Switch-on-to-Fault Schemes in the Context of Line Relay Loadability

A Technical Document

Prepared by the

System Protection and Control Task Force

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PURPOSE

The *Protection System Review Program – Beyond Zone 3* document, issued in August 2005, Appendix B stated:

> "When determining the switch on to fault element settings, each utility shall verify that the schemes will not operate for emergency loading conditions."

Unfortunately, this requirement was not accompanied by adequate guidance. This reference document is intended to provide transmission protection system owners with guidance for the review of existing switch-on-to-fault schemes to ensure that those schemes do not operate for non-switch-on-to-fault conditions or under heavily stressed system conditions. This document also provides recommended practices for application of new switch-on-to-fault schemes.

INTRODUCTION

Switch-on-to-fault (SOTF) schemes[1] are protection functions intended to trip a transmission line breaker when closed on to a faulted line. Dedicated SOTF schemes are available in various designs, but since the fault-detecting elements tend to be more sensitive than conventional, impedance-based line protection functions, they are generally designed to be "armed" only for a brief period following breaker closure. Depending on the details of scheme design and element settings, there may be implications for line relay loadability. This paper addresses those implications in the context of scheme design.

SOTF SCHEME APPLICATIONS

SOTF schemes are applied for one or more of three reasons:

1. When an impedance-based protection scheme uses line-side voltage transformers, SOTF logic is required to detect a close-in, three-phase fault to protect against a line breaker being closed into such a fault. A phase impedance relay whose steady-state tripping characteristic passes through the origin on an R-X diagram will generally not operate if there is zero voltage applied to the relay before closing into a zero-voltage fault. This condition most often occurs when a breaker is closed into a set of three-phase grounds which operations/maintenance personnel failed to remove prior to re-energizing the line. When this occurs in the absence of SOTF protection, the line protection will not operate to trip the breaker, nor will breaker failure protection be initiated, possibly resulting in time-delayed tripping at numerous remote terminals. Unit instability and dropping of massive blocks of load can also occur.

1 Also known as "Close-into-fault" or "Line pickup" schemes.

SOTF current fault detector pickup settings must be low enough to allow positive detection of close-in three-phase faults under what is considered to be the "worst case" (highest) impedance to the source bus.

2. When an impedance protection scheme uses line-side voltage transformers, SOTF current fault detectors may operate significantly faster than impedance units when a breaker is closed into a fault anywhere on the line. The dynamic characteristics of typical impedance units are such that their speed of operation is impaired if polarizing voltages are not available prior to the fault.

   Current fault detector pickup settings will generally be lower in this application than in (1) above. The greater the coverage desired, and the higher the source impedance, the lower the setting.

3. Regardless of voltage transformer location, SOTF schemes may allow high-speed clearing of faults along the entire line without having to rely or wait on a communications-aided tripping scheme. Current or impedance-based fault detectors must be set to reach the remote line terminal to achieve that objective.

The cited objectives may not be fully compatible with NERC line loadability requirements depending on the design of the SOTF scheme and on its attendant settings.

SOTF LINE LOADABILITY CONSIDERATIONS

The SOTF protection must not operate assuming that the line terminals are closed at the outset and carrying up to 1.5 times the emergency line rating, subject to applicable technical exceptions.

There is also a concern, based on actual events which have occurred in connection with blackouts, for the undesired operation of SOTF schemes when a breaker is closed into a line which is already energized from another terminal. The SOTF protection must not operate when a breaker is closed into an unfaulted line that is energized with a voltage exceeding 0.85 PER UNIT from the remote terminal.[2]

However, 0.85 per unit voltage should not be construed as a limit below which there is no concern. There have been situations where the pre-closing line voltage was 0.80 per unit or lower, and where the need to restore the transmission path was critical. The goal, therefore, is that SOTF schemes should not operate falsely for any condition where breaker closing is called for either by decision of the system operator or by an automatic reclosing scheme.

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2 Note that the voltage at the local end of the line may be greater than or less than 0.85 per unit at the remote end due to the effects of line capacitance or tapped load. Any such differences are ignored for purposes of this document.

This goal may be achieved with a combination of techniques including but not limited to:

- Utilize a SOTF scheme design which is enabled only in the period immediately following breaker closing.
- Set SOTF line voltage detectors (used to arm SOTF tripping) no higher than required to override induced voltages on the line when open at all terminals.
- Set SOTF current fault detectors no lower than required to clear a close-in three-phase fault under worst-case (highest source impedance) conditions.

