FACTS User Group Meeting

Software-in-the-Loop Simulation

SIL - a must for today's MMC grid forming converters

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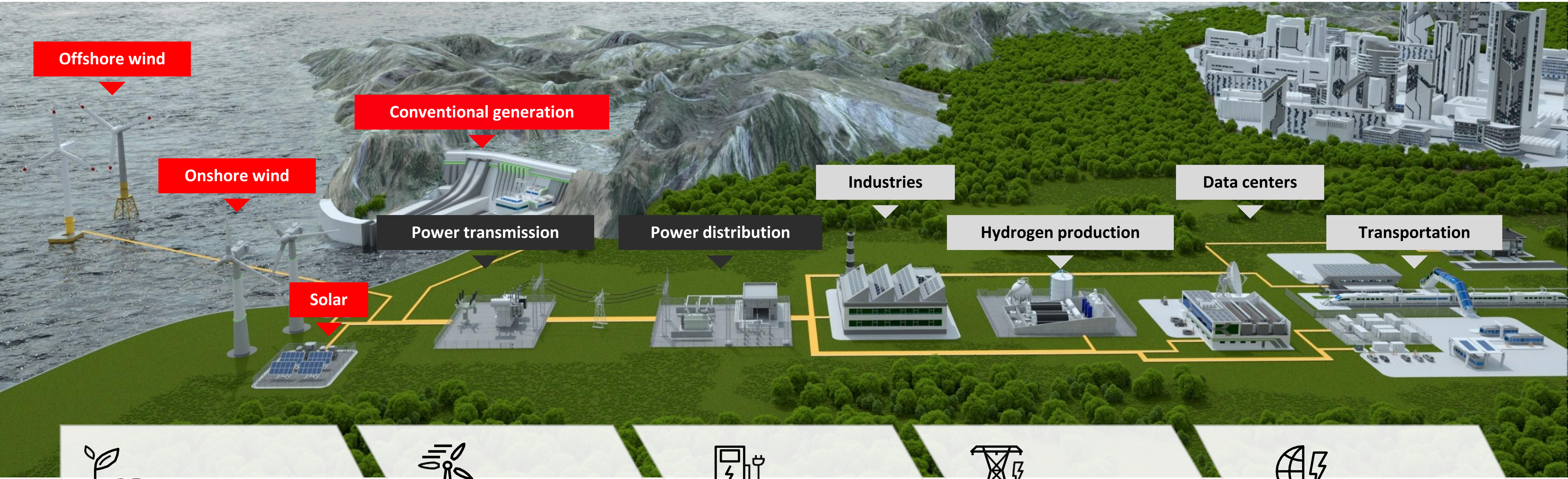
Supporting a changing power system

Power generation
Power transmission and distribution
Energy intensive industries



Transform through low-carbon technologies and digital solutions

Accelerate the shift to renewable power generation

Decarbonize through electrification

Expand and strengthen the transmission and distribution grid

Enable sustainable energy fuels

Grid Forming STATCOM global installed base since inception

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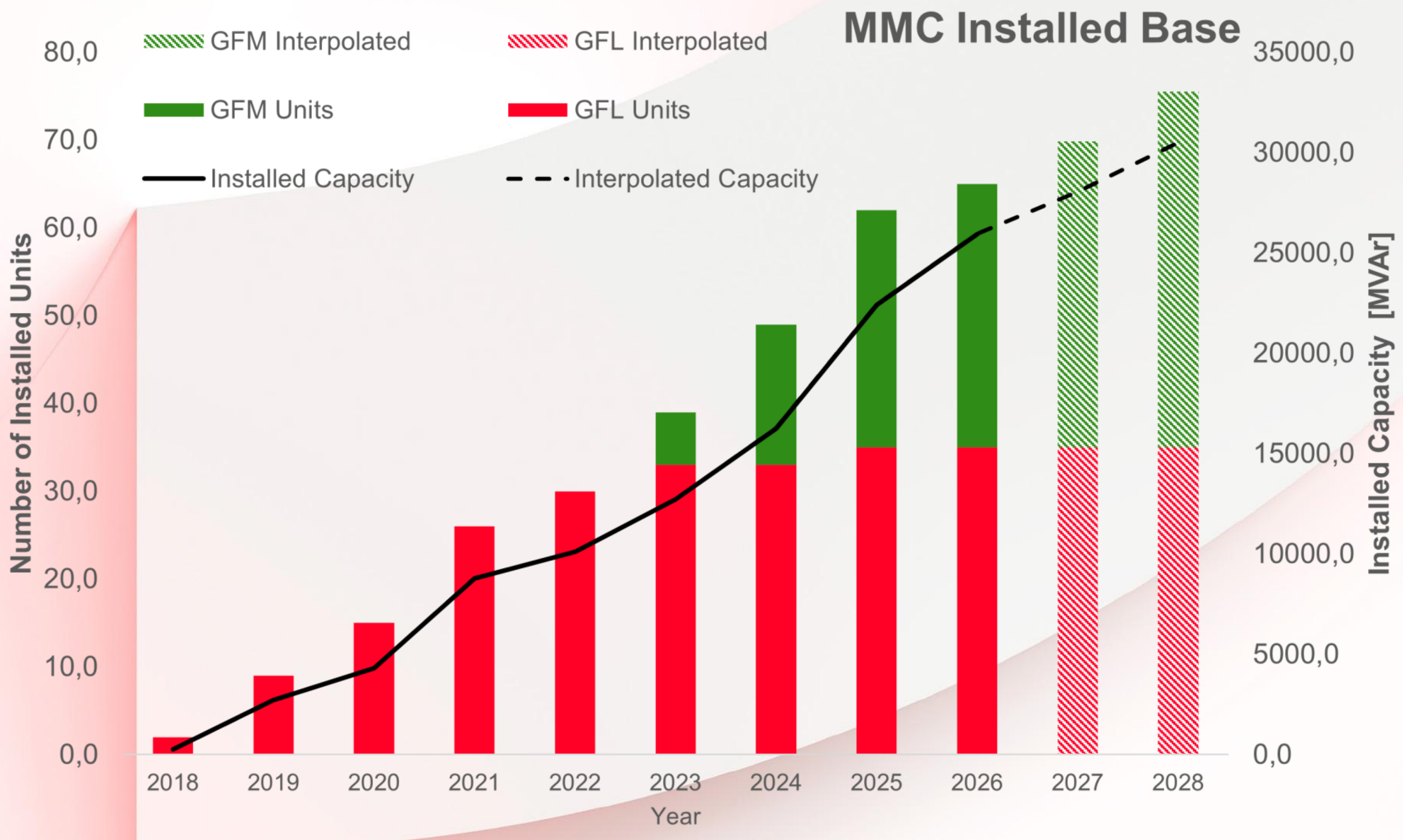
Industry references in offshore wind, transmission, and steel-making



