



PS1 – S1-06



Statistical Effectiveness Increase Methods of Relay Protection Tools

Alexander L. KULIKOV, Alexander N. KLYUKIN
FGC UES Affiliate – the Nizhniy Novgorod PMES
Russia

kulikov@npmes.elektra.ru

KEYWORDS

Relay protection, operating efficiency, probability of excessive operation of relay protection, imitating simulation, stochastic models, test of hypothesis, statistical algorithms.

1 INTRODUCTION

Imitating simulation (IS) is one of the most effective tools for the analysis and research of power grids and systems [1]. It allows to carry out experiments with models as real objects (systems) under conditions when that is practically impossible or inexpedient. In the domains of relay protection and anti-wreck automation (RP and A), IS plays an important role and is part of, for instance, the fundamentals of the information theory [2].

The term IS is known in a more narrow sense when stochastic models and experiments with them, with the use of the stochastic testing method (Monte Carlo method) are implied [1,3]. In this case, the inputs of the model and /or functional states between its various components may, or may not, contain the element of randomness subject to the probability laws.

If to observe the conditions of the model adequacy, as well as the required number of experiments (representativeness of sample) [1,3], stochastic imitating models may serve the experimental and applied methodology, which has as its aim:

- Description of the behavior of power objects and systems’;
- Working out of hypotheses and statistical algorithms, which may explain the observed behavior;
- Use of hypotheses and stochastic algorithms to predict changes in the power system or ways of its functioning.

From this stochastic side, the potential of IS methods in augmentation of RP and A efficiency has been practically neglected. The objective of this article is to illustrate the capabilities of stochastic IS, as well as those of RP algorithms obtained from IS results in RP and A devices.

2 BASIC PART

Current protections and a section of the 110 kV Nizhny Novgorod Power Grid (Fig. 1) being an example, we shall demonstrate the application of the statistic approach to increase sensitivity of current protections of distant reservation.

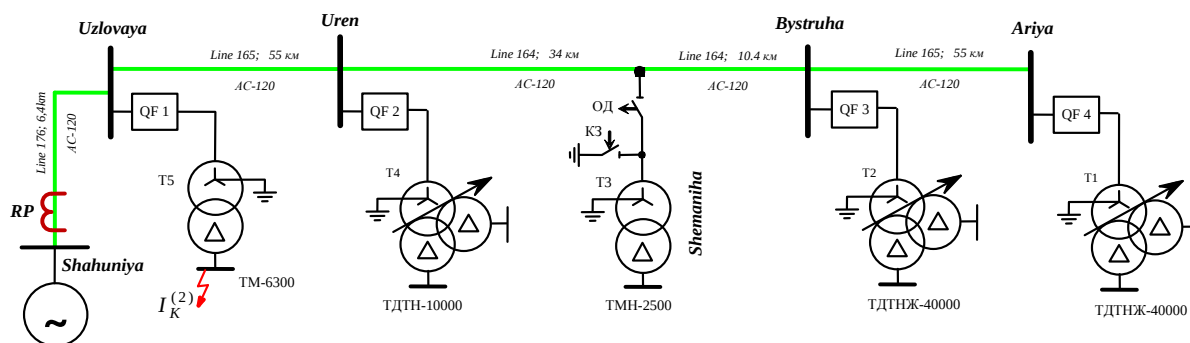


Fig. 1: Section of the 110 kV Nizhny Novgorod Power Grid

The stochastic imitating model of the above section was realized within the MATLAB software; and the model's variables, as well as the ranges of their variations are indicated in table 1.

