The analysis of circuit breakers kinematics characteristics using the artificial neural networks

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Abstract: - The paper presents the required parameters in the evaluation of the technical state for the High Voltage (HV) circuit breakers. It details some aspects regarding the influence of the kinematics characteristics to the circuit breakers performances. Also, it presents a possibility to use the artificial neural networks (ANN) in the analysis of the circuit breakers kinematics characteristics, in order to diagnostic their technical state. The required database necessary for learning of ANN has determined through the modelling of the mechanical system of movement transmission, using the systems of electrical nature, with RLC elements.

Key-Words: - Circuit breaker, Kinematics characteristics, Modelling and simulation, Monitoring, Diagnostic, Artificial neural network

1 Introduction

The maintenance policy of the circuit breakers is oriented to corrective maintenance (realized after the failure) and on the scheduled preventive maintenance, that is realized after pre-established criteria (for example time periods, number of short circuit disconnections).

Today, it follows to changing the scheduled preventive maintenance with that predictive maintenance, which is realized in accordance with the technical state of equipment.

In order to establish and prediction the technical state of the electrical equipment the monitoring and diagnostic activities are required.

The technical state diagnostic of the equipment is realized through the supervision of the some parameters of its, specially selected to offer concrete information about the technical state of the supervised equipment. The anterior presented technique is concretized in the appearance of the some specialized devices with the measuring and control role of the circuit breaker's functions and comparing of the recorded values with a reference set (of a some circuit breakers in normal state or values anterior recorded on the same circuit breaker). After the comparing the devices emit warning signals, alarms, recommendations, or intervene in the supervised equipment's behaviour.

The appearance and strong development of information technology, which allows to creates and store the information, open new possibilities of monitoring, diagnostic and control of electrical equipment, [1], [2], [6], [7], [10], [14].

It consists that classical technology don't allows, generally, the delivery of a desired assistance in opportune moments. Having in view the brut data delivered by the SCADA systems (Supervisory Control and Data Acquisition), the on-line help is limited, especially, in the substantiation and taking of decisions. In this context, the artificial intelligence techniques (ANN - Artificial Neural Network, ES - Expert Systems, FL - Fuzzy Logic, GA - Genetic Algorithms) its prove powerful instruments for solving, [11], [12].

In the field of circuit breakers, which knows a permanent evolution, obtaining equipment with more performance (some of them defined by the manufacturers "without maintenance"), in the world it puts a special accent on the usage of artificial intelligence techniques in monitoring, diagnostic, and control of them, [1], [9], [11], [13].

2 Kinematics characteristics

The HV circuit breakers monitoring and diagnostic are orientated to their functions and constructive sub-ensemble (e.g. insulation, the switching function, the operating mechanism etc.).

Table 1 Parameters for the circuit breaker monitoring and diagnostic

Function / sub-ensemble	Parameter / characteristic	Monitoring	Diagnostic
Switching	Contact resistance	-	M
	Contact temperature	L	-
	Current load	M	-
	Main contacts position	H	-
	Kinematics characteristics (movement, velocity, acceleration)	M	M
	Acting time, non-simultaneity	M	M
	Arcing time	M	-
	Electroerosion	M	-
Insulation	SF_6 density	H	-
	Partial discharges	-	L
	Oil level	L	H
	Oil quality	M	H
	Moisture in SF_6	-	M
	SF_6 purity	-	L
	Main contacts position	H	M
	Gas temperature	H	-
Operating mechanism	Operating number	M	M
	Operating time	M	M
	Stored energy	H	-
	Kinematics characteristics	M	M
	Motor state	M	M
	Vibration signatures	M	M
The control and auxiliary circuits	Supply voltage	H	H
	Current in coils	M	H
	Continuity of the circuits	M	H
	Auxiliary switches state	M	H

Note: The importance of the parameters: H-high; M-medium; L-low.

In Table 1, the used parameters in diagnostic and monitoring of the circuit breakers (SF_6, oil) are presented, with the specification of the importance of each parameter in these activities, [14], [15], [16], [17]. Between the parameters with a special importance in the knowledge of the HV circuit breakers technical state, and kinematics parameters are included (the total movement, the movement in contact, the opening/closing velocity, opening/closing time, non-simultaneity time between poles, respective between the chambers of the same pole), they influencing directly their performances, [1], [5], [6], [7].

