DC Microgrid

Ali Karimpour
Professor
Ferdowsi University of Mashhad, Iran

DC microgrid protection

Renewable and Sustainable Energy Reviews 151 (2021) 111546

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

ELSEVIER

Check for updates

DC microgrid protection issues and schemes: A critical review

Chetan Srivastava, Manoj Tripathy *

Department of Electrical Engineering, IIT- Roorkee, Roorkee, India

6328 IEEE TRANSACTIONS ON SMART GRID, VOL. 9, NO. 6, NOVEMBER 2018

Protection of Smart DC Microgrid With Ring Configuration Using Parameter Estimation Approach

Rabindra Mohanty, *Student Member, IEEE*, and Ashok Kumar Pradhan, *Senior Member, IEEE*

5646 IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, VOL. 9, NO. 5, OCTOBER 2021

A Cosine Similarity-Based Centralized Protection Scheme for dc Microgrids

Rabindra Mohanty, *Member, IEEE*, Subham Sahoo, *Member, IEEE*, Ashok Kumar Pradhan, *Senior Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

DC microgrid protection

Renewable and Sustainable Energy Reviews 151 (2021) 111546

ELSEVIER

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Check for updates

DC microgrid protection issues and schemes: A critical review

Chetan Srivastava, Manoj Tripathy *

Department of Electrical Engineering, IIT- Roorkee, Roorkee, India

Introduction


Renewable and Sustainable Energy Reviews 151 (2021) 111546

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

DC microgrid protection issues and schemes: A critical review

Chetan Srivastava, Manoj Tripathy *

Department of Electrical Engineering, IIT- Roorkee, Roorkee, India

DC microgrid protection is a challenging problem since:

- No phasor, frequency, and sequence components in DC microgrid.

→ Restriction on the implementation of well-established AC protection schemes.

- Lack of natural zero current crossings makes arc extinguishing a complex problem.

→ The AC circuit breakers doesn't work.

↓

Therefore, the DC circuit breaker (DCCB) employs an artificial arrangement to make the fault current zero.

DC microgrid protection challenges

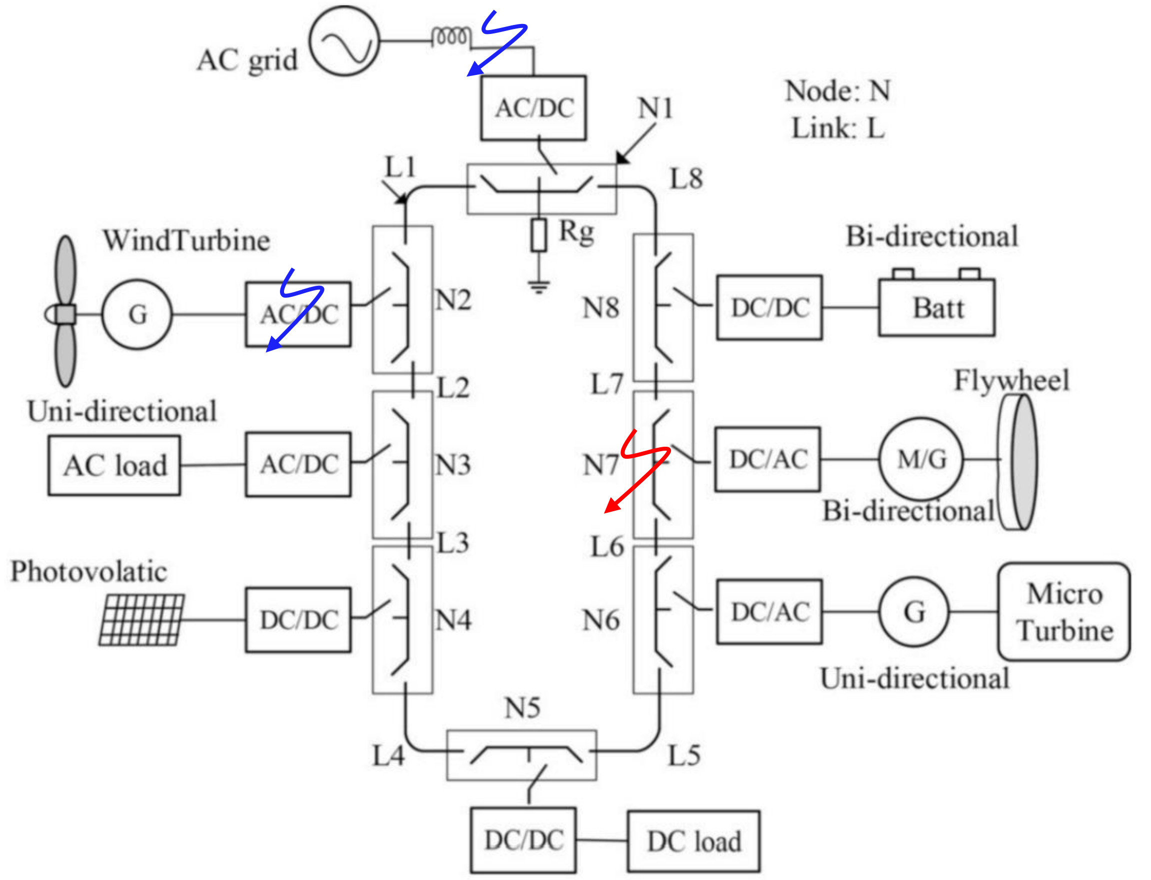
The challenges with DC microgrid protection:

- The bidirectional power flow.
- Renewable energy resources dynamics.
- Low inertia.
- Different operating modes of microgrid operations.
- Grounding issues.
- Lack of regulatory framework.

Different DC microgrid fault

Fault classification:

- AC side faults.
- Internal faults.
- DC network faults.



Ring-type DC microgrid architecture

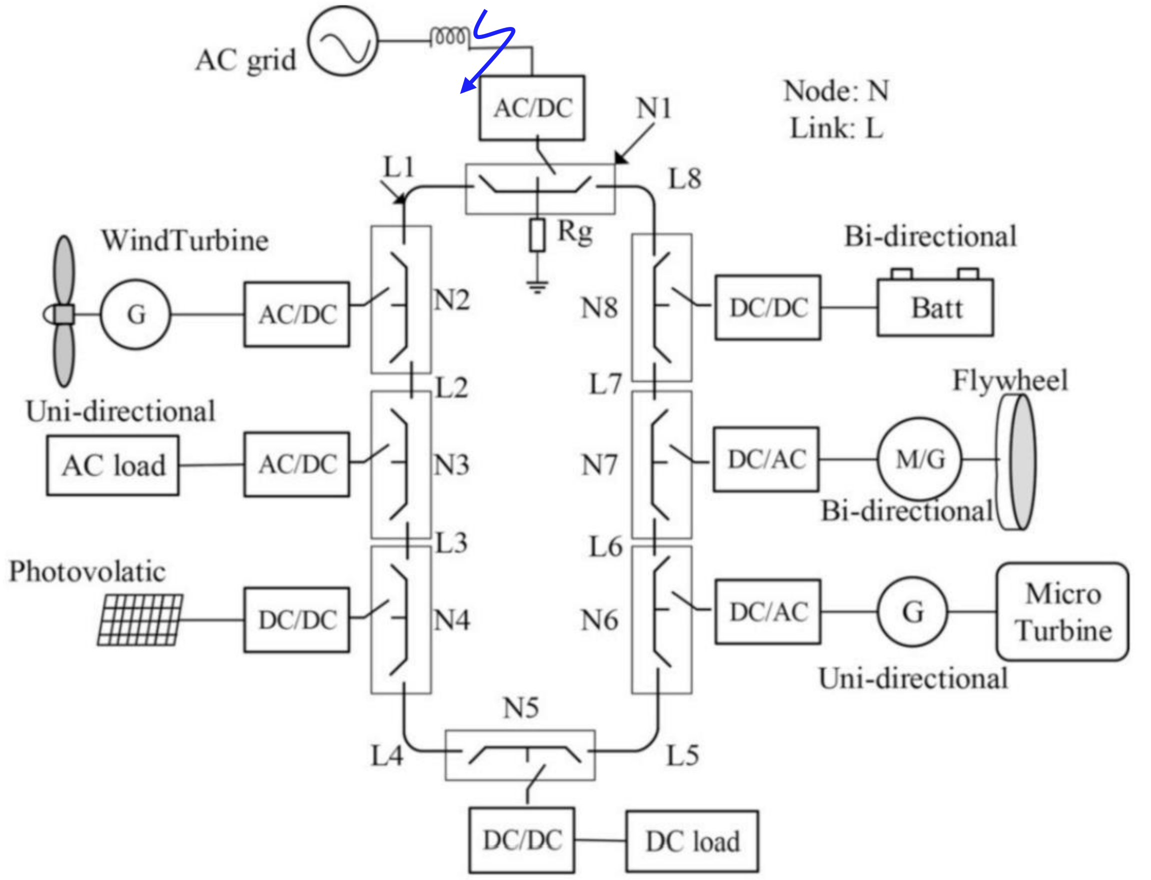
Different DC microgrid fault

AC side fault and its analysis:

It is generally implements AC protection schemes. AC fault diagnosis by:

- The magnitude;
- The relationship between the current and voltage sequence components;
- The zero sequence current;

Extraction failure features by:
- Artificial neural network
- Wavelet transform



Ring-type DC microgrid architecture

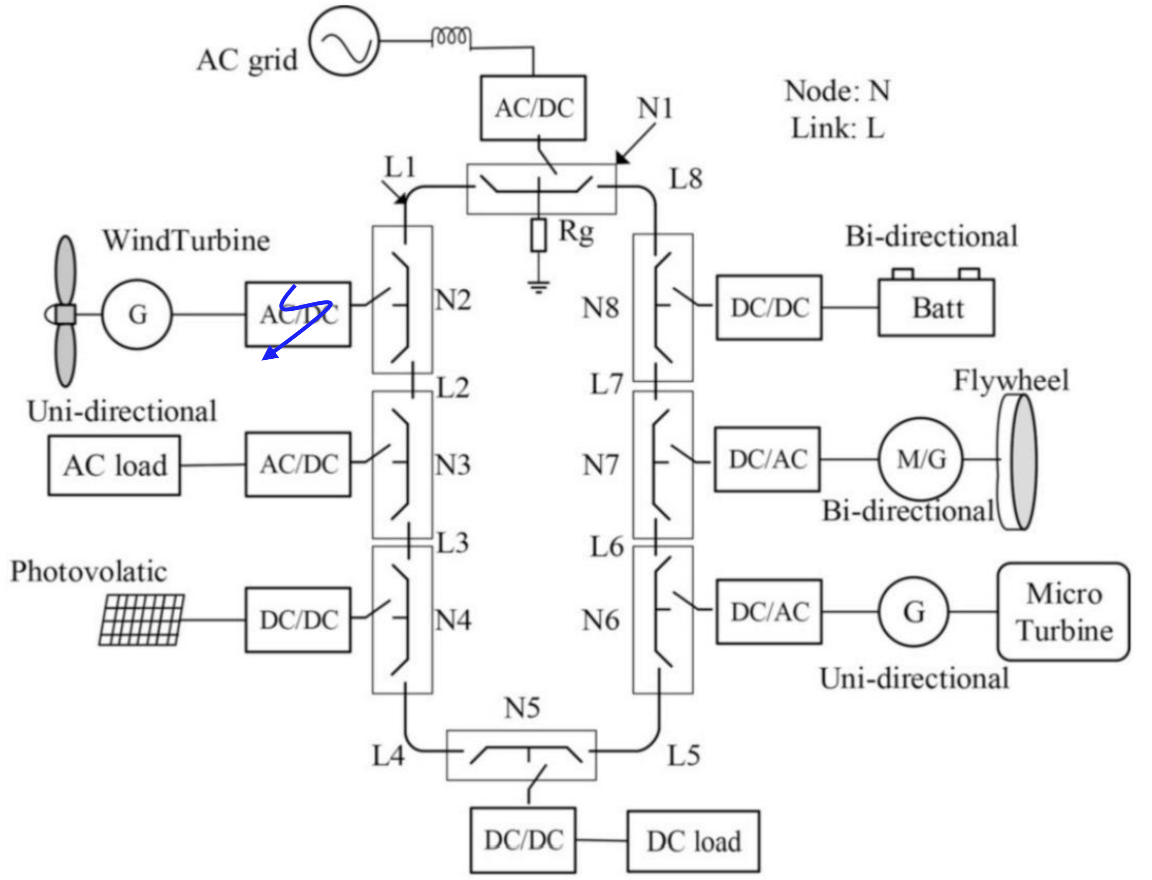
Different DC microgrid fault

Internal faults and its analysis:

- Punchers of power electronic components (such as IGBT) due to high potential thermal stress.

- Converter rating (cost) heavily relies on protection speed.

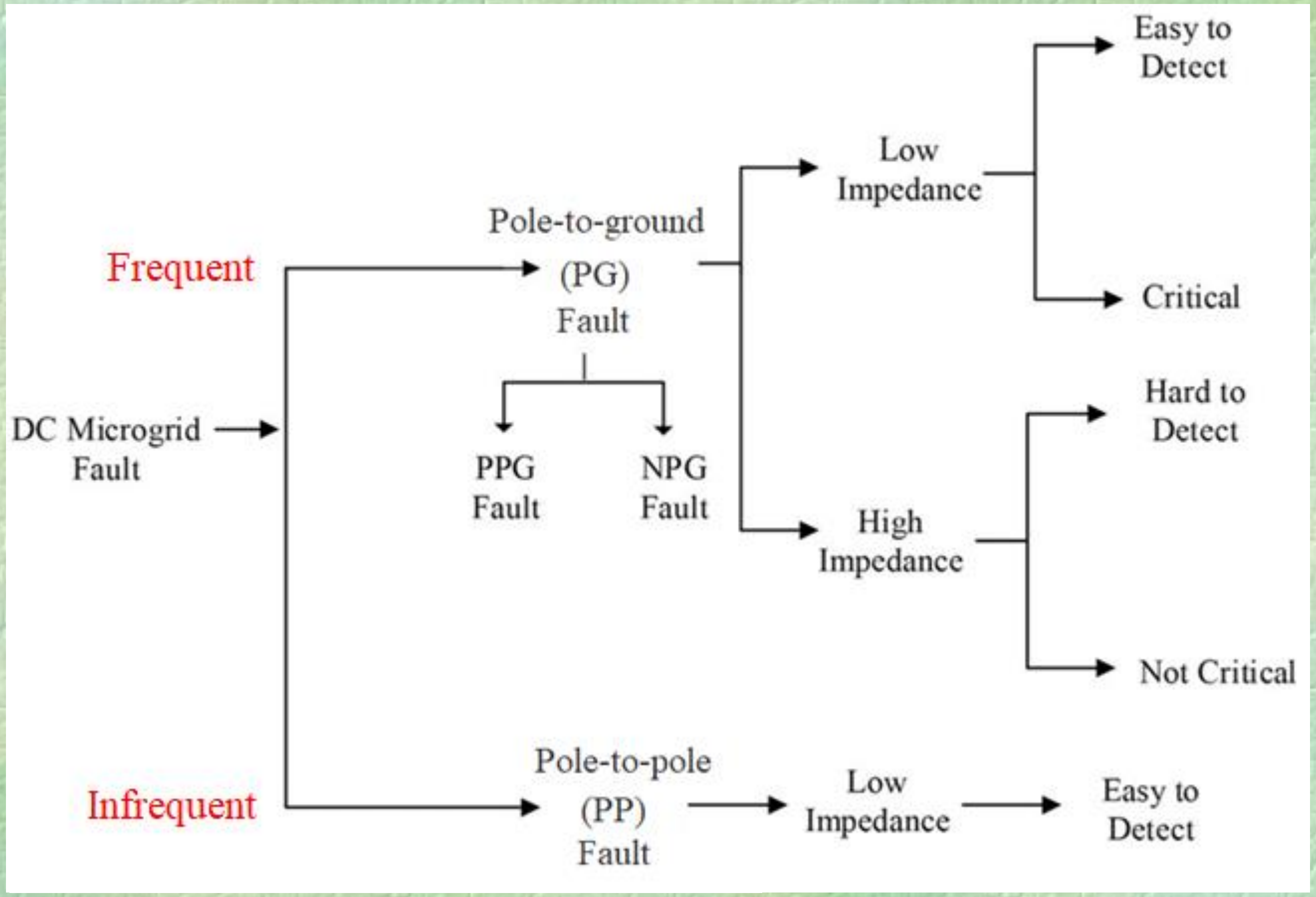
- Some literature suggests using standby converter or redundant devices, but an extra cost and typical coordination issues restrict its application.



Ring-type DC microgrid architecture

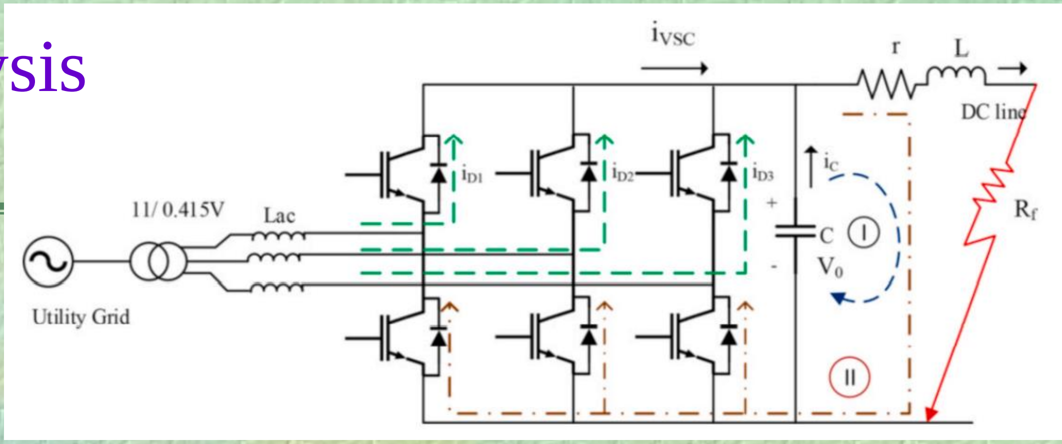
Different DC microgrid fault

- DC network faults.

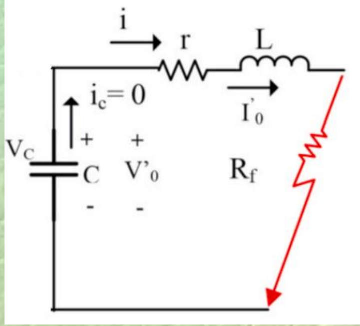


Unlike the phasor measurement-based protection in ac systems, the protection of dc systems deals with complex fault transients which mandate the isolation of the faulted segment within few milliseconds as continued fault current leads to overheating issue in power electronic converters.

DC microgrid fault analysis



1- Capacitor discharge stage



Due to a slow converter response, its contribution to fault current is considered negligible.