Table 1: Imitating model’s variables

Object	Variable	Range of variation
Source	Phase-to-phase rms voltage, kV	104,5 – 115,5
	Frequency, Hz	49,8 – 50,2
	Phase angle of phase A, degrees	30 – 70
	Resistance, Ohms	0,65 – 0,95
	Inductance, mH	6 – 8
Air line	Specific resistance, Ohms/km	0,19 – 0,26
	Specific inductance, mH/km	1,2 – 1,4
	Specific capacitance, nF/km	8,8 – 9,2
Transformer	Resistances, Ohms	14 – 16
	Inductance, H	0,35 – 0,39
	Magnetization circuit resistance, MOhms	1,1 – 1,4
	Magnetization circuit inductance, H	720 – 760
Consumers	Load, MBA	20 – 30,5
	$\cos(\varphi)$	0,75 – 0,95

Using the results of stochastic IS, it is expedient to plot the distributions of work current probabilities ($p_w(I)$) and short circuit currents ($p_f(I)$); the probabilities of excessive response P_{exc} and response failure P_{fail} may be determined from these distributions.

Under random (normal) distribution of $p_w(I)$ and $p_f(I)$, the probabilities of P_{exc} and P_{fail} constitute the areas under the curves of the respective distributions relative to the set-up (threshold) value of $I_{threshold}$ (Fig. 2).

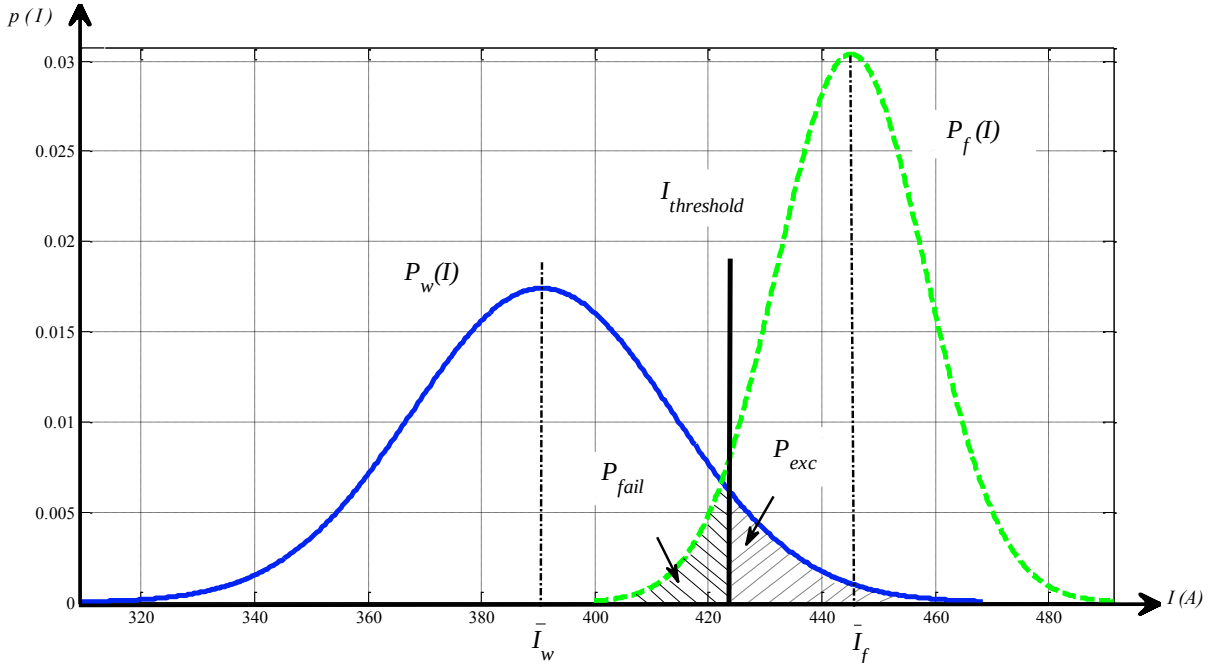


Fig. 2: Distribution of currents amplitude of air line 176 maximum work (—) and emergency (---) state

While plotting the statistic distribution of $p_w(I)$, one chooses such an operational mode of the power grid (loads, generations, conditions of power lines functioning, etc.), where maximum work current $I_{w.max}$ is assured. On the contrary, while plotting the statistical distribution of $p_f(I)$, one chooses such an operational mode of the power grid (loads, generations, conditions of power lines functioning, etc.), as well as the conditions of short currents occurrence, where its minimum value of $I_{f.min}$ is assured. Under such conditions, use of normal distributions of $p_w(I)$ and $p_f(I)$ is justified, since, for the current protections, these distributions reflect «the hardest load mode», and «the least detectable short circuit mode».

