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Real-Time Adaptive Protection Optimization using CAPE

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CAPE User Group Meeting

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THE UNIVERSITY OF NEW MEXICO
Emera Technologies
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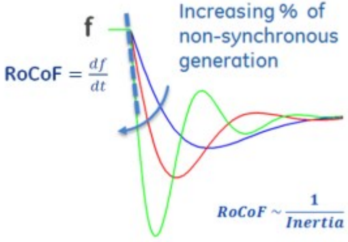
Problem Statement

- The grid is getting more complicated, with increasing number of possible states
- The conventional protection system lacks the intelligence required to modify the protective responses according to the system conditions

Current Protection Schemes

Local Fault Detection

- Well-tuned only for normal operating conditions
- Does not work with distributed energy resources (DER) with reverse current or inverter-based generation with low fault currents

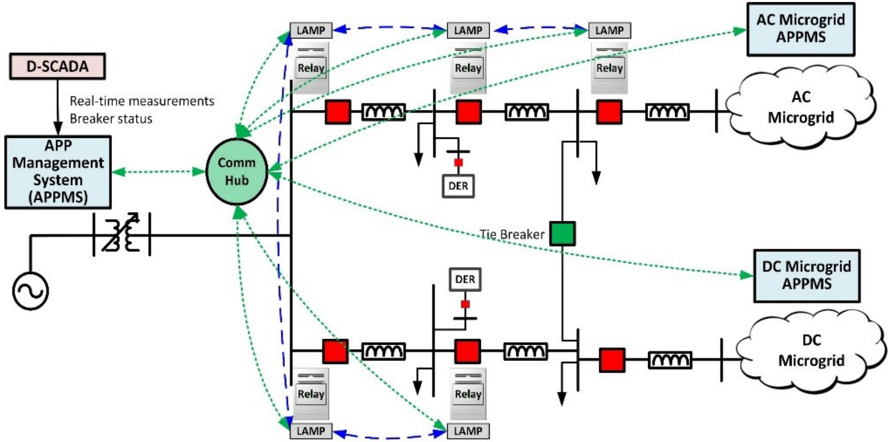


Logic-Based Adaptive Protection

- Reliant on communication, which also introduces cyber-security vulnerabilities
- Based on a set of pre-defined logics
- Covering a limited number of contingencies

Adaptive Protection Platform

- Adaptive Protection Platform (APP) to be utilized in modern distribution systems with high penetration of PV as well as AC and DC microgrids.



- Determine appropriate relay settings in real-time for all devices in the network based on the current system state (switching, grid-connected, generator dispatch, etc.)

Adaptive Protection Platform

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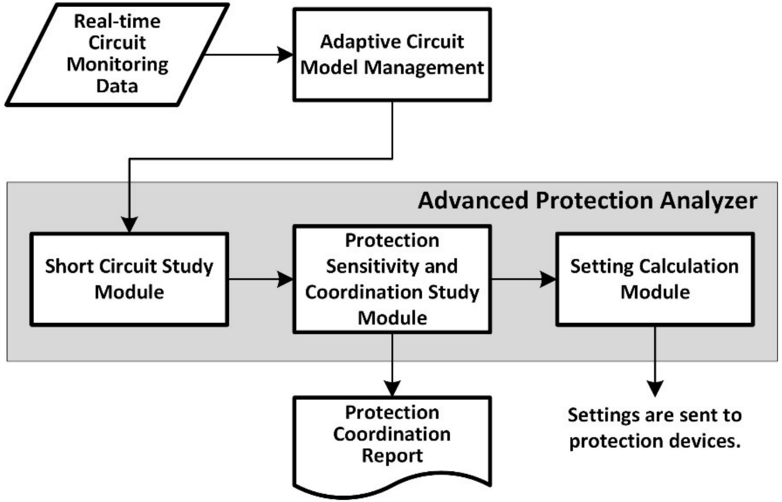
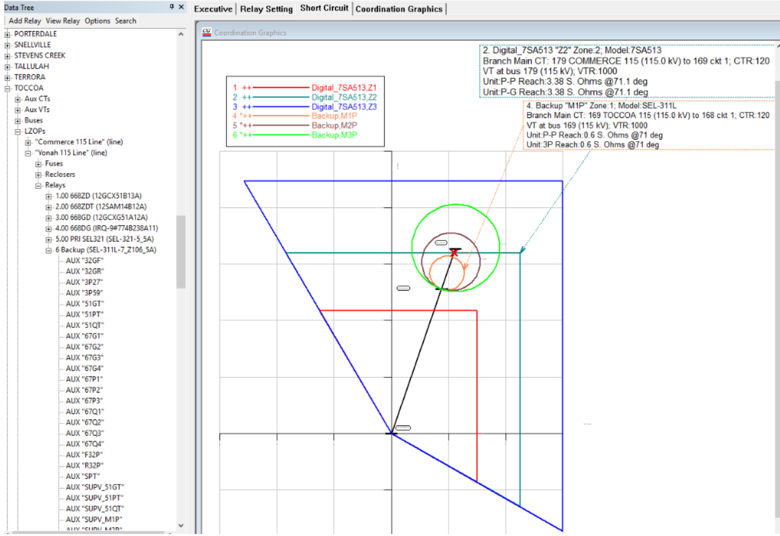
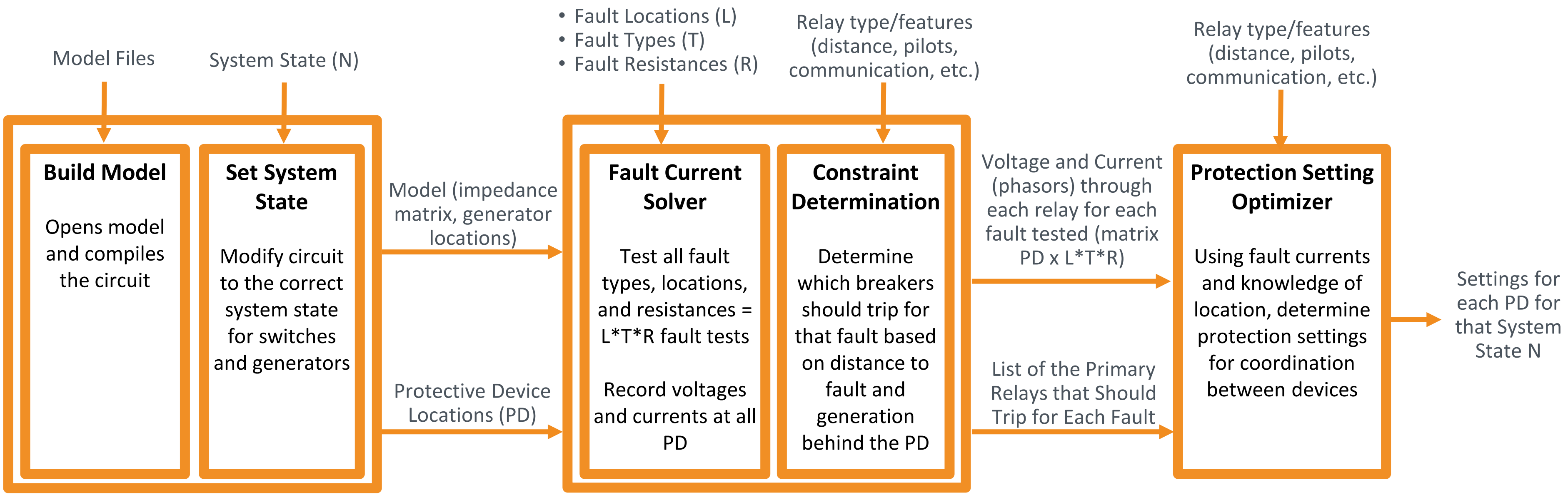
- APP Management System (APPMS)
  - Model-based algorithms in Adaptive Circuit Model Management
  - Uses CAPE for model-based Short Circuit Study Module, and wide-area Sensitivity and Coordination Study Module
  - Derive optimized and coordinated relay settings





