Some Real-Time Modelling and Automation Insights Gained From Utility Protection Test Studies on RTDS Simulators

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etalumiSe

Introduction

- This presentation provides an overview of some applied protection system testing projects that have been conducted using RTDS simulators in recent years.

- In addition to discussing the applications in their own right, the presentation will focus on practical issues, techniques and lessons learned, and the scope for future developments and improvements to real-time models that have arisen out of these studies.

Case Study 1: Overcurrent Relay Stability Tests

- **Problems reported from field experience with older technology O/C relays protecting shunt capacitor banks.**

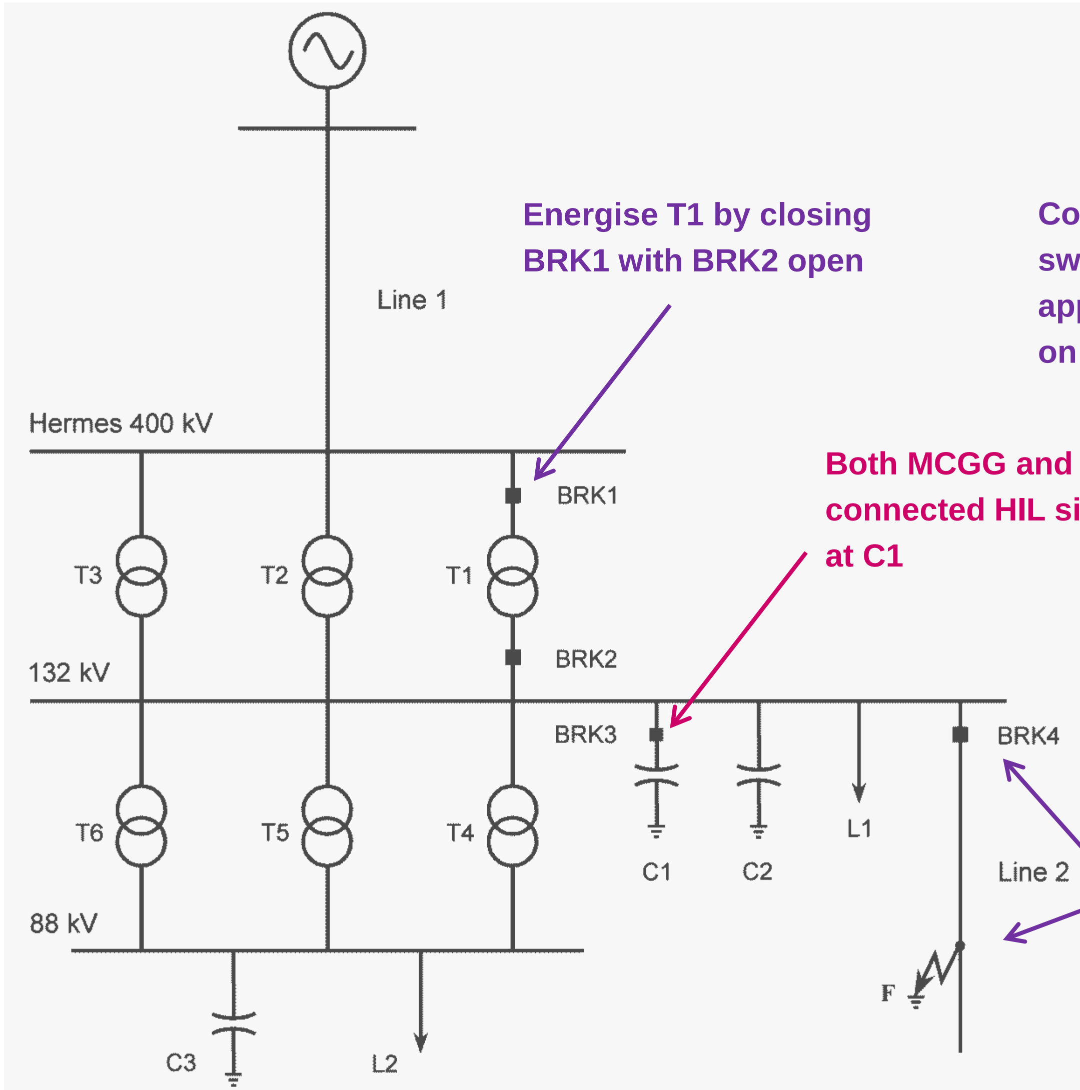
- **MCGG O/C Relay susceptible to incorrect tripping during transients following switching of the shunt capacitor bank or other similar events.**

  - **Problem thought to be due to absence of filtering on electronic-technology relays.**

- **New-technology numerical P122 O/C Relay (with filtering) had been identified within Eskom as a replacement.**

  - **HIL testing was carried out to formally verify the improved stability of the new numerical P122 O/C Relay.**

Overcurrent Relay Stability Tests: Study System Model



Energise T1 by closing BRK1 with BRK2 open

Control logic to allow all switching events to be applied at specified points on wave of C1 voltage

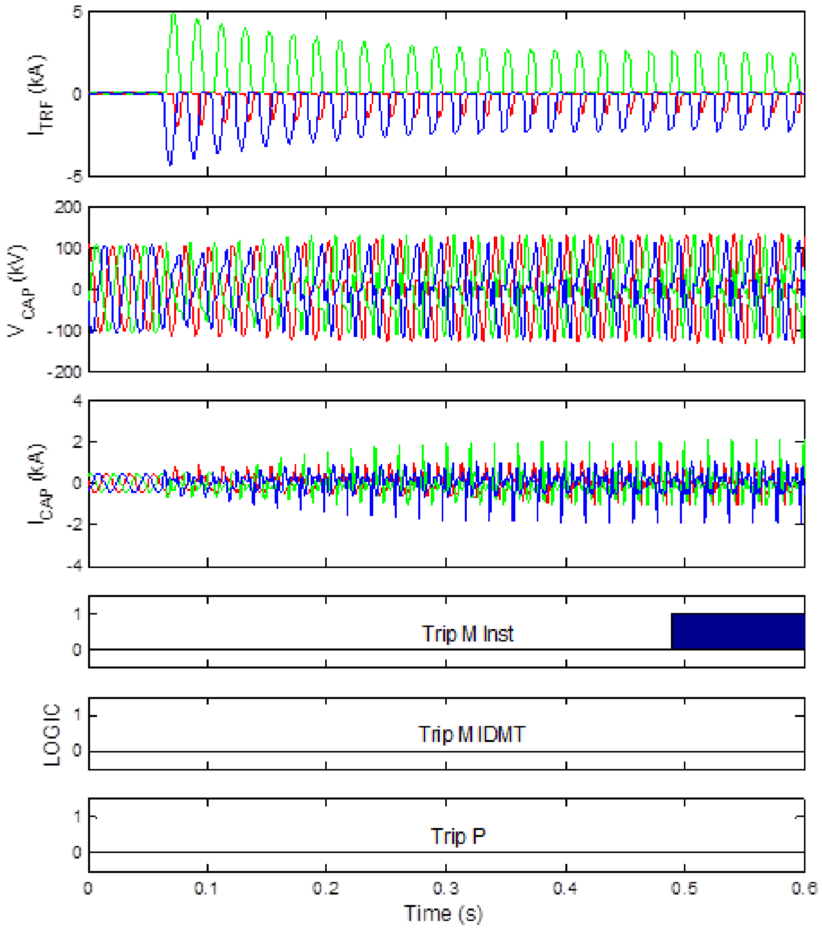
Both MCGG and P122 relays connected HIL simultaneously at C1

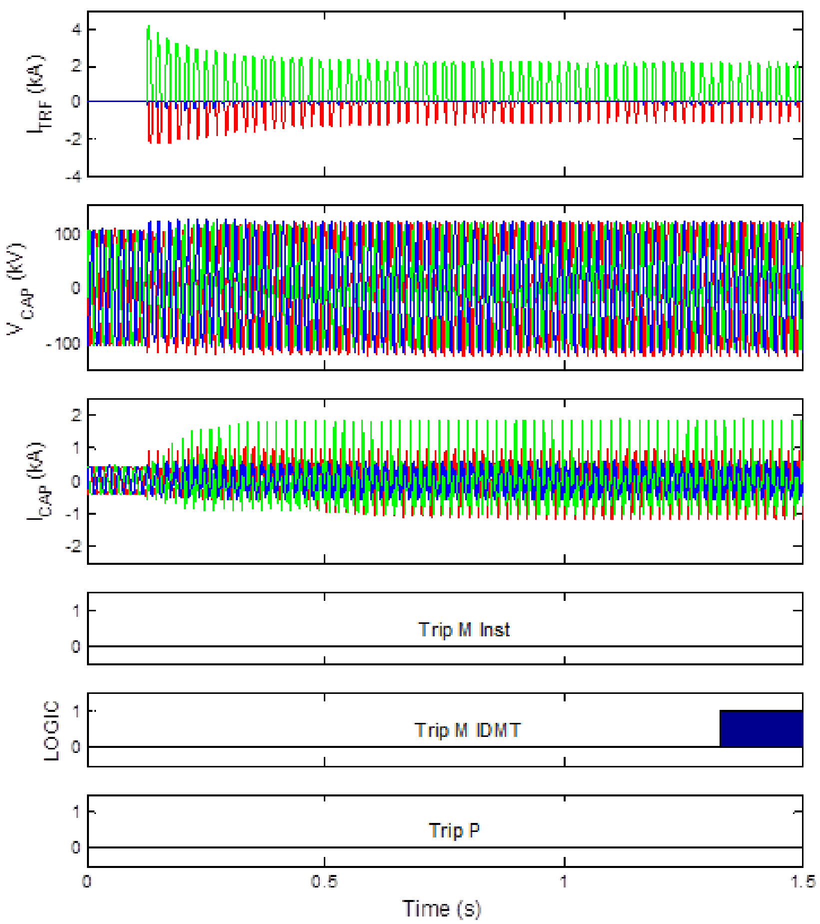
Fault at F followed by timed opening of breaker BRK4

HIL Connections

Sample Results: Energisation of Transformer T1

T1 energised by closing 400 kV breaker at constant point on wave of capacitor bank voltage