Worth noting, that probabilities of P_{exc} and P_{fail} are connected with other major and frequently used indices of RP efficiency, such as sensitivity and selectivity. Let's illustrate this connection by an example (Fig. 2) Thus, if the set-up value of $I_{threshold}$ is shifted to the right along the current axis (I), then the probability of excessive response P_{exc} will decrease and, consequently, the selectivity will increase (because there will be fewer situations when the protection responses excessively). But, at that, at the expense of an increase in set-up value of $I_{threshold}$ there will be an increase in the probability of response failure P_{fail} of current protection; and consequently, there will be a greater number of situations where the protection should have responded, but it had been insensitive to short circuit currents (decrease in sensitivity).

To develop the algorithm of digital current relay protection functioning with use of IS stochastic information, we shall employ the theory of statistical hypotheses verification [3,4]. Being investigated is the hypothesis of short circuit at the background of an alternative hypothesis of operational mode; the former is accepted by the results of the gauging of current amplitude. As applied to Bayesian approach, widely used in technical decisions, the task of plotting a new way of current protection comes to the criterion of verisimilitude ratio, which, in its turn, comes to the comparison with the threshold value (set-up value) of the probabilities' densities ratio.

$$\Lambda(I) = \frac{p_f(I)}{p_w(I)} \geq \Lambda_0, \quad (1)$$

where Λ_0 - threshold (set-up) value.

Under the normal law of probability distribution in work and emergency mode we shall get

$$p_w(I) = (2\pi\sigma_w^2)^{-\frac{1}{2}} \exp\left\{-\frac{(I - \bar{I}_w)^2}{2\sigma_w^2}\right\} \quad (2)$$

$$p_f(I) = (2\pi\sigma_f^2)^{-\frac{1}{2}} \exp\left\{-\frac{(I - \bar{I}_f)^2}{2\sigma_f^2}\right\} \quad (3)$$

where $\bar{I}_w, \sigma_w^2$ и $\bar{I}_f, \sigma_f^2$ – respectively mathematical expectations and currents variances in work and fault modes.

Likelihood ratio will look like

$$\Lambda(I) = \frac{\sigma_w}{\sigma_f} \exp\left\{\frac{(I - \bar{I}_w)^2}{2\sigma_w^2} - \frac{(I - \bar{I}_f)^2}{2\sigma_f^2}\right\} = \frac{\sigma_w}{\sigma_f} \cdot \exp\left\{\frac{I^2(\sigma_f^2 - \sigma_w^2) + 2I(\bar{I}_f \cdot \sigma_w^2 - \bar{I}_w \cdot \sigma_f^2) - \bar{I}_f^2 \cdot \sigma_w^2 + \bar{I}_w^2 \cdot \sigma_f^2}{2\sigma_w^2 \cdot \sigma_f^2}\right\} \quad (4)$$

Since the exponential function is monotonous, the decision may be based not on verisimilitudes ratio, but on this function's logarithm. After taking the logarithm and grouping, we shall obtain a new independent criterion of current protection, which lies in comparison of the value magnitudes

$$l(I) = I^2 \frac{\sigma_f^2 - \sigma_w^2}{2\sigma_w^2 \sigma_f^2} + I \frac{(\bar{I}_f \cdot \sigma_w^2 + \bar{I}_w \cdot \sigma_f^2)}{\sigma_w^2 \sigma_f^2} \quad (5)$$

with the threshold value

$$l_0 = (\ln \Lambda_0 - \ln \sigma_w + \ln \sigma_f) - \frac{\bar{I}_w^2}{2\sigma_w^2} + \frac{\bar{I}_f^2}{2\sigma_f^2} \quad (6)$$

