

A New High-Speed Fault Detection Scheme for Transmission Line Based on Traveling Wave

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Index Terms—Traveling waves, fault detection, fault location, line protection, superimposed components, power transmission lines.

Abstract—This paper presents a new fault detection scheme for transmission line based on traveling wave. Using two-terminal synchronized measurements of voltages and currents of all phases, fault detection index is derived. To eliminate the effect of post-fault values on the results, superimposed components are used. This paper describes a new criterion for the identification of internal faults from external faults by using a simplified method and discuss about the effect of sampling frequency on close-in fault detection. Nevertheless, with commercial sampling frequency (10 kHz), we have an appropriate ability to distinguish typical close-in faults (more than 4 km) with this algorithm.

The outputs from EMTP simulations are used to test and validate the proposed fault detection approach for typical power system faults by MATLAB program.

I. INTRODUCTION

The main idea and function of digital relays in power systems is to reduce the consequences of faults by fault detection, localization, and

clearance of faults. The continuous expansion of power networks in both scale and complexity has been imposing a requirement for fast fault clearance to improve system stability and reliability. Developing the techniques based on the traveling wave and superimposed components, high-speed protection has been investigated. Also, the performance of protection is degraded by many factors such as fault resistance, load flow, mutual coupling, infeeds, and series or parallel compensation elements. The consideration to overcome the above problems together with the desire to reduce fault-clearance times, had led to the development of traveling wave protection. It must be mentioned that the main power signal analysis tools, which are currently used in the

digital relay, have been proven very useful and efficient in power steady state analysis. Among these are (1) Kalman filtering based algorithm, (2) Fourier analysis based algorithm, (3) Least square method based algorithm, and (4) FIR filtering based protection. But the performance of these techniques in presence of non-stationary signals is limited. All of the above reasons show the advantages of traveling wave and make it a proper method for fast detection and finally for fast protection.

Among the limitations of the traveling wave methods, the requirement of high sampling rate is frequently stated. Other stated problems include the uncertainty in the choice of sampling window and problems of distinguishing between traveling waves reflected from the fault and from the remote end of the line. Recent developments in optical current transducers technology enable high sampling rate recording of transient signals during faults. Availability of such broad bandwidth sampling capability facilitates better and more efficient use of traveling wave based methods for fault analysis [1]. Also there are a lot of studies based on wavelet transport [1]-[4]. Other studies like [5] and [6] based on modal transforms.

In our proposed scheme, pure scheme is used. Only forward and backward waves are used to discriminate the location of fault. After segregation of post-fault signals from pre-fault signals, double new signals are made from forward and backward waves and with them, the maximum magnitude of peaks whose changes have been more at the first period than thresholds are detected. This period is depending on the distance of transmission line and the magnitude of peaks. The peak signs in two terminals determine where the fault has occurred. By means of GPS and the fiber optic communication system, high accuracy and speedy data transmission can be achieved. This provides the speedy, robust, and accurate fault detection and discrimination ability which is an important requirement in two-terminal synchronized measurements.

II. THEORY OF TRAVELING WAVE PROTECTION

When a fault occurs on a transmission line at an instant of a non-zero voltage, rapid discharge of the line charges will generate heavy surges which propagate as waves. These forward and backward waves will travel close to the speed of light along both directions of the transmission line from the fault point and reflect at discontinuities along the line, including the fault point itself. Each wave is a composite of frequencies, ranging from a few kilohertz to several megahertz, having a fast rising front and a slower decaying tail. Composite waves have surge impedance that will depend on line parameters. The waves continue to exist until they are damped out and new power system equilibrium has reached and sometimes there is no equilibrium because of the effect of faults and cause perilous condition in power system such as voltage swing and tripping of generators. The characteristic of these waves have enough information for faults which have been hidden in voltage and current measurements and make them significant parameters for protection and tripping decision.

