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Adaptive Distance Protection For Series Compensated Transmission Lines

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1. Introduction

The benefits of installing series capacitors in the power system include increased power transfer capability, improved power system stability, reduced system losses, improved voltage regulation, and the possibility to regulate power flow. Installation of series capacitors, however, introduces challenges to protection systems with regards for both the series compensated lines and the adjacent lines [1,2]. The protection of systems with series compensated lines is considered one of the most difficult tasks both for relay design and utility engineers.

The application of line differential systems, such as phase comparison or current differential protection, is straight forward also for series compensated lines as they do not need voltage measurement. However, a distance protection may be applied, either as a complement to the differential scheme or due to lack of communication media for differential protection. One of the main advantages with pilot distance protection schemes is that they operate over Power Line Carrier.

Distance relaying is one of the most important components of protection systems available to protection engineers. Distance relays can benefit from ideas in the newly developed field of adaptive protection, and can offer an even more selective and sensitive form of protection, under a variety of system configurations.

Based on the principle of superimposed transient signals outlined in [3], the first travelling wave relay was developed for commercial use. This relay satisfied the ultra high-speed requirements for one-cycle fault clearances and has been in service for many years. The drawback, however, is that it is not based on a continuous measuring algorithm. In order to overcome this drawback, the above mentioned method has been combined with an impedance measuring device. It is not possible to use only one algorithm but rather a hybrid solution with parallel and adaptive algorithms has to be implemented. This paper explores such a hybrid solution in order to obtain high-speed operation while maintaining high dependability and security.

Verification of the fast measuring algorithms is done by using EMTP/ATP [4], as well as by real time simulation with a power system simulator [5] and with a real time Digital Transient Network Analyzer [6]. The results are presented in this paper.

2. Application with series compensated lines

Series compensation is a method used to allow transmission of heavy load over long distances, with maintained stability. Short clearing time is the most important factor to maintain stability. This is especially true for close in faults with high fault current.

Protection and control of surrounding circuit elements, particularly transmission line protection, needs to be adapted to the measuring conditions presented by these devices. The protection in the neighborhood of the lines with series capacitors is also affected. Both fixed series capacitors and thyristor controlled devices introduce harmonics and non-linearities which adversely impact the protection function. To take a full advantage of the series capacitor installation in a utility network, it is necessary to explore the impact of series capacitors on protection and implement appropriate schemes.

Phenomena that affect the protection of network with series compensated lines are explored and outlined in [7].

In systems with series compensation, low frequency transients, large phase shifts, current and voltage reversals will influence the measured quantities. In addition, protective gaps and MOV's will change the voltages and currents used by the protection system.

A one-line representation of a simple system with a capacitor at the terminal and a fault F1 on the line (Figure 1) is used to describe some of the phenomena below, where m (p.u.) is the fault location .

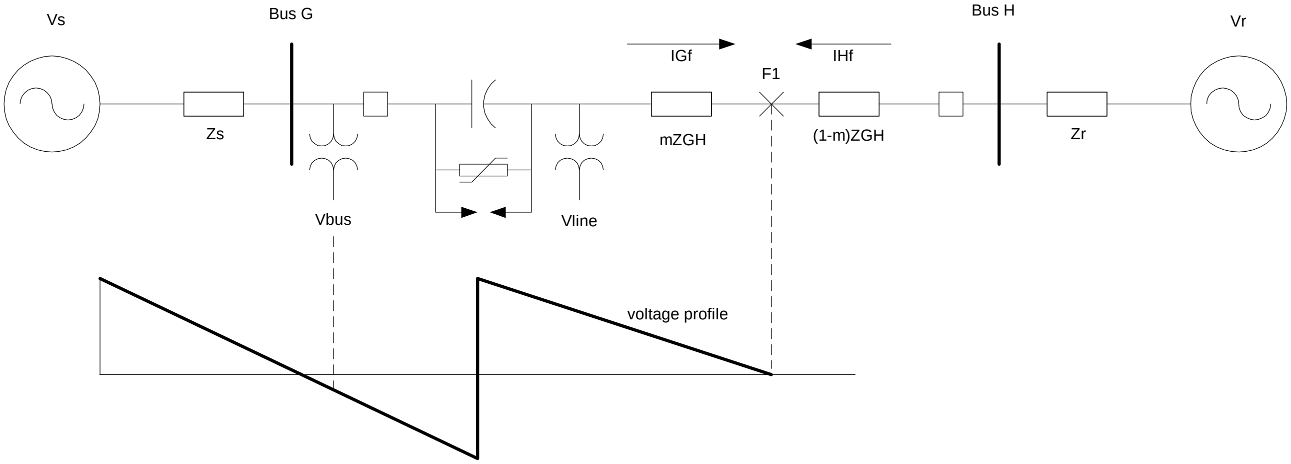

Figure 1. Voltage inversion

2.1. Voltage inversion

Voltage inversion occurs when a voltage at a relay location changes sign. The relay may see a fault on the protected line to be in the reverse direction. For the fault F1 in Figure 1 and the bus side voltage measurement V_{Gbus}, conditions for voltage inversion, assuming only reactances in the fault loop, are:

1a $X_C > m \cdot X_{GH}$

and

1b $X_C < m \cdot X_{GH} + X_S$

2 $X_C \leq \dfrac{|V_{\max}|}{|V_{\max}| + |V_s|} \cdot (m \cdot X_{GH} + X_S)$

Based on condition 1a, voltage inversion has more chance to occur for a fault close to the relay (unless source impedance is too small - condition 1b). However, if the fault is very close to the bus, condition 2 may not be satisfied. If condition 2 is not satisfied, the fault current may cause the gap to flash, and $X_C=0$. Thus, voltage inversion is restricted by the value of $|V_{\max}|$. If the MOV conducts ($V_c>V_{pl}$), the capacitive reactance in the fault loop is reduced to $X_{CMOV}<X_C$, again, reducing chance for voltage inversion. In conclusion, voltage inversion may occur for faults located within a certain range on the line. This range depends on: source and line impedance, fault resistance, and capacitor protection design. In addition, transient voltage inversion may occur before the MOV starts conducting. It depends on the fault inception angle and will last less than half a cycle.

Examples of voltage inversion using voltage profiles for the fault F1 is shown in Figure 1. Fault F1 is a forward fault for the relays 1 (bus side voltage) and 2 (line side voltage). The voltage profile for Fault F1 shows that Relay 1 will see the inverted voltage when bus side potentials are used.