After multiplying $l(I)$ and l_0 by $2\sigma_w^2 \sigma_f^2$, we pass on to the modified algorithm, possessing a greater simplicity of technical realization.

$$l'(I) = I^2(\sigma_f^2 - \sigma_w^2) + 2I(\bar{I}_f \cdot \sigma_w^2 + \bar{I}_w \cdot \sigma_f^2) \quad (7)$$

It should be noted, that the threshold (set-up) value l'_0 does not depend on the present-day values of current and may be calculated once by the results of simulation.

For the technical realization of current protection it is expedient to select the simplest calculating expressions, linked with the calculation of value $l'(I)$ and l'_0 . At that, the variant of structural scheme of digital current relay protection device, based on statistical data processing, may be done as follows (Fig. 3)

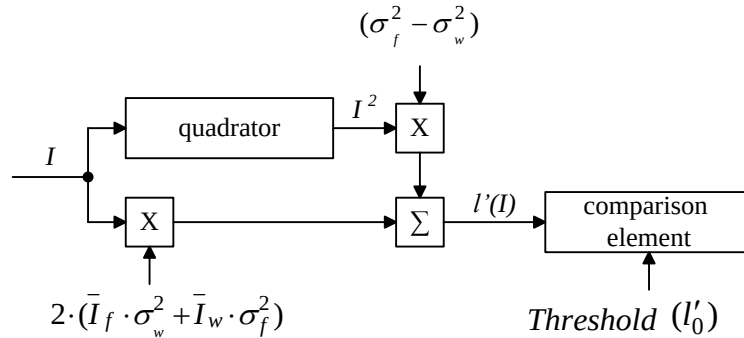


Fig. 3: Device of digital current relay protection

It is supposed, that the input of the device (Fig. 3) receives digital values of current module (instant amplitude). Thus, prior to the delivery onto the device's input, the current has been subjected to [4] low frequency analogue filtration, analogue-digital conversion, digital filtration of current counts (e.g., by the discrete Fourier transform algorithm), digital detection (calculation of the absolute value).

To assure the device functioning (Fig. 3), preliminary calculation of constant factors, using the obtained IS values $\bar{I}_w, \sigma_w^2, \bar{I}_f, \sigma_f^2$ is carried out

$$a = 2 \cdot (\bar{I}_f \cdot \sigma_w^2 + \bar{I}_w \cdot \sigma_f^2) \quad (8)$$

$$\epsilon = (\sigma_f^2 - \sigma_w^2) \quad (9)$$

as well as the selection of a set-up value

$$l'_0 = 2 \cdot \sigma_w^2 \cdot \sigma_f^2 \cdot (\ln \Lambda_0 - \ln \sigma_w + \ln \sigma_f) - \bar{I}_w^2 \cdot \sigma_f^2 + \bar{I}_f^2 \cdot \sigma_w^2 \quad (10)$$

A simpler (non-calculated) way of selecting a set-up (threshold) value, based, for example, on Neyman-Pearson criterion is possible. Here, a certain value of one of the efficiency indices of RP functioning is set up. For instance, provision of zero value of excessive response probability P_{exc} , or, according to the Power Installations Regulations - minimum sensitivity factor no less than 1.5 (1.2 for the back-up protection zone), proceeding from the statistical distributions (Fig. 2), with a definition of current value $I_{threshold}$.

