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Ensuring Relay Selectivity in Power Supply Systems using the Bayesian Method of Hypothesis Testing

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Abstract

The development of power supply systems, intelligent microgrid requires the improvement of electric grid relay protection. One of the promising principles of relay protection is Bayesian hypothesis testing. Multiparametric relay protection, created on the basis of the Bayes method, has more recognizability of grid regime than traditional relay protections. In the paper proposes method of reconciling settings of multiparametric relay protections among themselves, necessary to build an effective relay protections system of electric grid. The proposed method of calculation of settings can be used as the basis for automated procedures as an element of intelligent relay protection in power supply systems supporting the IEC 61850 standard.

An example of calculation one-dimensional overcurrent protections of electric grid section showed the effectiveness of the proposed method. The relay protection of the electric grid example is similar to the traditional overcurrent relay protection or better. Two-dimensional relay protection significantly improved the technical perfection of the relay protection of the same electric grid.

Keywords: electric power supply, relay protection, statistics, likelihood ratio test, setting, selectivity.

INTRODUCTION

In connection with the fact that traditional protection relay (PR) of power supply systems (overcurrent protection) possesses insufficient technical excellence, new multiparameter methods for their construction were developed [1-5], which in particular based on conditions recognition by the Bayesian criterion [6-8]. The simplest task for recognition of electric grid feeder bay is shown in Figure 1. Intellectual electronic device for protection (IED) estimates modes parameters continuously. IED classifies the controlled condition as normal operating condition (acceptable) or emergency condition by using current and voltage values as well as the preset decision rule.

By using the Bayesian method for hypothesis testing the rule for taking decision involves partitioning observation space Z for two parts: Z_0 and Z_1 (Figure 2). In case the observation R gets into Z_0 space, then hypothesis H_0 is taken for sure (the acceptable condition and feeder cutoff need not be applied), in case the observation R gets into Z_1 space, then hypothesis H_1 is taken (there is an emergency condition and the feeder is to be disconnected). The border, that divides Z for 2 parts Z_0 and Z_1 or the rule for obtaining the border will be considered as a trip setting.

Determination of setting values is carried out with the help of an objective function for minimization of decision-making risk – the classical Bayesian condition for hypothesis choice (tripping), that looks like the following way:

hypothesis H_1 is chosen, if $\Lambda(R) > \eta$,
hypothesis H_0 is chosen, if $\Lambda(R) \le \eta$,
where $\Lambda(R)$ – a likelihood ratio,

$\Lambda(R) = p_{H1}(R|H_1) / p_{H0}(R|H_0)$,
η – threshold (setting) of a criterion for likelihood ratio.

$$\eta = P_0\,(C_{10} - C_{00}) / (P_1\,(C_{01} - C_{11})) .$$

at a compulsory conditions adherence $C_{10} > C_{00}$ and $C_{01} > C_{11}$.
where $p_{H0}(R|H_0)$ – probability density function, that R observation corresponds to H_0 hypothesis, $p_{H1}(R|H_1)$ – probability density function, that R observation corresponds to H_1 hypothesis;

P_0 and P_1 are a priori probabilities of hypotheses correctness H_0 and H_1, accordingly, the probabilities of fault absence or inception (F) in the protected zone in each separate case of observation R; C_{00} – losses at the correct choice of hypothesis H_0 (feeder is not disconnected and its mode was allowable), C_{01} – losses in case of incorrect choice of hypothesis H_0 (feeder is not disconnected and its mode was emergency (F), C_{10} – losses in case of incorrect choice of hypothesis H_1 (feeder is disconnected and its mode was allowable), C_{11} – losses in case of incorrect choice of hypothesis H_1 (feeder is disconnected and its mode was emergency (F).

Values of losses in the Bayesian method of hypothesis testing are used for minimization of consequences of decisions taken by PR device. These consequences can be determined on judgement basis, approximately (the main constituents of consumers' losses due to a sudden power cut, energy companies' losses for emergency recovery work) or more precisely and detailed.

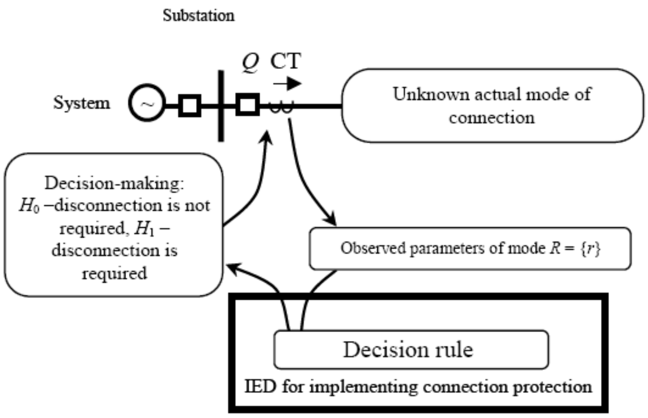

Figure 1: Elements of task for detecting of feeder bay mode

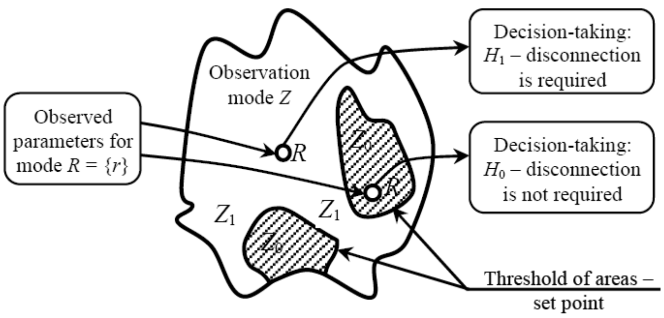

Figure 2: Split of decision areas– reception of decision making - up

For calculation of protection setting of a certain feeder bay the following steps are required:

- to determine functions $p_{H0}(R|H_0)$ and $p_{H1}(R|H_1)$, which means to store statistics for normal and emergency condition of this feeder bay. This is to be done either by observation of the existing feeder bay, or by calculation using the appropriate simulation model;
- to determine the a-priori possibilities P_0 and P_1;
- to determine the losses for all possible results of choice for this feeder bay: C_{00}, C_{01}, C_{10}, C_{11}.

