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Instantaneous and Time-Overangle Protection Against Three-Phase Faults on Radial Electrical Power Systems

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Abstract: This study presents, a theoretical approach to develop a digital protection method against 3-phase short circuits on radial electrical power systems that decreases the fault clearance time and thus, increases the stability of the system. The criterion used in this proposed, protection method is the inclination angle of the envelope of the short-circuit current. The concept of the current envelope has been introduced and its change during 3-phase faults has been analyzed. The inclination angle has been calculated and its use as a criterion for protection against 3-phase faults on radial electrical power systems has been discussed. The suggested protection method has been developed with the use of mathematical modelling of the radial electrical power system. The mathematical model has been represented as a system of differential equations for currents and a system of algebraic equations for bus voltages. This model has been formulated in a rectangular coordinate system and has been developed for both steady-state and transient analyses. The curves of the envelope of the short-circuit currents during the first 2 milliseconds after the fault instant and the time grading diagrams of the proposed protection method have been illustrated.

Key words: Digital protection, current envelope, inclination angle, mathematical model

INTRODUCTION

Protection of the transmission line, one of the main components of the radial electrical power system, has a central role in power system protection because transmission lines are vital elements of the network, which connects the generating plants to the load centers, also because of the long distances traversed by transmission lines over countryside. Transmission lines are subject to a majority of the faults occurring on the power system. The simplest protection system used at the lowest system voltages consists of fuses, which act as relays and circuit breakers combined. The protection system used for medium-voltage transmission lines is somewhat simpler than that used for high-voltage and extra-high-voltage transmission lines, which provide the major bulk transmission facilities (Ranjbar and Cory, 1974; Horowitz *et al*., 1988).

Knowledge of the currents resulting from various types of faults is essential for the effective operation of the protection system. Faults on a power system resulting high currents must be removed in the minimum of time. If short circuits are allowed to persist on a power system for an extended period, many or all of the following undesirable effects are likely to occur (Weedy and Cory, 1999):

- Reduced stability margins.
- Damage of the equipment that is in the vicinity of the fault due to heavy currents or low voltages produced by short circuit.
- Explosions, which may occur in equipment containing insulating oil during a short circuit and which may cause fire resulting in a serious hazard to personnel and damage to other equipment.
- Disruptions in the entire power system service area by a succession of protective actions taken by different protection systems, an occurrence known as cascading.

Which one of these effects will predominate in a given case depends upon the nature and operating conditions of the power system. With the advent of microprocessors and the integrated circuits, numerical protection devices are now the norm. The analogue quantities can be sampled and converted to digital form for numerical manipulation, by which the fault clearance can fast be obtained (Peck *et al*., 1989).

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Digital computers, initially used in electrical power systems for off-line calculations soon found their way into load dispatching centers and on-line applications (Koch, 1989). The appearance of microprocessors enabled ever simpler tasks to be performed at distributed locations and their use for protection and control, in electrical power systems, was logically the next step. Thus, memory and computing capacity is now available, which enabled the processing of additional parameters and also new parameters that could not be processed previously. Nowadays, digital techniques are widely used in protection engineering. Digital fault location techniques for transmission systems when digital fault recorded data are available at one terminal or two terminals is presented by Girgis and Fallon (1992). Digital protection method for power transformers based on an equivalent circuit composed of inverse inductance is developed by Inagaki *et al.* (1988). Digital differential protection of power transformers is discussed by Hamedani *et al.* (2004). And a formal software requirements specification method for digital nuclear plant protection systems is developed by Junbeom *et al.* (2005).

In this study, the focus is on simulation and performance-analysis of the 3-phase short-circuits at different locations on the radial electrical power system in order to find out a new criterion for its protection with the objective of decreasing the fault clearance time and thus increasing the stability margins of the system.