2.2. Current inversion

Current inversion occurs if current at the relay location is capacitive in regard to the source voltage due to the large capacitive reactance in the fault loop. Voltage and current inversion cannot happen simultaneously. Using Figure 2, fault F1 and bus side measurement, conditions for current inversion, assuming only reactances in the fault loop, are:

1. $X_C > Xs + m \cdot X_{GH}$
2. $V_C = \frac{1}{1-(m \cdot X_{GH} + X_s)/X_C} \cdot V_s \le V_{max}$

For condition 1 to be satisfied, the source reactance should be small and a fault should be close to the relay. Again, if the MOV conducts (Vc > Vpl), the capacitive reactance in the fault loop is reduced to $X_{CMOV}<X_C$, which consequently reduces the chance for current inversion. If condition 2 is not satisfied, the gap will flash and the capacitor will be by-passed. Because |Vmax| < |Vs| and condition 1 is satisfied, condition 2 cannot be satisfied assuming only reactances in the fault loop. However, if there is a significant resistance in the fault loop (e.g. high fault resistance), condition 2 is no longer valid and the fault current can be expressed as:

3. $I_{Gf} = \frac{V_s}{j(X_s + X_{GH} - X_c) + R_f}$

If the value of the fault resistance R_f is small, the current may be large and, consequently, the capacitor will be by-passed or the MOV will conduct. Thus, the capacitive reactance in the fault loop will be small and the probability of current inversion is greatly reduced. If the value of R_f is large, the MOV does not conduct. The fault current I_{Gf} will lead the voltage at the relay location by a small angle. The highest value of this angle is limited by the case when the MOV starts conducting. In conclusion, if current inversion occurs, the capacitive current will lead voltage by an angle with a limited value, thus, reducing the possibility for false relay operation. Current inversion does not occur for reverse faults unless the compensation is larger than 100%.

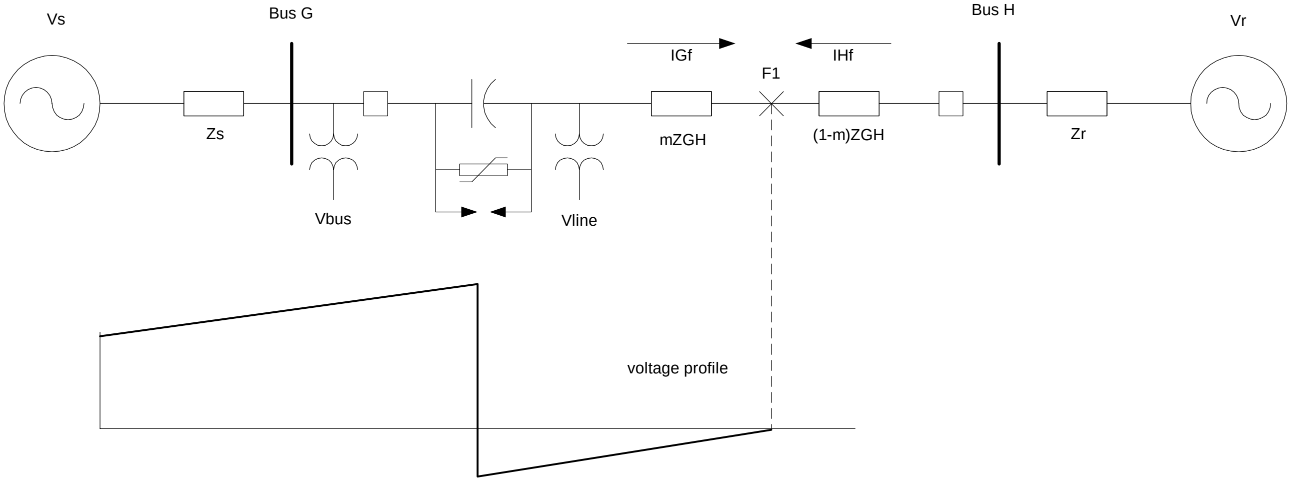

Figure 2. Current inversion

2.3. Reach

Relay reach measurement depends on the status of the capacitor (in or out of service) and the MOV protection response. In practice, the relays are set based on the worst case conditions for the particular pilot or non-pilot protection scheme. Examples of reach measurement problems will be described by analyzing operation of the protection in Figure 3. The desired setting of the relay at 1 is 90% and the capacitor reactance is 60%. If zone 1 of the relay is set to 90% and the capacitor is in service, zone 1 coverage will be 150%. The external fault F2 will be seen inside the zone (relay overreach). Thus, zone 1 should be pulled back to 30% to avoid overreach. However, if the capacitor is not in service or is by-passed, only 30% of the line will be covered and fault F1 will be seen outside the zone (relay underreach). For the realistic case of the MOV conducting, faults closer to the relay will cause reduction in the capacitor negative reactance value.

If zone 2 or pilot zone is set to 120% and the capacitor is in, the zone coverage will be 180% which may cause coordination problems with the protection on the adjacent lines, in particular, if the adjacent line is short. This problem is amplified with outfeed at the remote terminal. On the other hand, if the zone is set to 60% and capacitor is out (or by-passed), only 60% of the line will be covered which is unacceptable (underreach - relay may not trip for Fault F1).

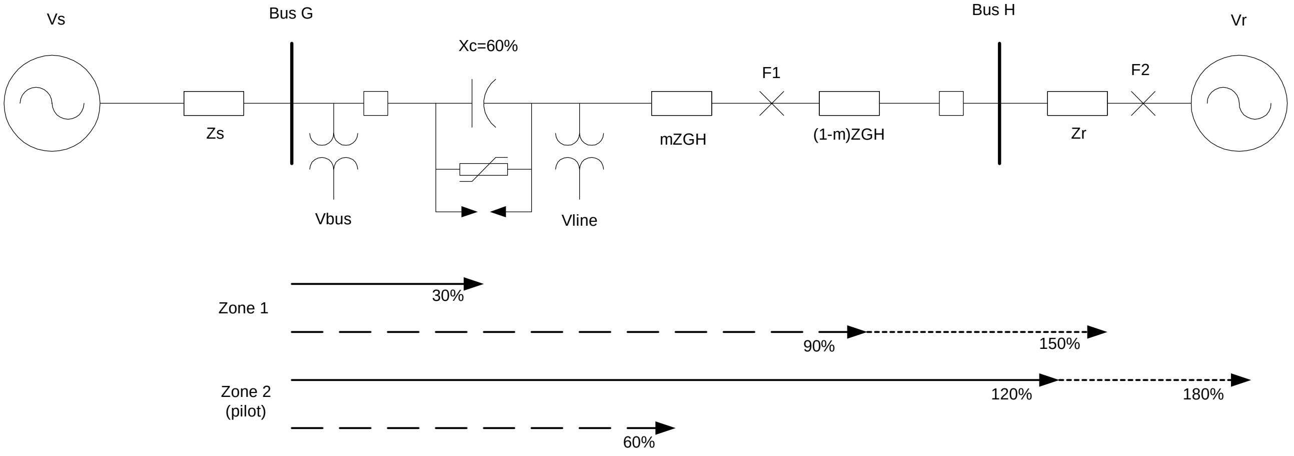

Figure 3. Reach

The conclusions are:

1. A conventional Zone 1 should be set taking into account the capacitor reactance to avoid overreach for external faults.
2. Zone 2 or a Pilot Zone should be set without including capacitor reactance to avoid underreach for internal faults if the capacitor is by-passed.
3. Pilot schemes are superior to stepped distance schemes.

Previous analysis has shown that zone 1 coverage can be extremely reduced in order to avoid overreach. This reach may need to be further reduced to avoid overreach due to the oscillations of the impedance locus caused by sub-synchronous frequency. Switched series capacitors further complicate setting of the protection schemes. The reach measurement can be singled out as the main source of problems for distance protection in series compensated networks.

