Grounding Faulted Feeder Detection with Fault Resistance Measurement in Mining Power Systems

Zeng Xiangjun
School of Electrical & Info. Engineering
Changsha Univ. of Science and Technology
Changsha, 410077, P.R.China.
Email: zengxiangjun@ieee.org

Li K.K. and Chan W.L.
Dept. of Electrical Engineering
The Hong Kong Polytechnic Univ.
Hong Kong, P.R.China
email: eekkli@polyu.edu.hk

Su Sheng
School of Electrical & Info. Eng.
Changsha Univ. of Sci. and Technol.
Changsha, 410077, P.R.China
email: sushengx@tom.com

Abstract—**Many mining power systems have been operated with floating neutral or high resistance grounded. The earth fault current is no more than a few tens of amperes. Traditional earth fault detection methods based on zero sequence current have poor sensitivity in this case. For improvement, a fault detection scheme with fault current and fault resistance measurement is presented in the paper. It can detect high impedance grounding faults (HIGF). The scheme has been verified by EMTP simulation, and fault detection prototype has been developed and tested. Results show that the scheme has with high sensitivity and robustness.**

Keywords-mining power systems, high impedance grounding faults (HIGF), protective relaying, fault detection.

I. INTRODUCTION

The mining power system has a unique industrial environment where earth faults easily occur in mobile electrical equipment. In order to restrict the fault residual current and to reduce outage and shock hazard, most mining power systems utilize ineffectively earthed neutral (unearthed, high resistance earthed, or resonance earthed) [1-4].

According to the IEEE standard 142, the residual current caused by single-phase earth fault needed to be limited to about ten amperes in ineffectively earthed systems [1]. The earth fault current is usually not more than ten amperes, and the fault behavior is affected by many physical and environmental variables, such as feeder configuration, load level and type, surface condition, and weather [5-7]. Some high impedance earth faults are difficult to be detected [7, 8]. Although several techniques have been proposed, and much progress has been made, which include zero sequence over-current protection, zero sequence current direction based protection, zero sequence wattmetric protection and some high harmonic currents based protections [9-18].

Fig.1 shows zero sequence current based earth fault detectors (EFD) installed in a small distribution system. The zero sequence current in the fault feeder *k* detected by EFD is the sum of capacitive charging current of all other sound feeders and neutral point grounding currents. Whereas, while other feeder grounding fault, the zero sequence current in the sound feeder *k* is its capacitive charging current. In some situation, the feeder's charging current is bigger than the sum of all others, so that the threshold of zero sequence over-current protection is difficult to be set.

In neutral point floating systems or high resistance earthed systems, the zero sequence current in the earth faulty feeder is opposite to that in the sound feeders in direction [1, 9]. In arcing grounding fault situation, their direction is difficult to be measured [10], so the zero sequence current direction based protection has limited application [7]. Zero sequence energy is employed in [7] to detect arcing ground fault. Because the magnitude of zero sequence voltage and current is very low, the transfer of zero sequence energy is very small in high impedance grounding fault (HIGF) situations. Zero sequence wattmetric protection thus has poor performance in detecting HIGF [7, 11].

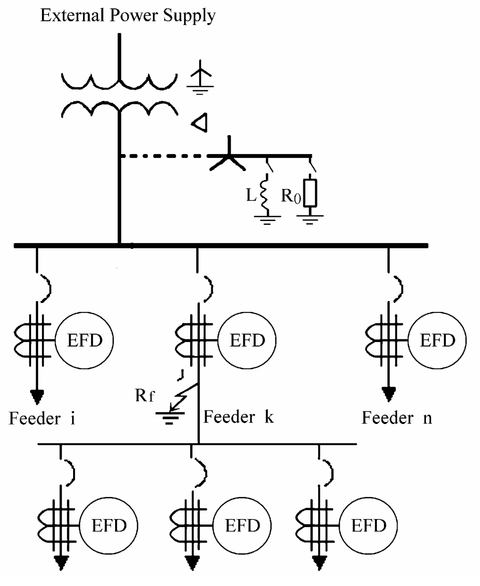

Figure 1. Zero sequence current based earth fault detecters (EFD) installed in a small distribution system

Some artificial intelligence (AI) techniques have been applied to detect earth faults. Simulation Models for pattern matching procedures, ANN and Fuzzy logic have been developed [12, 13], and some statistical approaches for

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identifying symptom parameters of incipient faults have been proposed [14]. At present, the AI based fault detection techniques are not yet mature for implementation in distribution system.

