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Intelligent High Impedance Fault Detection Technique in Power Distribution Network

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Abstract: *The challenging task of power distribution system is to manage the fault of the distributed network. Today, as there has been an increase in the interconnected systems as far as power systems are concerned. Load as well as power flow in tie-line are varying dynamically. So there is a need of robust control of system frequency as well as tie-line power flow system. Fast fault detection find out that the existing work of speed of protection is quite crude. When the rate of rise of the fault current and the operating time of the fault clearing equipment was taken into account, fast fault detection was defined to mean fault detection within small time measured from the inception of the fault. In this paper, the evaluation of algorithms suitable for fast fault detection led to the selection of two algorithms that are investigated, namely the LSQ-method, and the differential equation method. The simulation results shows the proposed work is efficient for fault detection.*

Keywords: *Fault Detection, Power System, LSQ-Method, Differential Equation Method.*

I Introduction

The power distribution of electrical network is the last level in the transformation of electrical power, it convey electricity from the transmission system to end consumers [1]. The distribution substations are connected to the transmission power supply and it minimizes the transmission voltage to medium voltage ranging from 2 kV to 35 kV using transformers. The primary distribution power lines convey this medium voltage electricity to the distribution transformers situated at customer's locations. Distribution transformers once again minimizes the voltage into utility voltage consumed by street lighting, industrial devices and equipment or home appliances [2]. Power are supplied to many customers from one transformer through secondary distribution power lines. Industrial and residential customers are generally connected to the secondary distribution power lines through service drops [3–5]. Consumers requiring a very huge amount of electricity are connected directly to the primary distribution level or the sub-transmission level [6–8]. General layout of electricity networks is presented in Figure 1.

The functions of power transition from transmission to distribution phase happens in a power substation are as follows:

- Power circuit breakers and switches enable the substation to be disconnected from the transmission grid or for distribution lines to be disconnected.
- Transformers step down transmission voltages, 35 kV or more, down to primary distribution voltages. These are medium voltage circuits, usually 600–35000 V.
- From the transformer, power goes to the busbar that can split the distribution power off in multiple directions. The bus distributes power to distribution lines, which fan out to customers.

The underground power distribution is used in urban regions, sometimes in common utility process [9]. In rural power distribution, ground with utility poles are used. Nearer to the consumer, a distribution transformer steps the primary distribution power down to a low-voltage secondary circuit, generally 120/240 V for residential customers [10]. The power comes to the customer via a service drop and an electricity meter. The final circuit in an urban system may be less than 15 meters, but may be over 91 meters for a rural customer [11, 12].

