Implementation and Analysis of a Digital Model of the Incremental Quantity Distance Element Using EMTP

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Introduction

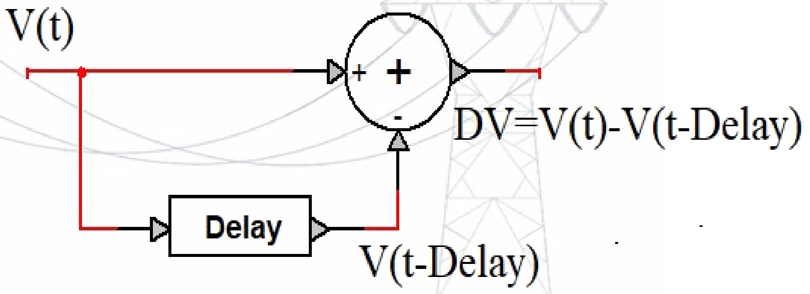
- Recently developed time-domain-based relays (TDRs) utilize the fault generated incremental quantities (IQ) and traveling waves (TW) to detect and locate faults
- IQ Distance Element (referred to as the TD21 element) can provide dependable high-speed transmission line protection
- The TD21 is an under-reaching element that relies on the IQ and the line impedance values to provide instantaneous protection
- Operating times in the range of a few milliseconds [1]
- Does not require communication with the remote relay
- TDRs are commercially available, but their detailed digital models are not yet readily available in transient analysis software packages

Project Summary

- The purpose of this presentation is to provide a detailed description of the design and digital modeling procedure of the incremental quantity distance element
- Implemented using the Electromagnetic Transients Program (EMTP)
- Model is validated at different stages of the design process using commercially available TDRs
- Presentation will cover the Event Playback Testing procedure for the SEL-T400L/T401L Relays, digital implementation of the TD21 element using EMTP, and operational comparison between the model and relay

Incremental Quantities

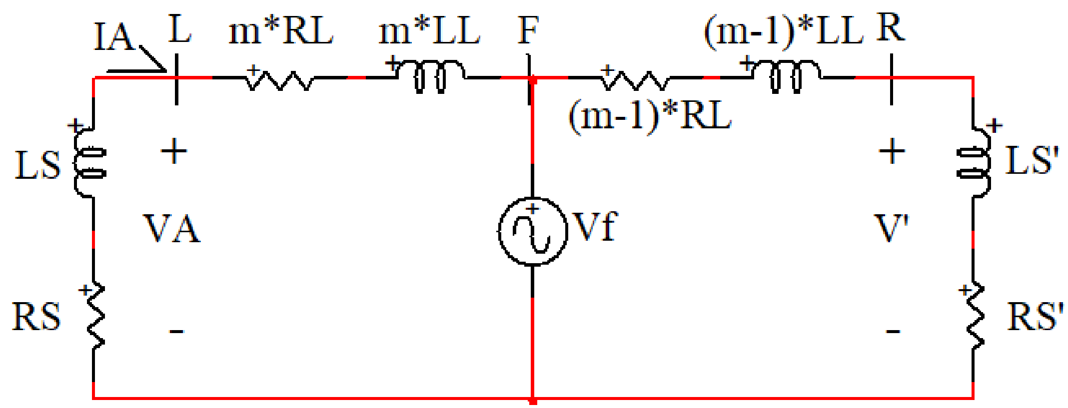
- IQs are derived using superposition and represent the change at the fault point voltage due to a fault event [2]
- IQs are extracted using a base delta filter [3]
- Output under steady-state conditions is zero, and is non-zero for a short duration following a fault representing the transients due to the fault



IQ Distance Element

- Incremental quantity distance elements provide instantaneous under-reaching line protection [4], relying on the changes at the fault point voltage to operate [5]
- Operation algorithm utilizes real-time and one-cycle-old instantaneous data, so trip decisions can be made very rapidly
- Operation is based mainly on the magnitude and polarity of two signals, namely, the operating signal and the restraining signal
- Restraining Signal
    - One cycle old steady-state signal at the reach point that represents the steady-state reach point voltage
- Operating Signal
    - Calculated incremental signal at the reach point whose value represents the magnitude of the change due to the fault

IQ Distance Elements



- Fault loop equations are derived from the analysis of the fault generated network by using Thevenin's theorem of two-port networks and the superposition principle [5]
- The loop with the largest operating signal is selected as the faulted loop [5]