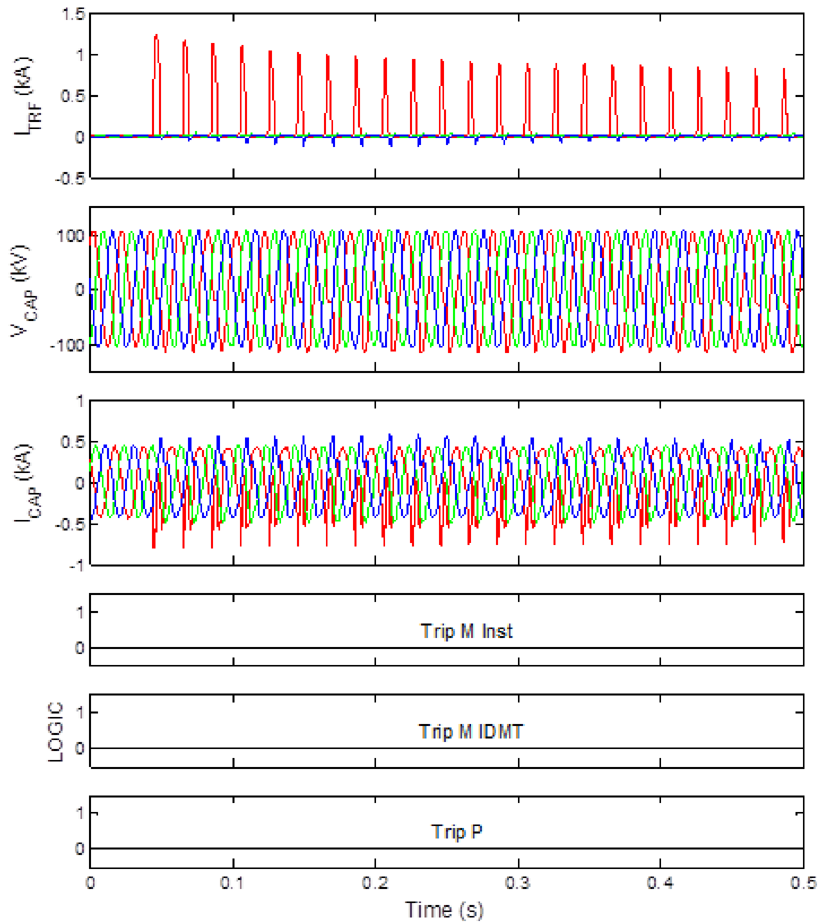


Electronic Relay (MCGG) trips on instantaneous O/C

Electronic Relay (MCGG) trips on IDMT O/C

Numerical Relay (P122) stable (no trip) in both cases

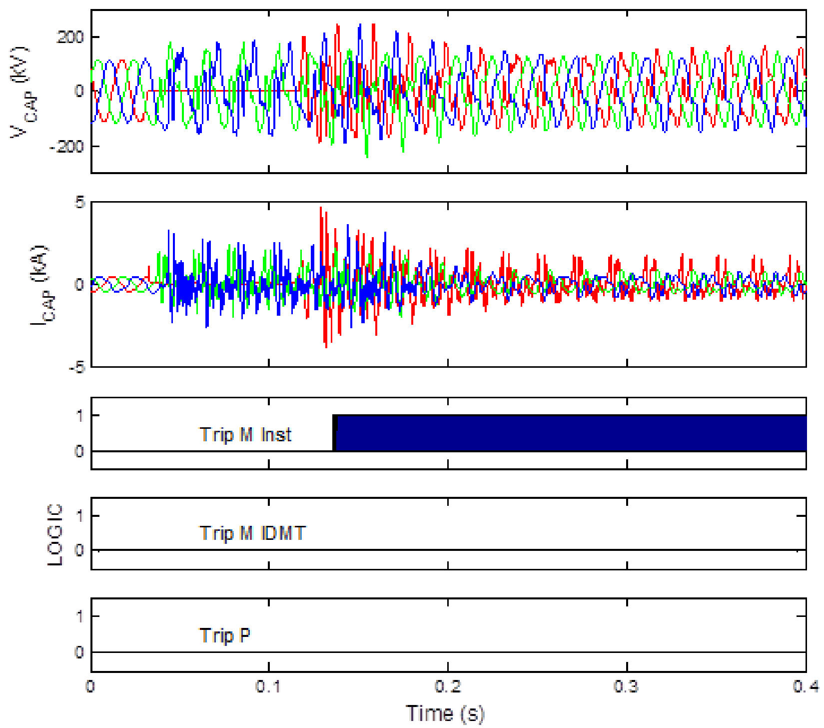
Sample Results: Energisation of Transformer T1

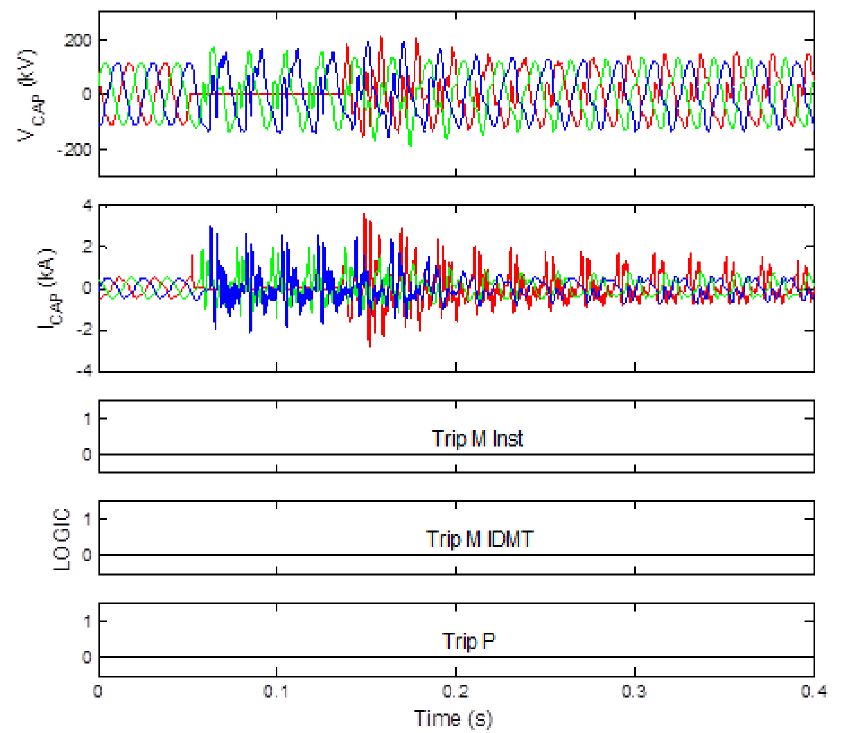


Both Electronic Relay (MCGG) and Numerical Relay (P122) stable in this case

Sample Results: Fault and Fault Clearing on Line 2

S/C fault applied on Line 2 and cleared 80 ms later by opening breaker BRK4 – same test repeated several times





Electronic Relay (MCGG) trips on instantaneous O/C

Numerical Relay (P122) stable

Both relays stable in this instance of the test

Case Study 2: Testing A Capacitor Bank Smart Switching Scheme

Switching shunt capacitor banks on utility networks can cause severe voltage and current transients that can damage utility and customer equipment and processes:

- When switching a capacitor bank back onto the network, the system voltage at that busbar collapses suddenly to whatever magnitude of voltage is present on the capacitor at the moment of reconnection.
- The bus voltage then returns toward its initial value, overshoots it, and exhibits an oscillatory transient superimposed on top of the normal fundamental-frequency waveform.

The severity of these switching transients is determined by the difference between the system voltage and the residual voltages on the capacitor at the moment of reconnection and therefore depends on both:

- The magnitudes and polarities of any DC voltages left trapped on the capacitor phases
- The point on wave of the system AC voltages at the moment of reconnection.

Fast reclosing of capacitor banks after they have been disconnected therefore requires particular care.

Capacitor Bank Switching

Various techniques are in use to overcome these challenges with the goal of either controlling, limiting, or damping the transients, eg:

- Permanently-inserted reactors.
- Pre-insertion of resistors or reactors.
- Attempts at synchronised closing of the breakers at ideal points on wave of the system voltage.

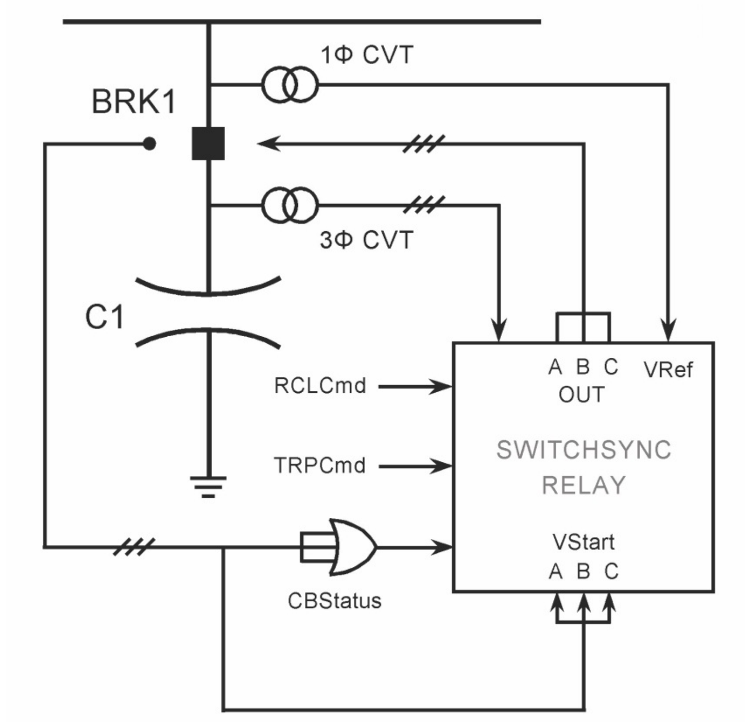
The particular strategy for implementing synchronised closing depends on whether the capacitor bank is of the earthed-star or delta-connected type connection.

The Switchsync relay being considered is designed for use in transmission line reclosing, where the best strategy for reclosing in the presence of trapped charge lies somewhere between the strategies for earthed-star and delta-connected shunt capacitor banks.

