Design and Implementation of Scenarios for Evaluating and Testing Distance Relays

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***Abstract*--This paper introduces a novel approach for evaluating protective algorithms and testing protective relays. The behavior has to be evaluated and tested for many scenarios in power system. The scenarios that encompass specific faults as well as a variety of the events in normal operating state are discussed. A set of power network models developed for studying distance relaying is introduced. Capabilities of these models, and some of dedicated software tools such as Alternate Transient Program (ATP), EUROSTAG and MATLAB'S Power System Blockset (MATLAB/PSB), to implement described events are discussed. An example of comparative simulation responses, by using different programs for implementing the same model and event is provided at the end.**

***Keywords*--distance relays, power system modeling, power system faults, electromagnetic transients, software tools.**

I. Introduction

THE problem of selecting the right transmission line relay settings or the best relaying algorithm to ensure proper operation for all possible scenarios is the problem of making sure that both dependability and security of the relay operation are maintained in all cases [1]. To solve this problem, extensive evaluation of relaying algorithms and testing of protective relays is performed. Evaluating and testing distance relays may require modeling of the power network and performing complex simulation for a variety of scenarios. These scenarios encompass many events, including faults and normal operating states. Diversity of power network models and software packages is important in proper implementation of the scenarios.

Some definitions of the scenarios that may cause unwanted operation of transmission line relays were analyzed in [2]. Practical method to evaluate values measured by distance relays in case of mutual coupling of parallel lines was described in [3]. Faults with time variant impedances, as well as the effect of load variations under normal conditions were analyzed in [4]. Problems related to power swings were discussed in [5].

This paper has two main objectives. First, to describe and summarize the scenarios (special faults and normal operating states) relevant for operation of distance relays. Second, to discuss their implementation using available network models and simulation tools. General fault events such as various types of shunt and serial faults including or excluding the fault impedances are very well known and defined, and are not considered.

Various network models and simulation tools are utilized for comprehensive implementation of defined scenarios. The following models of actual power networks are used in simulations: Stp-Sky and Nbelt-King section from Reliant Energy (RE) HL&P company developed earlier for testing distance relays [6], and Glen Canyon-Flagstaff section from Western Area Power Administration (WAPA) company, developed for evaluating fault location algorithms [7]. The following software packages are used in the modeling: ATP [8], EUROSTAG [9], and MATLAB/PSB [10,11].

The paper is organized as follows. Selected models of actual power networks are given in section II. Brief descriptions of specific fault events as well as events in the normal operating state are given in section III. Section IV analyses the capabilities of selected power network models and available simulation tools for implementing defined events. An example of comparative simulation results obtained by ATP and MATLAB/PSB for the same model and fault event is shown in section V. The conclusion is given at the end.

II. Power Network Models

Three typical 345kV power system sections, two from RE HL&P and one from WAPA, were modeled for relay testing and simulation studies. The modeling involved two major steps: first, obtaining reduced Thevenin equivalent circuits for all the boundary buses; second, detailed modeling of all the elements of the studied section. The reduced network equivalents were obtained by using the load flow and short circuit data offered by RE HL&P and WAPA. The models were verified using both the steady state and transient state results. Figs. 1-3 show one-line diagram of the reduced equivalent for all three used sections.

Stp-Sky section model (Fig. 1) has 9 buses and 11 lines, defined as lumped and distributed parameter models. Two important lines were modeled as frequency dependent, the rest as frequency independent (constant parameter). Even though the original system includes mutual coupling between some of

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the lines, this simplified model does not represent it.

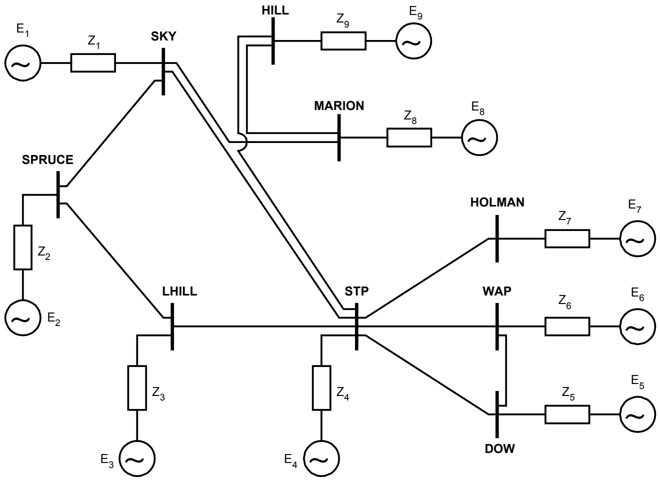

Fig. 1. Model of RE HL&P Stp-Sky Power Network Section

Nbelt-King section model (Fig. 2) has 6 buses and 6 lines, described with frequency independent lumped parameter models without mutual coupling.