Thus, the kinematics parameters strongly influence the contacts electroerosion, puffer nozzle wearing (for the SF_6 circuit breakers), arc extinction chamber wearing and quality decreasing of insulation and ignition environment of electric arc.

In order to obtain the kinematics characteristics of the HV circuit breakers, in generally, it uses the movement recording method (linear or angular) from an accessible point of the kinematics chain of the movable contacts. Exist many possibilities for movement recording: with drummer, numerical, with oscilloscope with memory etc., [15], [16].

Comparing the movement of movable contact vs. time, obtained at the circuit breaker operation, with a movement, normal considered, for that circuit breaker it can determinate a series of abnormal situations which can appears in its operation.

For example, in Fig. 1 are shown the comparing between the normal opening movement (1) and the movements (2) obtained in different abnormal situations: a) delays in the operation of opening electrical valve, caused by the existence of a high friction; b) low velocity at opening because of the energy decreasing charged in the operating mechanism; c) inadequate absorption given by the wearing of opening damper; d) too small distance between contacts, because of incorrect assembling, [1], [14], [15]. Generally, the determination methods of the kinematics characteristics are methods used during the circuit breakers maintenance and these follows the validation of these activities (for example, the replacement of a high pressure pipes, can leads to the introduction of a supplementary hydraulic resistance and in this way, to the modifying of the kinematics parameters). They are not methods used in the kinematics characteristics monitoring of the circuit breaker when this is under voltage.

The paper presents a possibility for monitoring and diagnostic of kinematics characteristics of the electrical equipment using the artificial neural networks. The required database which to include all possible situations in the operation of equipment has determined through the modelling of the mechanical system of movement transmission, using the systems of electrical nature, with RLC elements, [1].

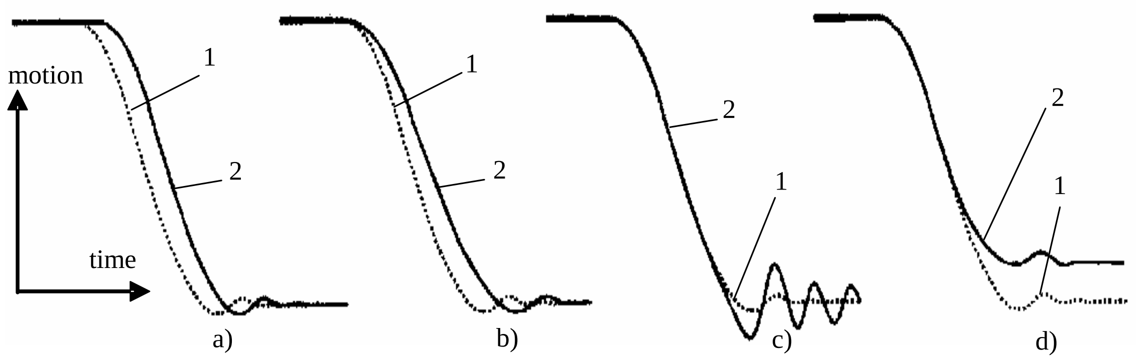

Fig.1 The motion of movable contact at disconnection in normal situation (1), abnormal respectively (2)

3 Modelling of mechanical system

3.1 Analogy between mechanical and electrical parameters

It considers a linear mechanical system with a single degree of freedom having the mass *m*, at this acting the excitation force *F(t)*, the elastic force given by the spring characterised by the elasticity constant *K* and the viscous absorption force proportional with the velocity given by a damper that has the absorption coefficient *r*, Fig. 2a.

Applying the dynamic equilibrium low it obtains the following equation which describe the response time of the mechanical system:

$$m\frac{d^2x}{dt^2} + r\frac{dx}{dt} + K \cdot x = F(t). \qquad (1)$$

For the series electrical circuit from Fig. 2b, the differential equation which describes its response is:

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{1}{C} \cdot q = u(t). \qquad (2)$$

It can consist that the both systems are described by the differential equations of the same shape. If it put in correspondence the measurements: *u(t)*, supply voltage ⇔ *F(t)*, excitation force of the mechanical system; *q(t)*, electric charge ⇔ *x(t)*, mechanical moving (motion); *R*, electrical resistance ⇔ *r*, absorption coefficient; *L*, electrical inductance ⇔ m, mass; *1/C*, inverse of capacity ⇔ *K*, elasticity constant; then, the behaviour of the mechanical system from Fig. 2a can be studied using the electrical circuit form Fig. 2b, based on the above correspondences, [1].

