Transformer Differential Protection Studies for Dominion Energy's Blackstart Operations

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Overview

- Introduction
- Protection Issues during Blackstart
- Transformer Differential Protection
- Real-time Simulation-Based Validation Methodology
- Results
- Conclusions and Future Work

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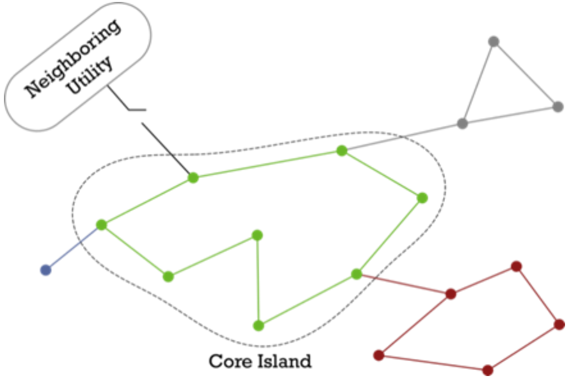
Introduction - Blackouts and Blackstart

Climate change, abnormal inclement weather conditions, converter-interfaced generation, cyber-attacks, and old equipment make it likely that a utility will face a ***blackout*** scenario

In compliance with NERC EOP-005-3 and PJM Manual 36, Dominion's System Restoration Plan (SRP) specifies the company's ***blackstart*** procedures. Dominion's SRP follows the core-island technique



Core-island Restoration Approach in Dominion's SRP

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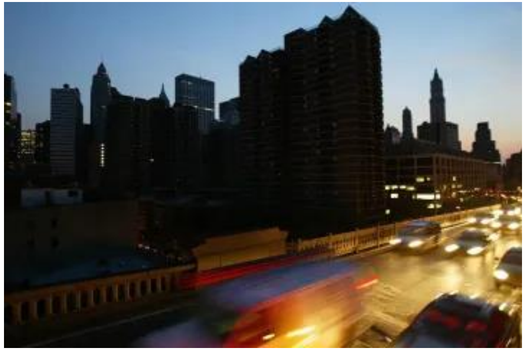

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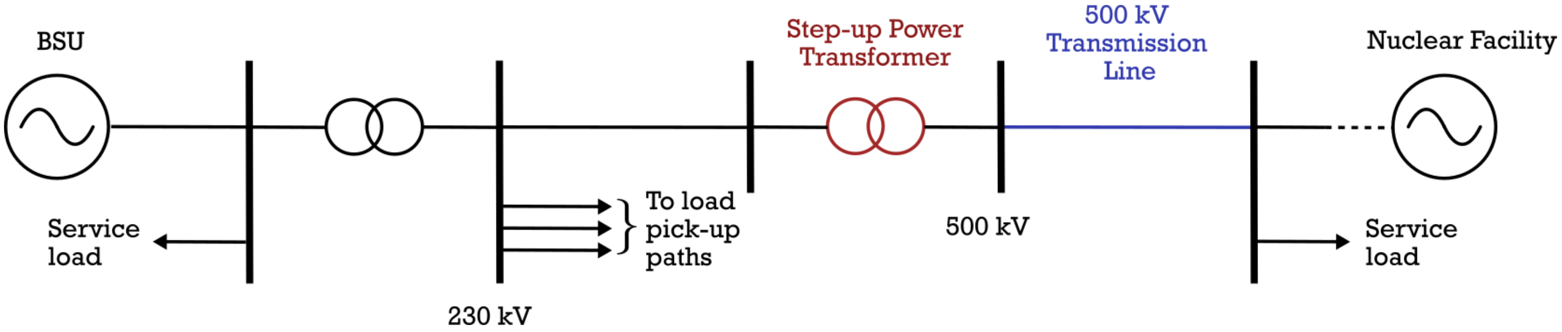
Protection Issues during Blackstart

Concern: relay maloperation during blackstart

Target: a ***methodology*** to ***test the protection schemes during blackstart conditions***