> 30 GFM STATCOM Installation Globally; 5 GFM STATCOM Installations in the US

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Overview of Control Hardware and Software

- PSCAD, Software-in-the-Loop testing

- Models for STATCOM with Grid Forming technology are not available in Simulation Tools due to fast development in technology
- Simulation models based on Software-in the-Loop testing and actual control code must be used to determine sizing and location.
- Models supplied to customers of black box type to protect IP sensitive Source Code.
- Models to be benchmarked against Hardware-in-the-Loop testing and validated in field.
- Trade Association guidelines are under devolvement (IEEE, CIGRE and IEC)

- RTDS, Hardware-in-the-Loop testing

- Models available for properly testing of the capacitor voltage balancing control.
- Models available for use as “Digital Replica”, i.e. protection of IP sensitive Source Code.

- Asymmetrical faults

- Asymmetrical faults is a challenge for MMC STATCOM technology due to balancing of DC capacitors
- Important to use detailed representation of converter, and STATCOM control and protection system
- Individual DC capacitor voltages required to test DC unbalance control and limitations for valve currents, i.e. model is not based on ideal DC capacitor voltage balancing control
- Several models available in PSCAD and RTDS without detailed representation of converter cells

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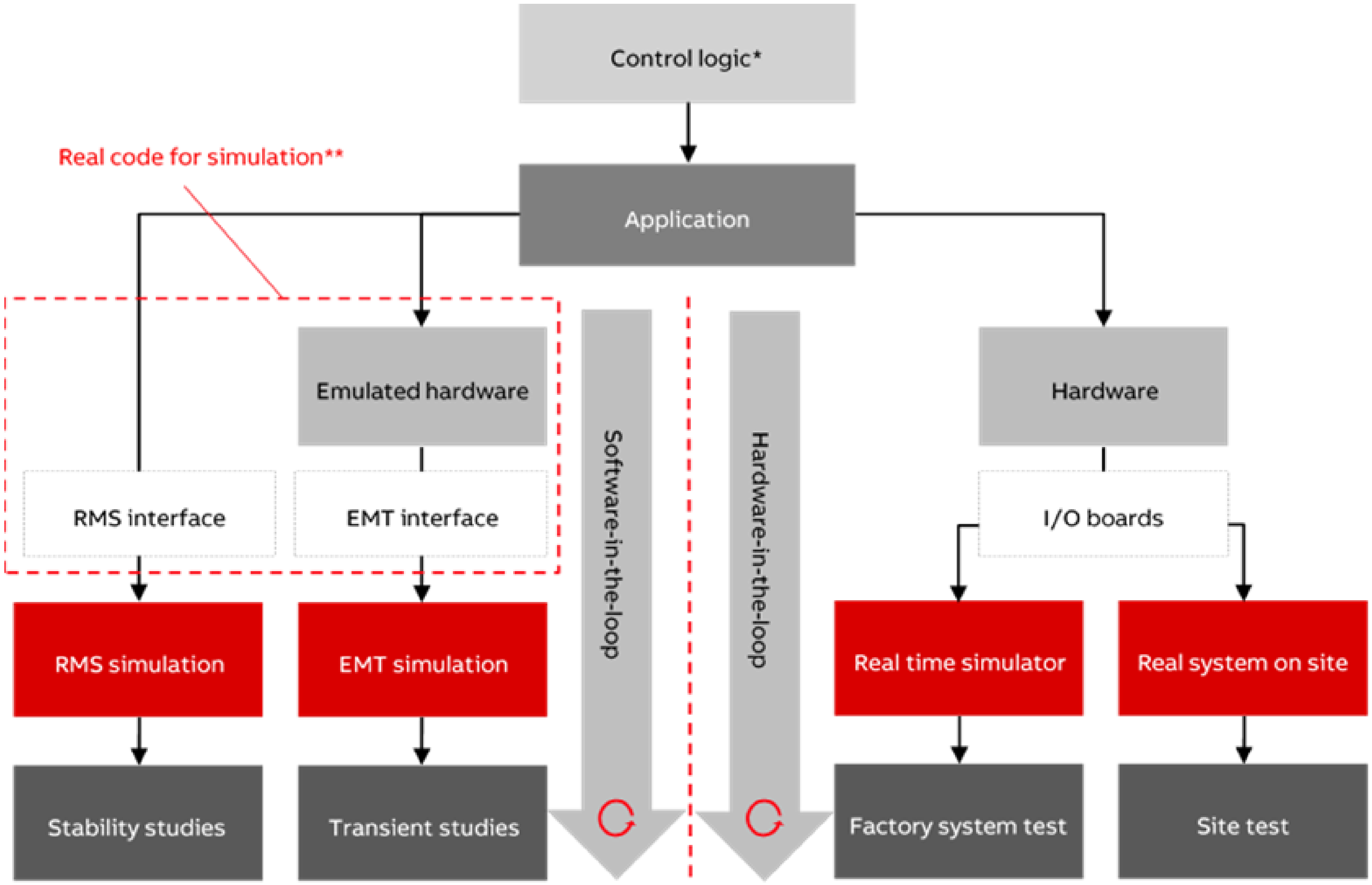
Overview of Control Hardware and Software



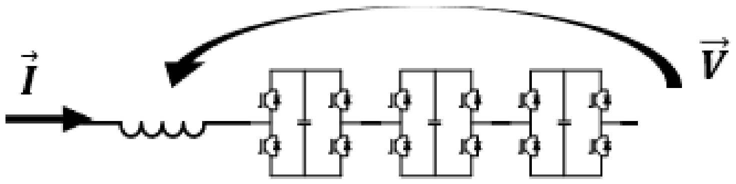
Internal

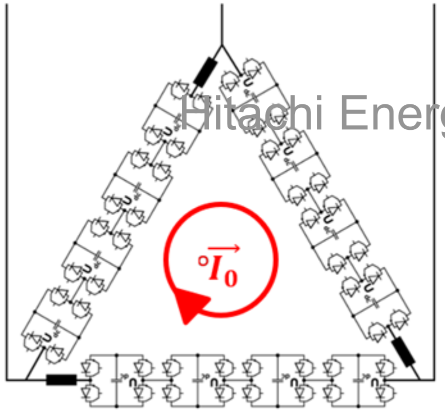
Asymmetrical faults

- MMC converters do not have a common energy for the three phases
- Therefore, they behave similarly to three single phase converters connected to the grid.
- The active power in each converter arm must be always zero or the cell capacitor voltage would diverge.

