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An Integrated Approach for Positional Protection of Transmission Lines

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***Abstract*--The fast development in both microprocessor and transducer technologies has enabled fault detection techniques to be considered which were impractical in the past and encouraged interest in the utilization of fault generated transients for protection. This paper presents an integrated approach for high-speed protection of transmission lines. The technique uses a fault transient detector unit at the relaying point to capture fault generated high frequency transient signals contained in the primary currents. The decision to trip is based on communication and the relative arrival times of these high frequency components as they propagate through the system. Simulation studies of technique were carried out to examine the response to different power system and fault conditions.**

***Index Terms*-- Integrated Protection, Transient Protection, Communication Network, High frequency Current Signals.**

I. Nomenclature

L : The length of the transmission lines
T : Time value
B : Busbar
F : Fault on the transmission lines
u : The propagation velocity of high frequency signals on the line conductors
i : The number of arrival signal
j : The busbar name
l : Local area
p : Fault position
s : Fault section

II. Introduction

With the development of microprocessor and control techniques, the performance of the protection relays has been significantly improved. At the same time, the availability of suitable communications schemes has provided a new opportunity to revisit the concept of integrated protection. Studies have found that the fault generated high frequency transients can be detected and quantified and open the possibility for developing new protection principles and techniques [1]. Considerable effort has now been devoted to research on high frequency transient detection. A number of new techniques have been proposed [2-6] and their associated measurement and signal processing techniques investigated [7-8]. Studies also shows that information obtained from multiple power plants and components can be used to derive new protection principles and schemes, which could have significant advantages over the existing protection techniques based on individual plant or component. In this respect, it has been found that the new transient based protection techniques not only inherit the capability to protect individual plant, but can also be used to produce novel schemes for the integrated protection of a power network.

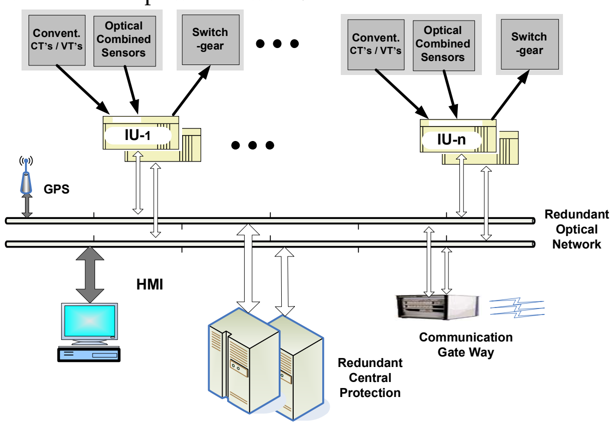

Fig.1 Diagram of a Centralized Integrated Protection System

The "Integrated Protection" is used to denote the integration of protective devices for multiple power apparatuses within the substation into one protective relay. Fig.1 shows an example of a complete integration, in which all protective functions in a substation are integrated into one relay to form a centralized protection system. As shown in the figure, the Interface Unit (IU) is a measurement and control unit, which interfaces to apparatus through different types of transducer, such as conventional CT's and VT's, optical combined sensors and electronic combined sensors. The analogue and digital signals measured are converted into optical format and sent to the central protection relay through the redundant optical network. The IU unit also receives and executes control signals from the relay through the control circuit. The optical network is a communication network

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interfaces not only to critical equipment IU and the relay, but also to a number of other equipment, such as communication gateway, Human machine interface and GPS clock, etc. The use of standard communication protocol for the network will enable IEDs from different manufacturers to be easily interfaced to the system. The central protection relay unit receives measurement from all locations in the substation through the network and information from other related substations through the communication gateway. The relay then performs all calculation to determine whether there is a fault within the substation or on its associated line section. The relay will issue a trip command to open the associated circuit breaker through the control unit if a fault is detected.