Adaptive Protection Platform

- Optimize relay settings (curve type, time dial, and pickup current)
  - Minimize the sum of the relay operating times for all possible faults
  - Ensure coordination with a coordination time interval (CTI) between relays of at least 0.25s for all fault types at various locations and resistances



Adaptive Protection Platform

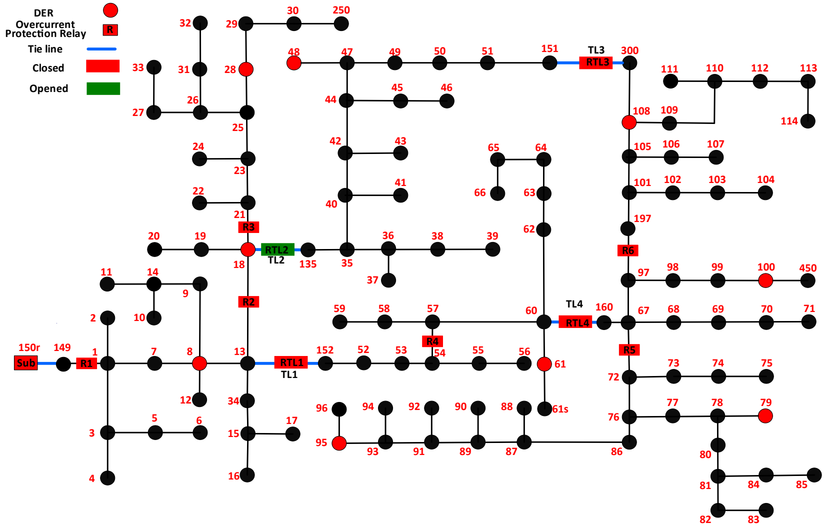
- Relay Settings Optimizer Functionality
  - Coordination between relays, reclosers, and fuses based on the capabilities of each protective device in CAPE – device type, pickup range, time dial setting range, time current curve choices
  - Uses relay, recloser, and fuse curves imported from CAPE
  - Fast and slow curve recloser coordination with fuse minimum melting and total clearing time
  - Multiple protection function choices:
    - Instantaneous overcurrent (50P/G)
    - Time overcurrent (51P/G) – pickup, time dial setting, curve type
    - Directional time overcurrent (67) – characteristic angle (ECA), forward angle limit
    - Voltage-restrained time overcurrent (51V)
    - Distance (21) – zone 1 and 2 impedance angle and magnitude, delay time

Adaptive Protection Interaction with CAPE

CAPE for Real-Time Adaptive Protection

1. Query equipment capabilities from CAPE
    - Available protection functions, curve types, and setting ranges
2. Read real-time breaker status and system steady-state pre-fault data from streaming data from relays, PMU, and DER
    - Updates real-time model in CAPE
3. Run short circuit study in CAPE to calculate voltages and currents at relays
4. Determine optimal protection settings for all relays
5. Update CAPE model with relay settings
6. Run CAPE coordination macro
7. Push settings to relays

IEEE 123 Node System



CAPE Short Circuit Study Macro

- Settings optimizer needs short circuit data to find out properly coordinated settings
- The model consists of inverter-based resources (IBRs), the power flow is bidirectional. During short circuit, fault is fed by both grid and IBRs.
- This macro produces short circuit currents and voltages at all relay locations.