RADIAL ELECTRICAL POWER SYSTEM PROTECTION

In the radial electrical power system shown in Fig. 1, the transformer, feeding bus one from a higher voltage supply point, supplies loads at buses 1-5 through 4 transmission lines. Time-overcurrent relays are used to protect the transmission lines of this system by providing primary protection for the line as well as the remote back-up for the neighboring line. Relays at each of the 4 buses 1-4 are provided to protect their respective lines as primary protection relays and to provide remote backup protection to one line downstream from the relay location. Selectivity here is achieved by adding time delay to the controlling relays of circuit breakers. For providing time delay to the circuit breakers CB_1, CB_2, CB_3 and CB_4 the tripping is delayed in the following manner: CB_4-no added time delay; CB_3 - 0.4 s added time delay; CB_2 - 0.8 s added time delay; CB_1 - 1.2 s added time delay. A step time delay generally between 0.3 and 0.4 s is necessary to account for the time of operation of circuit breaker and its relay operation times.

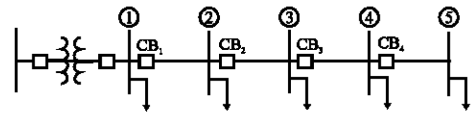

Fig. 1: One-line diagram of a radial electrical power system

The disadvantage of the time grading principle is that the faults near the source, which have a higher fault level than faults on sections further down the line are tripped after the longest delay. The destructive potential of a fault close to the source is thus several times greater.

The time-overcurrent protection using relays with an inverse characteristic approximately does not suffer from this drawback, because their time delay reduces as the fault current increases. The practice in this respect is somewhat divided, some countries preferring definite time-overcurrent relays to avoid the more complicated grading of the inverse characteristics of the various relays in a power system, while others have standardized on inverse definite minimum time relays. Today the grading of inverse definite minimum time relays is frequently performed by computer programs (Ungrad and Wiszniewski, 1995). Thus, the objective of this research is to develop a protection system that overcomes the disadvantages of the definite-time-overcurrent protection and the complexity of the inverse-time-overcurrent protection.

MODELLING OF THE STUDY ELECTRICAL RADIAL POWER SYSTEM

In this study, mathematical modelling is used as a tool to find out a new criterion that will be helpful to achieve the objective of this research. The radial electrical power system, which is to be modeled for 3-phase short-circuit current calculations is shown in Fig. 1. The high-voltage bus is assumed to be an infinite bus. The single-phase equivalent circuit is shown in Fig. 2.

To decrease the number of differential equations by one 3rd, the mathematical model is represented in a rectangular system of coordinates (x, y) (Al-Jufout, 2005). The differential equations in x axis are as follows:

$$\frac{di_{SX}}{dt} = \frac{\nu_{SX} - \nu_{1x}}{L_T} - \frac{R_T}{L_T} i_{SX} \quad (1)$$

$$\frac{di_{jkx}}{dt} = \frac{\nu_{jx} - \nu_{kx}}{L_{jk}} - \frac{R_{jk}}{L_{jk}} i_{jkx} \quad (2)$$

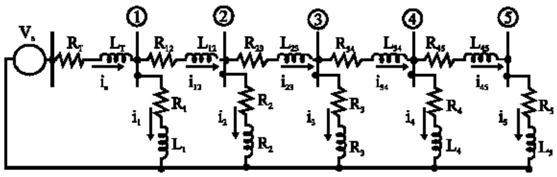

Fig. 2: Single-phase equivalent circuit of the study radial electrical power system

$$\frac{di_{lx}}{dt} = \frac{\nu_{lx}}{L_1} - \frac{R_1}{L_1} i_{lx} \quad (3)$$

where:

j = 1, 2,..., 4.

k = j + 1.

l = 1, 2, ..., 5.

and similarly in y axis:

$$\frac{di_{sy}}{dt} = \frac{\nu_{sy} - \nu_{ly}}{L_T} - \frac{R_T}{L_T} i_{sy} \quad (4)$$

$$\frac{di_{jky}}{dt} = \frac{\nu_{jy} - \nu_{ky}}{L_{jk}} - \frac{R_{jk}}{L_{jk}} i_{jky} \quad (5)$$

$$\frac{di_{ly}}{dt} = \frac{\nu_{ly}}{L_1} - \frac{R_1}{L_1} i_{ly} \quad (6)$$

The voltages at the high-voltage bus in x and y coordinates can be calculated using the 3-phase values as follows:

$$\begin{bmatrix} \nu_{SX} \\ \nu_{sy} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(0) & \cos(-\frac{2\pi}{3}) & \cos(\frac{2\pi}{3}) \\ -\sin(0) & \sin(-\frac{2\pi}{3}) & \sin(\frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} \nu_a \\ \nu_b \\ \nu_c \end{bmatrix} \quad (7)$$

where:

$$\nu_a = V_{smax} \sin(\omega t) \quad (8)$$

$$\nu_b = V_{smax} \sin(\omega t - \frac{2\pi}{3}) \quad (9)$$

$$\nu_c = V_{smax} \sin(\omega t + \frac{2\pi}{3}) \quad (10)$$

The equations of the nodal voltages for each axis can be derived from Kirchhoff's law for the current derivatives (Alyyan *et al*., 2005) as: the algebraic sum of the current derivatives entering any node is zero:

$$\sum \frac{di_x}{dt} = 0 \quad (11)$$

$$\sum \frac{di_y}{dt} = 0 \quad (12)$$

These equations for nodal voltages determination can be represented in matrix form as follows:

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix}^{-1} \begin{bmatrix} I_x \\ I_y \end{bmatrix} \quad (13)$$

where:

$$V_x = \begin{bmatrix} \nu_{1x} \\ \nu_{2x} \\ \nu_{3x} \\ \nu_{4x} \\ \nu_{5x} \end{bmatrix} \quad (14)$$

$$V_y = \begin{bmatrix} \nu_{1y} \\ \nu_{2y} \\ \nu_{3y} \\ \nu_{4y} \\ \nu_{5y} \end{bmatrix} \quad (15)$$

$$I_x = \begin{bmatrix} a_1 i_{1x} + a_{13} i_{12x} - a_T i_{sx} + (1/L_T)\nu_{sx} \\ a_2 i_{2x} + a_{23} i_{23x} - a_{12} i_{12x} \\ a_3 i_{3x} + a_{34} i_{34x} - a_{23} i_{23x} \\ a_4 i_{4x} + a_{45} i_{45x} - a_{34} i_{34x} \\ a_5 i_{5x} - a_{45} i_{45x} \end{bmatrix} \quad (16)$$

$$I_y = \begin{bmatrix} a_1 i_{1y} + a_{13} i_{12y} - a_T i_{sy} + (1/L_T)\nu_{sy} \\ a_2 i_{2y} + a_{23} i_{23y} - a_{12} i_{12y} \\ a_3 i_{3y} + a_{34} i_{34y} - a_{23} i_{23y} \\ a_4 i_{4y} + a_{45} i_{45y} - a_{34} i_{34y} \\ a_5 i_{5y} - a_{45} i_{45y} \end{bmatrix} \quad (17)$$

$$L=\begin{bmatrix} \frac{1}{L_1}+\frac{1}{L_{12}}+\frac{1}{L_T} & -\frac{1}{L_{12}} & 0 & 0 & 0 \\ -\frac{1}{L_{12}} & \frac{1}{L_2}+\frac{1}{L_{12}}+\frac{1}{L_{23}} & -\frac{1}{L_{23}} & 0 & 0 \\ 0 & -\frac{1}{L_{23}} & \frac{1}{L_3}+\frac{1}{L_{23}}+\frac{1}{L_{34}} & -\frac{1}{L_{34}} & 0 \\ 0 & 0 & -\frac{1}{L_{34}} & \frac{1}{L_4}+\frac{1}{L_{34}}+\frac{1}{L_{45}} & -\frac{1}{L_{45}} \\ 0 & 0 & 0 & -\frac{1}{L_{45}} & \frac{1}{L_5}+\frac{1}{L_{45}} \end{bmatrix} \quad (18)$$

where, the damping coefficients are calculated as follows:

$$a_i=\frac{R_i}{L_i} \quad (19)$$

$$a_{ij}=\frac{R_{ij}}{L_{ij}} \quad (20)$$

where:

R_i	=	The load resistance connected to bus i.
R_{iJ}	=	The transmission line resistance connected between buses i and j.
L_i	=	The load inductance connected to bus i.
L_{iJ}	=	The transmission line inductance connected between buses i and j.
R_T, L_T	=	The resistance and leakage inductance of the power transformer, respectively.

