Relay Protection of EHV Shunt Reactors Based on the Traveling Wave Principle

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Abstract--The measuring technique described in this paper is based on Electro Magnetic Transient Program (EMTP) studies of the traveling wave principle. The paper describes the fault protection of EHV Shunt Reactors. More particularly the paper describes the detection and relaying protection of turn-to-turn faults based on the traveling wave concept. Current computer technology has advanced, where it is possible, to sample and A/D analog signals at 1.2-10 Mbps to detect and measure the Traveling Current (TRC) waves generated by a single or multiple turn-to-turn fault within the shunt reactor. The relay described in this paper uses Rogowski Current (RC) transformers to measure TRC within the 30 – 70kHz bandwidth. The paper has been prepared to provide within EMTP the theory for the development of such relays.

Keywords – High speed relay, Rogowski CT, Traveling wave, Shunt reactor Fault detection

I. Introduction

At EHV level shunt reactors are used to regulate the reactive power balance of a system by means of compensating for the surplus reactive power generation of transmission lines.[1] Shunt reactors are normally disconnected at heavy load and are connected to the lines at periods of low load. Consequently, frequent On/Off switching is a significant characteristic. The main insulation of reactors can be overstressed if the breaker has high current chopping character. Furthermore, if a conventional arrester operates as a consequence of current chopping, or a re-strike occurs during the switching-off operation, the turn-to-turn insulation of the shunt reactor can be jeopardized by the steep voltage change. In this paper a comprehensive reactor protection is described that includes the detection and relaying of turn-to-turn faults using the TRC generated by the fault within the 30kHz to 70kHz bandwidth.

II. Discussion

It can be shown mathematically, that the first Traveling Voltage (TRV) wave that is generated by a turn-to-turn fault within the shunt reactor has exactly the same waveform and in phase with the first Traveling Current (TRC) wave.
At the instance of the fault, and a short time following, the voltage TRV is proportional to the current TRC. The constant of proportionality is known as the shunt reactor surge impedance Zs.

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$$\mathrm{TRV} = Z_s \times \mathrm{TRC} \qquad [1]$$

The surge impedance is equal to:

$$Z_s = \sqrt{\frac{L}{C}} \qquad [2]$$

where L represents the inductance in Henries and C represents the capacitance in Farads.
The shunt reactor one-line diagram is shown in Fig. 1.

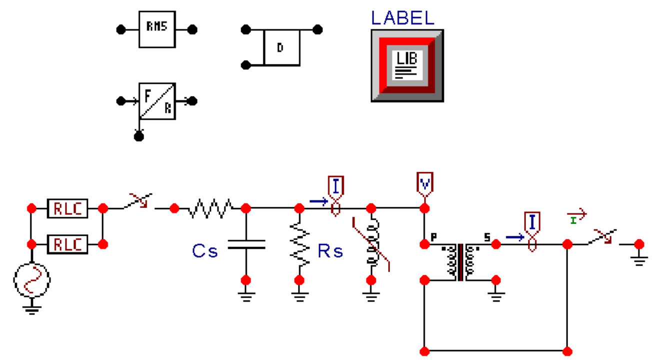

Fig. 1 One Line Diagram.

The 500kV, 60 MVAR shunt reactor is modeled as a single-phase, autotransformer (Zp = 4.5 +j1681). The shunt reactor saturation curve, modeled as a (type 98) variable inductor is shown in Fig.2
The 1000:1 turns ratio of the secondary winding is set to model a single turn-to-turn fault. The shunt reactor model stray bus capacitance is represented as Cs (0.0033 µF). The copper losses of the winding, the iron and dielectric losses of the core can be represented by lumped serial/parallel resistances Rs (2.0E6 Ω).
The frequency of the shunt reactor volt free oscillation (1320Hz) is defined by the value of the reactor inductance *L* and the stray bus capacitance C_s as:

$$f = \frac{1}{2\pi\sqrt{LC_s}} \qquad [3]$$

where *L* is the linear, unsaturated value of the reactor inductance, because the iron core has air gaps, resulting in high saturation level. The shunt reactor voltage free oscillation during switching the reactor OFF is shown in Fig.3.
The frequency scan of the shunt reactor volt free oscillation (f = 1320Hz) is shown in Fig. 4.
The frequency scan of the shunt reactor volt free oscillation with one-turn shorted (1380Hz) is shown in Fig. 5.