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int_{-\infty}^{t} i\,d\tau = 0, \qquad R = r + R_f$$

$$i(s) = \frac{V_0/L + i_{L0}s}{s^2 + (R/L)s + 1/LC}$$

Let α_1 and α_2 as the roots of characteristic equation.

$$i(t) = \frac{V_0}{L(\alpha_2 - \alpha_1)}\left[e^{\alpha_2 t} - e^{\alpha_1 t}\right] + \frac{i_{L0}}{(\alpha_2 - \alpha_1)}\left[\alpha_2 e^{\alpha_2 t} - \alpha_1 e^{\alpha_1 t}\right]$$

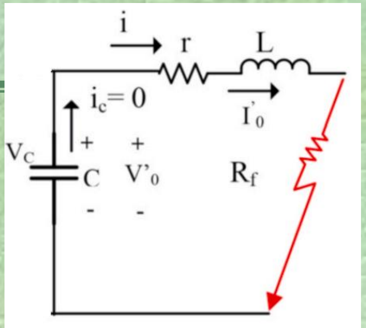
$$V(t) = L\frac{di}{dt} + Ri$$

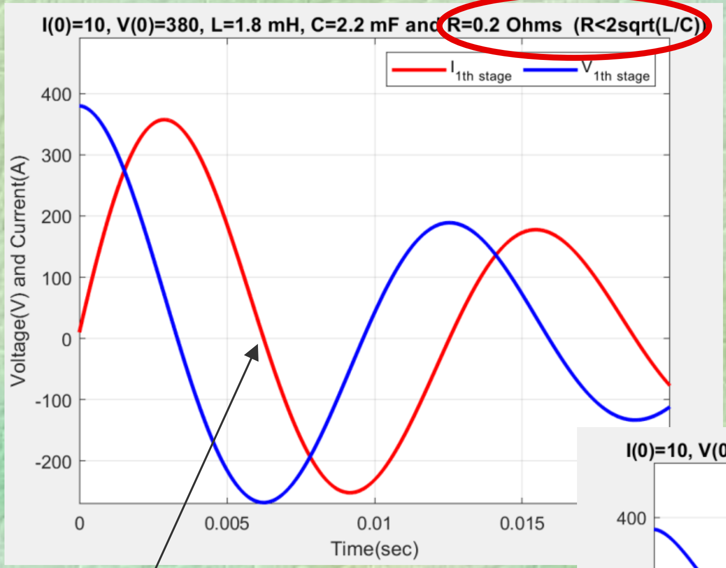
DC microgrid fault analysis

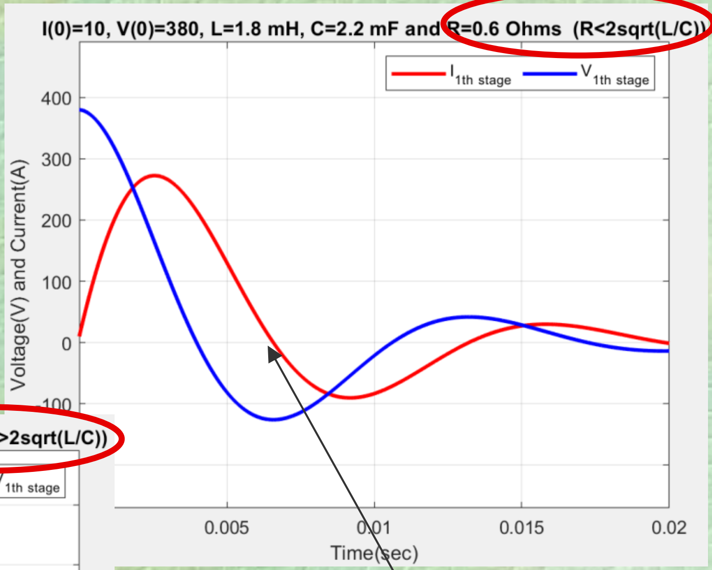
1- Capacitor discharge stage

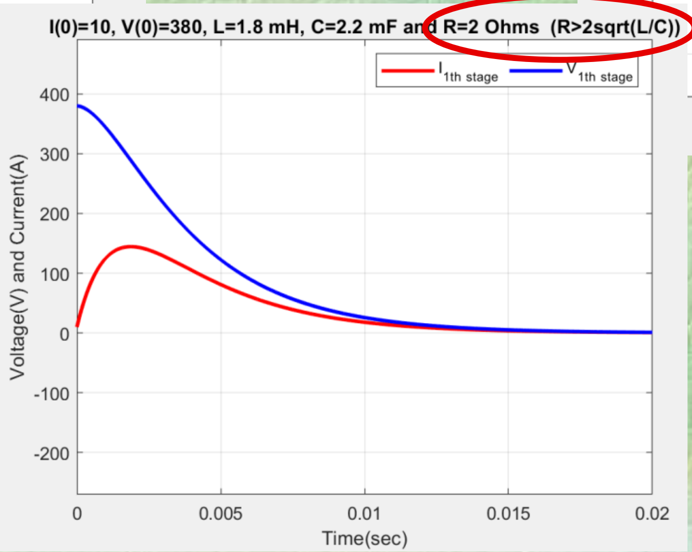
$$i(t) = \frac{V_0}{L(\alpha_2 - \alpha_1)}\left[e^{\alpha_2 t} - e^{\alpha_1 t}\right] + \frac{i_{L0}}{(\alpha_2 - \alpha_1)}\left[\alpha_2 e^{\alpha_2 t} - \alpha_1 e^{\alpha_1 t}\right]$$

$$V(t) = L\frac{di}{dt} + Ri$$







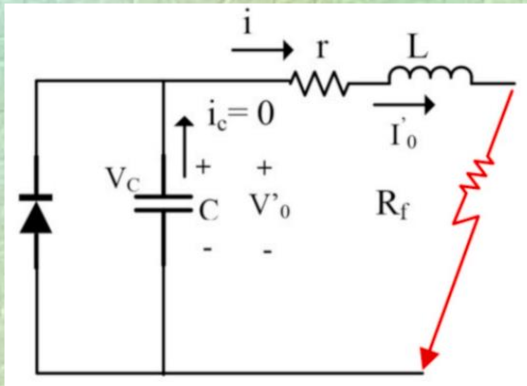


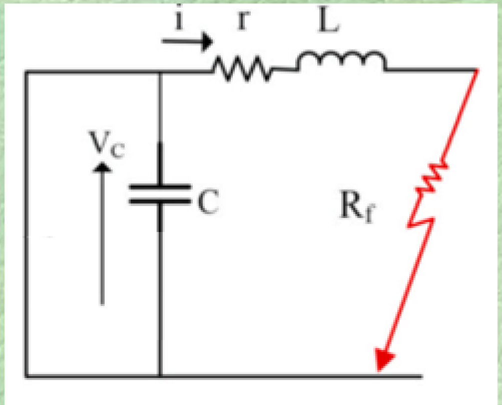
End of capacitor discharge stage

End of capacitor discharge stage

DC microgrid fault analysis

2- Diode freewheel stage





It starts when the DC link voltage reaches zero, and diodes start to freewheel the cable current.

The cable inductance drives the flow in this period.

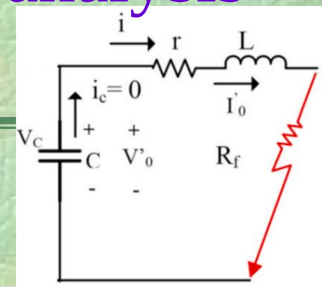
If the second stage initiates at a time instant t_1, and the value of the current be I_{L1} Then

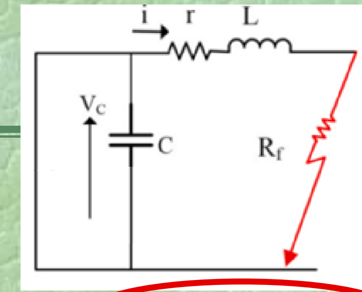
$$i(t) = I_{L1} e^{-\frac{R}{L}(t-t_1)}$$

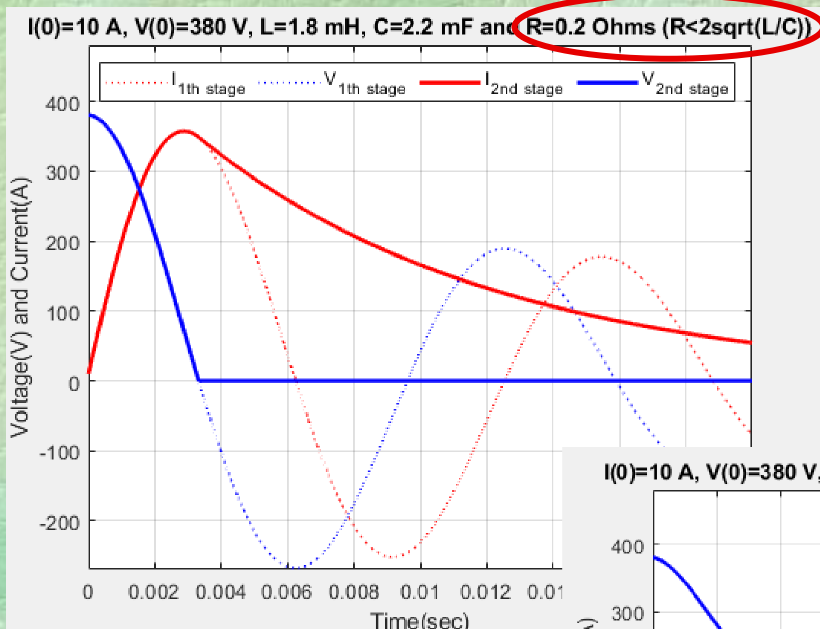
The protection schemes should operate well before reaching the **second stage** to prevent potential damage.

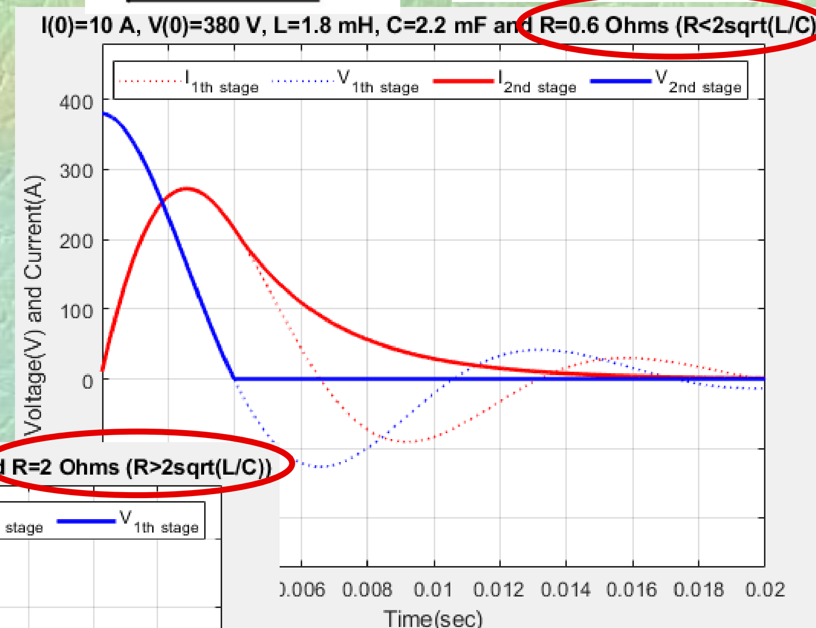
DC microgrid fault analysis

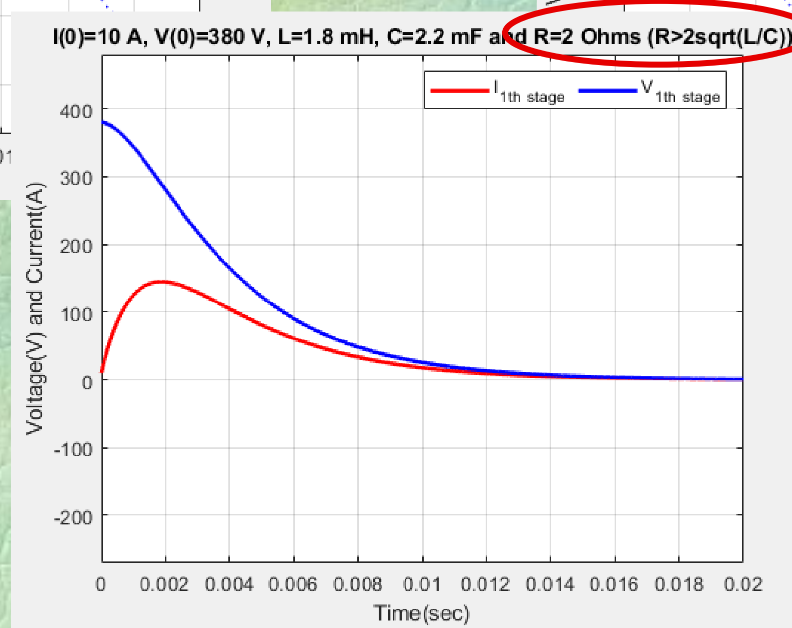
1,2- Capacitor discharge stage and diode freewheel stage.



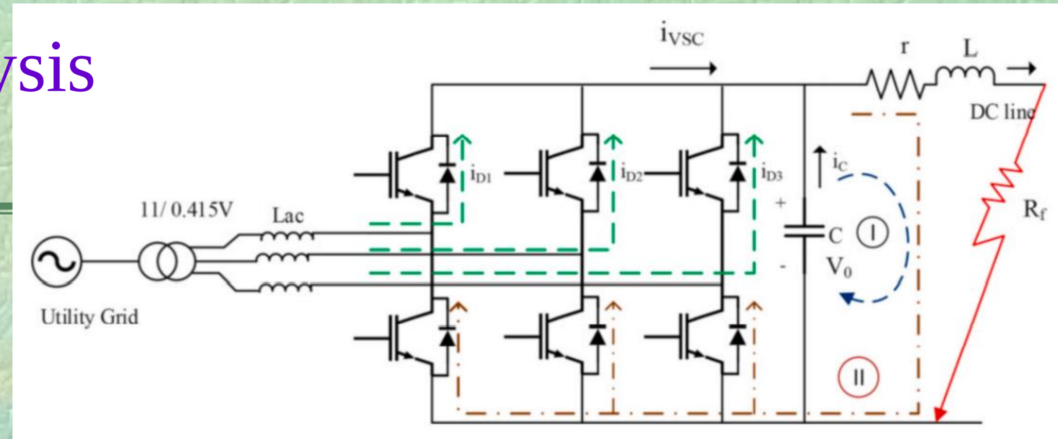




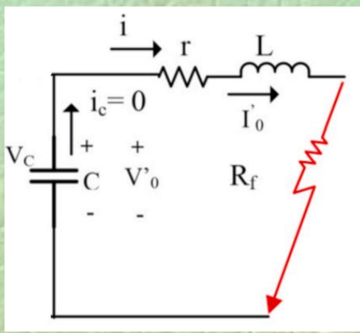


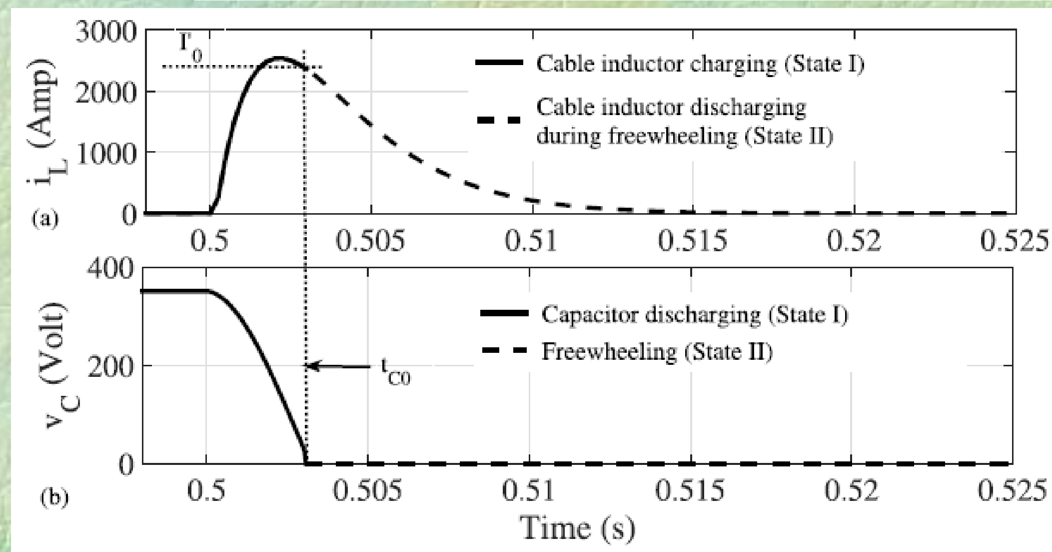


DC microgrid fault analysis

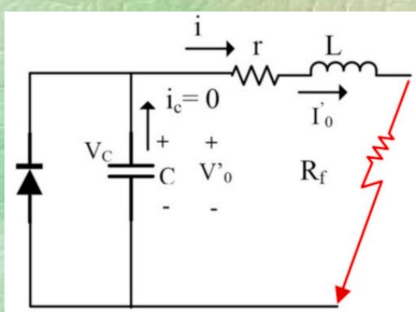


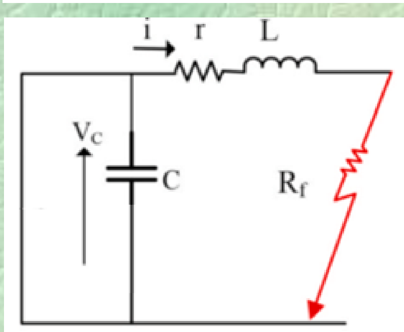
1- Capacitor discharge stage



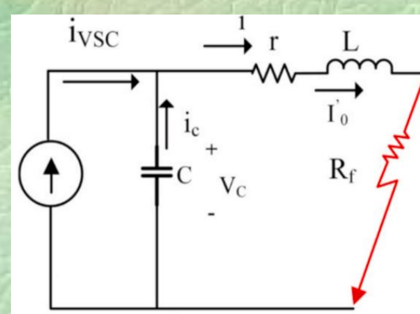


2- Diode freewheel stage





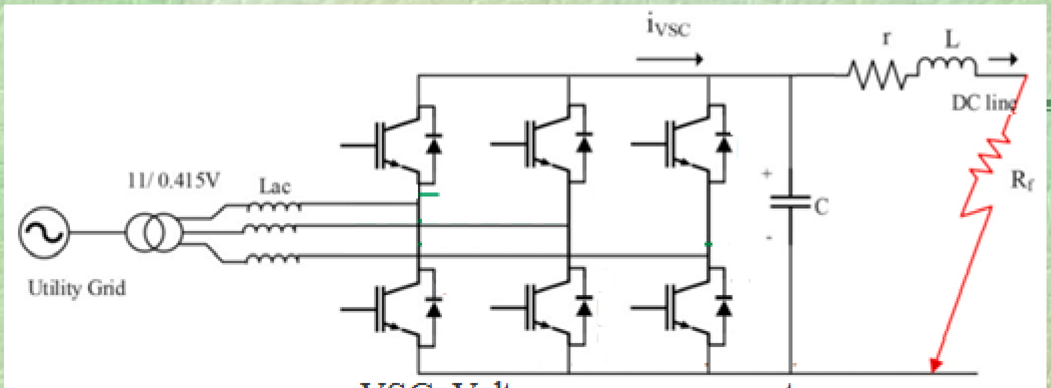
3- Grid-side current feeding stage



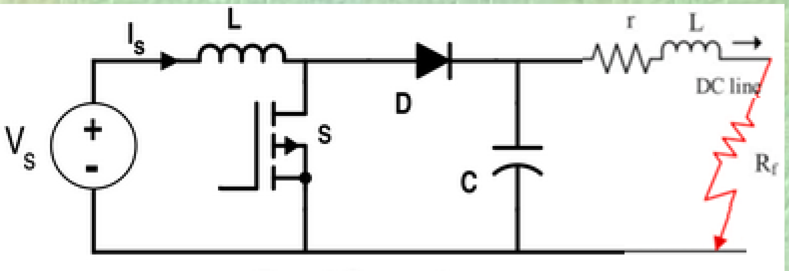
VSC: Voltage source converter

The protection system is expected to operate within the rise time of current (during stage 1) to protect the switches in the converters from overheating stress in other stages.

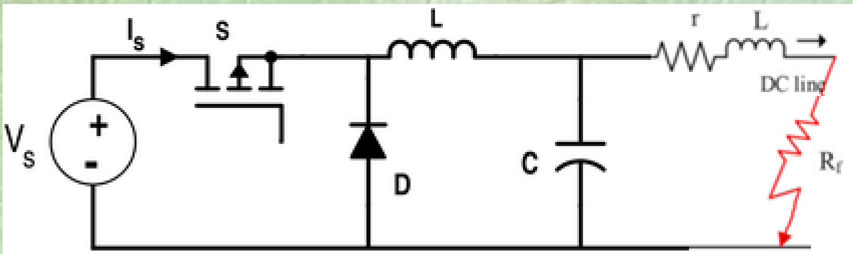
DC microgrid fault analysis



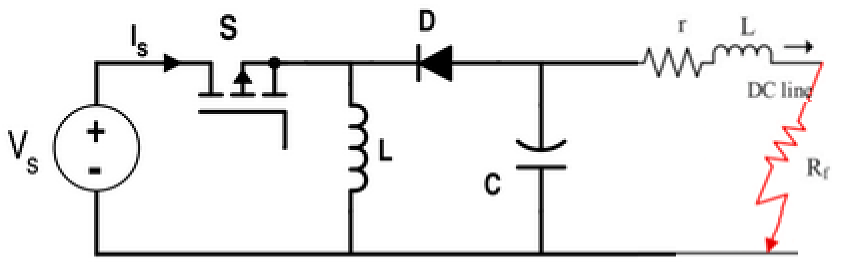
VSC: Voltage source converter



Boost Converter



Buck Converter



Buck-Boost Converter

The occurrence of these three stages depends on the converter topology and the type of fault.

Following table provides the stages of transient response for VSC and dc–dc converters during pole-to-ground (PG) faults in a unipolar dc microgrid.

DC fault current response	PG fault			
	VSC	Boost converter	Buck converter	Buck-boost converter
Stage 1	Yes	Yes	Yes	Yes
Stage 2	Yes	Yes	Yes	Yes
Stage 3	Yes	Yes	No	No

Problems associated with the DC microgrid protection

1 Power flow pattern

- Power flow is bidirectional in a microgrid due to the presence of renewable energy sources(RESs). Whereas, in a conventional system, power flow is unidirectional.

2 Renewable characteristic

- Temporal coordination states how RESs time-varying nature and intermittent nature affect the system's different components.

- The response time of various RESs is crucial to establish an effective protection scheme.

3 Nonsuitability of AC circuit breaker

- The DCCB constructs in a way such that the commutation circuit forces the fault current to zero.

- The solid-state circuit breakers (SSCB) are mostly used as DCCB.

Problems associated with the DC microgrid protection

4 Selectivity issue with overcurrent relay

- With the constraint in selectivity, OCRs are not suitable for primary protection.

- However, it may be used as backup protection.