2.4. Transient effects

The addition of series compensation to a system will introduce several transient effects in estimating the voltage and current phasors. These effects will impact protection for the series compensated lines as well as protection on the adjacent lines. These phenomena are outlined below.

Sub-synchronous frequencies

On series compensated lines, the capacitor will introduce a subsynchronous frequency. The frequency is dependent on the capacitor and system parameters. The natural frequency is proportional to the degree of compensation and is inversely proportional to the source to impedance ratio and the fault location m. The higher frequency occurs when the fault is close to the relay. The higher frequency will not be as critical for close in faults since the capacitor MOV will typically short the capacitor for these cases. However, when a fault occurs toward the end of the line the lower frequency components will cause the impedance estimate to oscillate.

MOV and overload protection operation

Once a fault has occurred, the bypass breaker will be closed following operation of the overload protection system. This will introduce a transient in the system as the breaker arcs and the impedance seen by the relay is altered. The effect will be to increase the impedance to the fault and lower the fault current, thus altering the phasor estimate. The quick response of the MOV will reduce the capacitance and limit the impact of the subfrequency component. The trip of the overload protection will remove the capacitor from the fault loop.

Asymmetrical gap flashing and high frequency components

Asymmetrical gap flashing, high frequency components, and other phenomena are expected to influence phasor estimate and relay performance. Impact of high frequency components is usually reduced by filters in the relay. Asymmetric gap-flashing mainly depends upon the operation and design of an MOV overload protection and has a similar effect as unbalanced faults. In addition, three-phase bypassing is very common, thus reducing the asymmetric gap-flashing effect.

3. New protection scheme

The presented distance protection with fast tripping algorithms has been designed with added features for protection of series compensated transmission lines:

- In order to maintain correct directional discrimination in case of voltage reversal a polarization function is added to the main distance protection. The polarization voltage is based on healthy phase and memorized voltage.
- The directional determination for high-speed ground fault detection utilize superimposed currents and polarizing voltages during a short interval after the fault inception. This makes it possible to extend the reach of the fast tripping zone regardless of the capacitor presence in the fault loop, since the apparent reactance changes slowly.
- The comparison of the current level with the voltage level gives impedance circles (Figure 5) for faults with high fault current. During this condition the effective compensation is reduced due to the influence of the overvoltage (MOV) protection. This enables the protection to be set to cover a larger portion of the protected line.

Figure 4 shows the schematic diagram of the new protection that consists of the main distance protection, a fast tripping algorithm for multi-phase faults, and a fast tripping algorithm for single phase to ground faults. Besides that there are also blocks representing the A/D converter circuit board and the logical output CPU. The binary outputs “Trip” and “Direction” are the phase selective tripping and the directional information, respectively, to be used in the pilot scheme.

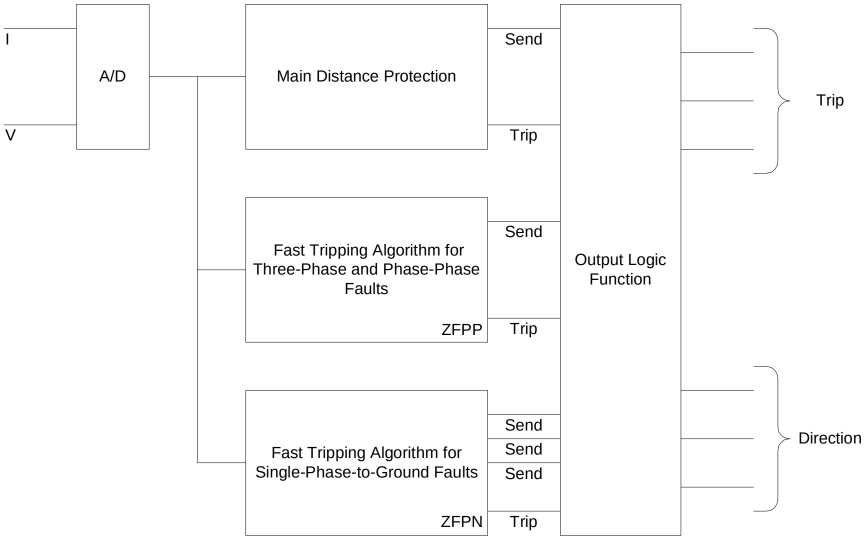

Figure 4. Block diagram of the new protection scheme.

3.1. Main distance protection

The main protection function is a full scheme distance protection with three impedance measuring zones. The zones have quadrilateral characteristic [7], as shown in Figure 5. The setting for each zone is independent for: reactive and resistive reach, resistive reach for single phase to ground and multiphase faults, zero sequence compensation factor and directionality.

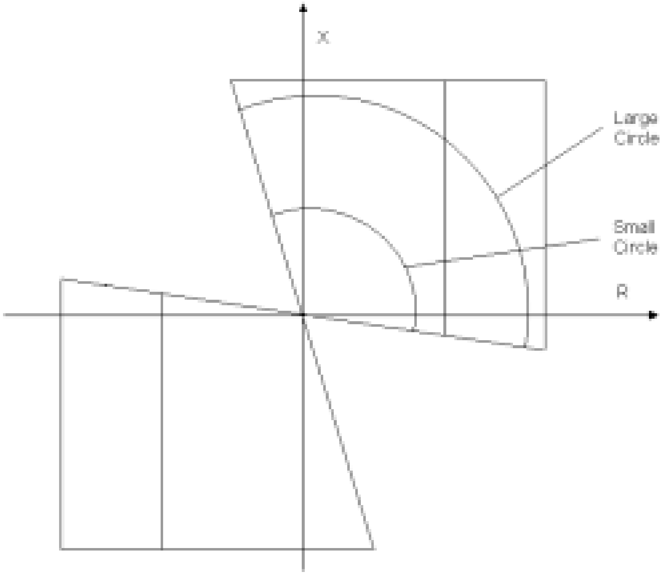

Figure 5. Fault detection elements and adaptive expanding characteristic

Ultra high-speed operation is achieved by the characteristic represented by the circle segments in Figure 5. The filter used for this function [7] gives initially an underestimation of the current, which increases security of the scheme. The comparison of the currents and voltages gives an impedance circle (small circle in Figure 5) and the operating time is shorter. The apparent characteristic will increase (large circle in Figure 5) when the filter factors are adjusted towards a narrower bandwidth and as the estimate of the fault current grows.

3.2. Theory of operation

The high-speed function is measuring the three phase-to-ground loops as well as the three phase-to-phase loops. The trip in case of three-phase faults is issued by the phase-to-phase measuring loops (operation of one of the loops is sufficient for a three phase trip).

The measurement is of full scheme type. The three phase to ground loops and the three phase to phase loops are calculated in parallel. A new set of samples is issued every ms. All calculations are repeatedly performed on each new set of samples and a result is available every ms. The trip as well as the pilot send function require that the operation criterion has been fulfilled during a number of calculations. The results are accumulated in a trip counter.

3.3. Basic characteristic

The characteristic can be described by Figure 5. Due to the transient character of the measuring principle, static measurement can not verify the characteristic. Dynamically, it can be verified that no operation will occur outside the characteristic.