3 SLG faults, 3 DLG faults, 3 LTL faults and one 3-phase faults are defined

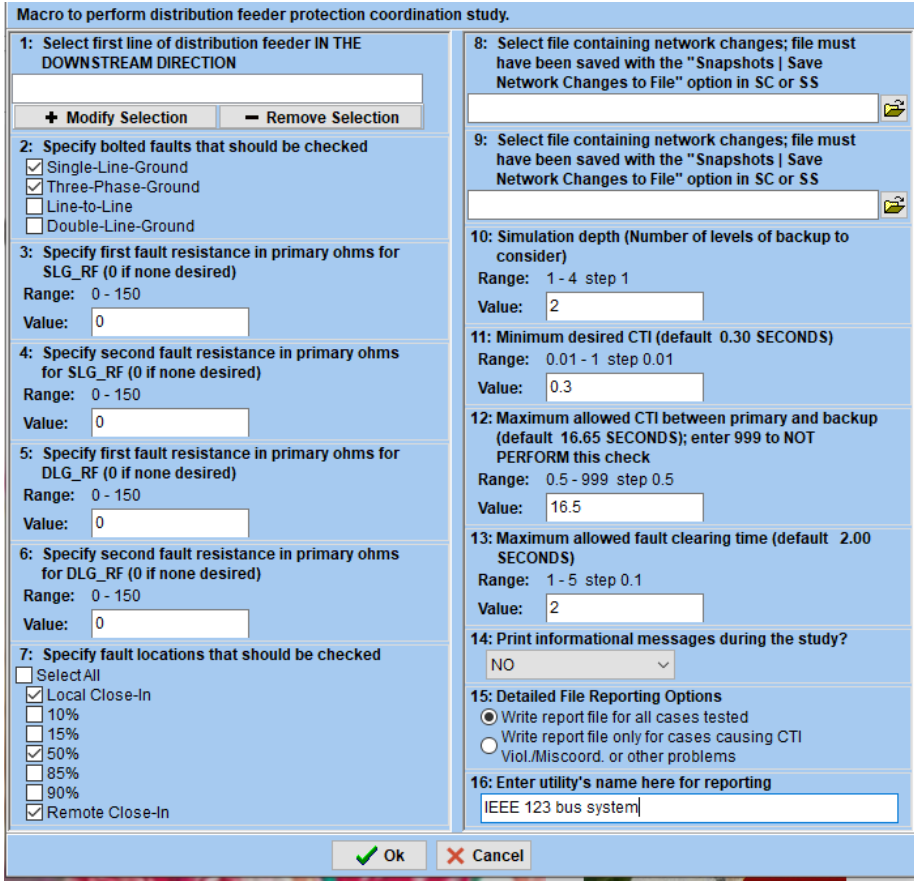
Each fault is attached with low 0.05 Ohm and high 1 Ohm Fault resistance.

Faults are applied to near node to the relay and far node from the relay.

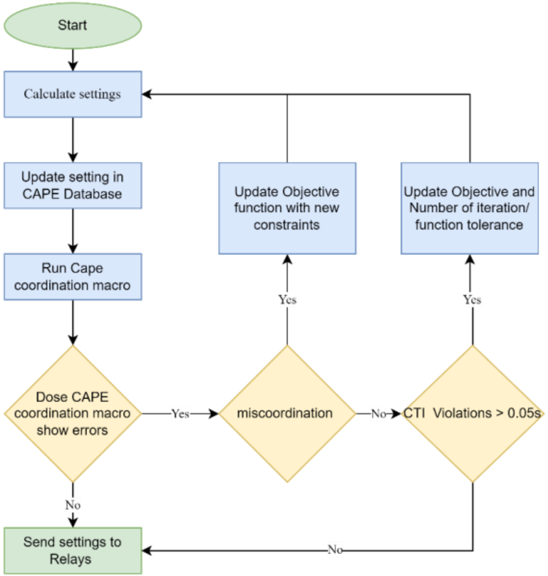
Fault currents and voltages are collected on all relays in “CSV” format.

CAPE Distribution Coordination Macro

- This macro runs to verify the validity of the settings from the adaptive protection optimizer
- Each line is faulted according to location specified.
- The macro finds out the pair of relays for coordination for a fault and their timing
- **UPDATE**:
  - Now includes information about primary/backup devices
  - Directional settings
  - Voltage restrained settings



