EVALUATION OF DIFFERENT SOLUTIONS OF FAULTED PHASE EARTHING TECHNIQUE FOR AN EARTH FAULT CURRENT LIMITATION

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ABSTRACT

The paper is focused on evaluation of different types of prototypes of automatics for additional faulted phase earthing (FPE), which are used for earth fault current reduction in resonant earthed distribution network. Three prototypes of these automatics have been installed in Czech distribution network, the first one utilizes direct connection of faulty phase to earthing system of supply substation, the second one utilizes connection through resistor and the last one through reactor.

The contribution is mainly focused on detail analysis of operational differences of these types of FPE systems base on case study of compensated distribution network. The main aim is to specify and describe benefits and disadvantages of individual FPE applications. The results could be used for evaluation of best solution of FPE application which could be chosen for an earth fault current reduction in compensated distribution network.

INTRODUCTION

The continual growth of consumption, especially in urban areas with increasing numbers of technological centres, leads to the expansion of cable distribution networks and therefore to increasing of earth fault current levels in such networks. One of the possibilities how to reduce the level of the residual earth fault current in compensated networks is utilization of an automatic system for the faulted phase earthing (FPE). The faulted phase earthing method involves creating of conductive path for the residual current of the earth fault (EF) directly to the earthing system of a HV/MV substation Fig. 1. The detailed description of the method can be found in [1-8]. There is no doubt that the method yields positive results in case of resistive earth faults that represent a vast majority of all earth faults in MV distribution networks. With the view to find best solution of the FPE application, which could be applied to national DSO's standard, three prototypes of FPE automatics have been installed under pilot project to different distribution MV networks. These automatics are designed to earth faulted phase to the earthing system directly, through resistor or reactor, base on its type. Individual types of FPE are differed in shunt impedance (Z_{SH}), which is connected between faulty phase and earthing system of supply substation as is shown in Fig. 1. Type 1 (**T 1**) presents design of FPE, where faulty phase is directly (Z_{SH} = 0 Ω) connected to earth by single pole circuit breaker (No 3. - Fig. 1), Type 2 (**T 2**) is label of resistor earth FPE automatic (R_{SH} = 10 Ω) and labels Type 3 (**T 3**) or Type 4 (**T 4**) are used for FPE automatics utilizing shunt reactor with value X_{SH} = 10 Ω and X_{SH} = 4 Ω respectively (value of reactance is optional from 4 Ω to 10 Ω). The presented case study of FPE applications will respect only difference between shunt impedances of individual types of FPE (T 1 - 4).

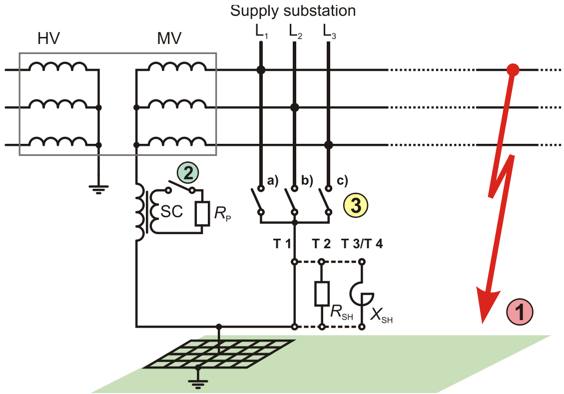

Fig. 1: Considered FPE application design (Type 1 - 4), 1) earth fault, 2) auxiliary resistor of arc-suppression coil, 3) FPE automatic

Factors influencing FPE method

For the purpose of proposing an optimal test network configuration and case study parameters, the basic factors which can influence characteristics of individual types of FPE are discussed below. All these factors will be respected and evaluated in the case study for each type of FPE application.

a) Earth fault current reduction (fundamental component)

The crucial factor affecting the affectivity of an earth fault current reduction by FPE is ratio of fault circuit impedance and shunt loop impedance (impedance between faulty phase and earth). Just the ratio of these impedances has significant impact to ability of FPE to reduce an earth fault current as it is described in [3][8].

