Protective Relay Testing for Relays Installed in the Vicinity of Active Power System Components

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***Abstract* – The paper describes the testing of transmission line protection which is to operate in the vicinity of active power system components such as HVDC, SVC and protected series capacitors. The relay's performance under highly non-linear conditions is tested using a real−time digital simulator. Details of the power system model and the relay testing are described.**

INTRODUCTION

A transmission line protection relay relies on the measurement of voltage and current signals at the end of the transmission line to determine whether the line has experienced a fault. The effective impedance seen by the relay is computed using the ratio of measured voltage to measured current. Fundamental frequency components of the measured voltage and current signals are required to compute the correct line impedance. It is often the case, however, that he measured voltage and current signals contain non−fundamental frequency components. Algorithms are thus employed within the line protection relay to extract the fundamental frequency components.

Components which can affect sudden changes in impedance, such as switched shunt elements or series capacitors with bypass switches, also present challenges to the performance of line protection relays.

In situations where the line protection is located near sources of non−fundamental frequency component voltages and currents, as well as, components which can cause impedance changes it is important that the relay be tested to verify its ability discriminate between a fault condition within its zone of protection and transients caused by action of the nearby components.

CLOSED LOOP TESTING OF PROTECTIVE RELAYS

Testing of protective relays is quite often done by applying fundamental frequency voltage and current signals of varying amplitude and phase to the relay and verifying that the relay operates in accordance with its setting. Such testing does not exercise the relay's capability to operate correctly in the presence of non−fundamental frequency voltage and current components.

Application of voltage and current signals recorded from an off−line power system simulation program to the relay does show the relay's performance when non−fundamental frequency components are present. However, such *open loop* testing does not permit the relay action to effect the simulation.

Power system simulators which operate continuously in real−time may be used to test the relay's performance under a wide range of system conditions. Voltage and current signals computed by the simulator are provided as input to the relay via voltage and current amplifiers. The relay's trip and reclose signals are used to operate breakers modelled within the simulator. With adequate modelling of the power system in the simulator, such *closed loop* testing enables the relay to be tested under conditions which most closely resemble those of the real power system.

STUDY OBJECTIVES

Simulation studies were done to evaluate GE L90 Current Differential and D60 Distance relay performance in the vicinity of active power system components. Fine tuning of relay settings would also be done as part of the study. The following items would be checked as part of the simulation study –

- Distance relay reach accuracy for series compensated lines.
- Reach accuracy when the relays are exposed to sys-

tem transients and CCVT transients

S Reach accuracy for resistive faults under heavy loading conditions

S Operation of the current differential relay during system transients and CT saturation.

S Charging current impact on current differential relay.

S Impact of system transients on relay operating time

Transmission line protection relays installed in the vicinity of active power system components will be presented with highly distorted current and voltage signals. In addition to the fault transients the relay may be required to cope with such things as operation of series capacitor protection, switching of voltage control devices and the fast protection sequences initiated by HVDC controls. It is important to understand the relay's performance under such conditions.

Real–time power system simulators are capable of simulating power system circuits which contain components such as HVDC, SVC and series capacitors with MOV and bypass protection. Models of CTs and CCVTs which include saturation effects are also available. When operated in continuously in real–time the power system simulator may be interfaced to the protective relays using voltage and current amplifiers. By using the relay trip and reclose signals to operate breakers modelled within the simulator complete closed loop testing of the relay is possible.

POWER SYSTEM MODEL

The modelled power system represents a portion of the 500 kV network belonging to Los Angeles Department of Water and Power (LADWP). Figure 1 shows the network near the lines which are to be protected by the relays under test. The protection is to be located in close proximity to a HVDC converter station including its switched filters, a Static VAR compensator, series capacitors with bypass switches and series capacitors with MOV protection and bypass switches.

Details of specific components comprising the system model are given below.

TRANSMISSION LINE MODEL

Various algorithms are available for modelling transmission lines. The most simple of these represent the line using lumped R–L–C elements. Although the correct fundamental frequency impedance of the line is achieved with the appropriate selection of the R–L–Ccomponents, the transient response of the line is not accurately represented. A *distributed parameter* model of the transmission line provides a more accurate transient response. Both the lumped parameter and distributed parameter line models represent the transmission line impedance at a single frequency (typically power frequency 50 or 60 Hz.) A line's resistance and inductance, however, change with frequency.