– Singularity for all Δ connected VSC when U+ = U- at the valve – phase-phase faults and phase-phase-ground faults

– Individual DC capacitor voltages required to test DC unbalance control and limitations for valve currents, i.e. model is not based on ideal DC capacitor voltage balancing control

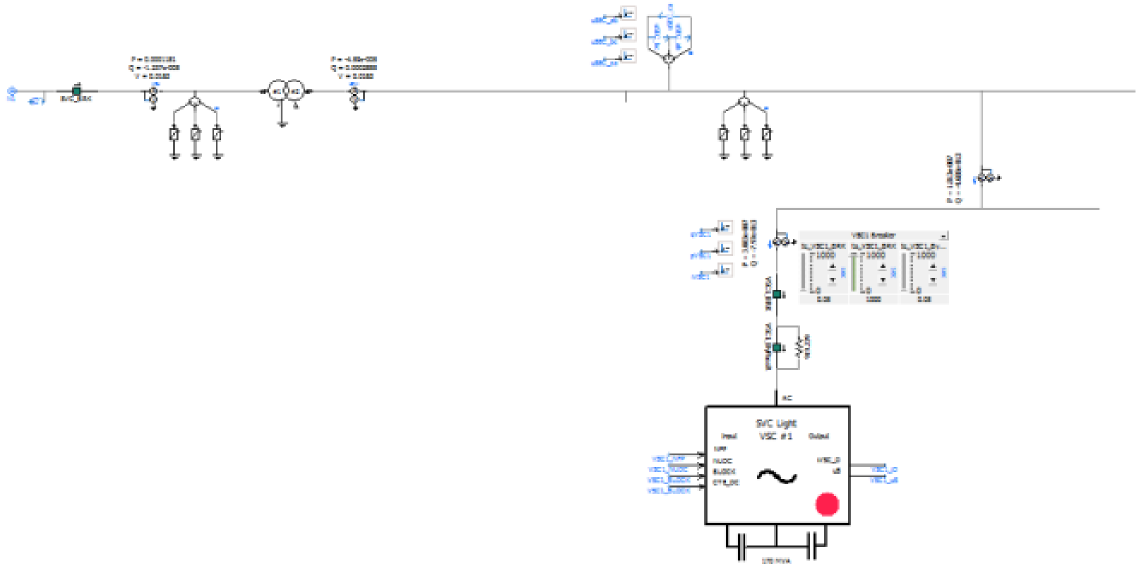


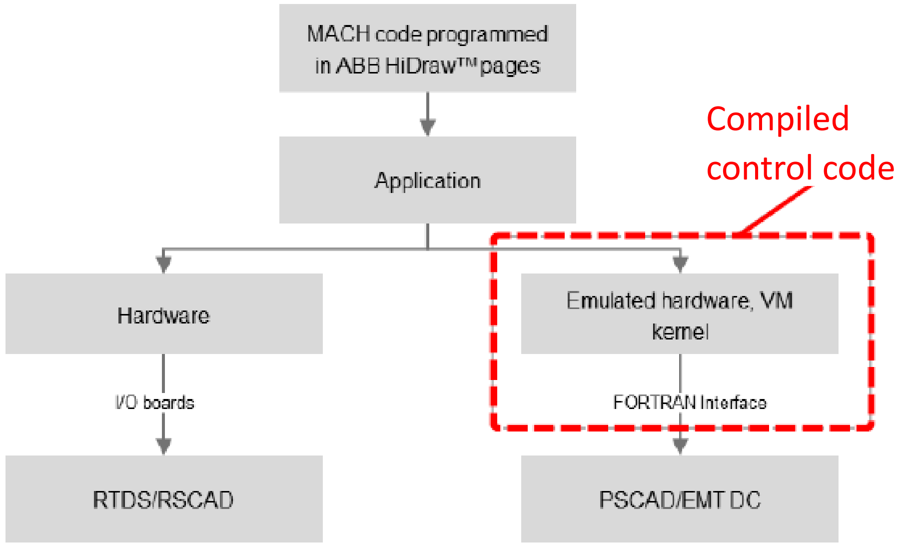


$$\vec{P} = \vec{V_1} \cdot \vec{I_1}^* + \vec{V_2} \cdot \vec{I_2}^* + \vec{V_1} \cdot \vec{I_2}^* + \vec{V_2} \cdot \vec{I_1}^* + \vec{V_1} \cdot \vec{I_0}^* + \vec{V_2} \cdot \vec{I_0}^*$$

Software-in-the-Loop concept

- MACH™ is the control hardware used for STATCOMs. In order to accurately model the controller in PSCAD, the compiled MACH code is connected to PSCAD via a FORTRAN interface thus using the actual MACH™ control hardware in a software model[1].
- Software model includes current and voltage protection functions.
- Voltage-source converter (MMC Switched model with DC capacitor)





Source: [1] E. Veilleux, M. Halonen, S. Hutchinson, “Dynamic modeling of STATCOMs and Hybrid STATCOMs for transmission applications”, CIGRÉ Canada, Vancouver, 2016

SIL Benefits all phases of a project

Effective Engineering During and After Project

Precise representation of the C&P system in all project phases and different test environments provides a performance guarantee chain from simulation to commissioning on site.

- Transient and dynamic performance studies (DPS) are conducted using EMT simulation tools to demonstrate that the control system parameters are enabling good performance in the total system according to specified criteria, for example, returning to normal operation as fast as possible after a fault and providing safe, and stable operation within specified conditions.

- SIL enables engineers to design, test and verify C&P logic and algorithms in an offline simulation environment. Thus, functionality and performance have already been tested and verified before reaching the factory system test stage, which allows engineers to switch focus from design to verification of the integration with real hardware works as intended.

- SIL makes investigating the effect on designing parameters during commissioning, and becomes even more relevant after commissioning in terms of providing after-sale support and pre-studies for future upgrades.

