VERIFYING THE INDICATION METHOD FOR HIGH-RESISTANCE EARTH FAULTS IMPLEMENTED IN CENTRALIZED PROTECTION SYSTEM

Ari NIKANDER
Tampere University of Technology – Finland
ari.nikander@tut.fi

Jani VALTARI
ABB Oy – Finland
jani.valtari@fi.abb.com

Ontrei RAIPALA
Tampere University of Technology – Finland
ontrei.raipala@tut.fi

Erkka KETTUNEN
ABB Oy – Finland
erkka.kettunen@fi.abb.com

ABSTRACT

The paper presents verifying test results of the primary substation level centralized functionality in laboratory. The attention is concentrated to verifying the indication method for high-resistance phase-to-earth faults in neutral isolated and compensated networks. The applied method is based on the studies and results carried out in TUT. For properly testing the test environment needed to be set up for centralized functionality. This environment was set up in TUT and it utilizes the Real Time Digital Simulator (RTDS®). The indication method for high-resistance earth faults has been implemented as centralized in order to test the new technology. It utilizes new possibilities of the centralized protection system. The essential method in this study was RTDS simulations of centralized protection system.

INTRODUCTION

In this study a high-resistance phase-to-earth fault is defined as a fault with fault resistance from 10 kΩ up to some hundreds of kilo-ohms. Medium voltage networks in the Nordic countries have mainly isolated or compensated neutrals. These neutral earthing practices lead to very low fault current with high-resistance earth fault. The part of the neutral compensated line length in relation to neutral isolated line length has increased rapidly during the past decade and this trend will probably continue. The detection of the high-resistance earth faults is a challenging task now and in the future.

In overhead line networks high-resistance earth faults may appear due to e.g. trees leaning against a conductor or when conductor falls to the ground with very high resistivity. Such faults also develop due to conductor break when the load side end of the conductor has an earth contact. Faults with covered conductors or other network component faults (e.g. metal oxide surge arresters, overhead line pin insulators, cable terminals) often have very high impedance. These faults tend to evolve gradually into a full-scale earth fault. Thus, early identification and location of such faults is of increasing importance in improving the safety and reliability of electricity distribution. Main motive for indication is electrical safety, however. No live parts that can cause dangerous hazard voltages for humans are allowed. Secondary target is anticipation of developing phase-to-earth faults and avoiding the interruption for customers. With the help of fault indication the zone affected by the developing fault can be limited before an interruption.

The typical fault resistance that is composed of an unseasoned tree is approximately in the range 15 - 200 kΩ including the resistance of the tree and its earthing resistance [2]. These resistance values are valid in those seasons when the earth is not frozen. In wintertime much higher resistances, ranging up to several hundreds of kilo-ohms or some megohms can be found. Most faults of this type cannot be detected by neutral voltage overvoltage relays or monitoring of the neutral voltage.

Conventional feeder protection cannot even detect an earth fault with very high fault resistance and thus it cannot trip the faulted feeder. Although the touch voltage regulations [1] do not require the tripping of the faults with very high fault resistance, such faults may cause unsafe situations. The major safety risk appears in the situation where the conductor or other live part of the system has an earth contact e.g. directly or via a tree and the fault current is not high enough to lead to tripping. E.g. falls and breaks in the conductor when the load side end of the conductor has an earth contact are especially dangerous if the live parts can be touched by the public.

The Department of Electrical Energy Engineering of Tampere University of Technology has developed the methods for identifying and locating high-resistance earth faults in due course [3]. Implementing the indication algorithm in the centralized protection system provides new possibilities for improving the sensitivity and reliability of the high-resistance earth fault indication.

CENTRALIZED PROTECTION SYSTEM

Traditionally all protection and control functionality in the substation has been implemented to bay level protection and control IEDs (Intelligent Electronic Device). Recent advancements in PC and communication technology have made it possible to redesign this architecture. The introduction and the increasing acceptance of the IEC 61850 standard have made available fast and standardised Ethernet based communication. First, the station bus (part 8-1 of the standard) allows replacing copper wirings on a horizontal level between IED devices. Secondly, the process bus (part 9-2) makes the digitized measurement information from instrument transformers available for other devices in a standardized way. When time synchronization can also be sufficiently handled with an Ethernet based IEEE 1588 standard, it is possible to utilize standard PC technology and centralize part of the substation functionality to one station computer. The concept is presented in Figure 1 and described in more detail in [4].