Earth fault loop impedance - this impedance is given by positive and zero sequence impedance of the line to fault, fault resistance and partly by soil resistivity (earth resistance).

Shunt loop impedance - is given mainly by shunt impedance of FPE (Z_{SH}) and earthing system impedance of supply substation.

In order to evaluate FPE applications, the case study has to contain sensitivity analyses of parameters, which can affect the impedance ratio and have high variability of its value, as line impedance to fault and fault resistance are.

b) Reduction of higher harmonic component of an earth fault current

In case that conventional arc-suppression coils are used, which are tuned into resonance with the network capacity on system frequency (50 Hz), the earth fault current is predominately composed of harmonic components. These components are injected to the earth fault from nonlinear loads and it is not compensated by the arc-suppression coil. As it is mentioned in [3], the RMS value of earth fault current is mainly given by 3rd, 5th and 7th harmonic component especially in urban or sub-urban distribution network. For this reason, the possibilities of reducing these harmonics by given types of FPE have to be necessary analyzed in case study.

c) Load transmission through earth fault point

The next problem related with FPE principle is transfer of a load current of faulty feeder through earth and fault point. It can cause significant increase of an earth fault current and thus deterioration of touch or step voltage levels around faulted area. This phenomenon can occur only during low-impedance earth fault at heavily loaded areas of distribution network, the issue is in detail discussed in the contributions [3] [8].

d) Overvoltage in healthy phases after application of FPE

Other discussed issue is overvoltage occurrence in healthy phases after application of FPE method. Where due to additional low-impedance earthing of faulty phase, the phase voltage of healthy phases is increased up to L-L operation voltage at least regardless of value of an earth fault resistance. High level of the overvoltage could then cause insulation breakdown of healthy line leading to ignition of the second earth fault i.e. ignition of short-circuit and interruption of power supply. Since this overvoltage is significantly influenced by the used shunt impedance of FPE, the evaluation of overvoltage level is also included to the study.

e) Earth fault current level during cross-country earth fault

Regarding to safety against electric shock, a cross-country earth fault (double earth fault) is the most hazardous state, it is state when earth fault current reaches highest values in compensated network. This fault current increases earth potential rise (EPR) not only in the area of second earth fault, but also in the area of supply substation earthing system. Therefore, assessment of the level of the earth fault current during the cross-country earth fault is also subject of the case study.

f) Overvoltage during cross-country earth fault

High overvoltage can also arise during cross-country EF ignition as well as it was described in section d) for single earth fault (EF). This overvoltage can damage insulation of distribution network component what could affect continuity of power supply in the future. Because of this, overvoltage strongly depends on R, L and C conditions during fault ignition, the case study is also focused on evaluation of overvoltage for individual types of FPE, the respecting variation of fault distance, capacitive current, faulty phase, moment of the fault ignition etc.

CASE STUDY

The testing network showed in Fig. 2 was designed to be able evaluate all factors mentioned in sections a) - f) for individual applications of FPE separately. The testing network simulates mixed compensated network 22 kV, which is supplied from 110 kV network over three winding supply transformer YnYD with the power 63 MVA and u_k=16,5 %. Contribution of symmetrical short-circuit current from HV network is 16 kA. MV distribution network consists of two healthy feeders - overhead line AlFe110/22 and cable line AXEKVCEY120. The cable line varies its length base on its operation variants (V1- V6) listed in Table 1.

Table 1: Parameters of the network for operation variants V1-6

Operation variants	Capacitive current	Residual current (I_w)
V1	6,1 A	4,3 A
V2	65 A	4,6 A
V3	212 A	8,2 A
V4	357 A	12,8 A
V5	494 A	18,5 A
V6	723 A	50 A

The third (faulty) feeder is overhead line 70AlFe6 with length 40 km, this feeder is used for simulation of earth fault with variations of fault distance 0, 10, 20, 30 and 40 km (P1-P5). For the case study, four basic values of earth fault resistance R_f are respected 10 Ω, 300 Ω, 600 Ω a 1200 Ω. To evaluate of all aspects of the study, not only ideally compensated state is respected, but also under compensated (compensation current is 20 % lower than the capacitive current of the network) and over compensated state (+20 %).

