



GE's HVDC ' reaker Solutions

February 23, 2017

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CAUTION CONCERNING FORWARD-LOOKING STATEMENTS:

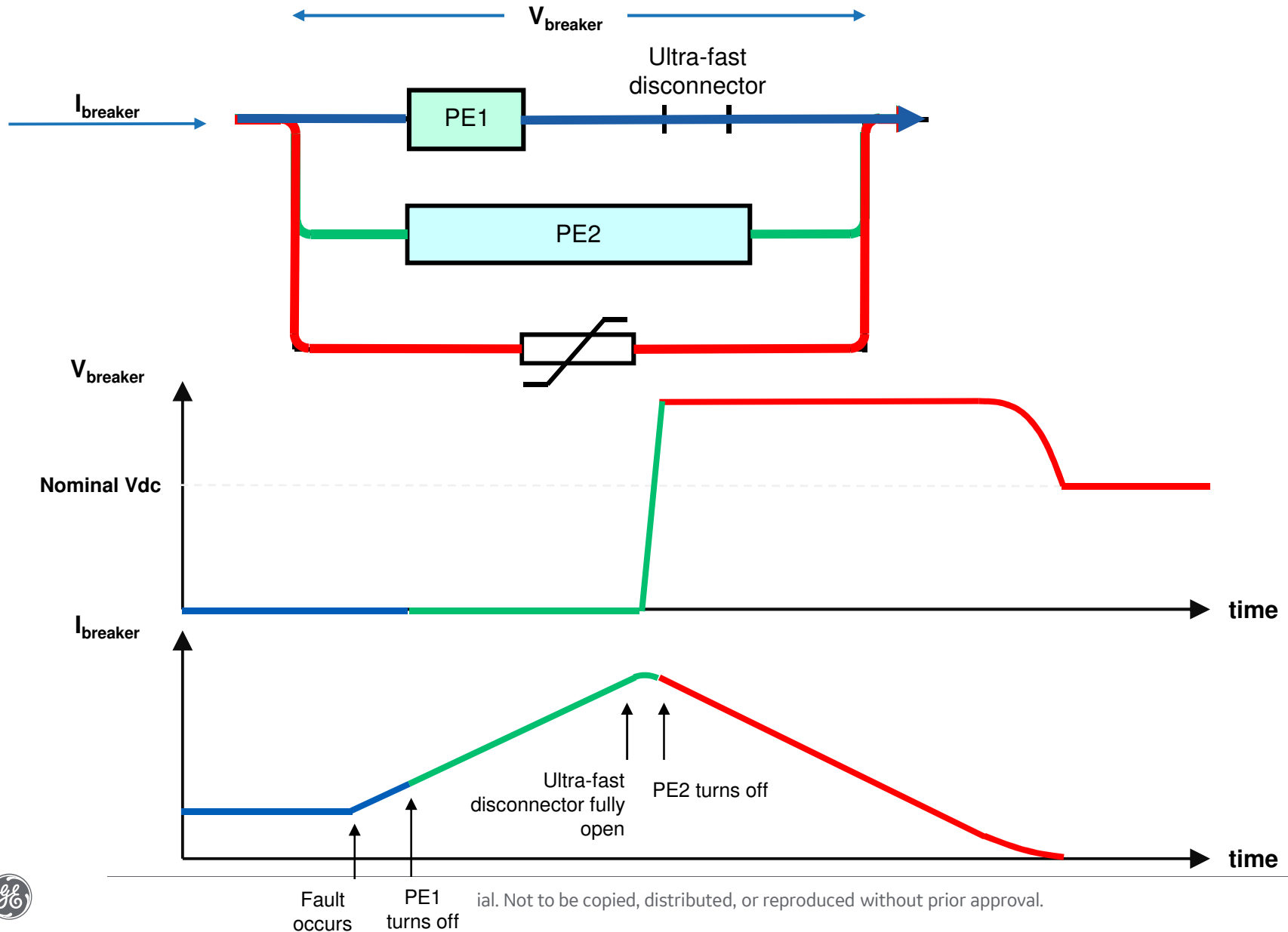
This document contains "forward-looking statements" – that is, statements related to future events that by their nature address matters that are, to different degrees, uncertain. For details on the uncertainties that may cause our actual future results to be materially different than those expressed in our forward-looking statements, see <http://www.ge.com/investor-relations/disclaimer-caution-concerning-forwardlooking-statements> as well as our annual reports on Form 10-K and quarterly reports on Form 10-Q. We do not undertake to update our forward-looking statements. This document also includes certain forward-looking projected financial information that is based on current estimates and forecasts. Actual results could differ materially. to total risk-weighted assets.]

NON-GAAP FINANCIAL MEASURES:

In this document, we sometimes use information derived from consolidated financial data but not presented in our financial statements prepared in accordance with U.S. generally accepted accounting principles (GAAP). Certain of these data are considered "non-GAAP financial measures" under the U.S. Securities and Exchange Commission rules. These non-GAAP financial measures supplement our GAAP disclosures and should not be considered an alternative to the GAAP measure. The reasons we use these non-GAAP financial measures and the reconciliations to their most directly comparable GAAP financial measures are posted to the investor relations section of our website at www.ge.com. [We use non-GAAP financial measures including the following:

- Operating earnings and EPS, which is earnings from continuing operations excluding non-service-related pension costs of our principal pension plans.
- GE Industrial operating & Verticals earnings and EPS, which is operating earnings of our industrial businesses and the GE Capital businesses that we expect to retain.
- GE Industrial & Verticals revenues, which is revenue of our industrial businesses and the GE Capital businesses that we expect to retain.
- Industrial segment organic revenue, which is the sum of revenue from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial segment organic operating profit, which is the sum of segment profit from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial cash flows from operating activities (Industrial CFOA), which is GE's cash flow from operating activities excluding dividends received from GE Capital.
- Capital ending net investment (ENI), excluding liquidity, which is a measure we use to measure the size of our Capital segment.
- GE Capital Tier 1 Common ratio estimate is a ratio of equity