The different measuring criteria can be identified in the characteristic and all of them have to be fulfilled for operation. The characteristic is principally identical for all type of faults. The reactive and resistive reach settings are different for the phase-to-ground and the phase-to-phase measuring loops.

3.4. Fast tripping algorithm for multiphase faults

The main interest is to gain speed at multiphase faults, especially when they are close to the relaying point. For such faults, the fault currents are high. This provides good measuring conditions and enables faster measurements. This has been achieved by a comparison of the estimated filtered current magnitudes with the corresponding voltage magnitudes, such that

$$I \cdot X_{lset} > k \cdot V,$$

where

X_{lset} is the set reactance

I and V are the estimated current and voltage magnitudes, respectively

k is a constant suitable for fast tripping

The presence of zero sequence current prevents unselective three phase tripping at ground faults, where single phase tripping is to be provided by the ground elements (by using the ZFPN scheme).

The fast tripping algorithm function uses fault quantities within one half cycle in order to avoid overreach during subsequent breaker opening transients and other phenomena. This function is supervised with an instantaneous measurement of the phase-to-phase current before an output is issued.

3.5. Fast tripping algorithm for single-phase-to-ground faults

The algorithm presents a new approach to the distance protection with adaptive features. It consists of three main parts. One part is for the determination of the direction to a fault using superimposed currents and polarized voltages. The directional function provides a very high-speed phase selective signal for directional comparison pilot schemes.

The second part is the determination of the faulty phases. The method of phase selection uses a novel technique utilizing the pre-fault quantities of the voltages and currents. The pre-fault quantities are obtained with help of information from the healthy phases. The phase selection is the most important function to prevent unwanted operation in the unfaulted phases.

The third part is the determination of the fault loop impedance. This is done by using an algorithm (*Z1*) that measures the impedance of the faulted loop by utilizing the line model, neutral model and the fault model. Correlation and adaptive filter techniques are applied to improve measuring conditions.

The fast tripping algorithm for the single-phase-to-ground fault module, ZFPN, will be described in more detail below. In the equations that follow, sample values will have lower case letters, while magnitudes will have upper case letters. The magnitudes are calculated from voltage and current samples and their derivatives.

The ZFPN scheme is a further development of the principles introduced in Ultra High-Speed Protections described in references [3, 8]. The philosophy of the hybrid solution is to enable the fast tripping algorithm to provide high security while the main distance protection algorithm improves the dependability. The ZFPN is optimized to give high-speed operation in case of single-phase-to-ground faults and is only activated by the following "ground fault conditions":

- currents in all phases $\hat{I}_n > 0.40 \cdot \text{rated current}$

and

- $\hat{I}_n > 0.20 \cdot$ maximum of differences of phase currents

where $\hat{I}_n$ is the magnitude of the sum of the phase currents

The phase selective function can define only one faulted phase. The measurement is performed during a time window of 15 ms.

As a next step, pre-fault load current and voltage values in the faulted phase are calculated from currents and voltages in unfaulted phases. These values are calculated by using derivatives of current and voltage samples. The pre-fault values are used to calculate superimposed voltage and current (Δ-quantities) in the faulted phase. The phase selection, directional, and distance measurement parts will be described below.

Phase selection (P)

The phase selection algorithm is common for both single-phase-to-ground and multi-phase faults. The phase selection is performed by comparison of changes in the phase-to-phase currents between phases A and B, B and C, and C and A. The changes in the phase-to-phase currents are obtained by subtracting the actual fault currents with corresponding pre-fault quantities.

The quantities (changes of currents) should be above certain operation levels in order to indicate the faulted phase. Due to the fact that the changes in the phase currents can not be measured continuously, the phase selection for all types of faults is blocked after 15 ms.

Direction (D)

The directional measurement is performed with full cross polarization. The polarizing voltage is taken entirely from the healthy phases. The change in the phase current (Δi_{phase}) is used for the directionality to eliminate the influence of load current. The change in current is calculated by subtracting the faulted phase current with corresponding pre-fault value.

The impedance is calculated for each phase. For example, for phase A, the impedance is calculated by:

$$v_{BC} / \Delta i_A$$

where v_{BC} is the difference of voltage between healthy phases B and C, and Δi_A is the change of current in phase A.

For the detection of a fault in "forward direction" the argument for the calculated "impedance" shall be within -15 to 115 degrees.

Fast zone 1 (Z1)

A zone 1 fault will be indicated if the measured impedance is within the rectangular characteristic defined by the zone 1 settings and if the following condition is satisfied:

$$I \cdot (X_{lset} + X_{nset}) > k \cdot V$$

This function is similar to the ZFPP scheme described above.

Logic functions

The output from the ZFPN algorithms are combined to form logic outputs. The internal signals for each phase are: phase selection (*P*), direction (*D*), fast zone 1 tripping (*Z1*) and overreaching pilot zone (*Z2*). Using * as an "and" operator, combinations used to form output signal from the logic are as follows:

$Send = D \cdot P \cdot Z2$
$Trip = Send \cdot Z1$

The *Z2* function is used to limit the reach of *Send*. The directional phase selection function can be used to speed up the main 2nd zone (pilot zone) tripping in the remote end. It could also be used in directional comparison if the ZFPN directional functions in both ends are used and compared.

4. Implementation

4.1. Hardware Platform

Implementation of the new distance protection with fast tripping algorithms has been made in a modular line terminal platform. The transformer module, the A/D conversion module, the main processing module, the power supply module, the binary I/O module and the communication module are shown in Figure 6.