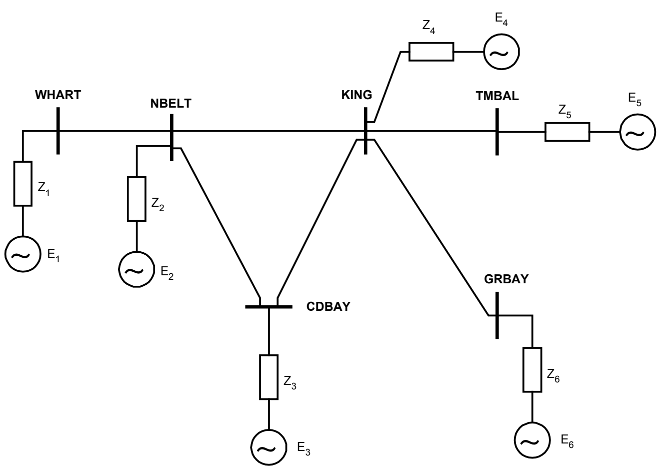

Fig. 2. Model of RE HL&P Nbelt-King Power Network Section

Glen Canyon-Flagstaff section (Fig. 3) includes 3 buses and 4 lines modeled as frequency independent distributed parameter lines, with mutual coupling between some of the lines. Only simplified representation of the model has been shown in Fig. 3. The model also includes series capacitors with capacitor bank, discharge circuit, MOV protection, as well as surge arresters.

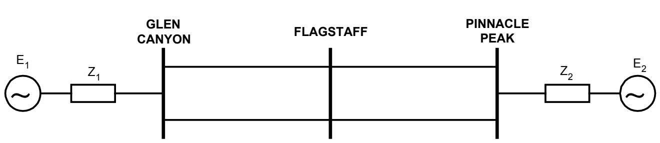

Fig. 3. Model of WAPA Glen Canyon-Flagstaff Power Network Section

These reduced systems are convenient for producing fault waveforms to be used for transient testing of distance relays.

III. An Overview of Specific Scenarios Related to the Faults and Normal Operation

This section describes some of the scenarios relevant for studying operation of distance relays widely used today. Simulation results from the scenarios could be used in evaluation and tuning the existing and any new transmission line relaying algorithms.

A. Specific Fault Events

Faults in reverse direction. Fault current direction can change in one circuit when circuit breakers open sequentially to clear the fault on the parallel circuit. A system configuration that could result in current reversals is shown in Fig. 4. For a fault on line L1, we may suppose that the circuit breakers do not operate simultaneously. We assume that the circuit breaker CB2 operates first, causing the direction of the current flow in line L2 to reverse, before the circuit breaker CB1 opens. The change in current direction may cause improper operation of permissive overreaching distance protection schemes and directional ground-fault blocking schemes. Protection can see the fault in the opposite direction to what was initially detected (distance protection settings of these elements must exceed 150% of the line impedance at each terminal). The race between the operating and resetting actions of the overreaching distance elements at each line terminal can cause the permissive overreach element to trip the healthy line. Similar situation can occur in the directional ground fault blocking scheme application.