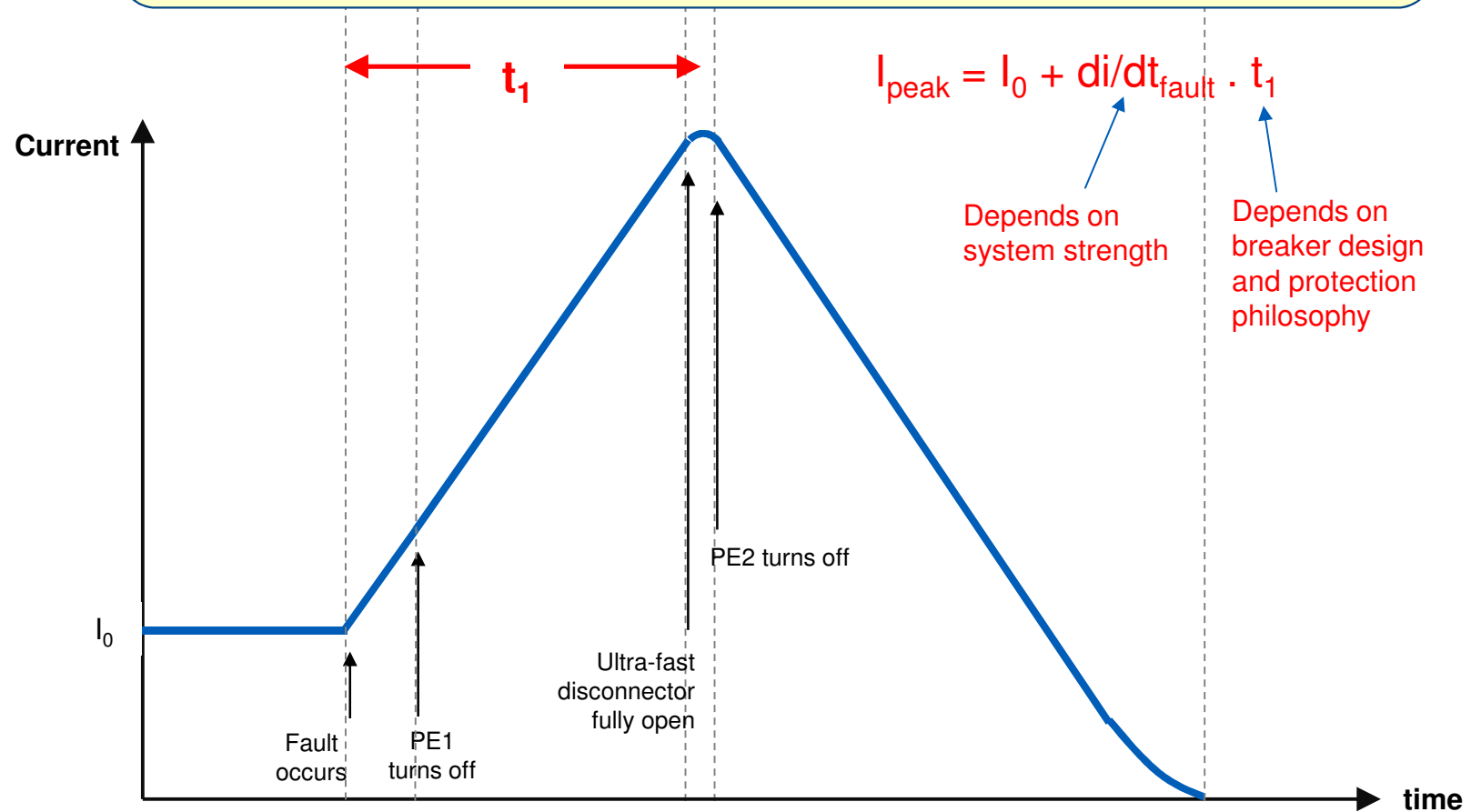
Hybrid DC breaker – operating principle



DC breaker – the importance of *speed*

To minimise the peak current rating of the breaker:

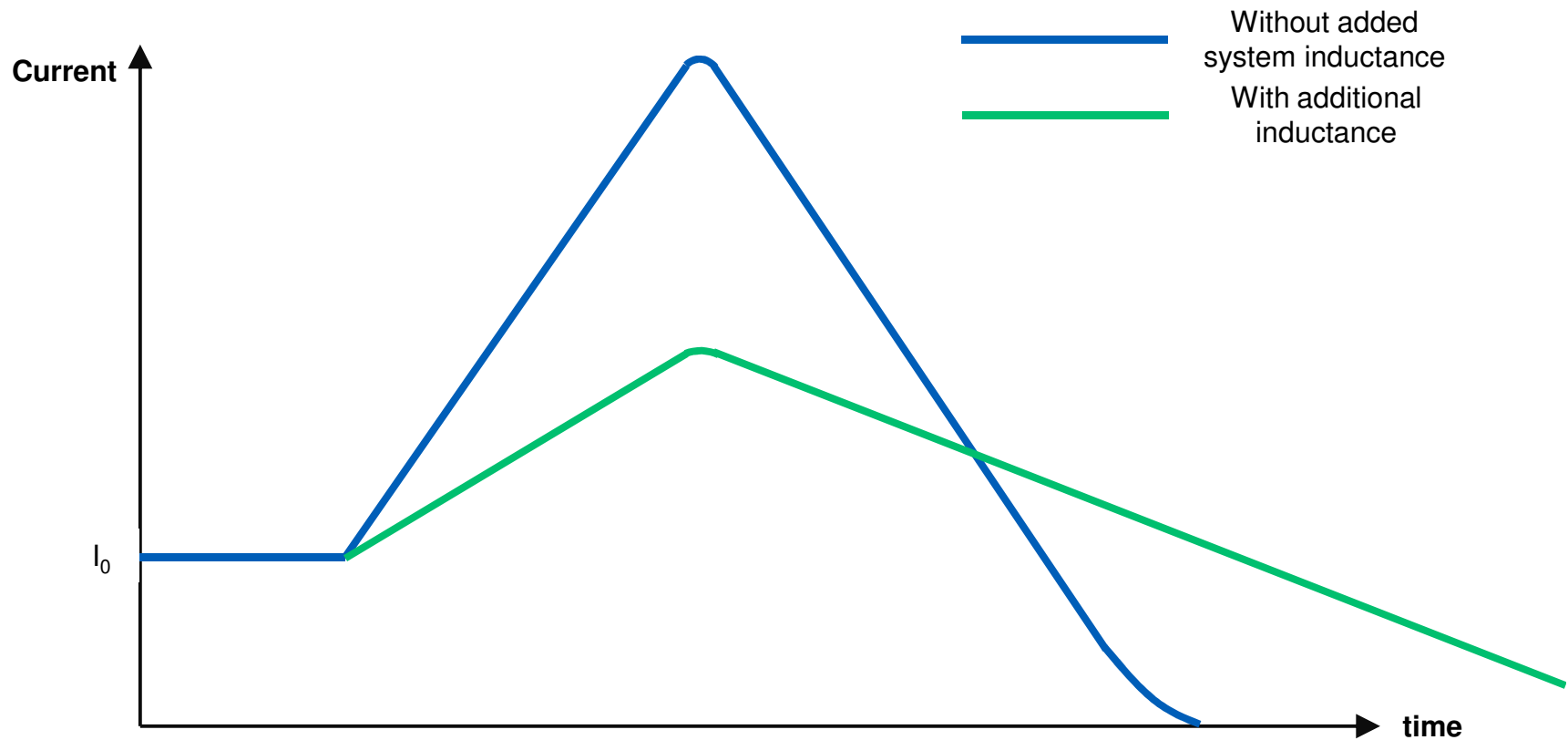
1. Detection, selectivity & relaying time to be as short as possible
2. Breaker operation time to be as short as possible