Approach: ***simulation-based testing involving the hardware settings deployed on the field***



Cranking path along a 500 kV corridor with a 230/500 kV power transformer and a 500 kV transmission line

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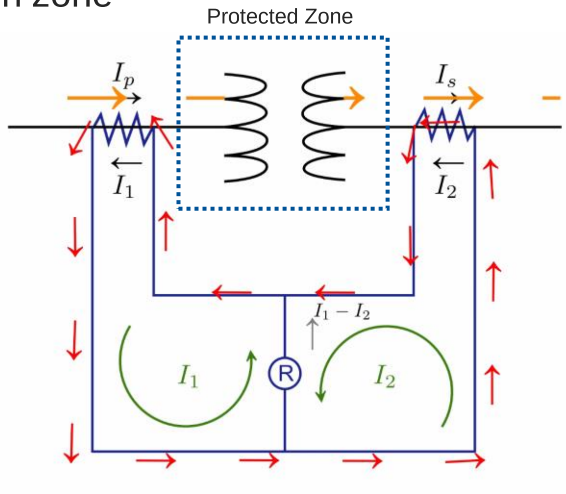
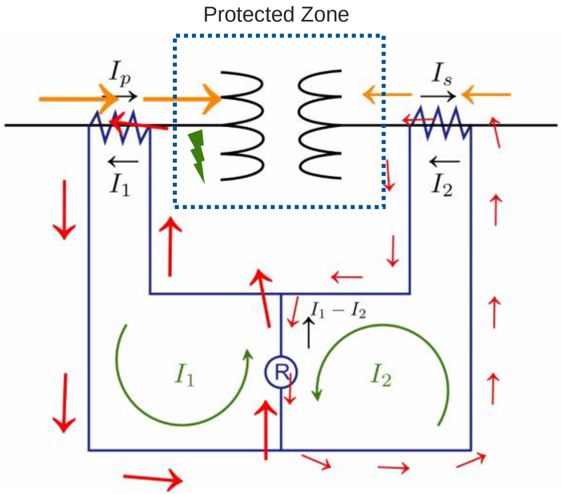
Transformer Differential Protection

Current-based ***differential protection*** is based upon comparing the currents flowing in and out of a protection zone



Normal Condition

- No differential current
- No tripping



Internal Fault

- Differential current
- Tripping of associated breakers

Transformer Differential Protection

Operate Current: $I_{OP} = I_1 - I_2$

Restraint Current: $I_{R,avg} = k\,(|I_1| + |I_2|)$ *average restraint*

$I_{R,max} = \max(|I_1|, |I_2|)$ *maximum restraint*

$I_{OP} \geq \kappa I_R$

Tripping Rule for Differential Protection

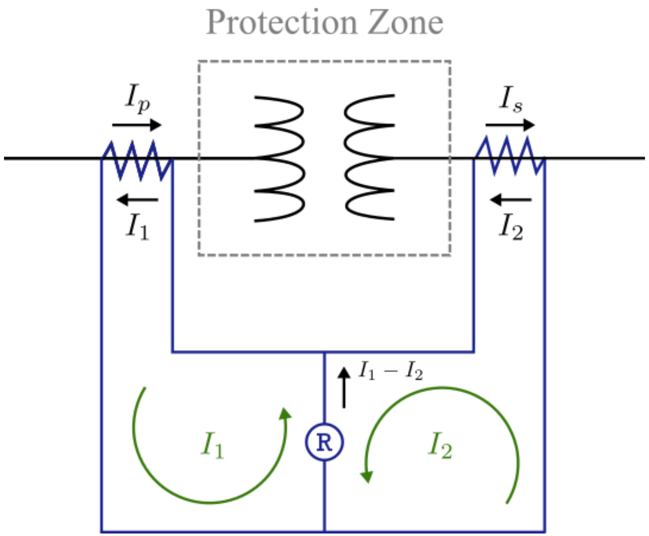
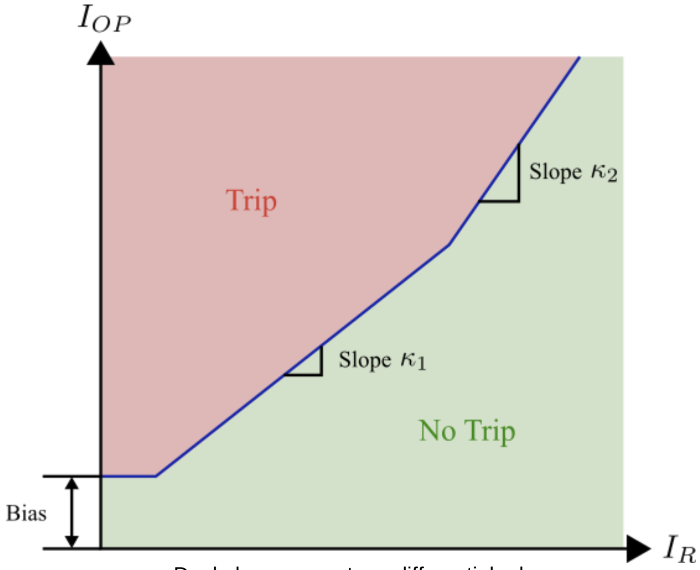


