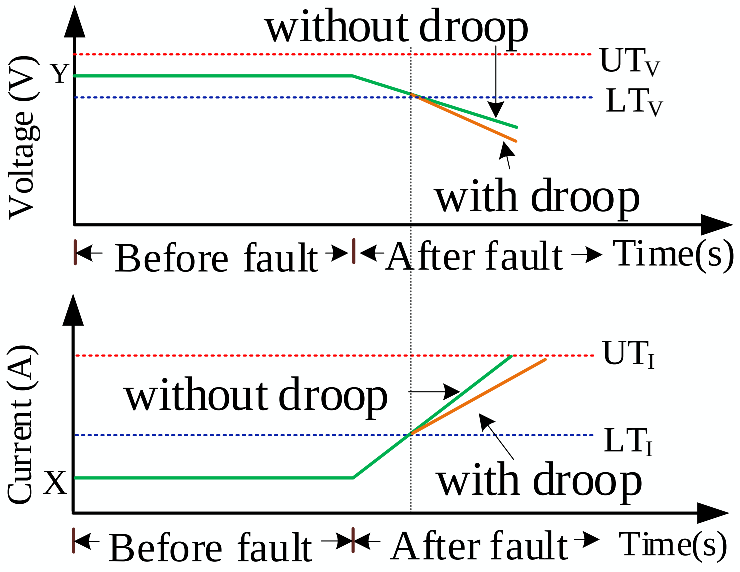


di/dt gradient measured for Converter-1 faults and bus#1 load change (a) 1Ω line-line fault (F_1) (b) 10Ω line-line fault (F_1) (c) 500Ω line-ground fault (F_3) (d) Load change from 3A to 8A, and (e) Load change from 3A to 4A.

Control Algorithm



(a)



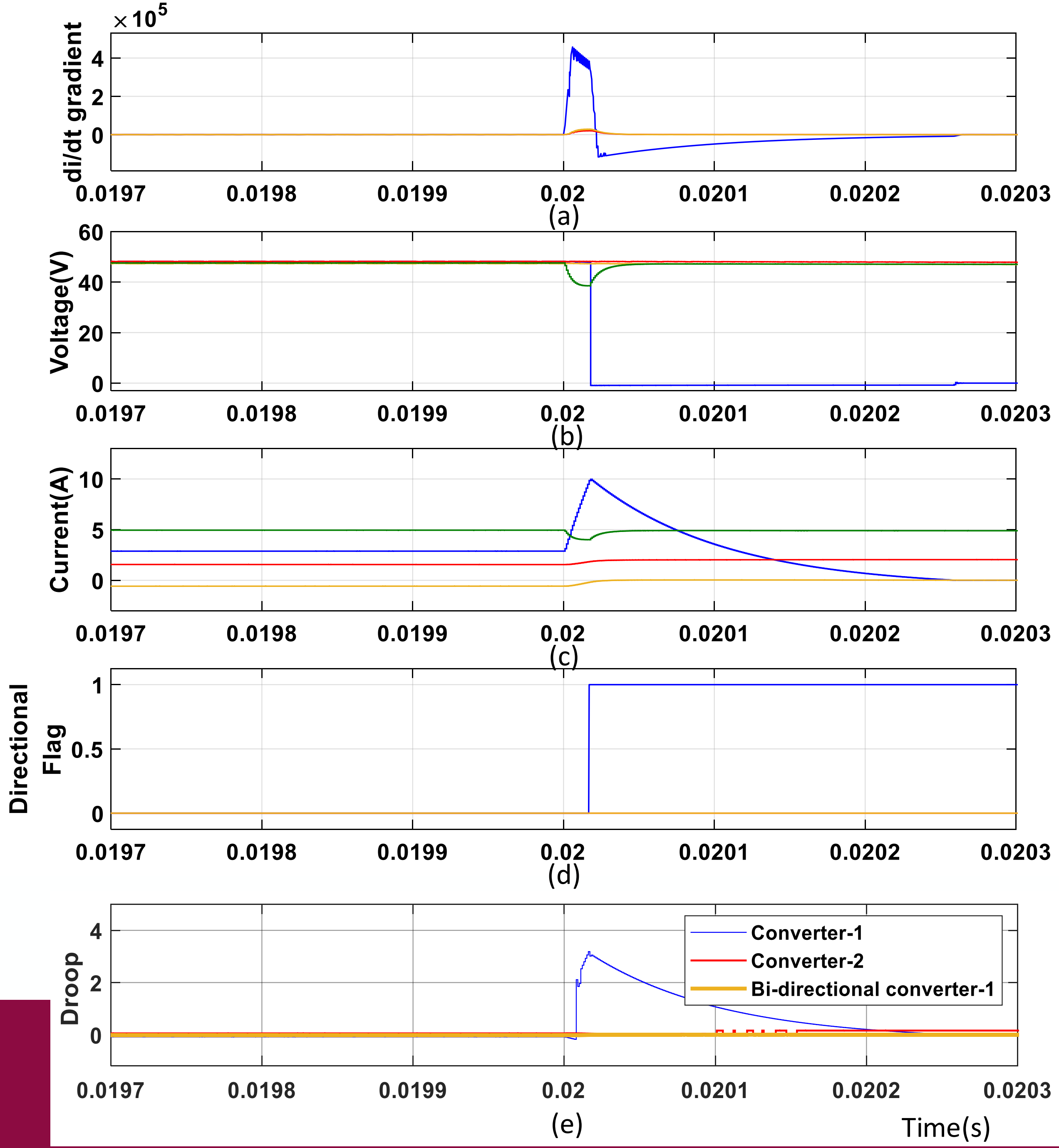
(b)

