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Transformer Differential Protection Studies for Dominion Energy's Blackstart Operations

S.A. DORADO-ROJAS
Rensselaer Polytechnic Institute
USA

X. LI, R. LIU, M.J. TILL
Dominion Energy
USA

SUMMARY

Blackout events are likely to happen in modern power systems due to abnormal weather events and weaknesses in the digital infrastructure of the grid. Utility companies design System Restoration Plans (SRPs) to provide the most secure and fastest way to bring customer service back by specifying detailed blackstart maneuvers. However, the system in a restoration condition lacks the electrical strength of the network during normal conditions. In particular, protective relaying is critical to the success of a blackstart. Misoperation of protection schemes could potentially delay the system-wide restoration efforts and further damage the affected equipment. This work addresses system protection performance during blackstart using an evaluation methodology based on real-time simulation in RTDS. The study case is a differential protection scheme for a 500 kV transformer within a cranking path outlined in Dominion's SRP. We showed that the protection scheme behaves correctly for internal faults, but our experiments were not conclusive regarding external faults. We analyzed this case further and proposed solutions to reach more demonstrative results so that the performance of relaying functions can be correctly assessed during blackstart.

KEYWORDS

Blackstart, Differential protection, In-rush current, Real-time simulation, RTDS

dorads@rpi.edu

I. INTRODUCTION

The resiliency of modern electric grids allows them to withstand a broad range of harmful events while keeping continuity of service. However, 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.

The process of restoring power after a blackout without the help of neighboring utilities, called a blackstart, must achieve a two-fold objective [1], [2]: it shall maximize the share of restored service while minimizing the elapsed time. 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 (Figure 1).

This method is designed to form a relatively highly meshed, stable island while supplying critical loads as soon as possible. The resulting stable island can also be connected to neighboring utilities more quickly, which leads to a more significant fault current capacity and small clearing times, thus strengthening the security margins of the system. An example of a cranking path within Dominion's SRP is presented in Figure 2.

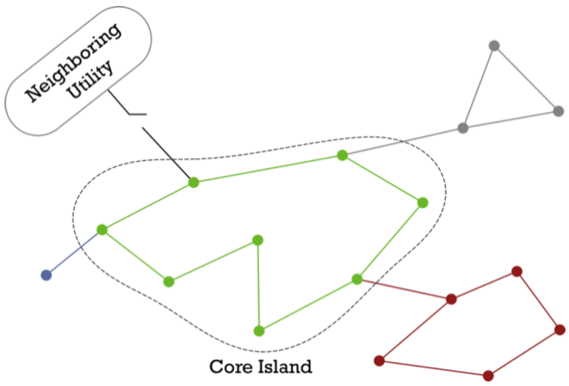

Figure 1. Core-island Restoration Approach in Dominion's SRP.

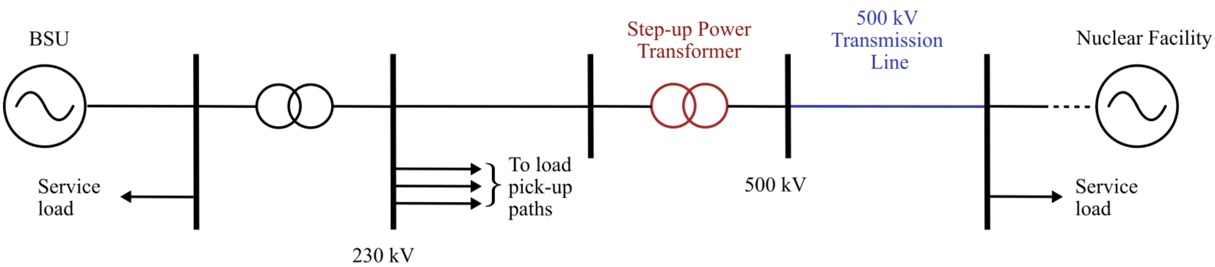

Figure 2. Cranking Path in the Dominion's SRP along a 500 kV corridor.