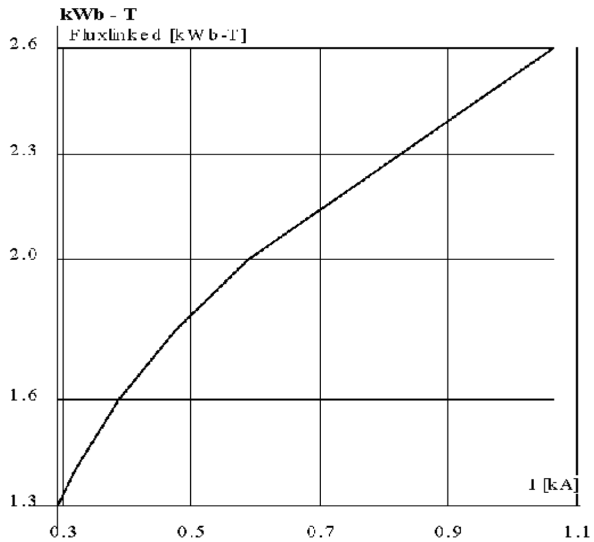

Fig. 2 500kV 60 MVAR Shunt Reactor Saturation Curve.

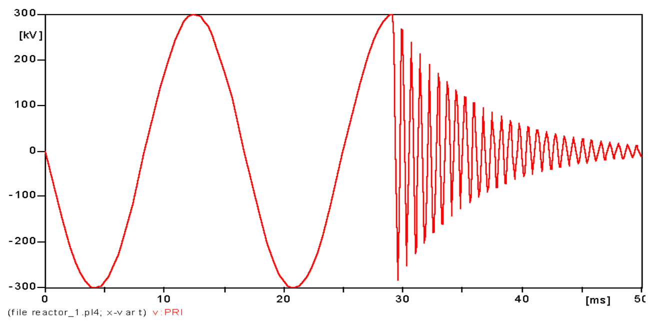

Fig. 3 Shunt Reactor Volt CB Switch OPEN.

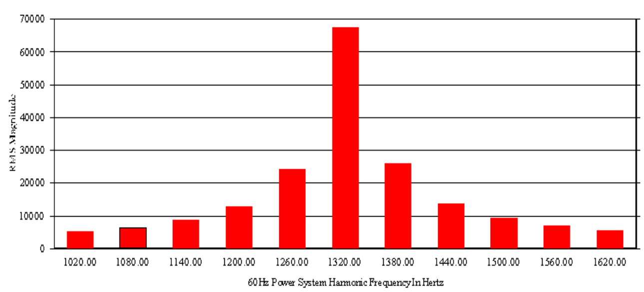

Fig. 4 Frequency Scan of the Shunt Reactor Voltage.

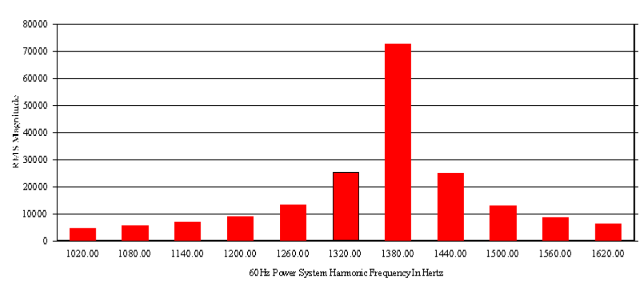

Fig. 5 Frequency Scan of the Shunt Reactor Voltage – one turn shorted.

The change in the free oscillation frequency indicates a change in the value of the reactor inductance L assuming that stray bus capacitance Cs remains constant.

The Circuit Breaker (CB) model is a time-controlled switch equipped with synchronous closing device with pre-defined current chopping level (10A).

The shunt reactor current during switching the reactor open is shown in Fig. 6.