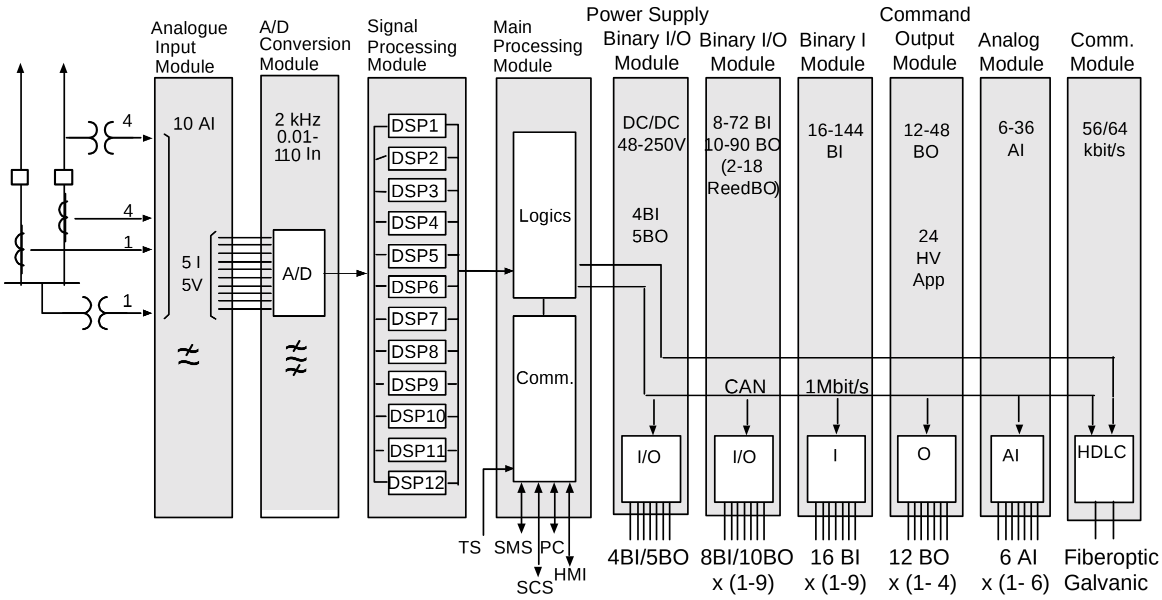

Figure 6. Protection platform

The main processing module can have up to 12 DSPs (Digital Signal Processors) and one 32 bit CPU (Central Processing Unit). The CPU is used for logic and communication. Figure 6 also illustrates the signal and information flow as a "pipe-line" within a line terminal. 5 currents and 5 voltages are connected to the A/D converter that has a sampling rate of 2 kHz or 34 samples/cycle in a 60 Hz system. In addition to the phase quantities, $3I_O$ of the parallel line for mutual compensation for fault location and the bus voltage for synch-check are included. The 2 kHz signal is filtered down to 1 kHz with sliding average filtering. This oversampling technique gives both fast operation and good transient behavior. Each millisecond numerical data for 10 analog (5 voltages, 5 currents) are sent to the 12 DSPs, which are operating in parallel. A separate continuous-measuring micro-processor is used for each main function, which allows for both rapid and complex algorithms, as well as tailor-made filtering for each function. The total capacity of the DSPs and CPU is approximately 100 MIPS.

The data from the A/D converter is available for all 12 DSPs. Each DSP performs both the specific filtering and algorithm as required for each function. By this architecture each DSP with its software can be seen as one protection function. A program change in one DSP will not affect any of the others. The two modules ZFPP and ZFPN are implemented on one DSP each.

4.2. Software Platform

The software platform is structured in different levels:

- Software for basic elements such as start-up routines, self-supervision, operative system, etc.
- Functional platform, with software library for different functions, programmable logic/timers, HMI, etc.
- Product specific configuration

The application library contains all the basic software modules. It also contains possibilities to connect future modules. The application library for protection, control and monitoring functions are shown in Fig. 7. Each software module corresponds to a function block. The function blocks for a particular protection terminal are chosen based on the application requirements. This concept offers the possibility to custom-design the protection and control terminals based on the actual field requirements.

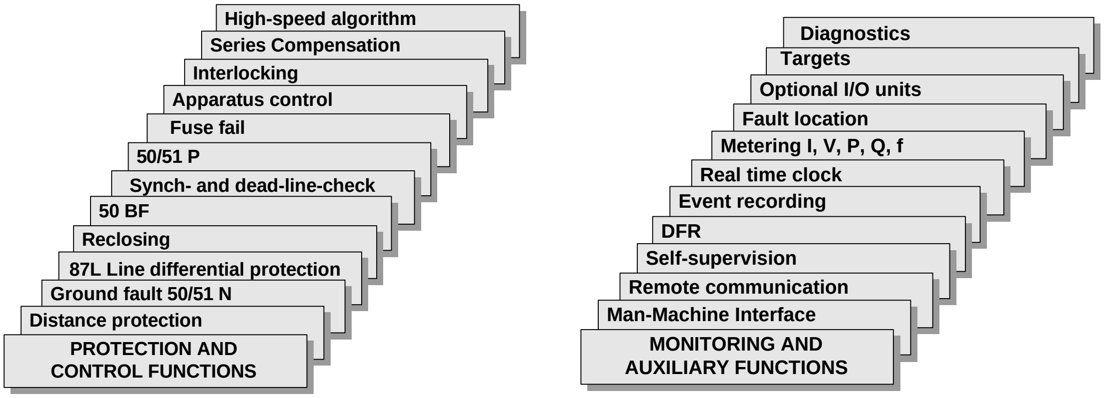

Figure 7. Protection, Control and Monitoring Functions Application Library

4.3. Functional Configuration

The various functions are arranged as individual blocks that can be combined as pre-determined schemes or custom-designed utilizing "connections" as shown in Figure 8. An output signal from one function can be used as an input signal to another function. The function blocks include all protection functions, tripping and reclosing logic, all control functions for apparatus control and interlocking, binary inputs and outputs as well as a logic function library with AND, OR and Timer elements. As an example, each distance zone can be programmed individually and also accessed individually in the logic. External (or internal) signals can be used to block or enable reclosing.

For the control functions different software modules are available. For apparatus control the select before execute principle is utilized. The protection and control functions can be integrated in the terminal in a cost efficient way. To allow the user to take advantage of the configuration flexibility, a Computer Aided Tool (CAT) for PC is available. The tool CAP 531 is based on the IEC standard 1131-3, and allows the user to configure the terminal using graphic symbols, which makes the handling of the configuration tool very simple.

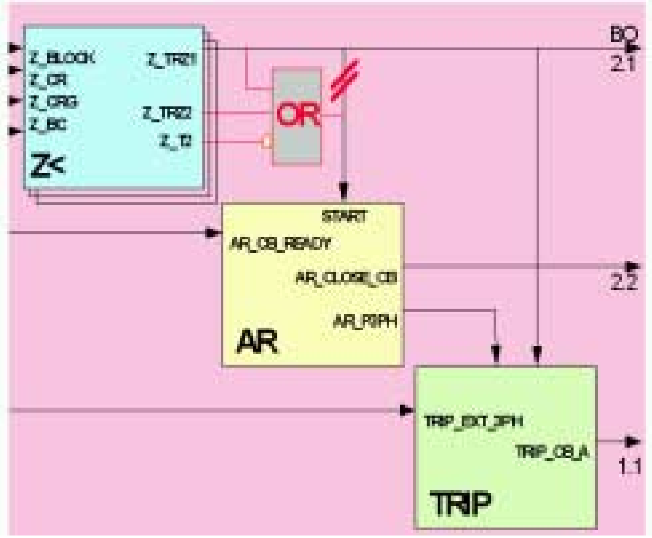

Figure 8. Programmable logic

5. Testing

Development and evaluation of the new protection scheme has been done within an interactive software environment. The software testing of the protection was made by using EMTP-MATLAB software tools. EMTP/ATP files and recorded data from a real-time power system simulator have been used as input data. To fully evaluate operation of the protection scheme, several network configurations have been simulated [9].