In some cases, if the simplified approach to the Bayesian method is used, the calculation of losses and a-priori possibilities are not required.

In case all this information is known, the threshold value η is calculated and with the help of it the zone borders Z_0 and Z_1 are calculated. After that the decision-making will be based on a simple testing, whether Z observation happens in Z_1 zone or not. In case, it happens, then disconnection is required, in case it is not, then disconnection is not required. The protection relay (PR) trained on imitation model will be able to recognize the emergency condition of this feeder bay correctly with minimal risk of loss.

STATEMENT

The calculations [6-8] have shown that the obtained multiparameter PR, based on statistical principles, has potentially better technical excellence for conditions recognition in comparison with the traditional protection due to a more efficient usage of information, that is received from the measurement transformer of current and voltage. However, a number of different protection sets function simultaneously in electrical grid and till now no methods for coordination of multiparameter protection sets have been offered, which are necessary for development of a complete efficient system of electric grid protection relay. The methods have to:

- provide a reliable PR system, where the failure of separate devices and communication channels would lead to minimal loss of the PR system efficiency on the whole;
- consider any types of protection: traditional, multiparameter, fulfilled in centralized as well as in decentralized variants;
- provide the highest possible complete automation of processes for PR settings and configurations and be suitable for implementations in PR terminal servers of "Plug and Play" type [9-11].

Selectivity ensuring of multiparameter protection tripping

It is offered to ensure action selectivity and the further backup of multiparameter PR, that have back-up protection space, by solving a multiparameter task [12]. An example of electrical grid scheme with distributed PR is considered here (figure 3a), where each PR set "observes" the grid regime only in one point (at PR installation place) with the help of current measurement transformer (CT) and voltage transformer (VT): multiparameter protection PR1 by resistance measuring has got the main protected zone 1, PR2 has got the main protected zone 2, PR3 has got the main protected zone 3 etc.

In accordance with build-own-operate experience [13] it is preferable to provide each protected zone with distant backup: protection PR1 shall go off even in protected zone 2 in case failure occurs in PR2, as well as in protected zone 3, if failure occurs simultaneously in protected zones PR2 and PR3 etc.

For each protection hypotheses have to be deduced, which correspond to all possible protected zones, in which this protection has to recognize emergency conditions.

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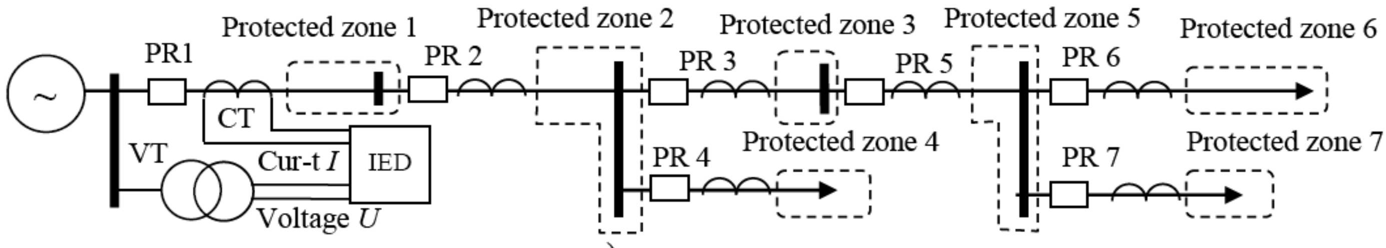
For example, for PR1 the following hypotheses have power:

H_0 – normal operating condition. Protection must not turn off the breaker (figure 3f);

H_1 – emergency condition in its main protected zone 1. Protection must turn off the breaker without any time-delay (figure 3b)

H_2 – emergency condition in its backup protected zone 2 (figure 3c). Protection must turn off the breaker with time delay Δt, that is equal to a traditional backup time stage for ensuring selectivity with the main protection of this zone PR2;

H_3 – emergency condition in its backup protected zone 3 or 4 (generally each zone must have its separate hypothesis, but in case protection has to go off in some areas with the same time period, the hypotheses can be united) – figure 3d. Protection must turn off the breaker with time delay $2\Delta t$, that is equal to double backup time stage, for ensuring selectivity with the main protection of this zonePR3 (or PR4) and with the closer backup protection of this zonePR2; etc. H_k – emergency condition in its backup protected zone of arbitrary power k proximity, where switching-off will be required with time delay $(k\text{-}1)\ \Delta t$.



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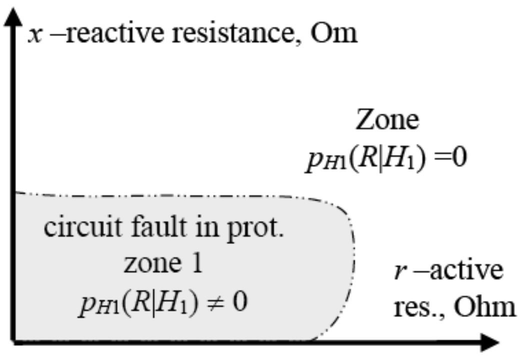

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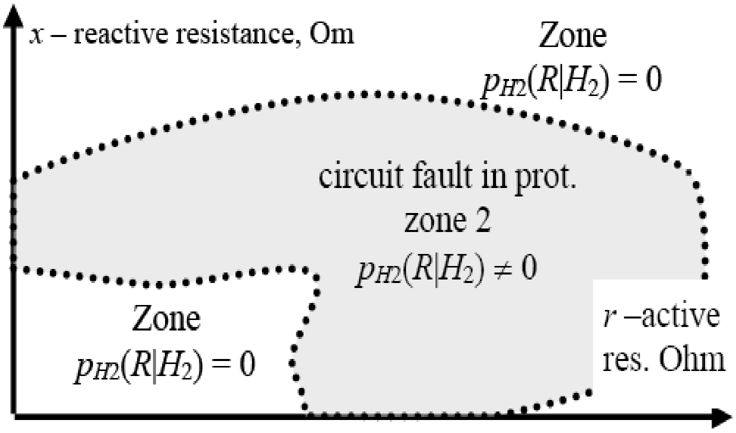