Overview of the Switchsync Relay

The relay measures:

- 3-Φ voltages on the capacitor-bank side of the breaker to estimate trapped charge
- 1-Φ voltage on the system side as the reference voltage for reclosing.



Two binary inputs, ordinarily supplied from a protection relay:

- Breaker Trip command.
- Breaker Reclose command.

Three binary outputs (**OUT A, B, C**) to close each pole of the breaker.

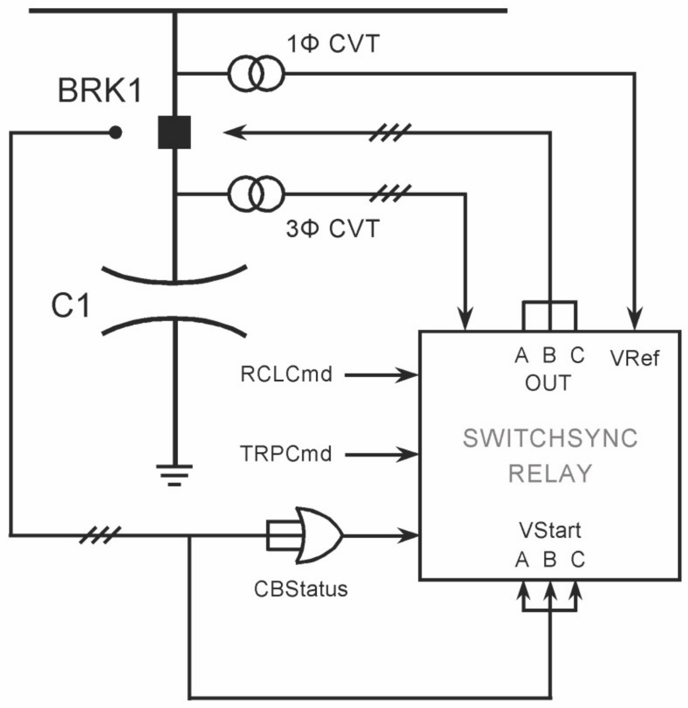
Two sets of status inputs from the breaker itself:

- **CBStatus** reflects the overall state (open / closed) of the breaker.
- **VStart A, B, C** used to measure the actual closing instants of each pole of the breaker, allowing adaptation by the relay to cater for changes in response time of the breaker over time.

Switchsync Modes of Operation

- Just prior to the opening of the breaker, the Switchsync must be supplied with a brief pulse at its **TRPCmd** logic input to tell it the breaker is opening and to start its timers and algorithms for detecting the magnitude and polarity of trapped charge.

- When the breaker is to be reclosed, the Switchsync is supplied with a pulse at its **RCLCmd** logic input.



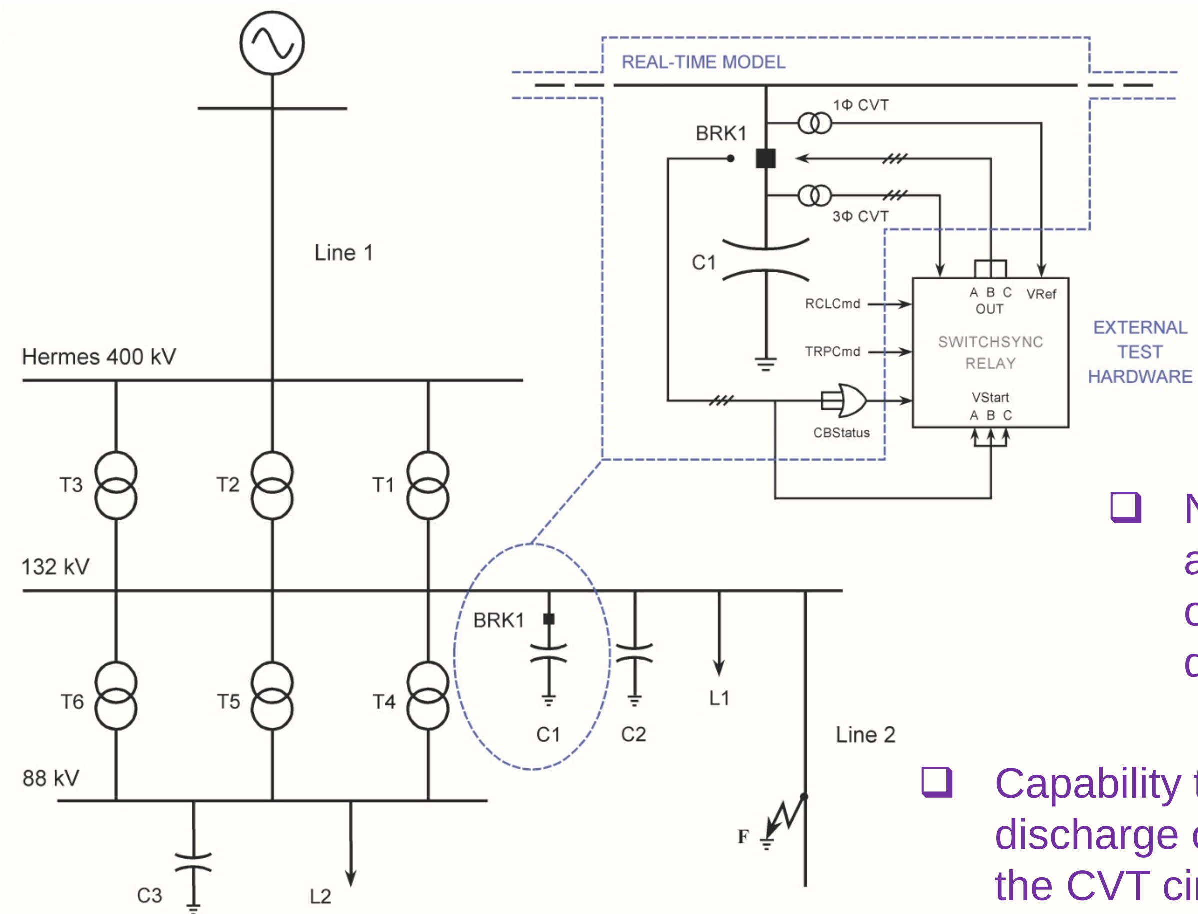
The relay then closes the breaker according to one of two fixed strategies:

- If the breaker closes less than 20 seconds after opening, it is assumed that trapped charge may still exist (normal reclosing).

- If the breaker closes more than 20 seconds after opening, it is assumed that the capacitances are completely discharged (planned closing).

Real-Time Simulator Modelling

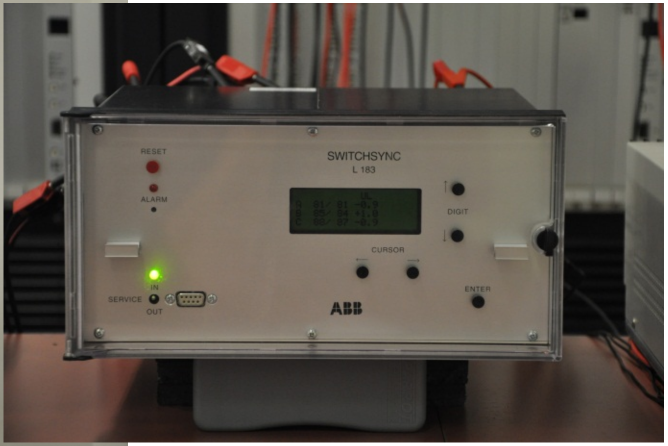
Switchsync relay hardware was interfaced to a detailed model of the Hermes substation on a real-time digital simulator (RTDS).



RTDS model included:

- Detailed representation of capacitor, breaker and CVT measurements for closed-loop connection to the external relay under test.
- Nearby line faults to represent asymmetric trapped charges on the capacitor phases upon disconnection.
- Capability to represent different rates of discharge of trapped charge through the CVT circuits to test the relay's ability to predict the rate of decay of trapped voltages under varying operating conditions.