Transmission line models which include the repre-

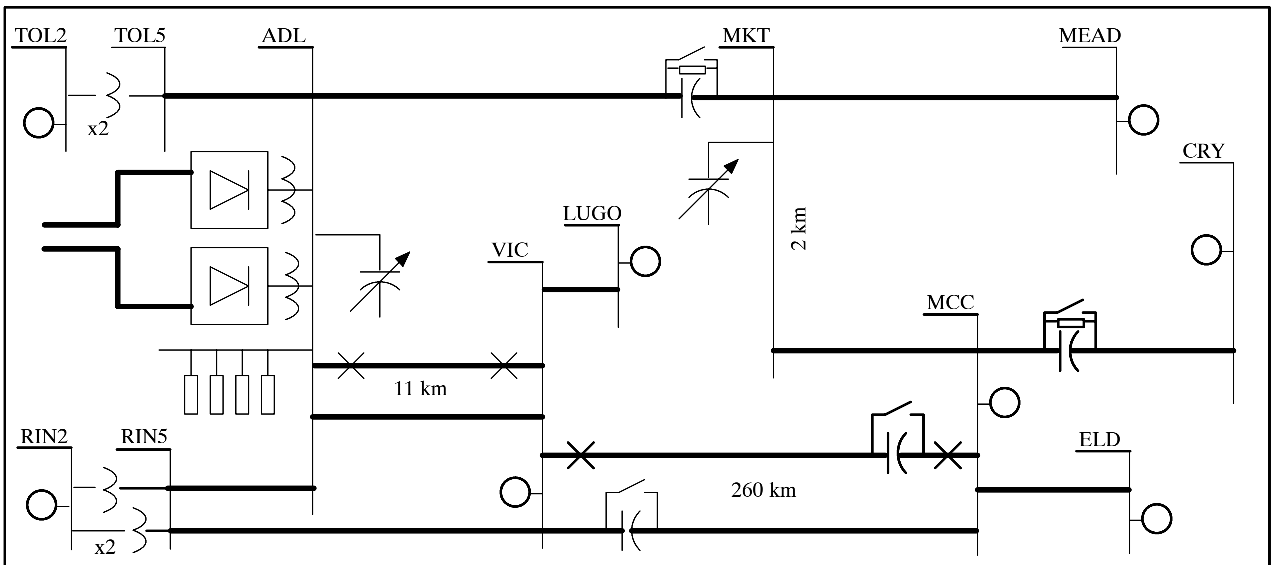

Figure 1: Power System Model

sentation of the line's frequency dependent parameters are available.

Distributed parameter and frequency dependent line models require that the simulation time–step be less than or equal to the line's shortest travel time. Assuming wave propagation at 3.0×10^8 m/s, the travel time for the 11km ADL–VIC line is 36.86 μs. Real–time simulation of the system of Figure 1, with the available simulator hardware configuration, required a time–step of 70 μs. Lines shorter than 21 km were thus required to be modelled using a PI section.

The no load step response of the 11 km. ADL–VIC line is shown in Figure 2. The receiving end A Phase voltage using a single PI section (Figure 2, plot A) is compared to that using a frequency dependent line model (Figure 2, plot B). The underdamped transient response of the PI section model is clearly illustrated.