1) *Principle of superposition*: With this method we can analyze pre-fault voltage and current and voltage and current deviation caused by faults separately. Fault can cause a deviation in pre-fault voltage v_p and current i_p and make them so-called post-fault voltage v'_p and current i'_p . The difference between pre and post values are mentioned as Δv_p and Δi_p which means fault generated voltage and current deviation from steady state pre-fault values respectively. So it can be written as follows:

$$\begin{aligned} v'_p(t) &= v_p(t) + \Delta v_p(t) \\ i'_p(t) &= i_p(t) + \Delta i_p(t) \end{aligned} \quad (1)$$

Based on superposition principle, we can assume that when fault occurred, a fictitious voltage source switches on with a voltage equal in magnitude and opposite in sign to the pre-fault voltage at the fault point. So the summation

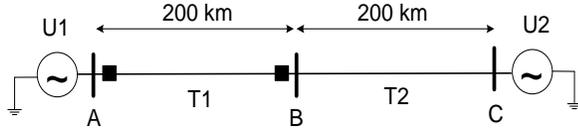


Fig. 1. A typical power transmission line.

of fault signals and the incremental signals produce post-fault signals. Because the pre-fault steady state signals are sinusoidal wave, The incremental signals $\Delta i_p(t)$ and $\Delta v_p(t)$ are readily obtained from the measured post-fault signals v_p' and i_p' by subtracting the sinusoidal pre-fault steady state quantities v_p and i_p . These superimposed signals are used for the rest of the paper.

2) *Traveling wave equation*: The fault initiates forward f_2 and backward f_1 traveling waves, where the direction towards protected line from the relay location is considered forward. The incremental voltage and current signals for a single phase lossless line can be expressed as:

$$\begin{aligned} \Delta v_p(x, t) &= f_1(x + vt) + f_2(x - vt) \\ \Delta i_p(x, t) &= \frac{1}{Z_c} [-f_1(x + vt) + f_2(x - vt)] \end{aligned} \quad (2)$$

Where Z_c is the surge impedance of the line and v is the surge velocity of the signals.

Then the traveling wave functions are defined as:

$$\begin{aligned} \Delta v_p(x, t) - Z_c \Delta i_p(x, t) &= 2f_1(x + vt) = S_1(t) \\ \Delta v_p(x, t) + Z_c \Delta i_p(x, t) &= 2f_2(x - vt) = S_2(t) \end{aligned} \quad (3)$$

Where $S_1(t)$ and $S_2(t)$ are twice as much as forward and backward signals and all of decisions are made with these two signals. However, the mutual coupling in three phase transmission line makes more difficulty and complexity in calculations. For more simplicity, these calculations are ignored. This means that there is not any difference between one earth and two aerial modes in this scheme. We considered all of these three phases as three independent phases and with these simple equations the judgment about whether the fault

is internal fault or external fault and also the discrimination that whether it is backward or forward fault is possible.

3) *Principle of decision*: A typical power transmission line system is shown in figure 1. There are two relays besides the A and B bus that protect line AB (T1). The simulation of this system was carried out using EMTP software and it included study of system for different fault types, different fault positions and different fault inception angles. After a lot of simulations and comparing the results, these observations can be derived from the simulations:

- If symmetrical internal faults occurred, the maximum peaks after the fault in the specific period and more than specific threshold for S_2 signal have the opposite signs in all three phases in the two terminals.
- If unsymmetrical internal faults occurred, only for phases that fault happens on them, the maximum peaks after the fault in the specific period and more than specific threshold for S_2 signal have the opposite signs in the two terminals and for the other phases we may not have this occurrence.
- If symmetrical external faults occurred, the maximum peaks after the fault in the specific period and more than specific threshold S_2 signal have the same signs in all three phases in the two terminals.
- If unsymmetrical external faults occurred, only for phases that fault happens on them, the maximum peaks after the fault in the specific period and more than specific threshold for S_2 signals have the same signs in the two terminals and for the other phases we may not have this occurrence.
- If there is no fault, there is no maximum peak which is more than thresholds and they are not detected by the relay to start the calculations for tripping decision.