Existing SOTF schemes may not have the requisite flexibility either as to scheme logic or range of available settings to satisfy NERC line loadability requirements while meeting the minimum fault protection requirements. In these cases, transmission system protection owners must implement scheme upgrades.

SOTF SCHEME DESIGNS

1. *Direct-tripping high-set instantaneous phase overcurrent*

This scheme is technically not a SOTF scheme, in that it is in service at all times, but it can be applied under certain circumstances for clearing zero-voltage faults. It uses a continuously-enabled, high-set instantaneous phase overcurrent unit or units.

This scheme must be applied such that all of the following conditions are satisfied:

- The overcurrent relays must be set to detect the fault under "worst case" (highest source impedance) conditions.
- The overcurrent relays must not operate for external fault conditions or for stable load swings.
- In accordance with the NERC relay loadability requirements as noted in *Protection System Review Program – Beyond Zone 3*, dated August 2005, the overcurrent settings must be greater than 1.5 times the four-hour emergency line rating, subject to applicable technical exceptions.

Where these requirements are in conflict, the scheme should be replaced with one that will meet all of these requirements.

2. *Dedicated SOTF schemes*

Dedicated SOTF schemes generally include logic designed to detect an open breaker and to arm instantaneous tripping by current or impedance elements only for a brief period following breaker closing. The differences in the schemes lie in:

- The method by which breaker closing is deduced
- Whether there is a scheme requirement that the line indicate dead for some period of time prior to arming SOTF tripping
- The choice of tripping elements
- Method by which the scheme is disabled after breaker closing

In the case of modern relays, every manufacturer has its own design, in some cases with user choices for scheme logic as well as element settings.

In some SOTF schemes the use of breaker auxiliary contacts and/or breaker "close" signaling is included, which limits scheme exposure to actual breaker closing situations. With others, the breaker-closing declaration is derived solely from the status of voltage and current elements. This is regarded as marginally less secure from misoperation when the line terminals are (and have been) closed, but can reduce scheme complexity when the line terminates in multiple breakers, any of which can be used to energize the line.

A second feature included in many SOTF schemes is the requirement that the line voltage be low enough to be considered dead as a precondition for arming SOTF tripping and in many cases as a condition which must still exist when the SOTF trip is declared. This is a security measure intended to prevent undesired SOTF tripping when the line is alive. A primary consideration in the design and application of schemes with line voltage supervision is the pickup setting of the voltage unit. Ideally, line voltage detector pickup should be set below any credible system voltage, but above any line voltage which could be induced by the proximity of lines on the same right-of-way. The higher the voltage unit pickup setting, the greater the risk that the breaker may be closing into a line which is alive but still indicates dead due to lower than normal voltage.

Under present NERC line loadability requirements, line voltage unit pickup settings above 0.85 per unit (or when line voltage is not included as part of the scheme), require that the current fault detectors be set above 1.5 times the four-hour emergency line rating, subject to applicable technical exceptions.[3]

Three individual criteria are suggested for the settings on the overcurrent units, depending on the line voltage unit pickup settings:

- For voltage settings above 0.85 per unit (or no voltage supervision), the overcurrent elements must be set for 1.5 times the four-hour emergency line rating or higher.
- For voltage settings between 0.70 and 0.85 per unit, it is recommended that the current (or other) fault detectors be set only low enough to detect a close-in, three-phase fault under "worst case" (highest source impedance) conditions assuming that they cannot be set above 1.5 times the four-hour emergency line rating criteria.
- For voltage settings less than 0.70 per unit, there is no suggested relay loadability criterion.

SOTF AND AUTOMATIC RECLOSING

The fact that automatic reclosing schemes are generally supervised by bus and line voltage elements gives rise to voltage coordination issues between reclosing and SOTF schemes. The subject of automatic reclosing of transmission lines under stressed system conditions will be the

3 Other types of fault detectors (e.g., impedance units with or without offset to include the origin) used in addition to or in lieu of current fault detectors are subject to the same requirement.

subject of a future paper; however, it is appropriate to discuss the inter-relationship in the meantime.

1. Closing into a De-energized Line

For both reclosing and SOTF schemes, the question in closing into a de-energized line is, "What constitutes de-energized?" Dead-line reclosing voltage supervision is often set as low as 0.2 or 0.3 per unit. With some lines, the setting must be significantly higher due to the capacitively-induced voltage from other circuits occupying the same right-of-way.

