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Evaluation of the correctness of operation of adaptive under-impedance criterion for HV single and double-circuit overhead power line with increased capacity

***Abstract**. The paper presents the idea of the developed adaptive algorithm of under-impedance criterion which improves the efficiency of operation of distance protection for HV overhead lines with increased capacity. The paper also presents results of the effectiveness of the developed algorithm for an HV single and double-circuit overhead line during resistive and non-resistive faults.*

Streszczenie.** W publikacji przedstawiono ideę działania opracowanego algorytmu adaptacyjnego kryterium podimpedancyjnego poprawiającego działanie zabezpieczeń w liniach o obciążalnościach znacznie przekraczających klasycznie określaną obciążalność dopuszczalną oraz wyniki skuteczności działania algorytmu dla ochrony linii w przypadku wystąpienia zwarć w liniach jednotorowych i dwutorowych. **Algorytmu adaptacyjny kryterium podimpedancyjnego poprawiającego działanie zabezpieczeń w liniach o obciążalnościach znacznie przekraczających klasycznie określaną obciążalność dopuszczalną

Keywords: power system protection, distance protection, adaptive protection, power line increased capacity.
Słowa kluczowe: zabezpieczenia elektroenergetyczne, zabezpieczenia odległościowe, zabezpieczenia adaptacyjne, intensyfikacja zdolności przesyłowych linii.

Introduction

Distance protection using under-impedance criterion is the most common HV line protection against consequences of short circuits in Polish Power Grid. The need to modify the distance protection zones which ensure the separation of impedance areas: permissible work and tripping is one of the disadvantageous effects connected with increased capacity of a power line. Limitation of tripping areas will reduce the ability to detect a resistive fault. It is especially important in the final area of the zones where the detection of resistive faults is the smallest. The lack of such modification may cause the existence of the common part of the impedance areas: permissible load and tripping. The result of existing such an area may result in malfunction of the line power system protection – tripping in the case of using the increased capacity of the line. Therefore there is a need to search for new solutions which will reduce the negative effects of the intensification of the line capacity. Those solutions should ensure the high efficiency and correctness of operation of distance protection.

Up to now the standard parameterization process of distance protection has not taken into account seasonal changes of the line capacity. For the whole year, the minimum load impedance has been calculated for the line capacity specified for the winter season ($Idop\_z$). This contributes to the occurrence of a significant zone between the tripping and allowable load areas for the summer season. A similar phenomenon occurs in the line using a dynamic line rating (DLR) under unfavorable weather conditions (high insolation, low parallel wind speed). It has been proposed that for such situations this zone should be included in tripping zones, thus increasing the ability to detect resistive faults [1].

However, for line load greater than the permissible capacity for the winter season (ex. using DLR), the load area on the impedance plate is expanding towards lower impedance. This can cause a risk of partial overlapping of the areas: of allowable loads and tripping. In order to achieve both high ability of fault detection and large capacity, a solution based on the continuous wavelet transform CWT has been proposed. It is designed to detect a short circuit and distinguish it from the permissible operating conditions in the part of a power network area covered by the distance protection.

Short circuit detection criterion KDeSZ

An advantageous resolution in the frequency and time domains (high resolution in time domain for high frequencies, low resolution in time domain for low frequencies) is the reason for using CWT. It also enables wide selection of scale and shift factors (of the wavelet transforms), thanks to which an extensive analysis of results can be performed (lots of information in the transformed signal).

Based on the research of CWT of current signals for different: scales, operating states of line, the line length and wavelet functions, there was identified (among others) a wavelet function - Symlet 3-tap which have a relatively short impulse response, a good frequency resolution and small sideband amplitudes of the amplitude spectrum. This function was chosen to develop a short circuit detection criterion KDeSZ which must have a short response time (shorter than the estimation of impedance components). To work properly, the criterion KDeSZ requires a sampling frequency of current signals equal to 25 kHz. In addition, the analysis of CWT of phase currents showed that the same set of transform scales is not always representative for short circuit detection and recognizing. After additional analyzes, there were selected the scales 1-35 for the implementation of these tasks. The further analysis of the CWT, for different cases, allowed defining the thresholds of transform coefficients, allowing distinguishing between a short circuit and a load line (changes within the acceptable range). For the detection of short circuits the threshold value is 200, while for the detection of earth faults: 150. The comprehensive approach to the research enabled development of an algorithm for short circuit detection criterion KDeSZ, shown in Figure 1.