Illustration of the Differential Protection Principle



Dual-slope percentage differential relay characteristic

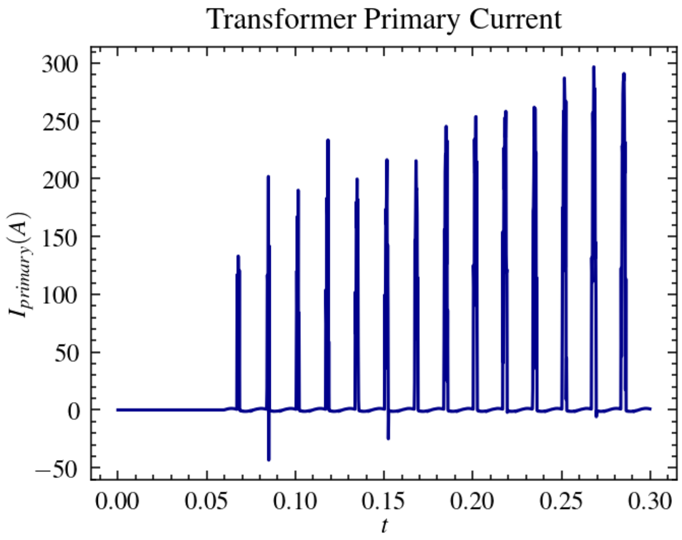
Issues during Blackstart

During transformer energization, the flux linkages reach the magnetic saturation region of the core, resulting in a *low inductance as seen from the source* (more source current is drawn)

The ***magnetizing in-rush current*** can reach **up to 200%** of the nominal current value during energization

Moreover, since it flows only through the winding being energized, *it could produce a differential current*

However, the ***in-rush current has a rich harmonic component***, from which the second component is the largest



Differential protection algorithms have ***harmonic restraint*** or ***harmonic blocking functions*** to avoid tripping due to in-rush currents during energization