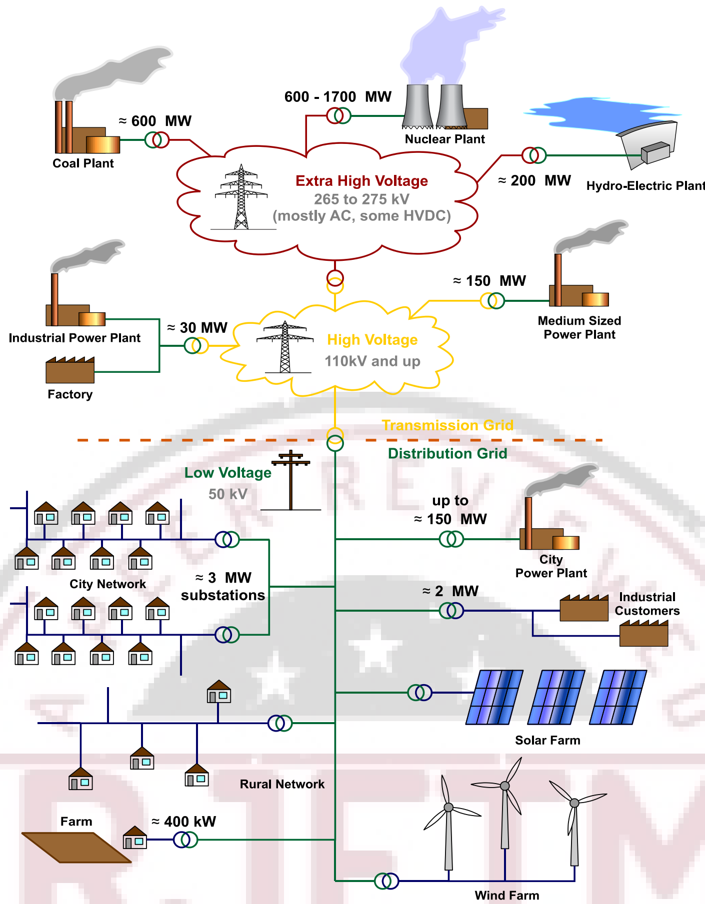

Figure 1: General Layout of Electricity Networks

I-A Theoretical Background of Power Faults

To prevent people end property from damage or injury, electrical faults in a power system must be cleared fast. In the early days of electrical power systems the fault clearing was administered by the maintenance staff, who visually detected the fault and manually operated a switch to clear the fault. As fault currents became larger and the operating requirements of the electric power system became more stringent, the need for automatic fault clearance became a necessity [13].

A typical fault clearing system consists of a circuit breaker and a relay protection system. The relay protection system consists of transducers, wiring, relay, auxiliary power supply, and the operating coil of the circuit breaker. In the early days of automatic fault clearing, a fault was detected by electromechanical relays. The measured quantity, such as for example a voltage or a current, was transformed to a mechanical force which operated the relay when a preset threshold was exceeded. Following the advent of electronics such as transistors and operational amplifiers, solid-state relays were developed. The characteristic of such relays were implemented by circuit design. Today, new relays are normally numerical relays. They are built around a microprocessor in which the relay characteristic is digitally implemented. The analogue measurements are converted to digital signals for evaluation within the microprocessor. The recent development of fast microprocessors has led to the possibility to implement highly sophisticated relay characteristics within the microprocessor [14–16].

II Literature Survey

When a fault occurs in a power distribution system, over-current protective devices such as a recloser or a fuse isolate the fault in order to prevent electric devices. This section presents various fault detection and isolation techniques to overcome these problems.

II-A An Initial Investigation for Locating Self-Clearing Faults in Distribution Systems

Kim *et al.* [17] discussed a simplified formula for locating self-clearing transitory faults by employing voltage injection at the faulted location and the superposition principle to calculate the line reactance to the fault using only the voltage and current signals measured at substation. A distinctive feature of the fault distance formula was that it did not need the inductances of the line or sources. Another feature of the proposed formula is that it uses the net fault quantities instead of the overall fault quantities. The detailed steps and processes of the formula implementation for practical application were detailed along with test results with 11 actual transitory faults involved in underground cable and cable racks. The validation of the formula was performed in a qualitative manner since for the outage list the relationship between the "fault distance" in miles were not clear as well as consistent enough to indicate if it was meant for the actual faults or the clearing devices.

The validation highlighted two things:

- The simplified model worked for the complicated distribution networks comprised of overhead and underground sections, especially so with better accuracy when the circuit sections are in conductor characteristics of impedance per distance relatively linear.
- There were also the examples where the results of the formula had poor accuracy. The problems led us to expand our investigation into the following three subjects:
  - Establishment in process and procedure to record the location of faults not clearing devices.
  - Continuation of the self-clearing fault data collection and validation tests, and revision of the formula, to build confidence in utilizing the method.
  - Investigation of a way to include more variables to the developed model.

They are currently working on how we improve and apply and coordinate the developed formula with our distribution/outage management system.

II-B Power System Transient Stability Assessment using Critical Fault Clearing Time Functions

Miki *et al.* [18] developed the method for assessing accurately and efficiently the transient stability by use of critical fault clearing time functions generated by simulation of transient phenomena. It has been applied to the model power system with 5 generators. Results of application have been clarified the following facts.