After substitution of I_{cp} into the expression for $l'(I)$ subject to $l'(I_{cp}) = l'_0$ we obtain

$$l'_0 = l'(I_{threshold}) = I_{threshold}^2 \cdot (\sigma_f^2 - \sigma_w^2) + 2 \cdot I_{threshold} \cdot (\bar{I}_f \cdot \sigma_w^2 + \bar{I}_w \cdot \sigma_f^2) \quad (11)$$

Thus, we have got, on the basis of statistical distributions, a simplified law of set-up value calculation.

After calculating the required-for-functioning values a, b and l'_0 the digital current protection device (Fig. 3) is ready for work. Upon delivery at the input of discrete values of current module I , a weighted summation for formation is realized.

$$l'(I) = a \cdot I + \epsilon \cdot I^2 \quad (12)$$

Later, value $l'(I)$ is compared to the set-up value (threshold) l'_0 to make a decision about availability of short circuit at the object.

Under $l'(I) \geq l'_0$ the protection responds, otherwise $l'(I) < l'_0$ it does not.

To evaluate the efficiency of the employment of statistical algorithms in digital remote reservation current protection, one has conducted IS of a section of the power grid (Fig.1) The results of the simulation under changing grid characteristics, according to Table 1, are given in Table 2 and testify to a substantial increase in sensitivity. For individual types of short circuits, the sensitivity of distant reservation current protections rises by ten and more times without deterioration of other efficiency indices. Such a phenomenon is caused by a fuller use of data, which characterize the protected grid section and its modes; by statistical distributions of operational and emergency modes' currents and by procedures (algorithms) of decision making (response) of relay protection.

Table. 2: Numerical magnitudes of the simulation results

Reservation zone	Object of reservation	Sensitivity of relay protection		$\Delta K_s = \frac{K_{s_stat.}}{K_{s_deter.}}$
		Deterministic method	Statistical method	
1	T5	–	+	9,66
2	T4	–	+	8,25
3	T3	–	+	14,2
	T2	–	+	7,9
4	T1	–	+	8,3

Use of the statistical principle for the case of vector gauging (multidimensional relay protection [2]) and for Gaussian (normal) distributions leads to an algorithm, when the set-up value (threshold) is compared to a scalar value of the type

$$\ln l = \frac{1}{2} (\bar{y}^T \cdot (\underline{\varphi}_w^{-1} - \underline{\varphi}_f^{-1}) \cdot \bar{y} + \bar{y}^T \cdot (\underline{\varphi}_f^{-1} \cdot \bar{x}_f - \underline{\varphi}_w^{-1} \cdot \bar{x}_w) + (\bar{x}_f^T \cdot \underline{\varphi}_f^{-1} - \bar{x}_w^T \cdot \underline{\varphi}_w^{-1}) \cdot \bar{y} + (\bar{x}_w^T \cdot \underline{\varphi}_w^{-1} \cdot \bar{x}_w - \bar{x}_f^T \cdot \underline{\varphi}_f^{-1} \cdot \bar{x}_f)) + \ln \left(\sqrt{|\underline{\varphi}_w| / |\underline{\varphi}_f|} \right) \quad (13)$$

where $\bar{y}$ – vector-column of gauged characteristics; $\underline{\varphi}_w$ and $\underline{\varphi}_f$ – correlation characteristics matrices of operational and emergency modes; $\bar{x}_w$ and $\bar{x}_f$ – vector-columns of mathematical expectations of operational and emergency modes' characteristics.

It should be noted, that it is expedient to select set-up values by the above considered Neyman-Pearson criterion. The basis for such a selection will be constituted by statistics distribution $\ln l$ for operational and emergency modes, obtained through IS.