Blackstart procedures are supported by several studies that investigated the steady-state and dynamic behavior of the system (e.g., [3]–[5]). Among the numerous studies associated with the SRP, one of the most critical analyses concerns the performance of protective equipment during restoration. In the early stages of a blackstart maneuver, the electrical island is electrically weaker than the system during regular operation. Since relay characteristics are set up by contingency analysis on the grid under normal conditions, it is not guaranteed that protective equipment will operate adequately during a system-wide restoration.

Real-time simulation represents a solid approach to validating the performance of protective equipment during a blackstart. A real-time simulation can dynamically represent the system under balanced and unbalanced conditions and is particularly helpful in validating different protection functions [6].

Dominion previously employed RTDS in different studies of its SRP (see [4], [7]). The scope of this work is to validate the performance of a protection scheme during blackstart via real-time simulation. More specifically, we focus on a differential protection scheme for a 230/500 kV transformer.

This paper is structured as follows: Section II discusses briefly the foundations of a current-based differential protection scheme and introduces the issues arising during blackstart. In Section III, we discuss the methodology to validate protection performance by means of real-time simulation using RSCAD. Results are discussed in Section IV. Conclusions and suggestions for future inquiry are presented in Section V.

II. TRANSFORMER DIFFERENTIAL PROTECTION

a. Differential Protection Foundations

The foundation of differential protection is Kirchhoff's Current Law (KCL), which maintains that during normal conditions, the currents entering a node must equal the currents flowing out. Current-based differential protection is based upon comparing the currents flowing in and out of a protection zone (Figure 3). If the difference between these currents exceeds a given threshold, corrective action is taken, and the current flow through the protected device is interrupted.

Ideal differential protection is the most selective protection strategy since it responds only to faults within its protection zone. In practice, a differential current may exist during non-fault conditions, causing an unwanted relay action that may harm the continuity of service. The main factor leading to undesired tripping is *false differential currents*. A false differential current flows through the current transformer (CT) windings and not through the protected apparatus ports. In practice, the principal cause of false differential currents is CT saturation.

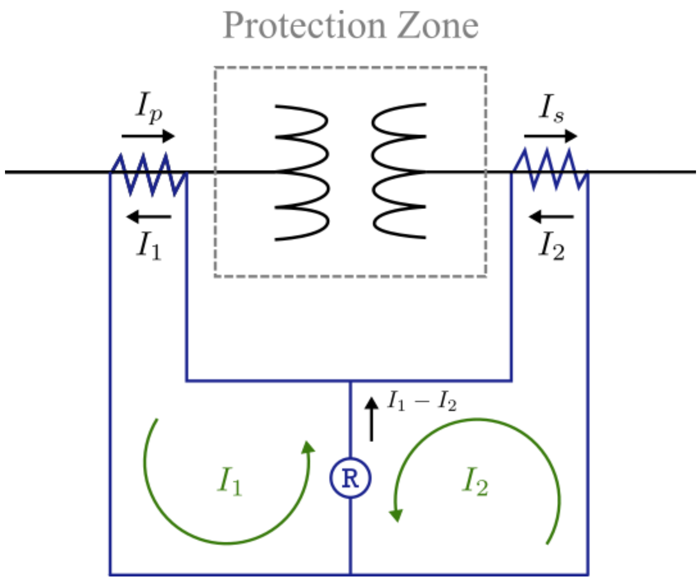

Figure 3. Illustration of the Differential Protection Principle

The *percentage restrained differential protection* scheme overcomes most of the practical challenges of the ideal differential scheme [8]. A percentage restraint differential relay operates as a function of two quantities: the operating current (I_{OP}) and the through or restraint current (I_R).