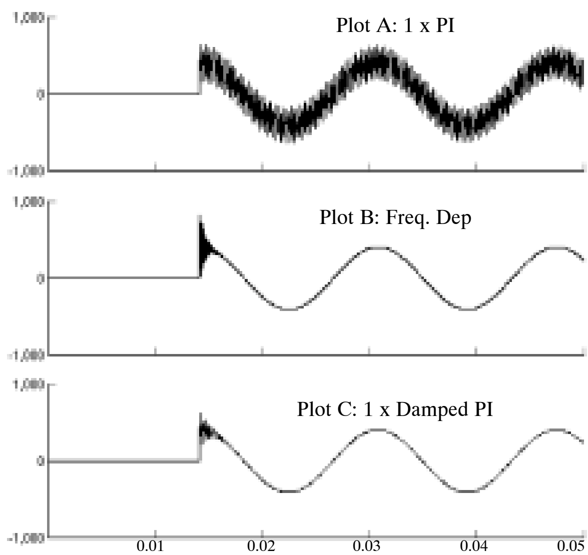

Figure 2: ADL–VIC Step Response

In order to increase the transient damping of the PI section line model, a resistance is added in series with the shunt capacitive components in the modal domain. The response of the damped PI line model is shown in Figure 2, plot C. Since the resistance is added only to the shunt components, the 60 Hz. impedance is changed very little. Charging current for the ADL–VIC line is –

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Un-Damped PI:       14.9 amps
Frequency Dep:      15.2 amps
Damped PI:          13.4 amps
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For lines longer than 21 km. the distributed parameter line model was used. A step response comparison between the distributed parameter line at 70 us and the frequency dependent line at 15 us is shown in Figure 3.

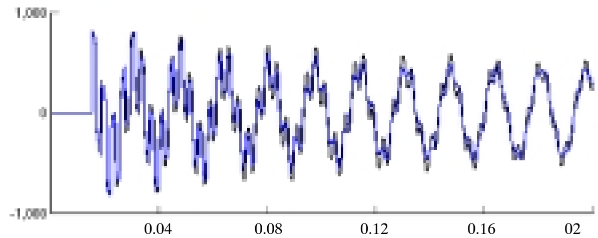

Figure 3: VIC–MCC Step Response

SERIES CAPACITORS

Series capacitors for the VIC – MCC lines are protected using a bypass switch which closes for 60 sec. if the capacitor voltage exceeds 80 kV. The MCC–CRY and ADL–MKT series capacitors are protected using both MOV and bypass switch. The bypass switch closes if the MOV energy exceeds 132.8 MJ or if the MOV current exceeds 9.0 kA.

Difficulties and methods of protecting series compensated lines is detailed in [1][2].

STATIC VAR COMPENSATOR (SVC)

SVC units consisting of three shunt Thyristor Switched Capacitor (TSC) elements are connected to the ADL and MKT buses via transformers. Control for the SVC units was modelled in detail and includes the following blocks [2] –

- voltage and susceptance measurement
- voltage and susceptance regulators
- TCR switching logic
- Power swing damping control
- TCR firing logic

IPP HVDC SYSTEM

The Intermountain Power Project (IPP) HVDC system was modelled using 12 pulse valve groups in a bipolar (+/–500 kV dc) arrangement. Controls for the HVDC system were modelled using the simulator. Details of the actual controls were not available and as such HVDC controls were modelled using a generic structure. The rectifier was operated in current control and the inverter in extinction angle (gamma) control.

MEASUREMENT TRANSDUCERS (CT / CVT)
Detailed models of current and voltage transducers were included in the model. System voltage and current are applied to the transducer models and the corresponding burden voltage and current are available at analogue output channels. Low level signals (+/−10 volt max) from the analogue output channels are provided to voltage and current amplifiers whose output is connected to the protective relay under test. The relay trip signal is used to operate the breakers modelled on the simulator.

LOAD FLOW
Load flow conditions were established by setting source impedance and magnitude values for sources connected to the system buses as shown in Figure 1. Source parameters were altered to represent the system in a *weak*, as well as, *strong* condition.

LIMITATIONS OF THE MODEL
Although the model and components described herein is deemed adequate for the testing of the relays, there are a number of items which could be modelled in more detail. Dynamics introduced by generator swings is not included in the model since all sources were modelled using a sine wave generator behind an impedance. Power swings due to generator dynamics can have a significant effect on the impedance measured by a relay [2].

To fully determine the effect of the HVDC system operation on the relays, detailed HVDC controls should be modelled. Control actions such as the response to rectifier and inverter faults and startup and shutdown sequences should be checked to determine their effect on the relay operation.