DC breaker – the effect of inductance

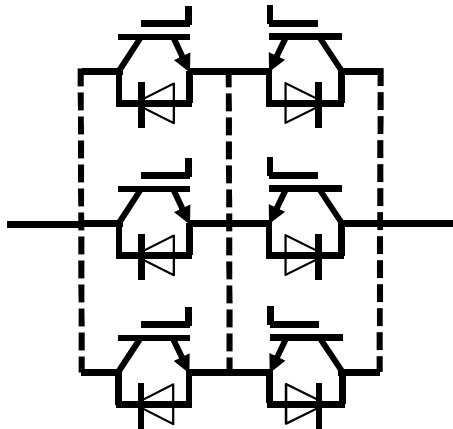
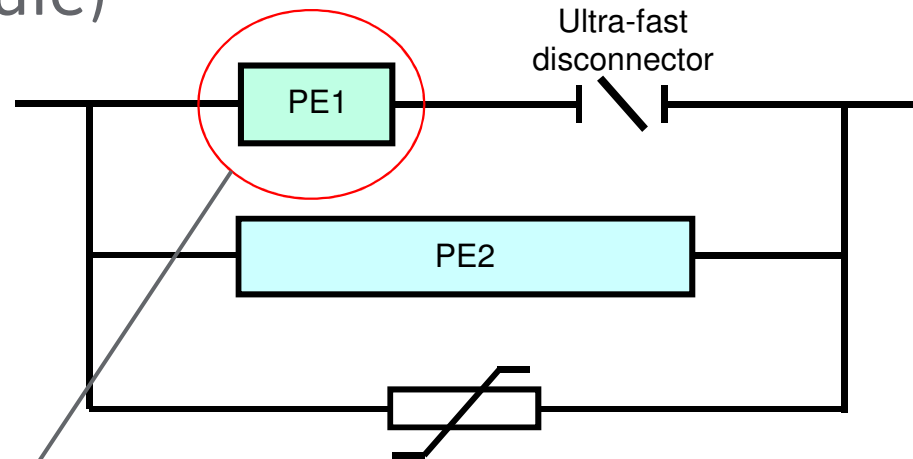
Additional inductance is a double-edged sword!

- It helps you on the way up...
- But makes life harder on the way down again



The GE hybrid DC breaker

Power electronics switch 1 (commutation module)

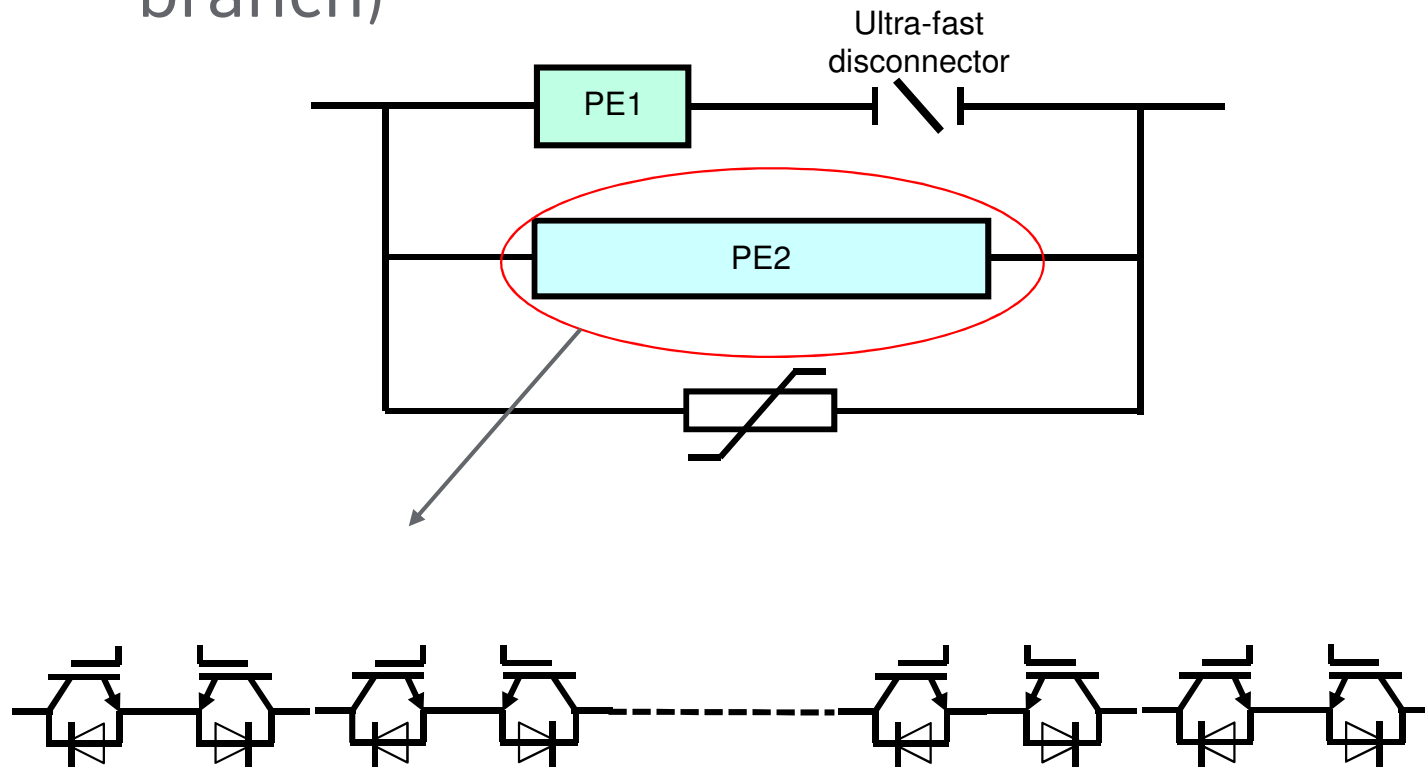


- Multiple IG' Ts in parallel
- Two inverse-series per commutation module
- Number of commutation blocks required depends on DC voltage
- Number of IG' Ts in parallel
 - High let-through current
 - Thermal reason
 - Lowest possible losses
 - Simplification of cooling
- Natural convection air cooling only
 - No forced cooling, No phase change media, Nothing to leak



The GE hybrid DC breaker

Power electronics switch 2 (auxiliary branch)

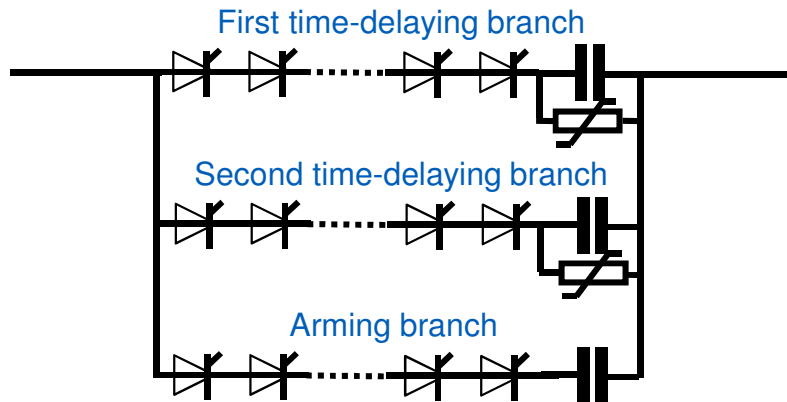
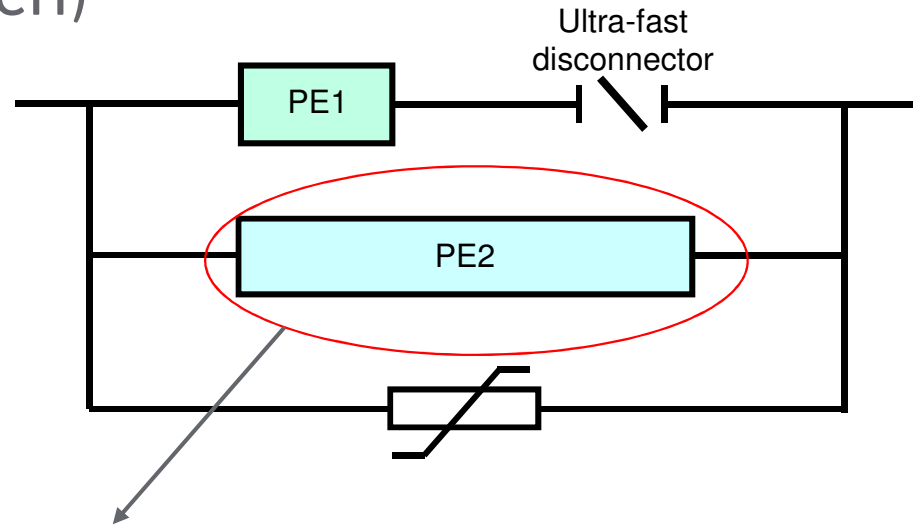