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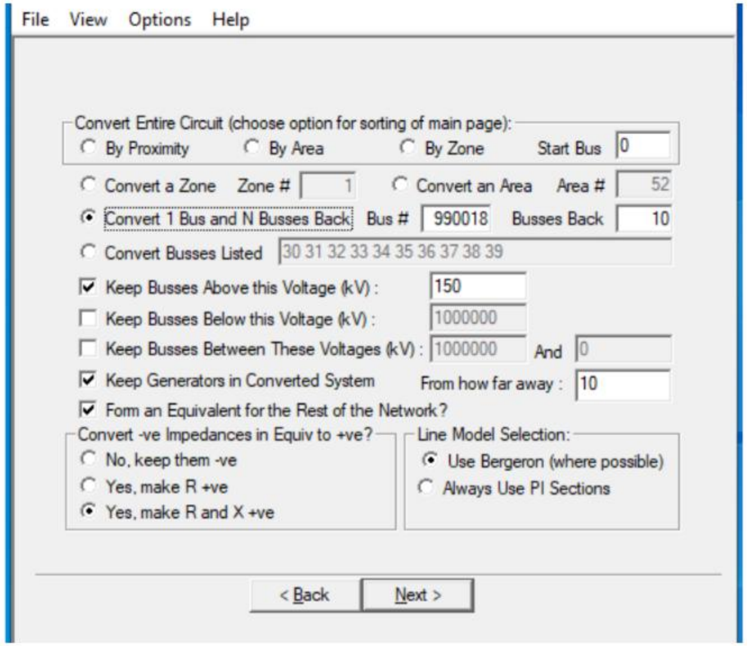
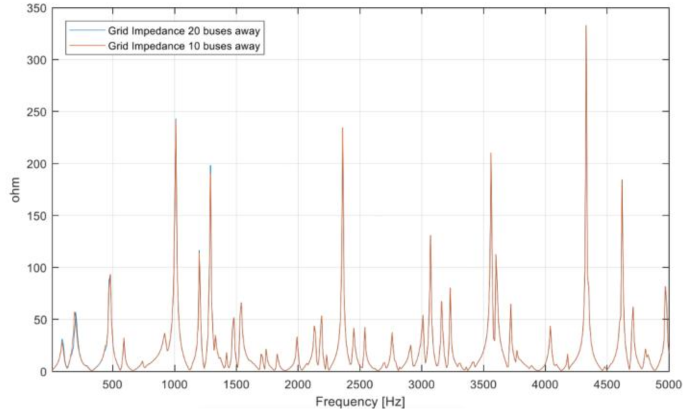
Detailed models in PSCAD but the request is for PSS\E or PSLF models (with larger networks)

- Users are requesting system studies to be performed with large power system models, i.e. several thousands buses in PSSE or other software
- Time consuming to perform network reduction
- Challenges with Users defined model and IP sensitive source code
- Need of testing approach to evaluate performance for selective test cases with hybrid models.



PSSE Summary

PSSE Busses:	14842
PSSE Generators:	1533
PSSE Loads:	9675
PSSE Branches:	22293
PSSE Transmission Lines:	9682
PSSE Transformers:	12573
PSSE DC Terminals:	2
PSSE Switched Shunt Branches:	2312
PSSE Fixed Shunt Branches:	1297



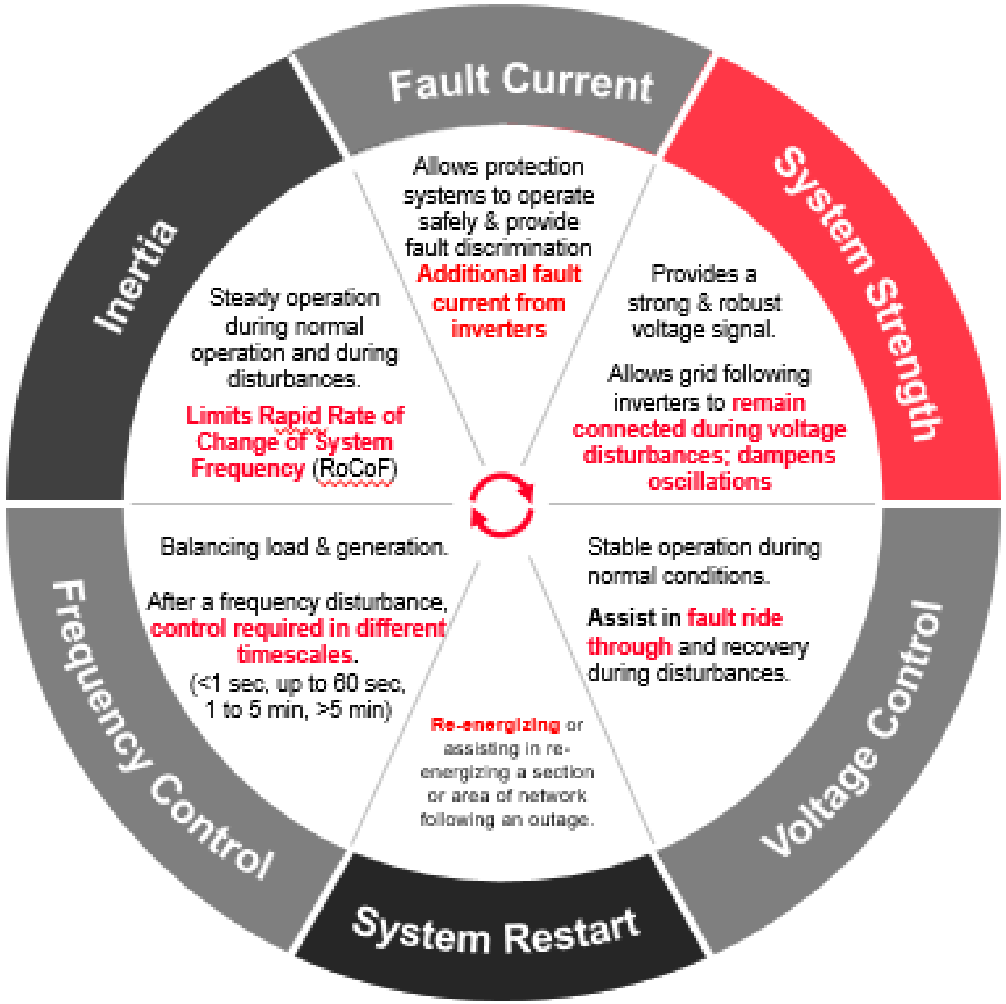
Trend for larger networks and need of Software-in-the-Loop testing for Grid Forming technology