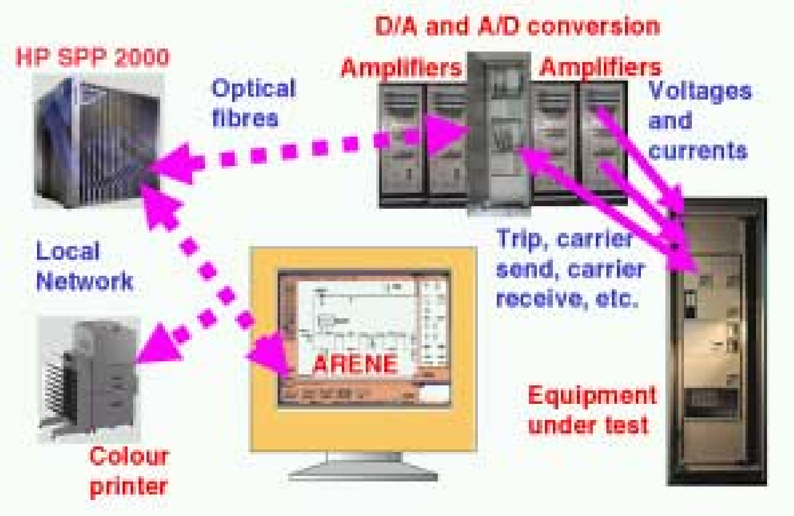

Figure 9a. Configuration of the new digital real time simulator, ARENE ™

Additional tests have been made with a real-time power system simulator [5] and a real time Digital Transient Network Analyzer (DTNA) [6]. The DTNA test was carried out on a 500 kV, 288 km (180 miles) double circuit transmission line as shown in Figure 9b. The transmission line has four (4) series capacitors (each with 28 % compensation) which are protected by MOV's. A phase to phase fault was initiated at point F3 (approximately 40% of the total length as seen at relay R1, Figure 9). The protections are placed at both end points (R1 & R2).

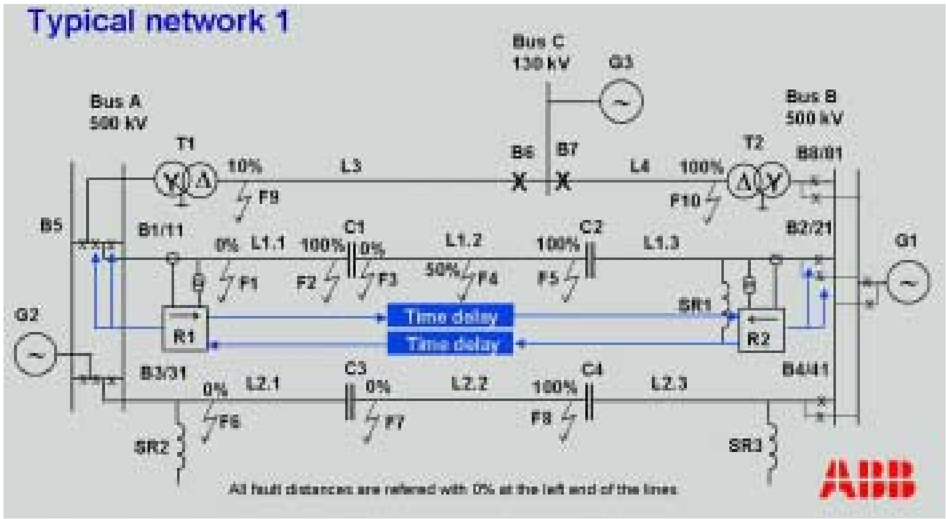

Figure 9b. A double circuit series compensated transmission line for DTNA test.

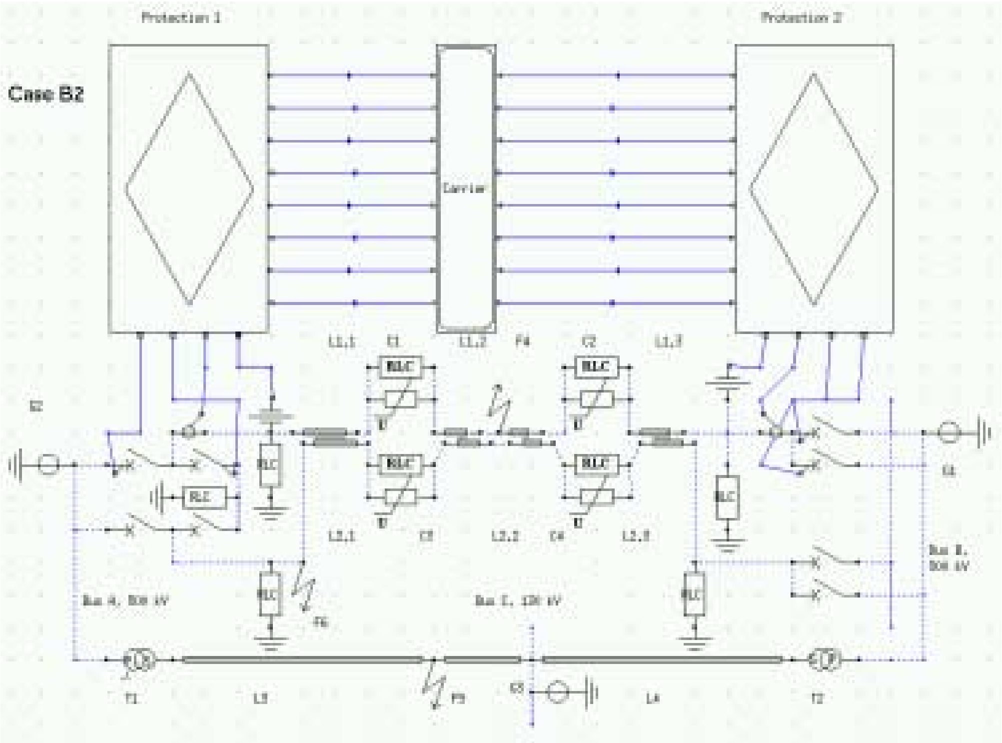

Figure 9c. The network built in ARENE™ for testing REL531 distance protection in a series compensated network.