With appropriate consideration of dead-line reclosing voltage supervision, there are no coordination issues between SOTF and automatic reclosing into a de-energized line.

2. Closing into an Energized Line

Reclosing logic for the "follower" terminal may include (in addition to a sync-check element) both live-bus and live-line voltage detectors set at or above the lowest system voltage for which automatic reclosing is deemed desirable. A setting in the vicinity of 0.8 PER UNIT is not unusual. If preclosing line voltage is the primary means for preventing SOTF tripping under heavy loading conditions, it is clearly desirable from a security standpoint that the SOTF line voltage detectors be set to pick up at a voltage below the automatic reclosing live-line voltage detectors, or in this case below 0.8 per unit. Where this is not possible, the SOTF fault-detecting elements are susceptible to operation for closing into an energized line, and should be set no higher than required to detect a close-in, three-phase fault under "worst case" (highest source impedance) conditions assuming that they cannot be set above 1.5 times the four-hour emergency line rating criteria.

3. Simultaneous High-Speed Reclosing of two or More Terminals of a Line

High-speed reclosing may elude the SOTF safeguards which exist for time-delayed dead-line reclosing, because substantial power flow can be expected within a very short period of time after closing into the dead line. For some SOTF schemes, the success of high-speed reclosing may depend solely upon the current fault detector setting and the through-load flowing at the instant that the breakers are closed. If the setting is insufficient to prevent tripping of one or both terminals, one or more time-delayed reclosures may yet be successful.

Immunity to false tripping on high-speed reclosure may be enhanced using scheme logic which delays the action of the fault detectors long enough for the line voltage detectors to pick up and instantaneously block SOTF tripping.

Some SOTF designs may provide load immunity by requiring that the line indicate dead for a period longer than the high-speed reclosing time, but use of this feature may compromise SOTF protection for a permanent, close-in, three-phase fault.

4. Other Closing Situations

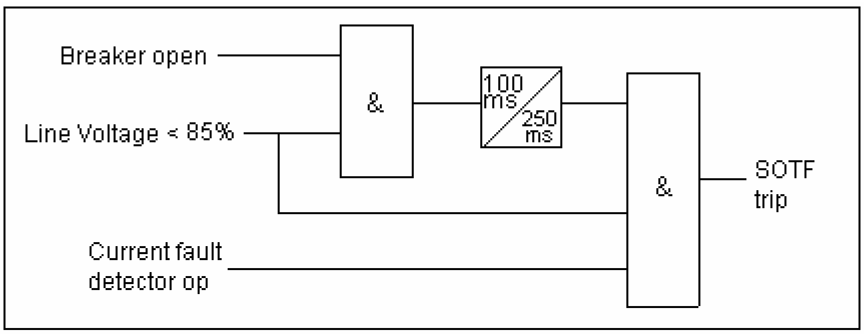
There will likely be a gap between the reclosing scheme's dead-line and live-line voltage settings. For those conditions, automatic reclosing will not occur. Other conditions which could prevent automatic reclosing include excessive angle across the open breaker and the operation of out-of-step reclose blocking schemes. Manual closing may or may not be desirable in these situations, and any such determination will have to be made by operators. Operators should be made aware that SOTF schemes (and for that matter, conventional line protective elements), may unavoidably prevent restoration of the line under those conditions.

It should be noted that large voltage angles across the breaker being closed, either when closing into an energized line or when simultaneously reclosing multiple terminals of a line, may result in transient currents considerably exceeding 1.5 times the four-hour emergency line rating. Depending on the specific type of SOTF elements used and their settings, they may operate under these conditions.

TYPICAL SOTF SCHEMES IN SERVICE

Several SOTF schemes are described below, not for the purpose of advocating any particular design, but to illustrate dependability and security aspects.