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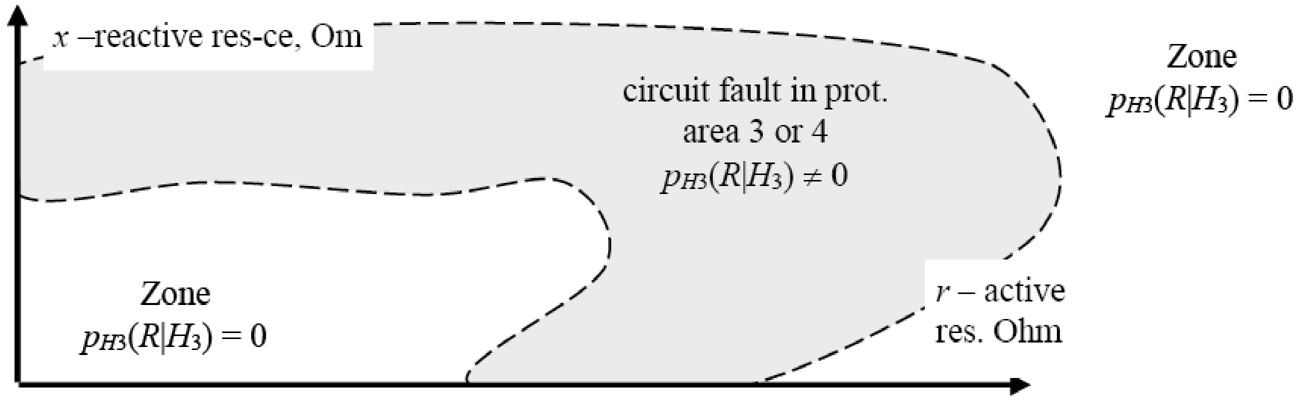

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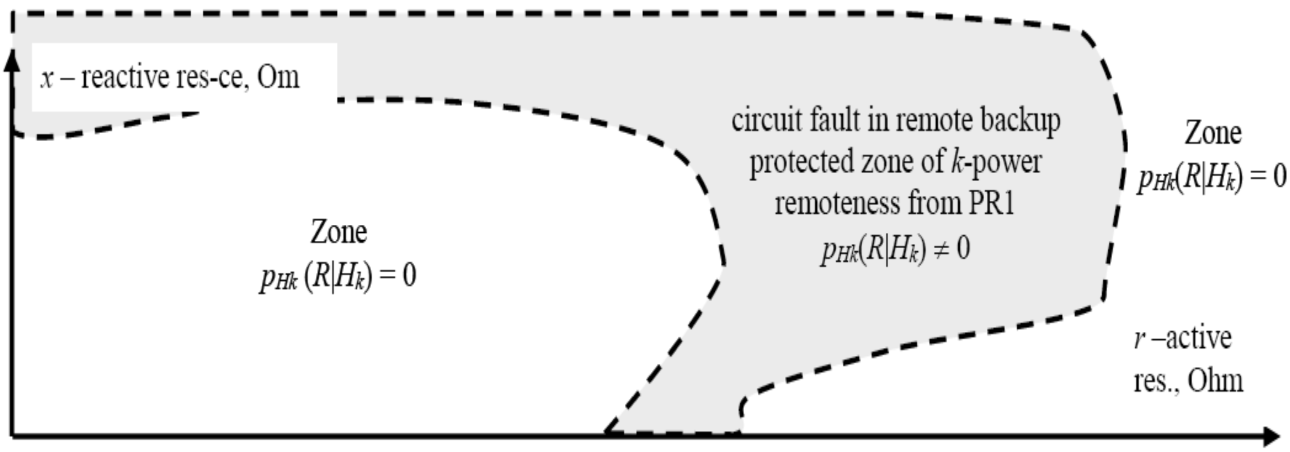

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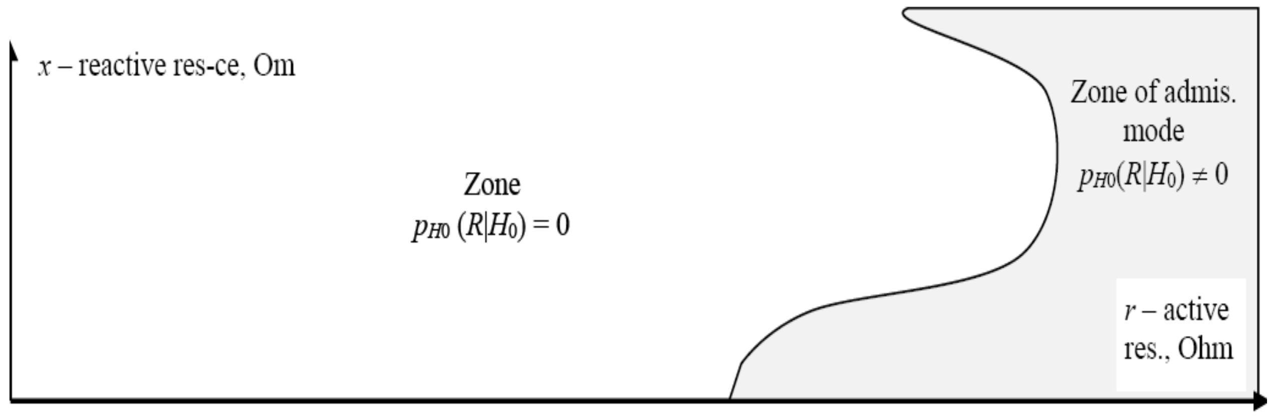


(f)

Figure 3: Remote backup with the help of multiparameter protections a) single-line diagram of grid, b-f) areas of nonzero probability density function for all hypotheses