- The effect of control and protection systems on transient stability can be visually grasped by graphs of critical fault clearing time functions.
- By use of the above functions, the average energy loss can be easily calculated and the effect of control and protection systems on transient stability can be easily and quantitatively assessed.
- The proposed methods for increasing the efficiency of assessment is effective, but more investigations are required in order to apply them to real power systems.

The developed method will greatly contribute to the improvement of the planning for preventing unstability of power systems.

II-C Identifying Fault Clearing Operations in Distribution Systems

Min *et al.* [19] developed rules that can be used to identify fault clearing devices. Necessary features associated with identifying the fault clearing devices are explained and implemented. Rules are developed so that the expert system can utilize these features to classify the operated device. The approach is validated using actual field data that recorded protective device operations.

II-C.1 Fault Measurement Method

For the analysis, voltage and current phasors, and real and reactive power demands are computed using instantaneous voltage and current measurements. Phasor conversion is implemented by multiplying the input voltage and current measurements by the coefficients of cosine and sine functions in fundamental frequency. For example, for every sampled voltage v, the phasor V is calculated as

$$t = \begin{bmatrix} 0 & T_s & 2T_s & 3T_s & \dots & (N-1)\,T_s \end{bmatrix}^T \tag{1}$$

$$V_{\text{real}} = \frac{\sqrt{2}}{N} \sum_{k=1}^{N} v_k \cdot \cos\left(2\pi f t_k\right) \tag{2}$$

$$V_{\text{imag}} = -\frac{\sqrt{2}}{N} \sum_{k=1}^{N} v_k \cdot \sin\left(2\pi f t_k\right) \tag{3}$$

$$V = V_{\text{real}} + jV_{\text{imag}} \tag{4}$$

where T_s is the sampling interval.

Calculated voltage and current phasors are then used to estimate real and reactive power load demand from the monitoring location by (5) and (6).

$$P = \text{Re}(VI^*) \tag{5}$$

$$Q = \text{Im}(VI^*) \tag{6}$$

These calculated quantities are then used to extract features that are necessary to identify fault clearing devices. In the demonstration, only the real power load demand is used for simplicity.

III Proposed Method

Algorithms for fault detection in numerical protection relays have been of academic and industrial interest. Early algorithms were constrained by the available computer performance of that time and commonly implemented in a low level machine language in order to speed up the algorithm. This section contains a brief description of common algorithms used in numerical protection relays. The additional discussion on the suitability to use the algorithms for fast fault detection is also presented.

III-A Differential Equation Algorithms

This class of algorithms has a common property, namely the assumption that the post fault voltage and current can be described by a sinusoidal signal $s(t)$ as for example in equation below.

$$s(t) = S_{\text{magn}}.\sin(\omega t + \phi) \tag{7}$$

Sampled data values of current and/or voltage are then fitted to the sinusoidal waveform using one of a number of available methods. The result is estimated values of $S_{magn}, \omega = 2\pi f$, and ϕ. The frequency f of the sinusoidal signal is often assumed to coincide with the nominal power frequency of the power system so that only the magnitude and the phase needs to be estimated. By comparing the estimated magnitude with the magnitude during normal operation, a fault can be detected.

The short-circuit current due to a fault often contains a decaying DC-component with a magnitude depending on the fault inception angle. Equation above does not take into account that DC-component. Whenever the fault current contains a DC-component, the estimation of the fault current will therefore contain an error.