- Well-known solution: multiple IGTs in series (and inverse-series)
- GE considered this, but ultimately chose a different solution for the demonstrator



The GE hybrid DC breaker

Power electronics switch 2 (auxiliary branch)



- Novel solution based on thyristors
- Very robust and capable of very high currents
- Number of time-delaying branches can be modified based on fault level and operating voltage



The GE DC breaker demonstrator



Part of EU FP7 “Twenties” project

- Built and tested at GE’s switchgear research facility in Villeurbanne, France
- Key ratings:
 - Rated voltage: 120 kV
 - Rated direct current: 1500 A
 - Overload current in closed state > 3000 A for 1 minute
- Test programme agreed with and witnessed by RTE
 - Dielectric tests between the terminals of an (open) breaker
 - Continuous and short-time current through a (closed) breaker (5kA (half sine) 10s ; 10kA (half sine) 1.6ms)
 - Interruption tests



**Low impedance branch
for permanent current
conduction**

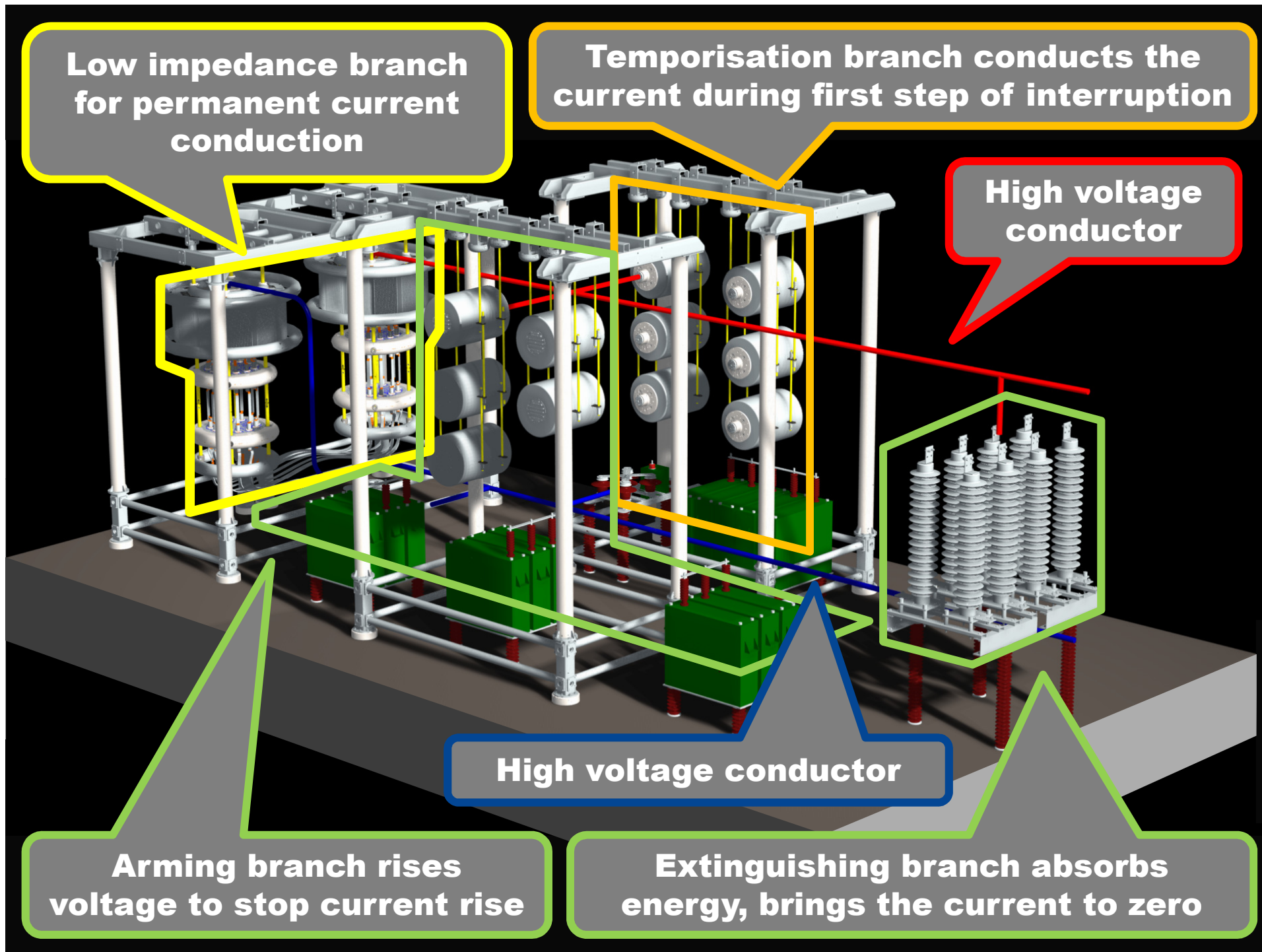
**Temporisation branch conducts the
current during first step of interruption**