III. Basic Principle

The scheme is based on the detection of fault generated transient current signals. In this scheme, a centralized positional protection relay is installed at a substation and interfaced to the transmission lines, through the CTs. The fault generated transient signals are captured by the relay, the arrival time and the polarities of the signals are then recorded, sent and compared, from which the location of the fault can be derived. The traveling times of the high frequency components are used to identify the faulted line section and position. With this technique, a centralized and integrated relay can be used for the protection of all the transmission lines associated with the substation.

A. Detection of Fault Position

Fault occurs on a transmission line will generate wideband voltage and current signals. These signals propagate away from the fault point along the power conductors. In time, these signals reach discontinuities on the transmission line and some of the signal is reflected back towards the fault point. The characteristics of these waves are dependent on several factors including: the fault position on the line, the fault path resistance and the characteristic impedances of the power conductors. This propagation can be shown graphically using a Bewley-Lattice diagram such as that shown as black lines in Fig.2.

The integrated positional protection relays are located at all of the sub-stations in the power system and independently monitor the power system. In Fig. 2, relays are therefore located at substations R, S and T.

The frequency range of interest for monitoring these fault generated high frequency signals is between 40 and 80 kHz and the signal processing is designed to determine the arrival of a high frequency transient characteristic of those generated by a fault. At these frequencies, busbars are dominated by their capacitive elements and as a result the incoming high frequency current signal is both inverted and reflected. A resistive fault in this frequency range will also reflect a current wave of the opposite polarity.

With the integrated protection system, the arrival of the high frequency transients can also send to other integrated protection relays. Each time when one relay captures one fault signal, a message should be first sent out with GPS time scale and local relay name. When the other relays received the message, they can calculate the fault position. The red dashed line in Fig.2 shows the process of data sending between integrated relays.

Referring to Fig.2 and assuming that a fault occurs at a point at distance x from busbar R on line P, the generate wideband signals would be initiated towards both busbars and away from the fault point. When these signals reach the busbars, they are both reflected and inverted.

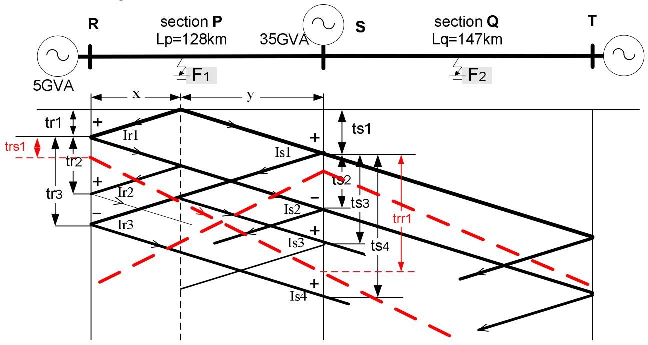


Fig. 2. Bewley-Lattice diagram for a multi-end transmission line

Referring to the relay at S, it first sees the incoming high frequency transient signal from the fault point. Immediately, it sends out one message in a time of trs1, and then sees the signal reflected from the remote busbar R. For the fault generates signals, the second signal will be inverted with respect to the first signal received. There is therefore a natural discrimination between these two signals.

The protective algorithm uses the arrival of these successive high frequency transients to determine which line in the network is faulted and to give an indication of the fault location.

Rule for enable : (RFE)

$$\begin{aligned} & If \quad (\forall i, j, \ \exists \sum_{i=1}^{n} T_{ji} > T_{set}) \\ & \quad T_{ji} = false; \\ & \quad i = 0; \\ & Else \\ & \quad T_{ji} \rightarrow validity; \end{aligned}$$

Rule for fault position(1): (RFFP1)

$$\begin{aligned} & If \quad (\forall i, j, \ \exists (T_{ji} - T_{li}) < k \frac{L_{i \rightarrow l}}{u}) \\ & \& \quad T_{ji} \rightarrow validity; \\ & Then \\ & \quad F_l = 1 \\ & Else \\ & \quad F_l = 0 \end{aligned}$$