III-B Two samples

Description

Assume that two consecutive current samples i_0 and i_1 at the time instants t_0 and t_1 respectively are available and that the angular frequency ω in Equation 7 corresponds to the nominal power frequency of the power system. Substituting into Equation 7 gives two equations for solving the unknown parameters (I_{magn}, and ϕ).

$$i_0 = i(t_0) = I_{\text{magn}} \sin(\omega_0 t_0 + \phi) \tag{8}$$

$$i_1 = i(t_1) = I_{\text{magn}} \sin(\omega_0 t_1 + \phi) \tag{9}$$

I_{magn}, and ϕ can now be solved from Equation 8 and 9. If it is first observed that the time-derivative of Equation 7 is:

$$i' t = \omega I_{\text{magn}} \cos(\omega t + \phi) \tag{10}$$

and then that:

$$i^2(t) + \frac{i'^2(t)}{\omega^2} = I^2_{\text{magn}} \sin^2(\omega t + \phi) + I^2_{\text{magn}} \cos^2(\omega t + \phi) \tag{11}$$

$$= I^2_{\text{magn}}(\sin^2(\omega t + \phi) + \cos^2(\omega t + \phi)) \tag{12}$$

$$= I^2_{\text{magn}} \tag{13}$$

Then the magnitude I_{magn} can be estimated from one current sample and one current derivative sample. The current derivative however is not always readily available. Two consecutive current samples can be used to estimate the following derivative.

$$i^1(t) = \frac{i(t_1) - i(t_0)}{\Delta t} \tag{14}$$

where Δt is the time between the two samples ($\Delta t = t_1 - t_0$). The magnitude can then be estimated from Equation 11 by substitution of Equation 14 which gives Equation 15.

$$I^2_{\text{magn}}(t_1) = i_1^2 + \frac{1}{\omega^2 \Delta t}(i_1 - i_0)^2 \tag{15}$$

III-B.1 Suitability for Fast Fault Detection for Differential Equation Algorithm

Since only two samples are needed to estimate the magnitude, the algorithm has the potential to be fast. However, the calculation of the derivative can produce poor estimates if the samples are noisy or of poor quality. The derivative is calculated by taking the differential between two current samples and then divide the differential with the time difference between the two samples.

$$i_1(t) = \frac{i(t) - i(t - \Delta t)}{\Delta t} \tag{16}$$

If the time difference Δt is small the differential will be divided with a small number, hence magnifying possible errors in the differential. The algorithm is applied to an actual sampled voltage signal that is sampled at a high frequency but with poor quality of the samples.

IV Result Analysis

IV-A Simulation Assumption

For simulation analysis of efficient fault detection the following ratings have been selected and power system impedances have been calculated based on the following parameters:

- System voltage $u_h = 12$ kV
- Nominal load (phase) current $i_n = 630$ A (measured at the load Z_L in Figure 2)
- Short-circuit phase current in case of a solid three-phase fault $i_k = 40$ kA

The time-constant of the power system (when no load is connected to the power system) was selected to 45 ms, corresponding to a power factor of $\cos\phi = 0.0705$. The power factor of the load was selected to $\cos\phi = 0.8$, a typical value for common load types. Figure 2 contains the single line diagram of the power system used in the simulation analysis.

