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Simulation Evaluation of an Integrated Boundary Protection Scheme

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***Abstract*--The paper presents extensive simulation studies with repect to a typical EHV transmission line systems, the proposed protection technique is able to give correct responses for various system and fault condition. Furthermoore, the protection scheme offers not only fast protection for individual line section, but also integrated protection for all lines connected to the substation, therefore it could reduce the costs and complexity of power line protection systems. The continue advances in measurement, communication and signal processing technologies could present a bright future for the practical application of the proposed relay and its associated scheme.**

***Index Terms*-- Integrated Boundary Protection, Transmission Line Protection**

I. Introduction

A centralized substation protection system based on a centralized computer system was proposed in the late 1960's [1]. The concept fits well with the concept of an overall integrated protection where the protection package would not only oversee individual units of plant but also a section of the network. However, the idea has not been put into practice thus far since the computer hardware/software and the communication technology were not available to support such an idea. Since then, relay technology has enjoyed successful development based on the application of digital techniques for power system protection. The introduction of microprocessors into protection in the 1980's generally followed the conventional approach with the implementation of distributed processing platforms that concentrated on protecting individual units of the system. Limited integrated protection was provided in the form of back-up protection and as such has remained a secondary function.

In recent years, there has been the further development in both microprocessor and transducer technologies. This 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. 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. Considerable effort has now been devoted to research on high frequency transient detection. A number of new techniques have been proposed and their associated measurement and signal processing techniques investigated [2].

At the same time, the dramatic growth in signal processing power of relay platforms, and the availability of suitable communications schemes, has provided a new opportunity to revisit the concept of integrated protection. Research 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 when supported by modern communication technology [3].

II. Integrated Boundary Protection Scheme

With the development of numeric technology, more and more protection functions for an apparatus (line, transformer, generator etc.) have been implemented within one protective device to achieve a certain degree of integration. For example, a numeric line protection relay may have distance or current differential function as the main protection, and directional and overcurrent functions, etc. as the backup protection. However in this paper the term "Integrated Protection" is used to denote the integration of protective devices for multiple power apparatuses within the substation into one protective device.

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. This advanced protection scheme must be supported by a redundant communication network, by which the high speed data exchange can be implemented easily between the interface units and the centralized integrated protection relay, and then the centralized relay can receive the real time information, perform protection algorithm calculation and make decision when there is a fault on the transmission line or apparatus.

Table I shows the expected functions generally classified depending on the abilities of "Integrated Protection". All protective functions have been developed based on the proposed protection scheme which is different from that of the conventional type relays. The new technique 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 when supported by modern communication technology.

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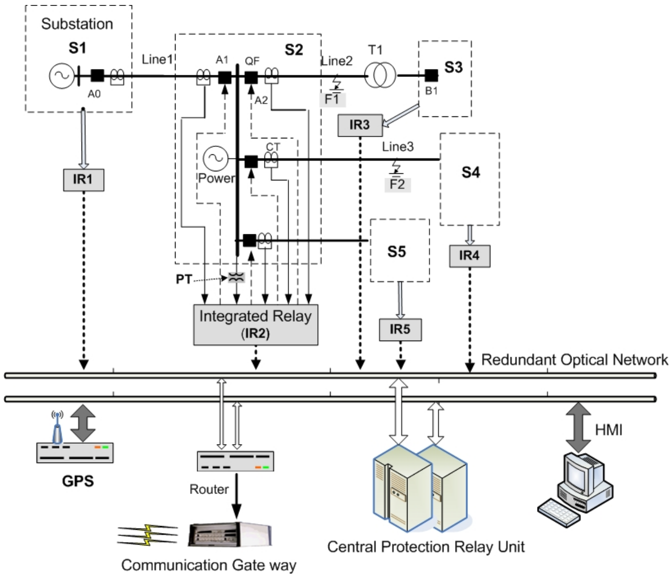