Integration with CAPE coordination Macro



- If CAPE coordination macro identifies any mis-operations, miscoordination is written as additional constraint with adaptive protection optimizer re-run

```
Faulted Segment Data - Start Bus: 76 IEEE123 ( 4.2 kV) End Bus: 86 IEEE123 ( 4.2

No.   Network Situation/Outages in Effect    Fault (RF)     Fault Location                    Time(s
----- ------------------------------------   ----------     ------------------------------    ------
 712 System Normal (Maximum short-circuit)   SLG      Close-in       : on   to 86 IEEE123      0.039

Event:  1 at   2.38 cycles;  0.040 seconds; (all times below in SECONDS)

                                                         Primary  LZOP  Brkr  Total  Avail
     Substation                 LZOP Name           TYPE Backup   Time  Time  Time   CTI
IEEE123             R5                              MISC  PRIMARY 0.040 0.000  0.040   N/A NORMAL OPERATION
Element: 31 AUX "VCTRL ENABLE1"; (SEL-351S)   ; Contact Logic Code: VCTRL1      ; Op. Time:  0.000
Element: 31 AUX "VCTRL ENABLE2"; (SEL-351S)   ; Contact Logic Code: VCTRL2      ; Op. Time:  0.000
Element: 31 DIR "32QFG"; (SEL-351S)           ; Contact Logic Code: DIRG FW     ; Op. Time:  0.001
Element: 31 DIR "32QRG"; (SEL-351S)           ; Contact Logic Code: DIRG RV     ; Op. Time:  0.001
Element: 31 TOC "51G1T"; (SEL-351S)           ; Contact Logic Code: 51G1 FW     ; Op. Time:  0.040
Element: 31 TOC "51G2T"; (SEL-351S)           ; Contact Logic Code: 51G2 RV     ; Op. Time:  0.040
Element: 31 TOC "51P1T"; (SEL-351S)           ; Contact Logic Code: 51P1 FW     ; Op. Time:  0.040
Element: 31 TOC "51P2T"; (SEL-351S)           ; Contact Logic Code: 51P2 RV     ; Op. Time:  0.040

IEEE123             RTL4                            MISC  BACKUP  0.406 0.000  0.406  0.366 PREDICTED
Element: 34 AUX "VCTRL ENABLE1"; (SEL-351S)   ; Contact Logic Code: VCTRL1      ; Op. Time:  0.000
Element: 34 AUX "VCTRL ENABLE2"; (SEL-351S)   ; Contact Logic Code: VCTRL2      ; Op. Time:  0.000
Element: 34 DIR "32QFG"; (SEL-351S)           ; Contact Logic Code: DIRG FW     ; Op. Time:  0.001
Element: 34 DIR "32QRG"; (SEL-351S)           ; Contact Logic Code: DIRG RV     ; Op. Time:  0.001
Element: 34 TOC "51G1T"; (SEL-351S)           ; Contact Logic Code: 51G1 FW     ; Op. Time:  0.406
Element: 34 TOC "51G2T"; (SEL-351S)           ; Contact Logic Code: 51G2 RV     ; Op. Time:  0.406
Element: 34 TOC "51P1T"; (SEL-351S)           ; Contact Logic Code: 51P1 FW     ; Op. Time:  0.444
Element: 34 TOC "51P2T"; (SEL-351S)           ; Contact Logic Code: 51P2 RV     ; Op. Time:  0.444

IEEE123             R4                              MISC  BACKUP  0.794 0.000  0.794  0.754 PREDICTED
Element: 32 AUX "VCTRL ENABLE1"; (SEL-351S)   ; Contact Logic Code: VCTRL1      ; Op. Time:  0.000
Element: 32 AUX "VCTRL ENABLE2"; (SEL-351S)   ; Contact Logic Code: VCTRL2      ; Op. Time:  0.000
Element: 32 DIR "32QFG"; (SEL-351S)           ; Contact Logic Code: DIRG FW     ; Op. Time:  0.001
Element: 32 DIR "32QRG"; (SEL-351S)           ; Contact Logic Code: DIRG RV     ; Op. Time:  0.001
Element: 32 TOC "51G1T"; (SEL-351S)           ; Contact Logic Code: 51G1 FW     ; Op. Time:  0.794
Element: 32 TOC "51G2T"; (SEL-351S)           ; Contact Logic Code: 51G2 RV     ; Op. Time:  0.794
Element: 32 TOC "51P1T"; (SEL-351S)           ; Contact Logic Code: 51P1 FW     ; Op. Time:  0.893
Element: 32 TOC "51P2T"; (SEL-351S)           ; Contact Logic Code: 51P2 RV     ; Op. Time:  0.893

IEEE123             RTL1                            MISC  BACKUP  1.073 0.000  1.073  1.033 PREDICTED
Element: 40 AUX "VCTRL ENABLE1"; (SEL-351S)   ; Contact Logic Code: VCTRL1      ; Op. Time:  0.000
Element: 40 AUX "VCTRL ENABLE2"; (SEL-351S)   ; Contact Logic Code: VCTRL2      ; Op. Time:  0.000
Element: 40 DIR "32QFG"; (SEL-351S)           ; Contact Logic Code: DIRG FW     ; Op. Time:  0.001
Element: 40 DIR "32QRG"; (SEL-351S)           ; Contact Logic Code: DIRG RV     ; Op. Time:  0.001
Element: 40 TOC "51G1T"; (SEL-351S)           ; Contact Logic Code: 51G1 FW     ; Op. Time:  1.073
Element: 40 TOC "51G2T"; (SEL-351S)           ; Contact Logic Code: 51G2 RV     ; Op. Time:  1.073
Element: 40 TOC "51P1T"; (SEL-351S)           ; Contact Logic Code: 51P1 FW     ; Op. Time:  1.473
Element: 40 TOC "51P2T"; (SEL-351S)           ; Contact Logic Code: 51P2 RV     ; Op. Time:  1.473
```