SIMULATION RESULTS & RELAY RESPONSE

Simulation base cases which included different system configurations (weak and strong), as well as, minimum and maximum loading conditions were setup. The following fault scenarios were run –

- all combinations of ground and line faults applied to the left and right bus terminals, 40%, 70% and 90% from the relay. SLG faults with 3 and 30 ohm fault resistance. LL and LLG faults with 3 ohm fault resistance.
- Faults behind series capacitors on adjacent lines.
- Asymmetrical CT saturation applied to current differential relay.
- Selective test cases were run with 100 ohm fault resistance.

Approximately, 200 simulation cases were run for each system condition. Simulation cases were run using an automated scripting feature of the real−time digital simulator. Results, including the relay's operation, for each simulation case were recorded by the simulator's script software.

Relay settings were set at –

- differential element pickup was set at its minimum value of 0.2 pu
- charging current compensation was disabled
- Zone 1 phase and ground elements set at 85% of the line impedance.
- Zone 2 reach was set at 125% of the line impedance
- The D60 impedance relay's dynamic reach control for series compensated lines was enabled.

It was found that the non−linear power system components had no observed impact on the protective relay operation. Under heavy load condition, the distance relay failed to detect a zone 2 fault as described below. However, the maloperation was not due to transient phenomena.

ZONE 2 MALOPERATION

Distance protection on the ADL−VIC line failed to detect a 3 ohm resistive fault applied at 90% of the line length (ie. zone 2) when 560 MVA was being transferred over the line. The circuit diagram for the conditions is shown in Figure 4.

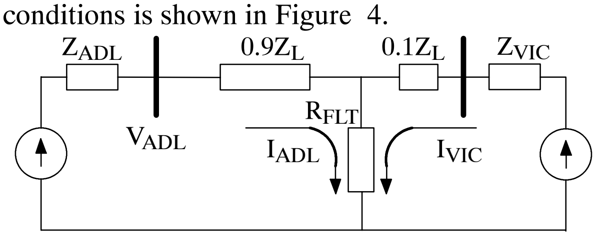

Figure 4: Equivalent Fault Circuit

Writing the loop equation –

$$\overline{V}_{ADL} = 0.9\overline{Z}_L * \overline{I}_{ADL} + R_{FLT} * (\overline{I}_{ADL} + \overline{I}_{VIC})$$

The apparent impedance seen by the distance relay at ADL is –

$$\overline{Z}_{APP} = \overline{V}_{ADL}/\overline{I}_{ADL} = 0.9\overline{Z}_{L} + R_{FLT}(1+\overline{I}_{VIC}/\overline{I}_{ADL})$$

The apparent impedance is dependent not only on the fault resistance, but also on the complex ratio between local and remote currents. Figure 4 shows the impact of the local and remote fault current for resistive faults.

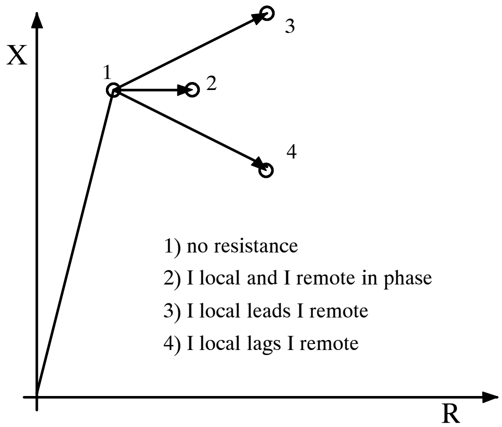

Figure 5: Impact of local and remote fault current on apparent impedance for resistive faults

Using the measured fault currents from the simulation for phase A and the ADL–VIC line impedance the apparent impedance seen by the relay at ADL is computed as –

$$\overline{Z}_{app} = 0.9*(0.16 + j3.68) + 3*(1 + 46.9\angle 114 \div 6.4\angle 100)$$

$$\overline{Z}_{app} = 24.5 + j8.6$$

With a CT ratio of 5000:5 and CCVT ratio of 500,000:115 the secondary impedance seen by the relay is –

$$\overline{Z}_{sec} = 5.63 + j1.84$$

Zone 2 reach is set to 0.03 + j 1.05 with a right blinder of 5 ohms resistive. Thus, for the fault conditions described above, the distance relay will not respond to the zone 2 fault.