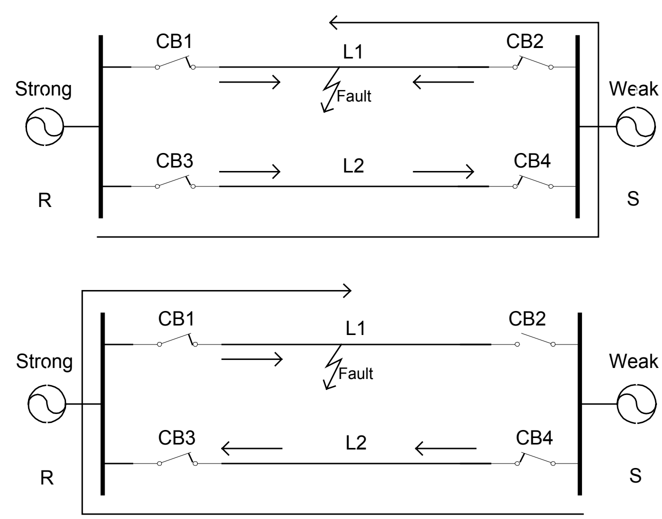

Fig. 4 Fault in reverse direction

Cross-country faults. They can occur between mutually coupled lines (generally speaking between lines on the same tower). A fault can occur, for instance, between phases A and B but the phases belong to different lines on the same tower. An example of the system configuration is shown in Fig. 5. The situation becomes critical if the fault is near one of the substations, for instance substation S. Protective relays on both lines at substation R will detect A-B-G fault in the forward direction. At substation S, relay on L1 will detect A-G fault in the forward direction and relay on L2 will detect B-G fault in the forward direction. If the fault location is moved away from the bus at substation S, the relays in substation R will also detect correct single-phase-to-ground faults. Condition shown in Fig. 5 may result in undesired tripping of all three phases of both lines at substation R (instead of a single phase tripping of each line), and proper single phase tripping at substation S. The undesired operation of the relays at substation R can occur because they must rely on the local phase selection to determine the fault type and which phase or phases to trip.

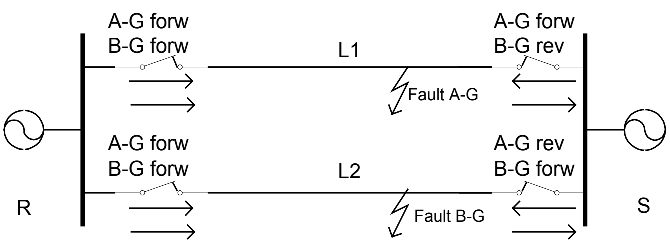

Fig. 5 Cross-country fault

Faults caused by unsymmetrical supply. They are of interest in certain operating conditions of transmission network. Unsymmetrical supply may cause unbalanced conditions in transmission network and initiate, either proper or improper, operation of protective relays. Although conventional distance relays usually do not misoperate for this event, the event has to be taken into account for design and testing of any new relaying algorithm.

Faults with time variant fault impedance. The fault impedance variation is due to the variable impedance of the arc itself. This is due to the varying fault and environmental conditions that affect the arc formation and intensity. The effect of the remote infeed may further contribute to the misinterpretation of the fault impedance measured by distance relays. In that case a distance relay may operate for a forward external fault, or may not operate at all for an internal fault.

Parallel line is out of service. This can cause unwanted operation of distance relays. When overhead lines are connected in parallel or run in close proximity for either whole or part of their length, mutual coupling exists between the two circuits. Typical application where the effects of mutual coupling should be addressed is the case with parallel line out of service and grounded at both ends (Fig. 6). For the case shown in Fig. 6, a ground fault at the remote bus may result in incorrect operation of the distance ground fault elements for zones 1 and 2. It may be desirable to reduce the distance ground fault reach for zones 1 and 2 for this application. To ensure adequate coverage an alternative reach setting may be required.

Weak infeed system. It may be considered whenever there are sources with high impedances in the network. Long line transmission systems with remote generation may have these characteristics. Weak infeed characteristics could also be found when small generators are installed and connected to the system, or when some of the generators are occasionally off line. Several protection complications may occur due to the weak infeed: there may be insufficient current contribution to a fault on the protected line for a relay to reliably detect a fault. In case of multiterminal lines with a weak source at one terminal as compared to the other terminals, protection at the weak source will not detect faults beyond the tap as successfully as relays at a strong source.