The maximum response time of the KDeSZ algorithm equals 8 ms due to the length of the wavelet function for the highest analyzed scale of the CWT transform, and the requirement to confirm the decision.

An exemplary operation of the KDeSZ module shown in Figure 2 for the phase to earth short circuit L1-E for R_F = 0,5Ω, occurring at 320 ms of simulation on the line L_{AB} of the load 193% I_{dop_z}. Figure 2c shows digital waveforms of the criterion signals. The criterion condition is met for the earth fault detection for phase L1.

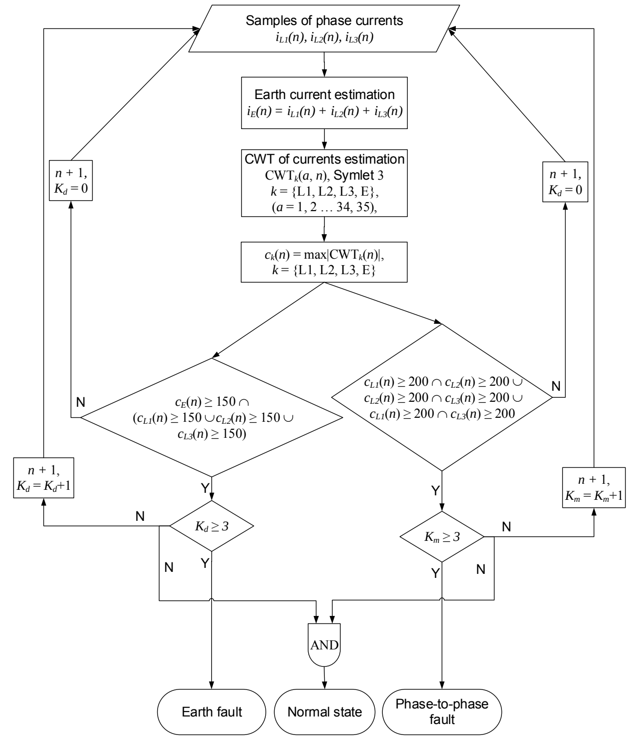

Fig.1. Flow chart of the developed criterion KDeSZ algorithm for short circuit detection, where: $c_k(n)$ - maximum of absolute value of CWT coefficients of phase and earth currents for all scales, K_d – coefficient of earth fault condition, K_m – coefficient of phase to phase fault condition,

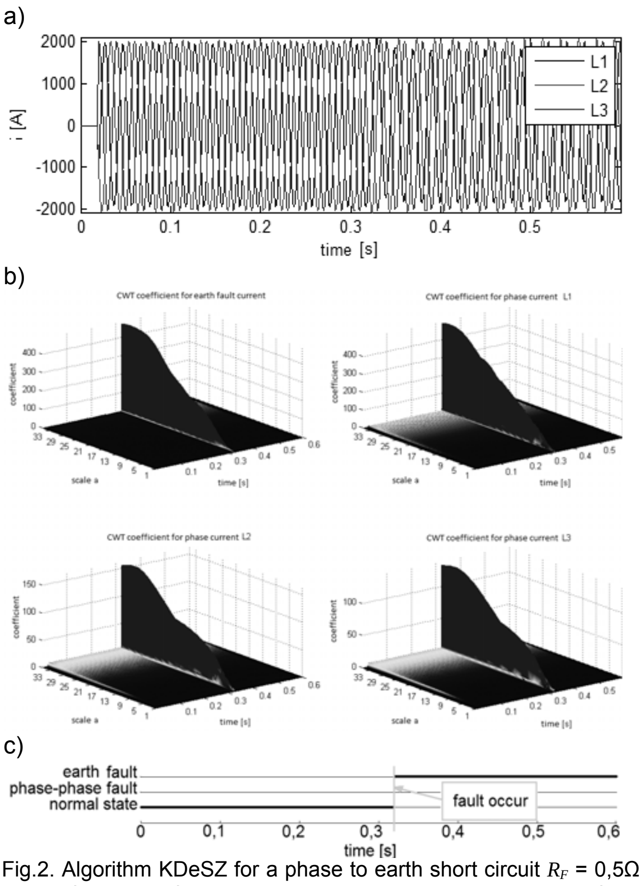

Fig.2. Algorithm KDeSZ for a phase to earth short circuit R_F = 0,5Ω on the final part of a high load line: a) instantaneous values of the phase currents, b) the estimated CWT for phase and earth fault currents, c) digital waveforms of KDeSZ algorithm decisions