The potential of use of processing statistical algorithms while realizing digital relay protection is shown by Fig. 4-6. In question is current protection, the operational conditions of which are characterized by current characteristics distributions, i.e., amplitude I (Fig. 4) and phase φ (Fig 5) for boundary conditions of operational (maximum) and emergency (minimum) modes. Analysis of Fig. 4 and Fig. 5 shows, that areas of possible values of current amplitude and phase (Fig. 6) overlap. This circumstance does not allow to detect a possible event of short circuit. Yet statistics distribution $\ln l$ (according to expression 13) in these modes testifies to a sure separation of modes and a possibility of current protection plotting by comparing $\ln l$ to the set-up value. In this case, in the capacity of a set-up value one may choose value $\ln l = 0$; the comparing procedure comes to determination of statistics sign $\ln l$.

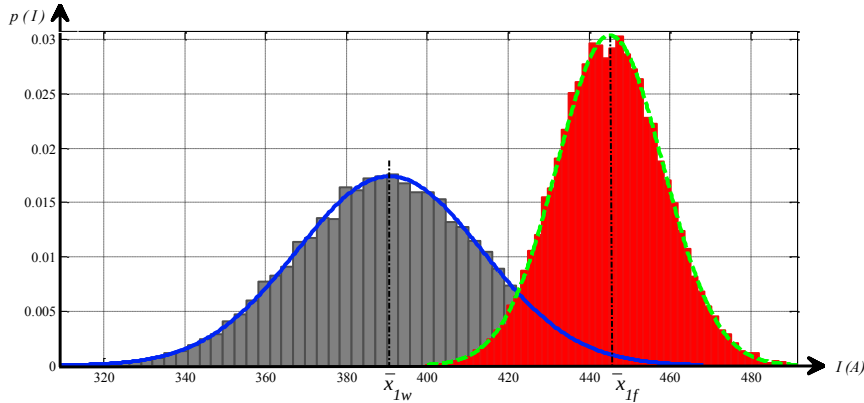


Fig. 4: Distribution of work (–) and fault (–) currents amplitude

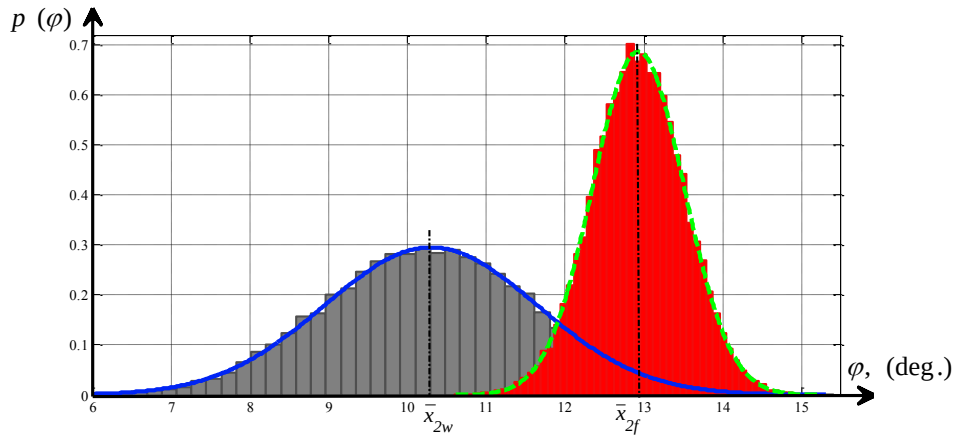


Fig. 5: Distribution of work (–) and fault (–) currents phase

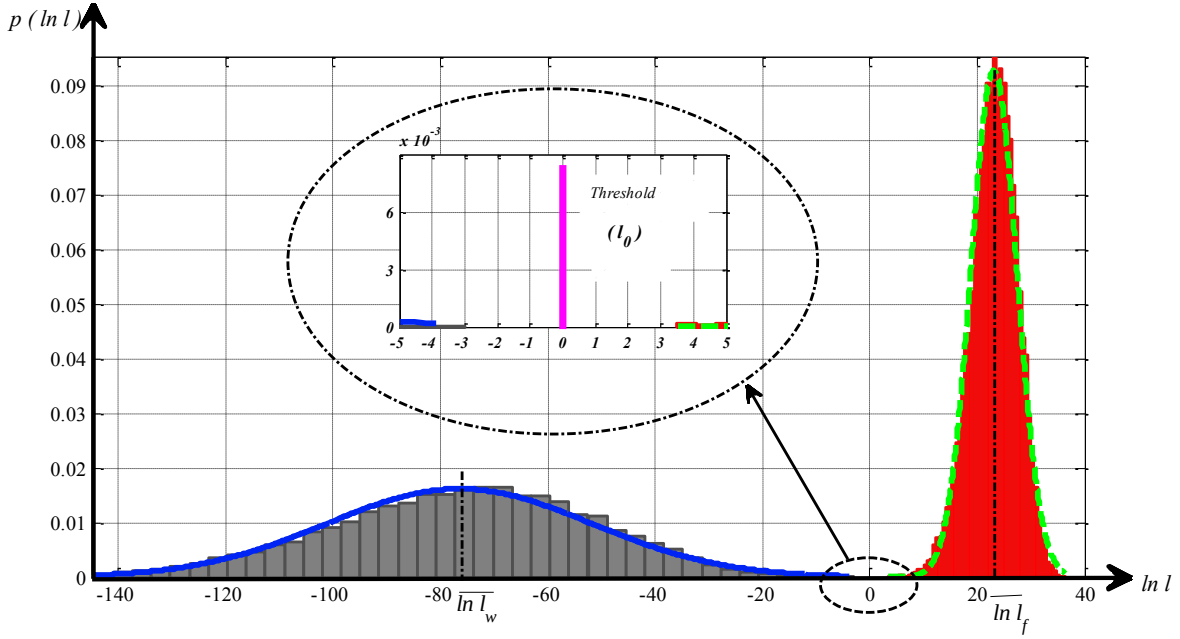


Fig. 6: Distribution of statistics $\ln l$ for work (—) and emergency (---) modes