The operating current corresponds to the differential current in the protection zone and is computed as (see [8]):

$$I_{OP} = I_1 - I_2 \tag{1}$$

The restraint current is a function of the winding currents. There are several definitions for I_R. The most common are the average restraint and the maximum restraint [10]. The average restraint corresponds to a weighted average of the current magnitudes where k is a slope or weighting factor:

$$I_{R,\text{avg}} = k\left(\left|I_1\right| + \left|I_2\right|\right) \tag{2}$$

Likewise, the maximum restraint corresponds to the maximum magnitude current flowing in the protection zone:

$$I_{R,\max} = \max\left(\left|I_1\right|, \left|I_2\right|\right) \tag{3}$$

The relay action is determined based on whether or not the operate current exceeds a given threshold of the restraint current. Therefore, the definition of the restraint current characterizes to a great extent the relay differential functionality.

The simplest tripping rule for percentage differential protection is given by:

$$I_{OP} \geq k I_R \tag{4}$$

where k is a slope factor; its definition depends on the desired selectivity. To compensate for false differential currents, a *bias* or minimum pickup is set. The higher the bias, the less sensitive the relay is to relay saturation and CT errors. In practice, a dual-slope characteristic is commonly used, as shown in Figure 4. This differential characteristic is employed in this study.

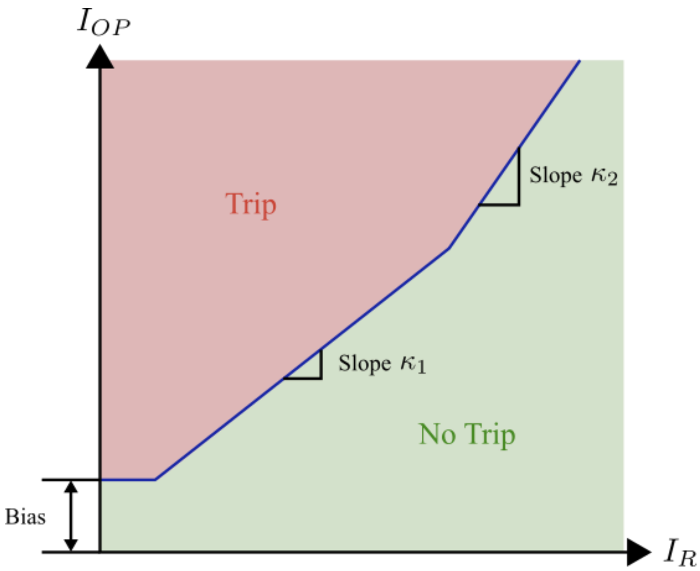

Figure 4. Dual-slope percentage differential relay characteristic

b. Issues during Blackstart

During transformer energization, the flux linkages reach the magnetic saturation region of the core transiently, resulting in a low inductance as seen from the source. Consequently, more source current is drawn. The magnitude of the so-called *in-rush* current depends on the instant of energization of the transformer (as with any RL circuit) and the remnant flux in the core.

The magnetizing in-rush current can reach up to 200% of the nominal current value during energization [8], [9]. Moreover, since it flows only through the winding being energized, it could produce a differential current that activates the protective relay of the transformer. However, the in-rush current has a rich harmonic component, from which the second component is the largest [8] (see Figure 5). Differential protection algorithms *have harmonic restraint or harmonic blocking functions* to avoid tripping due to in-rush currents during energization.