Requirements for AKOL

The proposed modification of the under-impedance criterion for an overhead line with varying permissible capacity (0 ÷ $2I_{dop\_z}$) is designed to protect the line against consequences of short circuits while maintaining the possible highest efficiency and correctness of operation.

The algorithm of the adaptive criterion AKOL should primarily involve modifications in the decision-making unit, compared to classic solutions. Parametric adaptability of tripping zones should be dependent on the actual permissible load area and the actual line load.

The above-mentioned requirements for the AKOL determine a complex structure of operation and data exchange. The proposed algorithm of developed AKOL criterion can be divided into three interrelated levels (Figure 3):

- the level of measurement data acquisition,
- the level of estimation data (estimation algorithms),
- the level of decision algorithms.

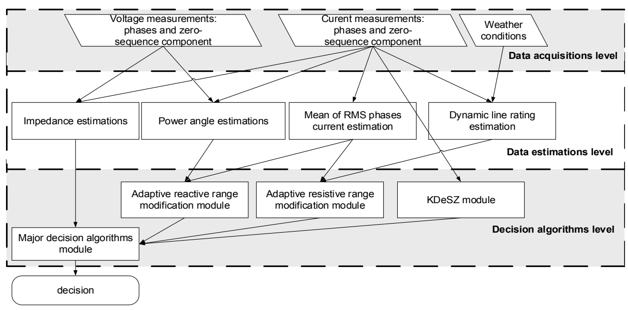

Fig.3. Structure of developed criterion AKOL: main components and directions of data exchange

One of the important tasks of the proposed solution AKOL is a distinction of the operating status of the line in the area of impedance common for the short circuit and permissible work exceeding the capacity for the winter. For this purpose the developed algorithm KDeSZ was use (module of decision algorithms level). This module is presented above.

A structure of the module of most decision algorithms module consists of:

- adaptive protection unit,
- basic protection unit,
- blockade of increasing load,
- time delays unit.

The main goal realized by the adaptive protection unit of AKOL is to verify the position of the ends of the impedance vectors on a complex impedance plane for each sample. The end of the vector location is compared with adaptively determined tripping zones. These zones are defined when rest of the decision modules taking into account. If the end of the impedance vector is in the common area of tripping and permissible load, module KDeSZ will be determine on the tripping.

The basic protection unit is next main decision algorithm module. This unit functions as the traditional under-impedance criterion. The operation of this unit depends as little as possible operation of additional modules. Parameterization of the unit is determined by the load area specified for the permissible maximum dynamic current ($2I_{dop\_z}$). In the case of failure of the components necessary for the proper operation of the adaptive protection unit, lack of communication with this unit or loads greater than permissible maximum dynamic current, the adaptive protection unit is blocked. The basic protection unit remains in operation.

Blocking of increased load is an important decision module of the proposed AKOL criterion. For situations of increasing the line load, in when the end of the impedance vector enters the common area of tripping zones and permissive load line area, and the KDeSZ module detects the normal state, it was assumed that the adaptive protection module should be blocked longer than the time of upgrading tripping zones (10 s). This blockade is deactivated, if the module KDeSZ detects a short circuit.

A detailed description of all the components of the developed criterion is presented in [2, 3, 4]. Example tripping zones of the AKOL criterion against the permissible load area are shown in Figure 4.