Running CAPE in Real-Time

Running CAPE in Real-Time

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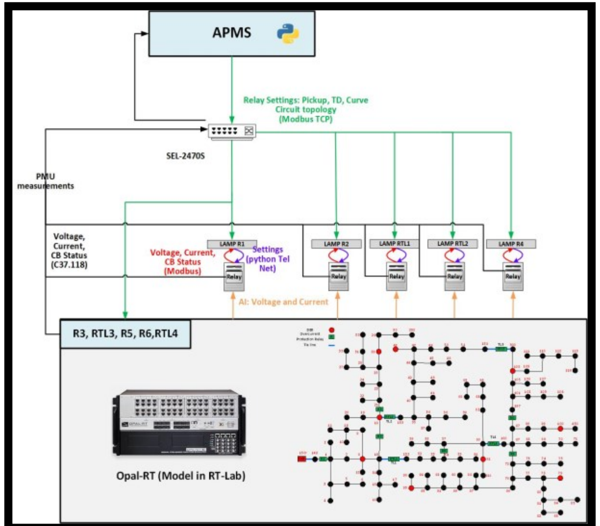
- For adaptive protection, CAPE represents a real-time digital twin of the system, which is updated based on system conditions
- Demonstrated using Opal-RT real-time hardware-in-the-loop simulator
  - Opal-RT grid simulator voltages and currents to the analog inputs of relays
  - Relays stream PMU data that updates CAPE model

A change in configuration was issued here. After blocking scheme was enabled, the system configuration took effect.

A Successfully change of circuit configuration. Closing Relay TL3 and Opening Relay TL 4.



CAPE Model Update with New Settings

- Uses PMU data to update real-time digital twin in CAPE
- Updates relay settings in CAPE based on the optimizer output
  - **UPDATE**: directional overcurrent settings are now available

This will run in sequence after the protection system sees the change in system.

Optimizer provides new set of settings.

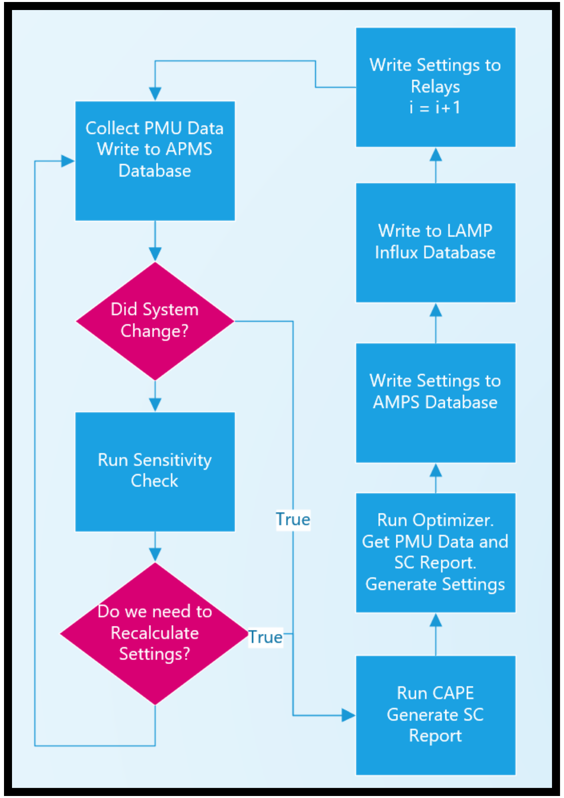
From CAPE, each LZOP are matched with corresponding data from optimizer.

CAPE model updater macro runs to update settings data in LZOP

Adaptive Protection Process

PMU data is streamed at 30 messages/sec

Sensitivity Check takes ~ ~~5~~, **0.3** seconds



Writing Settings to Relays Takes ~~~62,~~ **10** seconds*

Writing Settings to LAMP Database takes ~1 seconds

Writing Settings to AMPS Database takes ~1 seconds

Optimizer takes ~~~35~~, **11** seconds

CAPE SC Report takes ~35 seconds

The total process takes ~~~2~~ **1** min or ~4.5mins with the CAPE coordination check enabled

Adaptive Protection HIL

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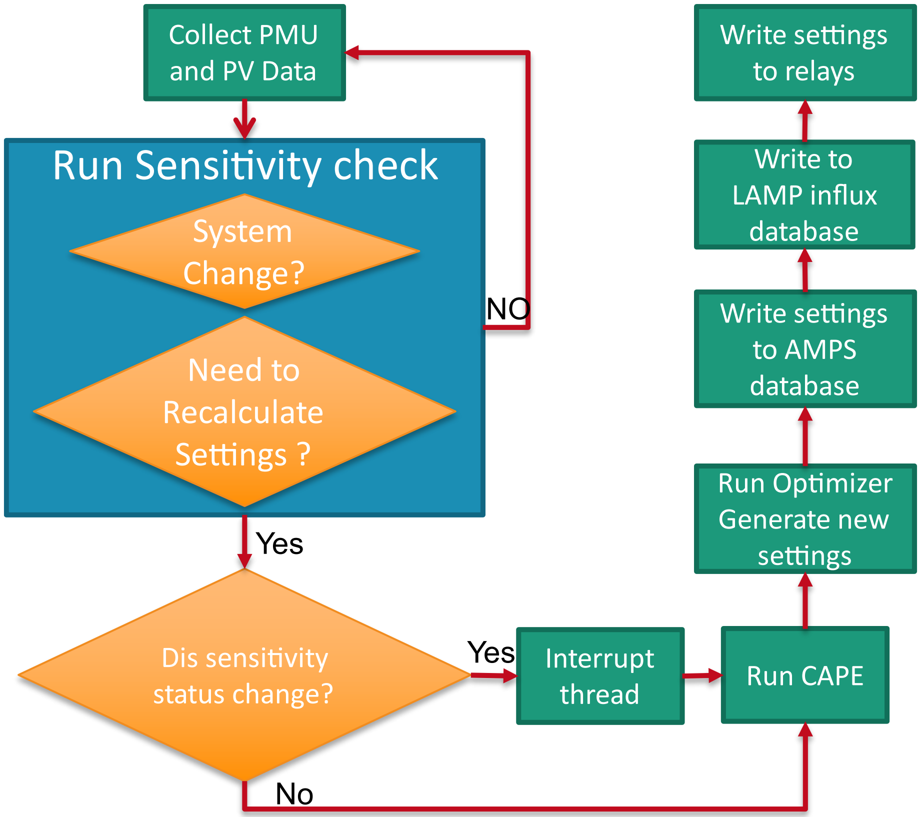
- CAPE can be run in a parallel thread for improved speed
- The parallel thread can be interrupted for real-time analysis