Parameter	Magnitude
Voltage	$UT_V = 46$ V $\quad LT_V = 35$ V
Current	$UT_I = 10$ A $\quad LT_I = 6$ A
$\frac{di}{dt}(th)$	1×10^4 A/s

Low impedance Fault:

- Conv-1: Converter to bus#1, line-line cable fault is activated at 0.02s
- Conv-2: Normal operation, no fault

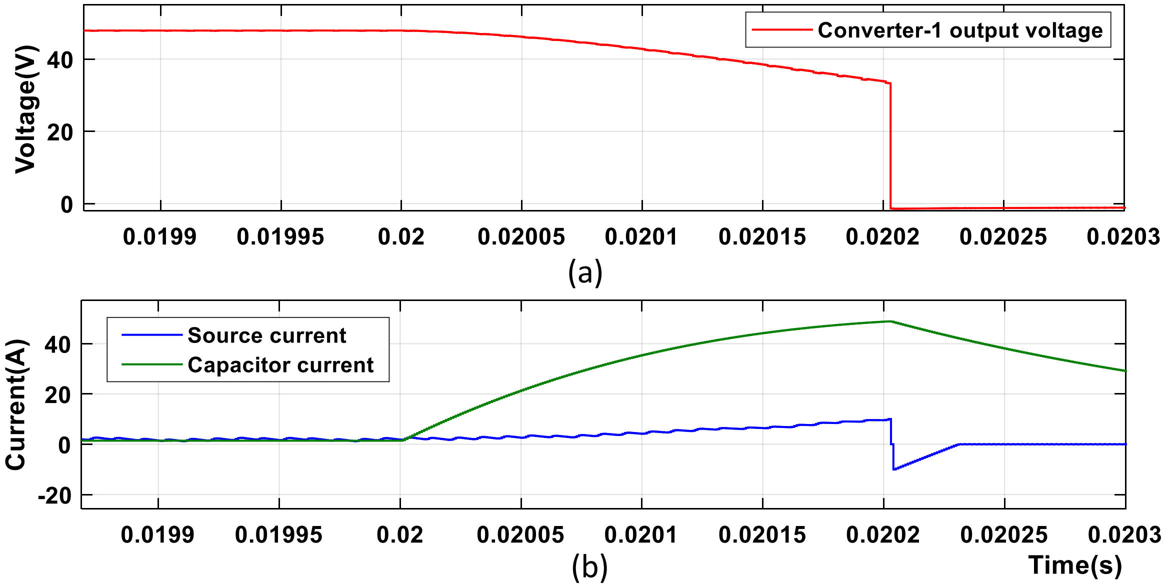
- di/dt of the converter-1 is high - Fault is detected.
- Trip signal is sent to isolate the converter when the current reaches 10A threshold.