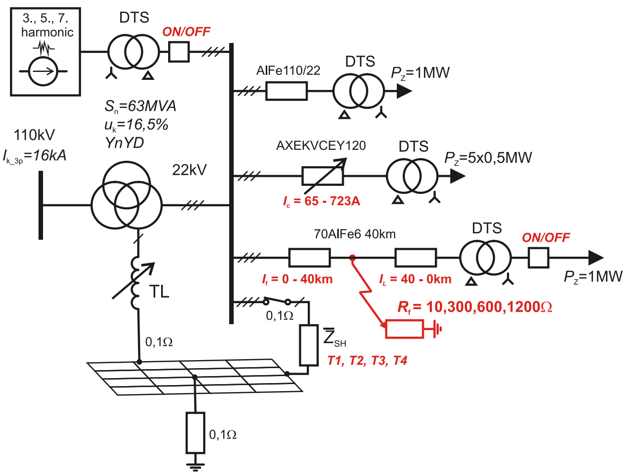

Fig. 2: Simplify scheme of the testing distribution network

Analyse of earth fault current reduction by FPE

The difference in the effectiveness of different types of FPE automatics can be evaluated based on Fig. 3. The figure presents relative value of an earth fault current after application of individual types of FPE during 10 Ω earth fault in ideally compensated distribution network. This relative value I_f indicates percentage value of an earth fault current which is flowing through fault point after application of FPE. In terms of earth fault current reduction by each type of FPE, the type 1 is the best solution because of lowest value of shunt impedance $\overline{Z}_{SH}$. The relative value of an earth fault current reaches value 0-30 % in this case. On the other hand, the type 3 is the least effective, the relative value of an earth fault current is reaching 90 % in this case.

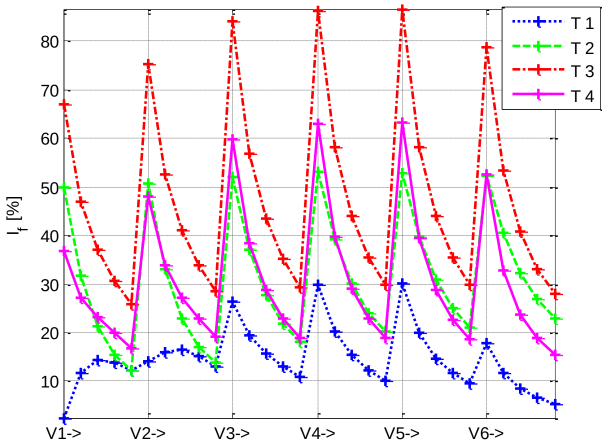

Fig. 3: Relative value of earth fault current after FPE - compensated state R_f=10 Ω (X axe shows each operational variant V1-6 changing location of the fault from the beginning to the end of the faulty feeder)

Table 2 is depicted to compare individual types of FPE base on its ability to reduce EF current. The table summarizes average, maximum and minimum relative values of earth fault current during all testing states in ideally compensated network categorized based on earth fault resistance 10, 300, 600 a 1200 **Ω**.