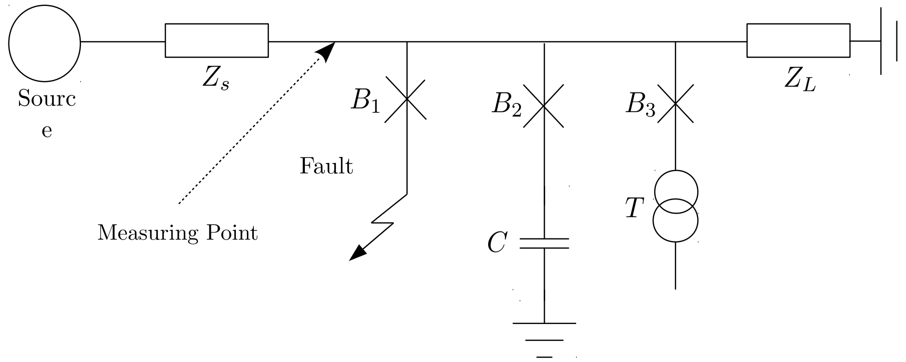

Figure 2: Single Line Diagram for Fault Analysis

The source is modeled as an infinite source, that is with no limits on active or reactive power production. The source impedance is $Z_S = 0.0122 + j \cdot 0.173\Omega$, which corresponds to a short-circuit current of 40 kA_{RMS}. The load impedance was $Z_L = 8.79 + j \cdot 6.44\Omega$, which corresponds to a load current of 630 A_{RMS}. Three circuit-breakers, B_1, B_2, and B_3 respectively, are used to apply three power system transients. The first circuit-breaker was used to simulate faults imposed on the power system. Mostly three-phase faults were studied, however a few two-phase faults were also studied to investigate if they also could be detected using algorithms from this paper.

Single-phase faults are only briefly considered within this report, since distribution systems are commonly high impedance earthed so that the fault current of a single-phase fault is in the order of a few Amperes. The second circuit-breaker was used to simulate capacitor energization, and the third circuit-breaker was used to simulate transformer energization.

IV-B Fault Detection with the LSQ-Method

The method uses three consecutive current samples and fit them to a sinusoidal current of unknown magnitude and phase by a LSQ method. The result is an estimate of the magnitude (and phase) of the current. Whenever the estimated current exceeds the predetermined trigger level a fault is likely to have occurred and a trip-signal is issued. First, three-phase faults were imposed on the power system. The fault inception angle, i.e. the phase angle of the system voltage when the fault occurs, was swept over a time interval corresponding to one period of fundamental power frequency. The MATLAB simulations were performed and for each simulation the fault detection time was observed. The sampling frequency was also allowed to vary and the simulations are repeated for four different sampling frequencies, namely 1, 2, 4, and 8 kHz respectively. The result is summarized in Table 1 from which it can be concluded that to achieve a fault detection

Table 1: Maximum Fault Detection Time for Different Sampling Frequencies (using LSQ)

S.No.	**Sampling Frequency**	**Maximum Detection Time**
1.	1 kHz	3 ms
2.	2 kHz	1 ms
3.	4 kHz	0.5 ms
4.	8 kHz	0.38 ms

time within 1ms a sampling frequency of at least 2 kHz is required, but to allow for a margin, 4 kHz was selected as an appropriate sampling frequency. The estimated current magnitude at a sampling frequency of 4 kHz is shown in Figure 3 together with the instantaneous current samples. When the sampling frequency was increased to 16 kHz.

Finally, single phase faults were simulated to verify that such faults were not detected by the algorithm. For some fault inception angles, a fault was detected in that phase were the single-phase fault was applied. However, such situations can be avoided by the requirement that a fault must be detected in at least two phases. For this particular study, the reason

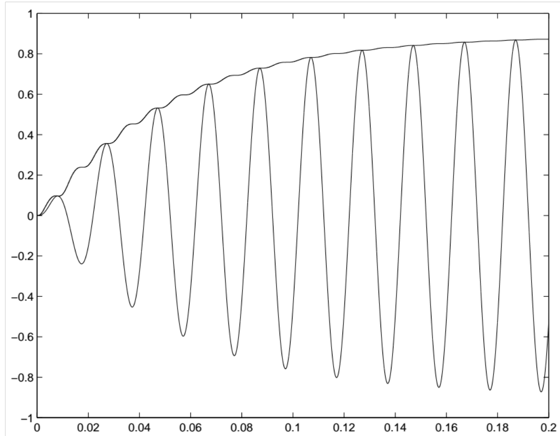

Figure 3: Estimated Current and Instantaneous Current Values

that a single phase fault gave rise to fault currents large enough to be detected as a fault is probably that the modeling of the system grounding resistance is inaccurate. The grounding resistance has no or little effect on three and two phase faults so the inaccurate choice of grounding resistance does not effect the results obtained in this case study concerning three and two phase faults.

IV-C Fault Detection with Differential Equation Method

A differential equation method is implemented as a user defined component to investigate if it was a possible algorithm to use for fast fault detection. The trigger level was treated in a slightly different manner for the differential equation method than for the LSQ-method since a low value of estimated resistance and inductance is a sign of a fault in the power system, whereas a higher value of estimated resistance and inductance is a sign of normal operating conditions.