WAVEFORMS

Figure 6 shows the waveforms obtained from the simulation for a fault behind a series capacitor on an adjacent line. The distance relay looks through two series capacitors, one on the protected line and one on the adjacent line. Fault current includes sub–harmonics contributed by the nearby SVC. The SVC's TCR units operate during the fault in order to try to maintain bus voltage. Traces at the bottom of Figure

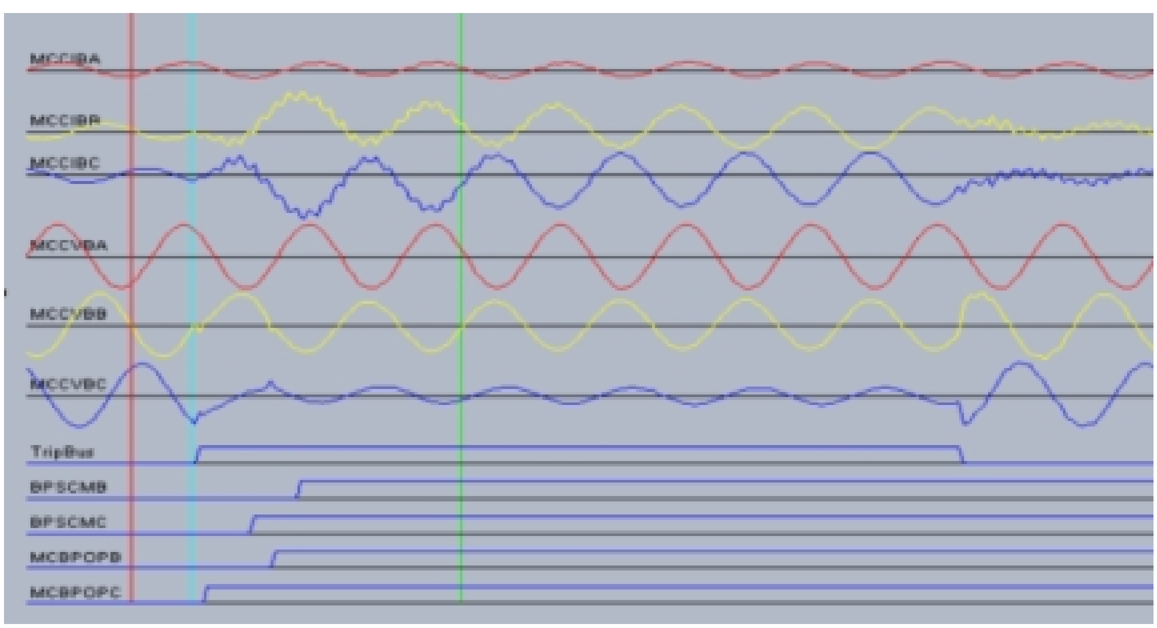

Figure 6: Waveforms obtained from Simulation of a Fault behind Series Capacitor

6 show that the series capacitor bypass switches operate in both B and C phases on the protected and adjacent lines.

SUMMARY

Testing of protective relays using a real–time power system simulator prior to their installation into the power system is an effective way of checking the relay's performance. Confidence may be gained that the relays will perform under a wide range of system conditions.

The GE L90 line differential relay and D60 distance relay were able to operate reliably in the presence of transients produced by the active power system components located near the relay connection point.

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BIOGRAPHIES

Rudi Wierckx received B.Sc (EE) 1983 and M.Sc (EE) 1985 degrees from the University of Manitoba. Between 1985 and 1993, he was employed by the Manitoba HVDC Research Center, working on the development of the Real–Time Digital Simulator (RTDS). In 1993 he left the Research Center to form RTDS Technologies Inc. and is currently a director of that company.

Ilia Voloh graduated from Power University in the Soviet Union. He then worked in Protection and Control for many years in progressive roles. Currently, Ilia is an application engineer with GE–Multilin, specializing in current differential and distance relaying. Ilia is an IEEE member and author of several papers.