On supposition of the sameness of correlation factor ρ of current characteristics of operational and emergency modes, forming vectors $\bar{x}$ and $\bar{y}$ (expression 14), the structural scheme of digital RP device is given in Fig. 7; the calculating algorithm is based on statistics calculation

$$\gamma = \frac{1}{1-\rho^2} \cdot \left\{ y_1^2 \cdot \left(\frac{1}{\sigma_{1w}^2} - \frac{1}{\sigma_{1f}^2} \right) + y_2^2 \cdot \left(\frac{1}{\sigma_{2w}^2} - \frac{1}{\sigma_{2f}^2} \right) - 2 \cdot y_1 \cdot y_2 \cdot \left(\frac{1}{\sigma_{1w} \cdot \sigma_{2w}} + \frac{1}{\sigma_{1f} \cdot \sigma_{2f}} \right) \right\} +$$

$$+ \left\{ \left(\frac{y_1 \cdot x_{1f}}{\sigma_{1f}^2} - \frac{y_1 \cdot x_{1w}}{\sigma_{1w}^2} + \frac{y_2 \cdot x_{2f}}{\sigma_{2f}^2} - \frac{y_2 \cdot x_{2w}}{\sigma_{2w}^2} + \rho \cdot \left(\frac{y_1 \cdot x_{2w}}{\sigma_{1w} \cdot \sigma_{2w}} + \frac{y_2 \cdot x_{1w}}{\sigma_{1w} \cdot \sigma_{2w}} - \frac{y_1 \cdot x_{2f}}{\sigma_{1f} \cdot \sigma_{2f}} - \frac{y_2 \cdot x_{1f}}{\sigma_{1f} \cdot \sigma_{2f}} \right) \right) \right\} \quad (14)$$

where y_1, y_2 – measured parameters of current (amplitude and phase); $\sigma_{1w}, \sigma_{1f}, \sigma_{2w}, \sigma_{2f}$ – variances of current parameters in work and fault modes; $x_{1w}, x_{1f}, x_{2w}, x_{2f}$ – mathematical expectations of current parameters (amplitude and phase) in work and fault modes (for example, Fig.4–6).