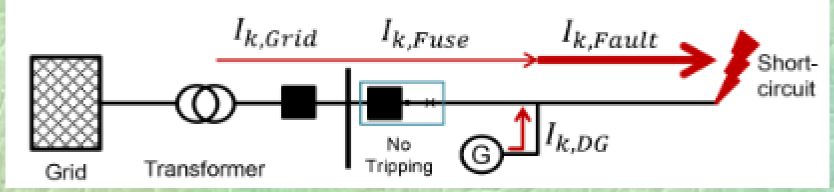
5 Speed of protection

- The high filter capacitance and lower DC cable impedance cause a steep rise in the fault current.

- Moreover, VSCs rating in DC microgrid is generally lower than the converters in AC systems, requiring a faster protection system.

6 Renewable integration protection concerns

-With RES parallel to the utility, the relay sense fault current lower than the fault current without RES. It is known as a blinding operation.



Problems associated with the DC microgrid protection

7 Relay coordination issue

8 Reduced stability margins

9 Complicated fault detection and fault clearance

10 Optimum RESs placement

11 Lack of guidelines and well-defined standards

12 Grounding issues

DC microgrid protection

Various protection schemes proposed for DC microgrids

Non-unit protection schemes.

- Local measurement which do not require communication.
- Requirement of high bandwidth measurement devices.
- Selection of thresholds.
- Accommodated only for long-distance dc line-based systems.
- These schemes do not guarantee selectivity.

Unit protection schemes.

- Exploit data from both ends of the line to be protected.
- Communication delay and link failure limit the application of unit protection.
- Higher cost.
- High resistance fault is hard to detect.

DC microgrid protection

Various protection schemes proposed for DC microgrids

Non-unit protection schemes.

- Distance protection.
- Overcurrent protection.
- Current derivative protection.

Unit protection schemes.

- Differential protection.

It is highly dependent on the current threshold, since the operating current may not exceed it during high resistance fault.

- Directional protection.

Similarly, the direction of fault current during high resistance fault does not alter.

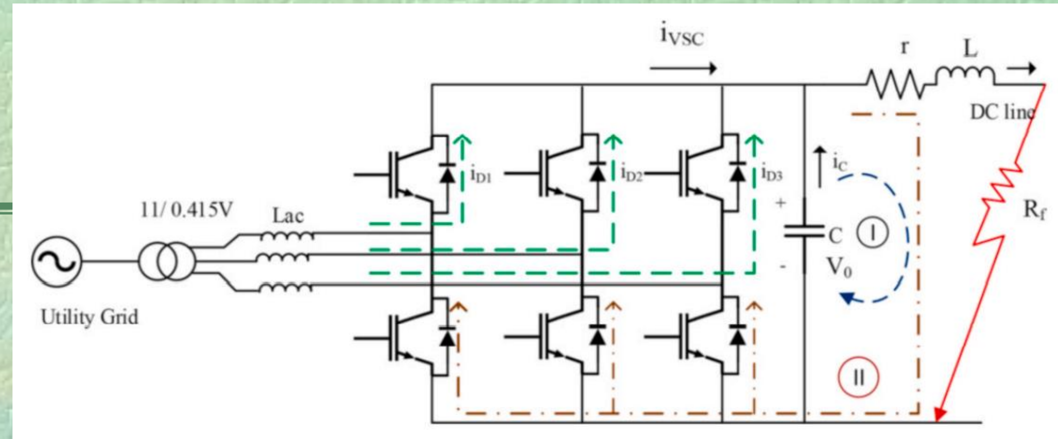
Unit protection schemes

Accuracy in the operation of any protection algorithm depends on proper fault characterization of the system.

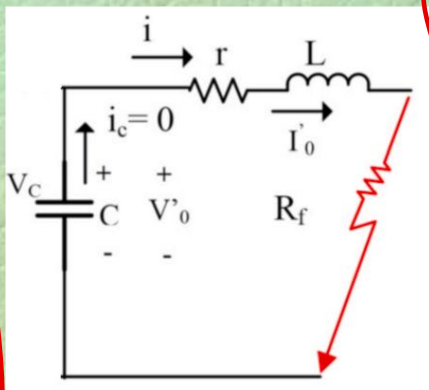
An accurate mathematical model of fault in a dc system is difficult to formulate since it is:

- Nonlinear.
- Time-varying.
- Strongly coupled with the control strategy of converters.

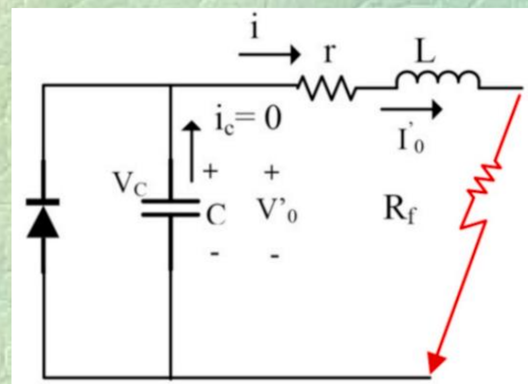
Unit protection schemes

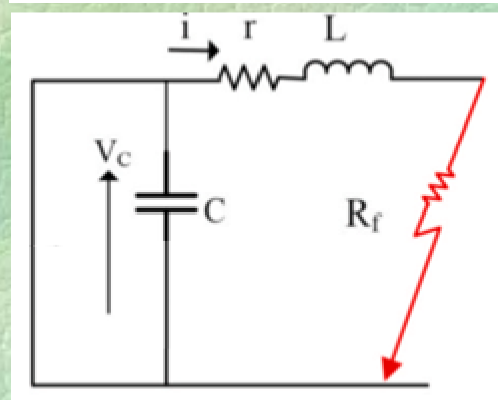


1- Capacitor discharge stage

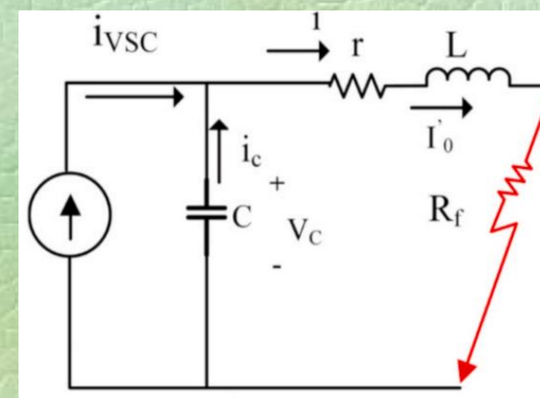


2- Diode freewheel stage





3- Grid-side current feeding stage

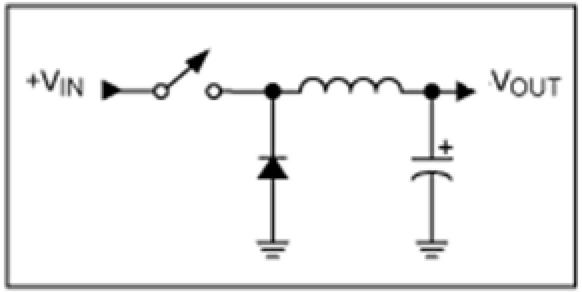


VSC: Voltage source converter

The current derivative-based protection is simple and computationally effective solution for dc microgrids.

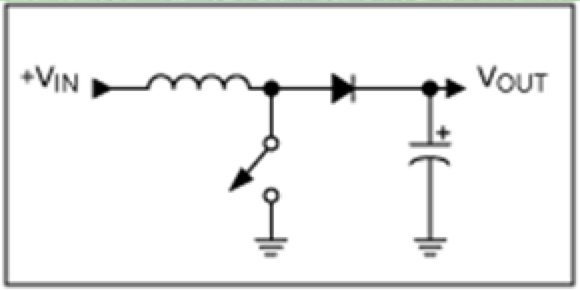
But see the next two slides:

Different Converters



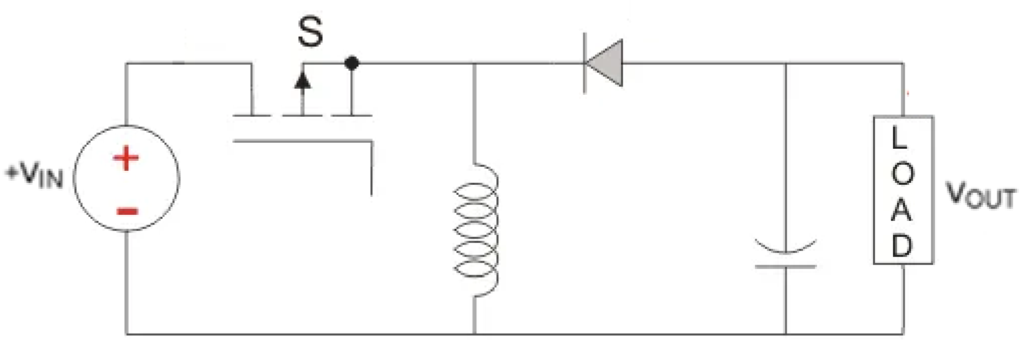
S: Simple buck(Step-down) converter

$$V_{out} = D.V_{in}$$



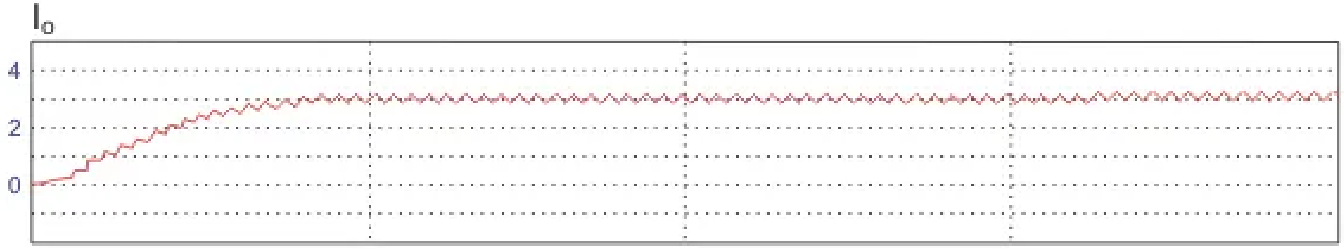
Simple boost(Step-up) converter

$$V_{out} = \frac{V_{in}}{1-D}$$



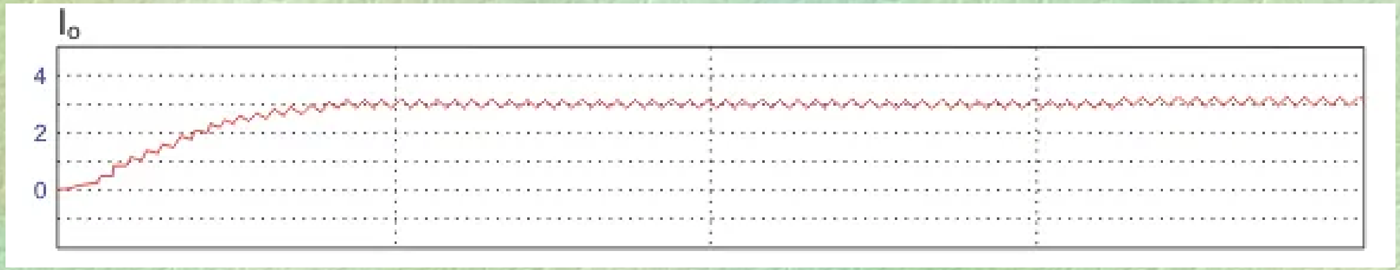
Simple buck-boost converter

$$V_{out} = \frac{-D}{1-D}V_{in}$$



Unit protection schemes(non-unit current derivation method)

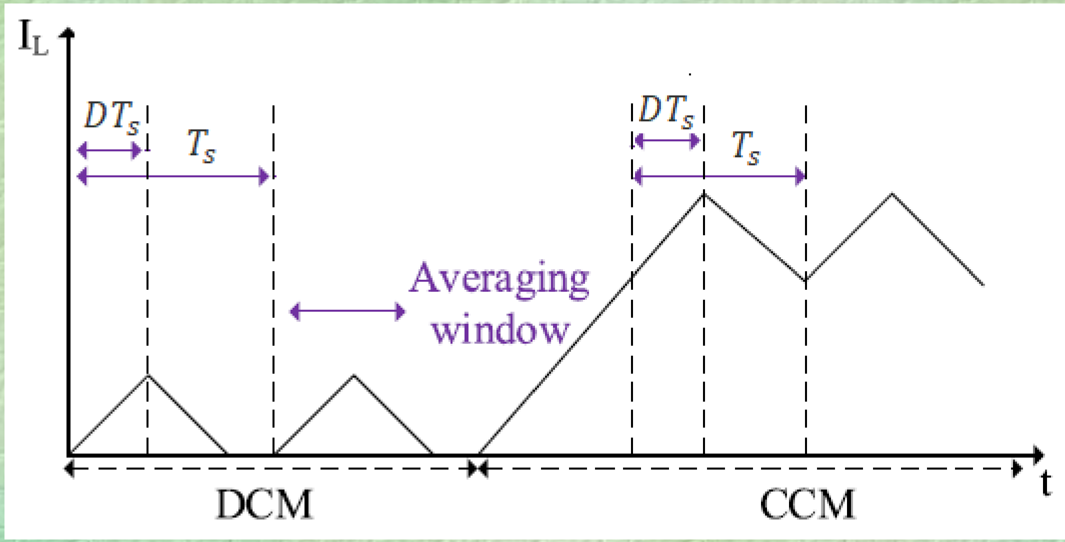
- The current derivative-based protection is simple and computationally effective solution for dc microgrids.
- Such methods take protection decisions within few milliseconds.
- However, the high-frequency switching ripples complicate the trip decision of current derivative-based protection methods.



- Figure shows ripple frequencies and magnitudes of current.
- Current derivative depends on various switching frequencies at the output of a dc–dc converter and can be significantly high, which can easily exceed the thresholds.

Unit protection schemes(Current derivation method)

Discontinuous conduction mode (DCM)/continuous conduction mode (CCM) are primarily dependent on the loading condition in the output



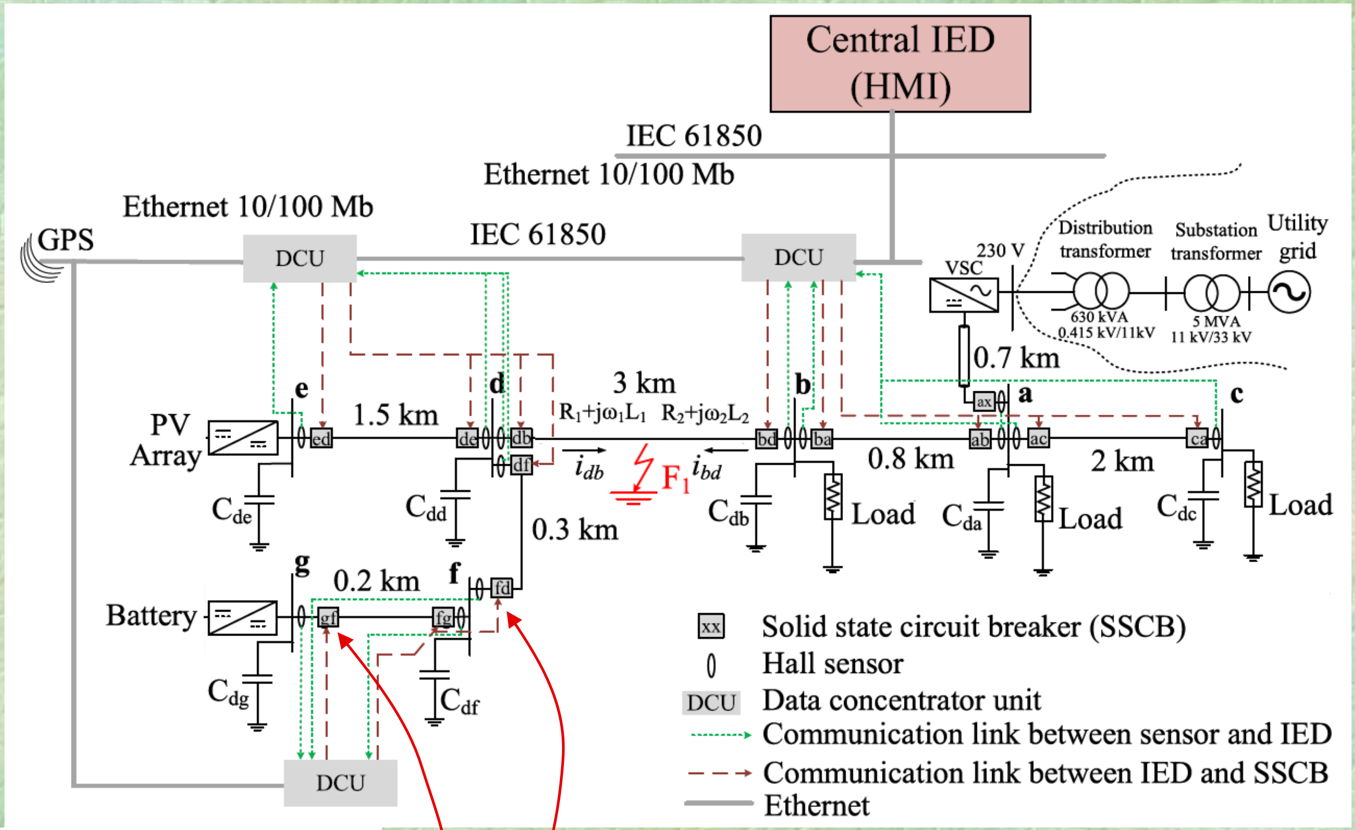
Usually, the existing protection mechanisms to detect a fault are based on the averaging mechanism for signals which does not contain any switching ripples from the sources, since they have been formulated for standard dc supplies.

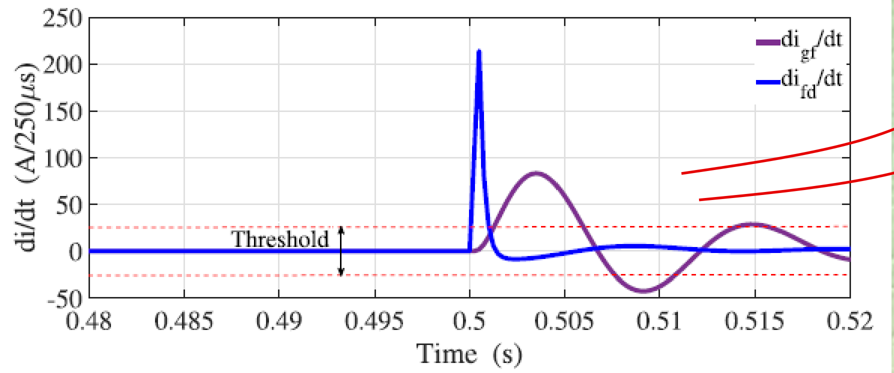
However, when they are tested for power electronic converters with switching ripples in the current, the following issues arise:

- The rate of change in current is not solely dependent on the fault but also dependent on other factors such as switching frequency, variable loading condition, voltage levels, etc.
- The design of averaging window with a fixed threshold to generate a decision under faults may be tricky, since the average values could vary for DCM/CCM modes (under different loading conditions), different window sizes, etc. → False tripping.

Unit protection schemes(non-unit current derivation method)

- In the microgrid with short line lengths, the (di/dt) of adjacent segments may exceed the predefined threshold values.





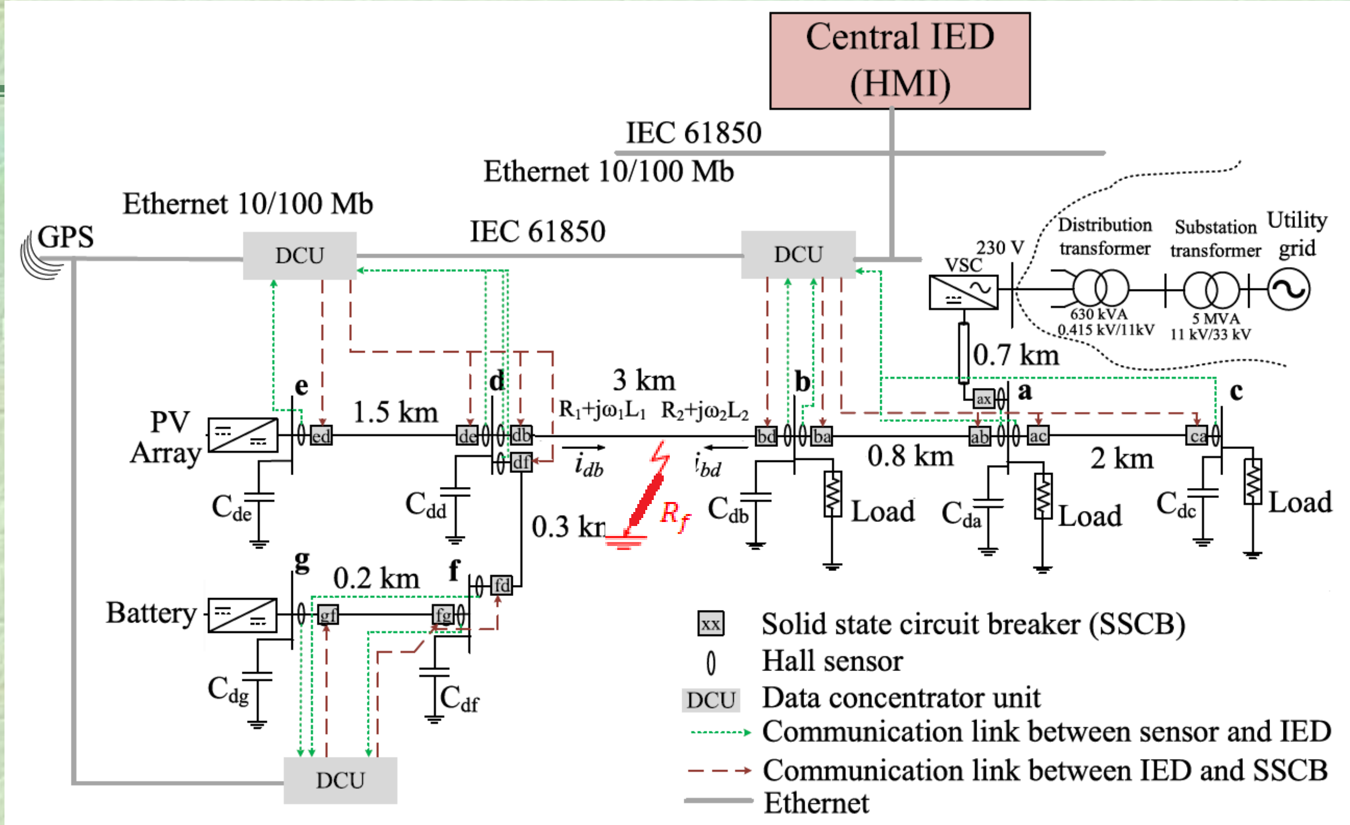
Thus, local data-based (di/dt) fails to identify the correct faulted section resulting into a selectivity issue.

