Digital Distance Protection Algorithm with selfadapting features and network communication

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A new algorithm for digital distance protection of medium voltage distribution lines is investigated, including selfadapting features to systemparameters and network communication to force fast fault detection and to reduce wrong releases of protection relays.

1. Introduction

In network protection systems the use of digital computerized protection systems increases in a short time because of a list of advantages these systems come with. The use of different kinds of protection algorithms on the same hardware reduces costs for development and implementation of new relays. Changing affords can be implemented by new or enhanced software and must not end in changing hardware. The configuration of digital protection systems can be done by altering only some parameters in the software directly on the relais or by loading a complete new set of parameters via diskette or from a notebook or laptop via cabling. In the future one more important feature of digital systems is the intercommunication between single protection systems as well as between the protection system and a station control or main control centre. This will be done by network cabling with Fibre optic cables allowing transmission rates greater then 100 MBit/s, so an online transmission of measured signals also is possible. In this paper a new digital distance protection relay is presented, which bases on an enhanced algorithm for fault recognition and distance calculation and also uses the above mentioned features for online communication for configuration and signal handling and also for selective stripping decisions.

2. Algorithms used for digital distance protection systems

In contrast to electronic distance relays, the measured signals for digital systems first have to be digitized. This will cause a loss of information because of the transformation of analog datas into timediscret measurement points. These digits have to be computerized by software according to the implemented algorithm. The main problem of digitalisation is the integration or differentiation of analog signals, which normaly represent the measured components voltage u and current i. To calculate the interesting quotient u/i for the searched fault impedance, three main groups of possible algorithms are mentioned in the literature (1).

Using the Fast Fourier Transformation lets build the steady-state phasors of the input signals, which can be used to calculate $\underline{Z} = \underline{U}/\underline{I}$. In none-faulted operation mode the result is very accurat, as long as no extremly high order frequencies will distort the measured signals. But in case of short circuits the input signals will have a great current increase and also great DC-components. This will disturbe the calculation of the wanted distance impedance. Caused by the FFT-algorithm there is also a minimum data window necessary to calculate the needed current and voltage phasors. This will increase the response time of these algorithms over more then half a period of the main oscillation (1).

Transient differential equations are based on a lumped line model for use in distribution networks with short lines.
For a three-phase model the following equation can be obtained:

$$u_{x_1}(t) - u_{x_2}(t) \cdot (x_2-x_1) \cdot [r \cdot i(t) \cdot l \cdot \frac{di(t)}{dt}] \qquad (1)$$

where x_1 and x_2 are any two locations on the line and u, i, r and l represent voltage, current, line resistance and inductance. Transformed in a single-phase model equation [1] can be obtained:

$$u \cdot x_f \cdot R \cdot i \cdot x_f \cdot L \cdot \frac{di}{dt} \qquad (2)$$

Several different kinds of approaches for solution of this equation were presented in the past.
One type of algorithm builds the integral over N intervals and then calculates the least-squares error. This type is often used with some improvments depending on the used error function and the number of intervalls. Another type of algorithms normaly uses numeric differentiation by building differences between consecutive samples. This type of algorithm shows a fast response time only depending on the used sampling rate and on the order of the difference approach. A great problem of this kind of algorithm is its sensitivity to higher frequencies. To eliminate this effect a few methods were presented of which one was the so called MDAA (2). This algortihm is the base for the enhanced solution method presented in this paper.

The third type of calculation category is named travelling-wave correlation methods. They use the information in the post-fault electromagnetic forward and backward travelling waves and the used signals can be written as

$$S_F = u(t) + Z_0 \cdot i(t)$$
$$S_B = u(t) - Z_0 \cdot i(t) \qquad (3)$$

Using correlation techniques such as crosscorrelation or autocorrelation to detect the time difference τ between the arrival of the forward surge S_F and the reflection signal S_B. The distance between the fault point and the relay point can be calculated as $x = 0{,}5 \bullet v \bullet \tau$. The response time of these algortihms is lesser then 5ms and the accuracy is very high, but the demanded hardware has to be fast, which will increase the costs of these protection relays. Another problem is the sensitivity to discontinuies along the protected line which will cause false peak correlations. The frequency invariant line paramteres generate also extra errors since travelling waves contain components from 0 Hz to very high frequencies (1).