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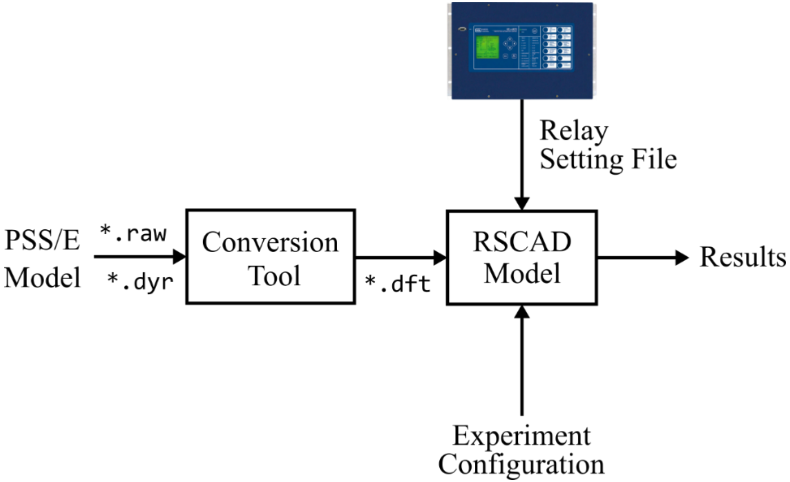
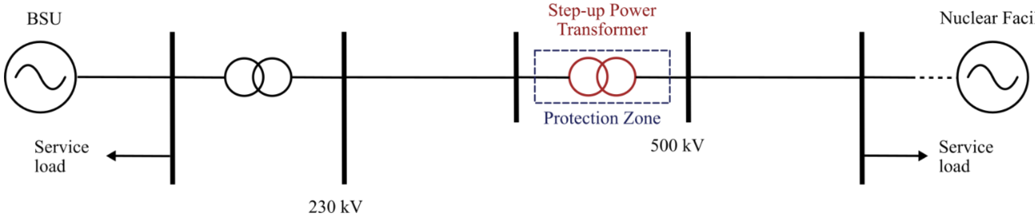
Real-Time Simulation-Based Validation

The RSCAD model was constructed from a phasor-domain dynamic modeled in PSS/E using the built-in conversion tool. Once imported to RSCAD, the model was adjusted for a blackstart simulation by adding the corresponding circuit breaker at all substation nodes.



Simulation methodology importing the network model settings from PSS/E and the relay configuration into RSCAD



Single-line diagram for the cranking path of study showing the transformer protection zone

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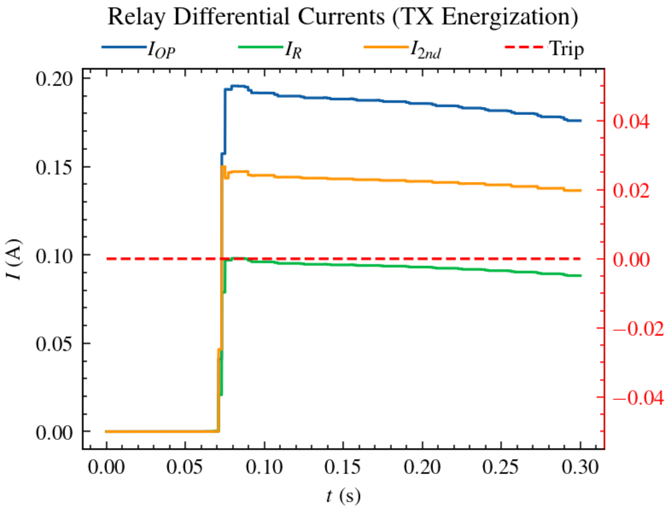
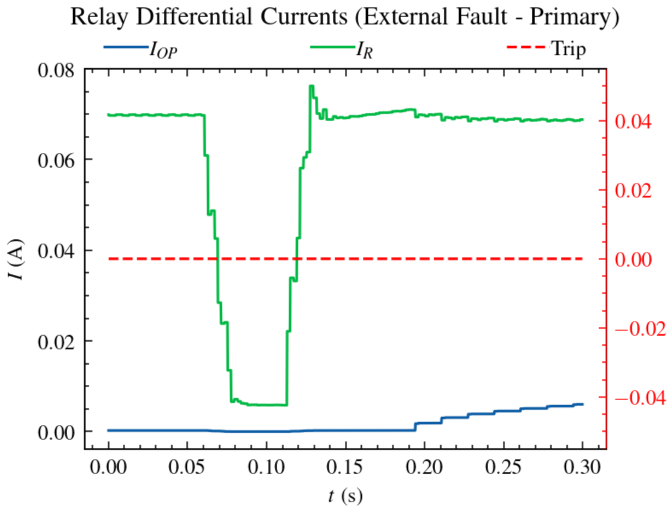
Results – Experiments

Several experiments proposed to characterize the behavior of the transformer protection under blackstart conditions were considered, including:

- energization from the blackstart unit (BSU);
- external faults on the transformer primary side;
- internal faults on the primary side;
- internal faults on the transformer secondary side;
- external faults on the transformer secondary side.