Rule for fault position(2): (RFFP2)

$$\begin{aligned} & If \quad (\forall i, \ \exists (T_{ji} - T_{li}) < k \frac{L_{i \rightarrow l}}{u}) \\ & \& \quad F_l = 1; \\ & Then \\ & \quad F_p = \left| T_{ji} - T_{li} \right| * u \end{aligned}$$

B. *Determination of Faulted Section*

The relays at any of the three ends S, R, T are required to determine the faulted section of the line respectively. The technique used to determine the faulted section is based on the identification of the reflected transients from the busbars on the system. Once a relay senses the arrival of the first transient, it sends out one message immediately and starts to record the arrival times of successive transients arriving at the busbar. These correspond to the high frequency transients reflected from the fault point and the other busbars on the system.

This record is taken for a time period corresponding to the transit time of the transient signal over twice the length of the longest line section of the local system.

Knowledge of the lengths of the transmission lines close to the relay and an approximate propagation velocity for the high frequency transient signals enables the arrival of the reflected signals to be predicted. The reflected transient signals from the other busbars in the system will arrive after a fixed time interval corresponding to the length of the lines. Comparisons of the polarities of the reflected wave, their arrival time and magnitude will ensure that the faulted section is correctly identified.

At the same time with the message information from other relays, result can be improved.

Rule for fault section: (RFFS)

$$If \quad (\forall i, j, \ \exists (T_{ji} - T_{li}) < k \frac{L_{i \to l}}{u})(F_l = 1)$$

$$\& \quad T_{ji} \to validity;$$

$$Then$$

$$Min\{T_{ji}\} \xrightarrow{Get\ j} j$$

$$F_s = B_j$$

IV. Integrated Positional Protection Relay

Fig.4 shows the proposed integrated relaying system, which can be divided into two major parts: the communication network and the integrated relay unit.

A. *Communication Network*

The red blocks in Fig. 3 show the connection logic for the integrated protection.

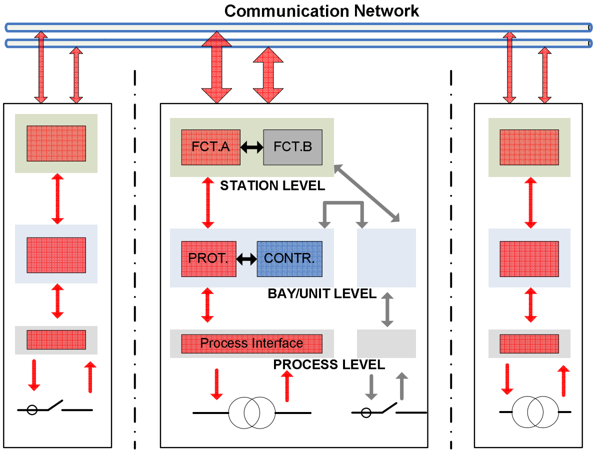


Fig. 3. Diagram of communication network

Ethernet is used as the substation communication network for integrated protection. The transducers are not connected directly to the protection relay as in the conventional approach, but grouped together through an Interface Unit (IU). A number of current and voltage transducers can be connected to the IU. The IU then supplied the relay via a multi-drop point to point link with a time coherent set of current and voltage data. The Ethernet also receives trip commend from the relay and sends to associated CBs. The new method of collecting measurement data and controlling switch gear brings changes to the design of substation protection and control equipments.

B. *The Relay Unit*

As shown in Fig.4, the Fault detection unit of the relay receives current signals from CTs through the Ethernet, a threshold is set to determine whether a fault is occurring on the transmission line system. The relay will start to act once the threshold is met. Although the relay is able to receive signals from all the CTs on the lines associated with the substation, information from one line CT is enough for the technical used to determine the actual fault position on the line as explained in the previous section. This also reduces the communication overhead for the network and saves the computation time of the relay.