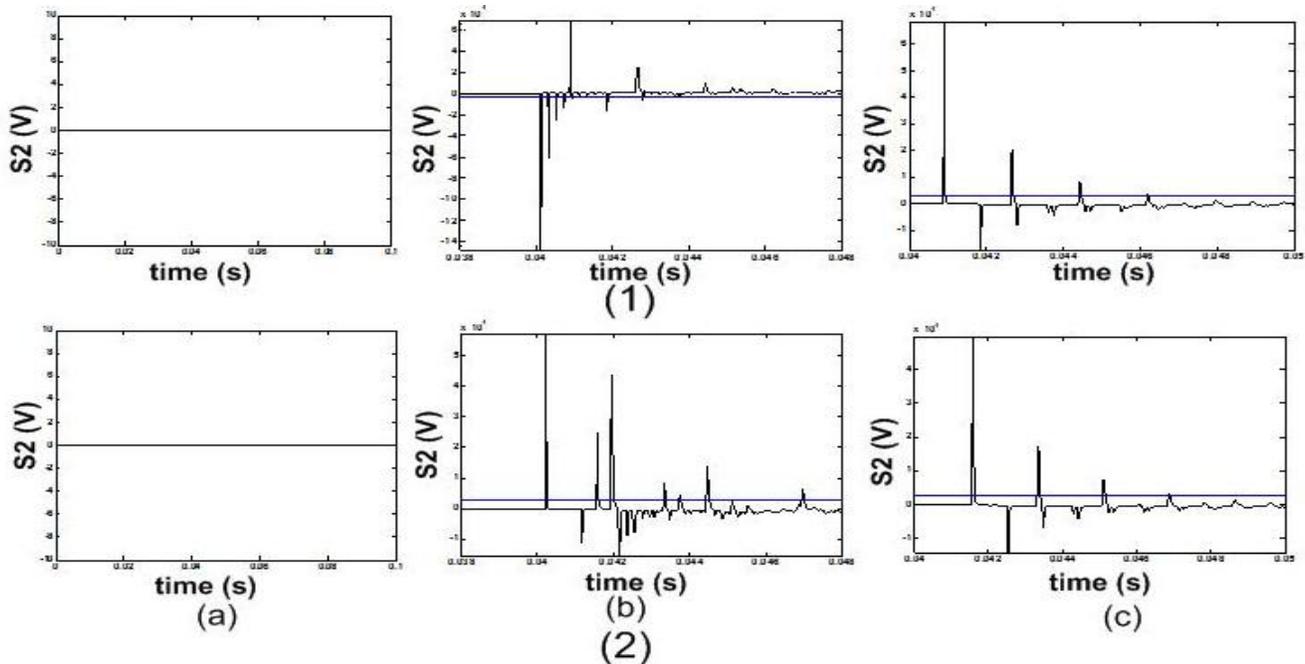


Fig. 2. S_2 signals in two terminals for phase A and for a symmetrical fault at the situation of (a) no fault. (b) internal fault which is 30 km away from bus A and (c) external fault which is 60 km away from bus B with fault resistance of 125Ω . (1) bus A, and (2) bus B.

By these considerations we can judge accurately whether we have internal or external faults. The period in which the search for finding maximum peak is about a half cycle and an appropriate threshold is implemented which is different for different cases of transmission lines and different parameters of transmission. In this study, ± 3 kV is implemented as a threshold. In the next session, the responses of relays for different kind of faults are shown in detail.

III. SIMULATION TESTS

The generator at side A is 145 kV (U1) and the generator at side C is 132 kV (U2). The transmission line is transposed and the sampling frequency is 10 kHz and the power frequency is 50 Hz. Z_c in this case is about 412.79Ω . The mission of relays that shows with black squares is to protect T1 from every internal fault. To demonstrate that the relays do their missions, several situations of the fault are simulated.