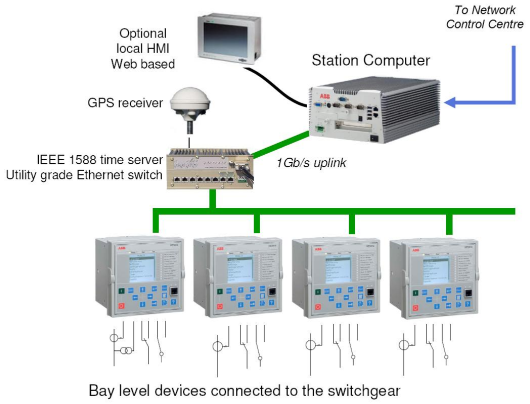

Figure 1. Overall setup of centralized protection and control system.

In the presented concept the most critical and important functionality would remain in the bay level IEDs assuring network safety in all situations. This creates the back-bone of a network protection system with a long life-cycle. When the bay level IED also sends the measurements to the station computer via IEC 61850-9-2, value added and less critical functions can be implemented to the station level where updating them is easier and cheaper. High-resistance earth fault protection function is a good example of such value-added function which is suitable for station level implementation. It is a function with less strict operate time requirements, and also a function which benefits from the possibility of having all measurements from all feeder bays available.

TEST ENVIRONMENT FOR CENTRALIZED PROTECTION FUNCTIONS

The simulation test bench was established with the help of the Real Time Digital Simulator (RTDS®). RTDS performs the network calculations and communications between external devices in real time which enables the interaction studies between real physical devices and modelled power systems. A simple distribution network model consisting of three MV feeders of different lengths was modelled with the help of graphical user interface to RTDS called RSCAD (Figure 2). Earth fault models with various fault resistances were placed to the tail parts of the feeders. The phase-to-earth voltages, phase currents, neutral voltage and sum current measurements from each feeder terminal were sent to the substation computer in IEC 61850-9-2 format. The high-resistance earth fault indication algorithm was implemented to the substation computer, and algorithm trip signals were sent from the station computer to a REF630 IED via GOOSE messages as defined in IEC 61850-8-1 standard. The REF630 then converted the GOOSE messages received from the station computer to digital format, and sent the commands forward to the RTDS. REF630 IED was used in a way as a protocol converter in the simulations. The test environment for the centralized protection system is presented in Figure 3.

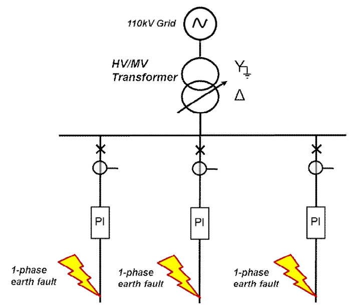

Figure 2. MV network modelled using RSCAD.

The station computer was equipped with IEC 61850 stack capable of receiving IEC 61850-9-2 data and communicating with GOOSE messages. The station computer was running a centralized version of high-resistance earth fault algorithm which protected all three bays of the network model constructed using RSCAD. The station computer was configured with ABB's PCM600 configuration tool. The same tool was used to monitor the outputs of the high-resistance earth fault protection functions running on the station computer. Utilizing the monitoring capabilities of the PCM600, it was possible to keep the record of the calculated fault resistances of the protection functions.

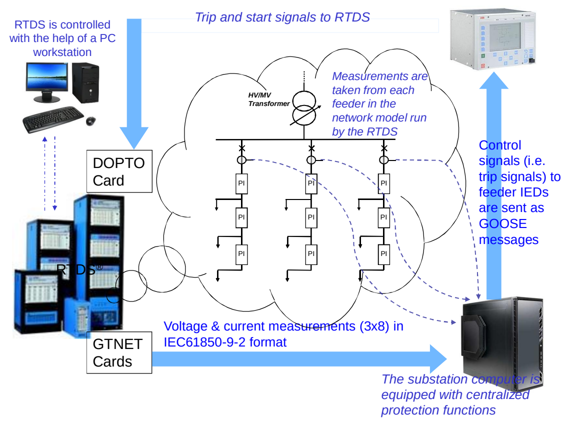

Figure 3. RTDS test environment for centralized protection.

IDENTIFICATION OF HIGH-RESISTANCE EARTH FAULTS

The indication method utilizes the standard measuring information available in practice in all primary substations.

The indication method may operate independently as a relay function. It can also be implemented as a central protection function utilizing measuring information collected from the MV bays. The patented process for the indication of the earth fault also includes the information on the faulty feeder and phase. When applied as a central functionality the results can be presented centrally.

Indication method for high-resistance earth faults

The method developed in Tampere University of Technology detects the magnitude of the fault resistance of the faulty phase of the faulty feeder. In the case of a healthy feeder the magnitude of the fault resistance is theoretically infinite. In practice the fault resistance value calculated for healthy feeder is different order of magnitude compared to faulty feeder. Thereby the faulty feeder can be detected reliably.