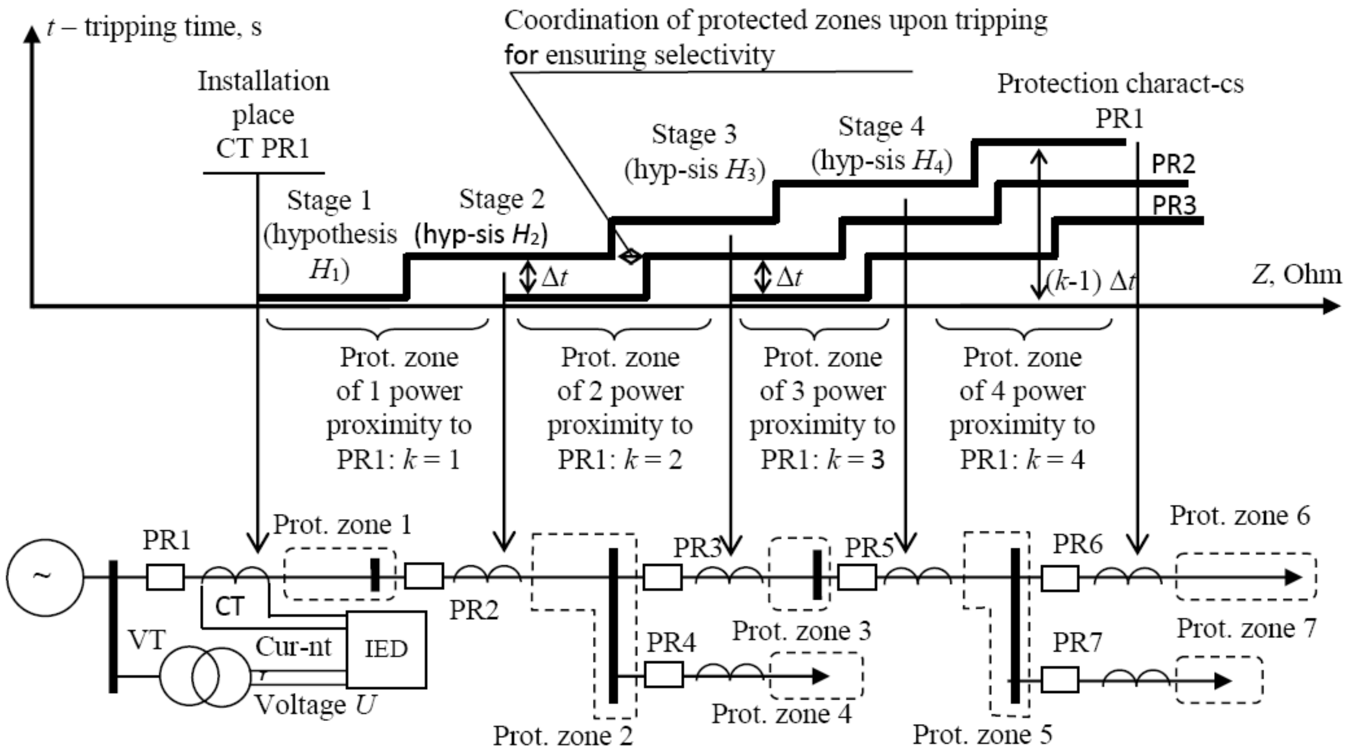


Figure 4 : Stage principle for ensuring the selectivity of protections operation

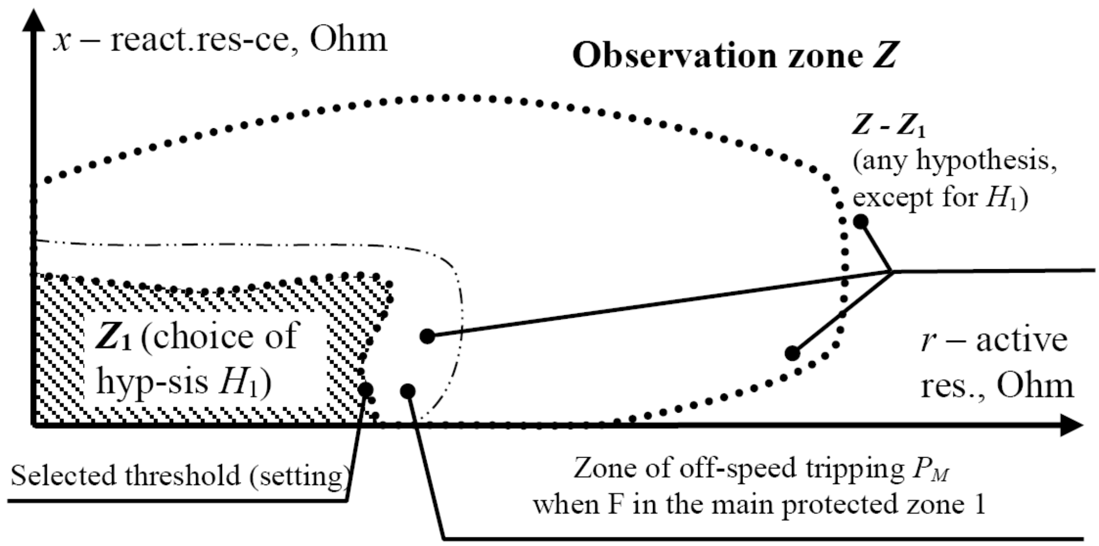


Figure 5: Ensuring selectivity in operation of protections PR1 and PR2 due to PR1 protection failure in protected zone 2

On the basis of such conditions selectivity will be provided due to time delay and multiparameter PR1 will be stage-by-stage protection with independent time delays in backup areas (figure 4).

Let functions of probability density function of normal operating condition ($R|H_0$) and emergency conditions $p_{Hk}(R|H_k)$ be deduced – figure 3 b-f.

The settings are to be found with the help of the probability density functions found – thresholds of zones Z_0, Z_1, …, Z_k, due to ensuring selectivity for protection operations: protection PR1 must be separated well from non-selective tripping in its all backup zones.

In accordance with the condition of selectivity all observations R have to belong to zone Z_k, if $p_{Hk}(R|H_k) \neq 0$ and $p_{Hk+1}(R|H_{k+1}) = 0$. The exception from this condition is zone Z_0 – it includes all points from $p_{H0}(R|H_0) \neq 0$.

Let consider the condition of selectivity ensuring on the example of setting choice PR1 for hypothesis H_1 (PR1 goes off in its main protected zone 1) – figure 5. Two zones of non-zero probability density function of protected zones 1 and 2 are depicted in observation Z - $p_{H1}(R|H_1)$ and $p_{H2}(R|H_2)$ (figure 3 b-c). Protected zones must be of contiguous proximity degree, in this case zone1 has got proximity degree k = 1 and zone2 has got proximity degree k = 2.