**High voltage
conductor**

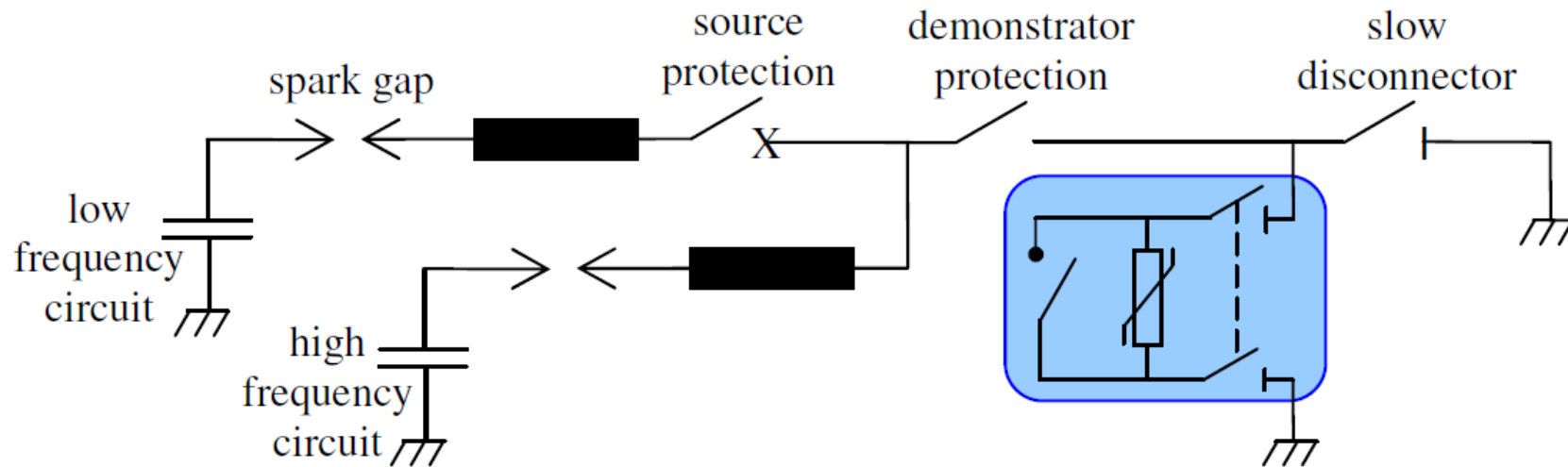
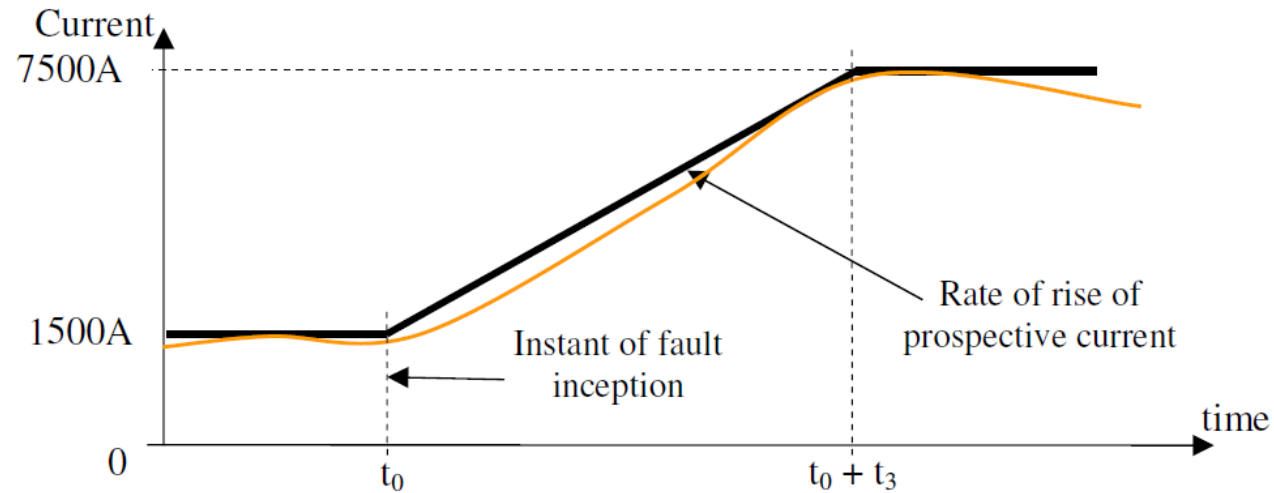
High voltage conductor