Fig.1 Diagram of a Centralized Integrated Protection System

TABLE I
EXPECTED INTEGRATED PROTECTION FUNCTIONS

Abilities	Protective Functions
Integration of Function	□ Main and backup protection □ Grounding and short-circuit protection □ Single-terminal and double-terminal measurement system
Real-time Ability	□ Dynamic protection corresponding with change of system configuration □ Protection not affected by load □ Protection of multi-terminal system
High Accuracy	□ Protection of the fault leaping over double-circuit power lines □ Specification of fault location for single-phase grounding □ Detection of minute grounding
Fast Restoration	□ Multi-phase re-close and control by single-terminal measurement □ Presumption of fault cause □ Unification of relay and fault locator
Enhancing of protection	□ Protection of parallel multi-circuit power lines □ Protection of series capacitor circuit
Reliability Improvement	□ Regular surveillance synthetically □ Maintenance free

Conventional non-unit protection relays, i.e. those that rely on only single-ended measurement, do not possess the instantly discriminative property of protection zone which covers the entire line section. This is so because there is no obvious difference of fundamental frequency components between faults at the remote end of the protected line and those at the beginning of the next line section(s). As a result, protection principles that use the information from both ends of the protected line were introduced in order to achieve fast fault clearance at any point of the line. However, the application of these principles requires communication channels, which not only results in increases in the costs and complexity of the protection schemes, but also reduce their reliability and tripping-speed. Therefore, it is obvious that fast fault clearance using single-ended measurement is significant. The line boundary is defined to be the position where the surge impedance changes significantly. In fact, the power apparatuses connected at line ends, such as busbars, line-traps, transformers, etc, can obviously alter the surge impedance at high frequency. That is to say, the line boundary does exist, and there are different high-frequency characteristics between inside and outside of the protected transmission line section, which have been researched [4-5]. Based on these different frequency characteristics at the line boundary, the protection scheme, which uses single-ended measurement of transient components to instantly distinguish internal faults from external ones for the whole line section, is called the Boundary Protection, a new principle in transmission line protection.

III. RELAY PRINCIPLE

Integrated boundary protection scheme for power transmission line systems is based on a combination of latest development in both areas of transient based and integrated protection. A typical power network as shown in Fig.2 is used to demonstrate the proposed protection scheme. As shown the integrated boundary protection relay (IBPR) is installed at each substation and interfaced to the CTs on each of lines connected to the busbar. The boundary protection algorithm with multiple settings is incorporated into the relay to be responsible for the protection of all the line sections associated with the busbar. These settings include the centre frequency of the filters and operating threshold etc. for each line section. When a fault occurs on the system, for example, at point F1 on line section Line P as shown in Fig.2, the protection algorithm within the relays IBPR1, IBPR2, IBPR3, etc. will detect the fault generated high frequency transient signals. Each relay will then determine whether the fault is on its associated line sections. The relays will trip instantly if the fault is on its associated line section and restraint if it is not.

A fault on a transmission system will generate wideband current signals which will travel outward in both directions from the fault point along the line. In time the signals will meet a discontinuity on the system, such as busbar, at which point part of the signal will continue to travel to the next line section while some will be reflected back. Recent research has found that a substantial amount of the current transient signals, particularly in the high frequency range, will be shunted to the earth by the busbar capacitance. This fact could be effectively used to develop a non-communication protection scheme in which the busbar at both ends of a protected line can be used as the boundary of the protected zone.

The proposed technique relies on the first detection of fault generated transient current signals, a multi-channel filter is then applied to the captured signals to extract two desired bands of signals, one at lower frequency and the other is higher. The fault generated transient signals are captured by the relay, the arrival time and the polarities of the signals are then recorded 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.

It is apparent from Fig.2, for a fault outside the protected zone of IBPR2, for example at F2, the higher band of the signal extracted will be severely attenuated by the busbar capacitance. In contrast, for a fault inside the protected zone say at F1, there will be no such attenuation. As a result, the ratio of the spectral energies of the higher band signal to that of the lower band will be able to be used to determine whether a fault is inside or outside to the protected zone.