Table 2: Relative earth fault current after application of FPE in ideally compensated network

R_f	Percentage value of earth fault current after application EPF											
	Type 1			Type 2			Type 3			Type 4		
	min	*max*	*Avg.*	*min*	*max*	*Avg.*	*min*	*max*	*Avg.*	*min*	*max*	*Avg.*
10Ω	2,5%	30%	15%	12,2%	53%	31%	25,9%	87%	48%	15,6%	63%	31%
300Ω	0,9%	3%	2%	1,1%	6%	3%	3,7%	8%	6%	1,7%	4%	3%
600Ω	0,9%	2%	1%	0,3%	5%	2%	2,2%	6%	4%	1,3%	3%	2%
1200Ω	0,8%	2%	1%	0,1%	4%	1%	1,6%	5%	3%	1,2%	3%	2%

Impact of load transmittion on earth fault current level

As it was expected, the rising of fault resistance leads to increase of FPE effectivity (reduces the level of the load transmitted through the earthing system), similarly increasing distance of the EF from the loaded distribution transformer reduces the level of the load transmitted through the earthing system as it can be seen in Fig. 4. In terms of comparison of the impact of each solution of FPE on load transmission, the shunt impedance of FPE plays key role. Therefore lowest effectivity of EF reduction is reached by Type 1 (direct FPE), next is Type 4 ($|\overline{Z}_{SH}| = 4\Omega$). Then solution Type 2 and Type 3 are comparable when impact of load is respected, absolute value of the shunt impedance is for these types equal ($|\overline{Z}_{SH}| = 10\Omega$).

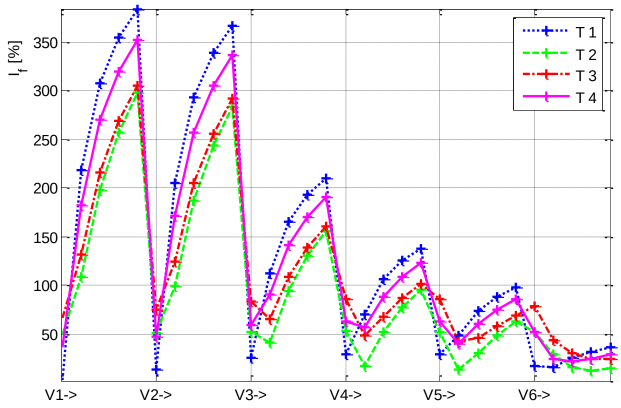

Fig. 4: Relative earth fault current after FPE application respecting impact of load - ideally compensated network, R_f=10Ω

Table 3 is depicted to compare individual types of FPE base on its ability to reduce EF current when impact of load transmission is respected. The table summarizes average, maximum and minimum relative value of earth fault current during all testing states in ideally compensated network categorized base on earth fault resistance 10, 300, 600 a 1200 **Ω**.

Table 3: Relative earth fault current after FPE application respecting impact of load - ideally compensated network

R_f	Percentage value of earth fault current after application EPF											
	Type 1			Type 1			Type 1			Type 1		
	min	*max*	*Avg.*	*min*	*max*	*Avg.*	*min*	*max*	*Avg.*	*min*	*max*	*Avg.*
10Ω	2,5%	384%	138%	13,0%	298%	96%	24,3%	306%	113%	22,0%	352%	128%
300Ω	0,9%	51%	15%	1,3%	47%	13%	3,7%	49%	15%	1,7%	50%	15%
600Ω	0,9%	29%	9%	0,8%	27%	8%	2,2%	28%	9%	1,3%	29%	9%
1,2kΩ	0,8%	18%	6%	0,1%	17%	5%	1,6%	17%	6%	1,2%	18%	6%

Overvoltage analysis

This analysis shows, that states when FPE is applied during high impedance EF (300, 600 and 1200 Ω) in cases of network with high capacitive current I_c > 300 A (V4, V5 and V6) are most problematic from hazardous overvoltage occurrence point of view. Especially Type 3 and Type 4 reach the highest values of overvoltage after FPE of high impedance EF, where overvoltage of healthy phase exceeding 25 kV. The maximum RMS value of overvoltage is 28,8 kV when Type 3 is used and 26 kV for Type 4. This overvoltage is caused by oscillation of neutral voltage due to energization of shunt inductance of the FPE automatic (X_{sh}). As this inductance and also current flowing through this inductance (I_{sh}) will be higher, as high value of overvoltage is possible achieve.