The relay extracts the high frequency signals associated with the faults generated current transients. The Modal mixing (or modal transformation) is employed to decouple the phase signals into their respective aerial modes. The signal mixing circuits receive the signals from the three-phase CTs and combine these to form Mode 1 & 2 signals. The multi-channel band-pass filter extracts the band of fault generated transient current signals from the modal signals. The relay is designed to interrogate signals in the range of frequencies from 40 kHz to 80 kHz. As a result, the response of the scheme is not affected by the power frequency short-circuit level at the busbar or the precise configuration of the source side networks. The sampling frequency is 1 MHz and with the speed of propagation of the high frequency transients similar to the speed of light, the measuring accuracy is 150 m. The relay also includes sequence recording, amplitude comparison and trip decision logic, which are employed to correctly identify the actual fault position.

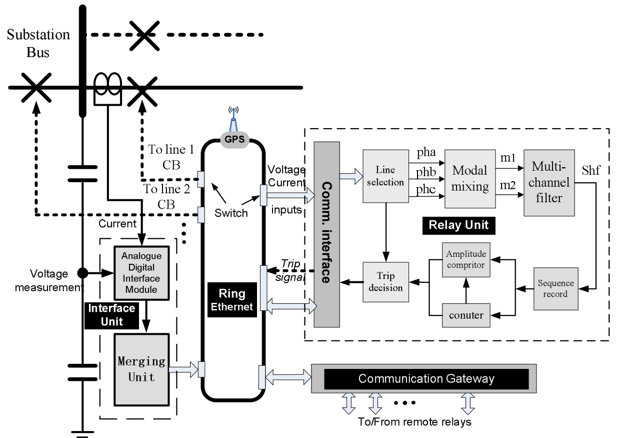


Fig.4 Block diagram of the integrated relay unit with the Ethernet

V. System Response Evaluation

The system response evaluation is based on digital model, which is together with the relay units. As shown in Fig.2, the transmission system is based on a 400 kV EHV transmission line. Two sections of the line are modeled with lengths of 128 km and 147 km respectively. The short circuit levels are 5 GVA, 35 GVA and 20 GVA at the three busbars R, S and T respectively.

The simulation of the faulted power system was carried out using the Electromagnetic Transient Programme (EMTP). Extensive simulation studies show that the relay is able to produce correct responses for various system and fault conditions.

A. Typical Fault Responses

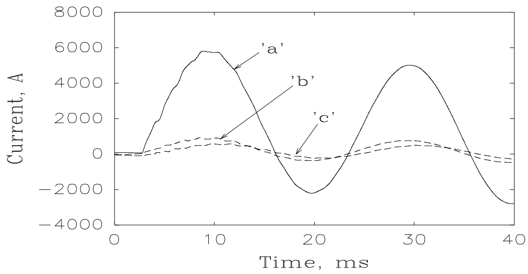
Fig.5 shows the responses attained for an "a"-earth fault 80 km from the end S on line P. Fig.5a shows the primary system currents on all phases in the immediate post-fault period. It is evident that the magnitude of the faulted phase current is significantly higher than that of the unfaulted phases; the high frequency transient components are produced on the faulted and unfaulted phases and are swamped by the dominant power frequency components.

Fig.5b shows the detector response at end R, again measured at point Z on fig.4. The second and third high frequency transient signals Ir_2 and Ir_3 respectively arrive at the busbar R at times tr_2, tr_3 respectively. Since the polarity of the second wave is the same as the first one, Ir_1, it is concluded that the second wave, Ir_2, is the reflection from the fault point. From the time intervals tr2 and tr3 it can be concluded that there is a fault on line P.