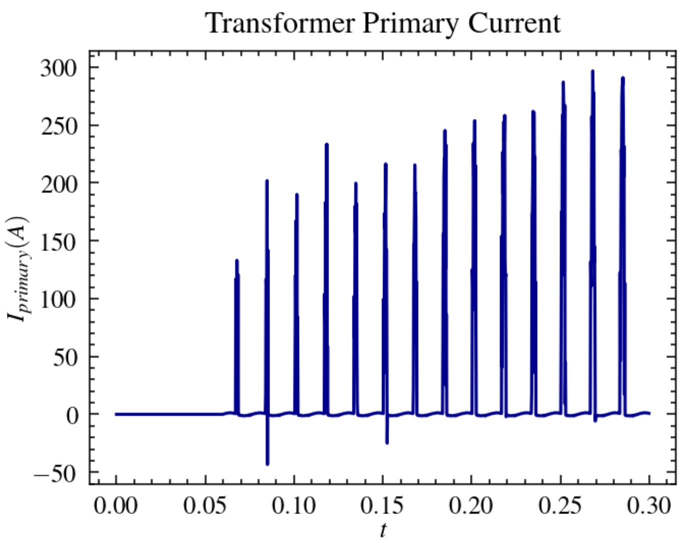

Figure 5. Typical waveform of transformer in-rush current during energization

In general, in-rush currents tend to have larger magnitudes when a transformer is energized from the low-voltage side. This scenario corresponds to the blackstart plan in Dominion's SRP where the 230/500 kV power transformer is energized from the low voltage side. Therefore, it is crucial to verify if the in-rush current settings set for energization in normal operation could cause misoperation of differential protection schemes when the system is undergoing a blackstart [10], [11].

III. REAL-TIME SIMULATION-BASED VALIDATION METHODOLOGY FOR PROTECTIONS

Validation of the protection scheme's performance was carried out by real-time simulation in RTDS. 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. The single-line diagram illustrating the protection zone is shown in Figure 6.

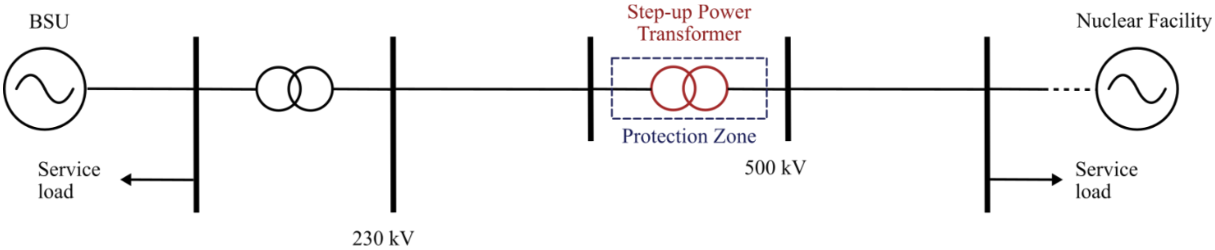

Figure 6. Single-line diagram for the cranking path of study showing the transformer protection zone

The relay functionality was implemented with a differential protection block included in the Protection & Automation library of RSCAD. The configuration of the protection model was modified to match the settings deployed on the field as closely as possible. More specifically, we matched the static dual-slope percentage differential settings. The simulation methodology is illustrated below in Figure 7.

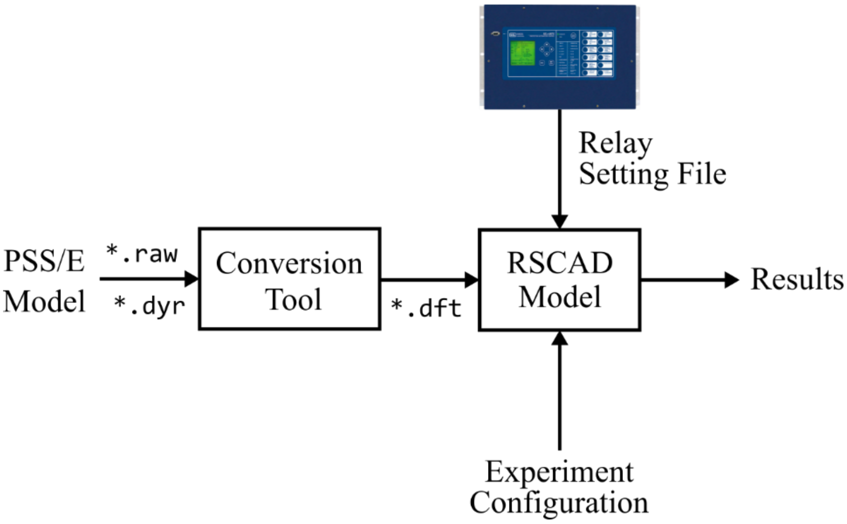

Figure 7. Simulation methodology importing the network model settings from PSS/E and the relay configuration into RSCAD

IV. RESULTS

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

1. Energization from the blackstart unit (BSU).
2. External faults on the transformer primary side.
3. Internal faults on the primary side.
4. Internal faults on the transformer secondary side.
5. External faults on the transformer secondary side.