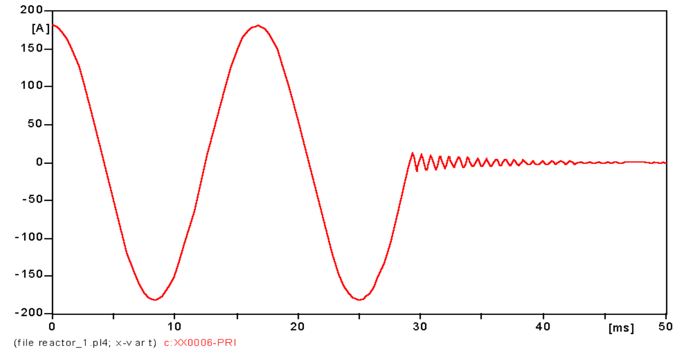

Fig. 6 Shunt Reactor Current CB Switch OPEN.

III. Rogowski CT Input Requirements

The operating principle was formulated by Rogowski and Steinhaus [2] in 1912. The theory of operation is described by Kojovic [3]. RC's provide linear, revenue quality, analog measurements of the rate-of-change of current (di/dt) over a broad range (700KHz) of frequencies. RC's are therefore, the ideal devices to measure TRC and the small incremental increases in shunt reactor current caused by a turn-to-turn short. The EMTP/ATP Model of the RC, in I_IN (amps) vs. VOUT (volts) is shown in Fig. 7.

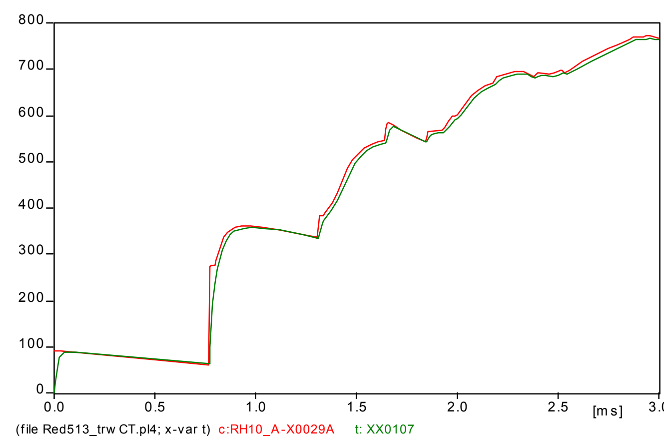

Fig. 7 RC input I_IN (amps) vs. output VOUT(volts)

The input current (I_IN) induced voltage E transfer function with 70kHz A/D aliasing filter is defined as:

$$E = \frac{0.00265|s1}{1.0|s0 + 1.428E-5|s1} \quad [4]$$

where I_IN (amps) is proportional to the output VOUT (volts) that is defined as:

$$VOUT = \frac{377E|s0}{s1} \quad [5]$$

IV. Shunt Reactor Protection

A. *Turn-to-turn faults*

The relay input filter logic one line diagram is shown in Fig. 8.

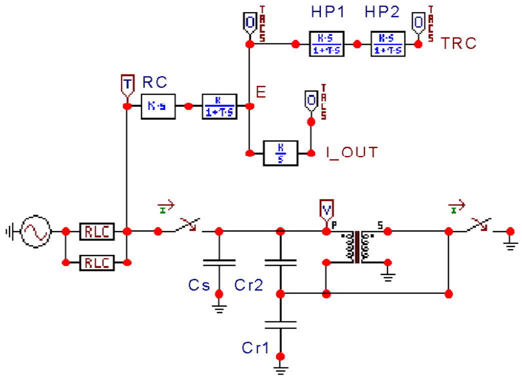

Fig. 8 Relay input one line diagram.

The change in shunt reactor current for a turn-to-turn fault is shown in Fig. 9. The fault is applied at 0.023 sec.

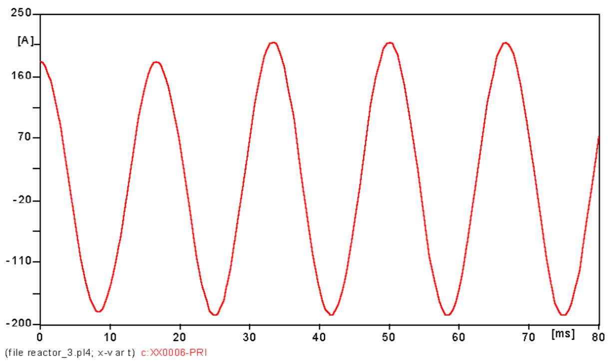

Fig. 9 Shunt Reactor Primary Turn-to-Turn Fault Current.