3. Protection algorithm and selfadapting fault locator

To get a maximum on accuracy and response time speed combined with a minimum on hardware equipment to reduce the costs a combination of transient differential equation solution and FFT-based algorithms seems to be a practicable method. In (2) a fitting algorithm is described for difference approximation of the current derivative. The line differential equation [2] is used for solving the fault distance calculation. Using three samples for u and i the searched R_1 and L_1 can be written as

$$R_L = \frac{(u_m - u_{m-1}) \cdot J_{m-1} - (u_{m-1} - u_{m-2}) \cdot J_m}{(i_m - i_{m-1}) \cdot J_{m-1} - (i_{m-1} - i_{m-2}) \cdot J_m}$$
$$L_L = \frac{(u_{m-1} - u_{m-2}) \cdot (i_m - i_{m-1}) - (u_m - u_{m-1}) \cdot (i_m - i_{m-2})}{(i_m - i_{m-1}) \cdot J_{m-1} - (i_{m-1} - i_{m-2}) \cdot J_m} \qquad (4)$$

where J_m is calculated as

$$J_m = \frac{di}{dt_m} + \frac{di}{dt_{m-1}} \qquad (5)$$

J_m is approximated for two fixed frequencies f_0 and $2{,}5 \bullet f_0$ and can be computed as

$$J_m = \sum_{k=1}^{N} K_k \cdot (i_{m+k-1} - i_{m-k}) \qquad (6)$$

where $N = 2$ and m the measurement point at time t_m.

In this case K_1 and K_2 are calculated like

$$K_2 = \frac{\omega_2 \cos(\omega_2 \cdot \frac{T}{2}) \sin(\omega_1 \cdot \frac{T}{2}) - \omega_1 \cos(\omega_1 \cdot \frac{T}{2}) \sin(\omega_2 \cdot \frac{T}{2})}{\sin(\omega_1 \cdot \frac{T}{2}) \sin(\omega_2 \cdot \frac{3T}{2}) - \sin(\omega_2 \cdot \frac{T}{2}) \sin(\omega_1 \cdot \frac{3T}{2})} \qquad (7)$$

$$K_1 = \frac{\omega_1 \cos(\omega_1 \cdot \frac{T}{2}) \sin(\omega_2 \cdot \frac{3T}{2}) - \omega_2 \cos(\omega_2 \cdot \frac{T}{2}) \sin(\omega_1 \cdot \frac{3T}{2})}{\sin(\omega_1 \cdot \frac{T}{2}) \sin(\omega_2 \cdot \frac{3T}{2}) - \sin(\omega_2 \cdot \frac{T}{2}) \sin(\omega_1 \cdot \frac{3T}{2})} \qquad (8)$$

Where $\omega_1 = 2 \bullet \pi \bullet f_0$ and $\omega_2 = 2 \bullet \pi \bullet 2{,}5 \bullet f_0$ and T is the sampling intervall.

This algorithm can be extended over more then only two approximation frequencies. The needed corrections factors K_i can be calculated by the following equation where N is the order of correction.

$$A_{N \times N} \cdot K_N = b_N \qquad (9)$$

The matrix elements a_{ij} obtain the following rules

$$a_{ij} = \sin\left(\omega_i \frac{(2j) \cdot T}{2}\right) \qquad (10)$$

and the vector b

$$b_i = \omega_i \cdot \cos\left(\omega_i \frac{T}{2}\right) \qquad (11)$$

The J_m- parameter will now be calculated from k=1 to k=N.