Modeling Inverter-Based DER in CAPE

Modeling Inverter-Based DER in CAPE

- For distribution protection studies, one of the key pieces is if DER will:

  A. Ride-through the fault and contribute fault current, or

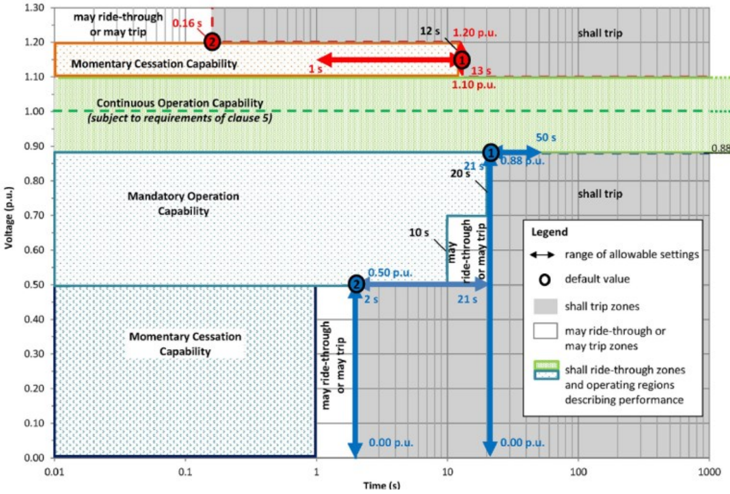
  B. Enter momentary cessation before the protective devices can react

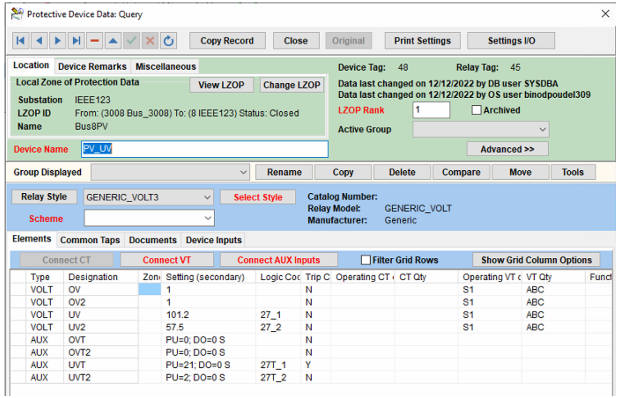
- Two methods developed for incorporating DER momentary cessation curves into CAPE

Modeling IBR in CAPE

- Adding Undervoltage Protection Relays to CAPE Model to each IBR to model the IEEE 1547 momentary cessation and disconnect
- Using the standard CAPE tools, such as sequence of operations and coordination studies, the IBR momentary cessation of each IBR will appear at the appropriate time

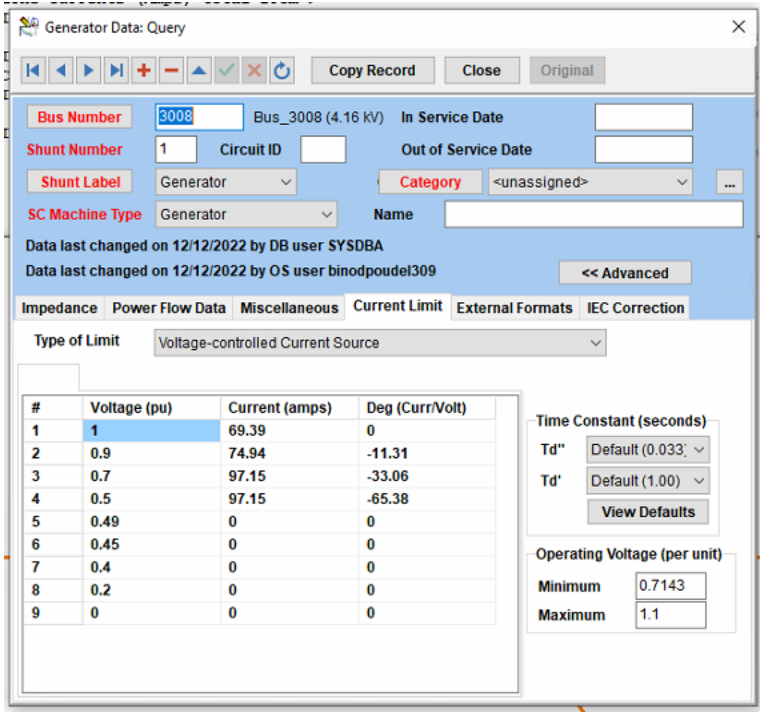
	Voltage	Clearing time (s)
OV2	1.2 pu	0.16
OV1	1.1 pu	13
UV1	0.88 pu	21
UV2	0.5 pu	2





Modeling IBR in CAPE

- To implement the momentary cessation requested by IEEE 1547, we used the voltage-controlled current source model in CAPE for IBRs.
- This helps us gather correct fault currents to optimize TOC elements since IBRs stop injecting current after 5 cycles if their voltage falls below 0.5 pu.