Hardware-In-Loop Connection of the Switchsync Relay to the Real-Time Simulator



Results: Base Case Simulations Without The Switchsync For Comparison

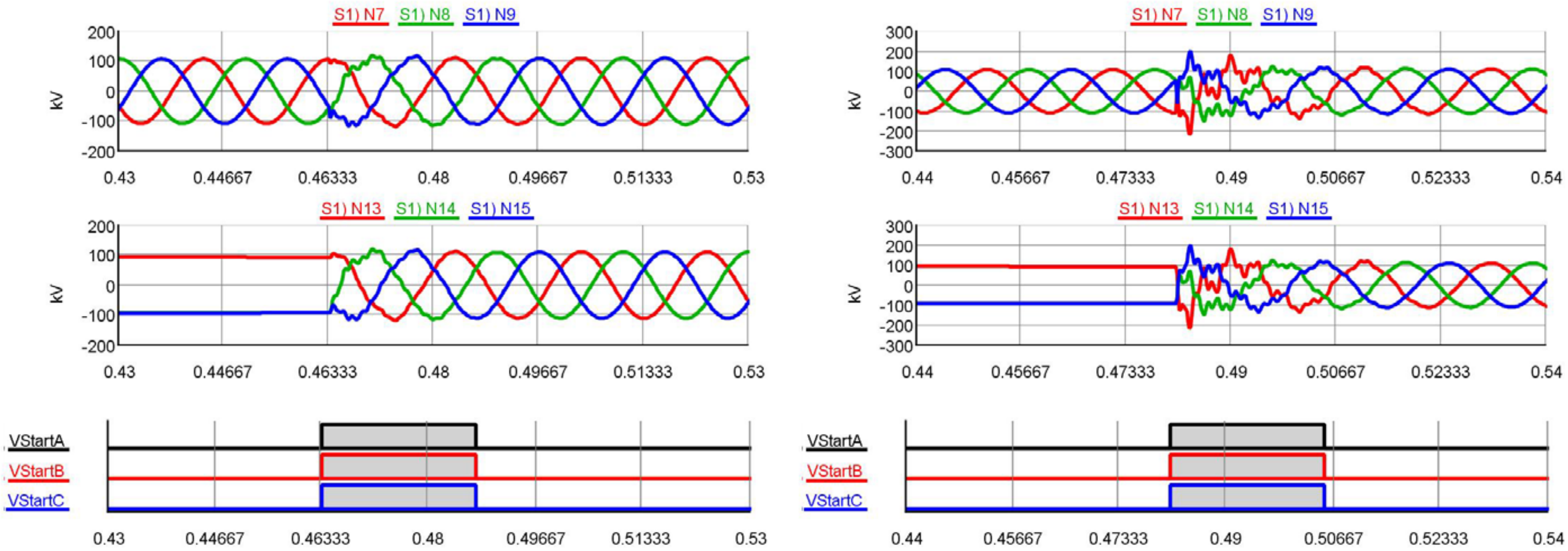
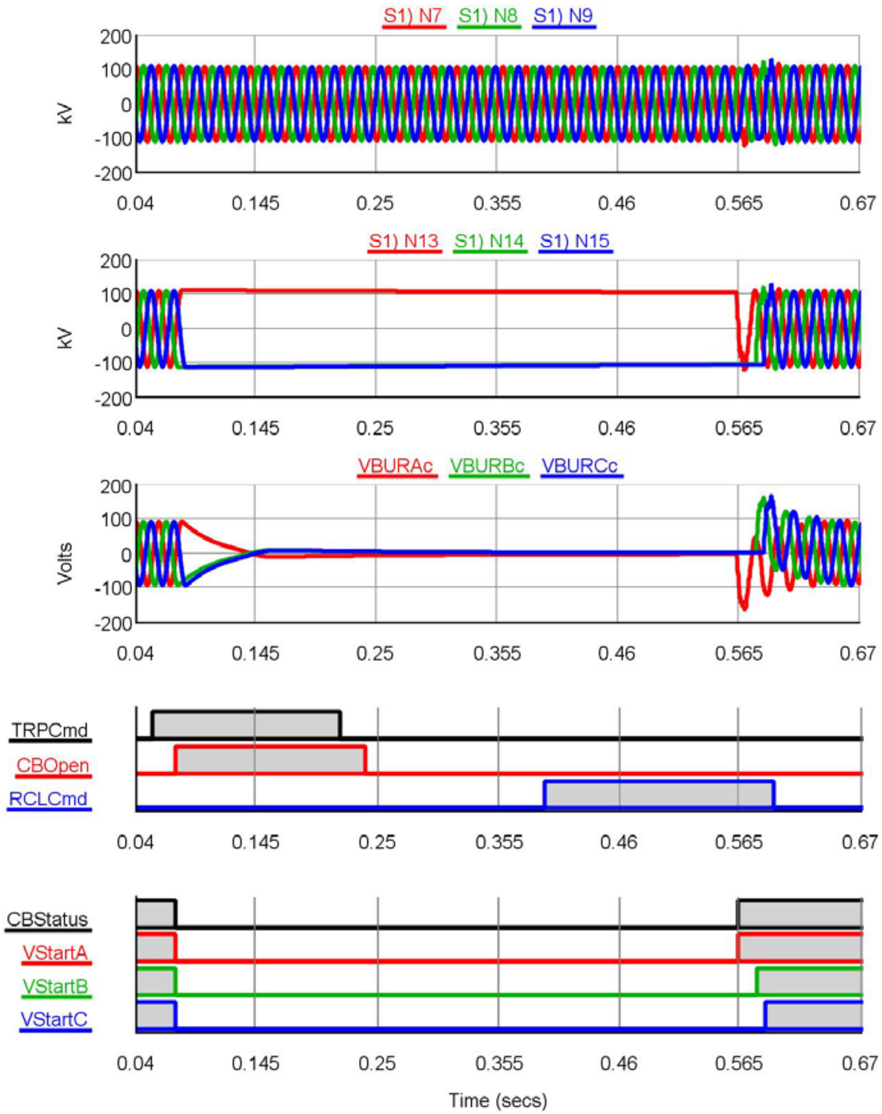
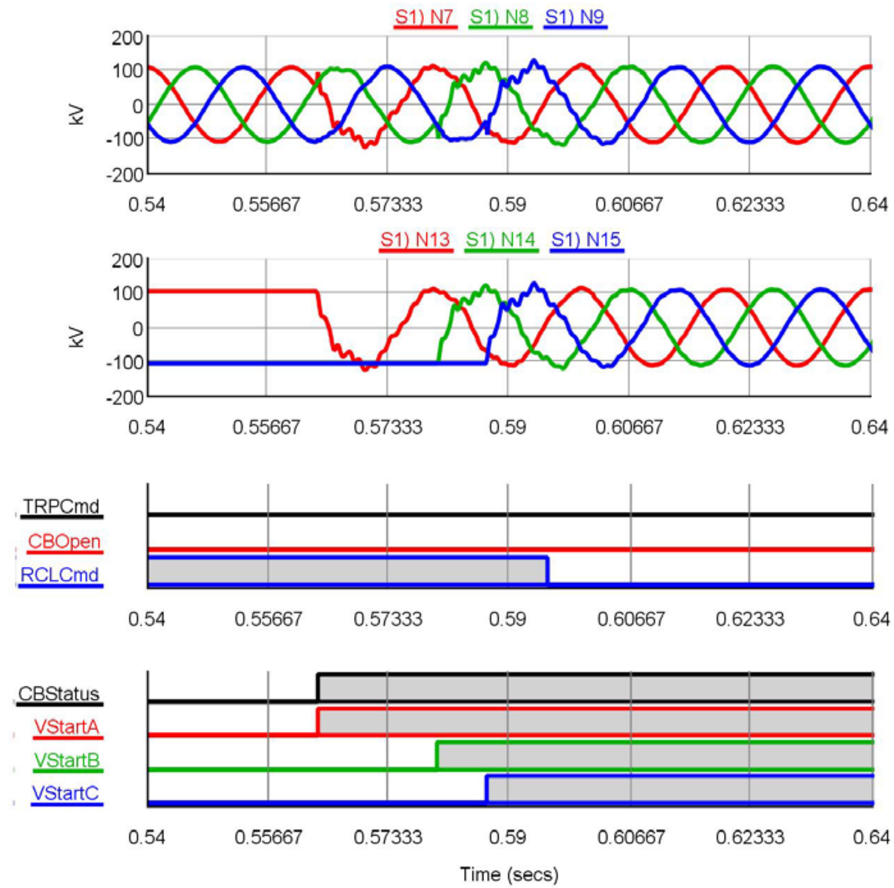


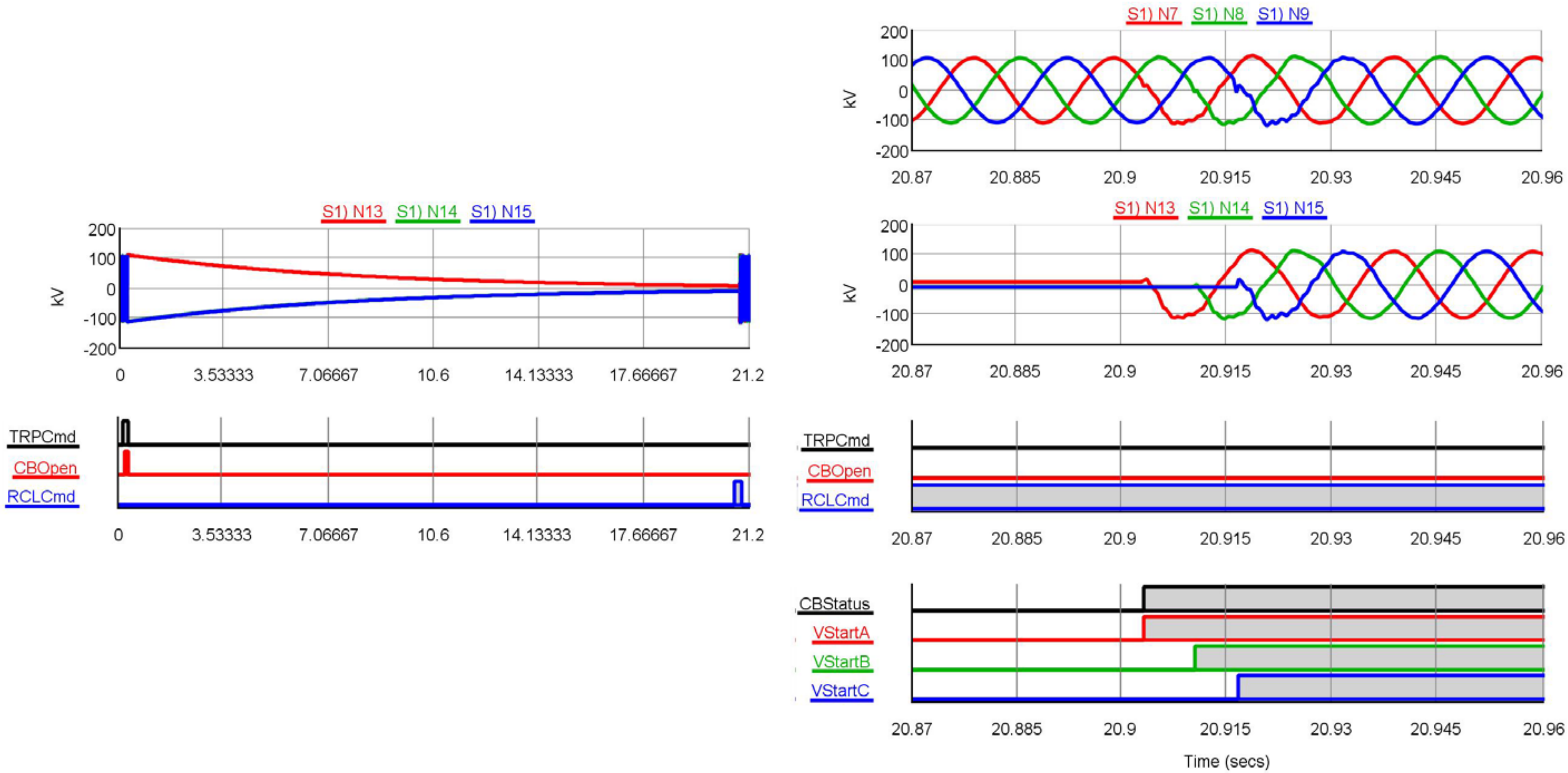
Fig. 2 – *All-simulation reference study: capacitor bank reconnected with maximum trapped voltages on its phases; (a) best point on wave for breaker closing; (b) worst point on wave for breaker closing in phase A.*