→ Using communication-assisted Tec.

Unit protection schemes(unit differential method)

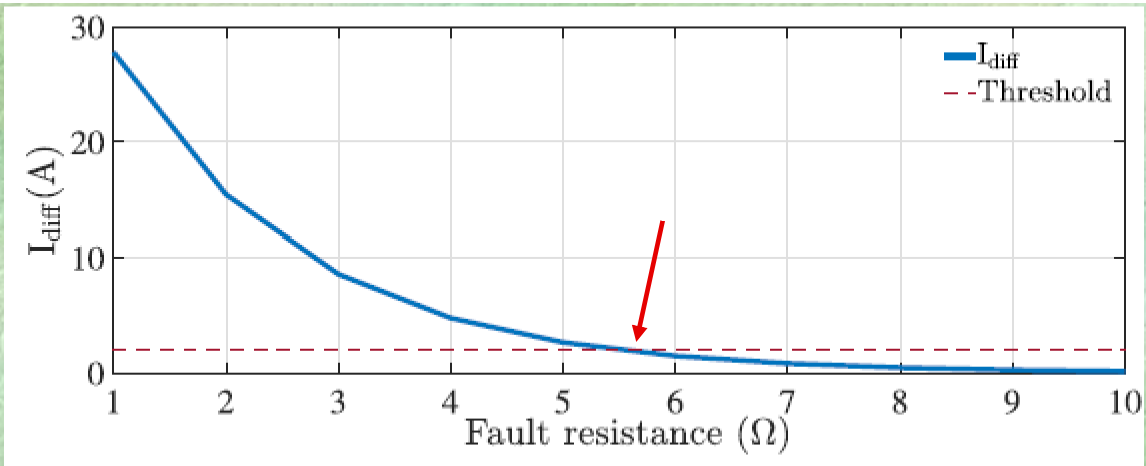
For reliable supply to Customers and to avoid unwanted disconnection of renewable resources, selectivity is important.

The selectivity issue Is solved using communication-assisted current differential, current directional, and centralized protections in the dc microgrid.

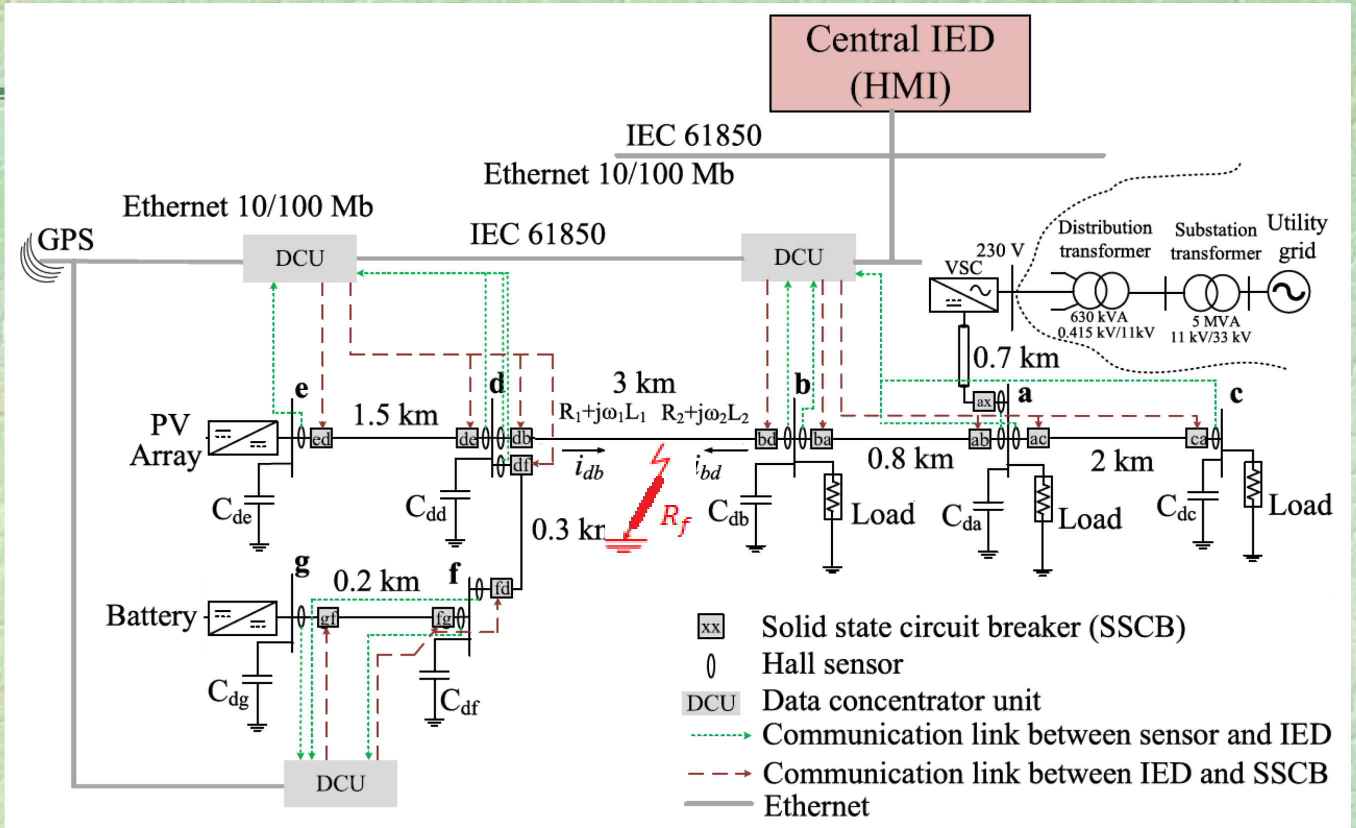


Effect of high resistance fault on current differential schemes.

Can not distinguish fault with $R_f > 5.5\ \Omega$

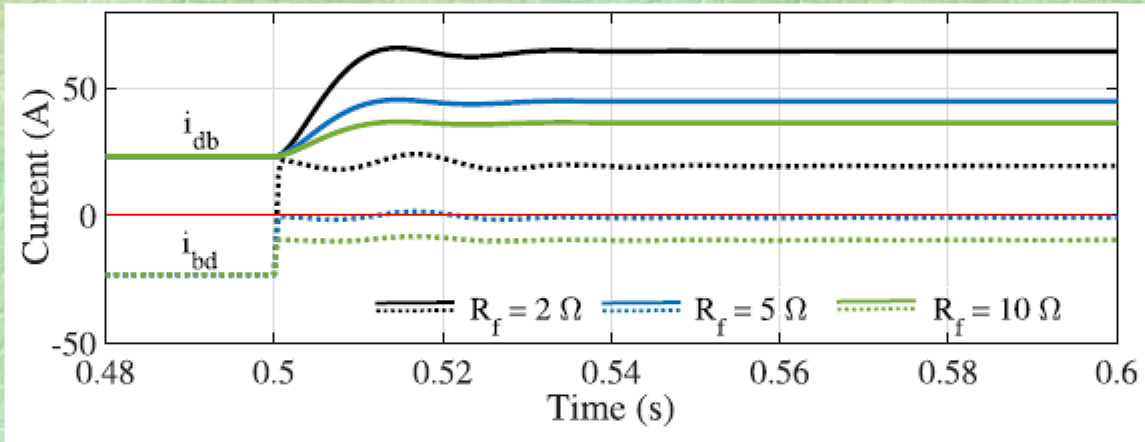


Unit protection schemes(unit directional method)



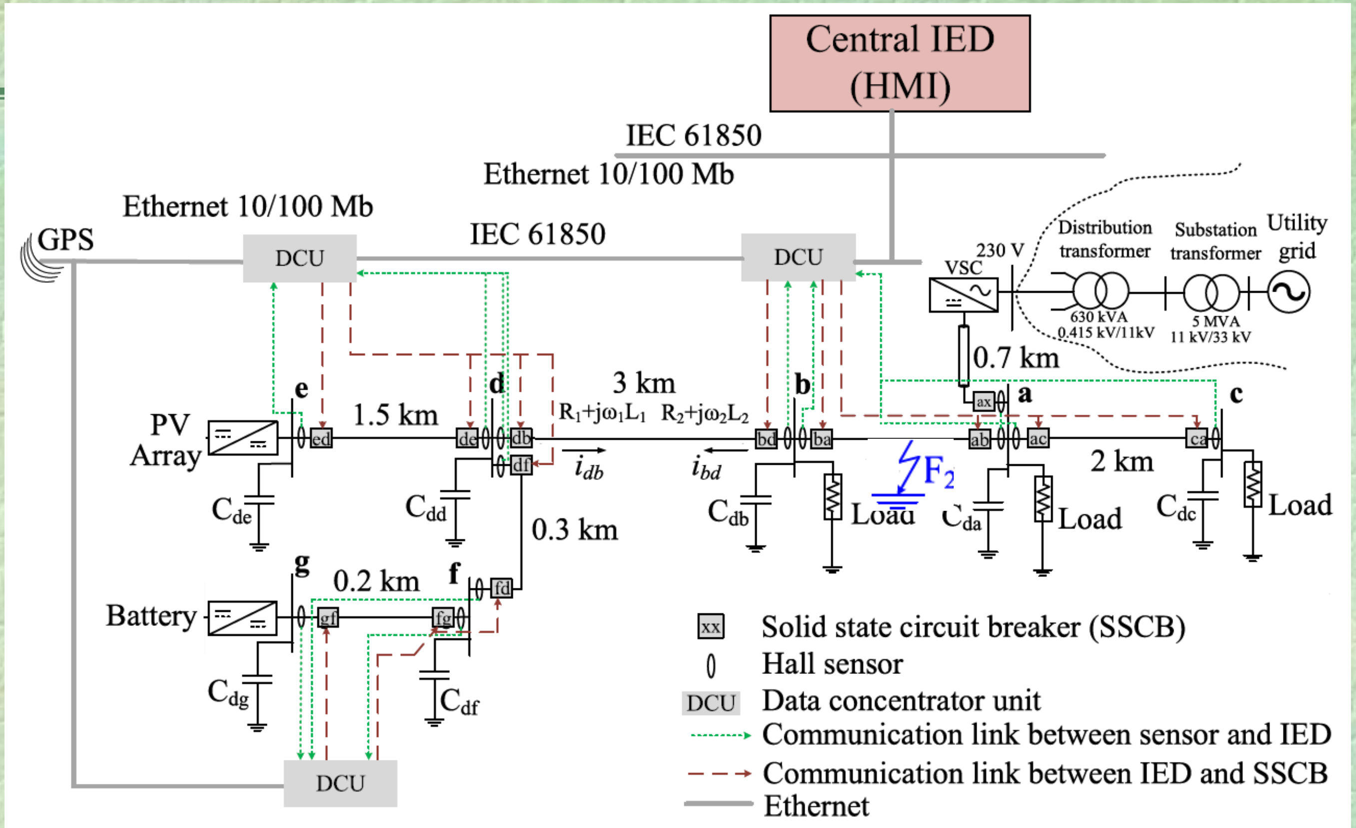
Effect of high resistance fault on current directional schemes.

Can not distinguish fault with $R_f > 5\ \Omega$

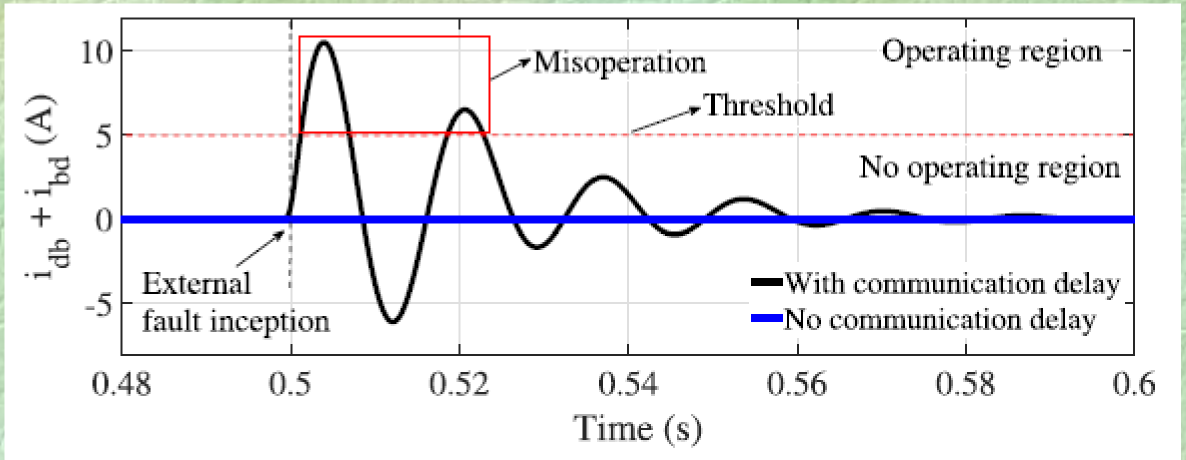


Unit protection schemes(unit directional method)

Communication delay results in maloperation of communication-based protection schemes such as scheme during an external fault.



The i_{bd} is communicated with a time delay, 1 ms with respect to i_{db}.



Unit protection schemes

To address the above mentioned problems:

6328 IEEE TRANSACTIONS ON SMART GRID, VOL. 9, NO. 6, NOVEMBER 2018

Protection of Smart DC Microgrid With Ring Configuration Using Parameter Estimation Approach

Rabindra Mohanty, *Student Member, IEEE*, and Ashok Kumar Pradhan, *Senior Member, IEEE*

5646 IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, VOL. 9, NO. 5, OCTOBER 2021

A Cosine Similarity-Based Centralized Protection Scheme for dc Microgrids

Rabindra Mohanty, *Member, IEEE*, Subham Sahoo, *Member, IEEE*,
Ashok Kumar Pradhan, *Senior Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

Unit protection schemes using parameter estimation approach

6328 IEEE TRANSACTIONS ON SMART GRID, VOL. 9, NO. 6, NOVEMBER 2018

Protection of Smart DC Microgrid With Ring Configuration Using Parameter Estimation Approach

Rabindra Mohanty, *Student Member, IEEE*, and Ashok Kumar Pradhan, *Senior Member, IEEE*

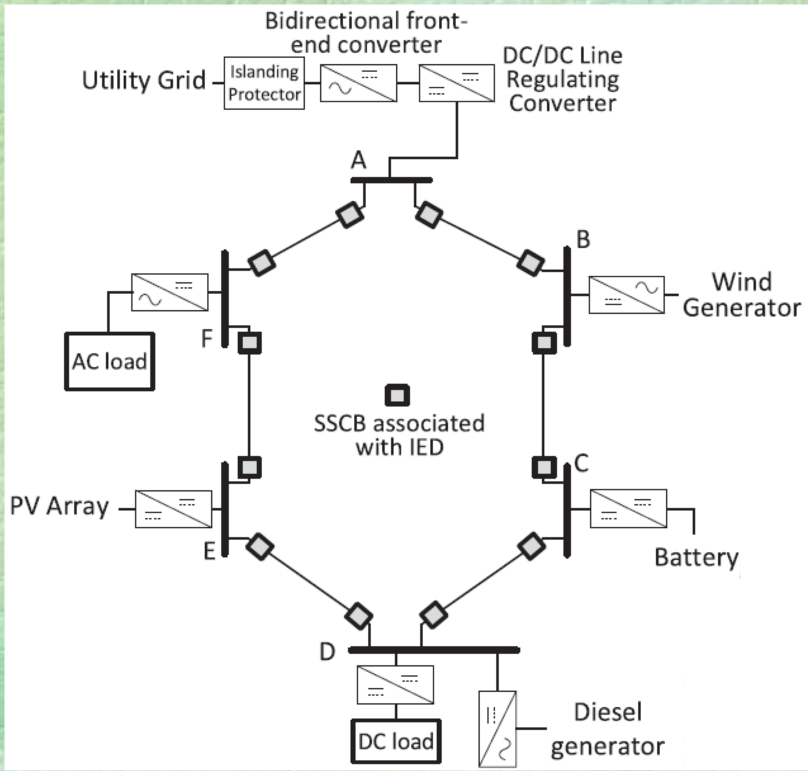
This paper, by using local intelligent electronic device (IED), voltage and current data during fault, a LS based technique estimates the inductance of the fault path which is able to discriminate forward and reverse faults with respect to the IED.

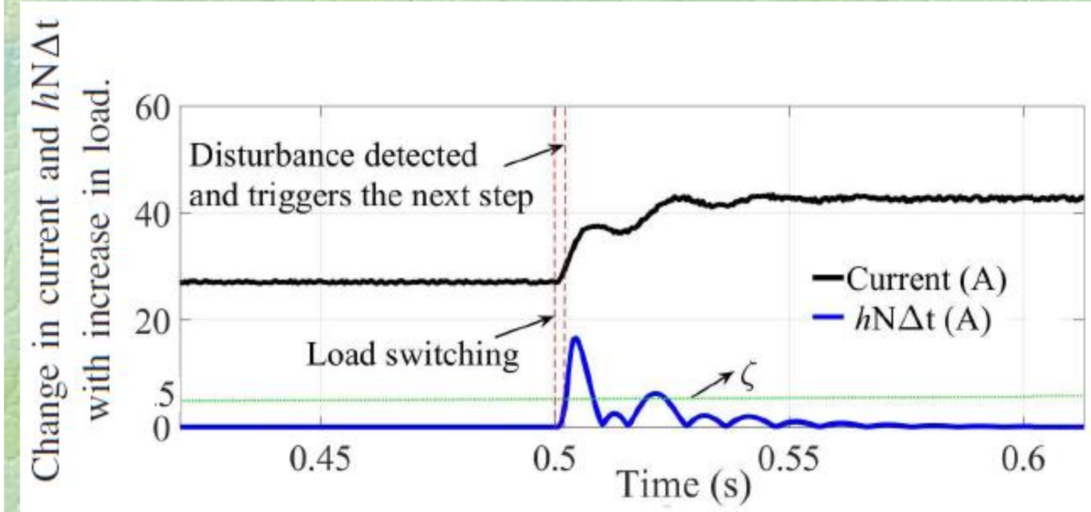
This fault direction information is communicated to the other end IED of a line segment.

Using the local and other end fault direction information, each IED identifies any internal fault of the line segment correctly.

Signals generally being contaminated by noise in a system, as proposed method uses least square filtering, it is able to estimate the seen inductance in IEDs accurately.

Unit protection schemes using parameter estimation approach





The IEDs acquire voltage and current at a sampling rate of 4 kHz.