**Arming branch rises
voltage to stop current rise**

**Extinguishing branch absorbs
energy, brings the current to zero**

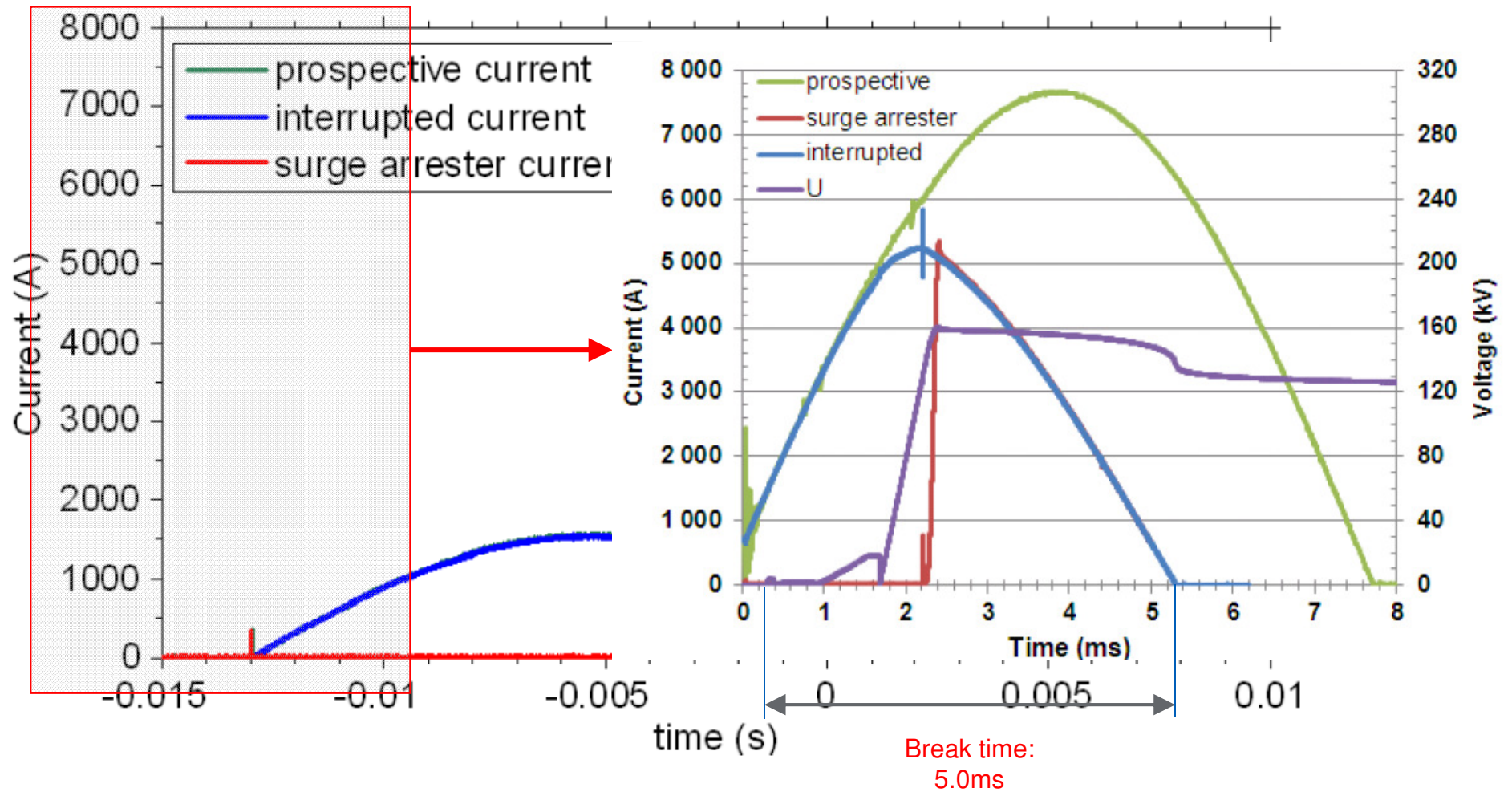


Interruption tests: acceptance criteria and test circuit

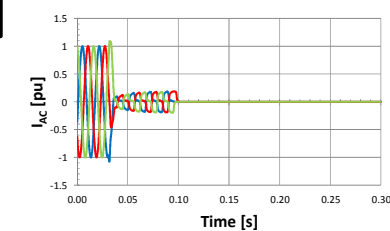
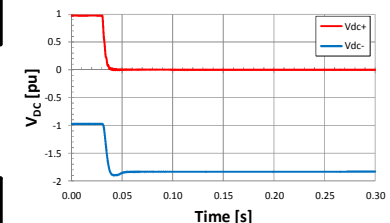
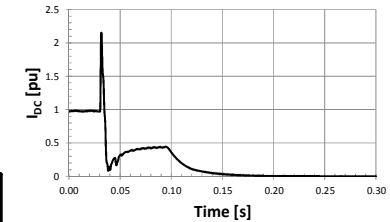
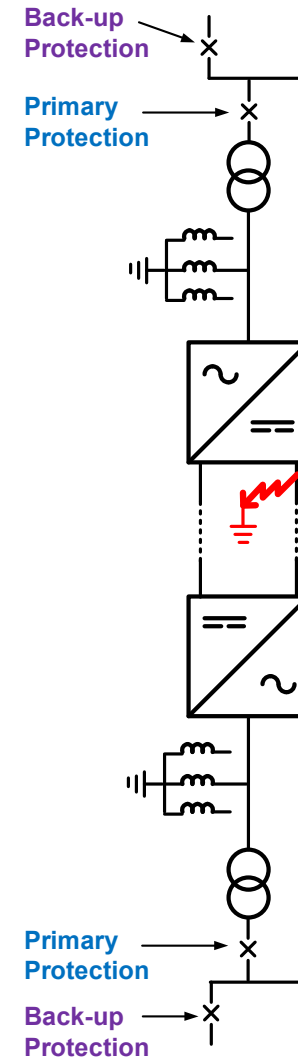
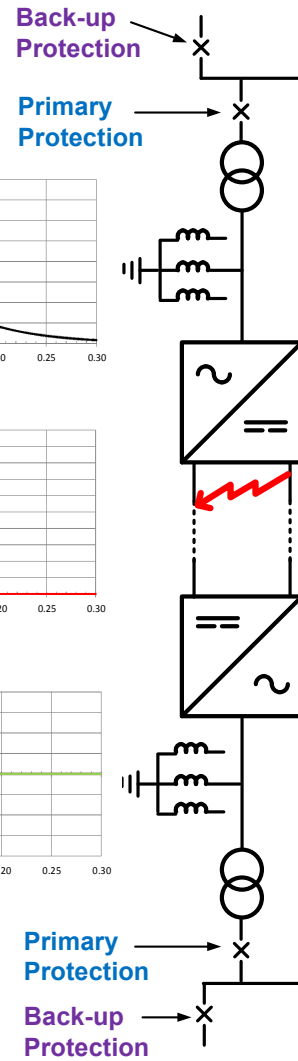
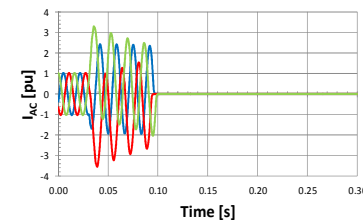
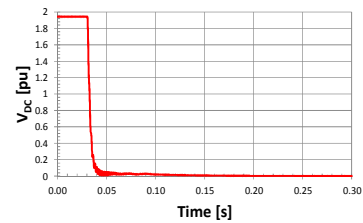
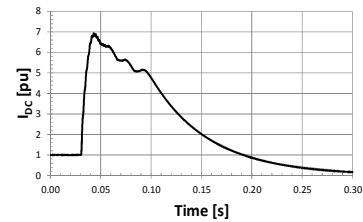
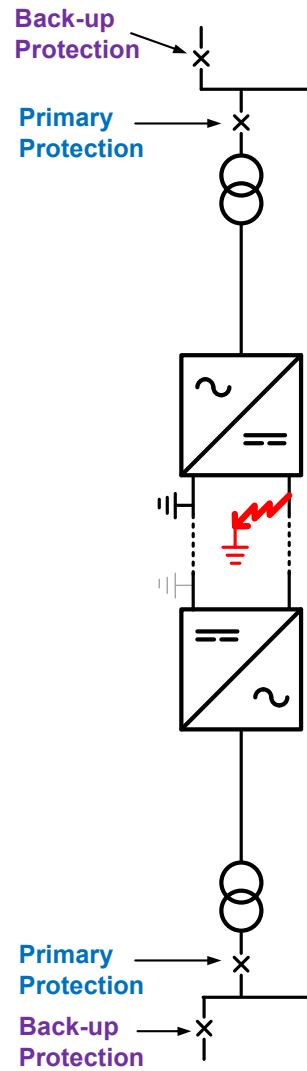


Interruption test results

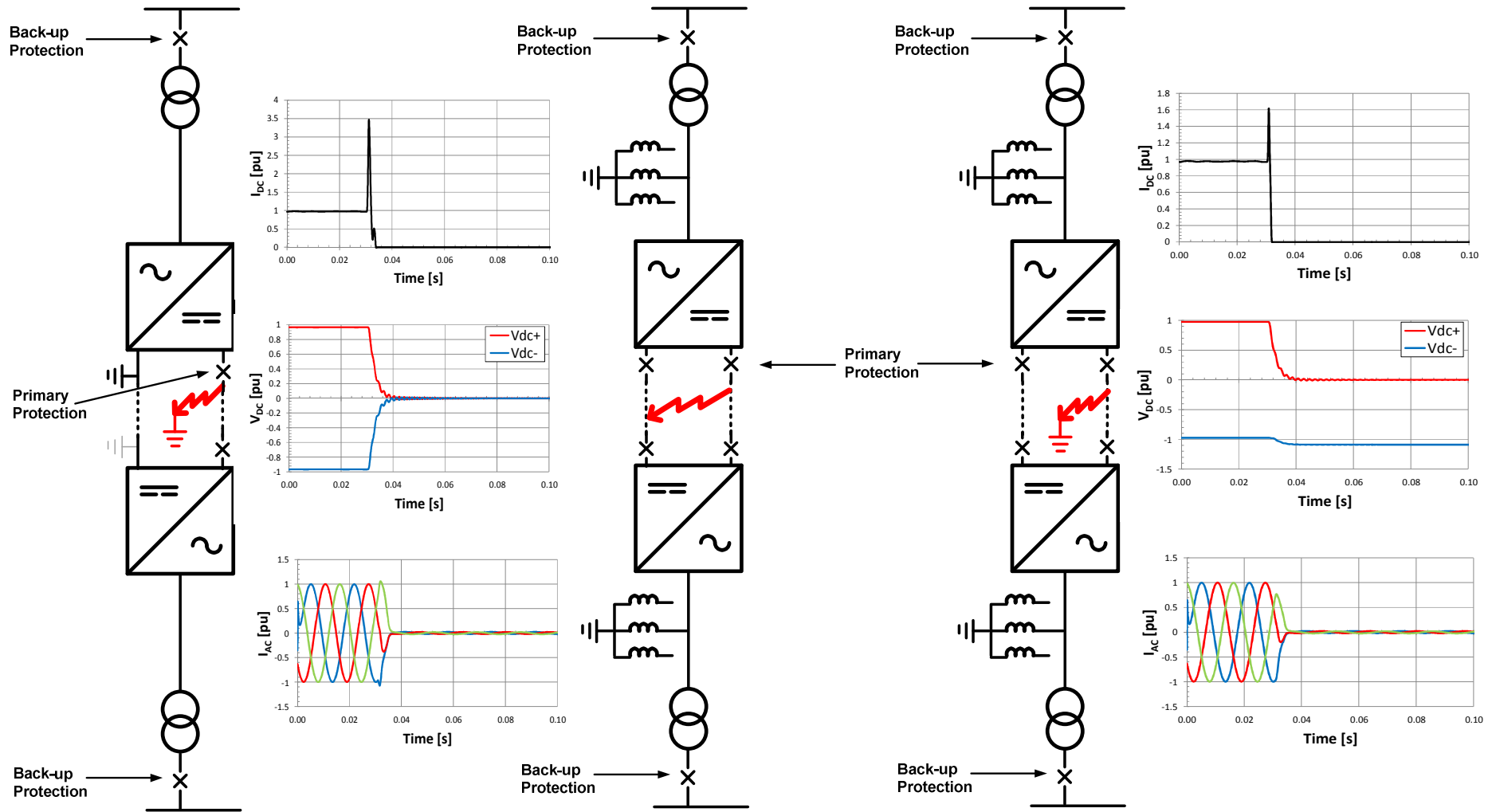
Prospective fault current of 7.6kA and $di/dt=2.9A/\mu s$