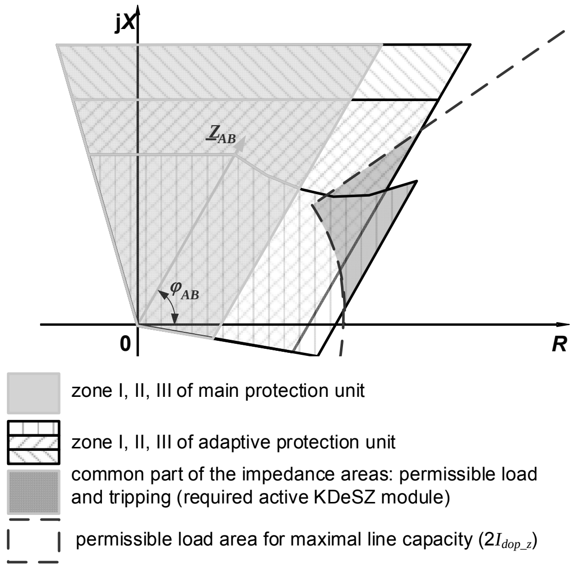

Fig.4. Example tripping zones of the AKOL criterion

Simulation studies

To verify the correctness of operation and to compare the effectiveness of short circuit detection and elimination by the developed criterion AKOL and the classic solution of digital distance protection, there were created simulation models of both types of protection algorithms in Matlab. The study was performed based on current and voltage signals from the line L_{AB} (Figure 5). The test system was modeled in Netomac.

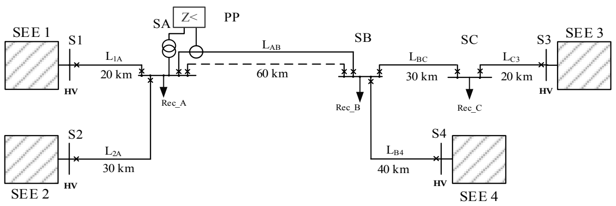

Fig.5. Structure of the test system with a single or double-circuit HV line L_{AB}

The presented above adaptive algorithm was developed for a single-circuit line. However some high voltage lines in the Polish grid are double-circuit. They are usually carried on one tower, which causes magnetic coupling between tracks. This may cause a malfunction of the classic distance protection and the developed solution. Moreover, in the case of double-circuit line operation with the ends working on common buses the short circuit currents are different depending on the operating status of each circuit. This also affects the correctness of impedance estimation and thus the correctness of distance protection operation. For double-circuit lines the paper focuses on the lines working on common buses at both ends. In this case at normal states, lines are loaded approximately equally.

The simulations included resistive and non-resistive faults of phase to earth (1F), phase to phase (2F), three phase (3F) or two phase to earth (2FE) occurring at selected locations of the test system (on the protected line, other lines, busbars) for different initial conditions (different voltage angle of power systems, parameters of loads). Simulated transients were initiated in 320 ms of the simulation. The analyses took into account, besides the correctness of reaction (the decision to keep the line in operation or tripping), the time between the fault occurrence and tripping.

Based on the simulation studies for the test system there was assessed among others the correctness of operation of the developed adaptive criterion AKOL and the classic digital distance protection. Exemplary results of efficacy for both criteria are presented in Table 1 (for a single-circuit line) and Table 2 (for a double-circuit line).

Table 1. Number of different cases of short circuit detection for classic and AKOL criteria depending on the type and location of the fault on single-circuit overhead lines

Fault type	Criterion	Fault location, km						
		5	10	20	30	40	50	55
1F	classic	140	140	140	140	132	127	120
2F		140	140	140	140	140	124	120
3F		137	135	130	126	123	116	108
2FE		140	140	140	140	133	126	120
1F	AKOL	140	140	140	140	140	139	128
2F		140	140	140	140	132	124	122
3F		140	140	140	140	132	124	122
2FE		140	140	140	140	140	134	130
number of faults	classic	560	560	560	560	560	560	560
	AKOL	560	560	560	560	560	560	560
quantity of detected fault	classic	557	555	550	546	528	493	468
	AKOL	560	560	560	560	544	521	502
efficacy, %	**classic**	**99,5**	**99,1**	**98,2**	**97,5**	**94,3**	**88**	**83,6**
	AKOL	**100**	**100**	**100**	**100**	**97,1**	**93**	**89,6**

Table 2. Number of different cases of short circuit detection for classic and AKOL criteria depending on the type and location of the fault on double-circuit overhead lines