A reliable and flexible solution for HIGF detection has still not been found in ineffectively earthed systems. In practice, about 12% of permanent grounding faults have a resistance above 4kΩ [7]. The voltage profile is not significantly modified due to the faults; nor is enough current produced. Nonetheless, such faults are dangerous, often causing high voltage to be present on equipment accessible to the public, even causing fire damp explosion in coal mine. As these faults are not easily detected by the above fault detection schemes, a novel fault detection scheme with fault current and fault resistance measuring is presented in the paper.

II. PROTECTION PRINCIPLE WITH FAULT RESTANCE MEASUREMENT

In distribution systems, some parameters (such as: zero sequence voltage U_0, zero sequence current I_0 for each feeder) are measured easily with voltmeter or ammeter. Other parameters (such as: capacitance to ground, dissipation factor, resonance deviation etc.) are difficult to be measured directly. In order to measure the parameters which can be applied to detect HIGF, some parameters measuring techniques are presented in [15-17]. Among them, a novel method for zero sequence parameter measurement with injection signal has been developed by the authors of [16, 17]. Other method for fault resistance measurement is developed in [18]. The global phase-to-ground-admittance is necessary to calculate the fault resistance which can be applied to decide earth faults directly. The global phase-to-ground-admittance is difficult to be measured with high precision. In order to improve it, a novel principle for fault resistance calculation without global phase-to-ground-admittance measurement is developed as follow.

Reference [18] shows that the fault component of faulted phase (A phase) current in the faulted feeder (that is faulted feeder's residual current) is composed of two parts.

$$\Delta\dot{I}_A = Y\Delta\dot{U}_0 + \frac{\dot{U}_A}{R_f} \tag{1}$$

Where, Y is the global phase-to-ground-admittances, $\Delta\dot{U}_0$ is the fault component of the zero sequence voltage, $\dot{U}_A$ is the faulted phase voltage, R_f is the fault resistance. The first part is due to the increased neutral-to-ground-voltage, that causes additional capacitive currents in three phases of each feeder—the faulted as well as the healthy ones.

$$Y\Delta U_0 = \Delta\dot{I}_0 = \omega C\Delta\dot{U}_0 \tag{2}$$

Where, ω is the power system frequency, C is the phase-to-ground-capacitance. The fault component of sound phase current is its' capacitive current.

$$\Delta\dot{I}_B = \Delta\dot{I}_C = \omega C\Delta\dot{U}_0 \tag{3}$$

From (1)-(3), the residual current is:

$$\dot{I}_f = \frac{\dot{U}_A}{R_f} = \Delta\dot{I}_A - \Delta\dot{I}_C = \Delta\dot{I}_A - \Delta\dot{I}_B \tag{4}$$

In order to reducing the influence of three-phase-asymmetry and currents measure errors, the (4) is changed to:

$$\dot{I}_f = \Delta\dot{I}_A - (\Delta\dot{I}_B + \Delta\dot{I}_C)/2 \tag{5}$$

The grounding fault resistance is thus calculated as:

$$R_f = \frac{\dot{U}_A}{\Delta\dot{I}_A - (\Delta\dot{I}_B + \Delta\dot{I}_C)/2} \tag{6}$$

With zero sequence voltage startup, when zero sequence voltage in distribution networks is larger than 10 percents of the rated phase voltage, the residual current I_f and grounding resistance R_f can be calculated by the phase voltage of the faulted feeder and the variation of three-phase currents according to (5) and (6). When the fault current is bigger than its threshold (usually set to 1A) or the grounding resistance is smaller than its threshold (usually set to 8kΩ), the grounding fault can be detected.

III. GROUNDING FAULT DETECTION SCHEME

The fault detection scheme with fault resistance measurement is shown in Fig.2. It includes the following steps:

1. Every phase voltage and current of the protected feeder is measured on-line. The sampling values of the zero sequence voltage, three-phase voltages and three-phase currents are recorded.
2. When the zero sequence voltage is larger than its threshold, grounding fault has occurred in the distribution system, and the grounding fault protection scheme is started.
3. The faulted phase voltage and the phase current variation before and after fault are calculated, and the grounding fault residual current and the fault resistance can be calculated according to (4).
4. When the fault current is bigger than its threshold or the resistance is smaller than its threshold, grounding fault is occurred in the protected feeder.
5. The grounding fault signal can then be sent out for maintenance.

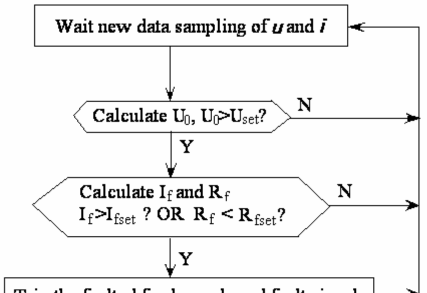

Figure 2. Grounding fault detection scheme

IV. SIMULATION & EXPERIMENTATION

A. Prototype development

The protection scheme only uses the measured voltages and currents in the protected feeder, and does not need the parameters of the distribution system or other feeders. It can be implemented on feeder terminal units (FTUs) with three-phase voltages and three-phase currents sampling in the distribution automation systems. The FTU prototype (shown in Fig.3) has been developed. It employs DSP TMS320F206, and its hardware frame is shown in Fig.4.