SUGGESTED OVERANGLE PROTECTION METHOD

The developed-above algorithm can be used for both steady-state and transient analyses. The system of the differential equations can be solved using 4th-order Runge-Kutta method and the system of the algebraic equations can be solved using gauss method. The infinite bus phase voltages are given. The initial values of all the variables (currents) are equal to zero at the first step of solution.

Table 1 shows the parameters of the loads connected to buses 1-5 (Fig. 2). These parameters are indicated in both actual values and per unit (p.u.), where the base voltage is:

$$V_{base}=\frac{\sqrt{2}V_L}{\sqrt{3}}=16.329\text{ kV} \quad (21)$$

and the base current is:

$$I_{base}=\sqrt{2}\frac{S_{rated}}{\sqrt{3}V_L}=816.497\text{A} \quad (22)$$

The 3-phase transformer is assumed to be rated 20 MVA, 138/20 kV with leakage reactance of 10% and resistance of 2%. The infinite bus voltage is assumed to be equal to 1.125 p.u. The transmission line resistance and inductive reactance are assumed to be 0.1284 and 0.788 $\Omega\ mi^{-1}$, respectively.

Table 2 shows the transmission line parameters. Based on the above-described algorithm, the steady-state pre-fault conditions have been calculated and are shown in Table 3.

The steady-state and inrush values of the short-circuit current have been calculated and are shown in Table 4 in both actual values and per unit. When using approximate calculation methods, where the resistances and static loads are negligible, the short-circuit currents differ approximately by 1% (Al-Jufout, 2006).

Figure 3 shows the waveforms of the phase currents of the transmission line, which is connected between buses 1 and 2, when a 3-phase fault occurs on bus 2, where the pre-fault current value is equal to 0.629 p.u. and the steady-state fault current is equal to 4.88 p.u. The bold curve in Fig. 3 shows the current envelope, which is calculated as follows:

$$I_m=\sqrt{\frac{2}{3}\left(i_a^2+i_b^2+i_c^2\right)} \quad (23)$$

where, i_a, i_b, i_c are the instantaneous phase currents.

Figure 4 shows the current envelope flowing through the transmission line, which is connected between buses 1 and 2, when a 3-phase fault occurs on buses 2-5. The current envelope is shown during only the first 2 ms after the fault instant. It is clear from Fig. 4 that the inclination angle of the current envelope depends on the fault location.

Table 1: Loads parameters

	Bus to which load is connected				
Parameter	1	2	3	4	5
Power, MVA	2.000	4.000	4.000	2.000	3.000
Power factor	0.800	0.800	0.800	0.800	0.850
Line current, A	57.70	115.5	115.5	57.50	86.60
Resistance, Ω per phase	160.1	80.05	80.05	160.1	113.3
Inductive reactance, Ω per phase	120.1	60.05	60.05	120.1	70.20
Resistance, p.u.	8.005	4.003	4.003	8.005	5.665
Inductive reactance, p.u.	6.005	3.003	3.003	6.005	3.510

Table 2: Transmission line parameters

	Transmission line			
Parameter	1-2	2-3	3-4	4-5
Length, mi	3.000	3.000	3.500	2.600
Resistance, Ω	0.411	0.385	0.449	0.334
Inductive reactance, Ω	2.522	2.364	2.758	2.049
Resistance, p.u.	0.020	0.019	0.022	0.017
Inductive reactance, p.u.	0.126	0.118	0.138	0.102

Table 3: Pre-fault loads parameters

	Bus to which load is connected				
Parameter	1	2	3	4	5
Bus voltage, p.u.	1.065	1.005	0.968	0.945	0.936
Real power, p.u.	0.091	0.162	0.150	0.071	0.112
Reactive power, p.u.	0.068	0.121	0.112	0.054	0.069
Line current, p.u.	0.106	0.201	0.193	0.094	0.140
Power factor	0.800	0.800	0.800	0.800	0.850

Table 4: Three-phase fault currents

		Bus on which fault occurred			
Fault current		2	3	4	5
Inrush	p.u	7.491	4.849	3.399	2.769
	kA	6.116	3.959	2.775	2.261
Steady-state	p.u.	4.880	3.167	2.214	1.798
	kA	3.985	2.586	1.808	1.468

Figure 5 and 7 show the current envelopes of the other transmission lines in the study power system of Fig. 1.