Internal

Grid Forming Control Introduces more reasons to use Software-in-the-Loop

More services provided by GFM

Services to operate a stabel and secure grid



Characteristic	Traditional SG Dominant	Low Renewable Penetration	High Renewable Penetration
Inertia	High	Medium	Low
SCR	High	High	Low
Protection	Traditional	Traditional	Adaptive
Frequency Stiffness	High	High	Low
Voltage Stiffness	High	High	Low

More services provided by GFM

Voltage Control

– Fast Dynamic reactive support

Fault Current

– Fault current needed

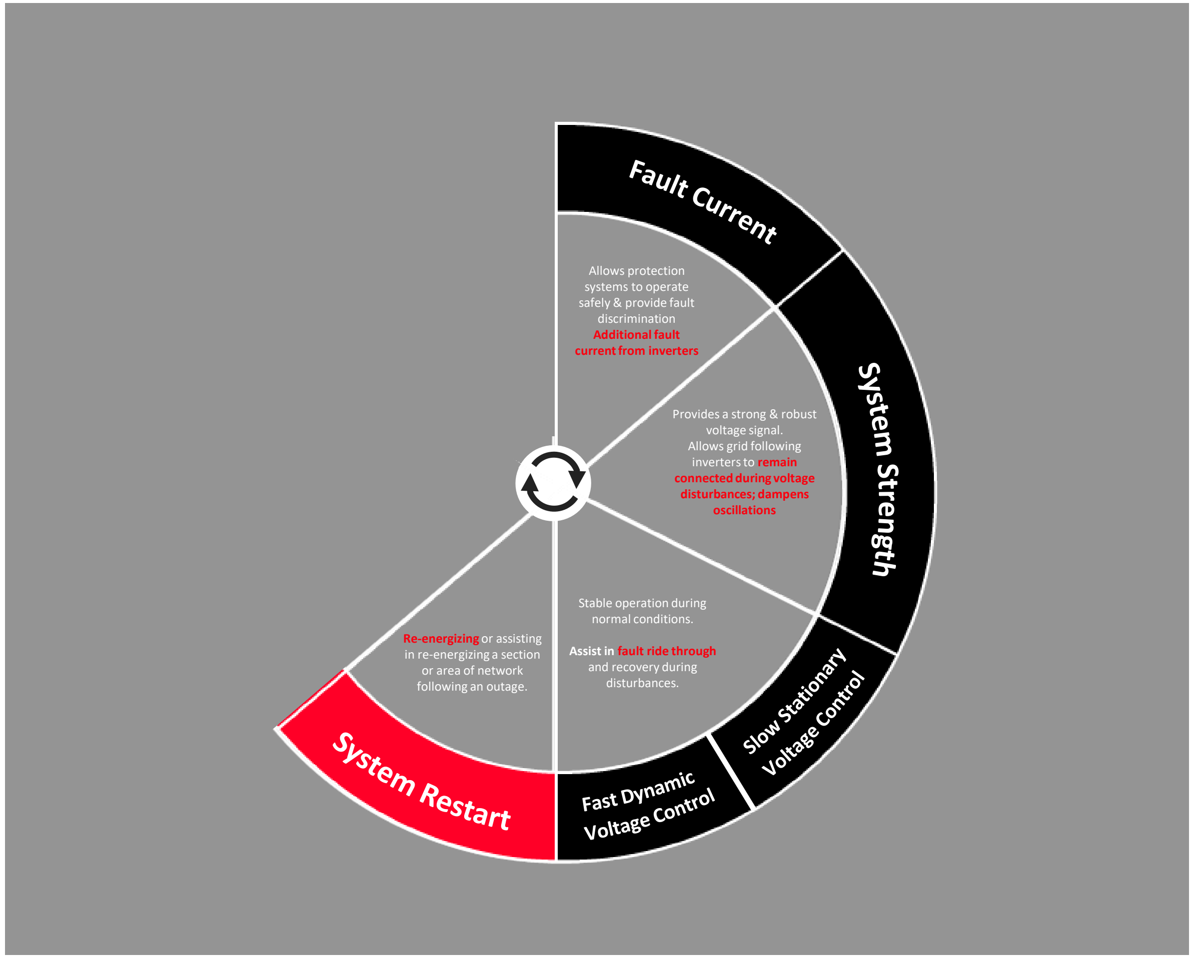
– Too much fault current

System Restart (Black-start)

Weak Grid system strength

Damping at High order frequencies

Damping at Sub-synchronous frequencies



Grid Forming – Impact on Grid Code

- **The term "Grid Forming" does not yet have a universally accepted definition**
- All requirements share one common objective:
  instantaneously react to any change on the grid system and contributing to maintain its stability.
- Behaving as a voltage source behind an impedance is generally considered a way to achieve the objective.

GC0137 Final Modification Report
National Grid, UK

"*The converter behaves as voltage source behind an impedance in the same way as a synchronous generator. This has two substantial benefits – it i) enables the **converter to instantaneously react to any change on the Grid system** without any independent control action and ii) power electronic converters with this capability all operate in synchronism with each other in the same way as synchronous generation **enabling wider system support during system disturbances***".

Connection of HVDC systems to the public network
VDE AR-N 4131, Germany

*"In response to a temporary voltage change at the connection point, the HVDC system shall modify the exchanged power without delay. **The objective** of providing this instantaneous reserve **is the immediate counteracting to changes** in the phasing of the fundamental component of a positive-sequence system **thereby contributing to the limitation of the maximum rate of change of frequency**."*

*"**The objective** of dynamic voltage control without any reactive current specification **is to counteract a short-term change** of the fundamental component amplitude of positive-sequence and negative-sequence systems **thereby contributing to the limitation of the voltage change**."*

Standard for Interconnection and Interoperability of (IBR)
IEEE P2800, US

"An." IBR with grid forming control should not be directly compared with a synchronous generator. The goal is not to attempt to precisely "emulate" the behavior of synchronous machines, although there are elements of this behavior which are desirable, in alignment with existing operation mode of the system
*The objective of grid forming IBRs should not be simply to reproduce the behavior of synchronous machines. Instead, **the focus should be on understanding the needs of the evolving power grid and utilizing the IBRs in the most effective way.***

GCC Grid Codes

In GCC, the grid code design criterion presently used, states that the grid shall recover from any single line to ground fault without load shedding. A vast amount of reactive power is required for induction motors to recover especially during summer peak load with up to 80% low inertia air conditioning motor loads.
Todays' Grid Codes in GCC are not stating requirements for GFM functionality. However, considering the fast-growing networks in GCC with large integration of renewables and the large variation of short circuit conditions (weak and strong) it will be a must to install converters with GFM in the future to secure system stability of power systems. GFM will also prevent unbalance seen after system faults since Grid Forming will inherently react to negative sequence in the grid and mitigate unbalances.