Figure 3. Prototype of FTU

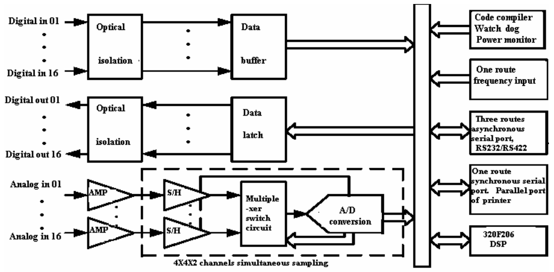

Figure 4. Principle of FTU hardware frame

B. EMTP Simulation & Result Discussion

A typical 35kV radial distribution system for EMTP simulation is shown in Fig.5. The parameters are shown in Table Ⅰ. Phase-to-phase capacitance for reactive power compensation is 1.65μF. Different earth faults in different neutral earthing conditions are simulated, and the influences of unbalance loads (such as rectifiers, drives, arc furnaces, and low voltage single-phase loads) are investigated. Waveforms for every phase voltage and current are recorded. Fault data generated from the EMTP simulation is input into the simulation program for analysis. Performance of the protection against earth faults is assessed. The precision and robustness of grounding protection schemes are tested.

TABLE I. PARAMETERS OF FEEDERS FOR SIMULATION

Name	Feed 1	Feed 2	Feed 3	Feed 4 (fault)
Attribute	Overhead	Equivalent*	Cable	Overhead
Length (km)	30	100	30	20
C (uF)	0.45	1.5	5.4	0.3
Damping	4%	4%	3%	4%
Load (KVA)	2000	10000	2000	1000
Power factor Cos α	0.85	0.80	0.82	0.85

*Equivalent means the equivalent of many feeders.

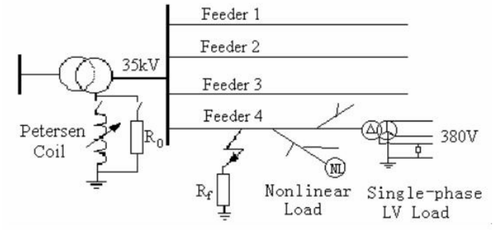

Figure 5. Earth faulted network for simulation

Table Ⅱ shows the relay simulation results for different fault resistance and different neutral point earthing conditions. In all conditions, the calculated resistance using (6) in the faulted feeder almost equals to the fault resistance. In the sound feeder the calculated result gives a large number, often more than 30kΩ. The grounding fault can then be detected by comparing the calculated resistance with its threshold (usually set to 8kΩ). If the calculated resistance is smaller than the threshold, grounding fault can thus be detected.

C. Experimentation

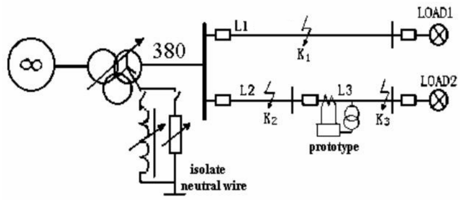

Figure 6. Dynamic power system model

The prototype has been tested on a dynamic power system model in the laboratory. The configuration for the test system is shown in Fig.6, where L1 is an exceptionally long line used to simulate several feeders to study the effect of earth faults in an ineffectively earthed distribution system, L2 and L3 are short lines, feeder terminal unit (FTU) is applied to test the currents and voltages of line L3. By changing the neutral earth method and the fault point, some ground faults are tested. When fault point is at K1, K2 or K3, the zero sequence voltage startup, and the test results are shown in TABLE Ⅲ. The calculated resistance using (6) in the faulted feeder with K3 fault almost equals to the fault resistance. In the sound feeder with K2 fault this calculated value is often more than 20 kΩ. With a threshold of 8kΩ, the fault at location K3 with resistance lower than 8kΩ can be detected and tripped with high sensitivity and robustness.