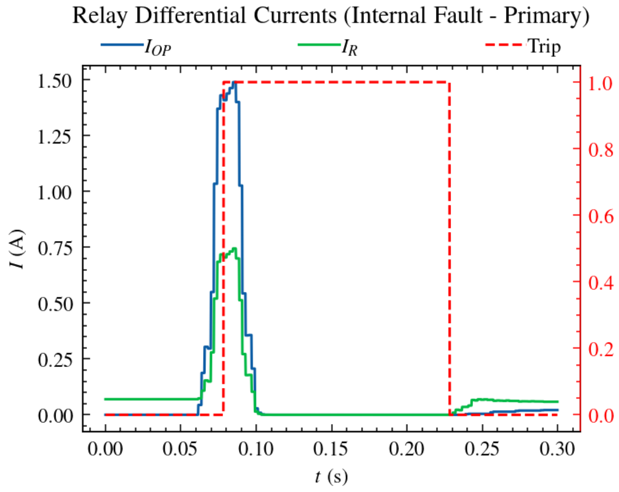
Results - Experiments

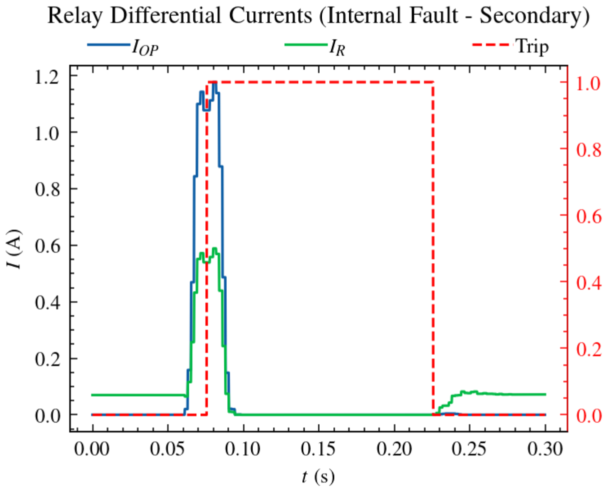




The in-rush current did ***not*** result in false tripping during transformer energization, despite the flow of operating current. Tripping does not occur when the fault is outside the protection zone

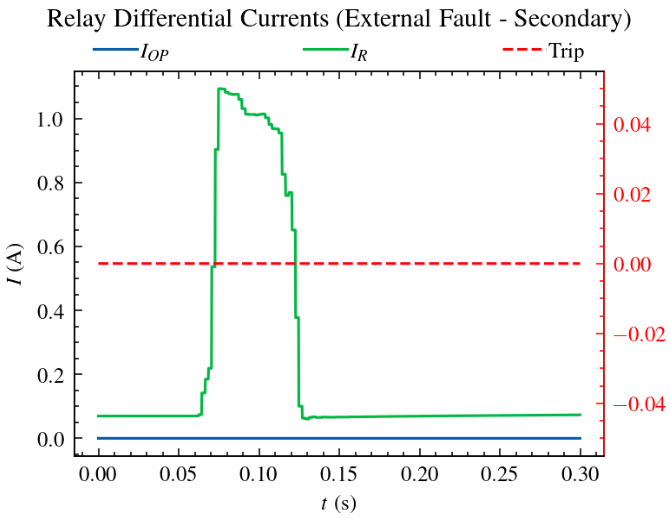
Results – Experiments (Internal Faults)