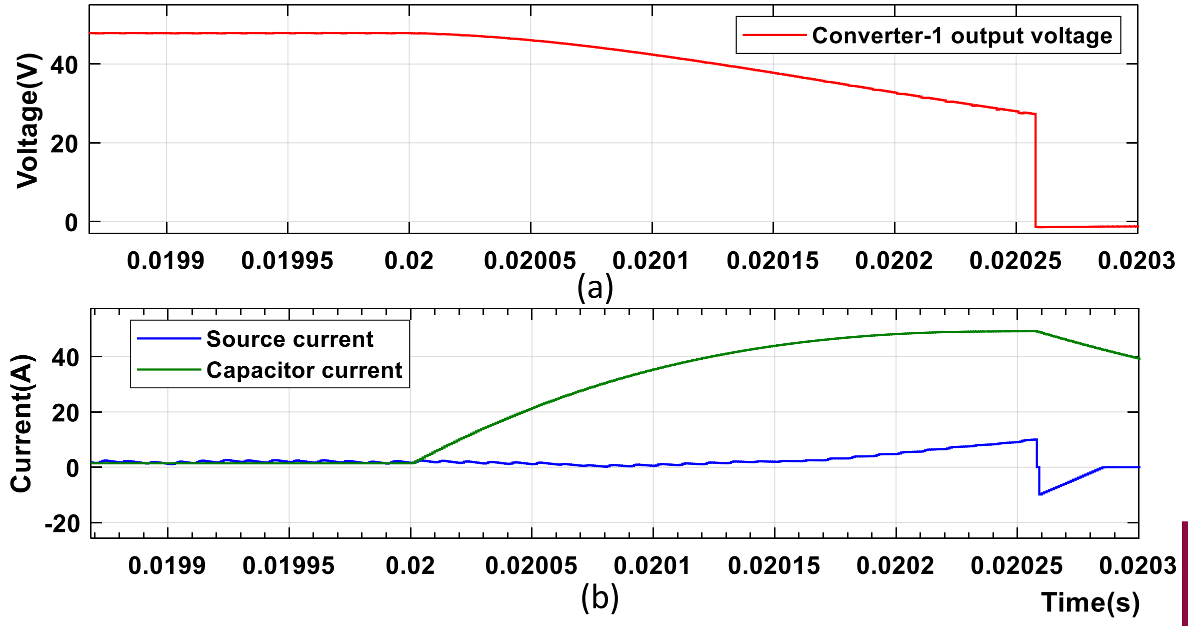
Droop Control:

- 10A is selected as the source current threshold instead of converter-1 output current threshold.
- Top Figure: The total time taken to clear the fault is approximately 205µs.
- Bottom Figure: The total time taken to clear the fault is approximately 265µs.