Voltage range (p.u.)	Operating mode/response	Minimum ride-through time (s) (design criteria)	Maximum response time (s) (design criteria)
$V > 1.20$	Cease to Energize[a]	N/A	0.16
$1.10 < V \leq 1.20$	Momentary Cessation[b]	12	0.083
$0.88 \leq V \leq 1.10$	Continuous Operation	Infinite	N/A
$0.70 \leq V < 0.88$	Mandatory Operation	20	N/A
0.50[c] $\leq V < 0.70$	Mandatory Operation	10	N/A
$V < 0.50$[c]	Momentary Cessation[b]	1	0.083

Ensuring Fault Clearing Before Equipment is Damaged

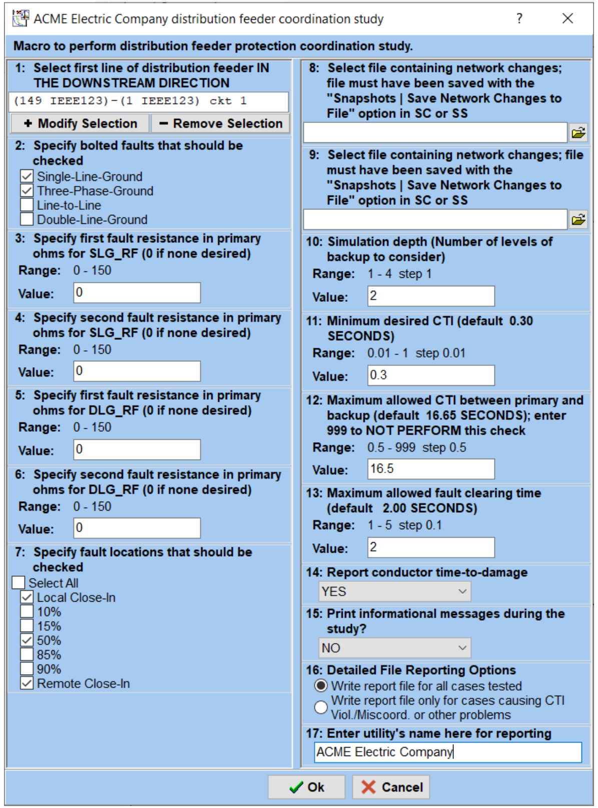
Using CAPE Equipment Databases

Equipment Damage Considerations

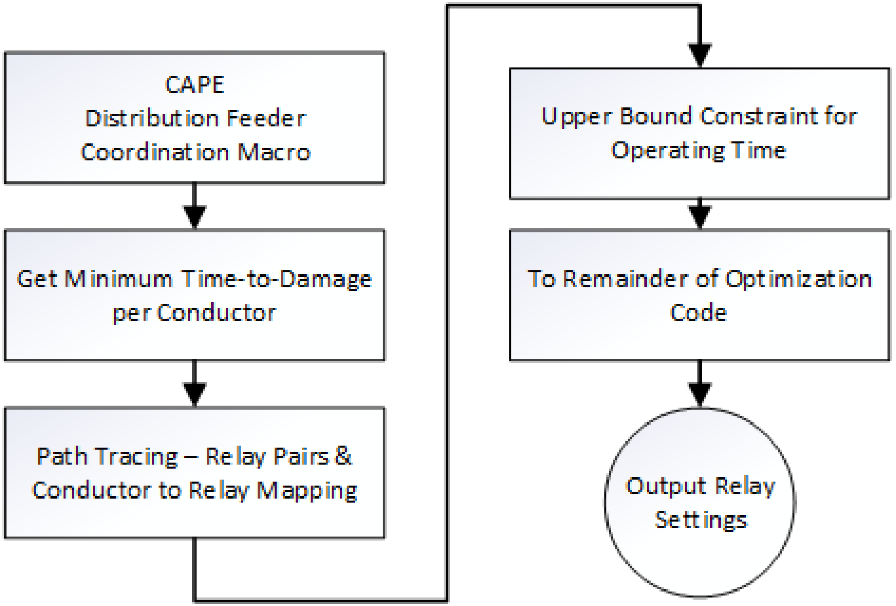
- Optimizer is minimizing the average clearing time for all possible faults in the system, but this does not necessarily guarantee all faults will be cleared fast enough to make sure we do not enter any transformer or line damage curves
- The equipment damage curves can be specifically added to the optimizer as a constraint to ensure all faults are cleared before equipment is damaged

Conductor Damage Constraint

Distribution Feeder Coordination Macro



Optimizer process diagram



Conductor Damage Constraint

Worst-case conductor in each relay's zone of protection.

Lowest system-wide time-to-damage highlighted.