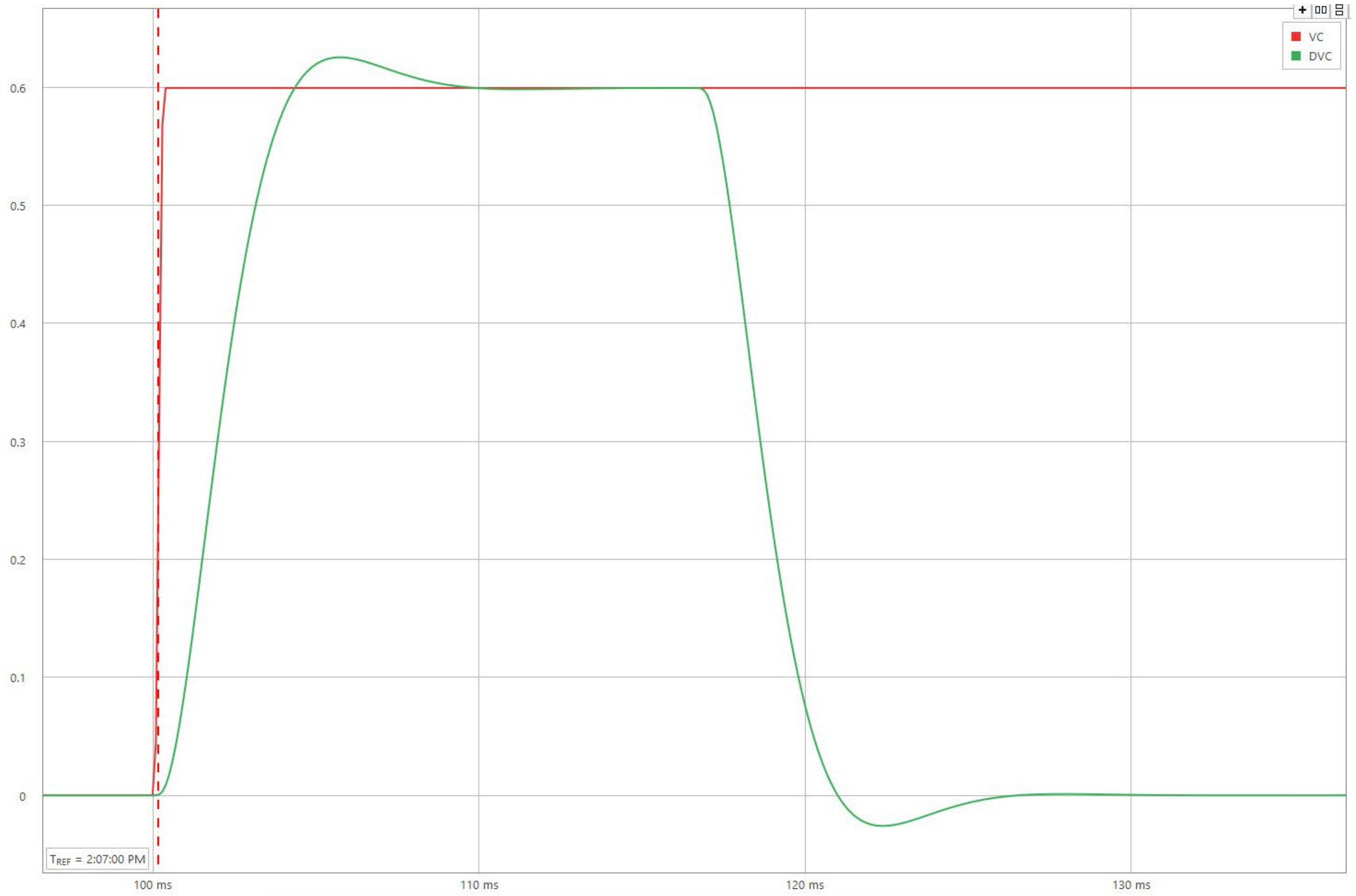
Relay Test Bench

Set-up in lab showing the EMTP and acSELerator software, and the SEL-T400L relays