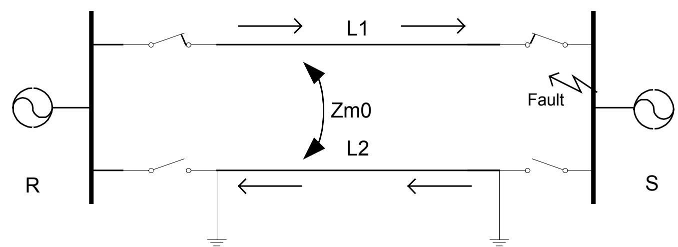

Fig. 6 Parallel line out of service or faulted

Switching on-to-fault (recognizing fault after energizing the line). This should occur following manual circuit breaker switching on-to a persistent fault. In such case, three pole instantaneous tripping (and auto-reclose blocking) should occur for any fault detected on the protected element. One complication is possible in case of switching on-to a fault close to the remote line end, when an underreach distance protection scheme is used. If the fault is not recognized as an immediate fault after the circuit breaker closing, fault clearance will be unnecessarily delayed.

Evolving faults. They start as a single-phase-to-ground fault and then involve additional phases during the time that the initial fault is being cleared or during the circuit breaker dead time of the original faulted phase. Evolving fault may lead to difficulties in coordinating the ground-fault relays and overcurrent relays.

B. Events in the Normal State

Source voltage variation. It can occur due to various changes in the power system network configuration. Response of the automatic voltage control at the generators also contributes to the voltage variation. The result is the varying measured voltage at the relay location. Hence voltage measurements of protection relays are influenced by the system voltage even though protected line may not be faulted.

Load variation. It may generally have the major influences on protective relay setting and operation. Usually, load is varying slowly and gradually due to the random changes in power consumption. In some situations, load change may be huge such as in the case of on/off switching of large customers, or due to a fault or power outages. Load current level may influence fault detection sensitivity. In some cases, load increase can lead to encroachment into a zone of distance protection that may further lead to unnecessary tripping.

Line switching. It is an event in the normal state that significantly contributes to the values measured by protective relays. Switching of parallel or adjacent lines can cause events similar to source voltage or load variation. Sudden changes of voltages and currents in some instances may lead to undesired operation of protective relays. Similar phenomena may also occur if there is a transformer at the remote end of a transmission line (harmonic occurrence during on/off switching of the power transformer).

Line parameters variation. This can occur due to some external influence (temperature changes, humidity variations, soil resistivity variations, etc.). Line parameters are also dependable on the aging factor. If these variations are significant, this can influence the values measured by distance relays.

System frequency variation. It may occur due to the transient events in the network and due to the unbalance between the generated and consumed active power. Even though the operation of distance relays should not be influenced by this event, it could be interesting to use it to evaluate any new relaying solution.

Power swings. Those are oscillations in the power flow, produced by various power system disturbances. They can be caused by faults, loss of synchronism across a power system, or changes in the direction of the power flow due to the line switching. Such disturbances can cause generators on the system to accelerate or decelerate to adapt to the new power flow conditions, which in turn leads to a power swing. The result of a power swing may cause the impedance measured by a distance relay to move away from the normal load area and into one or more of its tripping characteristics. Stable relay operation during the power swings is very important to avoid undesirable relay tripping.

IV. Capabilities of the Power Network Models and Simulation Tools for Implementing the Scenarios

The summary of simulation capabilities of available power network models: Stp-Sky, Nbelt-King and Glen Canyon-Flagstaff, as well as available software tools: ATP, EUROSTAG and MATLAB/PSB for implementing defined scenarios is provided in Table I. Plus and minus signs in the table indicate whether or not the implementation is feasible.

A. Power Network Models

The following faults and events are not specific to any particular network configuration and therefore there are no special requirements for implementing the models: faults with time variant fault impedance, switching on-to fault, evolving faults, source voltage variation, load variation, line switching, and system frequency variation. Since there is no any specific network configuration necessary to create conditions to simulate these events, all the network models are suitable.

Faults in reverse direction could be modeled in any of the available networks. Although there are no parallel, double circuit lines in Stp-Sky and NBelt-King models, it is possible to simulate current reversal through the network rings.

Cross-country faults are related to the case of two different lines being on the same tower. This event could be modeled in any of the available networks, except NBelt-King Section, since it does not have parallel lines.

Even though network models do not comprise detailed models of the generators (they include only simple source representation), faults caused by unsymmetrical supply could be created by disconnecting a particular phase in the network.