Table 5 shows the inclination angles of different transmission lines currents, when 3-phase short-circuit occurs on different buses of the power system. This inclination angle is calculated by the following formula:

$$\varphi = \tan^{-1}\frac{\Delta I_m}{\Delta t} \tag{24}$$

It is suggested to use this inclination angle as a criterion for protection against 3-phase faults on radial electrical power systems.

Protection zones (instantaneous and time delayed) and their settings are shown in Table 6. Calculations show that all the current envelope changes caused by normal operating conditions occur with an inclination angle, which is <10°. The latter fact can be used in back-up protection in order to avoid under functioning. Each protection unit provides primary and multi-zone back-up protection.

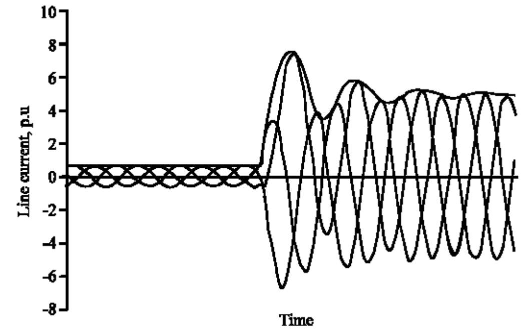

Fig. 3: Change of the transmission line (1-2) phase currents and the current envelope during fault on bus 2

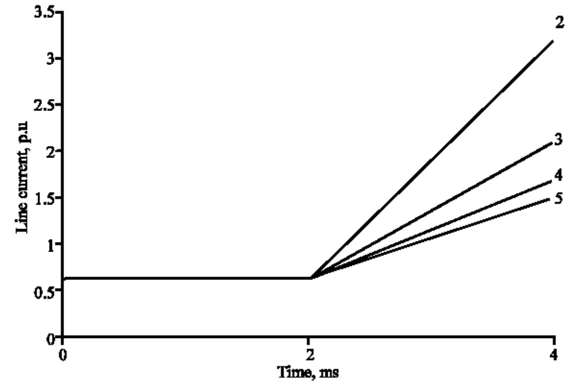

Fig. 4: Changes of the transmission line (1-2) current envelopes during faults on buses 2-5

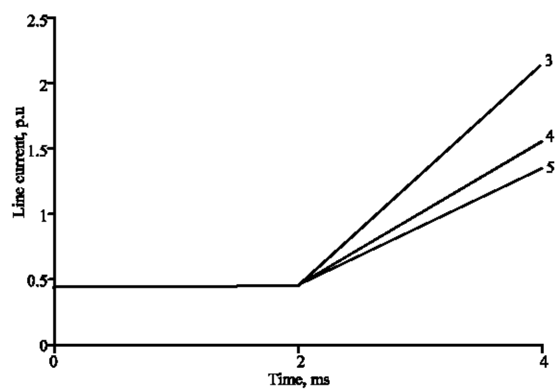

Fig. 5: Changes of the transmission line (2-3) current envelopes during faults on buses 3-5

The time grading diagram of the proposed instantaneous- and time-overangle protection is shown in Fig. 8.