In Fig.9 the primary pre-fault current peaks at 176 amps. After the fault, the current peaks at 203 amps. While the primary current change is small, the turn-to-turn fault produces a large current 2723 amps peak within the secondary shorted turn. The turn-to-turn fault current is shown in Fig. 10.

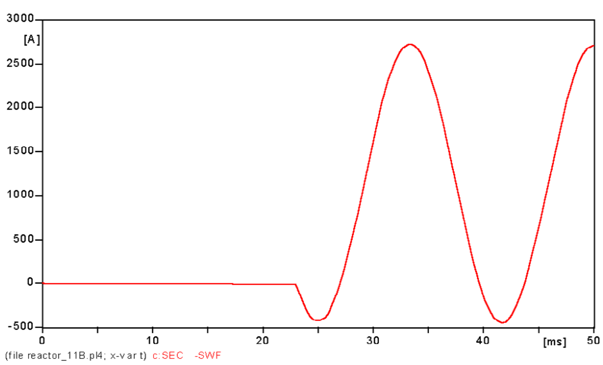

Fig. 10 Shunt Reactor Secondary Turn-to-Turn Fault Current.

The fault generates TRC that can be detected by using a 30kHz HP filter of E. The transfer function of the output named DIR is:

$$DIR = \frac{E|s1}{1s0 + 3.33E-5|s1} \qquad [6]$$

The output DIR is shown in Fig 11/a. The (100 volts) tracing pulse named TA generated by the rising edge of the DIR is shown in Fig. 11/b. The amplitude and width of the tracing pulse TA is adjustable.

To provide security, the relay logic requires a minimum of 2-4 percent increase in primary RMS current immediately following the DIR. Shunt reactors with large number of turns may require the shorting of multiple turns to achieve the 2-4 percent increase in primary RMS.

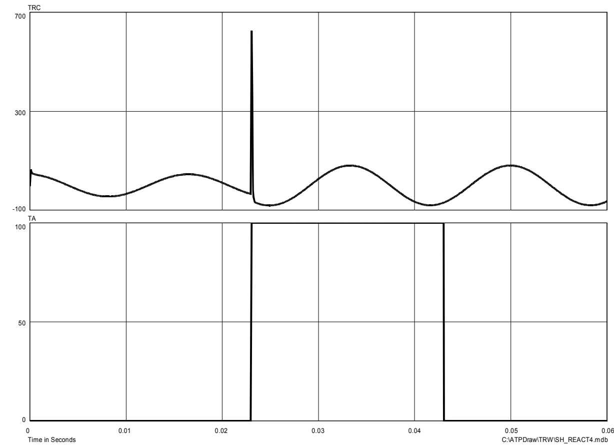

Fig. 11 a) DIR Output b) Tracing pulse TA

The RMS measurement of the shunt reactor current is shown in Fig. 12/a. The tracing pulse TA is shown in Fig. 12/b. The shunt reactor RMS current is measured within the TA generated "window" (RMS*TA/100). The rise is shown in Fig.13/a. The logic generates a TRIP when the amplitude exceeds a pre-set level shown in Fig. 13/b.