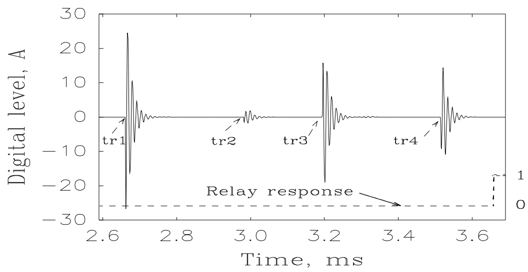
Fig.5c shows the high frequency transient signals as seen by relay S. Since the polarity of the second signal, Is_2, is opposite to that of the first signal, Is_1, it is concluded that this is the reflected wave from the remote busbar. The third transient signal, Is_3, however, has the same polarity as that of the first one, which indicates that this is the reflection from the fault point. The time interval indicates the presence of a fault. Both signals Is4 and Is5 recorded. The time intervals ts_2, ts_3 and ts_4 appear in this case, and satisfy equation (4) which indicates that the fault is on line P. This is supported by the comparison of the amplitude of Is_4 and Is_5, the former being larger that the latter. As a result, a trip command is issued.

Fig.5d shows the high frequency transient responses seen by relay T. As expected, these are similar to Fig.5c except that there is a strong presence of It_5 after time tt_5 with the same polarity as the first wave It_1; reinforcing the decision that the faulted section is not line Q and hence no trip command is generated.

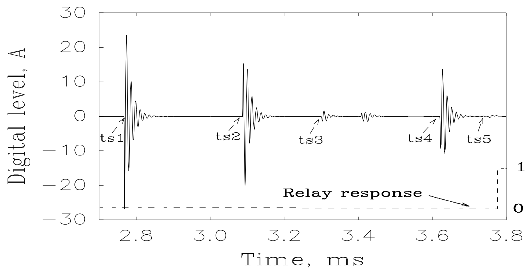
B. Effect of Point-on-wave of Fault Inception



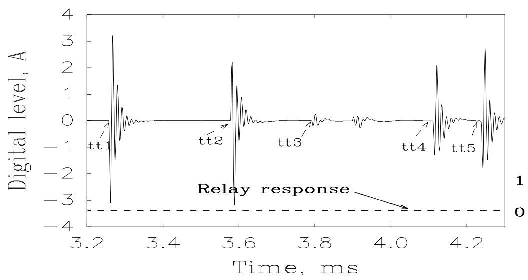
5a primary system currents



5b Relay response at end R



5c Relay response at end S



5d Relay response at end T

Fig.5 Responses for an "a"-earth fault on the line P at 80 km from the end S.

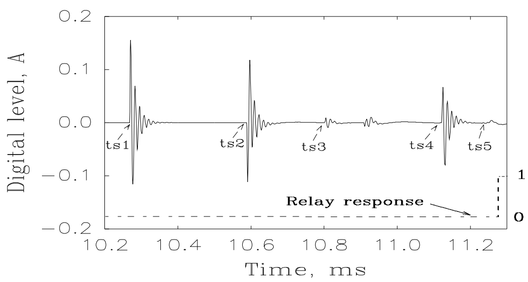


Fig.6 Relay response for an "a"-earth fault on the line P at 80 km from the end S, fault inception angle 0°.

Fig.6 shows the response of the relay at busbar S to an "a"-earth fault at inception angle of 0° and at the same point as that considered in Fig.5. Comparison of the waveforms shown in these figure reveals that the polarities of the signals are inverted. The propagation characteristics of the high frequency transients are similar and follow the predictions shown in Fig. 3. The comparison also shows that the level of the signals in Fig. 6 are smaller than those in Fig. 5. This demonstrates that this technique does not suffer from the limitations of zero voltage point-on-wave faults as suffered by pure travelling wave relays.

With the Integrated Protection System, studies show that the proposed technique is able to offer a very high accuracy and fast response in fault detection on transmission lines. The integrated Protection System is able to provide a fast response, high accuracy, and is not affected by power frequency phenomena, such as fault path impedance, power swing and CT saturation.

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VII. Biographies

Hao Zhang obtained his B.Sc. degree from Beijing Jiaotong University in 2006. And he worked in the design and application of protection relays as a research fellow, in AREVA Company U.K. in 2008. He is currently working toward the Ph.D. degree in the School of Electrical Engineering, Beijing Jiaotong University, Beijing, China. His research interests are integrated power system protection and substation communication.

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