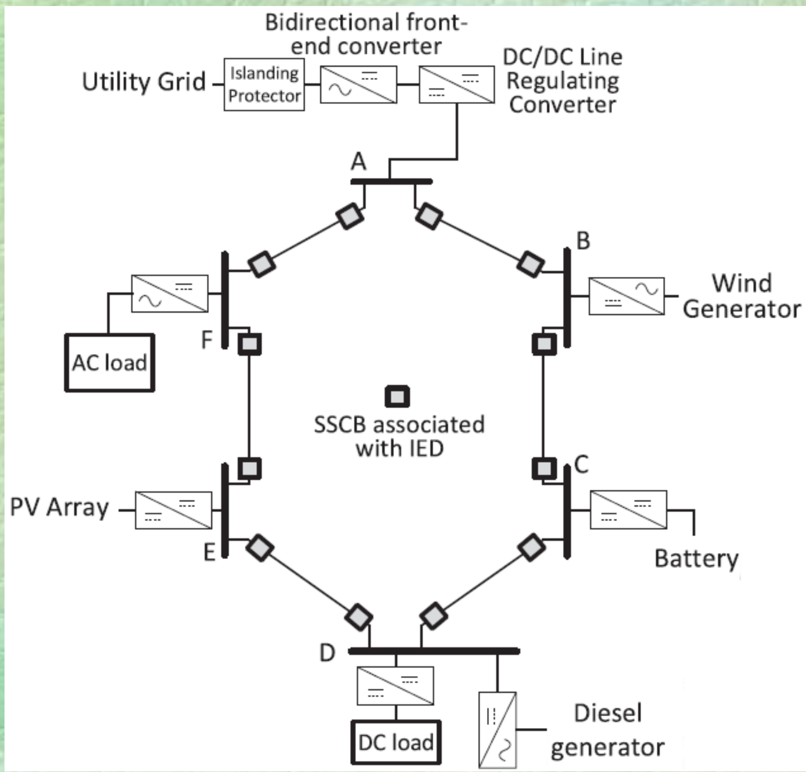
Derive disturbance index as:

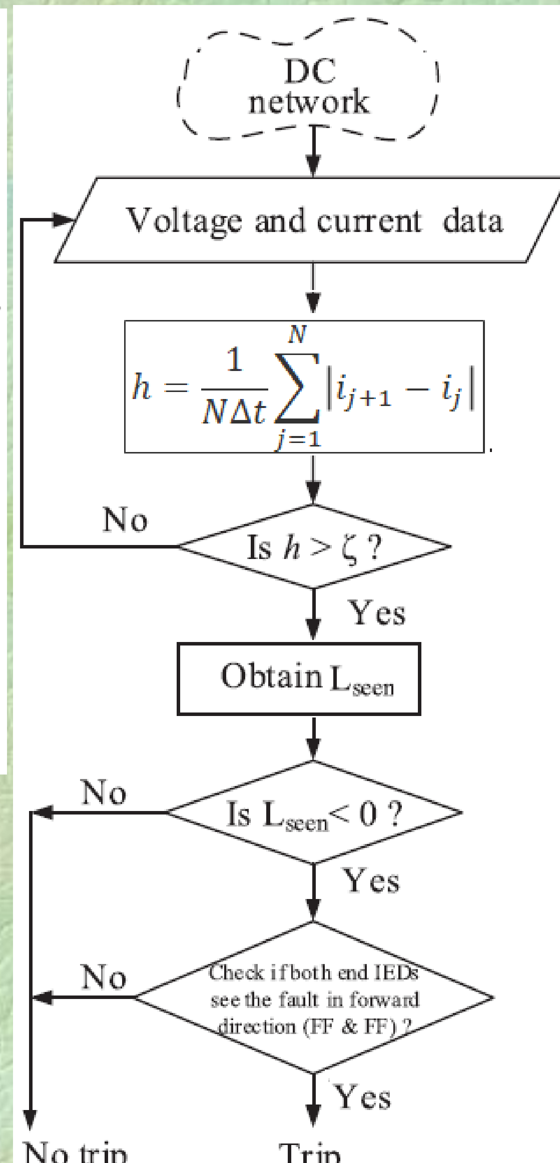
$$h = \frac{1}{N\Delta t}\sum_{j=1}^{N}\left|i_{j+1} - i_j\right|$$

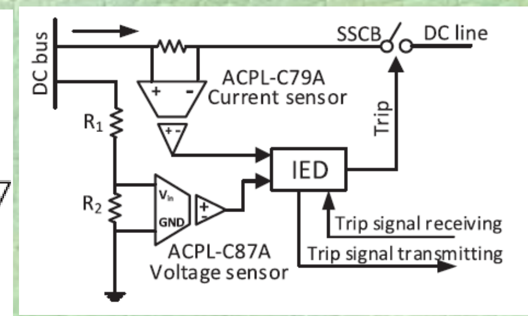
It is to be noted that the disturbance index h, becomes high even for load change or any other switching phenomena.

It is used to triggers the next step in the decision process.

Unit protection schemes using parameter estimation approach





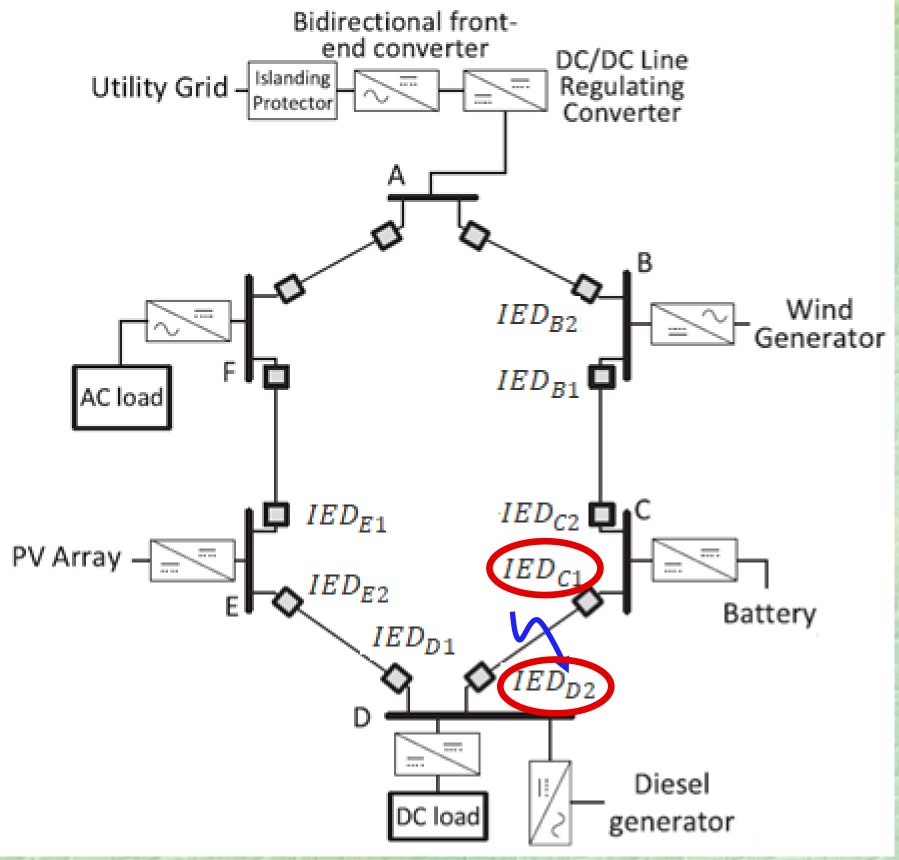


$$h = \frac{1}{N\Delta t}\sum_{j=1}^{N}\left|i_{j+1} - i_j\right|$$

These sensors provide high precision requirements, more transient immunity (15 kV/μ s) and accuracy. IED that receives data from sensors and generate control command for breaker operation is used as relay. For fast operation, SSCB is most suitable for DC networks. Operating time is in the range of 50 μs, which is considered in this work.

Unit protection schemes using parameter estimation approach

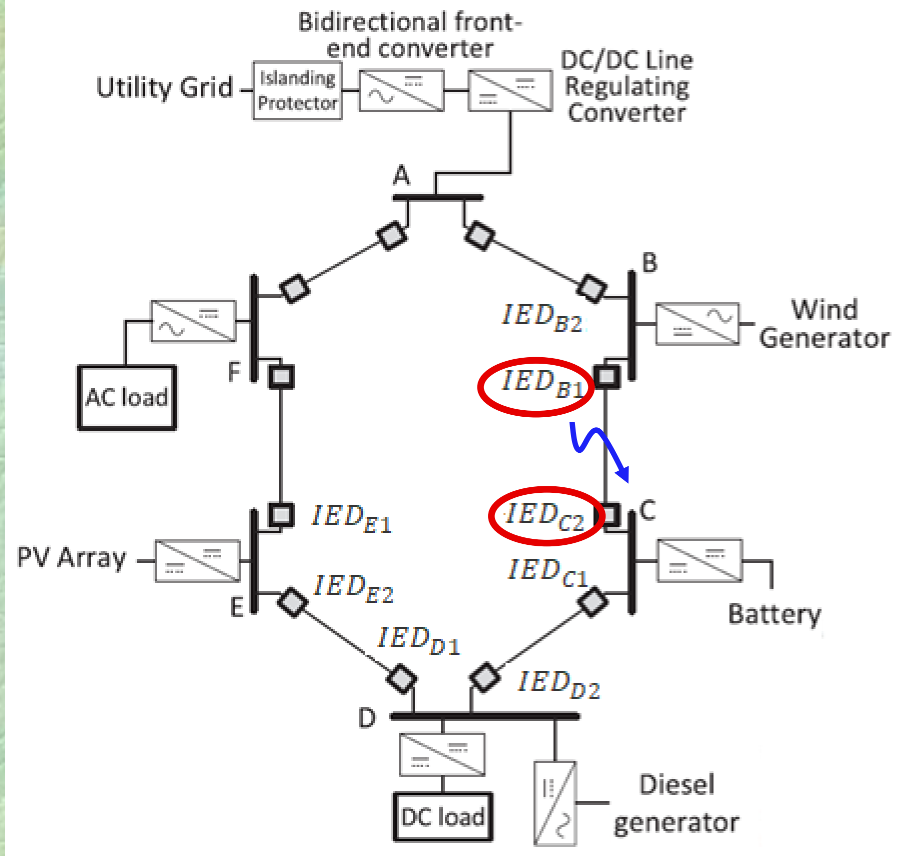
A: Performance of the method for fault in the line segment CD



Estimated direction of fault by IED for different line segments						Decision for SSCB operation in corresponding line segments		
CD		BC		DE				
$IED_{C.1}$	$IED_{D.2}$	$IED_{B.1}$	$IED_{C.2}$	$IED_{D.1}$	$IED_{E.2}$	CD	BC	DE
FF	FF	FF	RF	RF	FF	Trip	No trip	No trip

Unit protection schemes using parameter estimation approach

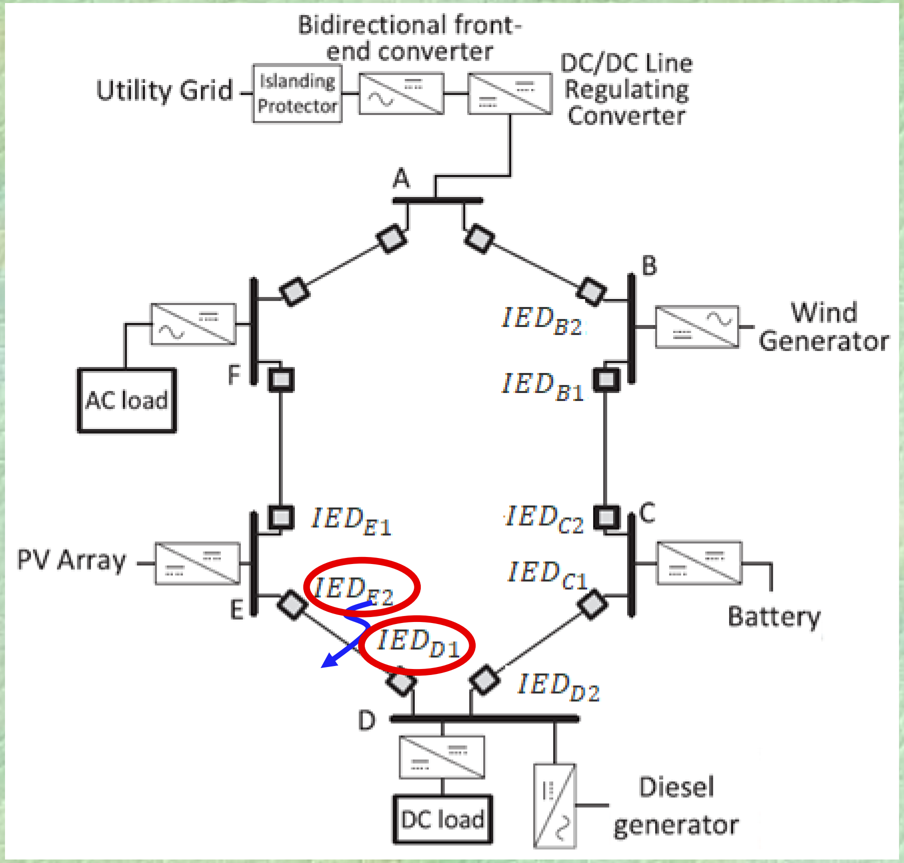
A: Performance of the method for fault in the line segment BC



Estimated direction of fault by IED for different line segments						Decision for SSCB operation in corresponding line segments		
CD		BC		DE				
$IED_{C.1}$	$IED_{D.2}$	$IED_{B.1}$	$IED_{C.2}$	$IED_{D.1}$	$IED_{E.2}$	CD	BC	DE
RF	FF	FF	FF	RF	FF	No trip	Trip	No trip

Unit protection schemes using parameter estimation approach

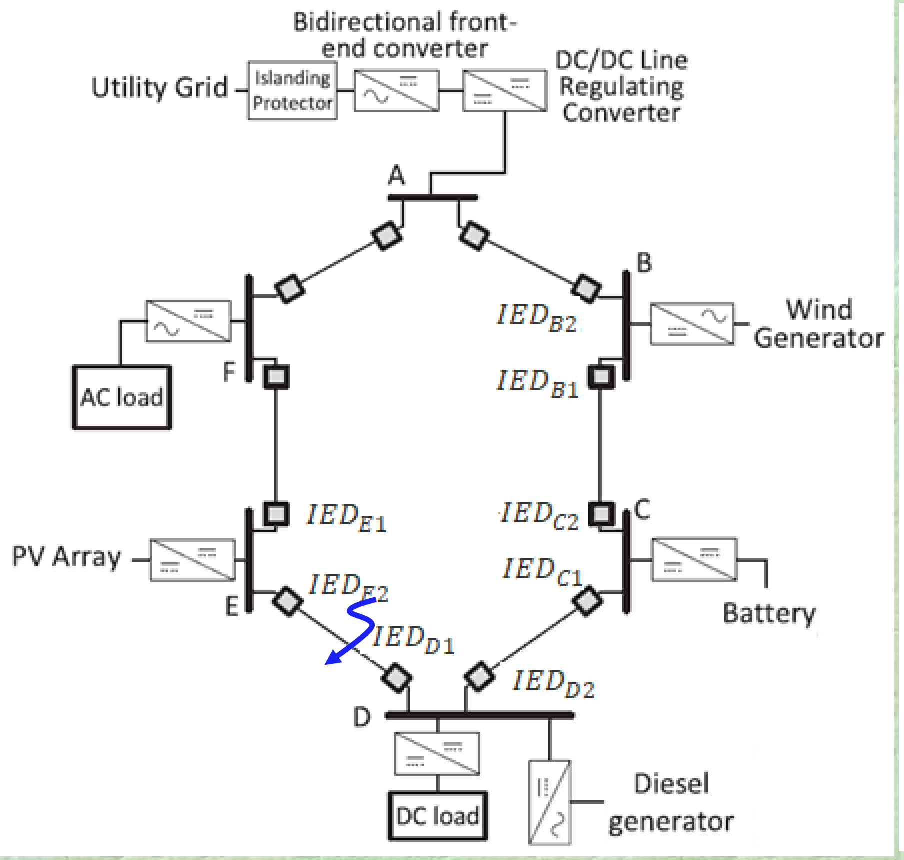
A: Performance of the method for fault in the line segment DE

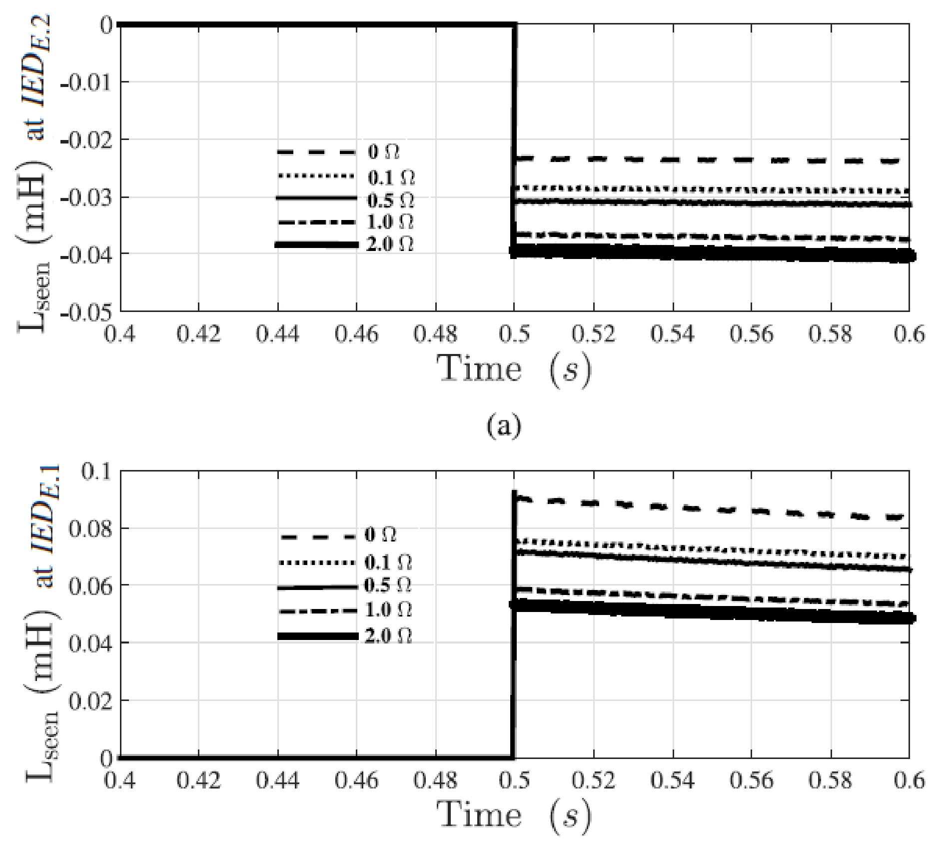


Estimated direction of fault by IED for different line segments						Decision for SSCB operation in corresponding line segments		
CD		BC		DE				
$IED_{C.1}$	$IED_{D.2}$	$IED_{B.1}$	$IED_{C.2}$	$IED_{D.1}$	$IED_{E.2}$	CD	BC	DE
FF	RF	FF	RF	FF	FF	No trip	No trip	Trip

Unit protection schemes using parameter estimation approach

B: Performance of the method with different fault resistance in the line segment DE



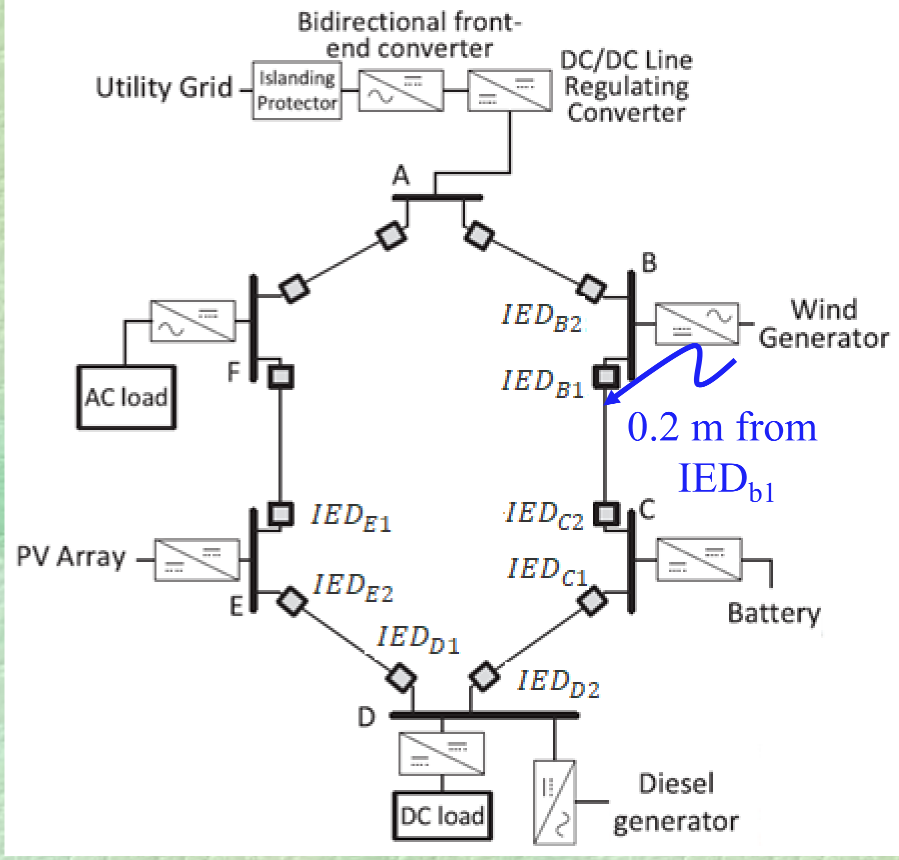


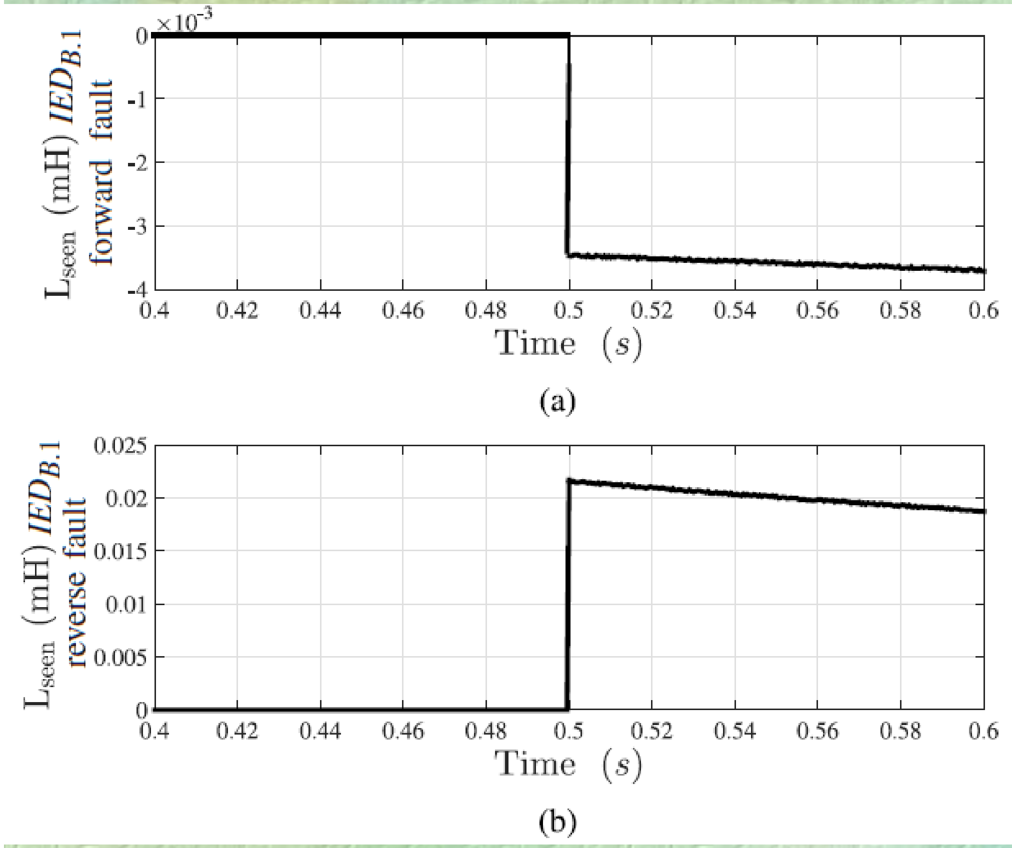
(a)

Unit protection schemes using parameter estimation approach

C: Performance of the method with close-in-internal fault

Fault resistance of 1.0 Ω is considered and data acquisition is performed at a rate of 4 kHz.