Reclosing with the Switchsync in less than 20 seconds, maximum trapped voltage amplitudes, slow rate of decay of trapped charge





Reclosing with the Switchsync after more than 20 seconds, maximum trapped voltage amplitudes, slow rate of decay of trapped charge



Case Study 3: Evaluation of Protection Relays Under GIC Conditions

- **Geomagnetic disturbances associated with solar storms can give rise to geomagnetically-induced currents (GICs) in transmission grids. These GICs can:**
  - **cause damage to key plant in the grid;**
  - **disrupt the normal operation of the grid.**

- **Eskom undertook a wide-ranging initiative that investigated a range of aspects related to the GIC problem.**
  - **The specific focus of our work was the performance of protection systems under GIC conditions.**

- **Power transformers in the grid that are subjected to near-DC GICs can become temporarily half-cycle saturated, causing elevated harmonic distortion in the variables of the transformers themselves, and in the currents and voltages in the surrounding network.**

- **These elevated harmonics could cause incorrect operation of protection relays, resulting in:**
  - **failure to clear genuine faults;**
  - **incorrect tripping of key network components such as transformers and capacitors (events that are known to have been factors contributing to system collapses in northern-latitude countries during severe geomagnetic storms).**

OBJECTIVES

The aim of our particular investigations into GIC preparedness was to understand (from the perspectives of both security and dependability) how the protection relays in Eskom's transmission network are likely to be affected:

- **in the presence of the DC currents associated with GICs;**
- **in the presence of harmonic distortions in their AC measurement quantities as a result of half-cycle saturation of the power transformers in the system caused by the flow of such DC currents.**

TESTING PHILOSOPHY

In the first stage of the work described in this paper, an intentionally small-scale study system was developed to focus on, and understand:

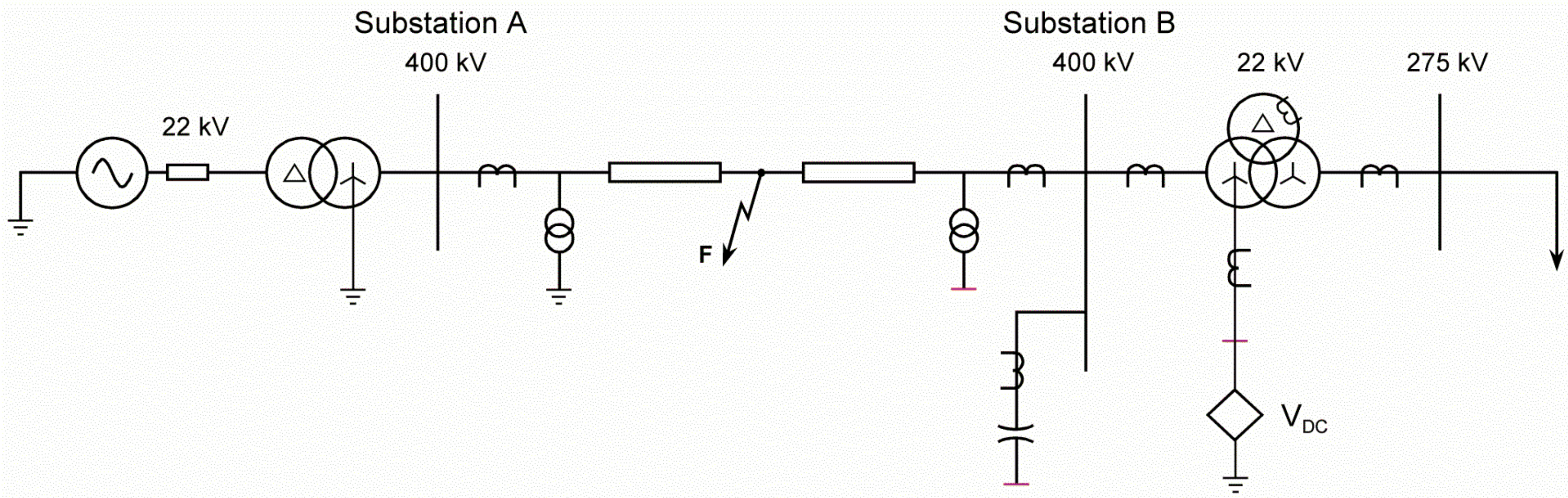
- **the mathematical models available for predicting the impact of GICs on specific power system plant using different simulation programs;**
- **the scope and limitations of such models for GIC analysis.**

A detailed model of the small-scale study system was then implemented on a real-time digital simulator (RTDS) in order to carry out extensive tests on a number of actual protection relays used in the field.

In selecting the relays to be included in the tests, the aim was to be able to assess, and document, the impact of GICs on:

- **all the principal *types* of protection scheme in use (e.g. impedance, over-current, current differential, etc.);**
- **a representative range of *relay technology vintages* still in use for each such type of scheme.**

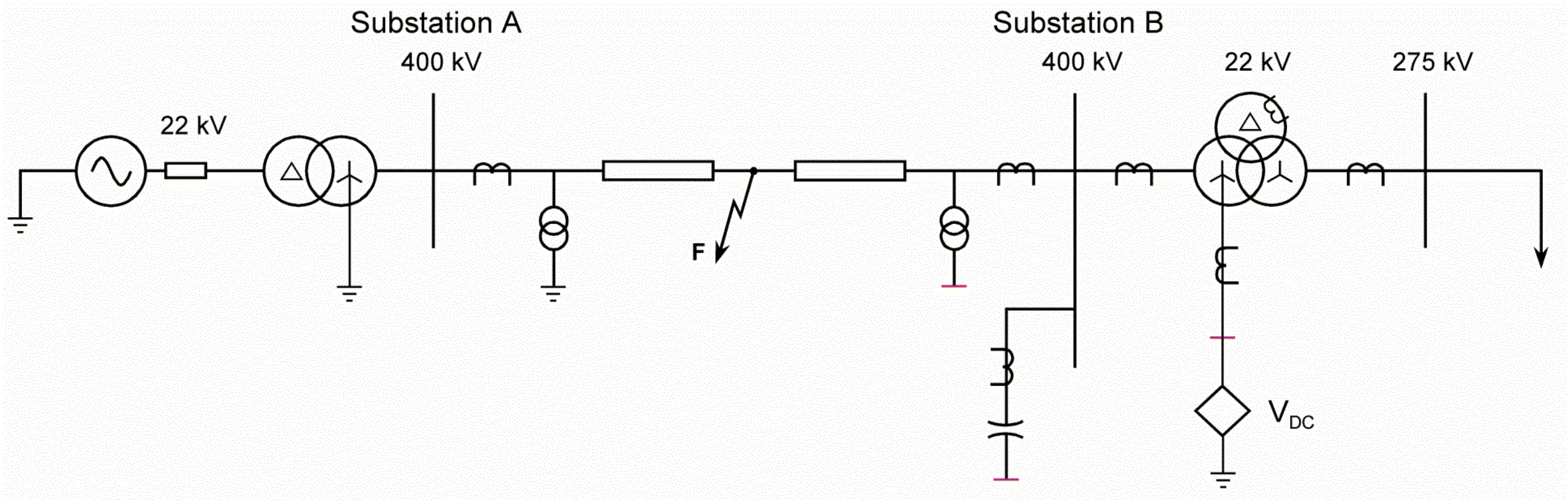
KEY MODELLING CONSIDERATIONS



The system topology was chosen:

- **To be sufficiently detailed to allow realistic representation of GIC flows and their effects on transformers and related plant.**
  - **DC voltage source used to create potential difference between the earth mats of the two substations, causing injection of DC current into the neutral of one transformer and return to ground via the neutral of remote transformer.**
- **To be sufficiently simple to be able to isolate and study the impact of GICs and other factors on the performance of protection relays during subsequent hardware testing.**

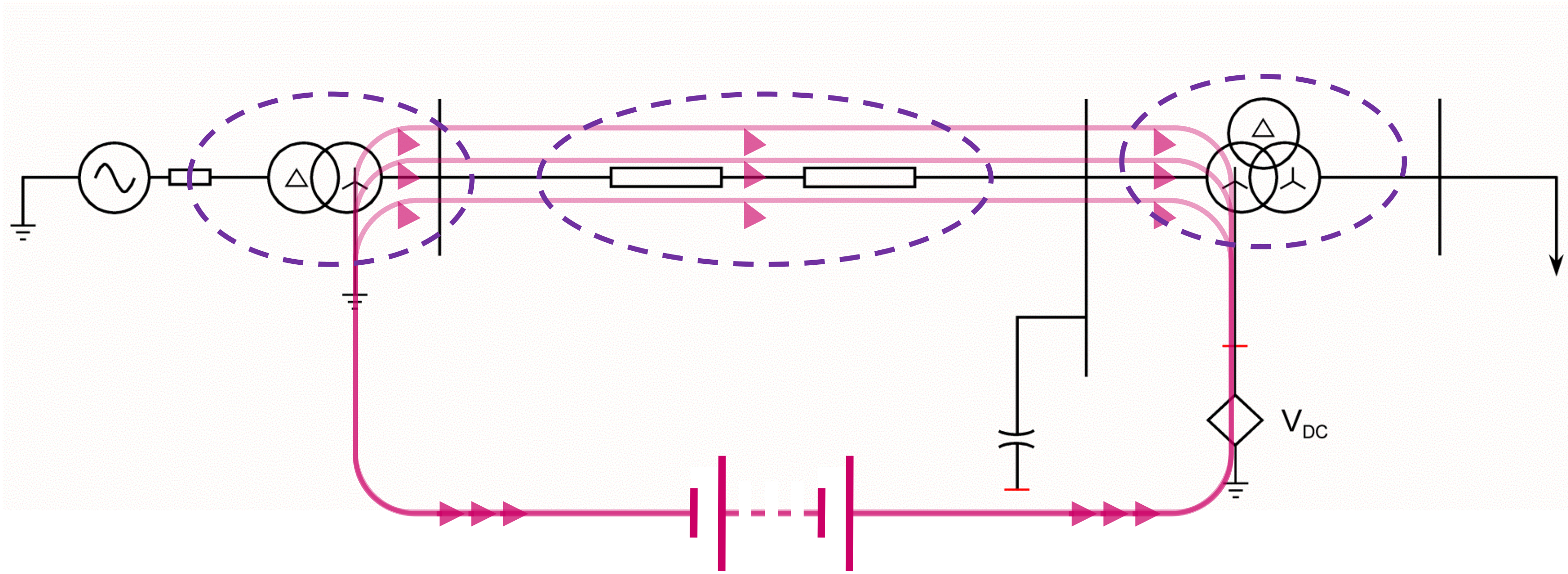
KEY MODELLING CONSIDERATIONS



The system topology was also chosen:

- **To allow the two main power transformer types and vector groups on Eskom's transmission network to be studied (2-winding Ynd1 generator transformer at Substation A, and 3-winding YNynd1 auto-transformer at Substation B).**
- **Enable all types of protection scheme of interest to be tested in a controlled, repeatable and comparable manner, for both internal and external faults in each case.**

IMPORTANT CONCLUSIONS FROM MODEL VALIDATION



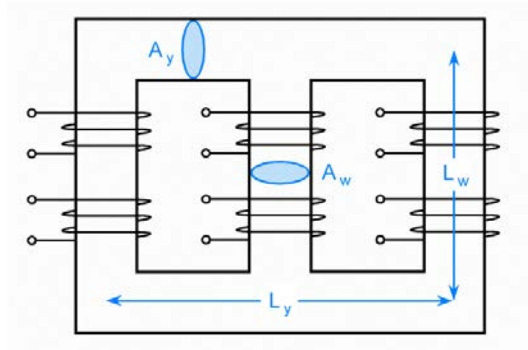
Transmission lines in such studies must therefore be represented using frequency-dependent models capable of correctly describing their impedances in the frequency range between DC and several multiples of 50 Hz.

Transformers in such studies must be represented using models that *not only* describe the coupled, multi-limb characteristics of their iron cores (magnetic circuits) but must do so correctly (i.e. the number of limbs, and the relative dimensions and reluctances of the each limb in the transformer core are very important).

Recall that when GICs flow in the network, the transformers at the points of injection of these currents may become half-cycle saturated, and the transmission lines between them would then carry a mixture of near-DC, fundamental-frequency, and higher-order harmonic currents.

THREE-PHASE TRANSFORMER MODELS AVAILABLE ON THE RTDS SIMULATOR

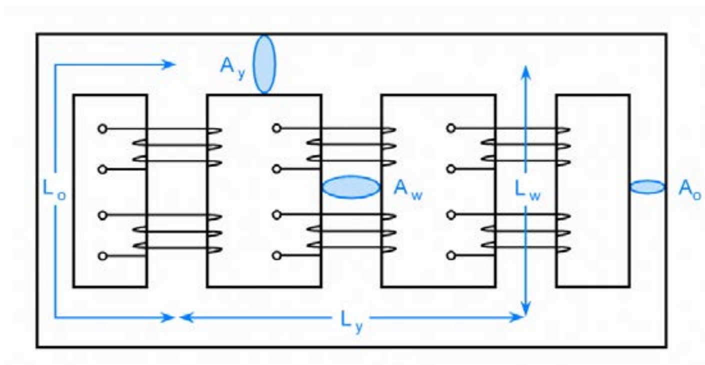
Detailed unified magnetic equivalent circuit (UMEC) transformer model (2-winding, 3-phase)



3-LIMB CORE STRUCTURE

Represents ratios between:

- x-sectional areas of core yoke and winding limbs;
- lengths of core yoke and winding limbs.

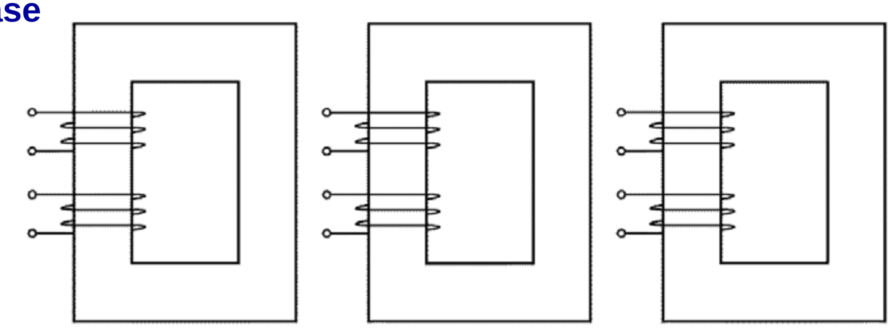


5-LIMB CORE STRUCTURE

In addition to the above, also represents ratios between:

- core-yoke and outer-limb x-sectional areas;
- core-yoke and outer-limb lengths.

“Regular” 2-winding 3-phase transformer model

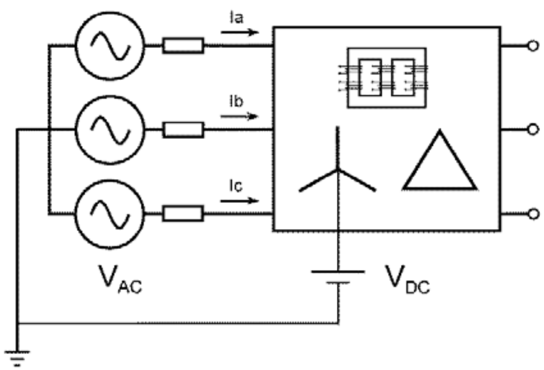


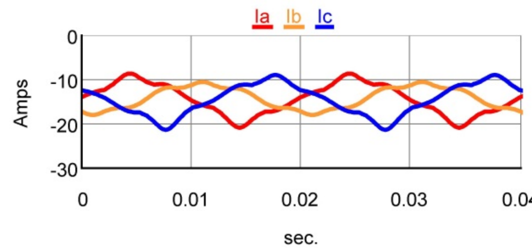
Three separate (uncoupled) cores (a common assumption in simulation models of three-phase transformers).

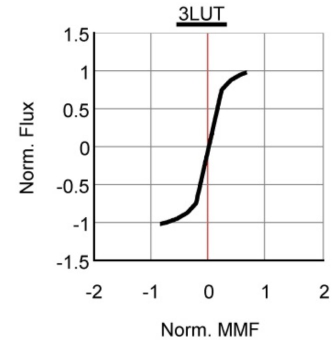
GIC SIMULATED UNDER NO-LOAD CONDITIONS FOR EACH OF THESE TRANSFORMER MODELS

TRANSFORMER MODEL | WINDING CURRENTS | B-H CURVE

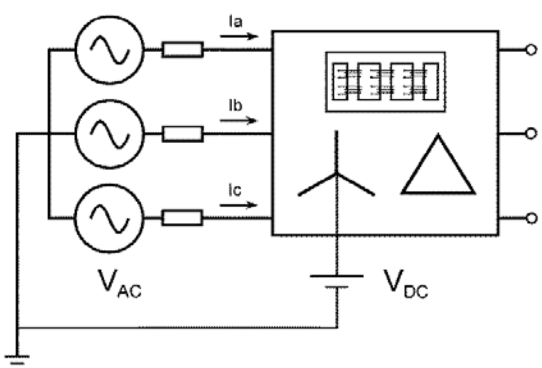
3-LIMB

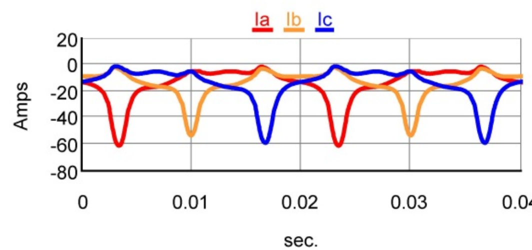


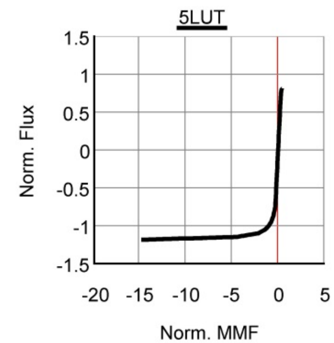




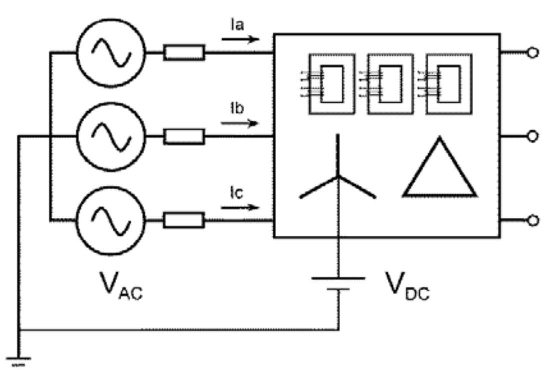
5-LIMB

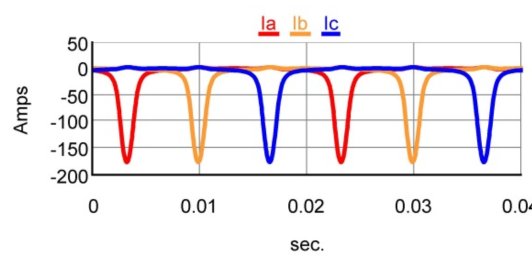


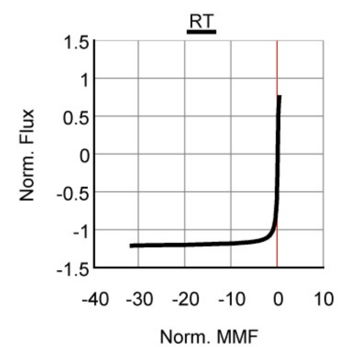




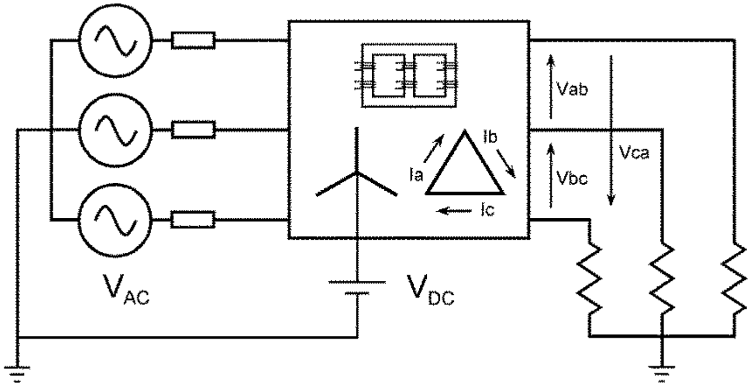
“REGULAR”