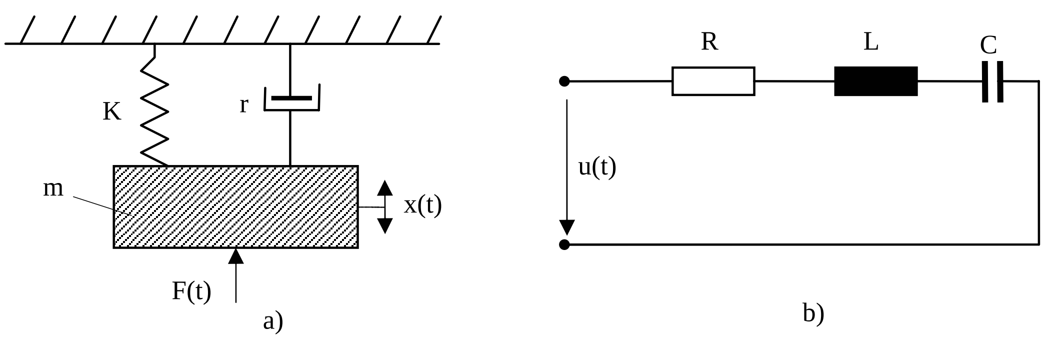

Fig.2 a) Mechanical system with a single degree of freedom; b) RLC series circuit

Because of the fact that the mechanical system for movement transmission of the circuit breakers suppose the existence of much more moving mechanical elements, it is necessary a dynamic replacement of the entire system with a single element, called reference element. Thus, if it has a motion of translation then it will has assigned a reduce mass and a reduce force of the entire system. In the case of a motion of rotation of the reference element, similarly it talks about the reduce moment of inertia and reduce moment of force, also.

The concept of reduce mass (reduce moment of inertia) is introduced on the base of equilibrium between the kinetic energy of the reduce mass (reduce moment of inertia) and the kinetic energy of all elements from the system, that is:

$$\frac{m_{red} v_k^2}{2} = \sum_{i=1}^{n} \left(\frac{m_i v_i^2}{2} + \frac{J_i \omega_i^2}{2} \right), \qquad (3)$$

where v_k is the velocity of reference element, v_i- velocity of i element of system, ω_i –angular velocity of i element , m_i, J_i - mass and inertia momentum of i element , m_{red} - reduce mass of mechanical system. From (3), the expression for m_{red} becomes:

$$m_{red} = \sum_{i=1}^{n} \left[m_i \left(\frac{v_i}{v_k} \right)^2 + J_i \left(\frac{\omega_i}{v_k} \right)^2 \right], \qquad (4)$$

If the reference element realises a rotation movement, then the reduce inertia momentum J_{red}, has de expression:

$$J_{red} = \sum_{i=1}^{n} \left[m_i \left(\frac{v_i}{\omega_k} \right)^2 + J_i \left(\frac{\omega_i}{\omega_k} \right)^2 \right], \qquad (5)$$

where ω_k is the angular velocity of the reference element.

The concept of reduce force (reduce moment of force) results from the equality's principle between the elementary mechanical work realised by the reduce force applied into a determined mode on the reference element, and the sum of the elementary mechanical work realised by the forces that operate to the all system elements.

For a system with n elements at which the reference element k has a translation movement, the reduce force, F_{red}, applied to the reference element k is given by the relation:

$$F_{red} = \frac{1}{\cos \alpha_k} \sum_{i=1}^{n} \left(F_i \frac{v_i}{v_k} \cos \alpha_i + M_i \frac{\omega_i}{v_k} \right), \qquad (6)$$

where: F_i - force applied to i element, M_i - momentum of forces couple applied to i element, v_k- velocity of application point of reduce force, α_k - angle between $\overline{v}_k$ and $\overline{F}_{red}$, v_i - velocity of application point of force $\overline{F}_i$, ω_i - angular velocity of i element, α_i - angle between $\overline{v}_i$ and $\overline{F}_i$.