Figure 1: Scheme A

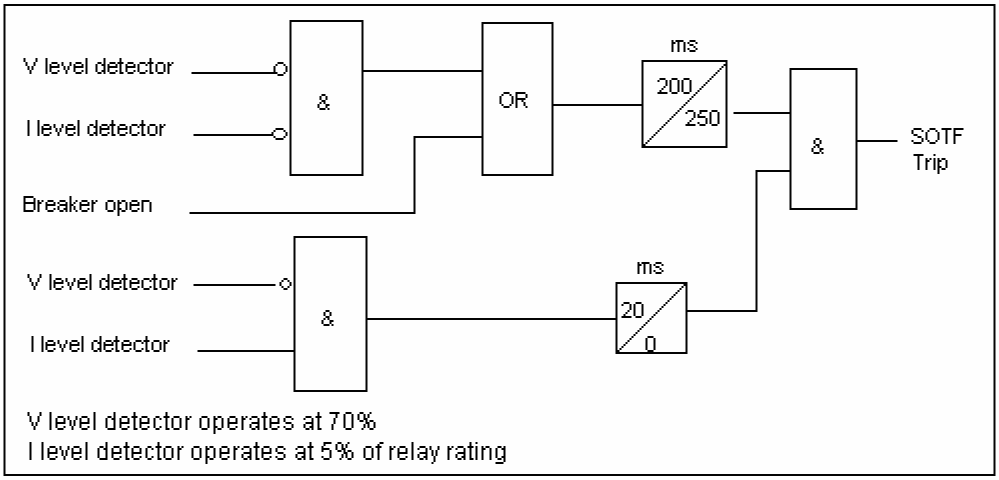


Scheme A describes a typical application of electromechanical current and voltage relays where the voltage relays are connected to line-side potentials. As is evident, tripping is only enabled for 250 milliseconds following breaker closing. The scheme is therefore secure from tripping under conditions when both line terminals are already closed, regardless of the load current or line voltage.

If the local breaker is being closed to energize an unfaulted line, the scheme is secure from tripping provided that the current fault detector is set above line charging current as well as any tapped load current, including transformer magnetizing inrush current. A short time-delay in the current fault detector input would increase security by allowing the line voltage detector time to block tripping. Such a feature might also be useful in simultaneous high-speed reclosing applications.

If the line is already energized from the remote terminal when the local breaker is closed, the scheme is secure from tripping on through-load provided that the voltage detector has picked up. In this example, the design of the voltage relay was such that it could not be set to pick up at less than 0.85 per unit voltage. A 0.85 per unit voltage setting is considered acceptable. However, as noted earlier, with a voltage setting this high, the current fault detectors should be set only low enough to guarantee clearing of a close-in three-phase fault assuming that they cannot be set above 1.5 times the four-hour emergency line rating criteria.

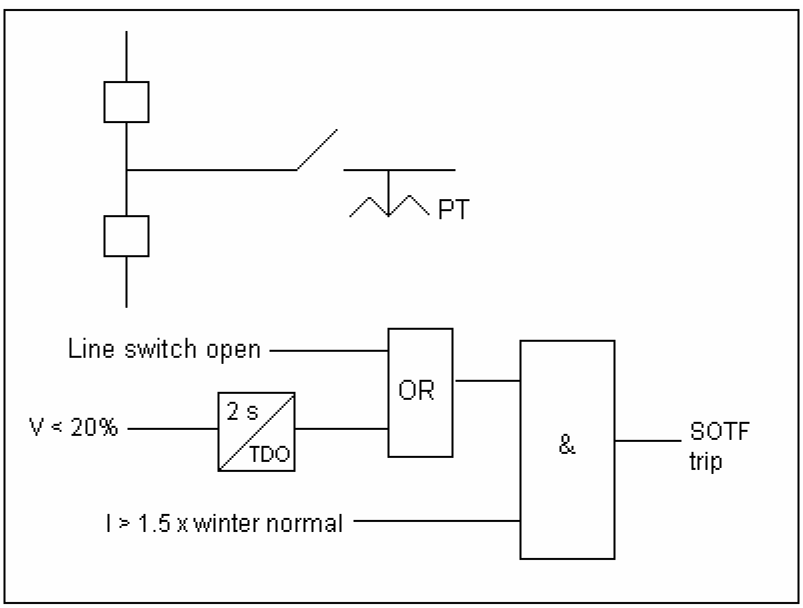
Figure 2: Scheme B



Scheme B does not rely on breaker auxiliary contacts to indicate a breaker closing situation, relying instead on a combination of line undervoltage and line undercurrent to arm SOTF tripping. This may be an attractive feature for lines terminating in multiple breakers.