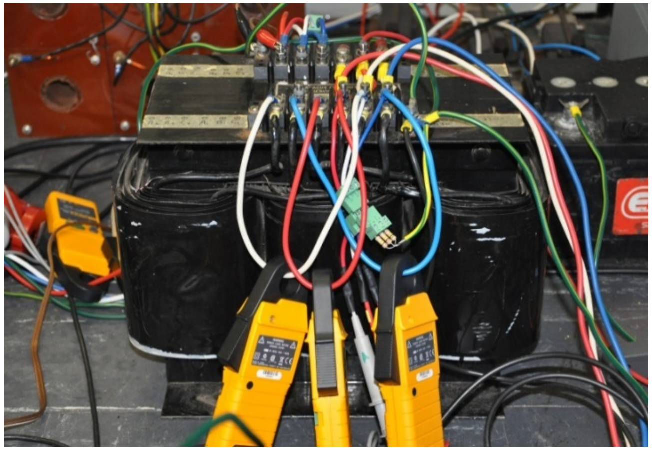




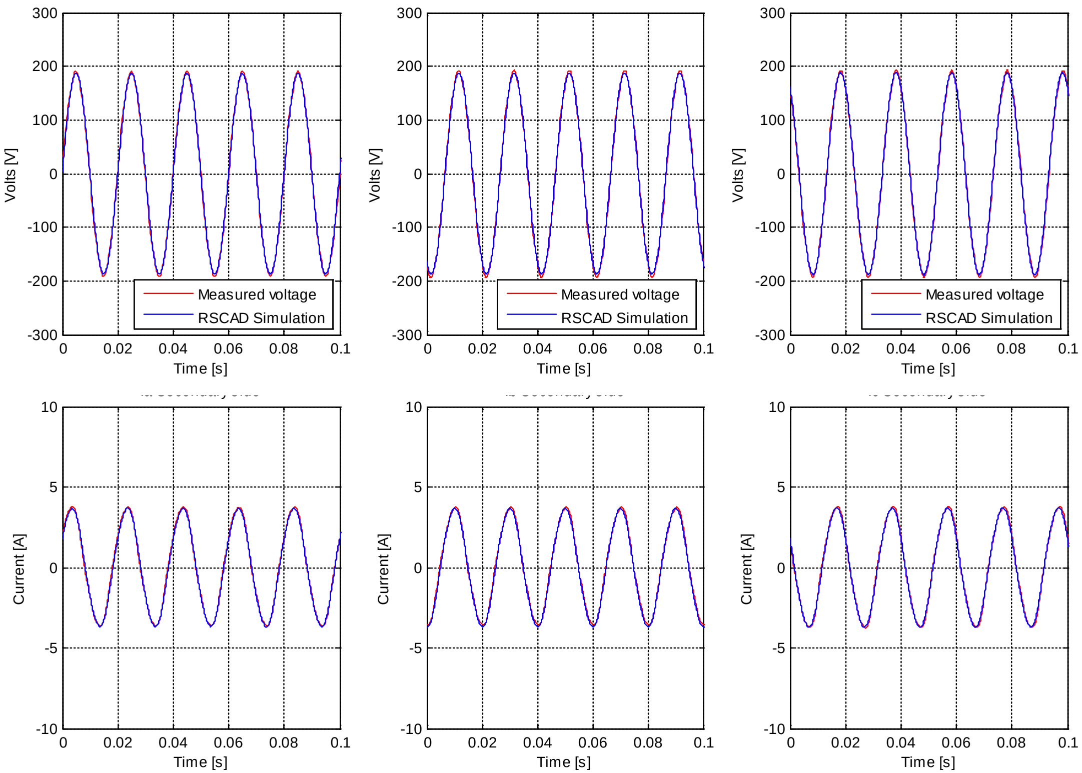


LABORATORY VALIDATION OF UMEC TRANSFORMER MODELS: 3-LIMB CORE STRUCTURE

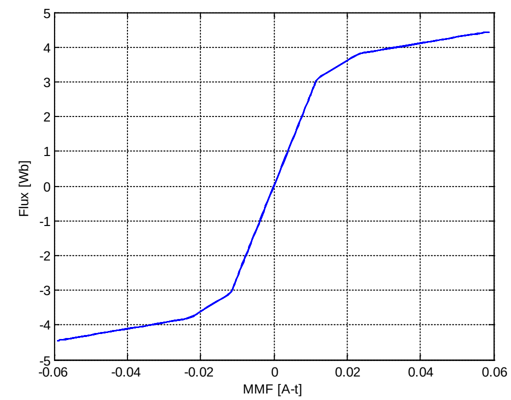




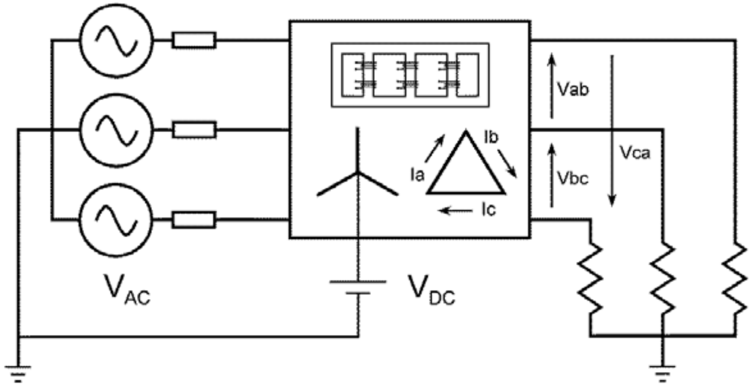
SIMULATED vs MEASURED CURRENTS AND VOLTAGES