If the reference element realises a rotation movement, then the expression of reduce momentum of force M_{red} is:

$$M_{red} = \sum_{i=1}^{n} \left(F_i \frac{v_i}{\omega_k} \cos \alpha_i + M_i \frac{\omega_i}{\omega_k} \right), \qquad (7)$$

where ω_k is the angular velocity of reference element k.

For the circuit breakers mechanical system, choosing a reference (point) element (usually it chooses the operating place of the main active force or on the movable contact) and calculating the reduce mass (reduce moment of inertia) and reduce force (reduce moment of force), respectively, it could describe the movement of the mechanical system using the equation (1), where m will be reduce mass, while $F(t)$ reduce force.

The mechanical system can be modelled, having in view the relations between the mechanical and electrical parameters, Table 2, using some series circuits which include resistances, inductances and capacitors.

Table 2 Correspondence between the mechanical and electrical parameters

Mechanical parameter	Electrical parameter
Travel - x [m]	Electrical charge q -[C]
Velocity - v [m/s]	Electrical current - I [A]
Force - F [N]	Electrical voltage - U [V]
Absorption coefficient - r [Ns/m]	Electrical resistance - R [V/A]
Mass - m [kg]	Electrical inductance - L [H]
Elasticity constant - K [N/m]	Inverse of electrical capacity - $1/C$ [1/F]

Using the electrical circuits which represent the model of mechanical system of movement transmission, it can study the transient processes of the system and determinate the kinematics parameters of the circuit breakers, for the closing and opening operation, in different situations.

3.2 Mechanical system’s model of circuit breaker

In order to simulate the kinematic characteristics, it will model the mechanical system of movement transmission of a HV circuit breaker, [1]. In Fig.3 is shown the scheme of mechanical ensemble of a HV circuit breaker through which it transmits the energy from the operation mechanism to the movable contacts.

The movement transmission is made through a kinematic chain realised from: piston with double effect and its rod 1, connecting rods 2, lever 3, connecting rods 4, movable rods of contact 5, all elements being articulated through bolts. The mechanical system for movement transmission includes over this kinematic chain and the following components: closing damper 6, opening damper 9 which avoids the mechanical shocks from the finish of travel; springs 7, which locks the movable contacts 8 in close or open position; springs and pistons of anticavitation devices.

The mechanical system of the circuit breaker, being a sum of elements, requires a reduction of masses and of forces at a reference element. As reference element, the piston with double effect is considered, which realises a translation movement and also the active force given by the operating mechanism acting to it.

The expressions of reduce mass (4) and reduce force (6) depends on the ratio between the elements velocities of kinematic chain and the velocity of reference element, which, during the circuit breaker acting, depends on the position of reference element (its shifting).

In order to determinate the reduce mass of mechanical system of HV circuit breaker, Fig.3. It takes in considerations five elements with their concentrated masses: piston with double effect 1 (its mass will includes: rod and piston with double effect‘s mass and piston mass of closing damper 6), connecting rods 2, cranks 3, connecting rods 4 and movable rods of contact 5 (at rod mass, the piston mass of opening damper 9 is added, respective for contact travel – at closing operation - in additional, is added and the piston mass of anticavitation spring 8).

In conformity with the relation (4) the reduce mass of mechanical system concentrated in *k* point placed on the reference element 1 (inferior part of rod of piston with double effect) is:

$$m_{red} = \sum_{i=1}^{5} \left[m_i \left(\frac{v_i}{v_1} \right)^2 + J_i \left(\frac{\omega_i}{v_1} \right)^2 \right]. \qquad (8)$$