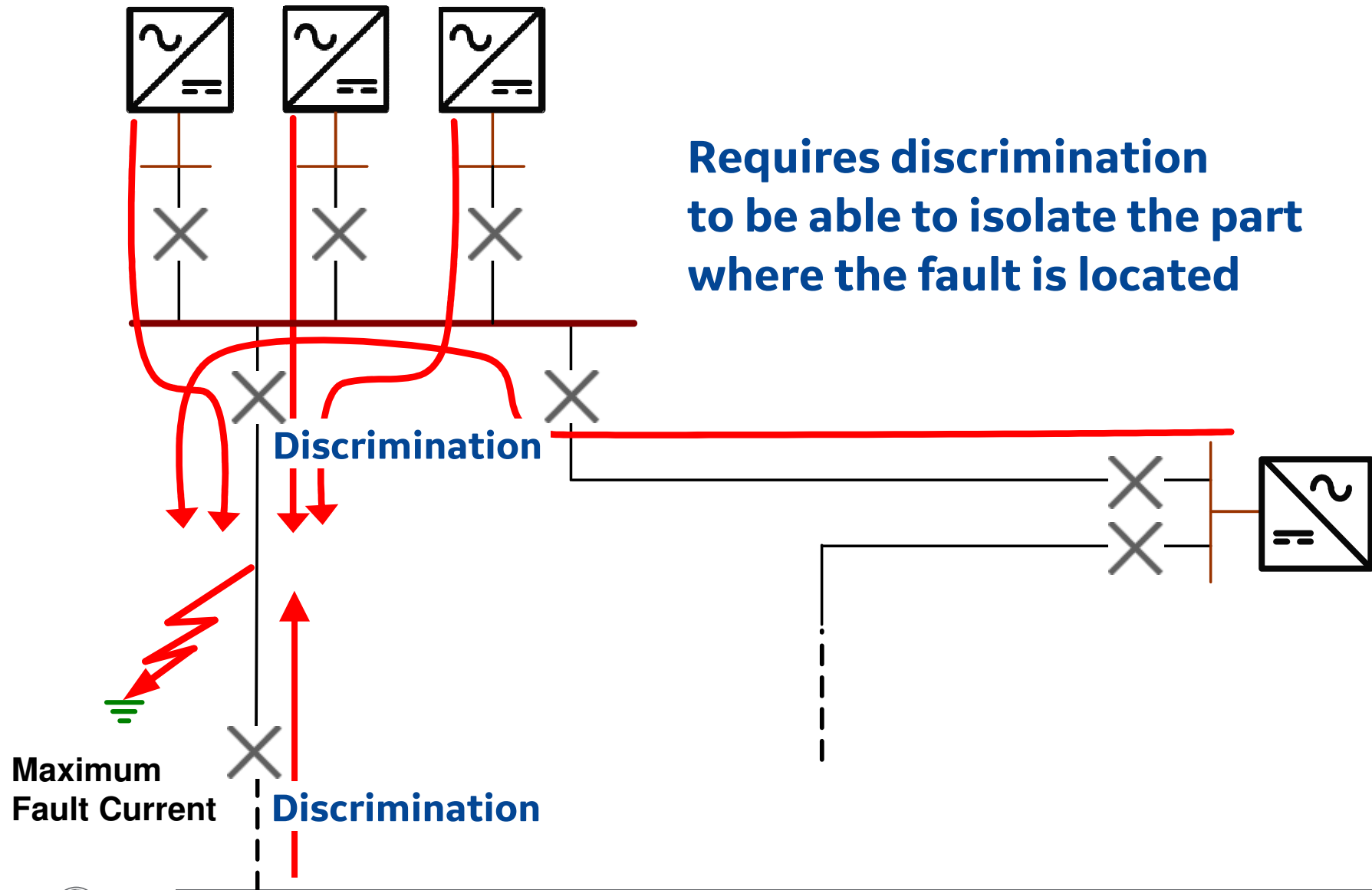
AC ' reaker Fault Clearance



DC Breaker Fault Clearance



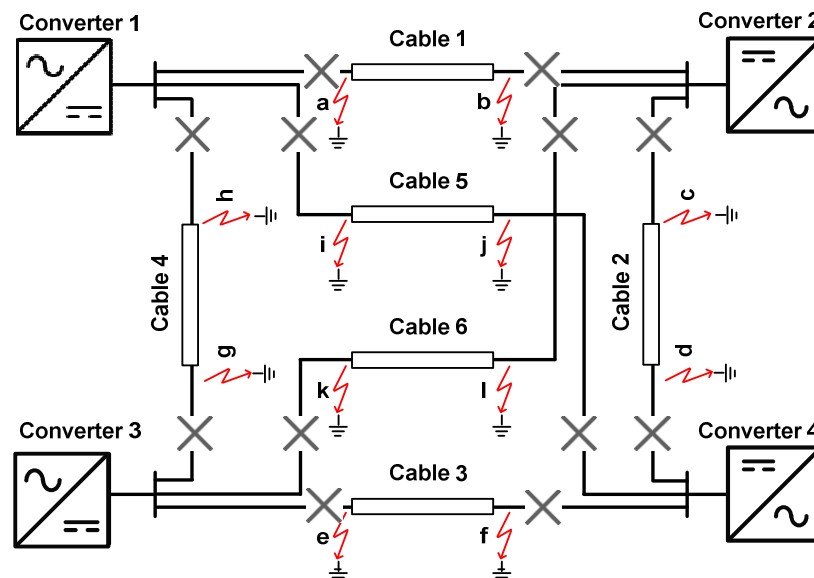
Network Protection Requirements in HVDC



Conventional Method of Discrimination: *Differential protection for HVDC VSC networks*