TABLE I Summary of the Events Implementation in the Available Power Network Models and Simulation Tools

	Event	Network Model			Simulation Tool		
		Stp - Sky	Nbelt - King	Glen Canyon - Flagstaf	ATP	Eurostag	Power System Blockset
Fault events	Faults in reverse direction	+	+	+	+	+	+
	Cross-country faults	+	-	+	+	+	+
	Faults caused by unsymmetrical supply	+	+	+	+	+	+
	Faults with time variant fault impedance	+	+	+	-	-	-
	The parallel line out of service	-	-	-	+	-	-
	Weak infeed	-	-	+	+	+	+
	Switching on-to fault	+	+	+	+	+	+
	Evolving faults	+	+	+	+	+	+
Normal state events	Source voltage variation	+	+	+	+	+	+
	Load variation	+	+	+	-	+	-
	Line switching	+	+	+	+	+	+
	Line parameters variation	-	-	-	-	-	-
	System frequency variation	+	+	+	+	+	-
	Power swings	-	-	-	+	+	+

Stp-Sky and Glen Canyon-Flagstaff-Pinnacle Peak are week infeed models. Nbelt-King model is not suitable to simulate the event.

For parallel line (line on the same tower) out of service, the model should reflect the mutual coupling between parallel lines. Nbelt-King model does not comprise (involve) parallel line, and Stp-Sky model does not reflect explicitly this relationship. Only Glen Canyon-Flagstaff model deals with mutual coupling and consequently is suitable for modeling this event.

Even though line parameter variation is not related to any particular network configuration, available models do not describe this variation as a function of external influences (aging, temperature, pressure, etc). The network configurations provided in this paper are not relevant for modeling of such event.

Network model should comprise double-end infeeds in transmission lines and detailed model of the generators to reflect power swings. Although all of the network models are of the ring type comprising double-end infeeds, none of them provides detailed modeling of the synchronous machines, and therefore are not suitable for modeling this event.

B. Software Tools

All three software tools, ATP, EUROSTAG and MATLAB/PSB, do include appropriate capabilities to simulate the following events: faults in reverse direction, cross-country faults, faults caused by unsymmetrical supply, weak infeed, switching on-to fault, evolving faults, source voltage variation, line switching, and power swings.

For implementing cross-country faults, software packages involve simulation of various types of faults occurring between different lines. Software packages allow phase switching and they are suitable for simulating unsymmetrical supply. They comprises modeling of various types of fault at different subsequent time intervals at the same fault location, and they are suitable for implementing evolving faults. Instrument transformer failure can be modeled by applying current or voltage signals.

EUROSTAG enables implementation of various load models and is convenient for simulating load variation. However, it can not simulate time varying fault impedance. ATP and MATLAB/PSB provide only time invariant load and fault impedances, and are not convenient for simulating these events.

ATP and EUROSTAG can simulate continuous variation of the system frequency and may be used for implementing this event. MATLAB/PSB deals only with the time invariant system frequency.

Each software package provides detailed modeling of the synchronous machines, and so it may be used for implementing the power swings.

ATP, EUROSTAG and MATLAB/PSB provide detailed modeling of the overhead lines. Except ATP, other two packages can not compute a variation of the zero sequence line impedance due to the changes in the line configuration. Whenever one of the parallel lines is grounded at both ends, three phases of the grounded line act similarly as the ground wires but with unsymmetrical position with respect to the phases of the line in service. Simulating this event by EUROSTAG or MATLAB/PSB, externally calculated value for zero sequence impedance has to be manually plugged into the system description.

Line parameter variation can not be implemented in any of mentioned software tools, because they do not provide capabilities for continuous variation of line parameters due to weather and/or aging conditions.

V. Simulation Results

An example of comparative simulation responses of ATP and MATLAB/PSB programs for the same faulted case is shown to emphasize their characteristics. Stp-Sky power network model has been implemented in both programs, ATP and MATLAB/PSB. The model has not been implemented in EUROSTAG, since the voltage and current waveforms are not accessible, but only their effective values. Stp-Sky model is used for simulating phase A-G fault on its Stp-Sky transmission line. Fault has been placed in the middle of the line, with zero fault impedance and it starts at 20ms after simulation begins. Voltages and current signals measured by protective relay at the Sky bus are shown in Figs. 7-8.