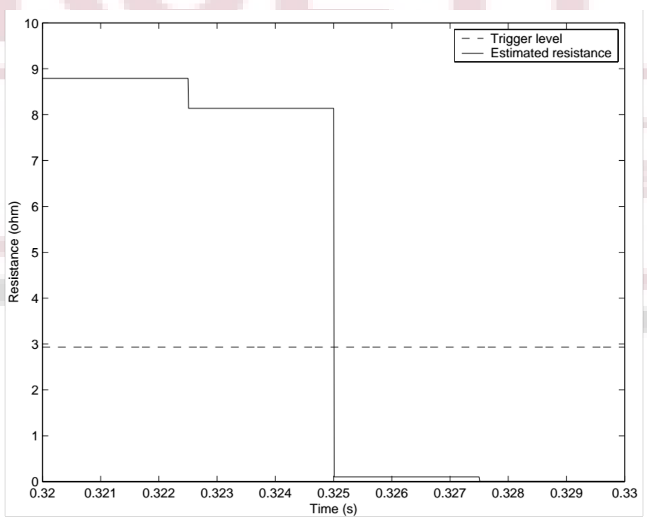

Figure 4: Estimated Resistance during a Fault

Finding a trigger level that makes it possible to compare the different methods to each other, the trigger level was selected to one third of the nominal resistance and inductance of the protected object. A first simulation was made to determine the nominal resistance and inductance of the protected power system i.e. the source and the load. An estimated resistance is given in Figure 4, where the resistance and the trigger level is plotted. For that particular simulation, the sampling frequency was 1 kHz and the fault was applied at $t = 0.35$ s. The fault detection in this particular phase was 5 ms. Once the trigger level is selected, a number of simulations are performed and the fault inception angle is moved 1 ms in between each simulation. The fault detectors were placed in each of the three phases of the power system and the sampling frequency was 1kHz as earlier mentioned. The 20 simulations were then repeated but now with sampling

Table 2: Maximum Fault Detection Time for Different Sampling Frequencies (using Differential Equation)

S.No.	Sampling Frequency	Maximum Detection Time
1.	1 kHz	3.5 ms
2.	2 kHz	1.8 ms
3.	4 kHz	0.75 ms
4.	8 kHz	0.45 ms

frequencies of 2, 4, and 8 kHz respectively. The result of simulations is summarized in Table 2, where the largest detection time for each sampling frequency is given. Since the point of wave of the fault initiation is a random value, fault initiation will eventually take place in a time so that the maximum fault detection time is obtained. The maximum detection time must always be shorter than approximately 1ms if fault clearing before the first prospective current peak is the target. From the maximum fault detection times given in Table 2 it can be concluded that for this particular system, fast fault detection can be obtained with the differential equation method with a sampling frequency of at least 2 kHz. To provide a larger margin it would be appropriate to select the sampling frequency to at least 4 kHz.

The application of the LSQ-method and the differential equation method gave as result that it is possible to use them for fast fault detection – at least in the simplified system.

V Conclusion

The main contributions of this paper as given by the list as follows:

- A structured analysis on the speed of fault detection and on the benefits of fast fault detection. In particular, “fast” fault detection is defined.
- An evaluation of possible algorithms appropriate for fast fault detection.
- Requirements on equipment and algorithms used for fast fault detection.
- A simulation analysis of the application of fast fault detection in one typical grid.

Fast fault detection find out that the existing work of speed of protection is quite crude. When the rate of rise of the fault current and the operating time of the fault clearing equipment was taken into account, fast fault detection was defined to mean fault detection within 1 ms measured from the inception of the fault. The evaluation of algorithms suitable for fast fault detection led to the selection of two algorithms that are investigated, namely the LSQ-method, and the differential equation method.

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