A. Results for different fault position:

To illustrate the effect of the fault position on the results, figure 2 shows S_2 signals in two-terminals for phase A and for a symmetrical fault at the situation of no fault, internal fault which is 30 km away from bus A and external fault which is 60 km away from bus B with fault resistance of 125Ω . As it is shown, under the condition of no fault, there is no peak that exceeds the thresholds. In the internal fault, S_2 signals in two-terminals have maximum peaks in opposite signs and in external fault; S_2 signals in two-terminals have maximum peaks in the same signs.

B. Results for different fault type:

To depict the effect of the fault type on the results, figure 3 shows S_2 signals in two-terminals for phase A and B for abg (i.e. double-phase of A and B to ground) and bg (i.e. single-phase of B to ground) fault at the situation of internal fault which is 80 km away from bus A

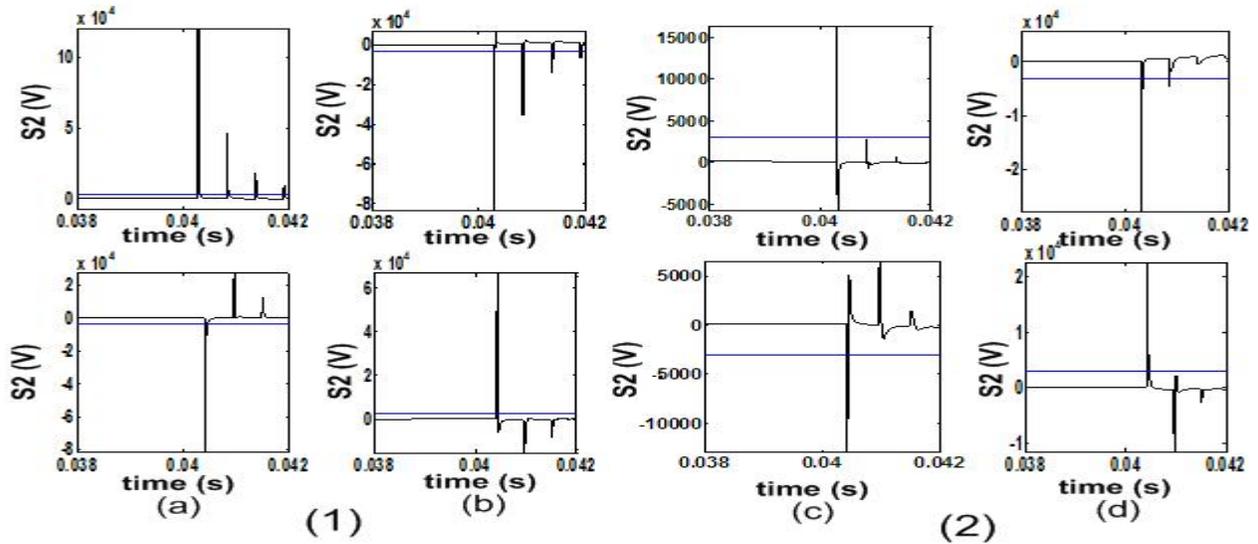


Fig. 3. Internal fault at 80 km away from bus A and fault resistance of 125Ω - S_2 signals in two-terminals (1) for abg fault at (a) phase A, (b) phase B, (2) for bg fault at (c) phase A, and (d) phase B. the top figures is related to bus A and the bottom figures is related to bus B.