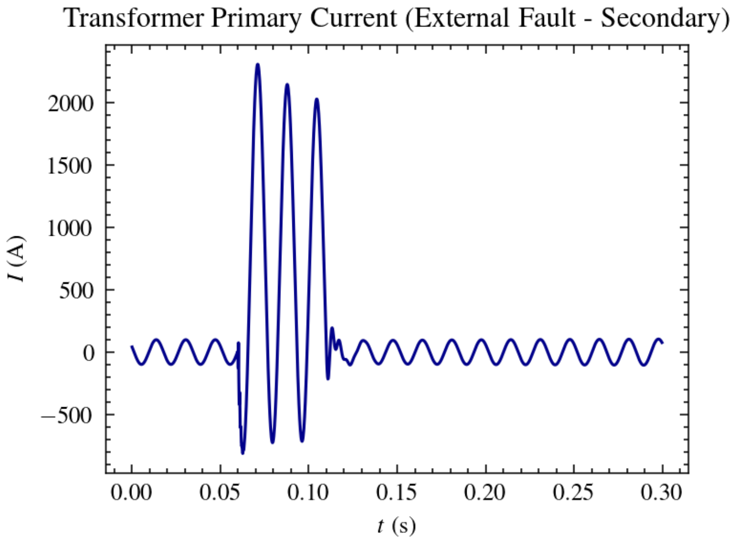




When a fault happens within the transformer protection zone (i.e., inside the substation), the relay logic ***operates adequately***, opening the associated circuit breaker to isolate the protected apparatus

Results – Experiments (External Faults)





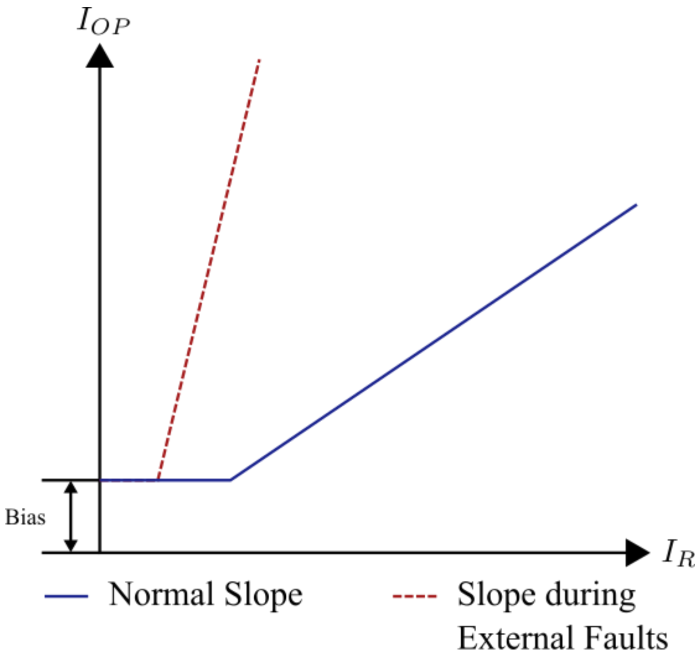
If external fault is applied on the outer region on the transformer secondary side, we observed no tripping signal. The fault current circulates through the transformer windings, which could could result in overheating and, in the long-term, aging of the equipment

Discovered Problem

Problem: mismatch between the software relay model and the actual relay deployed on the field

Software relay model: static percentage characteristic that stays the same regardless of the grid condition

Physical relay on the field: adaptive slope strategy which changes its selectivity threshold based on the level of the restraint current



Solution: Simulation with digital twins (e.g., Typhoon HIL) or Hardware-in-the-loop simulation with physical relay

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Conclusions

- Energization experiments showed that the harmonic restraint settings were valid to prevent undesired tripping when the transformer is connected to the network, despite the in-rush current causing a non-zero operating current.
- Likewise, the performance of the differential protection is satisfactory during internal faults
- External fault scenarios showed that a software relay model might be insufficient to correctly assess relay performance during blackstart. In our model, the flow of fault current through the relay did not issue a trip signal
- The adaptive characteristic of the percentage differential scheme would trip the circuit breaker when the current flow through the transformer increased due to an external fault

Future studies: differential protection functions utilizing Hardware-in-the-Loop simulations with the same relay hardware deployed in the field

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