Filter Design

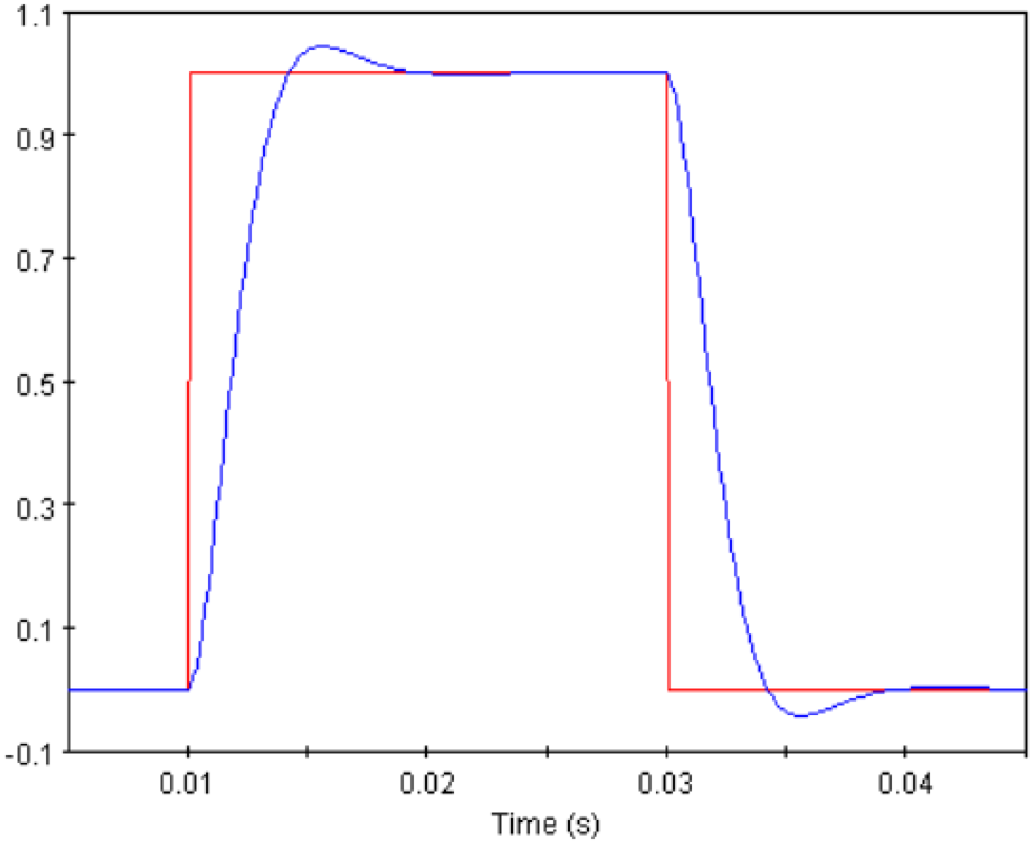
- One essential component of the TD21 element is the low-pass filter (LPF) that is used to control transients and remove high frequency content [6]
- Per Ref. [4], the TD21 element has an effective bandwidth of a few hundred hertz as a result of this filter
- Event reports obtained from the relays can be used to compare signals before and after the application of the LPF
- Unit-step input was applied to the TDR to observe the response of its internal LPF