The measuring accuracy does not allow the accurate determination of the phase-to-earth conductance of the MV feeder. Thus more reliable value for the fault resistances and thereby more sensitive fault indication can be achieved if the phase-to-earth admittances are assumed to be composed of pure capacitances. Thereby the reactive component of the sum current is separated and this alone is used for the calculation. The total sum current of the feeder also includes the component caused by the natural unbalance. The influence of the unbalance on neutral voltage and sum currents must be eliminated in order to achieve high sensitivity in the fault indication. Only neutral voltage and sum currents due to an earth fault are considered. The method can be applied with neutral isolated and compensated systems.

The most sensitive earth fault indicator is the change of the neutral voltage of the network. The indication process starts when the absolute value of the change of the neutral voltage $|\Delta\underline{U}_0|$ exceeds the specified threshold value (Equation 1). If the change of the neutral voltage is due to an earth fault, $\Delta\underline{U}_0$ refers to the neutral-to-earth voltage caused by an earth fault. When the specified threshold value U_{th} is exceeded, the determination process of the faulty phase and calculation of the fault resistance start in every feeder. The phasor $\Delta\underline{U}_0$ is used as a reference. Phasor $\Delta\underline{I}_0$ represents the sum current of the feeder due to an earth fault. The influence of the natural unbalance of the feeder on the sum current is eliminated when difference phasor is considered. Phase-to-earth voltages $\underline{U}_v$ are also referenced to phasor $\Delta\underline{U}_0$. With high values of the fault resistance the phase angle of $\underline{U}_v$ is equal to the phase angle of the earth fault current in the case of faulty phase if the fault impedance is supposed to be purely resistive.

$$\left|\Delta\underline{U}_0\right| = \left|\underline{U}_{0M} - \underline{U}_0'\right| > U_{th} \tag{1}$$

where $\underline{U}_0'$ is measured neutral voltage before a change
$\underline{U}_{0M}$ is measured neutral voltage after a change
$\underline{U}_{th}$ is specified threshold value of the neutral voltage

Indication of a faulty phase in neutral isolated system

When Condition 1 has been fulfilled, the faulty phase is determined. When the difference phasor $\Delta\underline{U}_0$ is considered the effect of the natural unbalance of the system is eliminated. According to the theory of the phase-to-earth fault neutral voltage phasor $\Delta\underline{U}_0$ and phase-to-earth voltage of the faulty phase $\underline{U}_{vF}$ draw a semicircle as a function of the fault resistance in neutral isolated system. This means that, with a neutral isolated system phasor $\underline{U}_{vF}$ has 90° phase difference compared to phasor $\Delta\underline{U}_0$ during an earth fault irrespective of the fault resistance. Phase-to-earth voltages of healthy state ($\underline{U}_1'$, $\underline{U}_2'$, $\underline{U}_3'$) are slightly unbalanced which results from natural unbalance of the system. Thereby the phase whose phase-to-earth voltage has 90° phase difference compared to phasor $\Delta\underline{U}_0$ during an earth fault is concluded faulty. With neutral compensated system the deduction of the faulty phase can be carried out in corresponding way taking into account that the compensation degree of the system affects the phase angle between phasors $\underline{U}_{vF}$ and $\Delta\underline{U}_0$ during an earth fault.

Calculation of fault resistance

When information on the faulty phase is available, the fault resistance of Feeder i (R_{Fi}) can be calculated using Formula 2. A neutral voltage, phase-to-earth voltages and sum currents of feeders are known as measured values at all 110/20 kV substations.

$$R_{Fi} = \frac{\left|\underline{U}_{vF}\right| \sin\varphi_{U_{vF}}}{\left|\Delta\underline{I}_{0i}\right| \sin\varphi_{I_{0i}} + B_{0i}\left|\Delta\underline{U}_0\right|} \tag{2}$$

where $\Delta\underline{U}_0$ is change of neutral voltage
$\underline{U}_{vF}$ is phase-to-earth voltage of a faulty phase
$\varphi_{U_{vF}}$ is phase angle of phasor $\underline{U}_{vF}$ referenced to $\Delta\underline{U}_0$
$\Delta\underline{I}_{0i}$ is change of the sum current of Feeder i
$\varphi_{I_{0i}}$ is phase angle of phasor $\Delta\underline{I}_{0i}$ referenced to $\Delta\underline{U}_0$
B_{0i} is phase-to-earth susceptance of Feeder i

SIMULATION RESULTS

Tables 1 – 3 present the calculated fault resistances of the faulty feeder and one healthy feeder. Table 1 is concerning to the neutral isolated system and Tables 2 and 3 neutral compensated system. In the case of Table 1 an artificial unbalance was generated in order to get initial conditions unbalanced which is normally the case in real networks. Angle U_{1F} in Table 1 correspond the phase angle of phasor $\underline{U}_{1F}$ referenced to phasor $\Delta\underline{U}_0$.