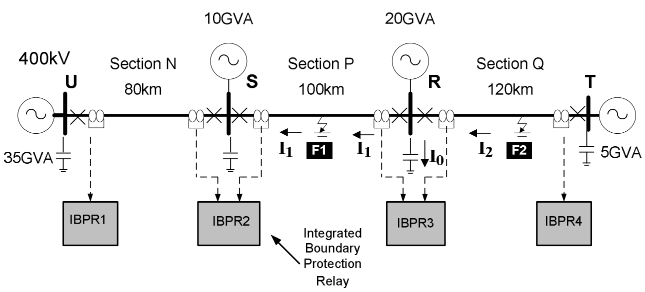


Fig.2 Integrated Boundary Protection Scheme

As shown in Fig.2, a busbar is normally connected to many power apparatuses such as power transformers and generating units, the characteristics of which will determine the busbar to earth impedance. This apparatus is normally conductive in nature; however, at significant high frequencies, the capacitance and capacitive coupling become the dominate factor in the busbar impedance. Here, IBPR2 is used to elucidate the technique. As shown, the IBPR2 is responsible for the protection of both line section N and P, and any more line sections connected to busbar S. When an external fault to relay IBPR2 occurs on the system, for example, at point F2 on line section Q as shown in Fig.2, the wideband current transient signal I_2 will be initiated towards busbar R. In time, this signal will reach busbar R, and a significant portion of the signal I_1 will continue to travel into sections P. Moreover, some of the signal I_0 will be shunted to earth by the busbar capacitance. As a result, the fault generated transient current signals I_1 detected by the relay at busbar S will be attenuated in comparison with the initial signal I_2. In particular, the attenuation will be significant at high frequencies than that at lower frequency since the busbar to earth impedance decreases with increasing frequency. In contrast, there is no such attenuation in the case of an internal fault, for example, at point F1 on line P.

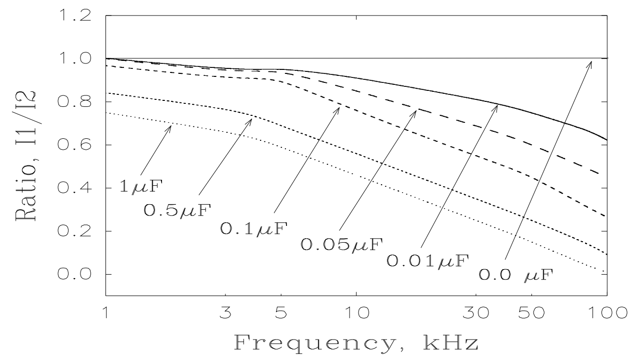


Fig.3 Attenuation of busbar capacitance to the incoming current signals

To examine the effects of the busbar capacitance on the attenuation of the signals, Fig.3 shows the ratio of the measured signal I1 to the initial signal I2 with the variation in frequency. The top line in the figure is the case with zero busbar capacitance which can be considered as an internal fault condition. As shown in the figure, for given busbar capacitance, the ratio of the signals decreases with increasing in frequency. It is observed that for an external fault, the signal ratio will be higher at lower frequency (for example, at 1 kHz) than that at higher frequency (for example at 100 kHz). In contrast, the ratio will remain constant for an internal fault condition. This important feature can be utilized to discriminate between internal and external faults without the need for communication link.

IV. Relay Design

Fig.4 shows the block diagram of the relay unit. As can be seen from the block diagram, the relay essentially consists of the communication interface, line selection, signal mixing circuit, transient filter, spectral energy extraction, discrimination ratio calculation and trip decision making logic. The current measurements from each CT are firstly converted to digital form, which are then sent to the IBPR relay through Ethernet. This communication structure significantly reduces wiring in the conventional structure. The use of standard communication protocol for the network will also enable IEDs from different manufacturers to be easily interfaced to the system.

The line selection unit switches between current inputs between each protected line section, this will allow protection algorithm to be applied to each line in turns. The modal mixing circuits receive the current signals from each line and combine the three phases to form modal signals. By this arrangement, not only different fault types are covered, but also any common mode interferences are eliminated.