Filter Design



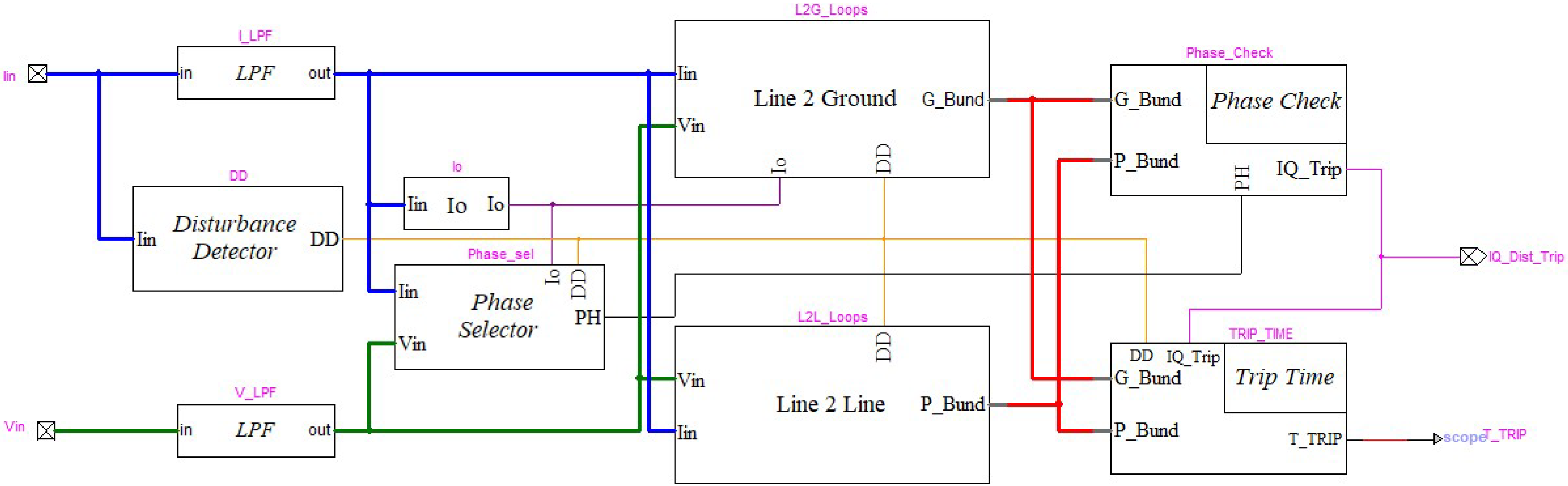
SEL-T400L internal LPF step response

Filter Design



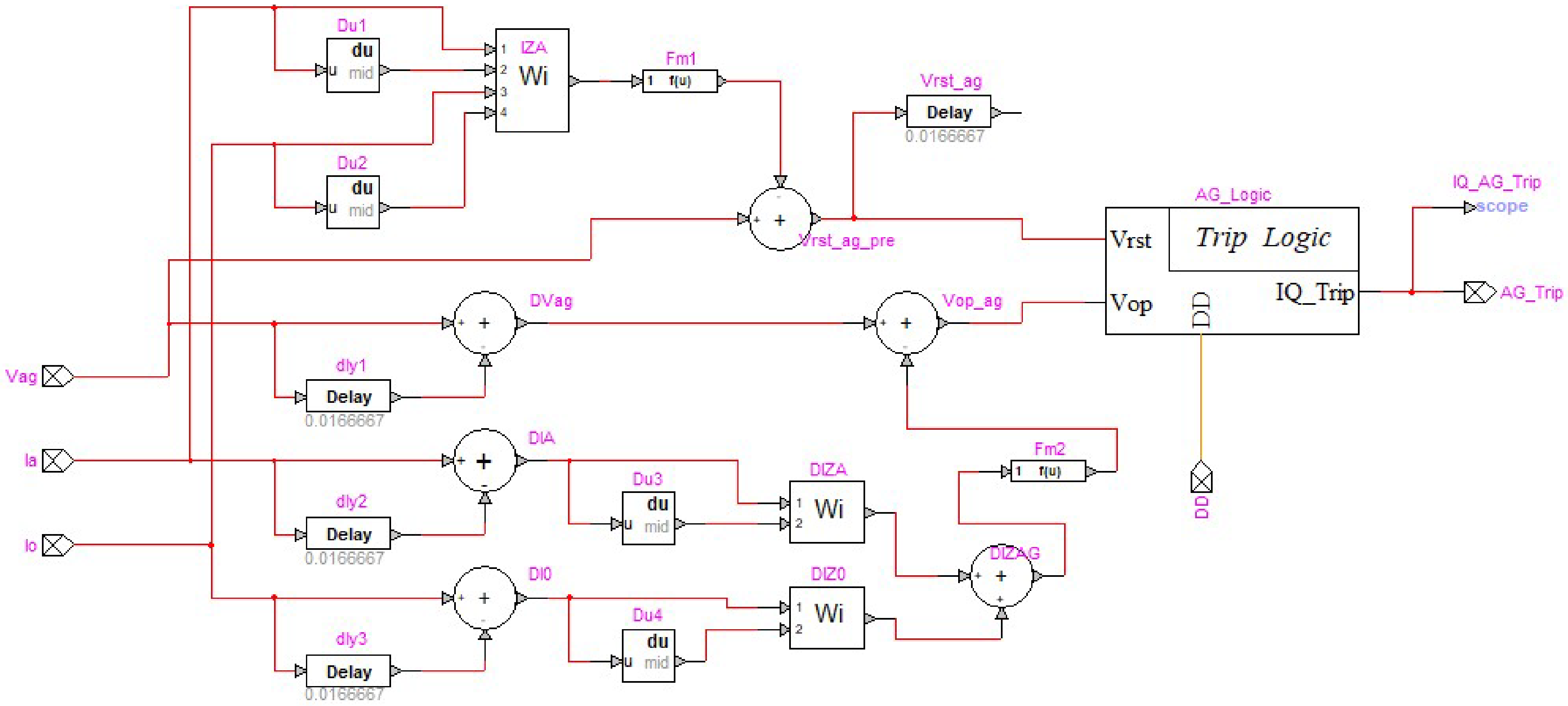
Step-response of the LPF implemented using EMTP

EMTP Distance Element Design



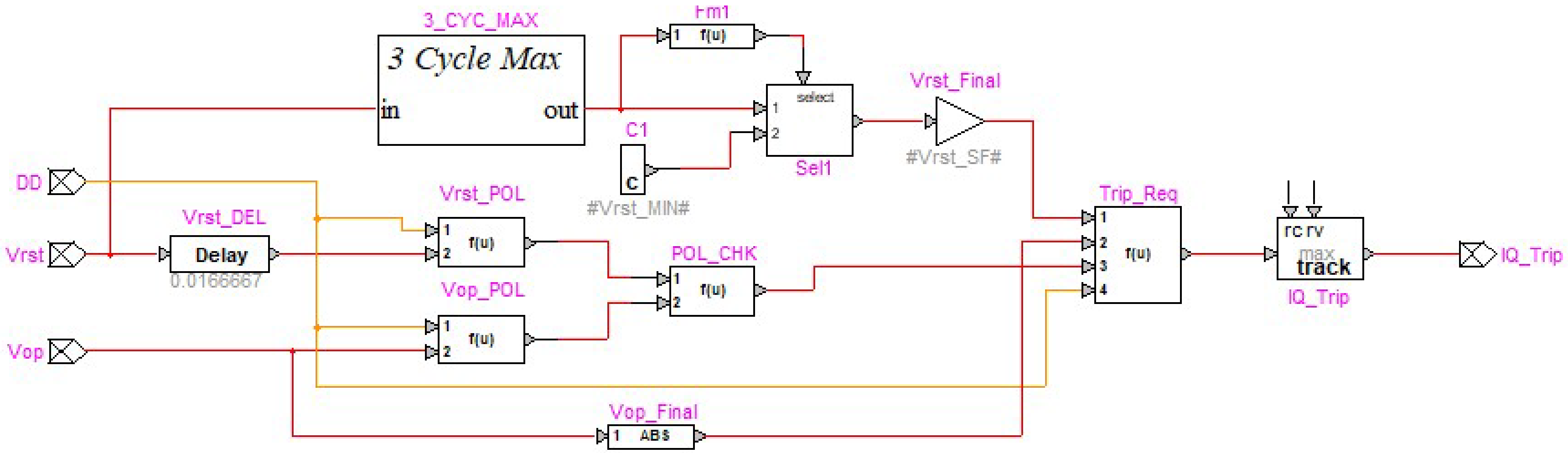
Top level subcircuit for EMTP-based incremental quantity distance element