Threshold of zone for instant going off Z_1 (setting) PR1 is chosen so that the protection would not go off for sure in case the fault occurs out of its protected zone 1 (figure 5). Herewith, malfunction error P_M in case of F is acceptable in the main protected zone 1, which means that the protection has an effect similar to decreasing the velocity of classical remote protection at the end of the main area. However, error P_M can be decreased till minimum due to the correct choice of parameters for observation R. For example, due to choosing the wave parameters of mode or the current difference between the beginning and the end of protected zone 1 as the example for observation, then error P_M will be reduced to zero. The value of P_M error is found by integration, for example for the main protected zone (proximity degree k = 1) the probability of off-speed tripping PR1 $P_{M.k=1}$ will be equal to:

$$P_{M.k=1} = \int_{Z-Z1} p_{H1}(R \mid H_1) \mathrm{d}R$$

Similarly, in order to ensure the selectivity thresholds of other tripping zones (settings) Z_0, Z_2, …, Z_k are determined for the considered zone PR1 – figure 6.

For ensuring the selectivity of protection stages operation according to tripping zone (horizontal gap between PR1 and PR2 characteristics in figure 4) it is necessary to ensure as low as practicable distance between Z_k PR1 and Z_{k-1} zone of adjacent protection PR2, that is determined by: measurement errors and simulation errors. If this gap is not ensured, then the backup stages of adjacent protections might go off unselectively: the protection that is closer to F place will go off during the same time as the remote protection after the moment, when F occurs.

To ensure such type of selectivity is possible by choosing settings – threshold grading for zone Z_k from $p_{Hk+1}(R|H_{k+1})$ – figure 7. Extension and grading for each zone Z_k of k-power are carried out proportionally to $k\delta R$ coefficient (figure 7), where δR is the maximum possible total error, which includes measurement error (only if it is not included into $p_{Hk}(R|H_k)$ statistics and into simulation error).

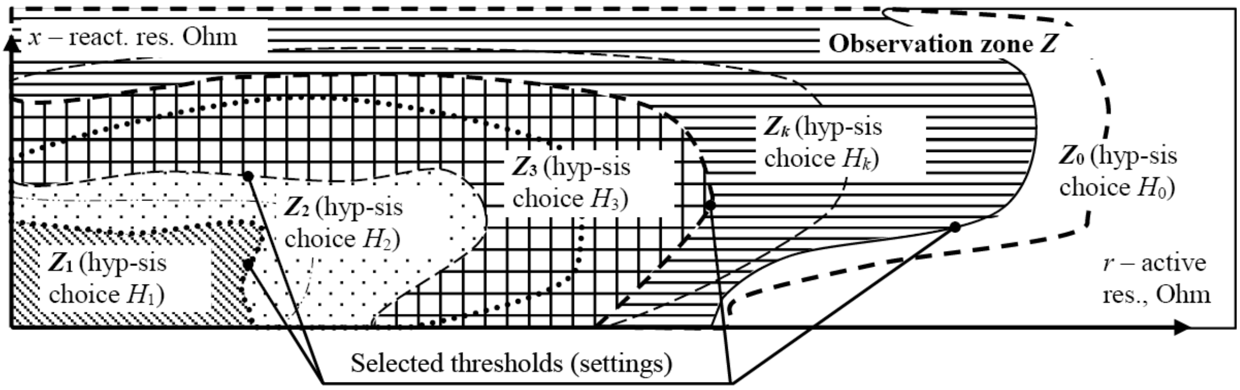


Figure 6: Selected thresholds of zones (settings) for multiparameter protection relay 1

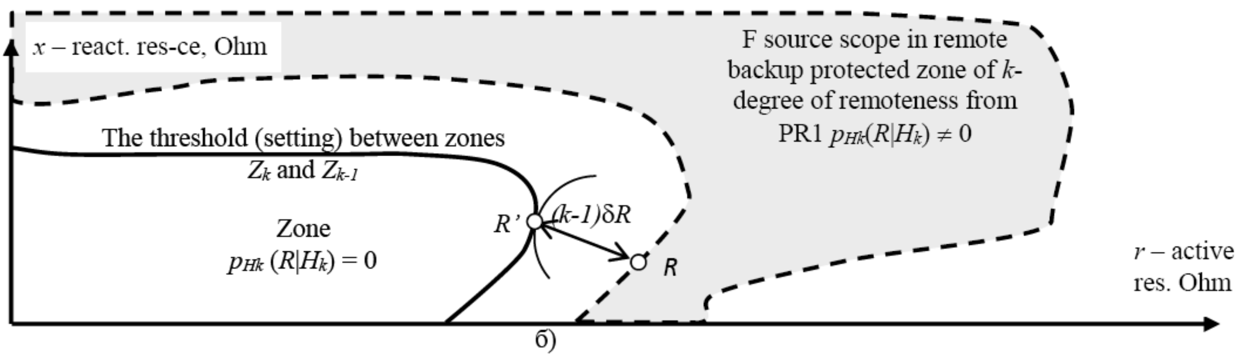


Figure 7: Ensuring selectivity in tripping zone by threshold shift

Protection grading from any other modes, in which protection operation must differ from the already existing hypotheses (for example, grading from generator swinging), can be carried out thanks to either new hypothesis introduction, in case separate identification of this regime is required, or extension of the zone for choosing the hypothesis of the accepted mode H_0.

If settings of other grid protections are found by the offered rules (figure 3a), then protection system of grid with only multiple selective distant reservation of protected zone will rise.

Advantages of the offered method for ensuring selectivity:

- method allows to coordinate any combinations of traditional stage-type protections and multiparameter protections;

- switching off in backup zones will be done with minimal time delay, that is equal to selectivity stage Δt;

- performance reliability – selective remote reservation can be fulfilled even with local measurements at protection installation place, for example, in case of feeder bay system disturbance;

- getting the maximum sensitiveness in backup areas when using multiparameter protections;

- the offered calculation method of settings is simple and can be used as the basis for automated procedures and software implementation.