The major part of the relay is the transient filter unit which works as a bandpass filter. Over the range of frequencies to which the filters are tuned, the relay effectively extracts a number of bands of fault generated transient current signals from the faulted line signal. In the studies here, in order to essentially form two discriminant signals, the transient filters are designed to produce two signal outputs I_{f1}, I_{f2} with centre frequencies centred around the two bands of interest with centre frequencies of 1 kHz and 80 kHz respectively.

The outputs of the filters are then fed to the spectral energy extraction unit, which is used to evaluate a running integral over a time window of the waveform to produce the restraint I_{re} and operate I_{op} signals. The ratio of the two discriminant signals operate I_{op} and restraint I_{re} determines whether the fault is external or internal to the protected zone.

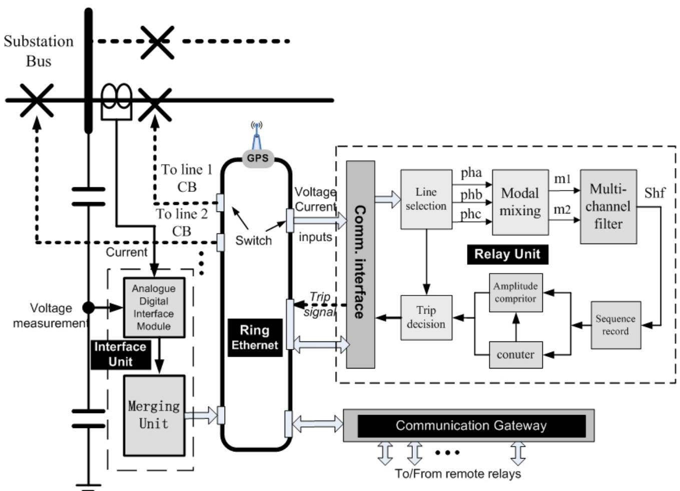


Fig.4 The integrated boundary protection relay unit

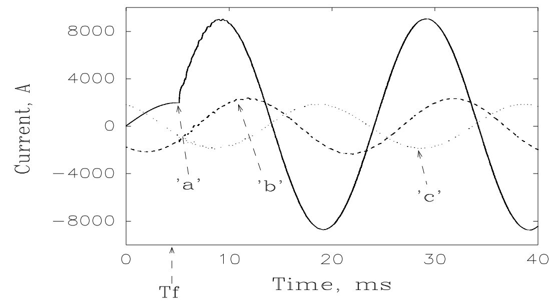
V. System Response Evaluation

As shown in Fig.2, the Integrated Boundary Protection Scheme is based on a typical 400 kV EHV line system. There are three line sections N, P and Q in the system with lengths of 80 km, 100 km and 120 km respectively. The short circuit levels are 35 GVA, 10 GVA, 20 GVA and 5 GVA at the ends U, S, R and T respectively. The simulation of the faulted power system was carried out using the Electromagnetic Transients Programme (EMTP). A non-linear fault arc model is also included in the simulation. When the fault occurs at a voltage zero point, the scheme relies on the detection of fault arc generated high frequency signals; this is so because travelling waves are virtually non-existent for this type of fault. In the studies, a typical value of 0.1 μF for the busbar capacitances is assumed at each busbar.

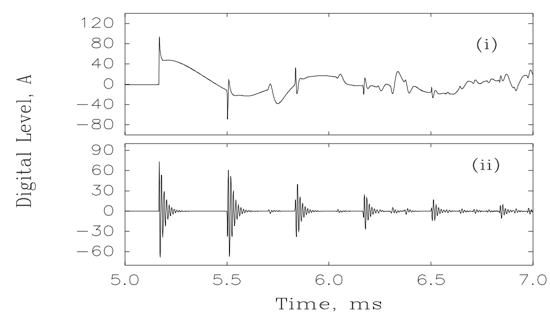
The simulation studies presented herein investigate the scheme responses to: fault position; fault inception angle; fault type and fault path resistance. The results presented here are examined by considering the signals derived for the mode-2 channel.