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Grid Forming – Impact on Technical Specification, Requirements

01

- **Normal Operation**
- Response to Steps in System Voltage Magnitude and Phase Angle
- Response to Step in Short Circuit Level
- Voltage Balancing
- Damping of DC Current Component

02

Constrained Operation

- Response to Steps in System Voltage Magnitude and Phase Angle
- STATCOM Fault Ride-Through Operation: Symmetrical and Asymmetrical faults

03

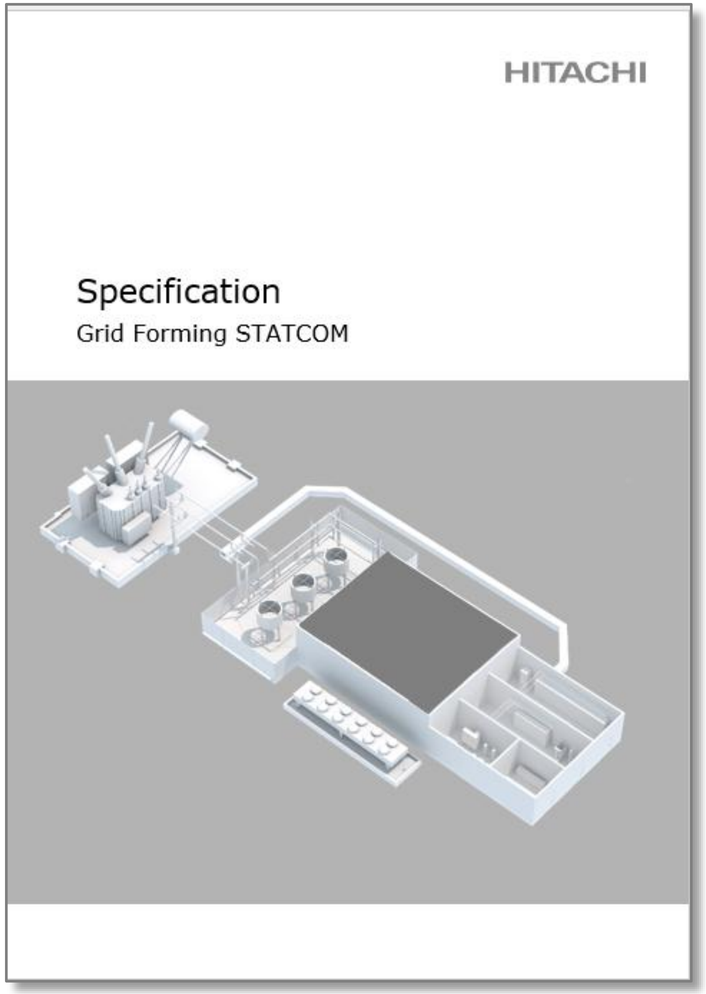
Simulation Models and Documentation

- Software-in-the Loop (SIL) testing connected to an EMT, the actual control code used in the real system, and the real hardware is emulated.
- Detailed modeling of converter cells with all DC-capacitors

04

Information to be Provided in the Bid

- SIL testing validating Normal and Constrained operation:
  - Voltage magnitude and phase angle step verification
  - Short circuit level step verification
  - STATCOM Fault Ride-Through Operation