Since, buses are assumed as zero-impedance power system elements and to discriminate between faults on the receiving end of the transmission line and faults on the sending end of the downstream transmission line as well

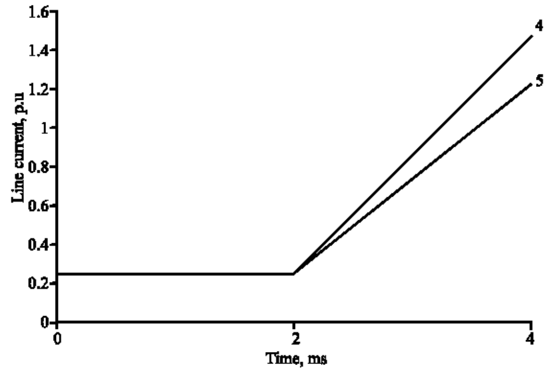

Fig. 6: Changes of the transmission line (3-4) current envelopes during faults on buses 4 and 5

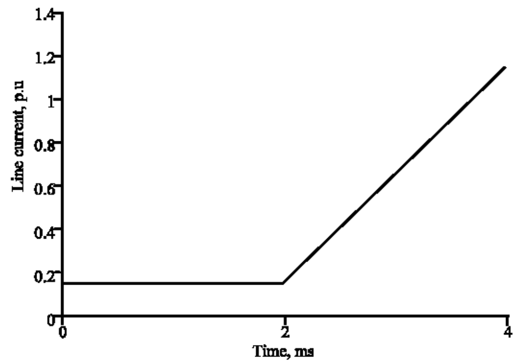

Fig. 7: Change of the envelope of the transmission line (4-5) current during 3-phase short circuit on bus 5

Table 5: Inclination angle of the transmission line current envelope

	Bus on which fault occurred			
Transmission line	2	3	4	5
1-2	51.936°	38.625°	28.502°	23.509°
2-3		39.693°	29.466°	24.371°
3-4			32.375°	25.641°
4-5				26.473°

Table 6: Instantaneous- and time-overangle protection settings

Circuit breaker	Zone	Setting	Time delay, s
CB_1	1	$\varphi_1 \geq 51.936°$	Instantaneous
	2	$51.936° > \varphi_1 \geq 38.625°$	(0.3-0.4)
	3	$38.625° > \varphi_1 \geq 28.502°$	2×(0.3-0.4)
	4	$28.502° > \varphi_1 \geq 23.509°$	3×(0.3-0.4)
	5	$23.509° > \varphi_1 > 10°$	4×(0.3-0.4)
CB_2	1	$\varphi_2 \geq 39.693°$	Instantaneous
	2	$39.693° > \varphi_2 \geq 29.466°$	(0.3-0.4)
	3	$29.466° > \varphi_2 \geq 24.371°$	2×(0.3-0.4)
	4	$24.371° > \varphi_2 > 10°$	3×(0.3-0.4)
CB_3	1	$\varphi_3 \geq 32.375°$	Instantaneous
	2	$32.375° > \varphi_3 \geq 25.641°$	(0.3-0.4)
	3	$25.641° > \varphi_3 > 10°$	2×(0.3-0.4)
CB_4	1	$\varphi_4 \geq 26.473°$	Instantaneous
	2	$26.473° > \varphi_4 > 10°$	(0.3-0.4)

as faults on the outgoing load feeders, the reach of each protection zone is decreased by 5%. Thus, the protection

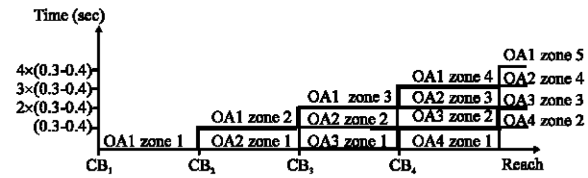

Fig. 8: Time grading diagram of the instantaneous- and time-overangle (OA) protection

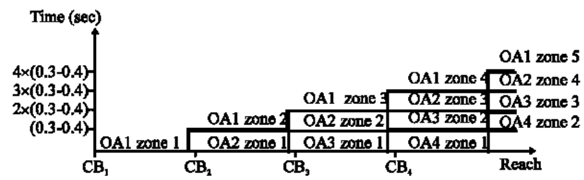

Fig. 9: Time grading diagram of the 95% instantaneous- and time-overangle protection

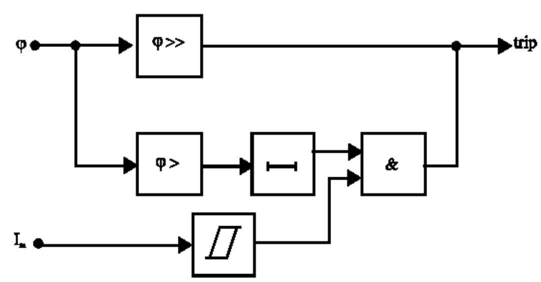

Fig. 10: Simplified block diagram of instantaneous- and time-overangle protection with one time-delayed zone

zones (instantaneous- and time delayed) and their settings become as shown in Table 7.