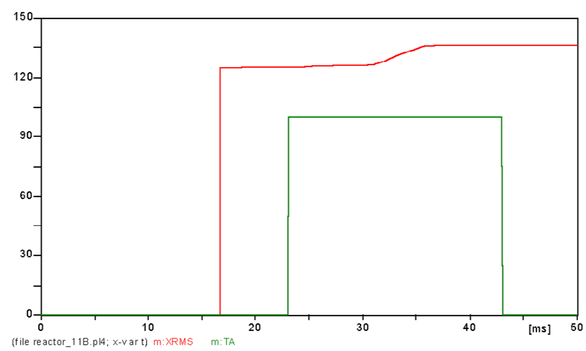

Fig. 12 a) RMS of I_IN b) Tracing pulse TA

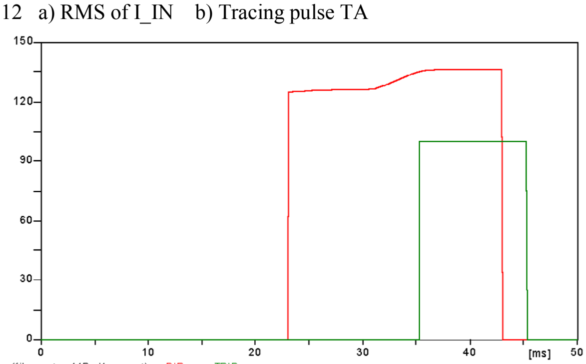

Fig. 13 a) RMS current measured within TA b) TRIP output

B. *Directional Fault Detection*

Equations [1,2] define the first theorem within the traveling wave time domain that at the instance of the fault, and a short time following, the voltage TRV is proportional to and in-phase with the current TRC. Furthermore, the RC polarity is reversed so TRC opposes TRV. The leading edge of D is negative when the fault is in the forward START direction and positive when the fault is in the reverse BLOCK direction. The directional fault detector D algorithm is:

$$D = TRV * TRC \quad [7]$$

where

$$START = -D \quad [8]$$

$$BLOCK = +D \quad [9]$$

The TRV, TRC, D the START and BLOCK signals are shown in Figs.14 a,b,c,d,e,

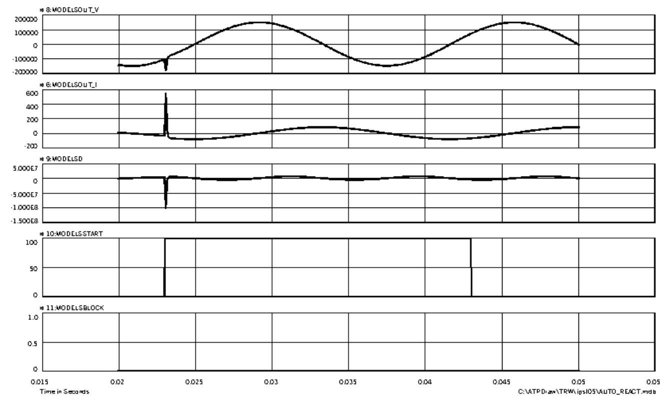

Fig. 14 a) TRV, b) TRC, c) D, d) START, e) BLOCK

C. *Hi Magnitude Faults*

The shunt reactor current for a bus or a bushing-to-ground fault within the RC protection zone is shown in Fig. 15. The fault is applied at 0.023 sec.

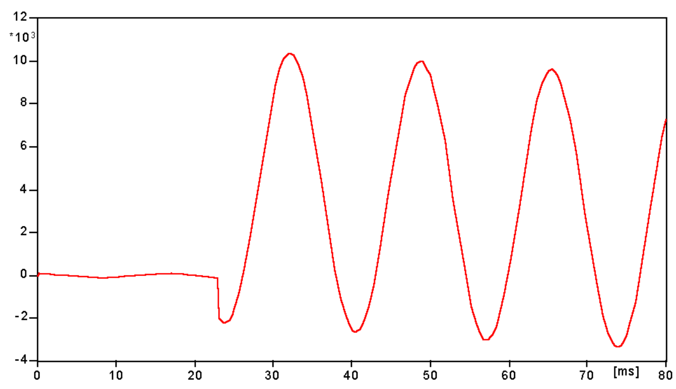

Fig.15 A phase-to-ground bus fault current (amps)

The shunt reactor current for a bus or a bushing-to-ground fault within the RC protection zone is shown in Fig. 16. The fault is applied at 0.023 sec. A Hi-set current detection logic named SI measures the instantaneous point-on absolute (abs) current within the TPA generated "window".

The logic in Fig. 16 generates a TRIP when the current amplitude exceeds a pre-set level of ten times rated or 2000 abs amperes.