In this algorithm the error is set to zero at every used approximation frequency ω_i and is also greatly reduced for frequencies between and nearby the approximation frequencies. The fitting frequencies ω_i are calculated from the measured signal i(t) by a FFT in contrast to the proposed method in (2), where the fitting frequencies are fixed values. This adaption allows the consideration of the actual system state and the inclusion of signal distortions to avoid errors at normal operating mode also as at fault situations (3).

As described above the proposed fault distance location algorithm uses a transient differential method for calculating the interesting line parameters R_L and L_L. The needed samples depend on the fitting order for the derivative approximation for J_m and are 2N.
The calculation has to be processed in realtime, so a fast hardware is necessary. To get response times lesser then 10ms a sampling rate of 10kHz is needed. Using a 10th order approximation means that 20 measurment points are needed for the calculation of J_m. At a sampling rate of 10kHz this means a time of 2ms for one calculation of J_m and therefore of R_L and L_L. To get a stabil result a minimum of four calculation cycles is necessary, so that the algorithm response time is about 8 to 9 ms. To perform such fast AD conversions and the following solution for the J_m equation digital signal processors are used.
To adapt the algorithm to higher frequencies, included in the measured current signal, a FFT has to be performed. The maximum approximation frequency is the 40'th harmonic resp. 2 kHz in a 50Hz system. To calculate the 10 greatest magnitudes in the spectrum of 50Hz to 2 kHz a data window of half a main osciallation period is enough. This will be done on a PC-CPU to get the needed approximation frequencies. By a processor frequency of 33 MHz and a time window of 10 ms about $30 * 10^6$ simple instructions can be performed, so that the

demanded FFT can be processed in this time.
Beside the signal harmonics also the power system state will cause higher frequencies in case of faults, especially at earth faults. The increasing part of cables even in distribution netwoks decreases the system natural frequencies in ranges, which affect the functionality of protection systems. Frequencies lesser than 1 kHz are not rare. To consider these natural frequencies it is possible to set a part of the approximation frequencies in accordance to the power system configuration. This will be done via computer communication from a host computer in the central station, which knows the actual system configuration. The central station computer has to estimate the needed natural frequencies of the network and to set the frequencies in the protection systems. In this way a two-fold adapting system is proposed. First the measured signals are used to adapt the algorithm to signal distortions to minimize wrong tripping signals in normal operating mode and to raise the accuracy in fault location calculation and second the power system configuration is used to raise the fault location detection especially in case of earth faults or in strong cabled networks.
The proposed intercommunication between the digital fault relay and the central station computer can also be used to adapt the tripping diagram for distance protection relays. The independent adjustment of the distance zones in X- and R-direction allows an optimal selection of the tripping zone. An assumption is that the actual system state is known in the central station computer, either by online reply of the switches or by offline input by the operation staff. So it is possible to change the distance zones according to a switch-off of a three-end pilot-wire scheme to a two-end pilot-wire scheme. Also it is possible to handle intertripping scheme and release resp. locking scheme at the same time (4).
The computer communication can be extend to the interconnection between the single protection systems. In this case also faults can be located, which happens on line feeders, not controlled by own fault relais. Normaly this kind of fault can not correct be calculated, but when two or more fault relays can communicate together also faults on not supervised feeders can be correct located. This kind of lines often appears in distribution networks where at present the fault location is done by short-circuit indicators directly at the stations and local controlled by the operation staff. Digital differential protection can be used to simplify this procedure by signal transmission. So a 100% line lenght protection and selectivity is possible(4).

4. Simulation equipment

To simulate the above proposed features, namely the enhanced adaptive algorithm for distance calculation and the possibility for intercommunication the following simulation technique is used.