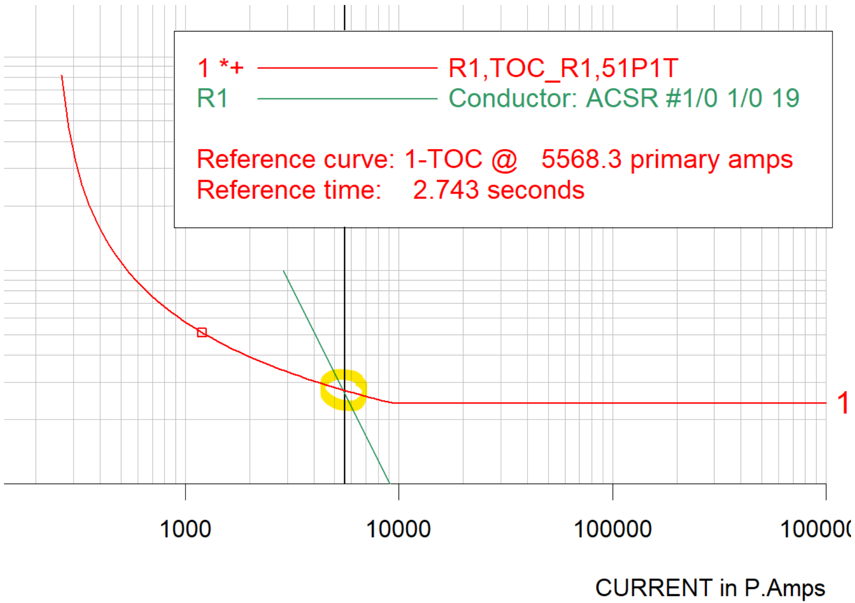
Example relay to conductor mapping

Relay	Element	Conductor From-To	Time-to-Damage (sec.)
R1	Phase	149 to 1	10.35
	Ground	13 to 34	3.02
R2	Phase	13 to 18	33.88
	Ground	18 to 19	3.92
R3	Phase	18 to 21	60+
	Ground	26 to 31	5.97
R4	Phase & Ground	57 to 54	60+
R5	Phase	60 to 62	10.12
	Ground	108 to 109	11.95
R6	Phase	60 to 62	10.12
	Ground	36 to 38	5.64
RTL1	(open)	N/A	N/A
RTL2	Phase	13 to 18	33.88
	Ground	18 to 19	3.92
RTL3	Phase	300 to 108	60+
	Ground	36 to 38	5.64
RTL4	Phase	60 to 62	10.12
	Ground	108 to 109	11.95

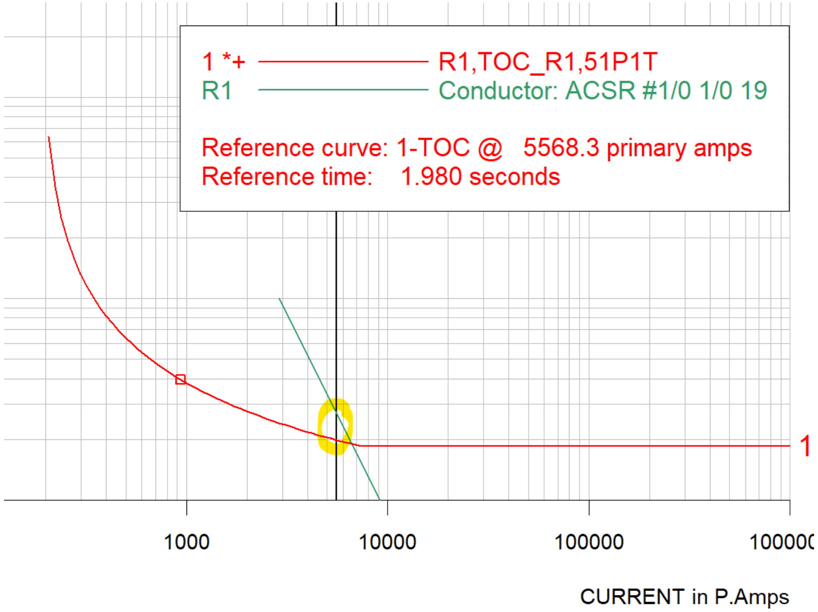
Conductor Damage Constraint

Example CTI improvement due to damage curve constraint:

Damage constraint **DISABLED**
CTI **Violated**



Damage constraint **ENABLED**
CTI **Achieved**



Conductor Damage Constraint

- Separate phase & ground constraint
- No damage violations
- Small impact on optimization time

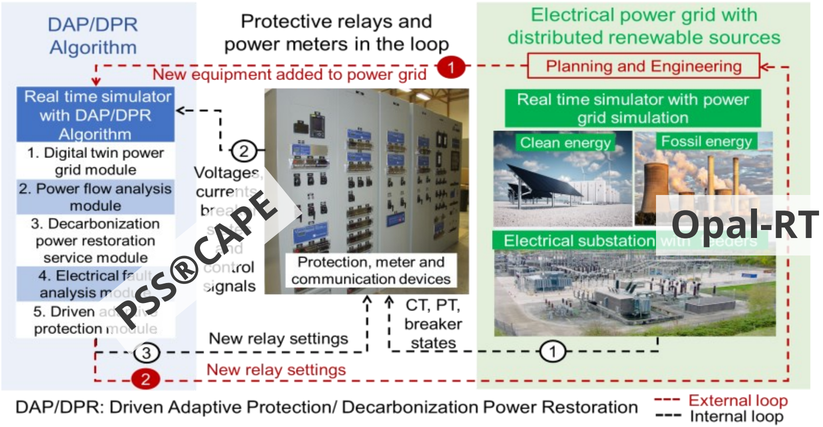
Optimization Runtime Summary

Case	Average Runtime (sec.)	Damage Violations
Base	32	N/A
Single Constraint	41	2
Separated Constraints	38	0

Conclusions

- The protection setting optimizer can determine the optimal protection functions and settings based on device capabilities
  - Adaptive protection updates in real-time with changing system conditions
- Integration with CAPE provides a robust and trusted fault current solver
- CAPE macros for protection coordination studies can be run in real-time to check for any issues with the current system configuration and protection settings
- Next Steps
  - New projects are expanding this to transmission systems
  - Could the real-time adaptive protection be used with grid-forming inverters and microgrids?

Questions?



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