The time grading diagram of the 95% instantaneous- and time-overangle protection is shown in Fig. 9.

To avoid over functioning, particularly when a time-delayed zone operates, a condition of that the current envelope is greater than the current envelope of the maximum load must be obtained. This condition is represented in the block diagram of Fig. 10 and can be achieved by using a level detector with an and-gate. A tripping signal is issued when the corresponding criterion is fulfilled by one of the 2 channels. The first channel represents the instantaneous overangle protection, where the inclination angle is greater than the first zone setting. The second channel issues a tripping signal when the corresponding criteria are fulfilled by both sub-channels: the inclination angle should be within the setting range (Table 7) and the current envelope should be greater than the current envelope of the maximum load.

Table 7: The 95% instantaneous- and time-overangle protection settings

Circuit breaker	Zone	Setting	Time delay, s
CB_1	1	$\varphi_1 \geq 54.533°$	Instantaneous
	2	$54.533° > \varphi_1 \geq 40.556°$	(0.3-0.4)
	3	$40.556° > \varphi_1 \geq 29.927°$	2×(0.3-0.4)
	4	$29.927° > \varphi_1 \geq 24.685°$	3×(0.3-0.4)
	5	$24.685° > \varphi_1 > 10°$	4×(0.3-0.4)
CB_2	1	$\varphi_2 \geq 41.678°$	Instantaneous
	2	$41.678° > \varphi_2 \geq 30.939°$	(0.3-0.4)
	3	$30.939° > \varphi_2 \geq 25.590°$	2×(0.3-0.4)
	4	$25.590° > \varphi_2 > 10°$	3×(0.3-0.4)
CB_3	1	$\varphi_3 \geq 33.994°$	Instantaneous
	2	$33.994° > \varphi_3 \geq 26.923°$	(0.3-0.4)
	3	$26.923° > \varphi_3 > 10°$	2×(0.3-0.4)
CB_4	1	$\varphi_4 \geq 27.797°$	Instantaneous
	2	$27.797° > \varphi_4 > 10°$	(0.3-0.4)

Using the suggested instantaneous- and time-overangle protection overcomes the disadvantages of the definite-time-overcurrent protection and the complexity of the inverse-time-overcurrent protection. In addition, faults can be sensed within the first millisecond.

CONCLUSION

The concept of the current envelope is introduced and its formula, in terms of the instantaneous phase currents, is shown. The curves of the transmission line current envelope versus fault location are obtained and analyzed. Analysis shows that the inclination angle of the current envelope can be used as a criterion for radial electrical power system protection against 3-phase faults.

Based on the inclination angle an instantaneous- and definite-time overangle protection system is developed. Each protection includes main zone with instantaneous action and multi-time-delayed zones, which represent back-up protection for the downstream transmission lines. The developed protection overcomes the disadvantages of the long time-delay of the definite time-overcurrent protection and the complexity of the inverse-time-overcurrent protection of radial electrical power systems. In the developed protection system, discrimination between faults on the receiving end of the transmission line and faults on the sending end of the downstream transmission line, is achieved by the 95% instantaneous overangle protection. While the rest 5% of the transmission line length is protected by the definite-time-overangle protection with an added time delay of 0.3-0.4 s.

The suggested protection system is achieved with the use of mathematical modelling of a radial electrical power system, where the model is presented as a system of differential equations for currents and a system of algebraic equations for bus voltages. These equations are written in a rectangular coordinate system, thus their number is reduced by one third. This model allows analyzing both the symmetrical transient and steady-state conditions.

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