Example of calculation variants for protection of electrical grid zone of power supply

Let consider the offered principles for multiparameter protections principles on the example of protections settings calculation for grid area 10kV of power supply system (figure 8a).

The simple protected zone “a’” includes the feeding power system (PS), the first busbar section 10 kV of electric power substation (EPS) and the load connected to it; protected zone “b” includes cable link (CL1) and the first busbar section 10 kV of power distribution center (DS); protected zone “g” includes asynchronous motor (AM1); protected zone “d” includes power transformer of transformer substation (TS) T1; protected zone “z” includes busbar section of switch-gear (DD) 0,4 kV, that is electrically supplied by the section – figure 8b. The simple protected zones for the second symmetrical half of grid are built by analogy.

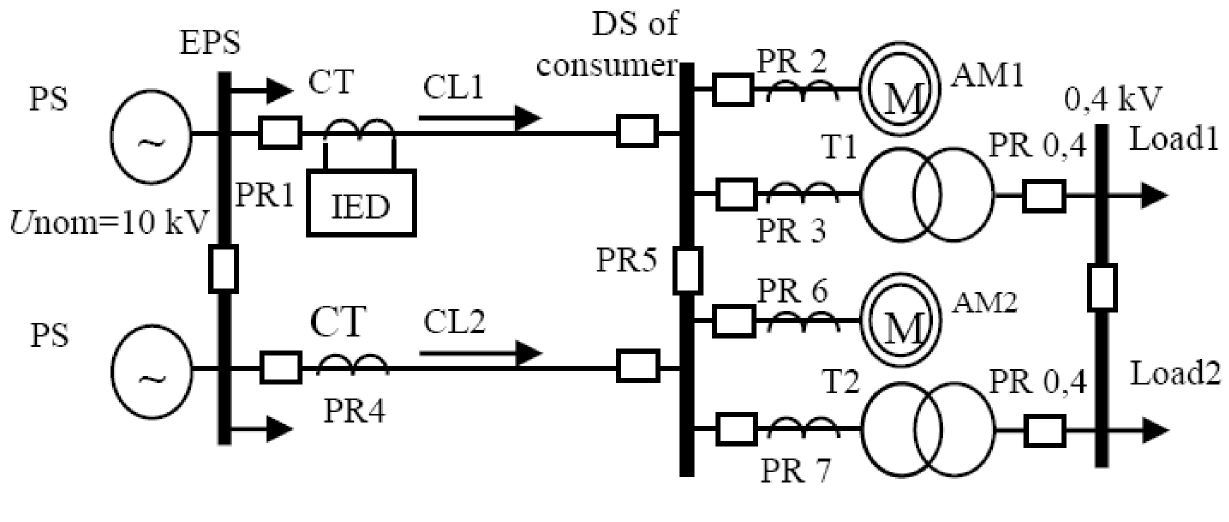
The enterprise is powered through two cable lines of 2 km length APvP 500/35. Transformers as well as induction power motors are connected through cable lines. Cable lines lengths: from DD 10 kV to AM: 70 m, from DD 10 kV to stage-down transformer 10/0,4 – 100 m.

Transformer DS of consumer: TM-1600/10-D1 with nominal power 1600 kW, $U_к$ = 6%, control type: Off-load tap changing ±2x2,5%, nominal coil voltage - 10/0,4 kV.

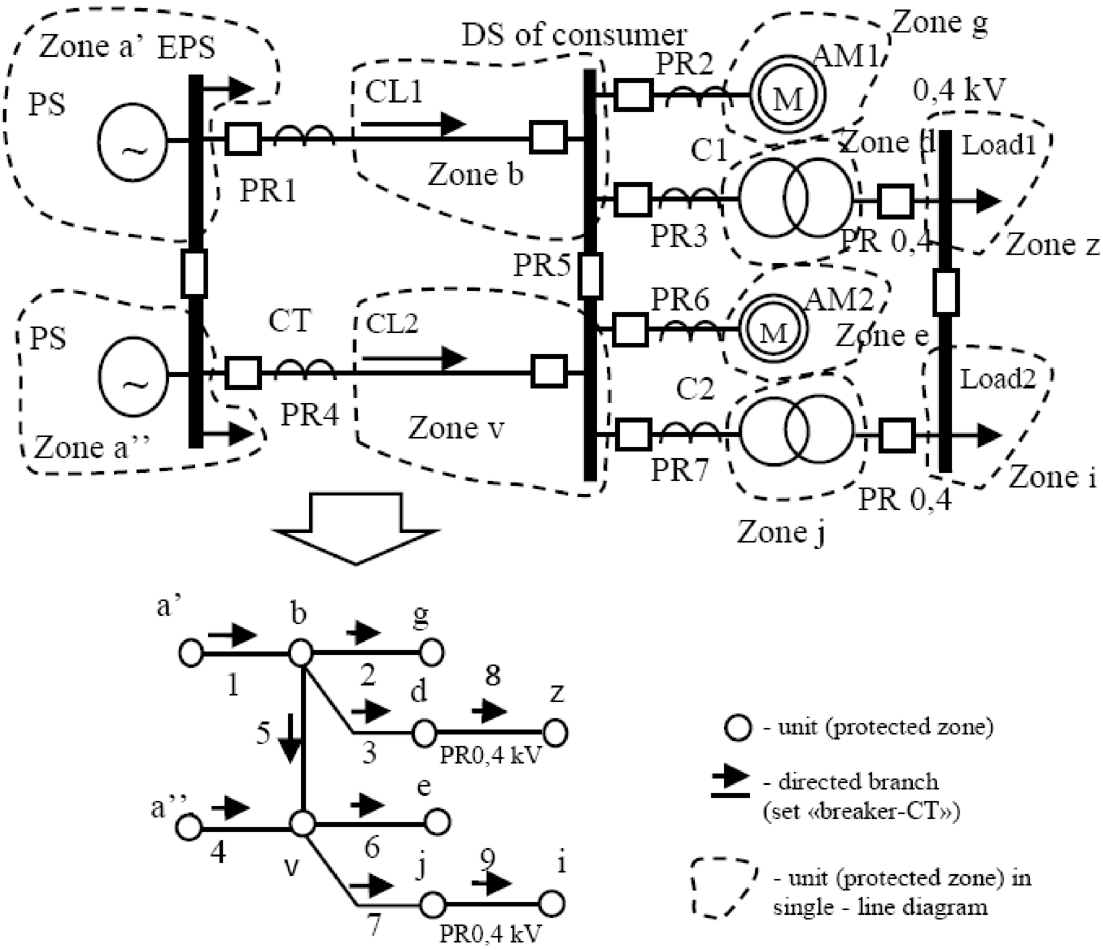
The consumers at the enterprise: 2 asynchronous motors 10 kV with Nominal power 3150 kW as well as general load on the side 0,4 kW with total power 2 MW (full power S = 2,155 MVA, reactive power Q = 0,8 MVAr, current 124 A). Induction motor 4AZM-3150/10000 UHL4, 3150 kW - Nominal power of motor, 10 kV - nominal voltage; 0,969 – efficiency; 0,89 – power factor; reactive power Q = 1,6 MVAr, 5,3 - starting current ratio. Loading equal to 0,4 kV is considered to be a general, industrial one. Longitudinal coupling on the side is 0,4 kV– VA-303R-200A.