Table 1. Calculated fault resistances for faulty and healthy feeders with neutral isolated system and unbalanced initial conditions. The fault was in Phase 2.

Real R_F/ kΩ	Faulty feeder Ph2	Healthy feeder Ph2	Change in neutral voltage, sum current and phase angle of phasor U_{1F}		
	R_F/kΩ	R_F/kΩ	ΔU_0/V	ΔI_0/A	U_{1F}/deg
1	**1.017**	-27.59	3584.8	11.6	90.7
5	**5.085**	-139.03	669.3	2.4	90.7
10	**10.17**	-281.19	282.6	1.2	90.7
20	**20.33**	-572.37	88.5	0.6	90.7
30	**30.50**	-887.19	23.8	0.4	90.7
50	**50.84**	-1388.53	28.0	0.2	90.7
70	**71.15**	-1907.40	50.2	0.2	90.7
100	**101.70**	-2785.20	66.9	0.1	90.7
150	**152.40**	-4108.30	79.8	0.1	90.7
200	**203.30**	-5335.27	86.3	0.1	90.7

Table 2. Calculated fault resistances for faulty and healthy feeders with neutral compensated (overcompensated) system with 8.4 A residual fault current.

Real R_F/ kΩ	Faulty feeder: Ph1	Healthy feeder: Ph1	Change in neutral voltage, sum current and phase angle of phasor U_{1F}	
	R_F/kΩ	R_F/kΩ	ΔU_0/V	ΔI_0/A
1	**0.92**	5.64	9581.07	6.58
5	**4.61**	28.29	3407.99	2.35
10	**9.22**	56.62	1793.88	1.24
20	**18.47**	115.07	898.77	0.63
30	**27.75**	177.11	590.86	0.42
50	**46.30**	295.89	352.16	0.25
70	**65.0**	4560.94	241.44	0.18
100	**92.60**	5572.82	181.11	0.13
150	**140.35**	3358.65	107.79	0.084

With neutral isolated system the fault indication was succeeded even up to 200 kΩ fault resistances (Table 1). With neutral compensated system the sensitivity range of the fault resistance was 100 - 150 kΩ (Tables 2 and 3).

Table 3. Calculated fault resistances for faulty and healthy feeders with neutral compensated (undercompensated) system with 7.8 A residual fault current.

Real R_F/ kΩ	Faulty feeder: Ph1	Healthy feeder: Ph1	Change in neutral voltage, sum current and phase angle of phasor U_{1F}	
	R_F/kΩ	R_F/kΩ	ΔU_0/V	ΔI_0/A
1	**1.094**	-5.53	9710.17	5.95
5	**5.47**	-27.69	3514.88	2.16
10	**10.94**	-55.34	1858.48	1.14
20	**21.89**	-110.80	949.62	0.58
30	**32.85**	-167.16	629.97	0.39
50	**54.83**	-278.16	382.35	0.23
70	**76.79**	-392.21	273.23	0.17
100	**109.86**	-567.11	187.41	0.12

CONCLUSIONS

RTDS environment was developed for testing centralized functionality suitable to be run in a primary substation. The indication method for high-resistance earth faults was implemented as centralized in order to test new technology. With RTDS GTNET cards it was possible to test the protection of the whole substation with one protection computer and without any analogue signals. According to the tests the indication algorithm was able to detect and locate faults up to 100 - 200 kΩ. Indication of the faulty phase and faulty feeder operated reliably in simulated tests and the accuracy of calculated fault resistances seemed to be adequate for the indication. These results are also a good indication of the benefits of centralized protection, not only for real life substations but also for research purposes.

REFERENCES

[1] Anon., European Standard EN 50522: Earthing of power installations exceeding 1 kV a.c. European Committee for Electrotechnical Standardization (CENELEC), November 2010, 66 p.

[2] Pakonen, P., Detection of Incipient Tree Faults on High Voltage Covered Conductor Lines. Tampere University of Technology, Publication 681, Doctoral thesis, Tampere 2007, 238 p.

[3] Nikander, A., Järventausta, P., Safety aspects and novel technical solutions for earth fault management in MV electricity distribution networks. Proceedings of Third IEE International Conference on Reliability of Transmission and Distribution Networks (RTDN 2005), London, UK, 15 – 17 February 2005, 5 p.

[4] Valtari, J. and Verho P., Requirements and Proposed Solutions for Future Smart Distribution Substations. Journal of Energy and Power Engineering (JEPE), 5(8):766–775, 2011.