Example

Software-in-the-Loop concept and a STATCOM trip at energization

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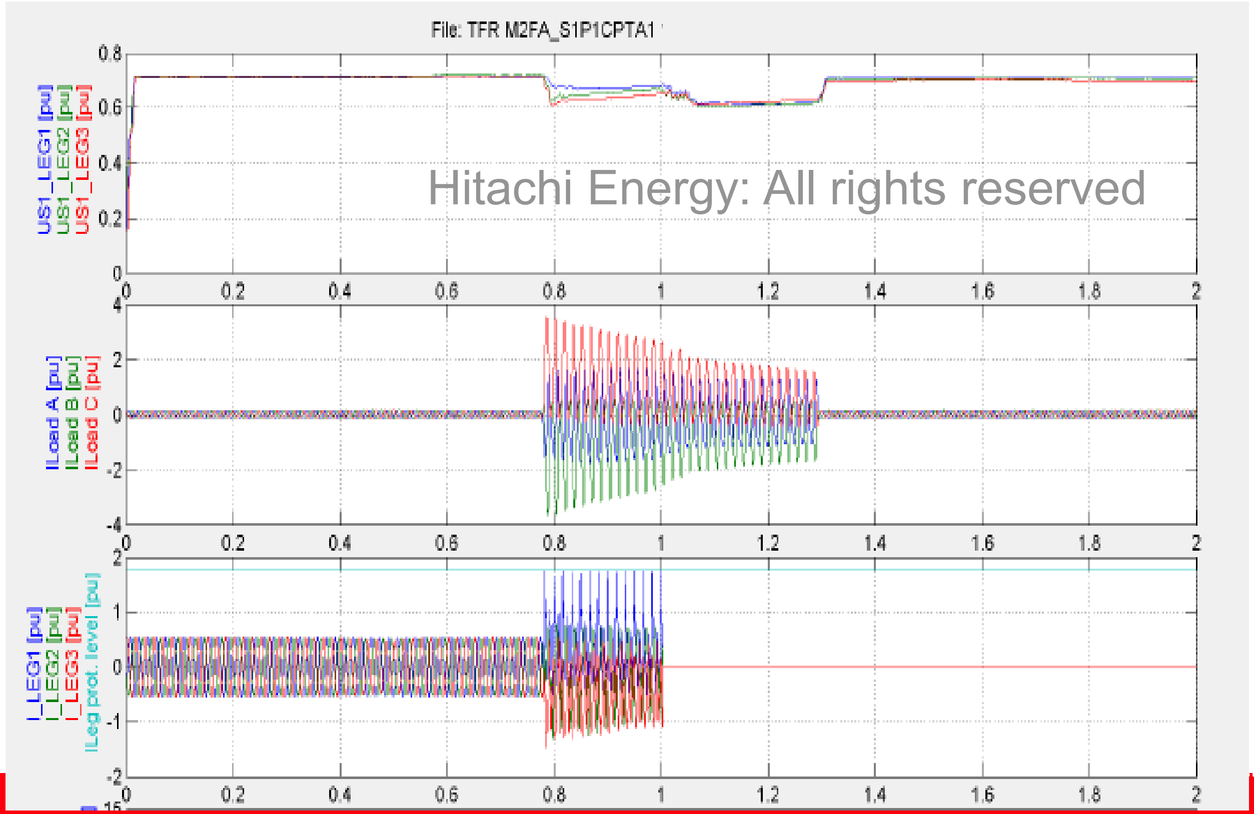
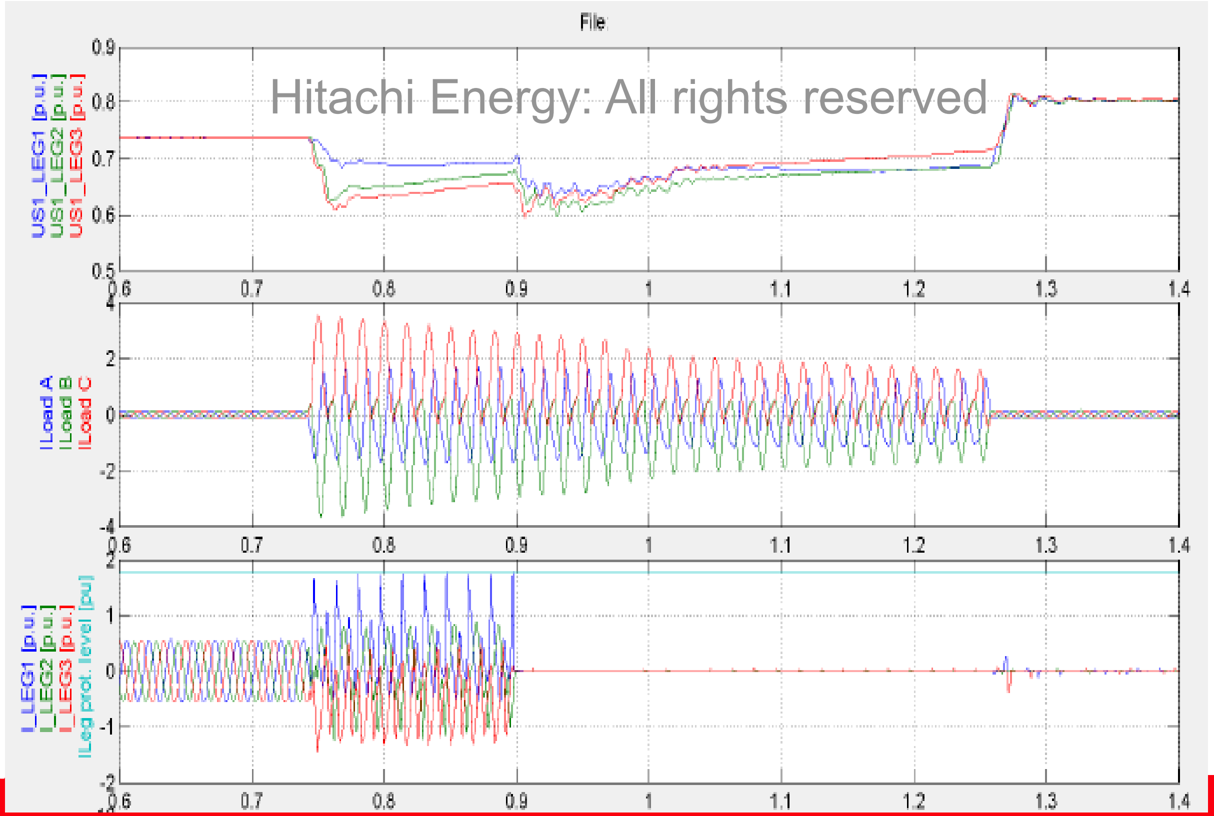
Actual recordings of contingency