Two analog computers simulate a three-phase line model with ground return system and allow every kind of short

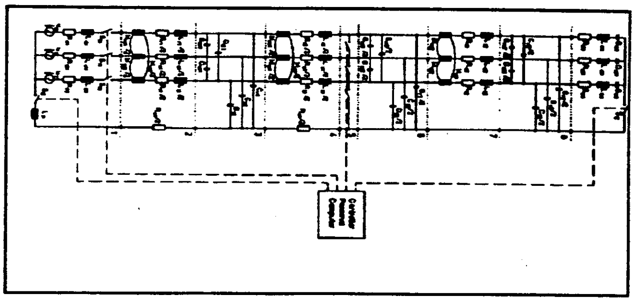

Figure 1

circuit to be switched, controlled by a personal computer. As seen in figure 1 the simulated line consists of two equivalent circuit diagrams. The first part is represented as a T-equivalent diagramm and the second part as a π-circuit. Every kind of phase-to-phase coupling and also the capacitive coupling of phase-to-earth is replicated (Figure 1). The measured signals u and i are the input for two digital distance protection systems, which base on digital signal processors for fast fault localisation and a PC-CPU for the needed FFT calculation (Figure 2). Both protection systems are equipted with 8 analog inputs for measuring the three phase voltages and currents and also the neutral-point displacement voltage and the earth current can be measured. This is important, because in Germany the medium voltage distribution networks often

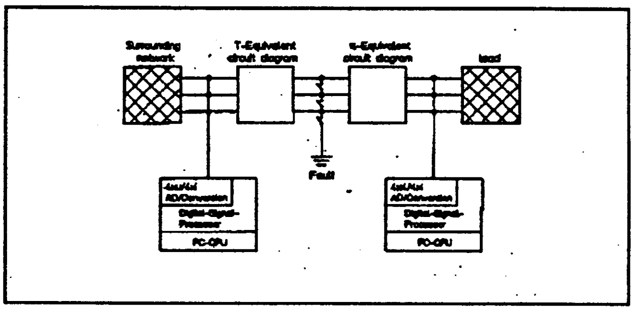

Figure 2

are supplied with earth-fault neutralizers, so that even this device is imitated and can be measured. The used signal processors are AT&T DSP32C with 50 MHz and a computing power of 25 million floating-point operations per second. The measured-data acquisition is controlled by two parallel working AT&T DSP16A signal processors. The two protection systems are connected together by a fiber optic FDDI-cabling for fast data transmission. The used cabling technique is a dual attach ring circuit, which allows operation even in the case of a fault on one circuit. A workstation simulates the surrounding distribution network and is also connected with the two protection computers via FDDI. The surrounding network consists of three lines, three loads and three power supplies from 110kV transmission network. The network model is computed in Clark transformation components to simulate the needed

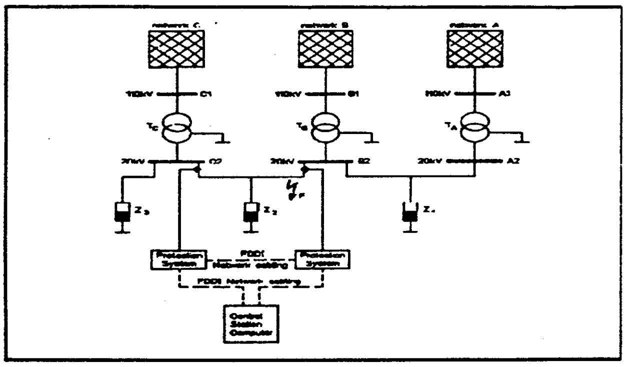

Figure 3

transient processes. The used workstation is a HP 725 with 50 MHz. (Figure 3). It is now possible to simulate the fault calculation in realtime by the protection computer and also the proposed variation of system parameters via computer network either from another protection system or from the central station computer, simulated by the workstation.

5. Conclusion

A new enhanced algorithm for fast and accurate fault detection and localisation was presented in this paper. The proposed system uses at the one hand a transient differential equation approach, adapted by measured higher frequencies to raise the accuracy of fault detection and at the other hand transmission systems for computer communication between the protection systems and a central station computer and between the protection system themselves. Specialy the possibilities of computer intercommunication will expand the employment of digital protection systems in the future from single solution relays to allround usable protection components also in distribution networks.

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