Additional 60µs is available to clear the fault



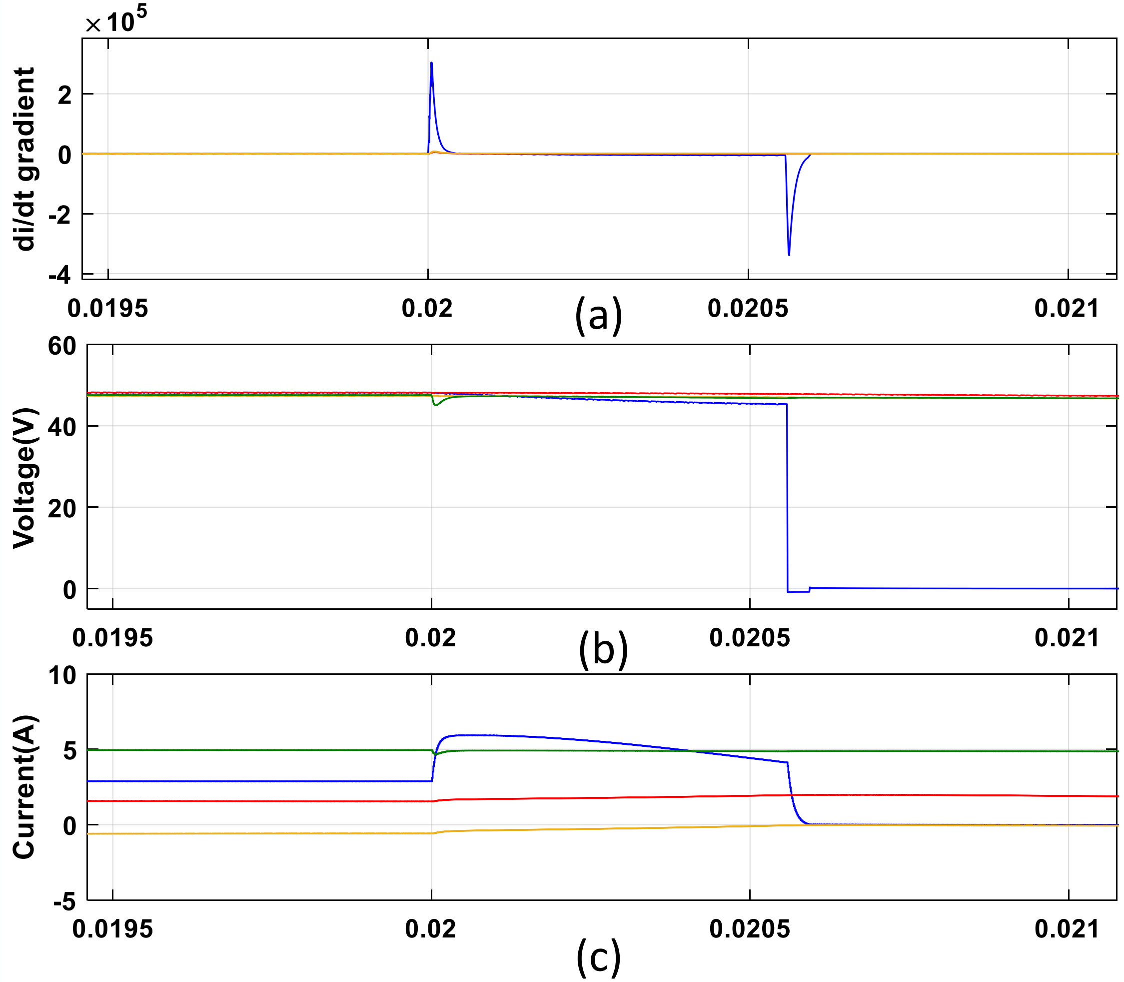
(a)



(b)