Re-run the sequence with SIL in PSCAD



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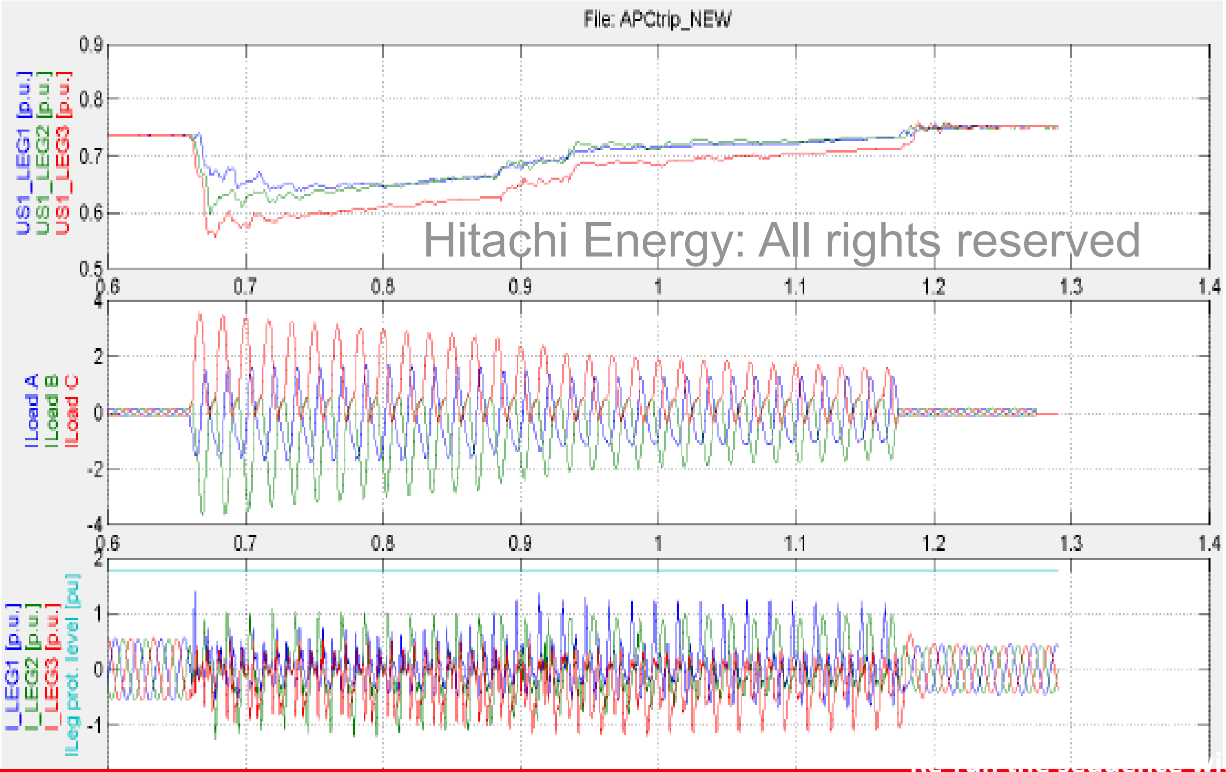
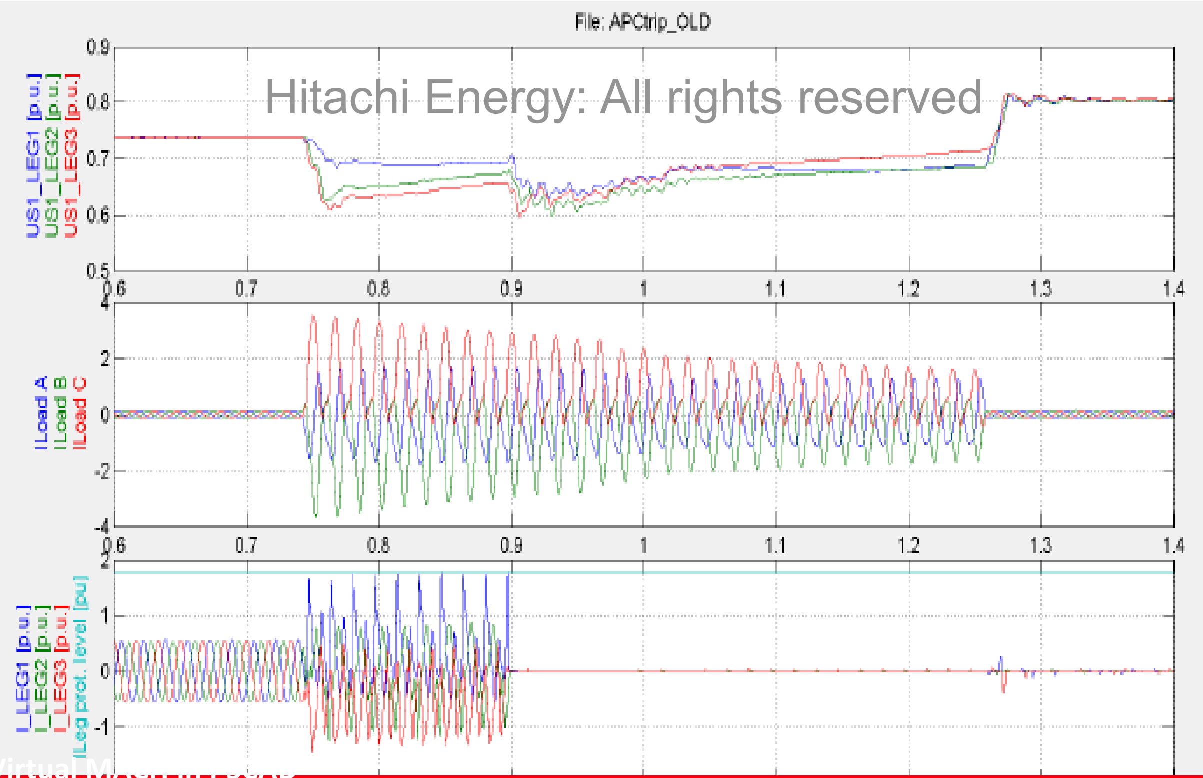
Software-in-the-Loop concept and a STATCOM trip at energization

Contingency run with <u>new</u> settings and control code



Contingency with old settings and control code



Internal

Simulation Models - Online vs. Offline Simulations

Offline Simulations - Pros & Cons

	Offline
+	**Real-time simulations with Hardware In Loop/HIL**
-	**Simulations are fast (i.e. real-time)**
+	**Perform variety of EMT cases that may be difficult to perform on site**
-	**Lack of flexibility to model non-linear, sophisticated power system elements**
-	**Inability to include black-boxed models of nearby devices, forcing the need to use simplified models of complex devices**
-	Potential for numerical instability due to real-time restrictions
-	Consider a limited number of power system nodes and elements due to hardware limitation and complexity
-	Minimum time step is determined by number of calculations, not by study needs
-	**No snapshot function, Approximate switching representation (on time step only), tests can not be automated**

Online Simulations - Pros & Cons

	Online
-	**Non-real-time simulation with model of controller (Software In Loop/SIL)**
-	**Simulations can take a long time to complete**
+	**Perform variety of EMT cases that may be difficult to perform on site**
+	**Flexible for non-linear power system modeling**
+	Customer models which are black-boxed can be easily included in simulations for testing of many complex models in the same platform
+	Less sensitive to numerical instability due to non-real-time simulations
+	**Practically no hardware limitations (aside from inherent computer power limitations)**
+	**Lower time steps are possible**
+	**Snapshot, test automation, exact switching representation (interpolation)**

Source: IEEE GM 2021, panel session “Emerging Trends in Modelling and Control of HVDC and FACTS (Part II)”, “Using Real Code in Modeling HVDC and FACTS Devices in EMT and RMS Simulation Platforms”; Soubhik Auddy, Hitachi ABB Power Grid

Simulation Models - Online vs. Offline Simulations

Offline Simulations - Pros & Cons

	Offline
-	**Must be performed on hardware at the end of the project before shipping to site**
-	Device parameters must be changed in the HMI, making it more cumbersome to perform a series of cases in batch.
-	Tests can be run in the factory system test during the project stage by a limited number of engineers
-	Difficult to study the new contingencies after commissioning in real time that needs access to the replica.

Online Simulations - Pros & Cons

	Online
+	**Can be performed at an earlier stage in the project**
+	**More flexibility to perform cases in batch by modifying device parameters such as slope, gain, voltage reference, etc.**
+	Tests can be run at any time, any computer and by multiple engineers
+	Offline simulations make it possible to validate performance after commissioning without having a control system replica.

- Using Real Code in Modeling HVDC and FACTS Devices in EMT and RMS Simulation Platforms can replace RTDS simulation studies to verify system performance with HVDC and FACTS converters. RTDS simulations can be used for functional testing with HIL.
  - Offline simulations for evaluating system performance, online for functional tests.

Source: IEEE GM 2021, panel session “Emerging Trends in Modelling and Control of HVDC and FACTS (Part II)”, “Using Real Code in Modeling HVDC and FACTS Devices in EMT and RMS Simulation Platforms”; Soubhik Auddy, Hitachi ABB Power Grid

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