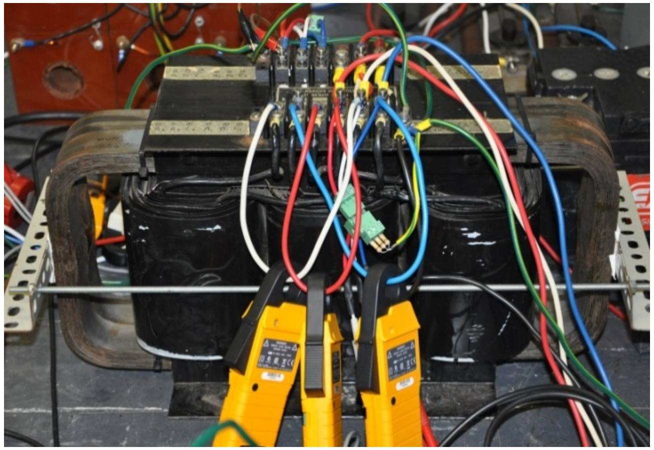


B-H CURVE

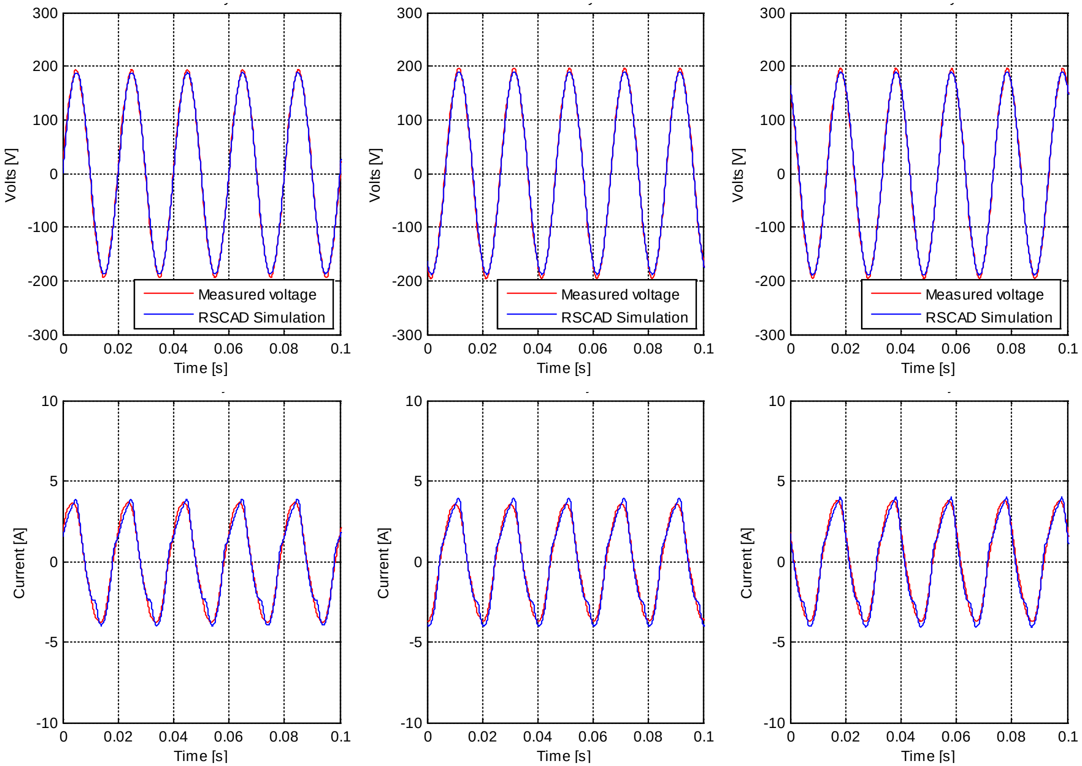


LABORATORY VALIDATION OF UMEC TRANSFORMER MODELS: 5-LIMB CORE STRUCTURE

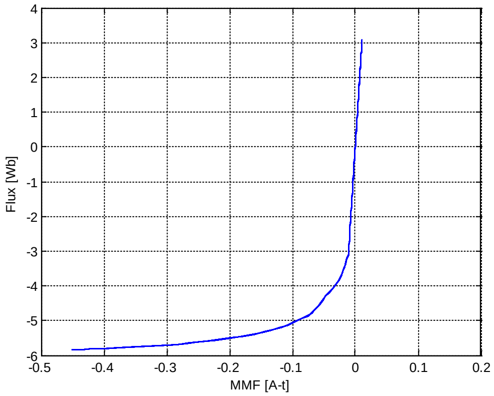




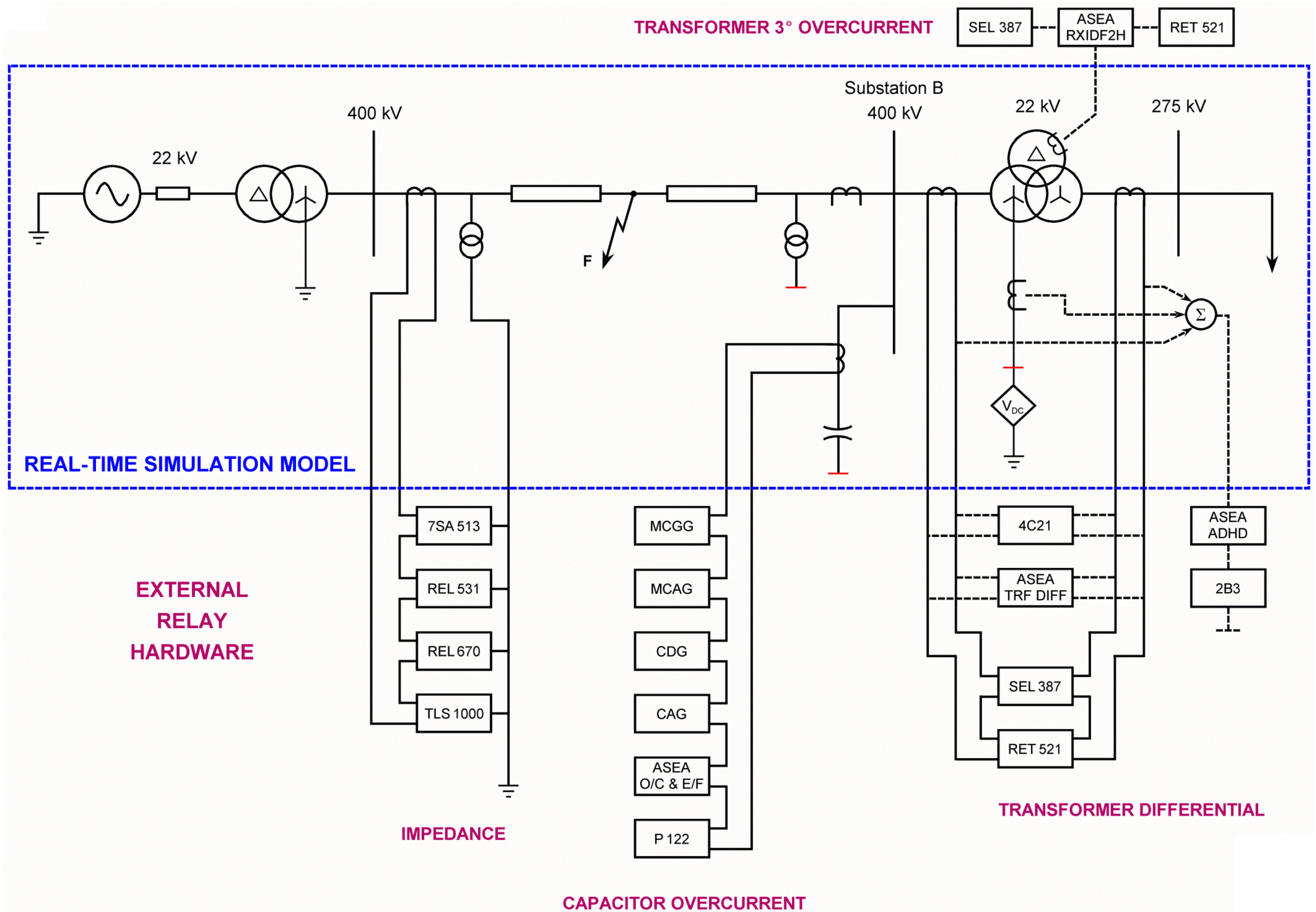
SIMULATED vs MEASURED CURRENTS AND VOLTAGES



B-H CURVE



HARDWARE IN LOOP RELAY TESTS USING RTDS MODEL OF SMALL-SCALE SYSTEM




RTDS ™
Real-Time Digital Simulator
ABB
MCGG
MCAG
SEL

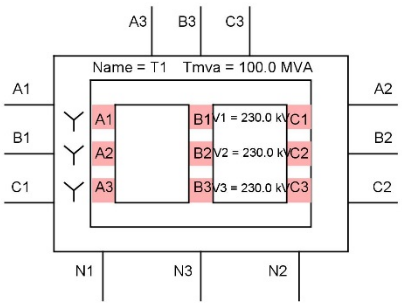
ELECTRONIC RELAY ON-SITE TESTS ON 400KV LINE

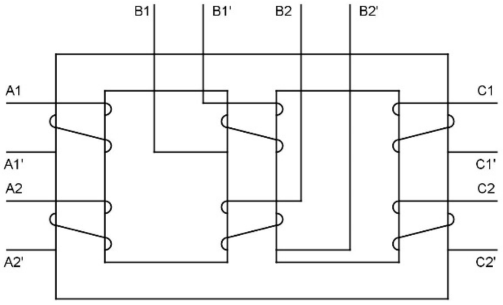
Conclusion

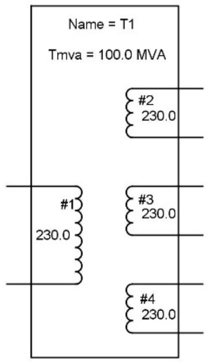
- These utility applications will hopefully provide some insights for other users as to what kind of studies and research applications are possible in the field of protection relay testing using the RTDS simulators.

- Also, these applications illustrate the possibilities for future RTDS model developments and model enhancements…

Model Development Issues…







3-PHASE, 3-WINDING

UMEC MODEL

3-PHASE, 2-WINDING

UMEC MODEL

"OPEN WINDINGS"

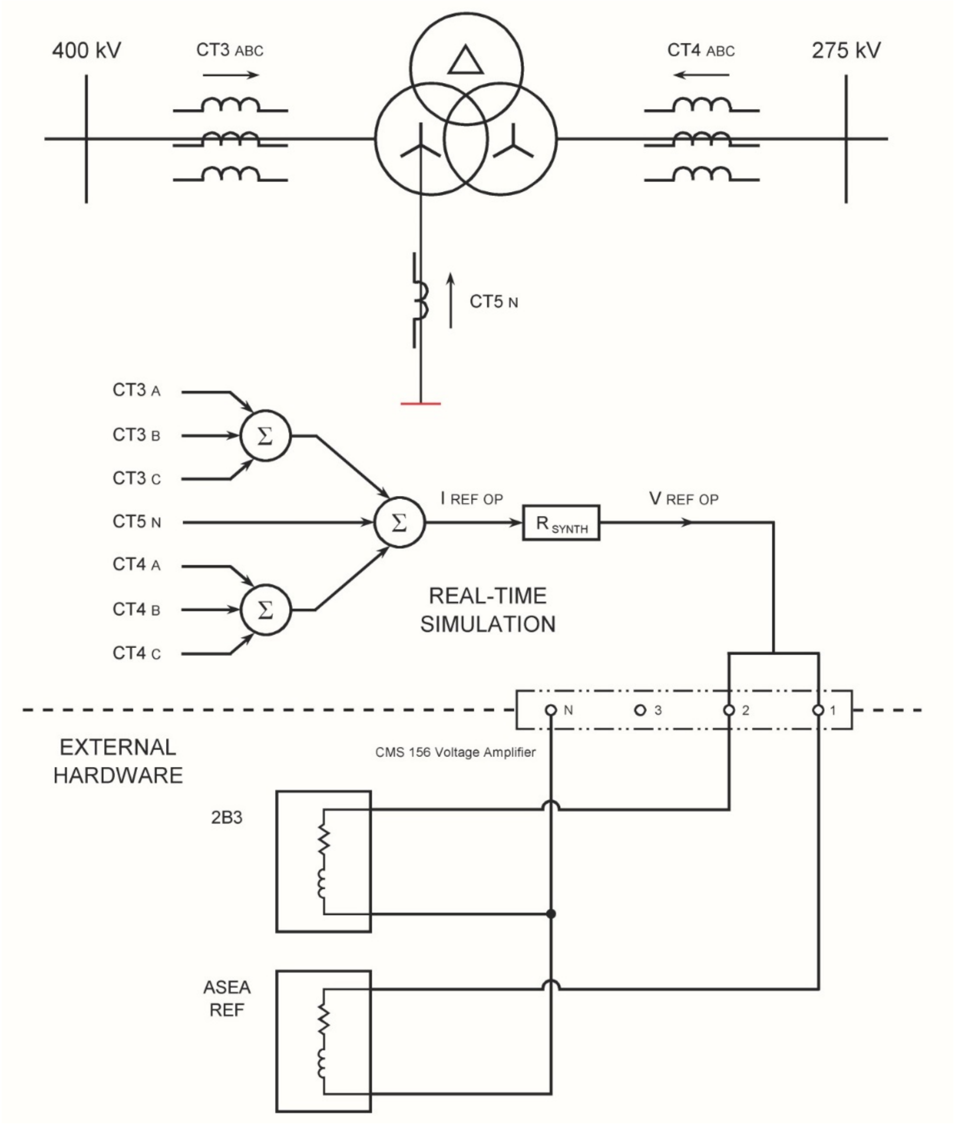
VERSION

1-PHASE, 4-WINDING

UMEC MODEL

- **"Open windings" version of 3-Φ, 3-winding UMEC transformer model?**
- **3-Φ, 4-winding UMEC transformer model with open windings?**
- **etc…**

Model Development Issues…



Improved CT models suitable for restricted earth fault relay testing?