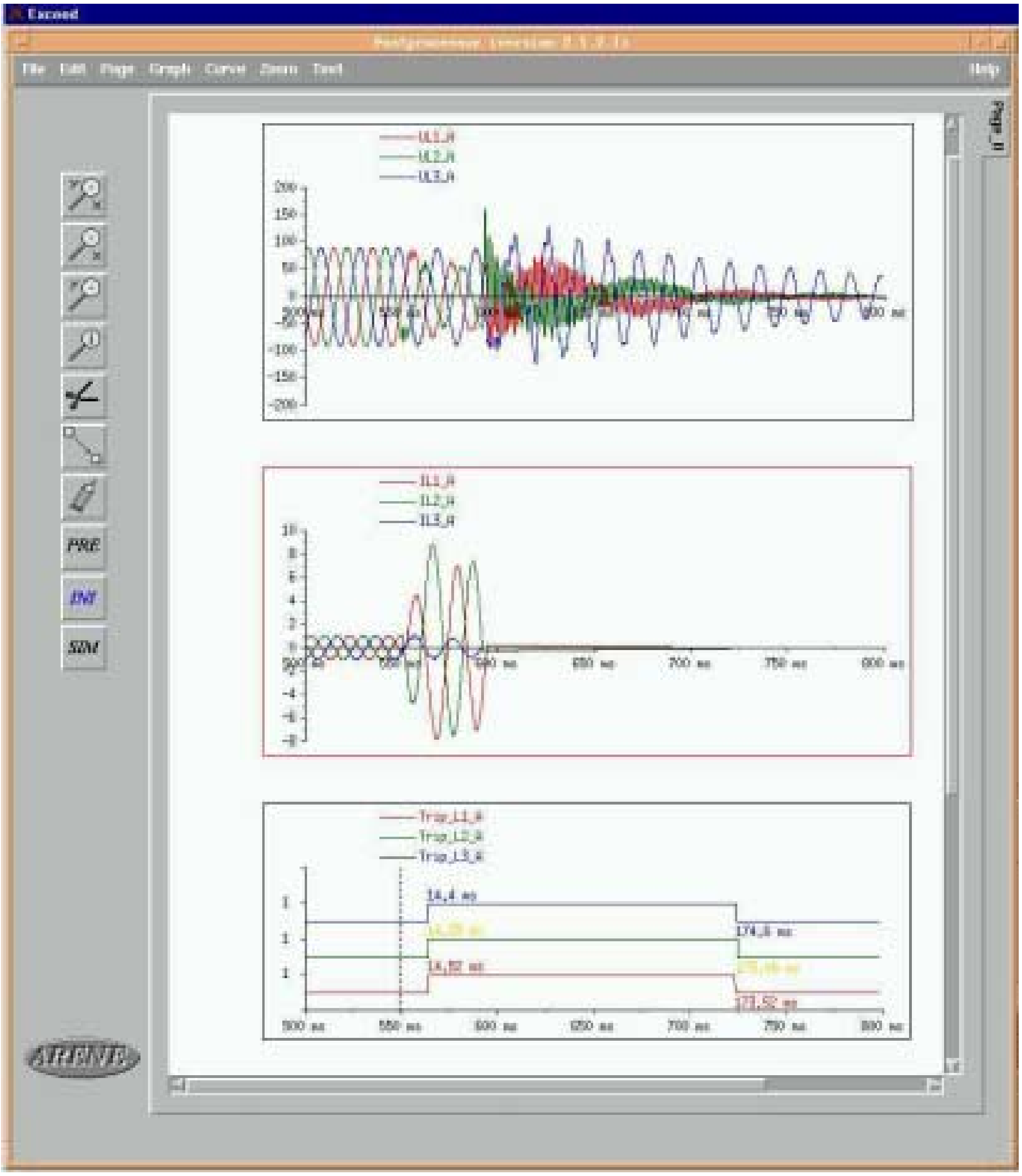

Figure 10. Phase-to-phase fault at F3 as in Figure 9b.

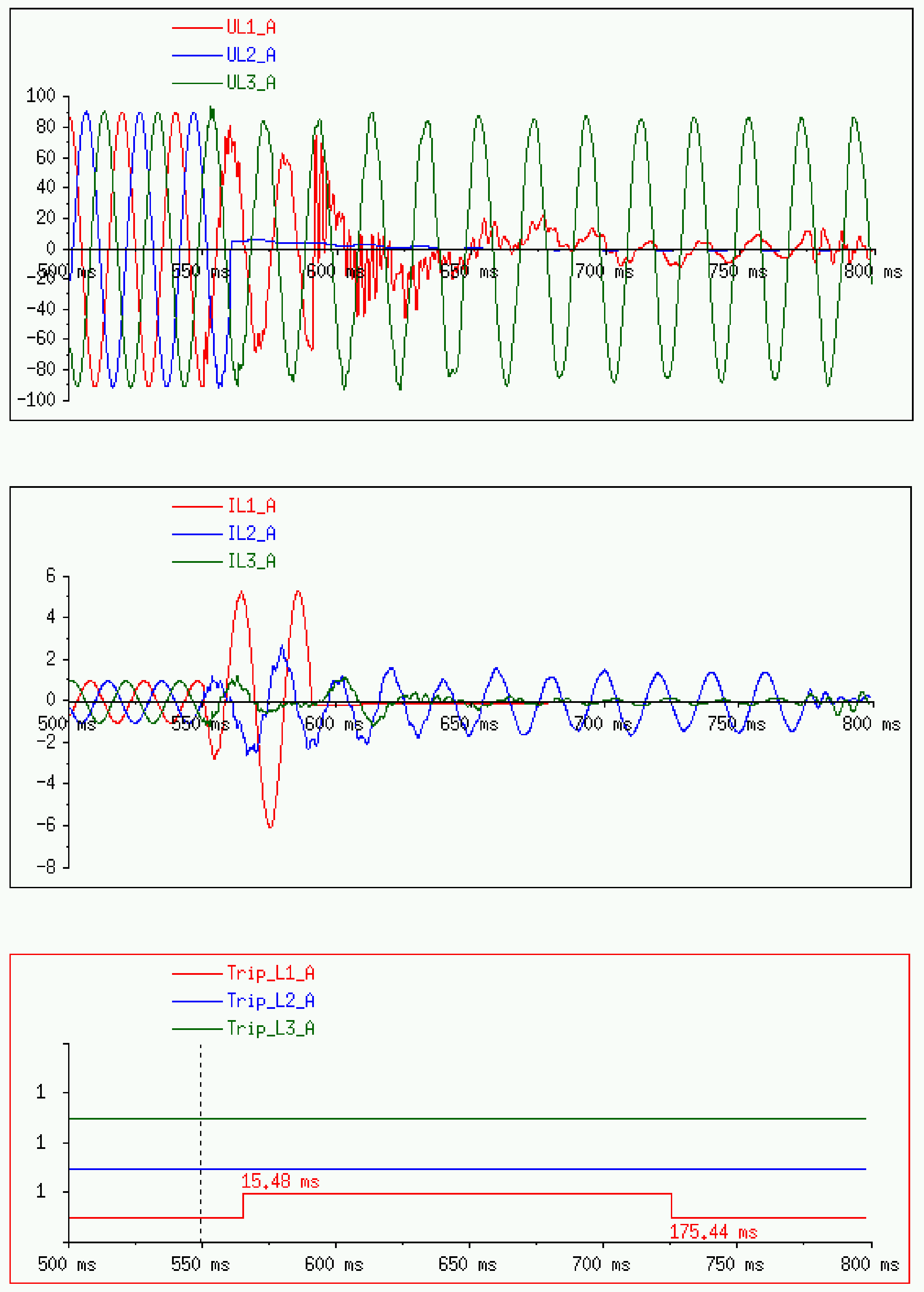

Figure 11. Evolving fault. Simulated currents and voltages in one end of the 500 kV line at a single-phase-to-ground fault in phase A (L1) on the protected line followed by a single-phase bus fault at the beginning of the parallel line (Figure 9b).