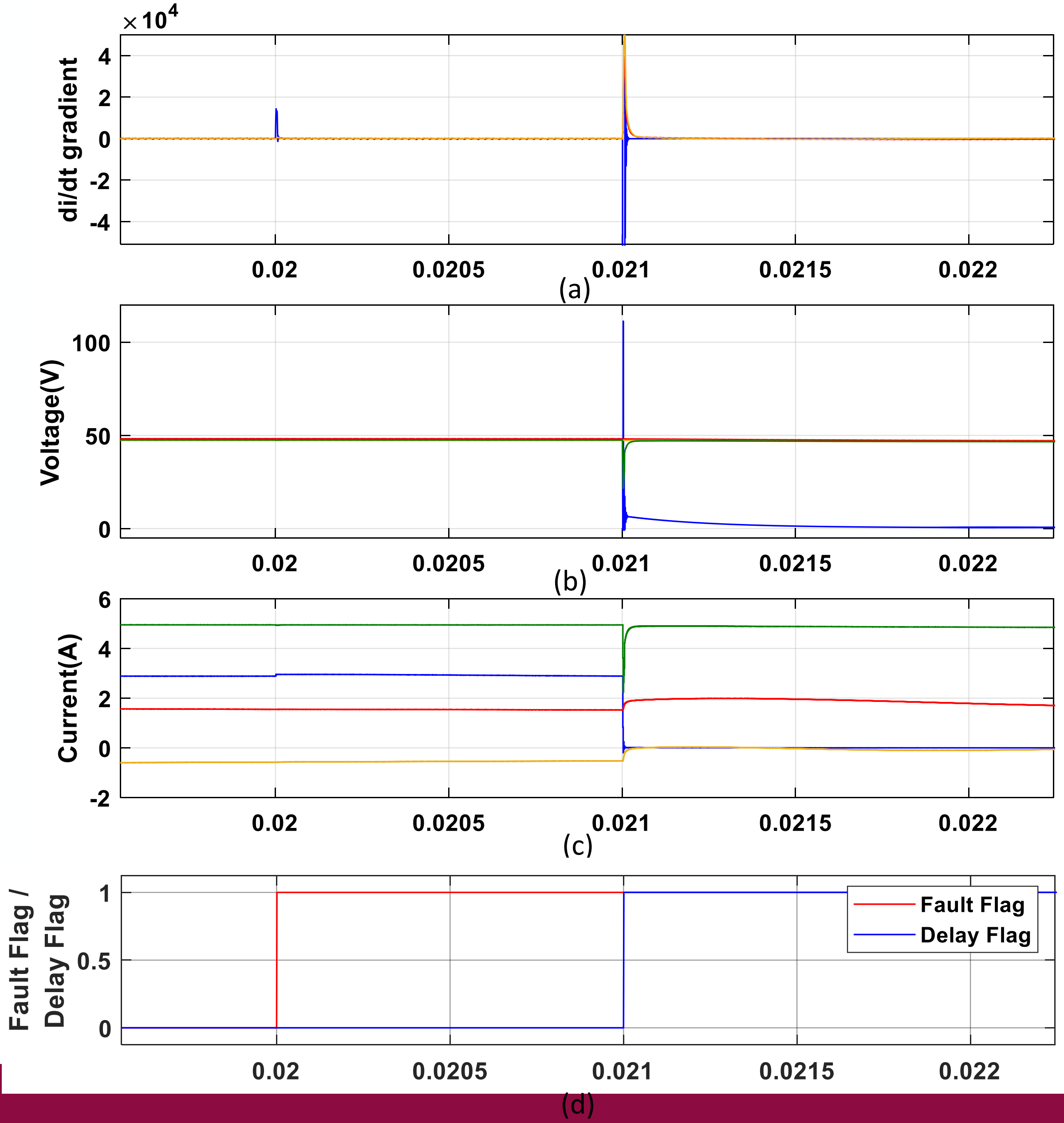
10Ω L-L Fault:

- Conv-1 : Converter to bus#1 line-line cable fault is activated at 0.02s
- Conv-2 : Normal operation, no fault
  - Measured fault current: 6A
  - At 0.02059s, the trip signal is generated based on the changes in the current direction at the bus side IED1 .
  - The fault time is measured as 590μs.



500Ω High Impedance L-G fault (F_3)

- The fault signal is activated at 0.02s.
- Differential current comparison is used, and a flag is activated with a current difference threshold of 50mA.
- The corresponding trip signal is generated after a preselected delay of 1ms.
- The delay is provided to make sure the high impedance fault is not a temporary fault.



Fault Simulation Analysis:

Fault/Load Change	**Fault Clearing Time (s)**	$\frac{di}{dt}$ **(A/s)** (measured)
Low impedance fault (without $\frac{di}{dt}$ and droop)	$205\mu s$	-
Low impedance fault (1Ω) (with $\frac{di}{dt}$ and droop)	$265\ \mu s$	4×10^5 A/s
Low impedance fault (10Ω) (with $\frac{di}{dt}$ and current direction)	$590\ \mu s$	3×10^5 A/s
High impedance fault ($500\,\Omega$) (with $\frac{di}{dt}$ and current differential)	1 ms (pre-selected)	$1.5 times 10^4$ A/s
Small load change (3 A to 4 A)	-	1×10^4 A/s
Large load change (3 A to 8 A)	-	7×10^4 A/s

Conclusions

- Better control over converters output current / input current and the voltage during fault.
- Rate of change of converter fault current can be controlled.
- Fault Characterization
- Increases the total fault clearing time – Approximately extra 60μs.
- Therefore, more time to fault identification and characterization.
- Communication delay can be accommodated.

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[1] S. Augustine, M. J. Reno, S. M. Brahma and O. Lavrova, "Fault Current Control and Protection in a Standalone DC Microgrid Using Adaptive Droop and Current Derivative," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*.

[2] S. Augustine, J. E. Quiroz, M. J. Reno, and S. Brahma, “DC microgrid protection: Review and challenges,” in Sandia National Laboratories, SAND2018-8853, 2018.

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