Similarity between responses in both programs is obvious. Some differences exist for the voltage signals during one/two periods after the fault starts, due to variable integration step size in MATLAB/PSB contrary to fixed integration step size in ATP.

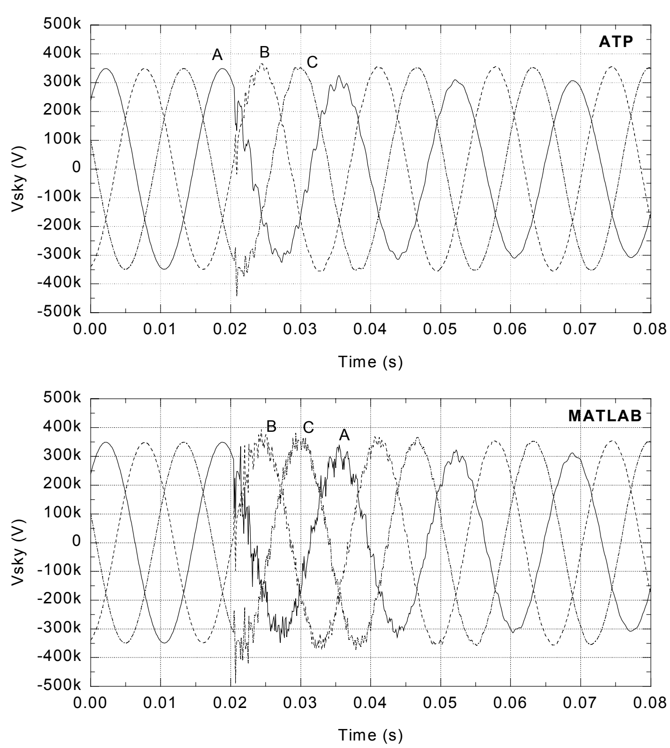

Fig. 7. ATP and MATLAB comparative voltage responses for the same fault conditions

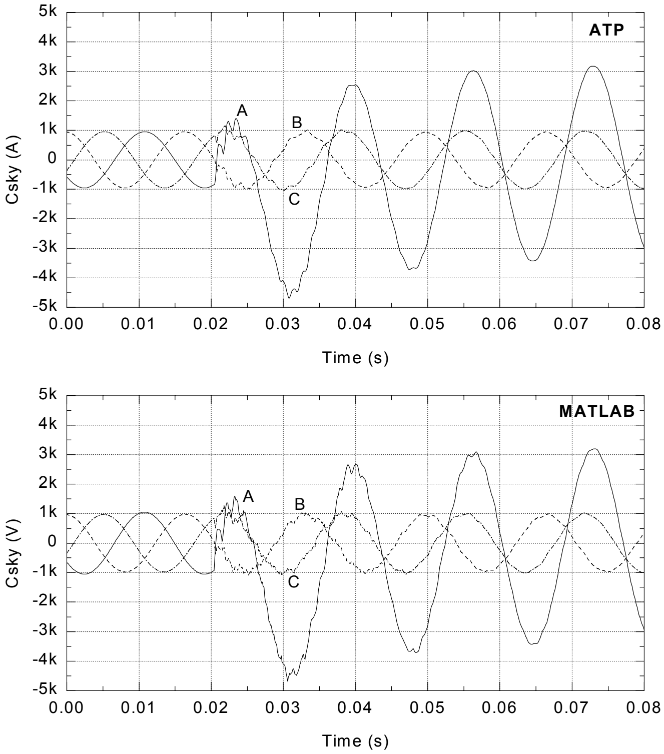

Fig. 8. ATP and MATLAB comparative current responses for the same fault conditions

VI. Conclusion

This paper discusses distance relaying evaluation in many real situations in power networks. Specific fault events, as well as events in normal operating states important for distance relays operation have been described. The set of available power network models which may be used for the events modeling and simulation have been investigated. The capabilities of these models and some of widely used simulation tools for implementing a variety of fault events and operating states have been studied. A brief summary has been shown in a tabular form. One of the power network models has been used to simulate the fault on one of the lines by using ATP and MATLAB/PSB programs. Comparative results show similarity between signals obtained in both programs.

VII. References

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VIII. Biographies

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