TABLE II. THE EMTP SIMULATION RESULTS FOR THE FAULT DETECTION SCHEME

Fault Type	**Neutral earthed Methods**	v	**U_0(kV)**	**The Calculated Resistance and Fault Detection Results**							
				R_{f1}(Ω)	***Fault?***	***R_{f2}(Ω)***	***Fault?***	***R_{f3}(Ω)***	***Fault?***	***R_{f4}(Ω)***	***Fault?***
Feeder 4 Grounding Fault in Phase A (R_f=5Ω)	Unearthed		20.20	32,235	No	33,843	No	34,438	No	7.7	Yes
	Resistance (400Ω)		20.03	31,825	No	32,578	No	33,223	No	7.6	Yes
	Petersen-Coil	-5%	20.19	31,656	No	32,370	No	32,670	No	8.4	Yes
		-10%	20.18	31,632	No	32,465	No	32,679	No	8.5	Yes
	Petersen Coil in series with resistance	-5%	20.16	31,683	No	32,435	No	32,769	No	8.4	Yes
		-10%	20.16	31,665	No	32,450	No	32,693	No	8.4	Yes
Feeder 4 Grounding Fault in Phase A (R_f=1000Ω)	Unearthed		7.69	95,800	No	111,400	No	129,300	No	1,009	Yes
	Resistance (400Ω)		7.40	82,500	No	112,500	No	114,600	No	1,009	Yes
	Petersen-Coil	-5%	18.53	78,400	No	95,400	No	106,400	No	1,007	Yes
		-10%	18.20	77,100	No	95,200	No	104,200	No	1,007	Yes
	Petersen Coil in series with resistance	-5%	14.60	79,400	No	96,500	No	107,300	No	1,008	Yes
		-10%	14.21	78,300	No	94,800	No	105,400	No	1,007	Yes

Note:* ν is the resonance deviation of the compensated network,

TABLE III. EXPERIMENTATION RESULTS

Fault type	**Neutral point earthed method**	ν	**K2 Fault**		**K3 Fault**	
			Resistance (Ω)	***Operation***	***Resistance (Ω)***	***Operation***
Low impedance grounding fault (R_f=5Ω)	Unearthed		35,000	no trip	7	trip
	Resonance earthed	0	25,000	no trip	14	trip
		-10%	26,000	no trip	13	trip
	Resonance earthed with resistance in series	0	28,000	no trip	18	trip
		-10%	27,000	no trip	14	trip
High impedance grounding fault (R_f=2kΩ)	Unearthed		46,000	no trip	1,960	trip
	Resonance earthed	0	47,000	no trip	1,950	trip
		-10%	49,000	no trip	2,030	trip
	Resonance earthed with resistance in series	0	49,000	no trip	2,010	trip
		-10%	52,000	no trip	1,980	trip
High impedance grounding fault (R_f=10kΩ)	Unearthed		79,000	no trip	9,700	no trip
	Resonance earthed	0	80,000	no trip	9,800	no trip
		-10%	82,000	no trip	9,560	no trip
	Resonance earthed with resistance in series	0	76,000	no trip	9,850	no trip
		-10%	79,000	no trip	9,970	no trip

Note: the threshold is set as 8,000Ω

V. CONCLUSION

Many mining power systems have been operated with floating neutral or high resistance grounded. The ground fault current is no more than a few tens of amperes, fault is difficult to be detected. A novel fault detection scheme with fault current and fault resistance measurement is developed in this paper. The protection scheme only uses the measured voltages and currents in the protected feeder, and does not need the parameters of the distribution system or other feeders. It can be implemented on feeder terminal units (FTUs) with three-phase voltages and three-phase currents sampling in distribution automation systems. The prototype has been developed, EMTP simulation and experimentation results show that the protection with fault resistance measurement is sensitive and robust to detect all kinds of grounding faults, including high impedance grounding faults.

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BIOGRAPHIES

Zeng Xiangjun received his MSc. degree from Wuhan University, and Ph.D degree from Huazhong University of Science & Technology. He is at present a Professor in Changsha University of Science and Technology, China. He currently works as a Post-doctor in the Department of Electrical Engineering, Hong Kong Polytechnic University. His research interest is real-time computer application in power systems control and protection.

Li K. K. received the MSc. degree from the University of Manchester Institute of Science and Technology, Manchester, U.K., and the PhD degree from City University, London, U.K. He has worked as a Protection Engineer in Hong Kong. He is currently an Associate Professor in the Department of Electrical Engineering, Hong Kong Polytechnic University. His research interests are power system protection and applications of artificial intelligence in power systems.

Chan W. L. obtain BSc(Eng) and Mphil from University of Hong Kong and PHD from City University, London. He is currently an Associate Professor in the department of Electrical Engineering, Hong Kong Polytechnic University while his major interests are in microprocessor applications in power systems and applications of artificial intelligence.

Su sheng received the B.S degree from Wuhan University of Hydraulic and Electrical Engineering, China in 1998 and M.S degree from Wuhan University, China in 2002. He currently works as a Research Assistant in the Hong Kong Polytechnic University. His interests including load modeling and artificial intelligence.