A. Typical Internal and External Fault Responses

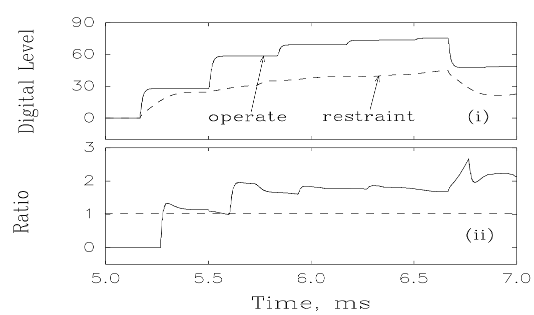
Fig.5 shows the system responses to a typical internal 'a'-earth fault at 50 km from end S on the line P. Fig.5a shows the primary system currents on all phases in the immediate post-fault period. It is evident that the magnitude of the faulted phase current is significantly higher than that of the unfaulted phases; the travelling wave components are produced on the faulted and unfaulted phases and are swamped by the dominant power frequency components. The outputs of the two filters are given in Fig.5b. As shown in the figure, the two signals exhibit different waveforms over the time span of 2 ms. A continuous waveform with a high frequency travelling wave supper-imposed on top is evident at filter 1 output whose centre frequency is 1 kHz. There are spurious bursts of noise observed in the case of filter 2 outputs with a centre frequency of 80 kHz. However, since this is an internal fault in the protected zone of IBPR2, the magnitudes of the two signals are compatible and as expected, the operate signal derived is higher than that of restraint signal as shown in Fig.5c(i), which results in the discrimination ratio well over unit as shown in Fig.5c(ii). As a result, a trip decision is issued by the relay.



5a CT outputs



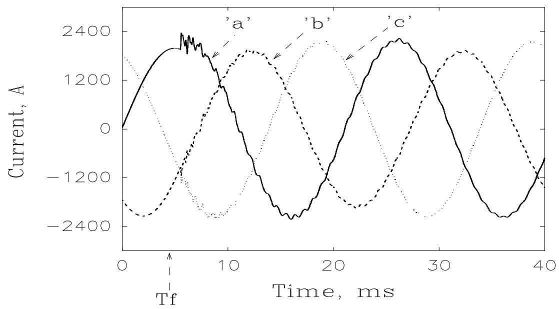
5b Filter outputs; (i) Filter 1; (ii) Filter 2



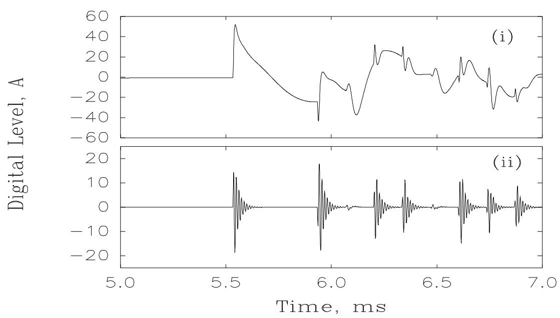
5c (i) operate and restraint signals; (ii) Discrimination Ratio

Fig.5 An 'a'-earth voltage maximum fault at mid point of line P, T_f=5ms

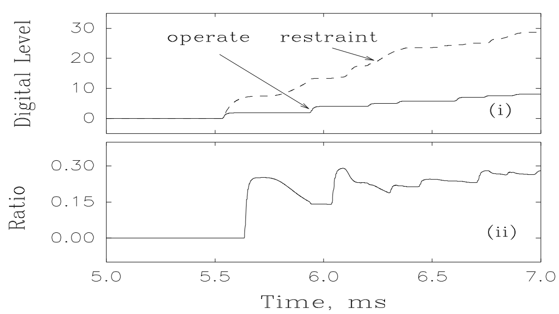
Fig.6 shows the corresponding responses when a fault occurs at mid point of line section Q outside the protected zone IBPR2. Since the fault is far from busbar S where the relay is installed, the changes in the faulted current signals at power frequency as shown in Fig.6a are much smaller than that of the former case, as shown in Fig.5a. Nevertheless, the high frequency oscillation supper-imposed on top of the power frequency signal is clearly evident. Again, the pattern of the two waveform of the filter outputs as shown in Fig.6b are similar to those in the case of an internal fault. However, the magnitude of the filter 1 output is higher than that of filter 2, and as a consequence, the level of the operate signal is lower than that of restraint signal, as shown in Fig.6c(i) and the discrimination ratio is well below unit as shown in Fig.6c(ii). Therefore, the relay restrains.