- **Results:**

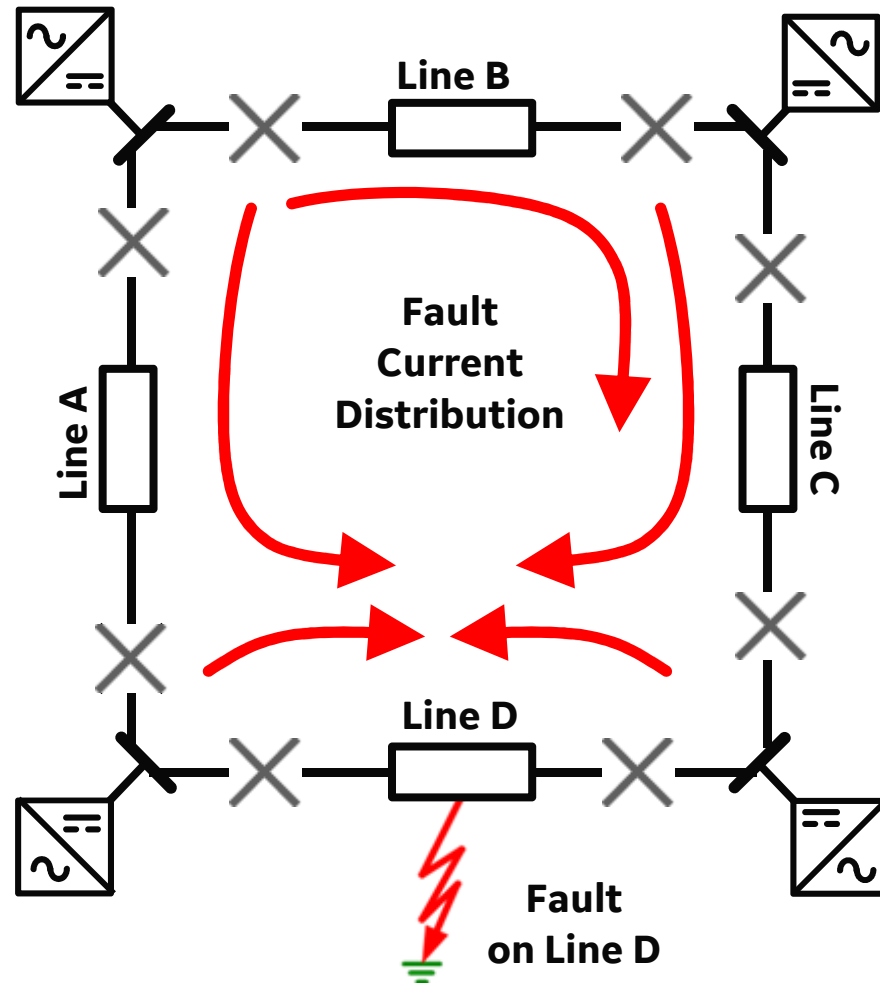
- Faulty branch identified in every case
- N' false resp' nses
- Identical pr' tecti' n setting f' r every line



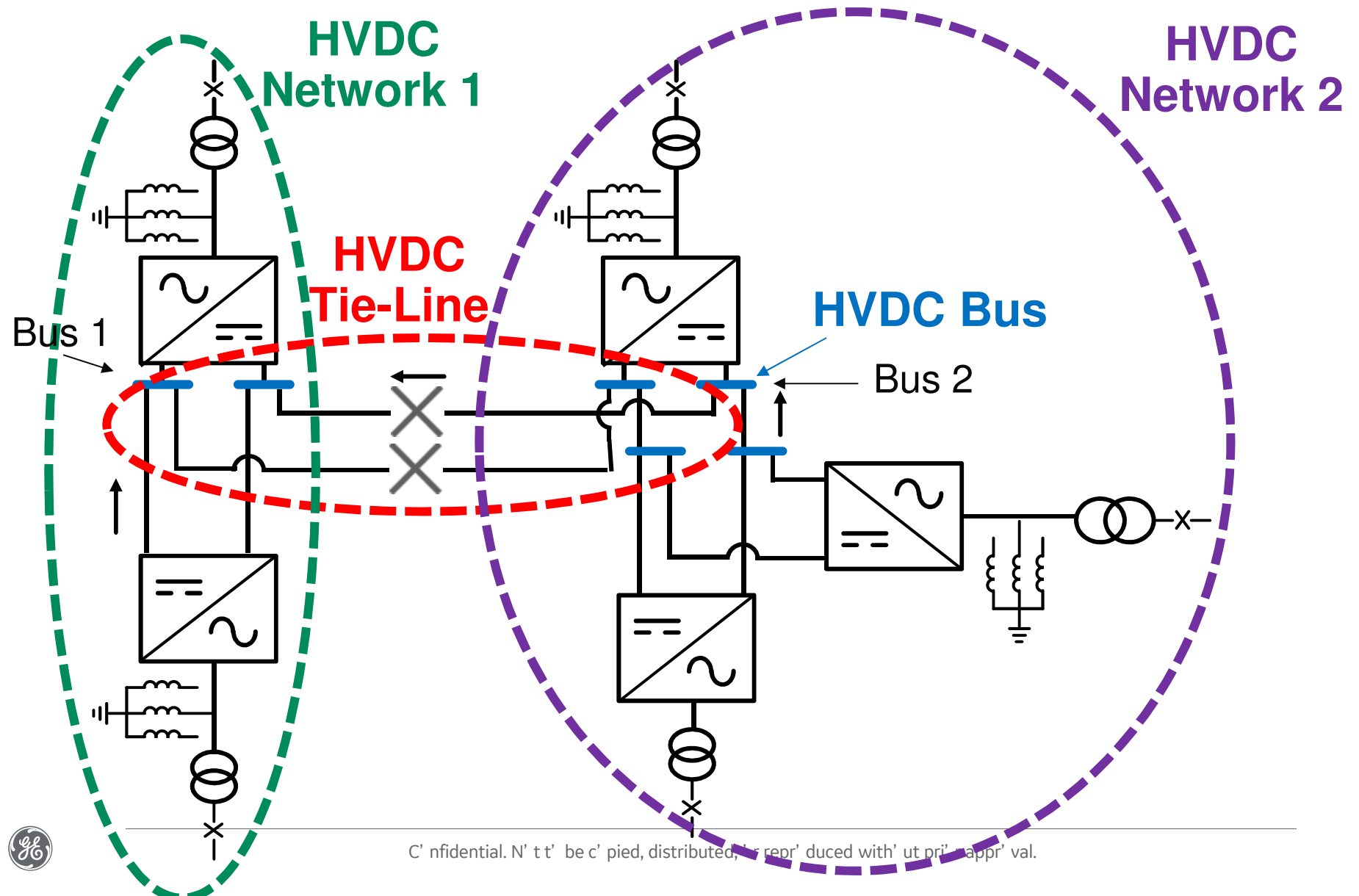
Alternative Method of Discrimination: *DC Protection 'Open Grid'*

Alternative Protection Strategies:

1. Fault appears on network
2. Current flows towards the fault
3. Local order given to circuit breakers
4. Circuit breakers to close if connected line is "healthy"



Network Connections: *Segmentation of DC networks – “Tie-Lines”*



Conclusions

- **Speed** is everything
- Adding extra inductance is not necessarily helpful
- Successful demonstration built and tested as part of “Twenties” project – whole system verified
- Interruption of 7.6kA prospective with total interruption time 5.0ms (including clearing time)
- Triggering protection mechanism has a significant impact on HVDC breaker design