All fault scenarios were tested on single-phase, two-phase, and three-phase short circuits.

The in-rush current did not result in false tripping during transformer energization, despite the flow of operating current seen in Figure 8. Our experiment confirmed that the employed setting in the harmonic restraint function also holds for system-wide restoration conditions.

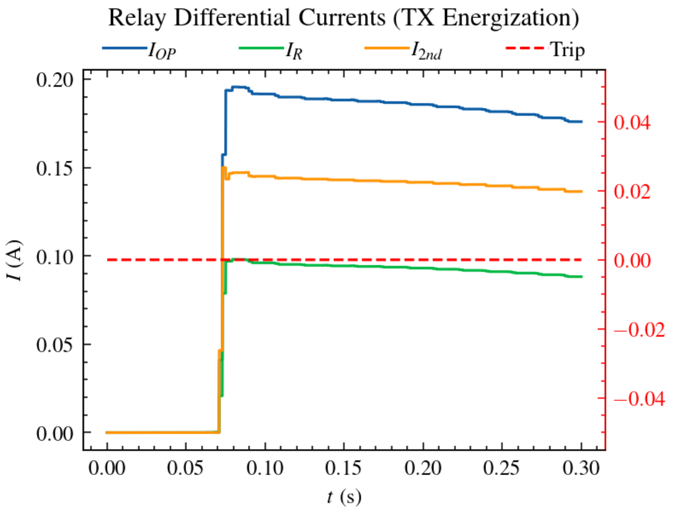

Figure 8. Operate, restraint and second harmonic current during energization in blackstart operation

Regarding the external fault scenario on the primary side, we did not observe any tripping action (Figure 9). This was expected since the fault was outside the protection zone, and the fault current did not flow through the transformer windings.

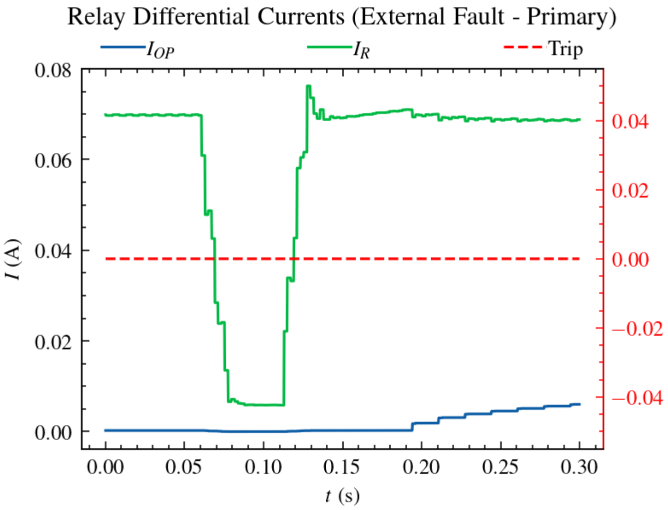

Figure 9. Differential currents following an external fault on the primary side

Now, when a fault happened within the transformer protection zone (i.e., inside the substation), the relay logic operated adequately, opening the associated circuit breaker to isolate the protected apparatus. The tripping signal was correctly issued for all fault types (Figure 10).