EMTP Distance Element Design



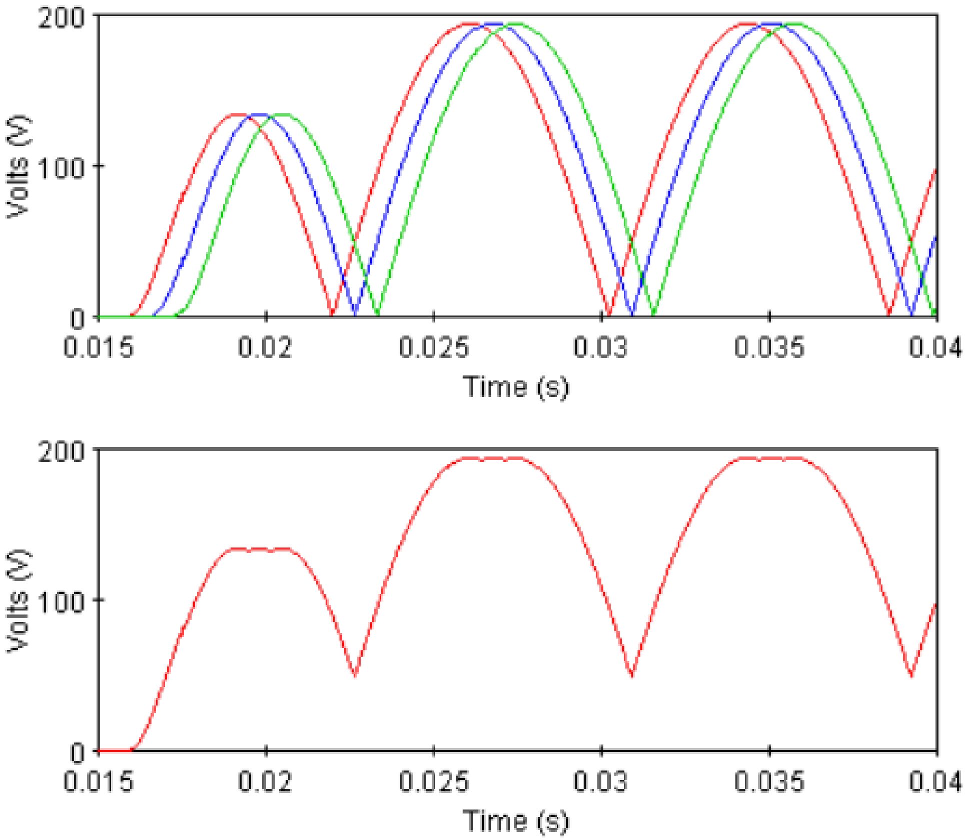
AG subcircuit for EMTP-based incremental quantity distance element

EMTP Distance Element Design



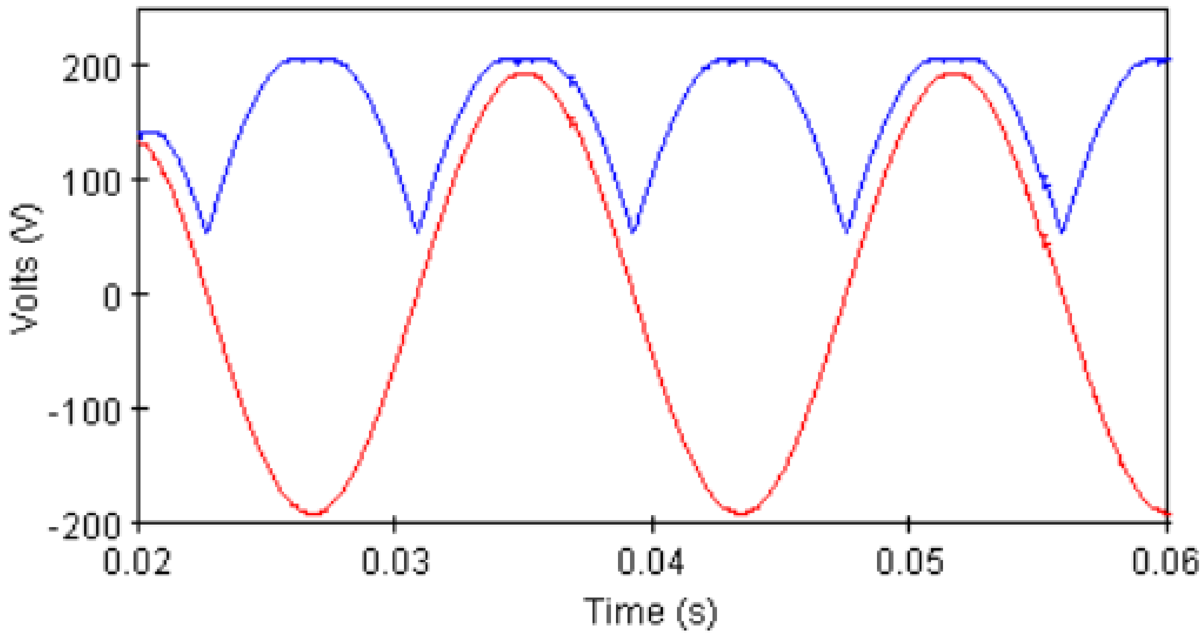
Trip logic subcircuit for EMTP-based incremental quantity distance element