6a CT outputs



6b Filter outputs; (i) Filter 1; (ii) Filter 2

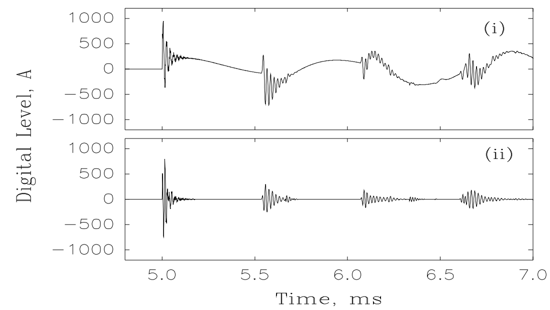


6c (i) operate and restraint signals; (ii) Discrimination Ratio
Fig.6 An 'a'-earth voltage maximum fault at mid of line U, T_f=5ms

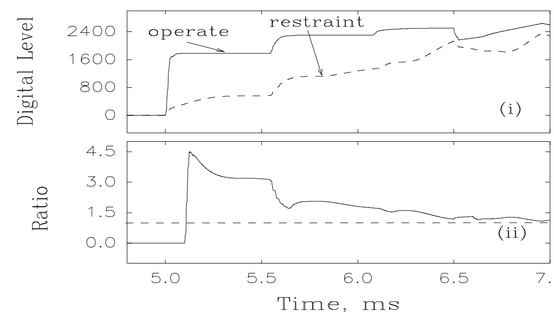
B. Faults close to busbar

A major drawback for the aforementioned non-power frequency wave based directional comparison and distance protection techniques is that their accuracy for faults near the boundary is affected by different system and fault conditions. The reason is that the directional comparison techniques use voltage signals to estimate the direction of the fault. They thus have a small dead band for close-up faults for which the voltage signal is close to zero. In addition, for a close-up fault, the time difference between the arrival of an incident wave and the arrival of its reflections from the busbar will be so short that the waves are unlikely to be detected separately. This could mean that distance schemes are unable to interpret the information available in the first few milliseconds after the arrival of the first wave front. Therefore, for the technique presented here, it is vitally important to examine the relay response for close-up fault conditions.

Fig.7 shows a 'b'-'c' phase to phase in zone fault occurring immediately adjacent to the CTs on the line section P. In this case, more high frequency noise appears on the waveform of filter 1 output, as shown in Fig.7a(i), this is due to the strong multiple reflections between the busbar and the fault point. Results in Fig.7b show that the proposed technique is able to produce correct responses under this fault condition. The ratio is greater than one which enables the relay to make a tripping decision.



7a Filter outputs; (i) Filter 1; (ii) Filter 2



7b (i) operate and restraint signals; (ii) Discrimination Ratio
Fig.7 A 'b'-'c' phase fault on line P close to busbar S, T_f=5ms

VI. CONCLUSION

This paper presents the integrated boundary relaying principle and extensive simulation studies with repect to a typical EHV transmission line systems, in which the fault generated high frequency noise in system current waveform can be successfully detected and processed to effect a new non-communication transmission line protection scheme.

The simulation results show that the proposed protection technique is able to give correct responses for various system and fault condition. Furthermore, the protection scheme offers not only fast protection for individual line section, but also integrated protection for all lines connected to the substation. The continue advances in measurement, communication and signal processing technologies could present a bright future for the practical application of the proposed relay and its associated scheme.

VII. ACKNOWLEDGMENT

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IX. Biographies

Moxue Li received her BSc in 2007 in the Department of Electrical engineering and Automation, China Agriculture University. Presently, she is working on her MSc degree in the same field in Beijing Jiaotong University. Her main research interests are Protective Relaying, Fault Distance Measurement and Location in Power System and Traction System.

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