Total capacity of other consumers on busbars 10 kV substation is equal to 10 MW (10,4 MVA). Parameters for substitutional feeder bay are shown in table 1.

Calculation of traditional overcurrent protection of the grid area under consideration for independent current-time characteristics has given the following results – table 2.



(a)



(b)

Figure 8: Example of grid of power supply system for multiparameter protection calculation (PR 1, 2, 3, … , 7):
a) single-line scheme, b) main graph of protected zones

Selective tripping plan for traditional protections – low set over of overcurrent protection (LCP) and fast overcurrent protection (CP), are shown in figure 9. Selectivity stage is taken 0,5 s for the sake of simplicity.

Table 1: Parameters of substitutional feeder bay

Parameter	**Value**
Nominal voltage of grid, kV	10
Resistance CL 1 (CL 2), ohm	0,25+j 0,121
Resistance T1 (C2), brought to high-voltage side, ohm	j 3,75
Resistance CL to AM 1 (to AM 2), ohm	0,009+j 0,006
Name-plate current AM, A	211
Resistance AM in starting mode, ohm	j 5,17
Resistance CL to C 1 (to C 2), ohm	0,013+j 0,008
Starting resistance of load 0,4 kV on 1 busbar section, ohm	j 32,483
System resistance, ohm	j 0,334

With the help of simulation model of grid, the calculation of single-parameter and multiparameter protections of one and the same grid area is carried out. In F calculations incident active transition resistance at F location with maximum value 5 Ω was taken into consideration, that restrains F current and makes PR delicacy worse. This leads to a sharp decrease of F cranking voltage minimum current values: on busbars 10 kV TR – up to 1 kA, on busbars 10 kV DS – up to 0,95 kA, on busbars 0,4 kV TS – up to 0,4 kA. In comparison with dead short-circuit, accounting of transition resistance leads to a significant decrease of protection efficiency as a traditional current one as well as statistical one (table 3).

Table 2: Calculation of F currents and protection settings LCP and CP

Parameter	**Value**
F current on busbars 10 kV TR (minimum / maximum), kA	14,97 / 19
F current on busbars 10 kV DS (minimum / maximum), kA	9,63 / 12,3
F current on busbars 0,4 kV TP (minimum / maximum), brought to voltage 10 kV, kA	1,2 / 1,5
Current for one section start DS, kA	1,3
Current for simultaneous 2 sections start DS, kA	1,9
Current for starting one AM, kA	1
Trip current of LCP of TS transformer, kA	0,8
LCP delicacy coefficient of transformer in the main zone, p.u	1,75
CP trip current of TS transformer, kA	2,42
Delicacy coefficient of CP transformer, p.u	5
Trip current of AM protection, kA	1,5
Delicacy coefficient AM protection, p.u	6,5
LCP trip current pf section breaker (SB) DS, kA	1,92
LCP delicacy coefficient SB (switched busbar circuit-breaker) DS at F behind the transformer, p.u	0,7
LCP trip current, kA	2,8
LCP delicacy coefficient CL in the main zone, p.u	3,4
LCP delicacy coefficient CL in the backup zone, p.u.	0,5
Trip current CP CL, kA	17,2
Delicacy coefficient of CP CL, p.u	1,1

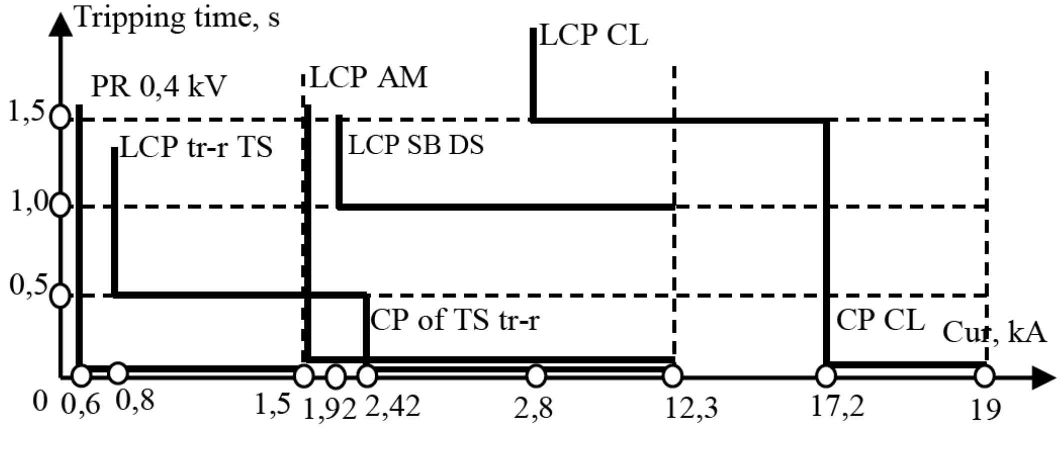


Figure 9: Map of protection selection LCP and CP power supply grid

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Table 3: Technical improvement of protection variant for CL1 (protection № 1) with an account of transition resistance at F location