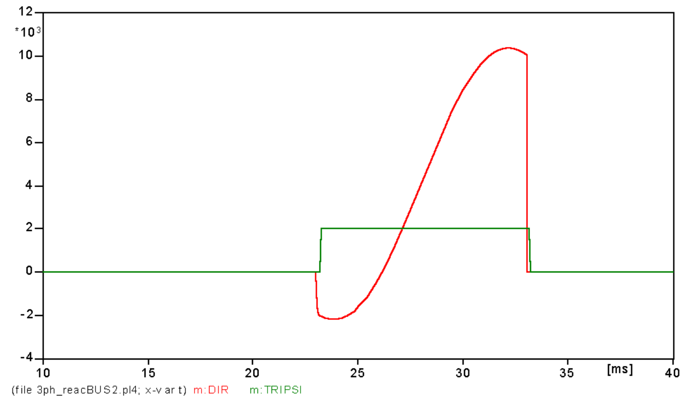

Fig 16. Shunt reactor SI instantaneous current logic.

The SI logic point-on TRIP times for a bus or a bushing-to-ground fault are shown in TABLE I.

There is no TRC generated if the fault occurs at the zero current crossing. In those rare events, the traveling wave relay will have to rely on the conventional (60Hz) "backup" relay logic.

TABLE I.

Fault	Hi-Set
Time-ms	TRIP-usec
21	459
22	146
23	264
24	0
25	0
26	778
27	448
28	155
29	356
30	43
31	45
32	314
33	0
34	0
35	314
36	162
37	82

V. Shunt Reactor Normal ON-OFF Switching

The shunt reactor RMS current measured within the TA generated "window" when the CB is switched OFF is shown in Fig. 17. The CB is equipped with a time-controlled, synchronous closing device to control dc-offset. The shunt reactor RMS current measured within the TA generated "window" when the CB switched ON is shown in Fig. 18. In both cases, the RMS is below the setting therefore, there is no TRIP.

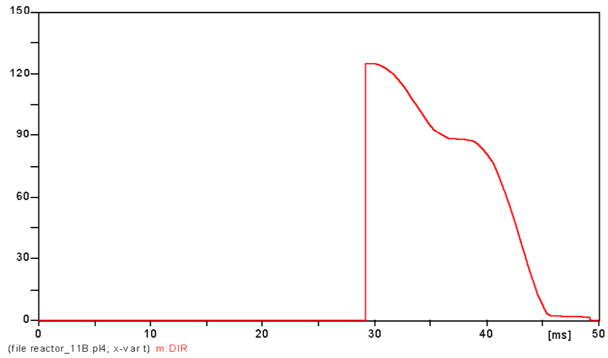

Fig. 17 RMS measured within TA - CB open.

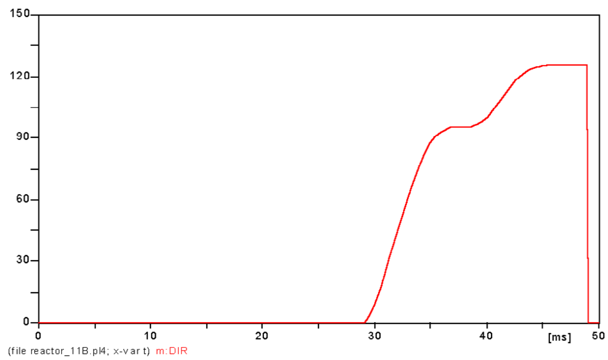

Fig. 18 RMS measured within TA -CB close.

VI. CONCLUSIONS

The paper described the algorithms and logics to detect a single or multiple turn-to-turn faults in a 500kV, 60 MVAR shunt reactor using linear RC devices. The logic uses 1.2Mhz A/D sampling of the RC output E. High A/D sampling is required to detect the TRC generated by the fault. The TRIP time for a turn-to-turn fault is within 12 milliseconds. . The TRIP time for a hi-set SI fault is within one millisecond.

VII. REFERENCES

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VIII. BIOGRAPHY

Jules Esztergalyos is a retired chief system protection engineer for Bonneville Power Administration. He serves as consultant in power system control and protection, with specialties that include EMTP/ATP modeling and studies of large power systems switching surges, stability, sub-harmonic oscillations, relaying. He has a BSEE from Washington State University and a registered professional engineer in Oregon.