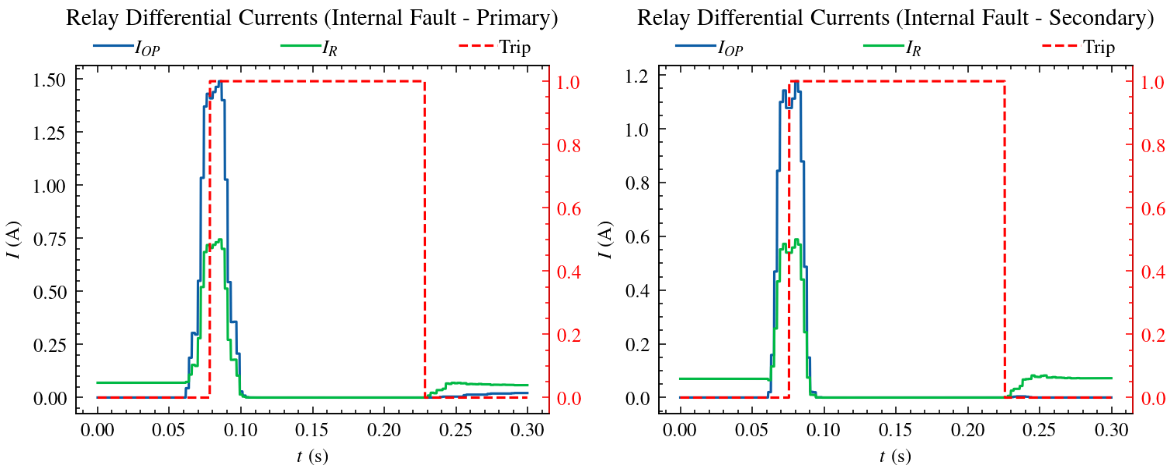

Figure 10. Differential currents following an internal fault in the protection zone

For the scenario where an external fault was applied on the outer region on the transformer secondary side (Figure 11), we observed no tripping signal. Since the fault was located outside the protection zone, such behavior aligns with the differential protection philosophy.

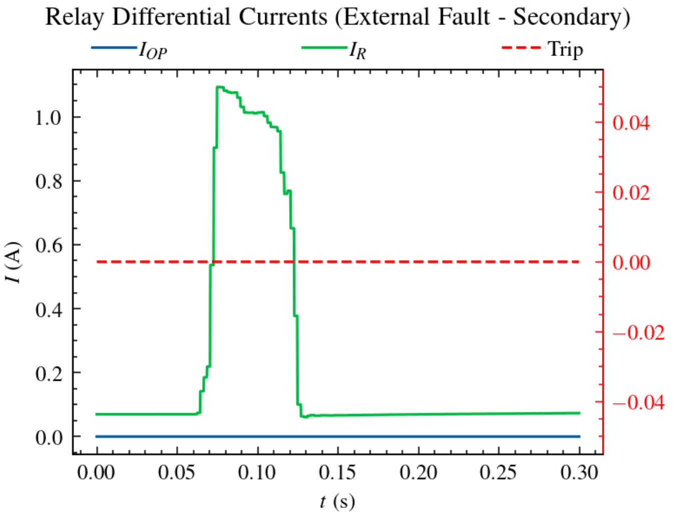

Figure 11. Differential currents following an external fault outer to the secondary zone

However, the fault current circulates through the transformer windings (see Figure 12). Such current flow could result in overheating and, in the long-term, aging of the equipment. Therefore, such behavior is not acceptable in practice.

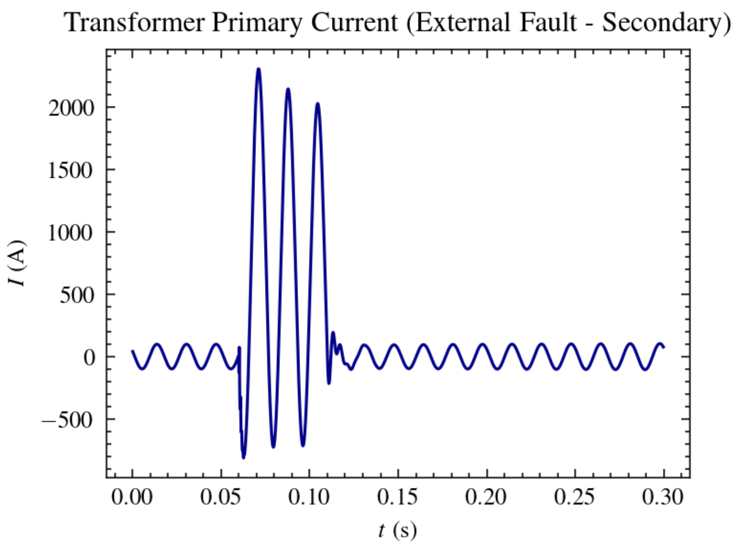

Figure 12. Current through the primary windings during an external fault on the secondary side