Detection coefficients	**Protection variants**		
	Traditional LCP, CP	*I* (single-parameter protection on statistical principles)	*I, U* (double-parameter protection on statistical principles)
Detection probability of F in the main zone (elementary protected zone «b»), p.u	0,335	0,335	0,722
Detection probability of F in backup zone (elementary protected zones «v», «g», «d»), p.u	0,120	0,120	0,372
Detection probability of F in backup zone (elementary protected zones «e», «j», «z»), p.u	0,024	0,024	0,103
Detection probability of F in backup zone (elementary protected zone «i»), p.u	0	0	0,011
Probability of F cut-off in the main area, which is slowed down for selectivity stage Δt (elementary protected zone «b»), p.u	1	0,987	0,984
Probability of slowed down F cut-off in back-up zone (elementary protected zones «v», «g», «d»), p.u	1	1	0,979
Probability of slowed down F cut-off in back-up zone (elementary protected zones «e», «j», «z»), p.u	1	0,976	0,917

Remark: Probability values are received by integrating probability-density function of fault occurrence $p_{Hk}(R|H_k)$ in integration area limited by settings and that coincides with area Z_k – where protection goes off for each of these three protection variants. Functions $p_{Hk}(R|H_k)$ were received by simulation experimentation on the model of grid feeder bay. The number of F simulations on lines, busbars and loads was taken the same, that is equal to 10 000. More than 4 million F simulations were carried out in total.

Single-parameter protection CL1, based on statistical principles (figure 10), has some advantage in comparison with classical LCP и CP CL (table 3 and figure 10) due to the fact that it has got an instantaneous stage, as there is no necessity to tune out from DC component rush because of digital filtering, as well as some reduction in current of tripping due to error decrease during protection coordination. Besides, in the presented example the reduction in current of instantaneous steps of protection leads to an increase of velocity of PR slow steps for one selectivity stage – 0.5 s. In other aspects singe-parameter protection of current is fully equal to traditional LCP and CP.

Change-over to double-parameter protection, watching the operating current and voltage values at the place of protection installation (figure 11) make its efficiency better – F detection probability increases greatly (table 3). From the point of view of velocity increase, the effect is not that great – the probability of F delayed trip in elementary areas are kept more than 0,9.

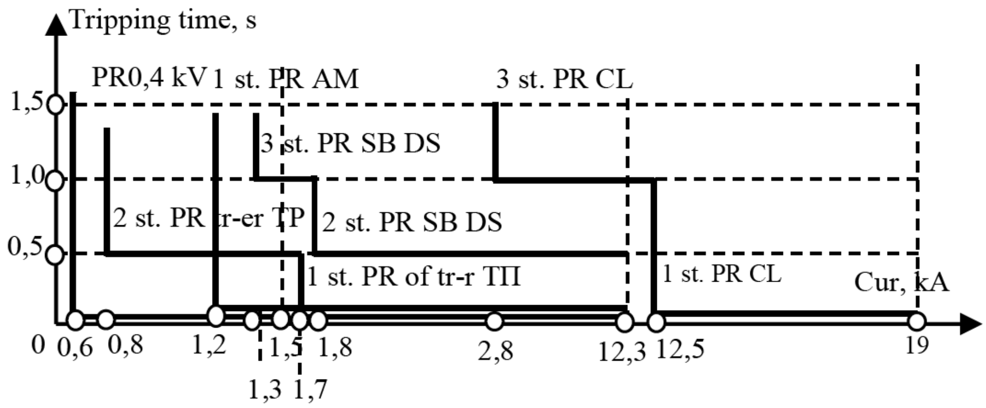

Figure 10: Map of single-parameter protection selectivity of power-supply grid, based on statistical principles

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CONCLUSION

1. The approach for ensuring selectivity of tripping in backup zones of multiparameter protections is proposed. It is proposed to ensure selectivity of protections due to time-delay according to traditional staged-principle. Multiparameter protections will be considered as satged protections with independent time-delays. This approach allows to efficiently coordinate multiparameter protections with each other as well as with the already installed stepped protections of traditional type.
2. The example for calculation of the simplest single-parameter (according to the effective value of line current of fundamental component) staged grid protection, based on statistical principles. The calculation has shown the efficiency of the offered method as it allows to obtain the grid protection similar to the traditional overcurrent protection of grid or with improved characteristics.
3. The example of calculation of the protection, based on statistical principles, of one grid feeder has shown the applicability of the offered method to multiparameter protections as well. The usage of double-parameter decentralized stepped protection has allowed to greatly increase the technical excellence of grid feeder protection – the detection probability of F in the main zone with an account of incidental transition resistance with maximum value of 5 Ω has increased from 0,335 up to 0,722, and in the nearest backup zone – from 0,120 to 0.372.
4. The increase of protections dimensionality and optimal choice of the measured values will allow to greatly increase technical excellence of power supply protection and reliability [14,15].

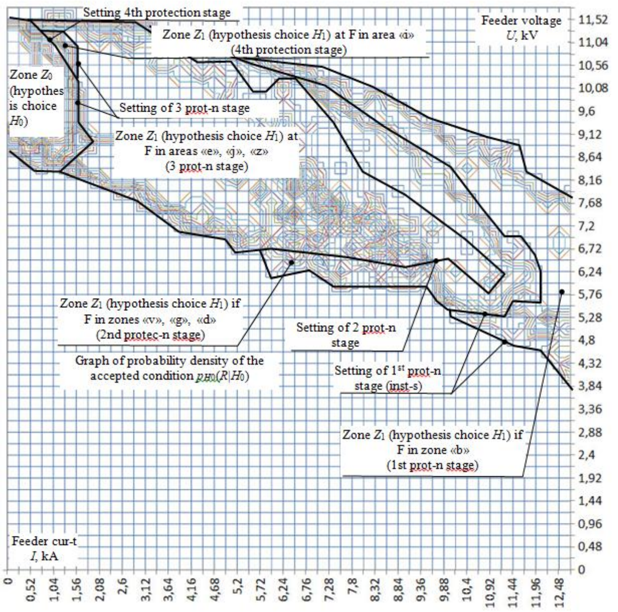

Figure 11: Variant of double-parameter protection, based on statistical principles, that controls current and voltage of CL feeder (protection #1)

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