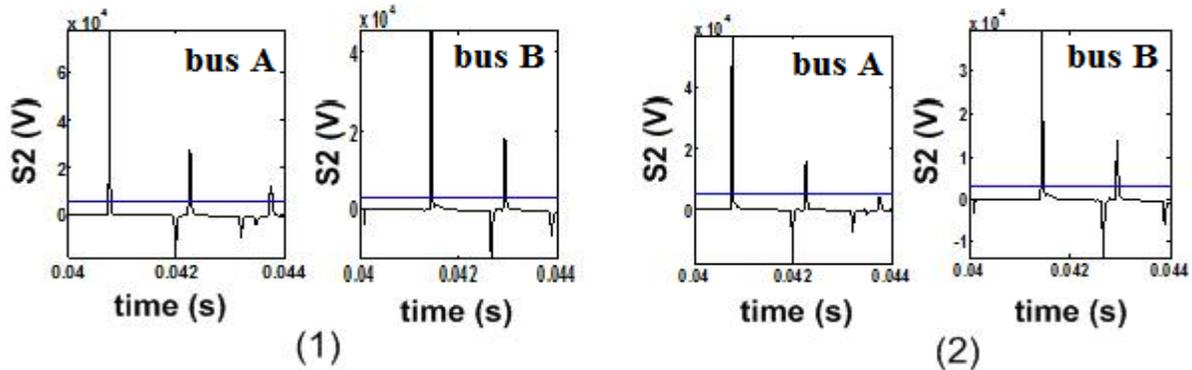


Fig. 4. S_2 signals in two-terminals for phase A and for a symmetrical fault at the situation of external fault which is 20 km away from bus B with fault resistance of (1) 100Ω , and (2) 150Ω .

with the fault resistance of 125Ω . The same results for external fault are obtained and all of them shows that even if in one phase we do not gain the same results as the other phases (e.g. in bcg internal fault, we gain the desired results for phase B and C and no fault for phase A), fortunately, we can see in that phase that the maximum peak does not exceed the thresholds and with the other phase we can correctly decide that the internal fault has occurred. So in this manner there is not any problem for decision making.

C. Results for different fault resistance:

One of the advantages of this method and generally, traveling wave method is that they are independent from the values of the fault resistance. Because regardless of the values of fault resistance, forward and backward waves move without any hurdle in front of their ways. Figure 4 shows S_2 signals in two-terminals for phase A and for a symmetrical fault at the situation of external fault which is 20 km away from bus B with fault resistance of 100 and 150 Ω . As it is shown, the change of fault resistance cannot affect very much on the response and

maximum peaks. So it seems that decisions are independent from fault resistance.

IV. EFFECT OF SAMPLING FREQUENCY ON CLOSE-IN FAULT DETECTION

One of the important parameters in detection and protection with traveling wave method is sampling frequency. In this paper, 10 kHz sampling frequency has been used and we can detect faults which are more than 4.5 km distance away from bus A. Higher sampling frequency causes more close-in fault detection distance. If the sampling frequency has been doubled and 20 kHz sampling frequency is used, we can detect faults which are more than 1.5 km distance from bus A. Because of technological and economic limitations, we cannot increase the sampling frequency more than this. Also, if we can do that, there is always a distance near bus A that we cannot detect the faults which have occurred in that distance. Reference [7] discusses an impedance measurement to improve the reliability of protection. So one of the drawbacks of this method is detecting close-in faults and must be considered to prevent the fault that occurs in unprotected part of the transmission line.

V. CONCLUSION

The fast fault detection capability of traveling wave protection schemes can be utilized in transmission line protection. This scheme possesses fast fault detection capability and is reliable. Only in close-in fault we have a problem for the detection and protection of the transmission line which is the main problem in the entire traveling wave scheme. With combining them with the other schemes of protection like impedance measurement, we can make a reliable scheme to protect transmission line.

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APPENDIX

The transmission line details used for simulation are given below:

Phase conductor:

| | |
|-----------------------------------|---------------------------------------|
| Conductor radius: | $8.01 \times 10^{-3} \text{ m}$ |
| Number of conductors in a bundle: | 3 |
| DC resistance: | $5.215 \times 10^{-2} \text{ ohm/km}$ |
| Bundle spacing: | $18 \times 10^{-2} \text{ m}$ |

Ground conductor:

| | |
|-------------------------|---------------------------------|
| Conductor radius: | $1.93 \times 10^{-3} \text{ m}$ |
| DC resistance: | 2.61 ohm/km |
| Number of ground wires: | 2 |