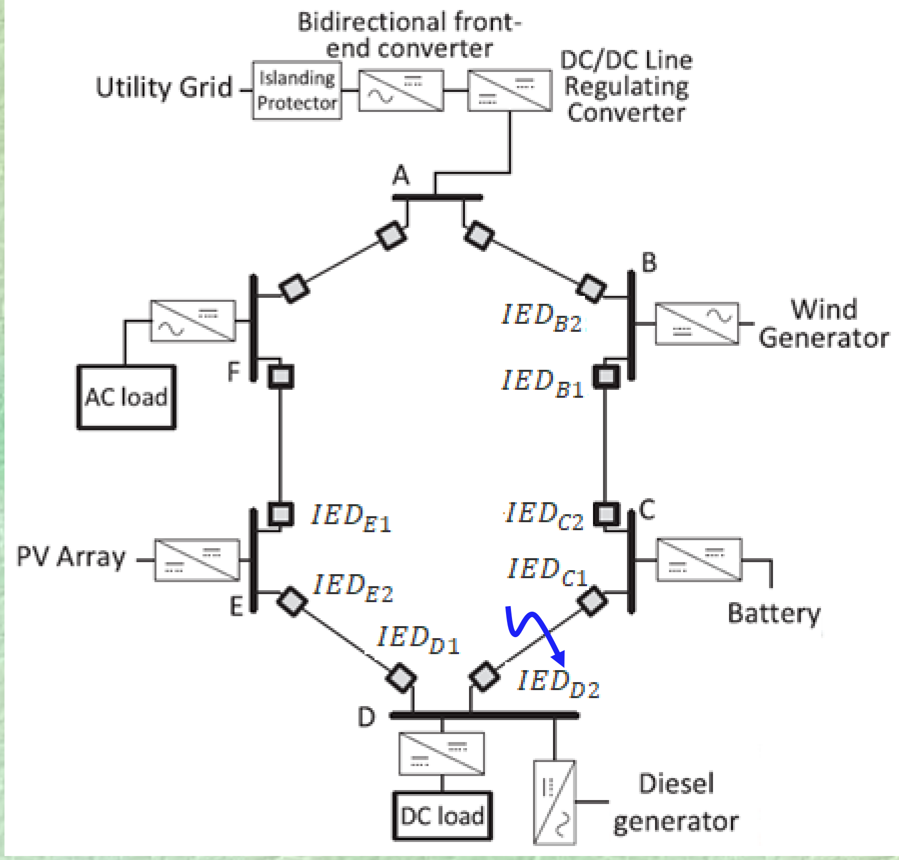


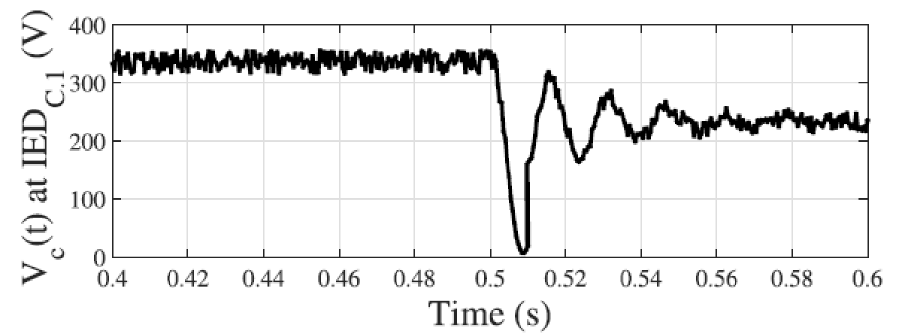


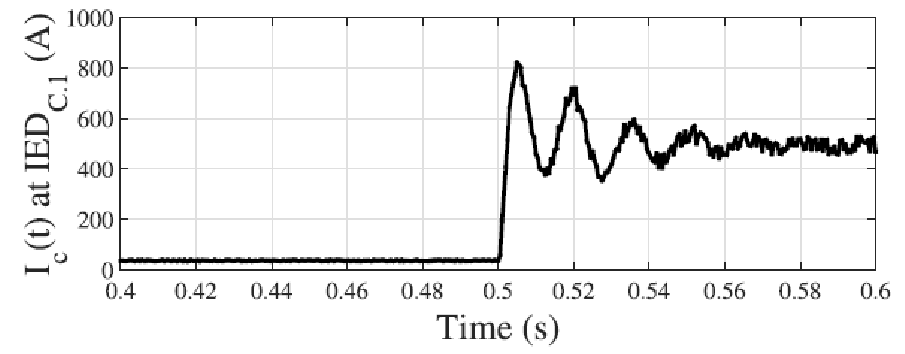
Unit protection schemes using parameter estimation approach

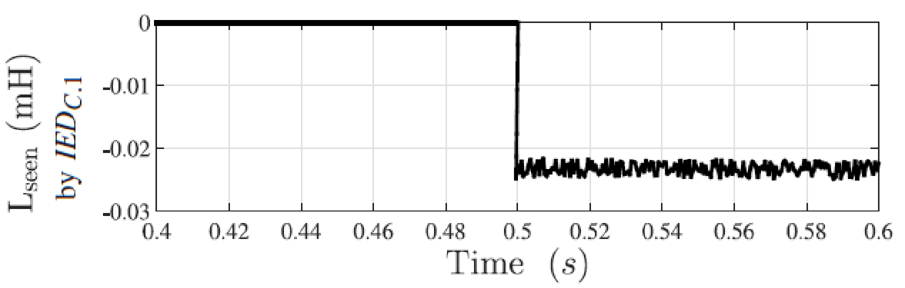
D: Performance With Noisy Signals

The voltage and current signals contaminated with uniform distribution noise with zero mean and a standard deviation of 2.5%.







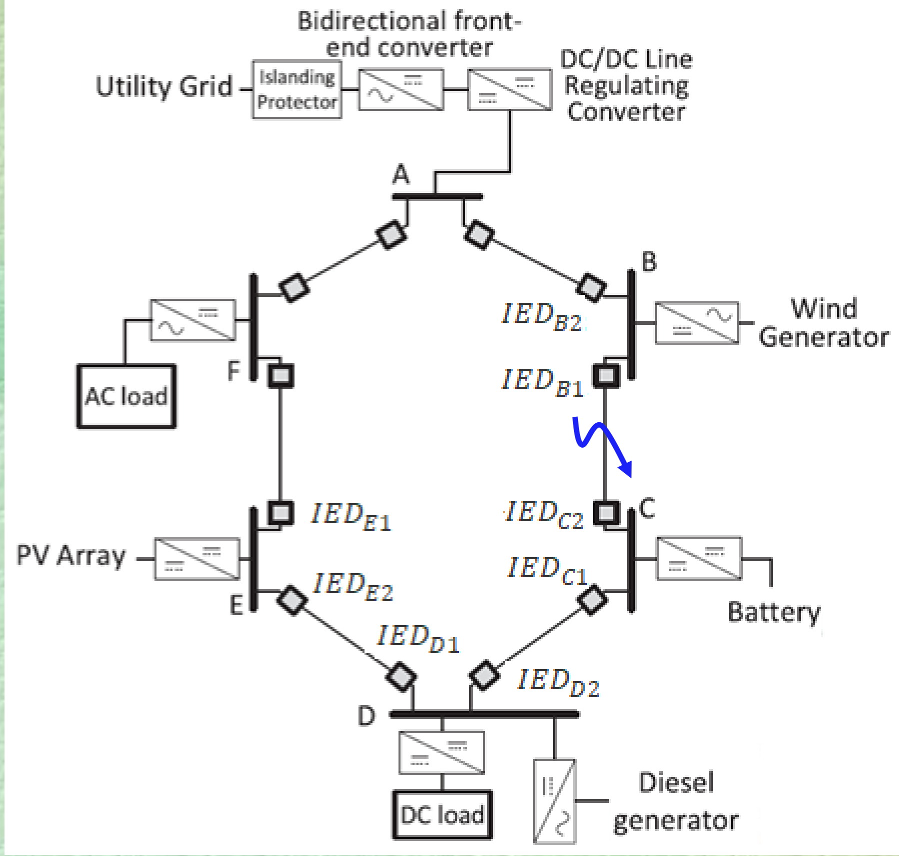


Unit protection schemes using parameter estimation approach

E: Comparative assessment with fault in the segment BC

In a DC system, direction of fault can be known from sign of current available to an IED [A. A. S. Emhemed, et al.].

Such a technique has limitation for high resistance fault as current change may not happen as expected.



	Currents in IEDs (A) [A. A. S. Emhemed, et al.]		L_{seen} (mH) (proposed method)	
R_f (Ω)	$IED_{B.1}$	$IED_{C.2}$	$IED_{B.1}$	$IED_{C.2}$
0.1	466.7 (FF)	299.7 (FF)	-0.024 (FF)	-0.026 (FF)
1	194.4 (FF)	12.5 (FF)	-0.03 (FF)	-0.032 (FF)
1.5	165.3 (FF)	-18.0 (RF)	-0.031 (FF)	-0.032 (FF)
2	149.2 (FF)	-35.0 (RF)	-0.031 (FF)	-0.033 (FF)
5	117.4 (FF)	-68.6 (RF)	-0.032 (FF)	-0.036 (FF)

Unit protection schemes using parameter estimation approach

6328 IEEE TRANSACTIONS ON SMART GRID, VOL. 9, NO. 6, NOVEMBER 2018

Protection of Smart DC Microgrid With Ring Configuration Using Parameter Estimation Approach

Rabindra Mohanty, *Student Member, IEEE*, and Ashok Kumar Pradhan, *Senior Member, IEEE*

CONCLUSION

DC microgrid protection with ring configuration is challenging because of current limiting control in converters and bidirectional power flow.

In this work, a parameter estimation based protection technique is proposed for smart DC microgrid with ring configuration.

The method uses LS technique for estimation of seen inductance at each IED during fault from which forward and reverse faults are discriminated.

This fault direction information is communicated to other end IED for identification of internal fault if any in that line segment.

Unit protection schemes by cosine similarity based approach

5646 IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, VOL. 9, NO. 5, OCTOBER 2021

A Cosine Similarity-Based Centralized Protection Scheme for dc Microgrids

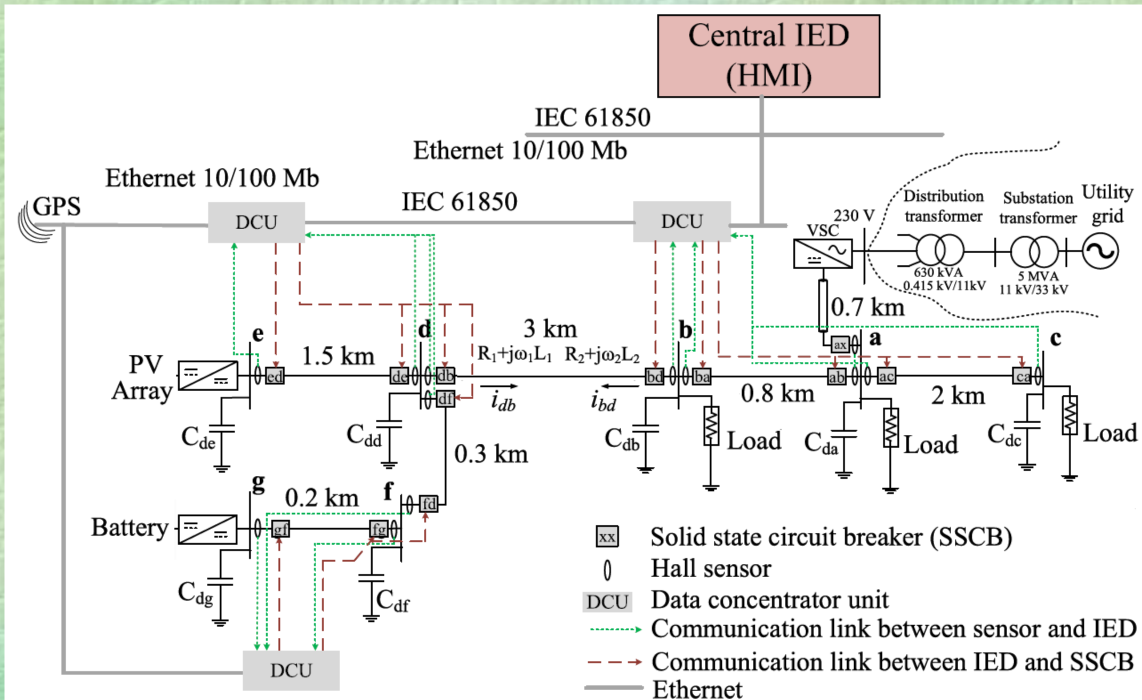
Rabindra Mohanty, *Member, IEEE*, Subham Sahoo, *Member, IEEE*,
Ashok Kumar Pradhan, *Senior Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

Propose a centralized protection scheme based on the similarity of current change over a window of both ends of a line segment is proposed for dc microgrids.

The cosine similarity index (CSI) is used to differentiate the internal and external faults.

Sample-to-sample-based → a window of data set (to overcome the effect of communication delay in the protection scheme)

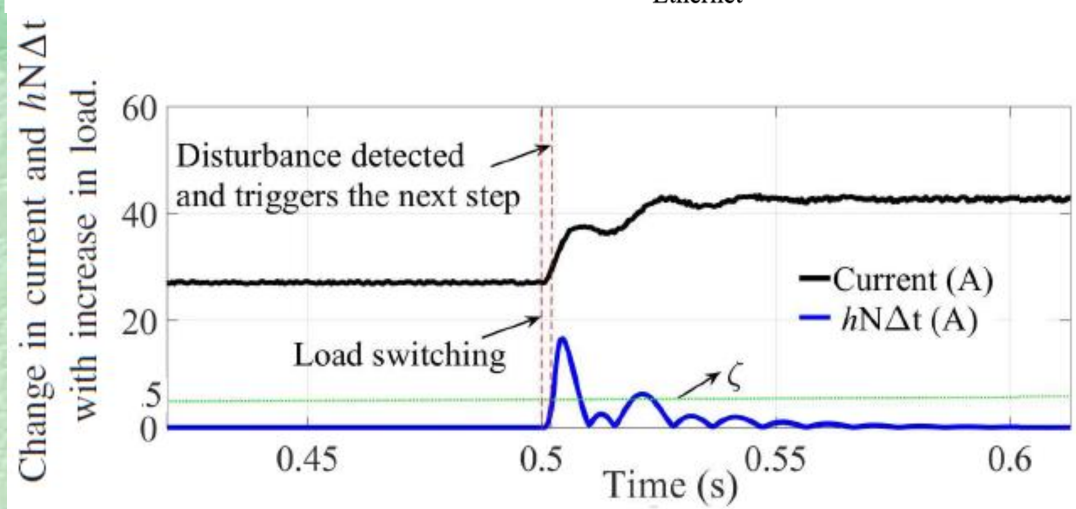
Unit protection schemes by cosine similarity based approach



The IEDs acquire voltage and current at a sampling rate of 4 kHz.

Derive disturbance index as:

$$h = \frac{1}{N\Delta t}\sum_{n=1}^{N} |i_{n+1} - i_n|$$

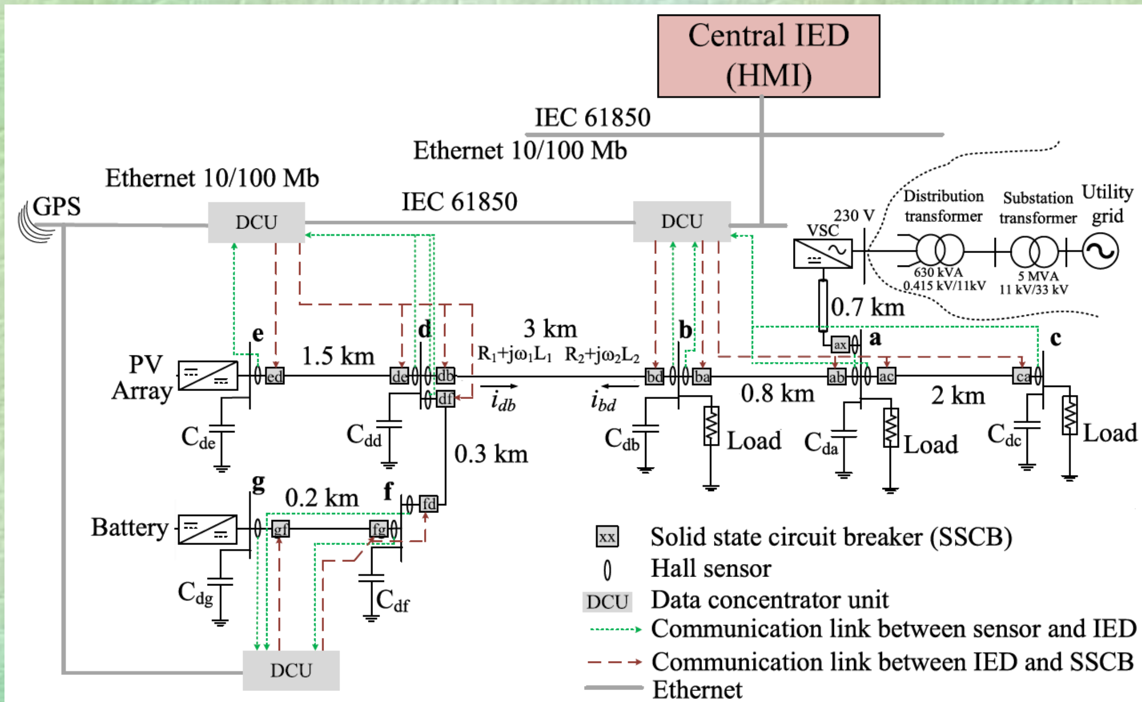


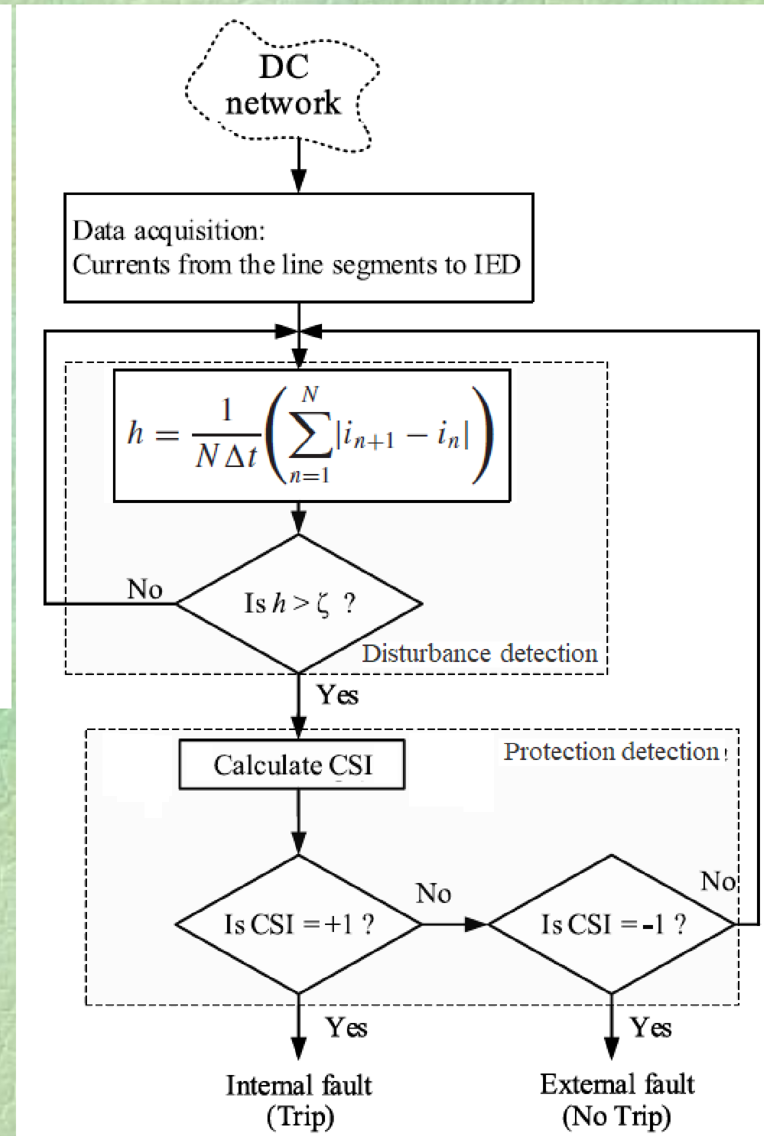
It is to be noted that the disturbance index h, becomes high even for load change or any other switching phenomena.