Regarding the solution Type 1, the level of self overvoltage is mainly caused by discharge current given by faulty phase, the duration of this overvoltage is very short (about a quarter of a period) and it is usually suppressed in real systems. The recorded values of neutral voltage and healthy phase L3 voltage are shown for all modeled cases in Fig. 5 and Fig. 6.

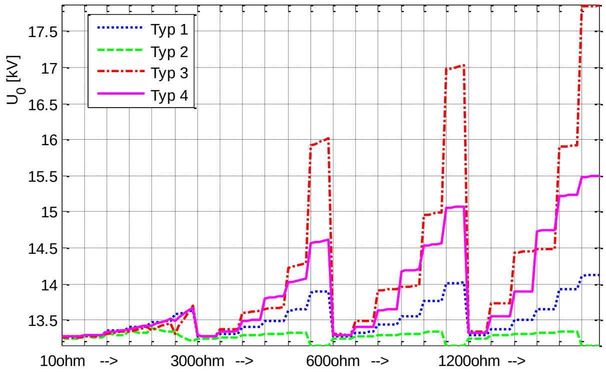

Fig. 5: Maximal RMS value of neutral voltage for all simulated cases - ideally compensated network

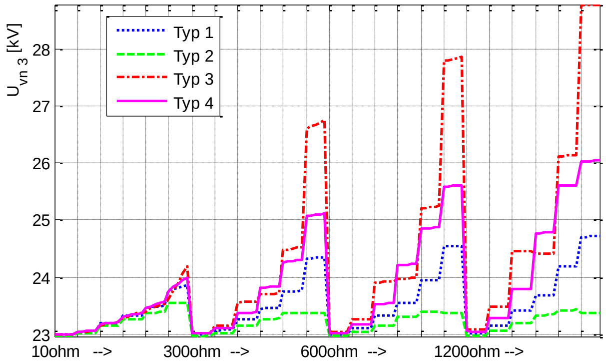

Fig. 6: Maximal RMS value of phase L3 voltage for all simulated cases - ideally compensated network

Waveforms of instantaneous value of recorded phase voltages for case of FPE through reactor 10 Ω (Type 3) is presented in Fig. 7. There can be seen extreme overvoltage exceeding value 40 kV (> 210 % of nominal voltage). The overvoltage duration is approximately a period and it is caused by neutral voltage oscillation (U_0), as it can be seen in Fig. 7. Value of the neutral voltage is close to 19 kV, what is 140 % of nominal voltage of the network. The application of FPE based on Type 3 (partly Type 4) is not suitable from high overvoltage point of view.

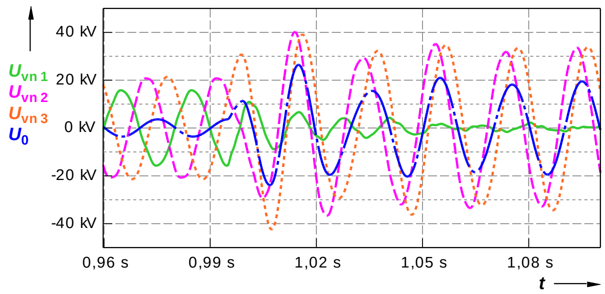

Fig. 7: Instantaneous value of recorded voltages for FPE by Type 3 fault resistance is 1200 Ω

COMPLEX EVALUATION OF RESPECTED TYPES OF FPE

It follows that any solution of FPE automatic has its advantages and disadvantages with respect to characteristics of an earth fault and distribution network configuration. Comprehensive comparison of respected types of FPE applications in terms of the case study is possible on the basis of Table 4, which shows the percentage values of the suitability of each type of FPE. For this comparison, the value of 100 % is used for most appropriate solution of FPE and the remaining are proportionally lowered with respect to their ability (efficiency) to reduce an earth fault current and overvoltage.