Fault type	Criterion	Fault location, km						
		5	10	20	30	40	50	55
1F	classic	140	140	140	138	126	121	111
2F		140	140	140	140	133	120	111
3F		140	140	131	126	120	108	99
2FE		140	140	140	140	133	123	116
1F	AKOL	140	140	140	140	139	132	128
2F		140	140	140	140	136	129	121
3F		140	140	140	140	129	126	115
2FE		140	140	140	140	140	136	123
number of faults	classic	560	560	560	560	560	560	560
	AKOL	560	560	560	560	560	560	560
quantity of detected fault	classic	560	560	551	544	512	472	437
	AKOL	560	560	560	560	544	523	487
efficacy, %	**classic**	**100**	**100**	**98,4**	**97,1**	**91,4**	**84,3**	**78**
	AKOL	**100**	**100**	**100**	**100**	**97,1**	**93,4**	**87**

Example of the reaction of both solutions are presented in Figure 6 for a phase to phase resistive fault (L1-L2) R_F = 20 Ω, occurring 320 ms since the beginning of simulation at 50 km of line L_{AB} for the line load at pre-fault state 440 A (less than the DLR). The classic distance protection will not trip line L_{AB} the ends of the impedance vector estimated during the short circuit will not be within the tripping area due to the small values of the resistive ranges of zones (Figure 6a). For the proposed solution AKOL the end of the estimated impedance vector during short circuit is in the tripping area so the line can be tripped. For this situation the end of the estimated impedance vector is also in KDeSZ module area (common part of tripping and permissible load areas for DLR) (Figure 6b). Since the module KDeSZ detected the phase to phase short circuit (Figure 6c), tripping the line L_{AB} was allowed (according to the AKOL algorithm). In addition, it should be emphasized that the elimination of the faulted line will be with the time of the first zone, which means practically instantly.

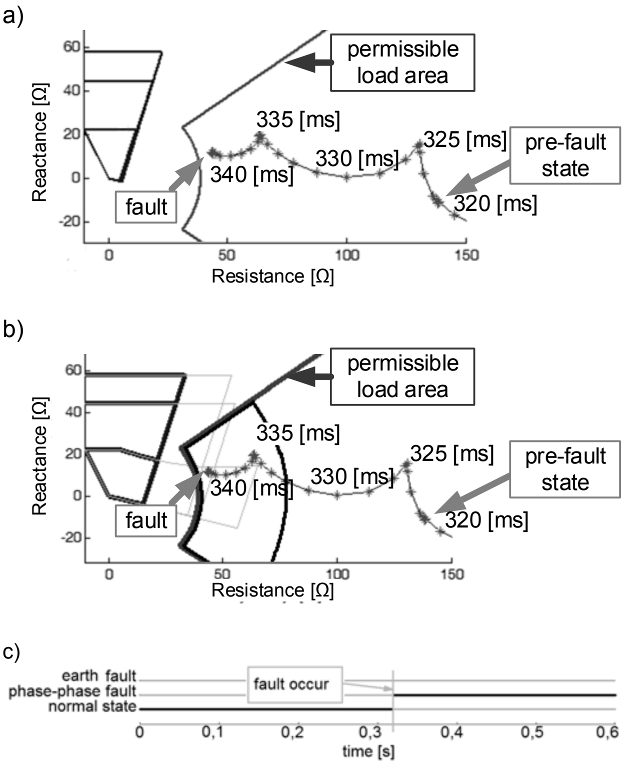

Fig.6. Estimated impedance trajectory on the impedance plate for phase to phase fault with load area and operating characteristics of distance protections for: a) classic solution, b) developed adaptive criterion AKOL, c) digital waveforms of KDeSZ algorithm decisions

Conclusions and observations

The increased capacity of an overhead HV line (by using the dynamic line rating) may cause a malfunction of the line power system protection especially distance protection. In the paper there has been described the developed criterion for detecting a short circuit condition KDeSZ. It uses a continuous wavelet transform of current signals. Achieving a high ability to detect resistive faults in the case of significant permissible capacity (larger than the standard capacity limit) is possible thanks to the use of the short circuit detection criterion KDeSZ.

Based on the research one can state that the developed algorithm of the line adaptive under-impedance criterion AKOL allows protecting lines with loads variable in a wide range, with greater correctness than the currently used classic solutions of distance protection, for single-circuit and double-circuit overhead lines (with the ends working on the same buses). With the increase of the fault resistance and fault location, advantageous properties of the developed solution become more apparent.

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