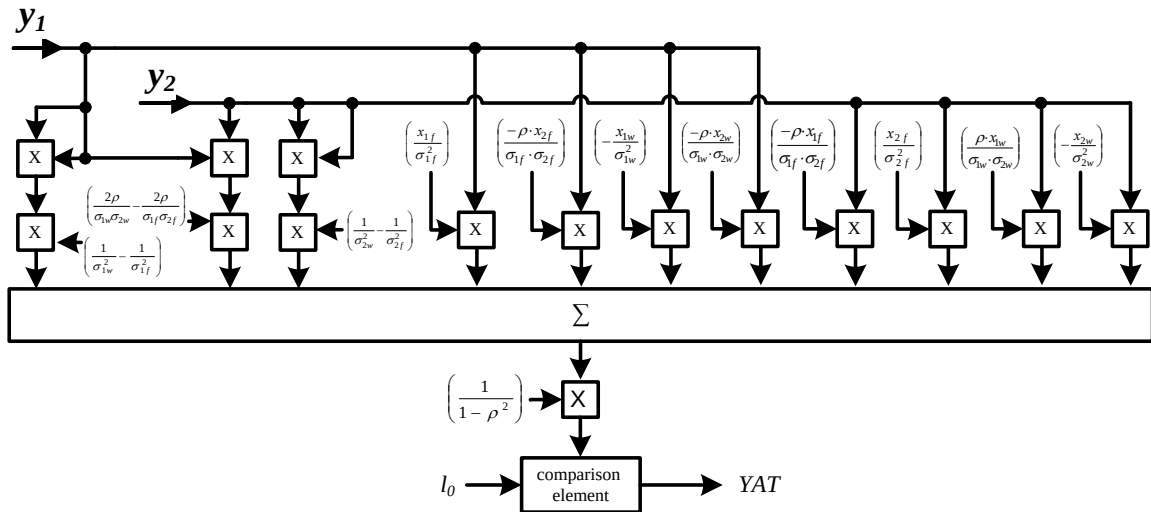


Fig. 7: Structural scheme of digital relay protection for two controlled value

It is important, that despite a complicated algorithm and hardware version, (Fig. 7), the suggested digital relay protection realizes a physically justified and comprehensible processing operations :

- Accumulation of data, comprised in current characteristics, by summation of standardized differences values of these characteristics in emergency and operational modes;
- Inter-element standardizing of characteristics by level according to dispersions (mean square deviations); with less importance is considered a sampling element, which possesses greater dispersion and, consequently, a characteristic with a lesser precision of evaluation;
- Compensation of correlated parts of evaluated current characteristics (rule-out of excessive data); that, along with standardizing, assures making-up of different intensity characteristics.

3 CONCLUSION

Use of statistical data together with stochastic decision-making algorithms ensures a high sensitivity of relay protection under conditions of changing characteristics of a power grid and dynamic modes. The developed relay protection algorithm may be introduced into the existing terminals of micro-processing protection and does not require their considerable design changes, or additional costs. The suggested principle of use of IS and statistical data may be spread to various types of protection with a view to increase their efficiency.

REFERENCES

- [1] Шеннон Р. Имитационное моделирование систем – искусство и наука. – М.: Мир, 1978.
- [2] Лямец Ю. Я., Ефимов Е. Б., Нудельман Г. С., Законьшек Я. Принципы информационного совершенства релейной защиты // Электротехника, №2, 2001.
- [3] Cramer H. Mathematical methods of statistics. – М.: Mir, 1975.
- [4] Леман Э. Проверка статистических гипотез. – М.: Наука. Главная редакция физико-математической литературы, 1979.
- [5] Шнеерсон Э. М. Цифровая релейная защита. – М.: Энергоатомиздат, 2007.