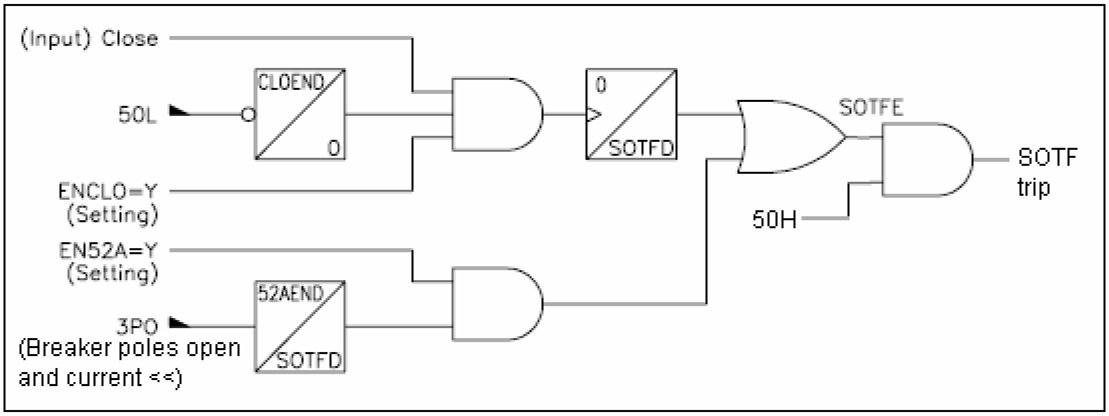
There is only one (very low-set) current level detector, used for both undercurrent and overcurrent detection, which would seem to make this scheme susceptible to undesired operation. However, the 20 millisecond time-delay and the overall scheme logic should provide immunity against false tripping for high-charging current and tapped load situations, and also for simultaneous high-speed reclosing applications, since the voltage level detector should pick up prior to the expiration of the 20 millisecond timer.

Figure 3: Scheme C



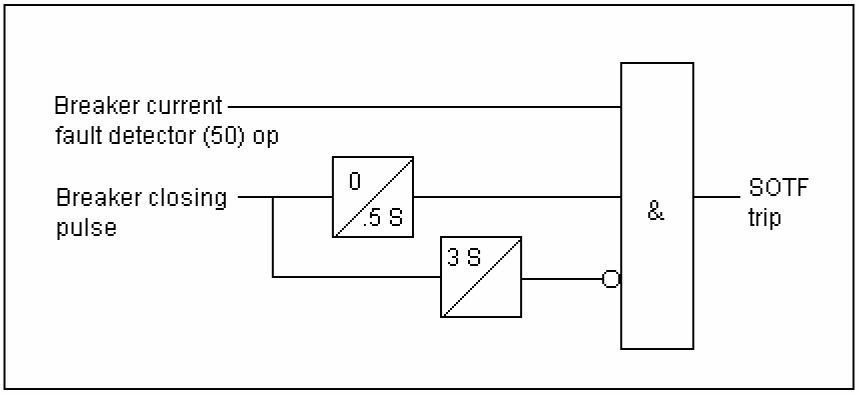
Scheme C protects against closure into a bolted fault and also provides instantaneous stub bus protection with the breakers closed and the line switch open. Since undervoltage is the sole condition which arms SOTF tripping, it is important that consideration be given to the possible loss of three-phase potential. With the voltage setting indicated, the scheme is otherwise immune to undesired operation upon closing into an energized line.

Figure 4: Scheme D



Scheme D is a microprocessor-based design which does not utilize a voltage element. Overcurrent tripping (50H) is momentarily enabled immediately after the breaker is closed regardless of whether the line is alive from the remote terminal or not. Use of this scheme "as is" would require that the 50H setting conform to NERC line loadability requirements. Note that with the capabilities of microprocessor-based relays, the user may have considerable control over the dependability and the security of the SOTF protection by adding additional logic.

Figure 5: Scheme E



Scheme E uses electromechanical relays and is applied on a breaker basis rather than on a line basis. It is in service only at the instant of breaker closure, but as with Scheme D, it does not discriminate between a live and a dead line. This requires that the breaker current fault detector be set in accordance with NERC loadability requirements.

The three-second timer is a security measure intended to disable the scheme if for some reason the close signal is maintained.

The 0.5 second timer is a "pulse stretcher", which may be required for dependability if the nature of the breaker closing control causes the closing pulse to cut off prematurely.

CONCLUSION

SOTF schemes are an important element of transmission system protection. However, unless they are carefully applied, they may compromise the ability of the transmission system to tolerate heavy loading. This paper has presented the relationship between the intended purpose of SOFT schemes and introduced methods by which SOFT schemes can be made more tolerant of heavy load conditions.

APPENDIX A — SYSTEM PROTECTION AND CONTROL TASK FORCE

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