This undesired behavior was not due to an incorrect setting in the Dominion's protection system. Instead, it was caused by a mismatch between the software relay model and the actual relay deployed on the field. The software relay model offers only a static percentage characteristic that stays the same regardless of the grid condition. The physical relay on the field counters with an adaptive slope strategy which changes its selectivity threshold based on the level of the restraint current. The relay characteristic becomes steeper when the current flowing through the transformer exceeds a given magnitude (Figure 13). The larger the current flowing through the transformer, the more sensitive the relay is to external faults. Therefore, when the restraint current becomes too large, the relay will command the associated circuit breakers to protect the transformer.

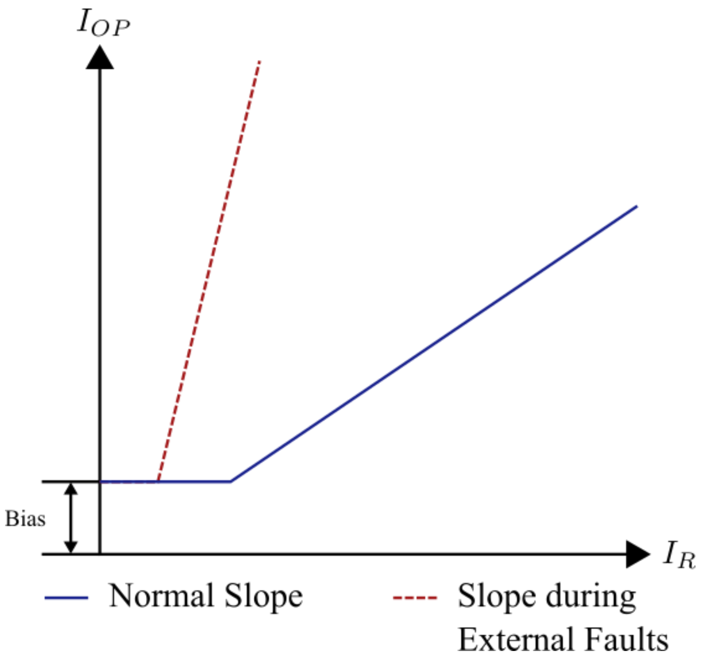

Figure 13. Adaptive slope characteristic (illustration for single-slope)

There are several alternatives to overcome such limitations of software protection models. On the one hand, one could construct the adaptive relay logic as it is implemented in the physical device and match its settings to what is deployed on the field. Likewise, a digital twin[1] relay model would guarantee the same functionality in the real-time model as the corresponding setting file. The former alternative would require significant effort and would have to be validated against the actual relay settings. As per the latter, such digital twins of SEL relays were not available in RSCAD at the time of this writing, to the best of the author's knowledge.

Another alternative is to perform Hardware-in-the-Loop (HIL) testing using the relay hardware configurations used in the field. While this solution requires a more elaborate setup, it should give the most accurate results concerning protective delay performance during a blackstart. HIL experimentation can be the scope of future work.

V. CONCLUSIONS AND FUTURE WORK

This work represents the first step towards a real-time simulation-based methodology to evaluate the performance of protection schemes during blackstart. We created an RSCAD model for blackstart conditions by importing an existing PSS/E model for the cranking path of interest. A built-in software model for transformer differential protection was set to match the relay configuration on the field. 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, resulting in a breaker opening to isolate the transformer from the grid.

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

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[1] Siemens and Typhoon HIL are two examples of digital twin solutions for relay equipment.

issue a trip signal. However, in practice, 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. A direction for future studies would be the validation of differential protection functions utilizing Hardware-in-the-Loop simulations with the same relay hardware deployed in the field.

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