Table 4: Mutual comparison of respected types of FPE

Type FPE	Earth fault current reduction						Load impact	All impacts respected	Over-voltage
	Fundamental comp.			Harmonic comp.					
	comp.	under.	over.	3rd	5th	7th			
T 1	100%	100%	100%	100%	100%	100%	70%	75%	92%
T 2	48%	15%	13%	12%	8%	16%	**100%**	**100%**	**100%**
T 3	31%	12%	10%	6%	4%	6%	85%	77%	79%
T 4	48%	23%	20%	6%	6%	5%	75%	68%	87%

Evaluation of FPE authomatics during cross-country earth faults

Lowest value of an earth fault current during cross-country fault can be achieve with application of FPE Type 2 eventually Type 3. In case that FPE with shunt impedance 10 Ω (Type 2) is used, the earth fault current of cross-country fault is limited up to 1140 A and 1340 A in case of Type 3 (reactor 10 Ω), respectively. The least suitable solution of FPE automatics is a direct earthing of faulted phase (Type 1), where the level of an earth fault current during the cross-country EF with resistance of 10 Ω is approximately two times higher (2190 A). Similarly, with regard to highest value of overvoltage, the best solution is also Type 2 (R_{sh}=10 Ω) and the worst one FPE with reactors (Type 3 and Type 4). Maximal recorded values of overvoltage for individual types of FPE application are listed in Table 5.

Table 5: Maximal value of recorded voltage during cross-country EF with fault resistance 10Ω

Voltage [kV]	**Phase to earth voltage level in supply substation**							
	Type 1		**Type 2**		**Type 3**		**Type 4**	
	EF in L2	*EF in L3*	*EF in L2*	*EF in L3*	*EF in L2*	*EF in L3*	*EF in L2*	*EF in L3*
U_0	14,1	13,6	13,1	13,4	15,3	13,5	15,5	13,6
U_{L1}	0,7	0,6	11,9	11,8	14	14,1	8,3	8,3
U_{L2}	23,4	23,7	23	24,3	23,1	24,7	23,3	24,2
U_{L3}	26	23,7	23,3	23,4	29,1	23,9	29	23,8

Presented overvoltage was prepared for cross-country EF with fault resistance 10 Ω, where phase L2 was additionally earthed and phase L3 was affected by second EF. Complex comparison of respected types of FPE applications in terms of the cross-country earth faults is possible on the basis of Table 6, which shows the percentage value of the suitability of each type of FPE. For this comparison, the value of 100 % is used for most appropriate solution of FPE and the remaining are proportionally lowered with respect to their ability (efficiency) to reduce an earth fault current and overvoltage during cross-country EF.

Table 6: Mutual comparison of respected types of FPE during cross-country EF

Type of FPE	Average value of overvoltage	Overvoltage in faulty phases and neutral voltage			Evaluation base on earth fault current
		U_0	U_{L2}	U_{L3}	
T 1	95 %	95 %	100 %	90 %	52 %
T 2	99 %	100 %	98 %	100 %	100 %
T 3	88 %	88 %	95 %	80 %	85 %
T 4	88 %	86 %	98 %	81 %	62 %

CONCLUSION

The results show that any solution of FPE automatic has its advantages and disadvantages with respect to characteristics of an earth fault and distribution network configuration (capacitive current, harmonics, load, neutral point connection etc.). With respect of the case study conditions, the most suitable type of FPE application for compensated distribution network is earthing of faulted phase through 10 Ω resistor. This type of FPE automatic achieves the best results while respecting all the key influences (impact of loads, harmonics, overvoltage, fault current levels) not only during the earthing of faulted phase but also during the upcoming cross-country faults (double-earth faults).

Acknowledgments

This research work has been carried out in the Centre for Research and Utilization of Renewable Energy (CVVOZE). Authors gratefully acknowledge financial support from the Ministry of Education, Youth and Sports of the Czech Republic under NPU I programme (project No. LO1210).

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