It is used to triggers the next step in the decision process.

Disturbance detection
Protection detection

Unit protection schemes by cosine similarity based approach

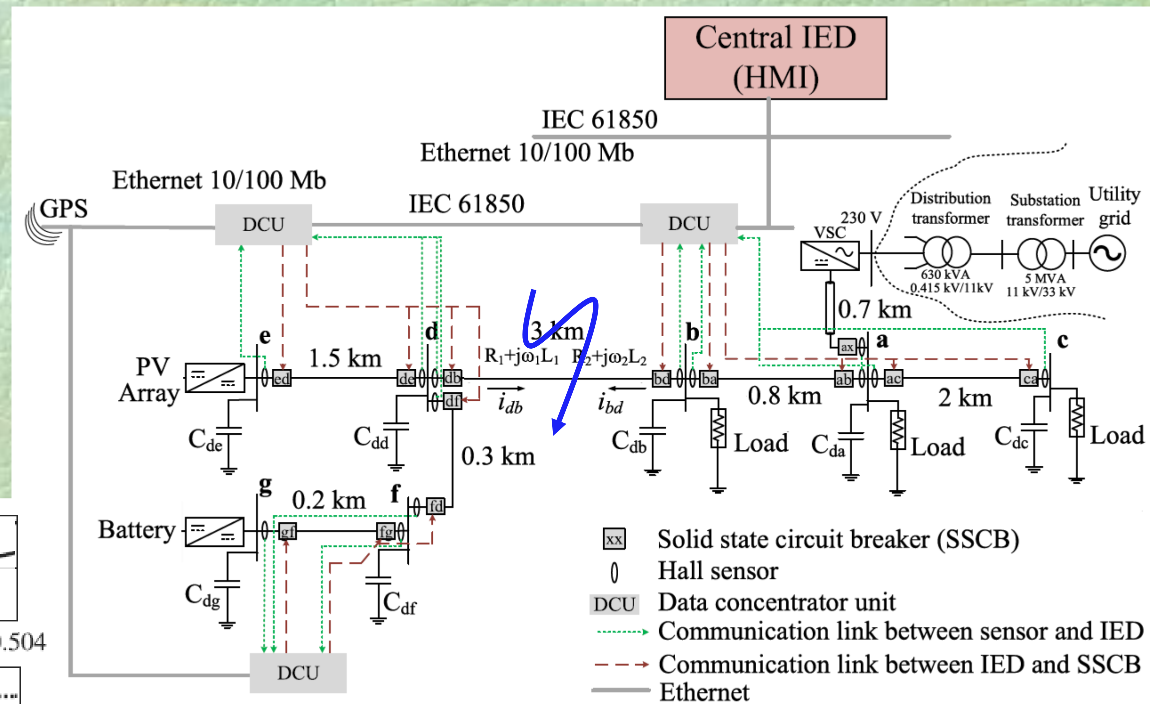


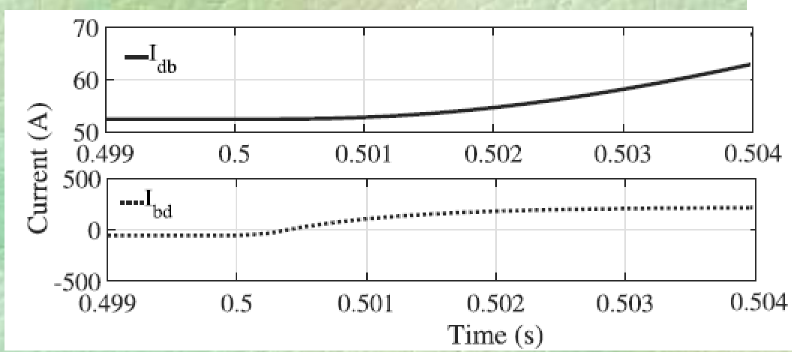


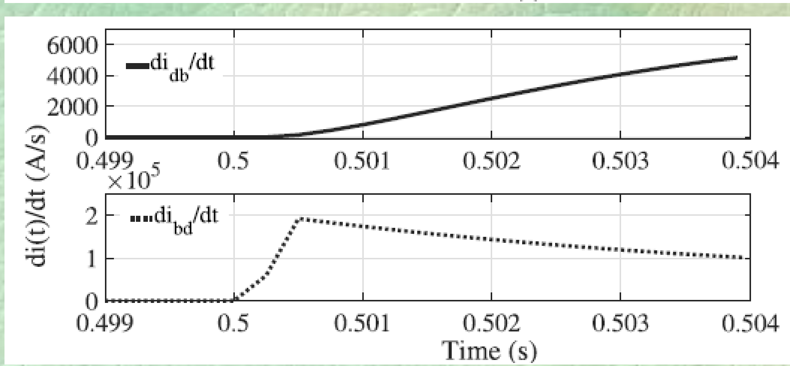
$$h = \frac{1}{N\Delta t}\left(\sum_{n=1}^{N} |i_{n+1} - i_n|\right)$$

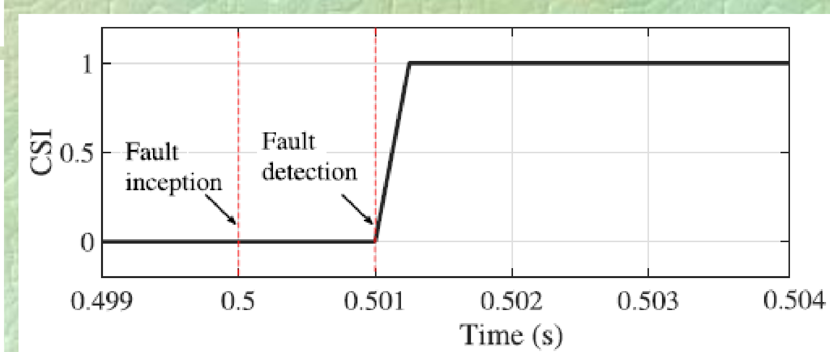
Unit protection schemes by cosine similarity based approach

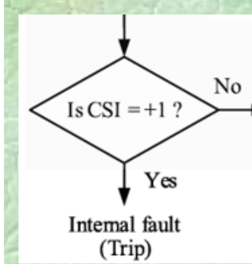
A: A PG with a fault resistance of 5 Ω is simulated at 0.5 s.





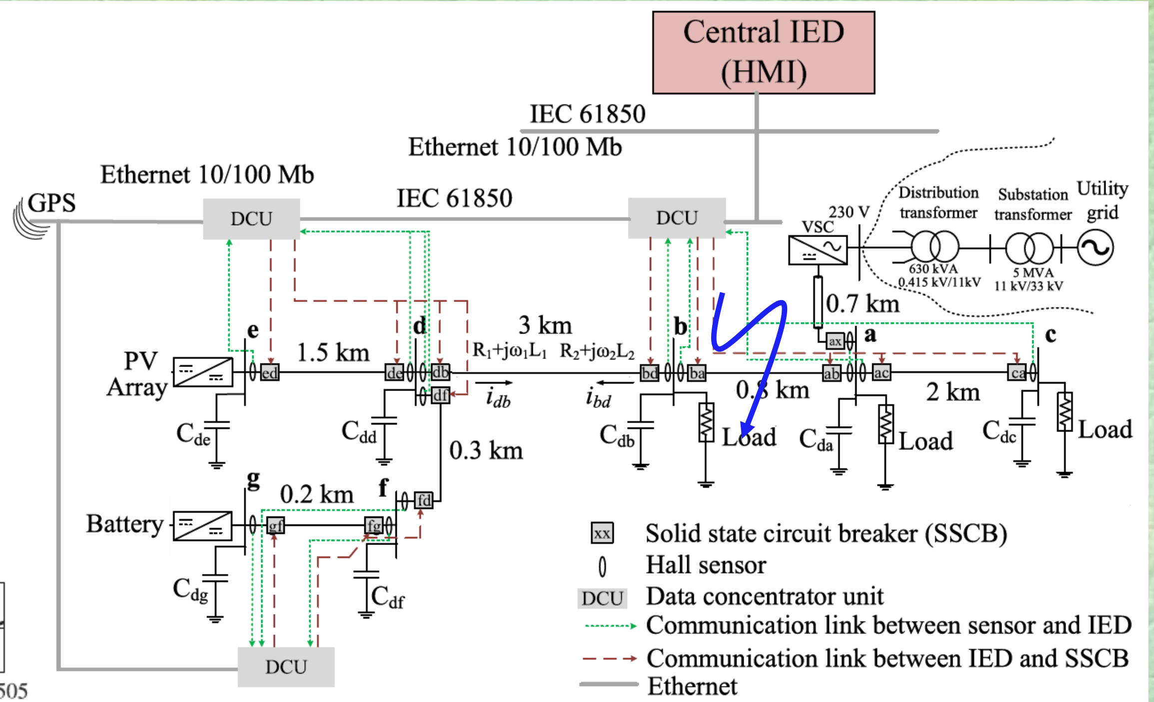


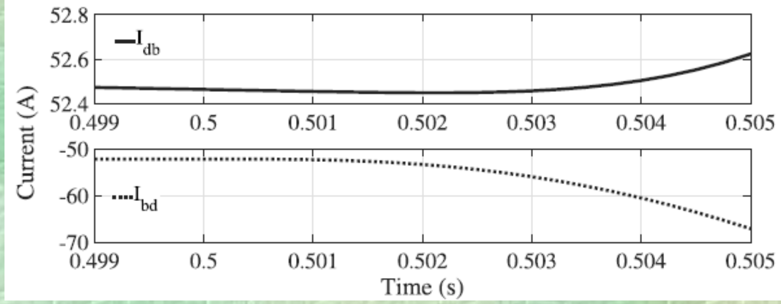


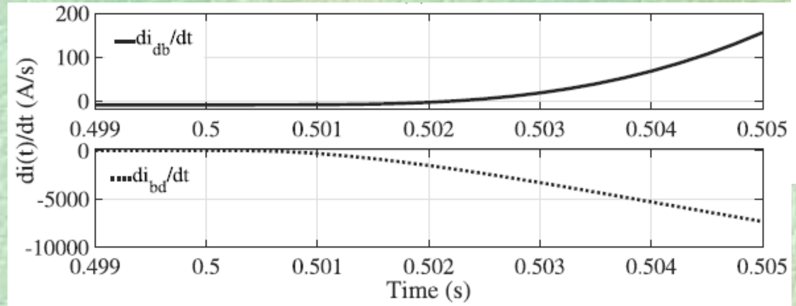


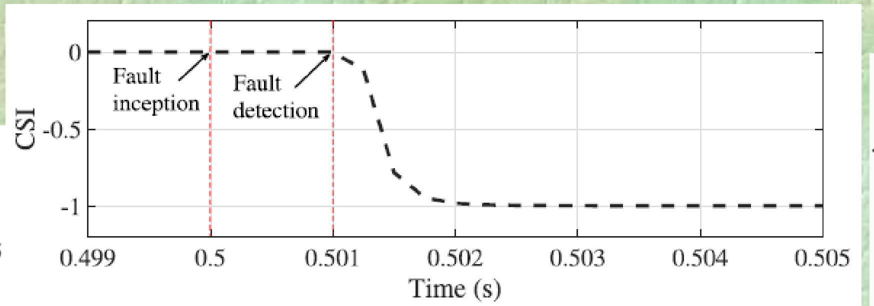
Unit protection schemes by cosine similarity based approach

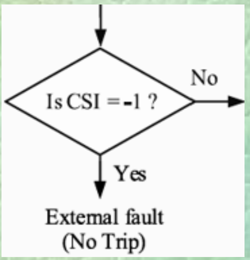
A: A PG with a fault resistance of 5 Ω is simulated at 0.5 s.







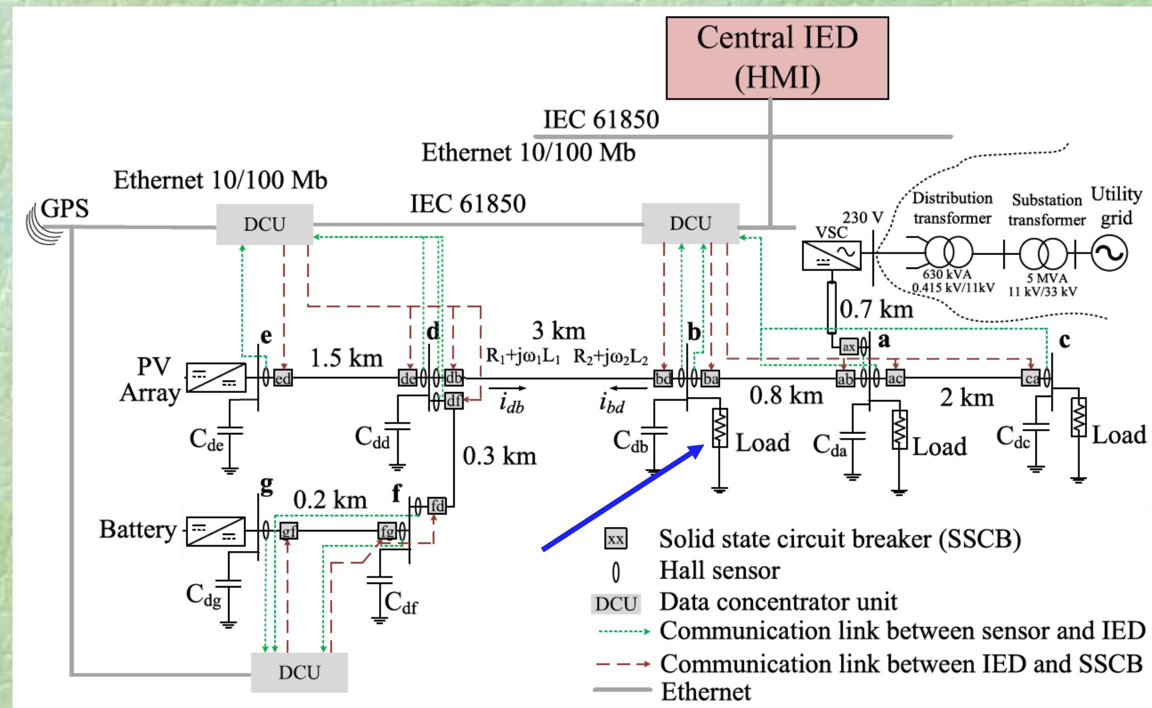


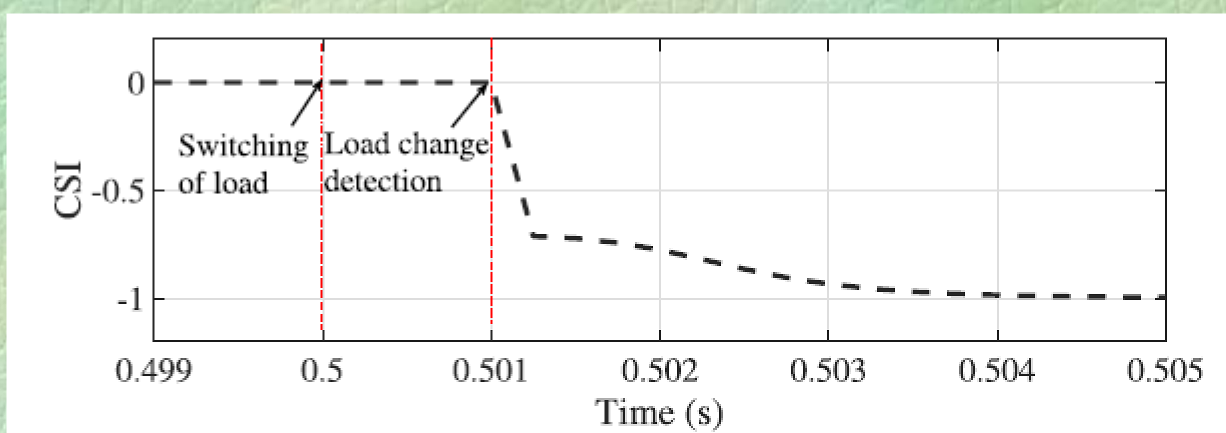


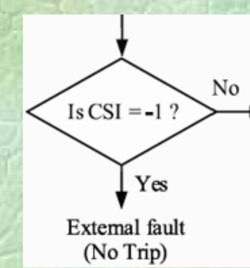
Unit protection schemes by cosine similarity based approach

A: The performance of the method is also tested for a sudden change in loading conditions.

The load is varied from 60% to 110% of rated value at bus-b.