EMTP Distance Element Design



3-cycle max waveforms

EMTP Distance Element Design

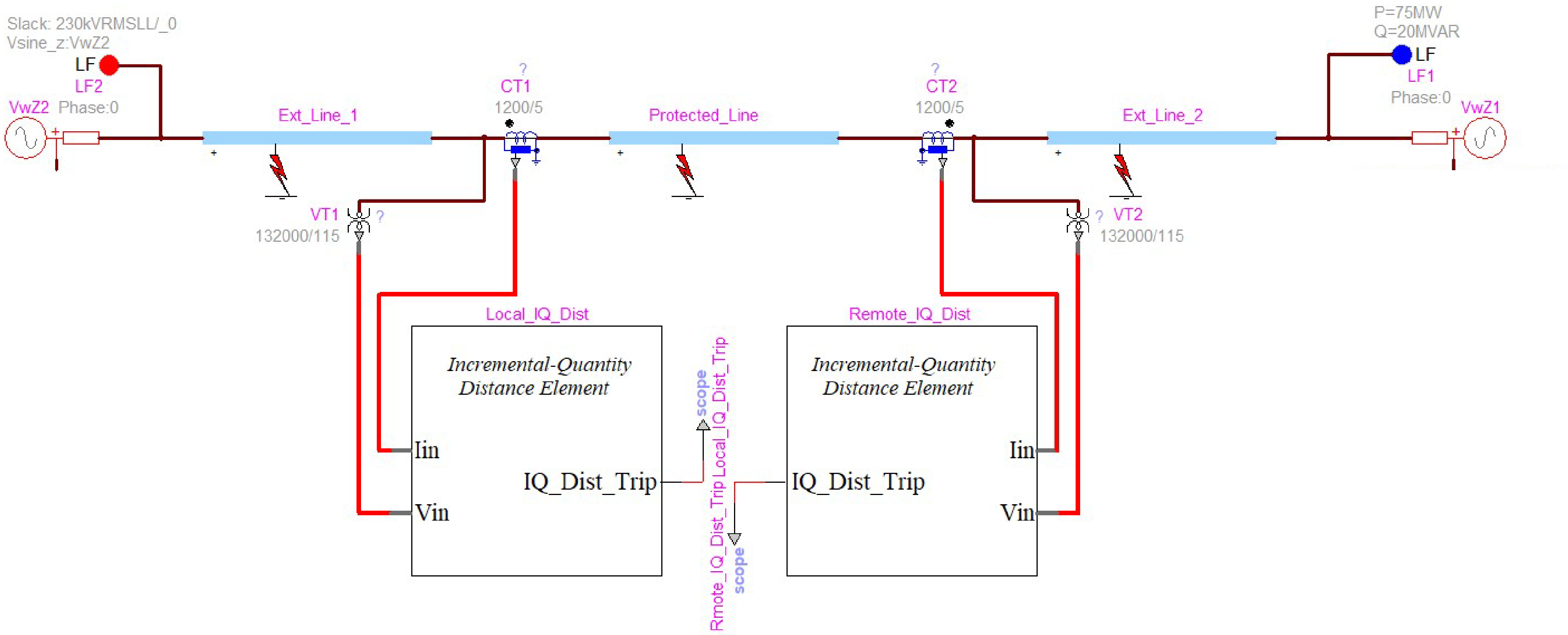


Initial vs final restraining voltage comparison

Experiment Setup Summary

- Incremental quantity distance element (TD21) was developed and tested on a 230 kV simple test system with two machines and constant parameter lines; protected line length was 175 km
- Settings were developed for the test system and preliminary simulations were run
- EMTP generated event files were played on the SEL relays to record their response
- Response of the digital model and the SEL Relays were compared against one another
  - Setting and parameters of the TD21 model were tweaked and modified until the response aligned with that of the TDR