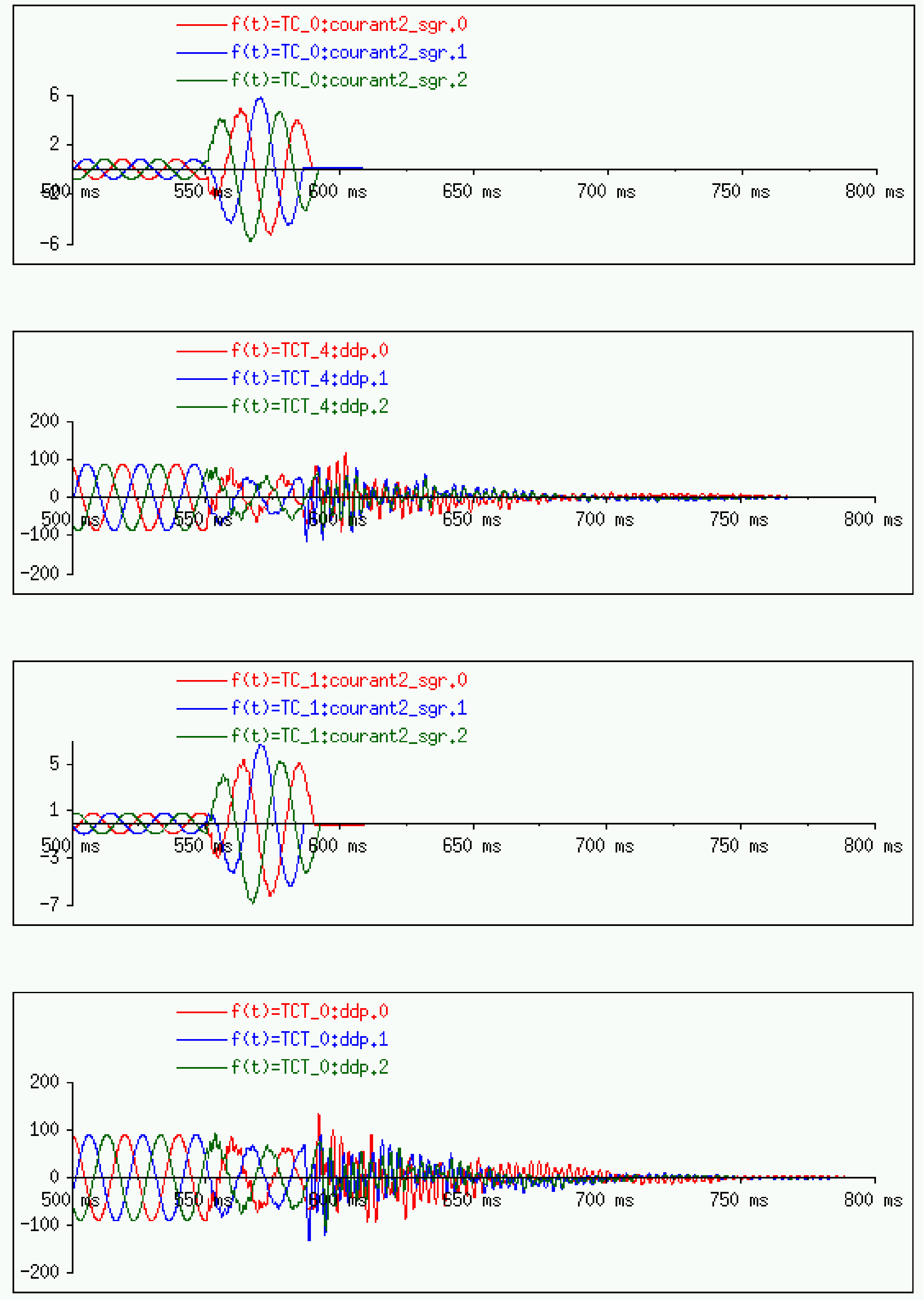

Figure 12a. Simulation results in the two ends of the 500 kV line at a three-phase-to-ground fault between the series capacitors.

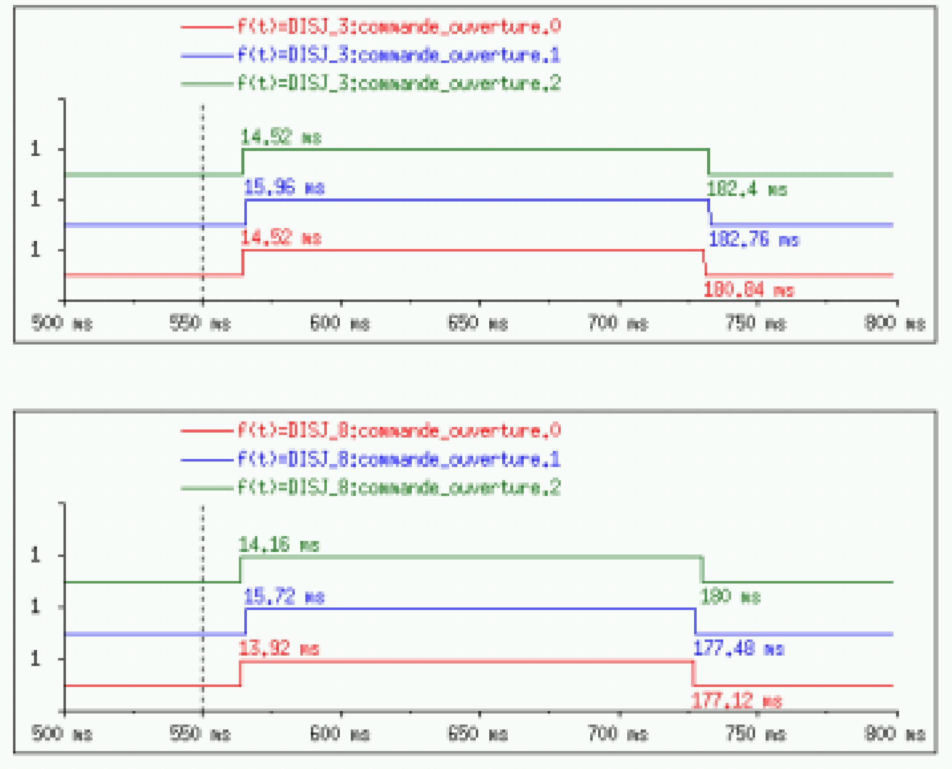

Figure 12b. Test results showing REL531 tripping in the two ends of the 500 kV line at a three-phase-to-ground fault between the series capacitors.

The response of the protection as well as voltages and currents at relay point R1 are shown in Figures 10 - 12. The total operate time including output relays is 14.5 ms. The DTNA tests have confirmed the validity of the high-speed protection algorithm presented in this paper.

6. Conclusions

This paper describes a new, high-speed protection for EHV transmission lines. The presented scheme also performs well on series compensated lines. The protection consists of a main distance protection and fast tripping algorithms for multi-phase faults and single-phase-to-ground faults. The fast tripping algorithm for multi-phase faults (ZFPP) and for single-line-to-ground faults (ZFPN) are introduced to overcome the effects if the series capacitor present in the fault loop. Comprehensive test results on various test systems and a utility system [10] show the benefits of the scheme. The fast tripping algorithm (ZFPN) that minimizes the fault duration for single-phase-to-ground faults is described in detail in this paper. The highlights of the scheme are:

1. Combination of measuring algorithms provides a solution for high-speed protection for EHV as well as for series compensated transmission lines. The scheme provides a high-speed operate time (typically less than half a cycle). Total protection operate time is less than one cycle.
2. The protection high-speed zone can be set to cover up to 70 % of the total uncompensated positive sequence reactance.
3. The overreaching high-speed pilot zone (Z2) operating in a directional comparison scheme provides high-speed operation for all faults on the line.
4. The scheme is now in operation in some 20 countries around the world.

7. References

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9. Biographies

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