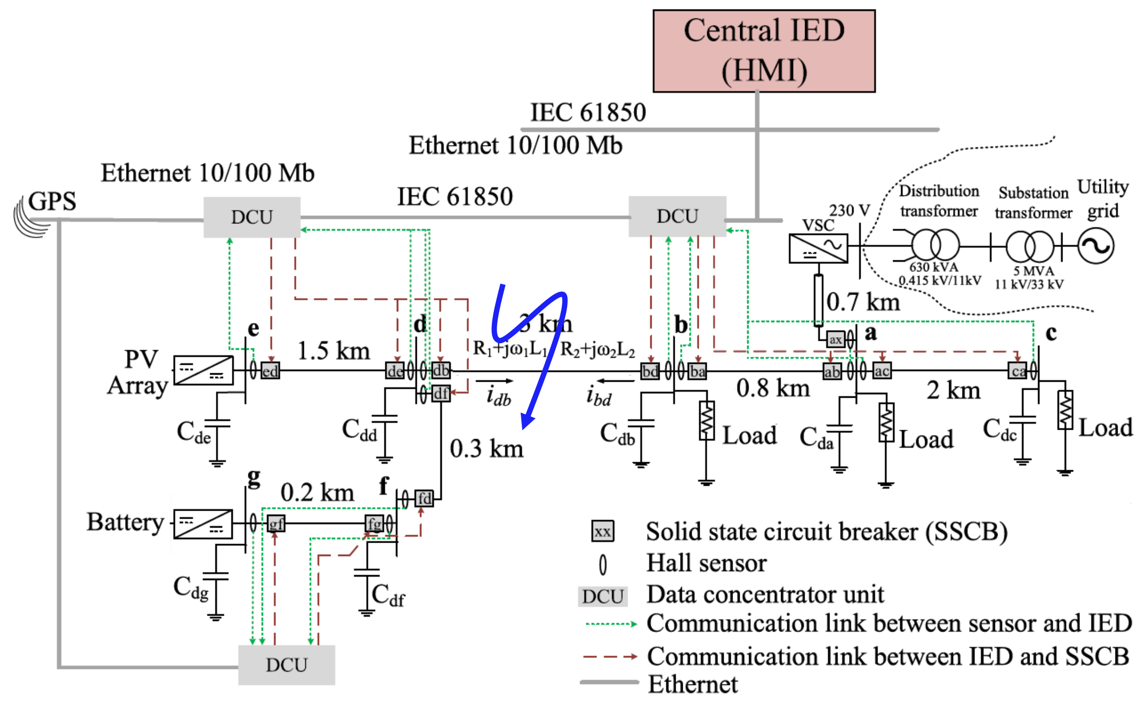






Unit protection schemes by cosine similarity based approach

B: Performance During Communication Link Failure

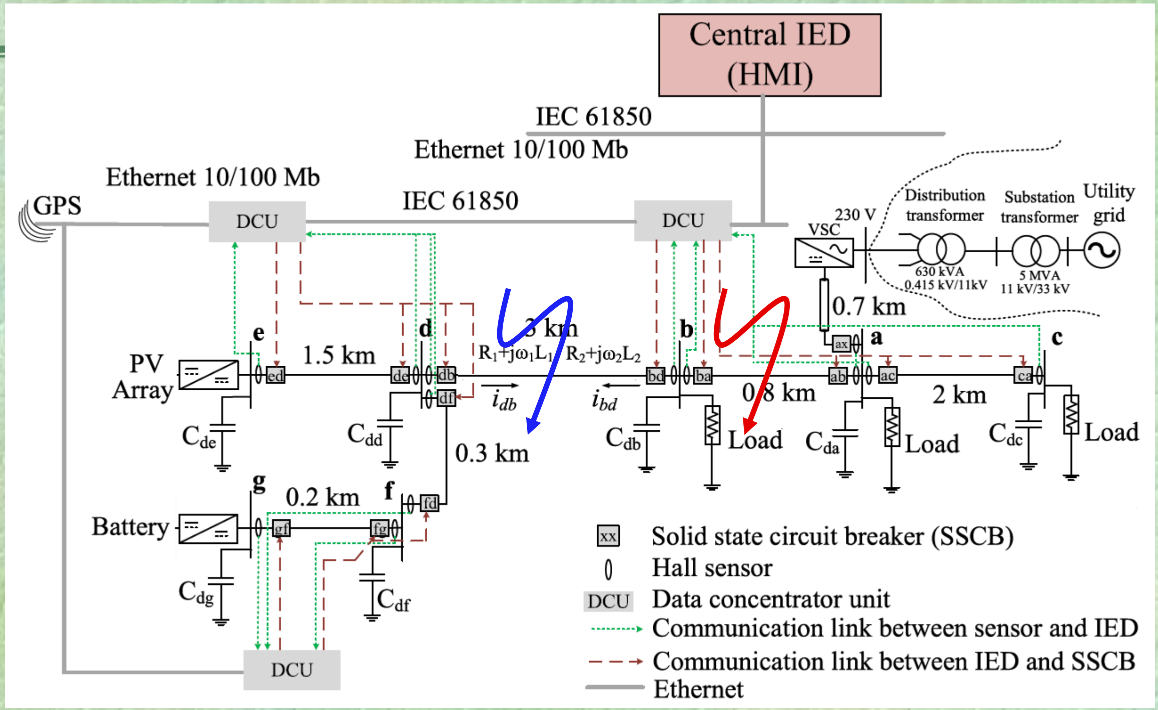


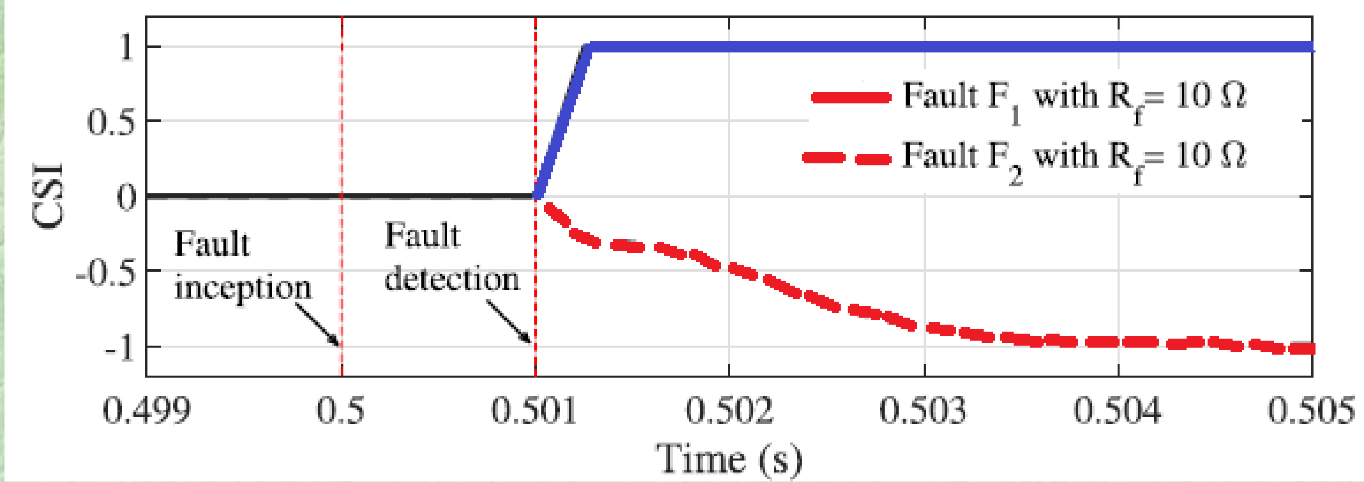
Events	Bus-d	Bus-b	Central IED	Remarks
No communication failure	i_{db} is available	i_{bd} is available	X and Y are positive and CSI = +1	Trip SSCB-db and SSCB-bd
One end communication failure	i_{db} is not available	i_{bd} is available	Apply KCL at bus-d, satisfied the criteria as in section IV-E	Trip SSCB-db and SSCB-bd
Both ends communication failure	i_{db} is not available	i_{bd} is not available	Apply KCL at bus-d and b, satisfied the criteria as in section IV-F	Trip SSCB-db and SSCB-bd
Both ends and one end from adjacent lines fails	i_{db} is not available	i_{bd} and i_{ba} are not available	Apply KCL at bus-d and a, satisfied the criteria as in section IV-F	Trip SSCBs at segment-bd and ab
Load change in bus-b	i_{db} is available	i_{bd} is available	i_{db}, i_{ab} are positive and i_{bd}, i_{ba} are negative, CSI = -1	No trip signal

Unit protection schemes by cosine similarity based approach

C: Comparative Assessment

1) Performance During High Resistance Internal Fault





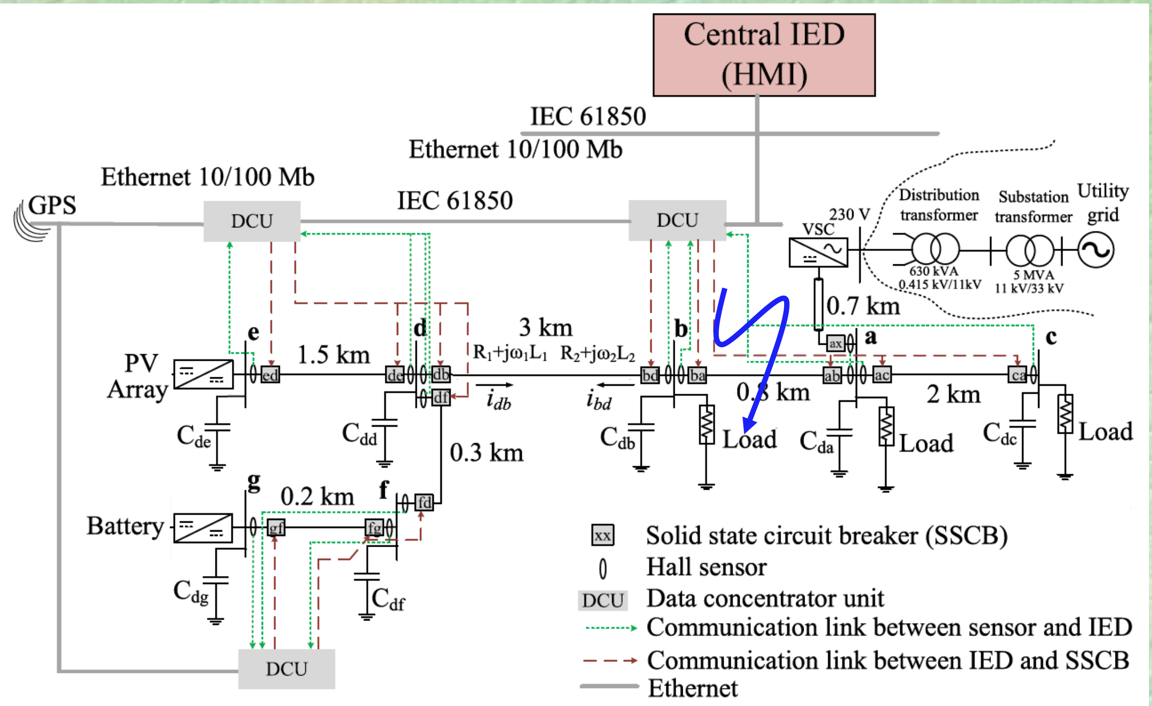
Unit protection schemes by cosine similarity based approach

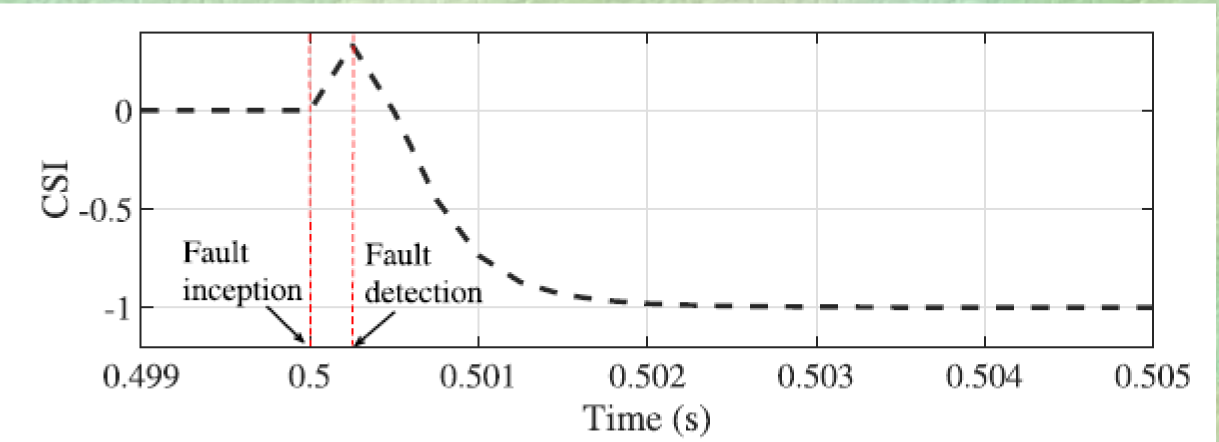
C: Comparative Assessment

2) Performance in the Presence of Communication Delay:

Fault resistance of 2 Ω at 0.5 s

A communication delay of 1 ms is introduced in the current signal from the sensor at SSCB-bd of the line segment-db.

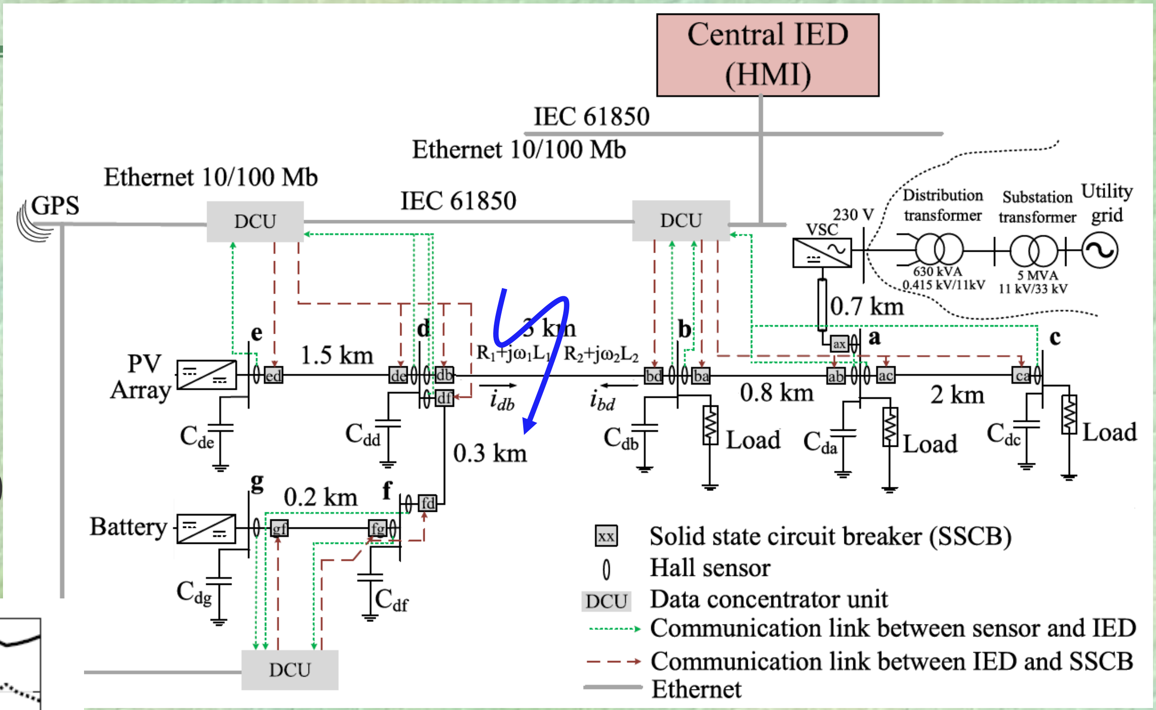


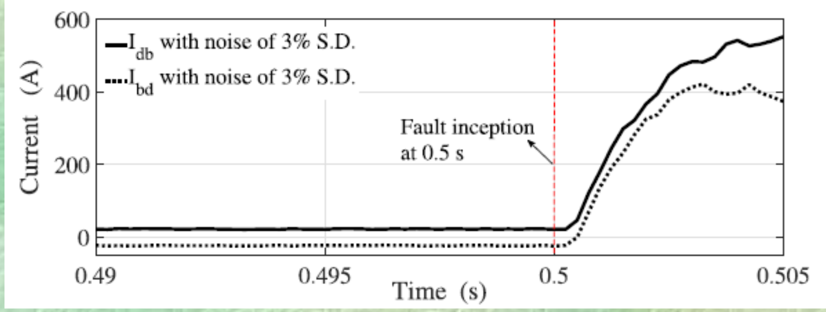


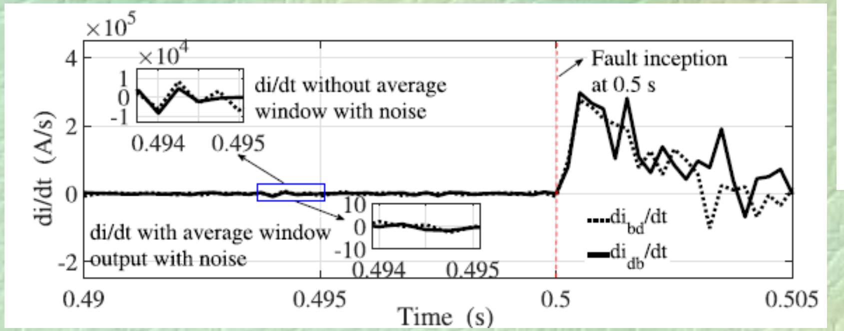
Unit protection schemes by cosine similarity based approach

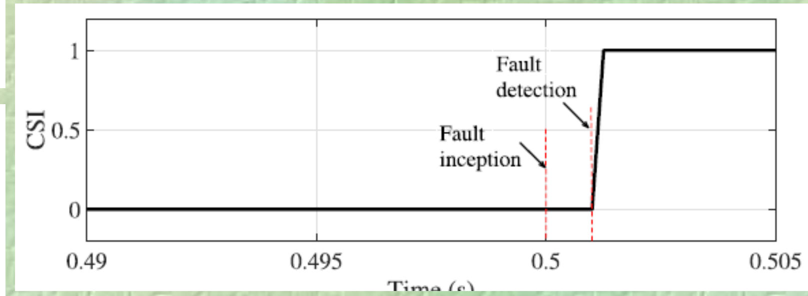
D: Performance of the Proposed Method With Noisy Signals

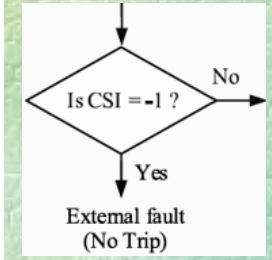
The performance of the method is tested for the current signal contaminated with uniform distribution noise with zero mean and a standard deviation (S.D.) of 3%





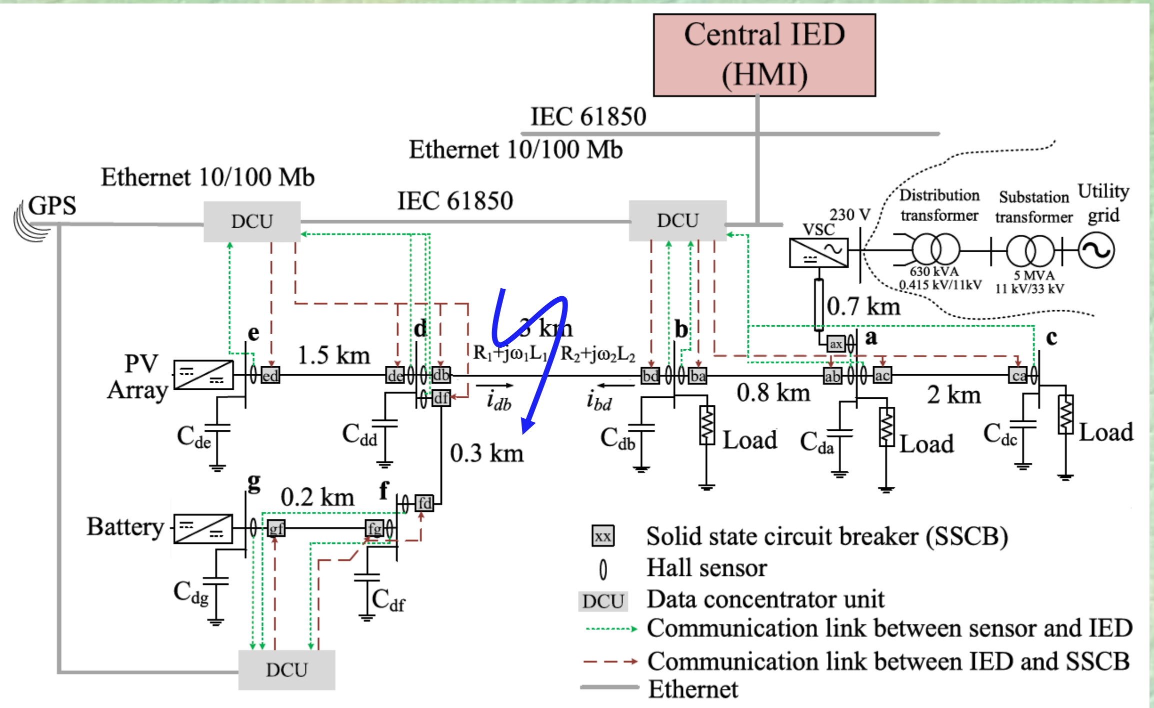






Unit protection schemes by cosine similarity based approach

Selectivity during communication fault



Events	Bus-d	Bus-b	Central IED	Remarks
No communication failure	i_{db} is available	i_{bd} is available	X and Y are positive and CSI = +1	Trip SSCB-db and SSCB-bd
One end communication failure	i_{db} is not available	i_{bd} is available	Apply KCL at bus-d, satisfied the criteria as in section IV-E	Trip SSCB-db and SSCB-bd
Both ends communication failure	i_{db} is not available	i_{bd} is not available	Apply KCL at bus-d and b, satisfied the criteria as in section IV-F	Trip SSCB-db and SSCB-bd
Both ends and one end from adjacent lines fails	i_{db} is not available	i_{bd} and i_{ba} are not available	Apply KCL at bus-d and a, satisfied the criteria as in section IV-F	Trip SSCBs at segment-bd and ab
Load change in bus-b	i_{db} is available	i_{bd} is available	i_{db}, i_{ab} are positive and i_{bd}, i_{ba} are negative, CSI = -1	No trip signal

Unit protection schemes by cosine similarity based approach

5646 IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, VOL. 9, NO. 5, OCTOBER 2021

A Cosine Similarity-Based Centralized Protection Scheme for dc Microgrids

Rabindra Mohanty, *Member, IEEE*, Subham Sahoo, *Member, IEEE*,
Ashok Kumar Pradhan, *Senior Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

CONCLUSION

In this work, a centralized dc microgrid protection scheme is proposed.

The similarity of the rate of current change over a window of both ends of the line segment identifies an internal fault.

The performance of the protection scheme is tested for high resistance fault, communication delay, and link failure.

The protection decision is taken within 3 ms or even faster in case of no delayed signals.

As compared to available protection schemes that use both voltage and current data, the proposed protection scheme entails an economic alternative, which employs only one central IED for the entire microgrid and one current sensor for each end of a line segment.