Experiment Setup



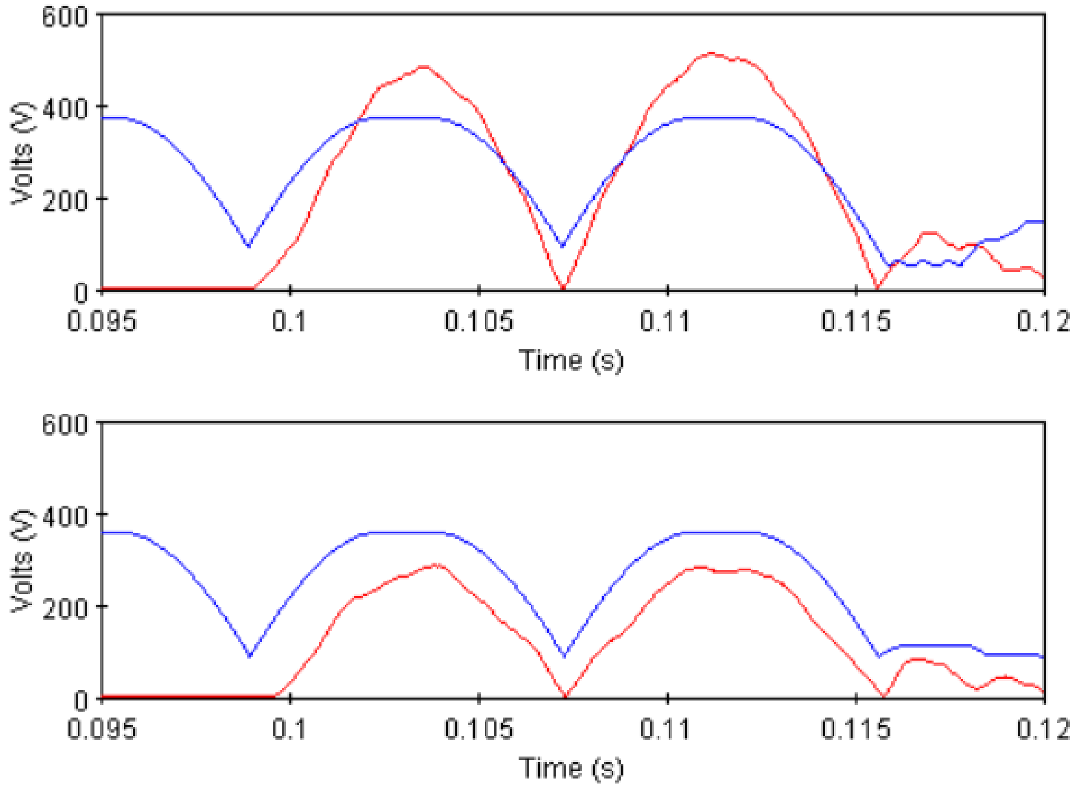
Simple system for incremental quantity distance element testing

Model Verification Simulation Results

Fault introduced at 0.099 seconds				
Line Length (km)	**Fault Distance from Local Relay (km)**	**Fault Type**	**I.Q. Distance Element Local**	**I.Q. Distance Element Remote**
175	**-10**	CG	NT	NT
	-5	AB	NT	NT
	1	AG	TRIP	NT
	1	CA	TRIP	NT
	20	CG	TRIP	NT
	20	AB	TRIP	NT
	25	BG	TRIP	NT
	25	BC	TRIP	NT
	75	AG	TRIP	TRIP
	75	AB	TRIP	TRIP
	95	BG	TRIP	TRIP
	95	CA	TRIP	TRIP
	120	CG	NT	TRIP
	120	BC	NT	TRIP
	135	AG	NT	TRIP
	135	BC	NT	TRIP
	145	CG	NT	TRIP
	145	CA	NT	TRIP
	173	BG	NT	TRIP
	173	AB	NT	TRIP
	178	CG	NT	NT
	181	AB	NT	NT

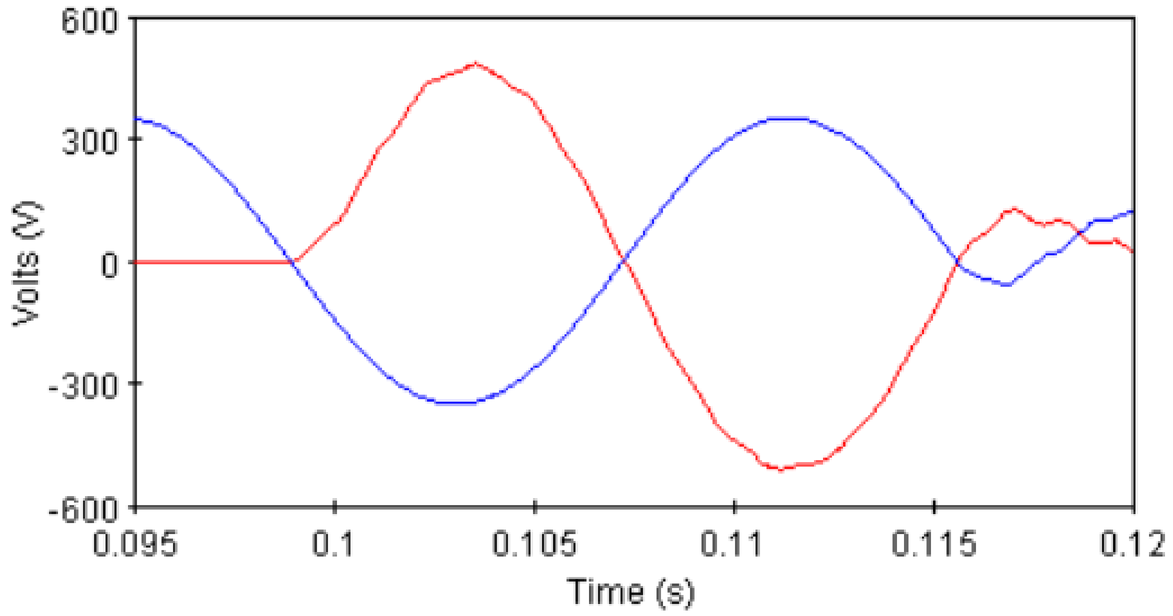
Test results obtained using the simple system

Analysis of Results



Final operating and restraining signals for CA fault near the local bus

Analysis of Results



Raw operating and restraining signals for CA fault near the local bus

Comparison of Results

Incremental Quantity Distance Element Comparison						
Fault Introduced at 0.099 seconds						
Line Length (km)	Fault Distance from Local Relay (km)	Fault Type	T400L Relays		EMTP Model (K=1.06)	
			TD21 Local	TD21 Remote	I.Q. Distance Element Local	I.Q. Distance Element Remote
175	66	AG	TRIP	NT	TRIP	NT
	66	BC	TRIP	NT	TRIP	NT
	67	CG	TRIP	NT	TRIP	NT
	67	AB	TRIP	TRIP	TRIP	TRIP
	68	BG	TRIP	TRIP	TRIP	NT
	68	CA	TRIP	NT	TRIP	NT
	69	CG	TRIP	TRIP	TRIP	TRIP
	69	AB	TRIP	TRIP	TRIP	TRIP
	70	BG	TRIP	TRIP	TRIP	TRIP
	70	BC	TRIP	TRIP	TRIP	TRIP
	98	CG	TRIP	TRIP	TRIP	TRIP
	98	AB	TRIP	TRIP	TRIP	TRIP
	99	BG	TRIP	TRIP	NT	TRIP
	99	AB	TRIP	TRIP	TRIP	TRIP
	100	AG	NT	TRIP	NT	TRIP
	100	BC	NT	TRIP	NT	TRIP

Comparison between the SEL-T400L Relay and the EMTP model TD21 element results

Conclusion

- Results indicate that the incremental quantity distance protection (TD21) element is a secured protection scheme
  - The EMTP model operated for all close in faults and never operated for any external faults
  - This element can operate very rapidly (in the order of a few milliseconds [4]), especially for faults well within the set reach
- The digital model of the TD21 element implemented herein using EMTP closely mimics the response of the TD21 element of TDR
  - Most differences between the EMTP model and the TDR occurred for faults that were close to the reach point
- Digital model can be used in electromagnetic studies to predict the response of relays on the field

References

[1] E. O. Schweitzer, A. Guzman, M. V. Mynam, V. Skendzic, B. Kasztenny, and S. Marx, "Locating faults by the traveling waves they launch", 40th Annual Protective Relay Conference, October 2013.

[2] M. Vitins, "A fundamental concept for high-speed relaying", IEEE Transactions of Power Apparatus and Systems, vol. PAS-100, no. 1, pp. 163–173, January 1981.

[3] G. Benmouyal, N. Fischer, and B. Smyth, "Performance comparison between Mho elements and incremental quantity-based distance elements", 43rd Annual Western Protective Relay Conference, October 2016.

[4] SEL-T400L Ultra-High-Speed Transmission Line Relay Traveling-Wave Fault Locator High-Resolution Event Recorder Instruction Manual, Schweitzer Engineering Laboratories Inc., Pullman, WA, 2017-2019.

[5] E. O. Schweitzer, B. Kasztenny, A. Guzman, V. Skendzic, and M. V. Mynam, "Speed of line potection - can we break free of phasor limitations?", 41st Annual Western Protective Relay Conference, October 2014.

[6] E. O. Schweitzer, B. Kasztenny, and M. V. Mynam, "Performance of time-domain line protection elements on real-world faults," 42nd Annual Western Protective Relay Conference, October 2015.