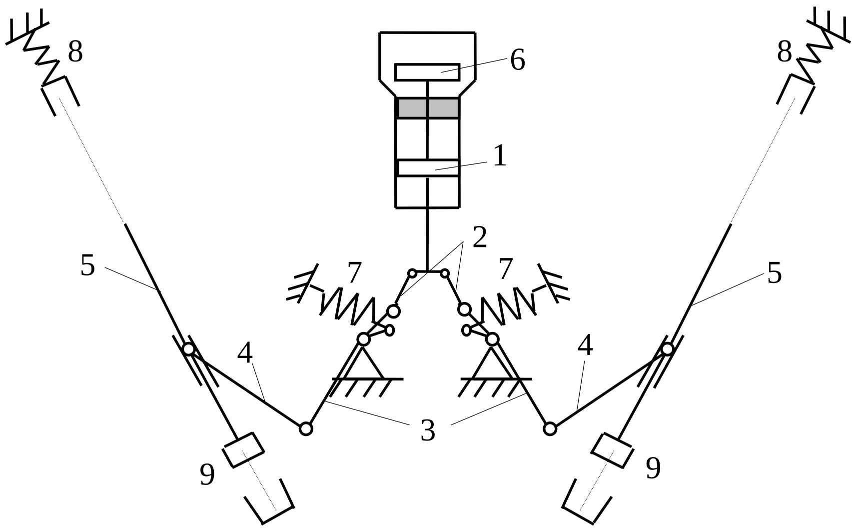

Fig.3 Mechanical system of a HV circuit breaker

The elements 1 and 5 realise just translation movements and thus, their angular velocities are null (ω_1=ω_5=0), the element 3 has just rotation movement (v_3=0) while the elements 2 and 4 have rotation and translation movements.

The Fig.4 shows the kinematic chain of the circuit breaker and forces that acting during the closing or opening operation, on different time domains, to the mechanical system, like as: $\overline{F_a}$, active force given by the operating mechanism; $\overline{F_i}$, force of closing damper; $\overline{F_d}$, force of opening damper; $\overline{F_{ac}}$, force given by the spring of anticavitation device; $\overline{F_t}$, force given by the tumbler spring (frictions are omitted). The forces given by the closing and opening dampers it will considers proportional with the velocity, while the forces given by springs will be proportional with the travel.

The mechanical system of movement transmission of circuit breaker, after reduction of masses ad forces, can be simulated using two RLC circuits, one corresponding to the closing operation and other for opening operation, Fig.5, conform with the equivalences from Table 2.

Notations have the following significations: *u(t)* is voltage supply which model the resultant active force, *L* - inductance corresponding to the reduce mass of the system, R_1 - resistance which equates the coefficient of viscous absorption given by repression force during the closing operation, R_2 - resistance which equates the coefficient of viscous absorption of force given by the closing damper, R_3 - resistance which equates the coefficient of viscous absorption of force given by the opening damper, C_1 - capacity which equates the inverse of elasticity constant of reduce force given by the spring of anticavitation device, C_2 - capacity which equates the inverse of elasticity constant of reduce force given by the tumbler spring, I_1, ..., I_6 are controlled switches which leads to introducing or taking out from circuit of some elements in accordance with the development of processes during the closing or opening operations.

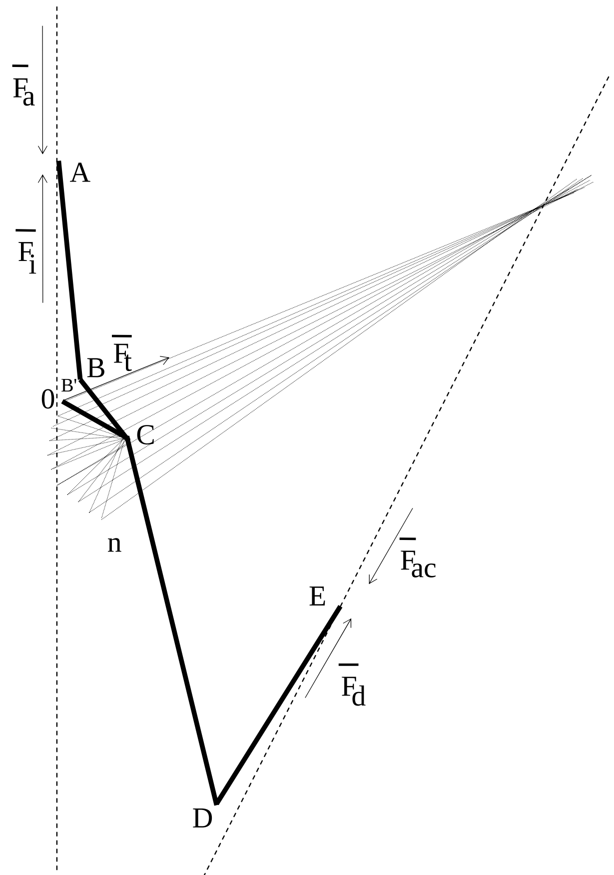

Fig.4 The forces which acting to kinematics chain of circuit breaker

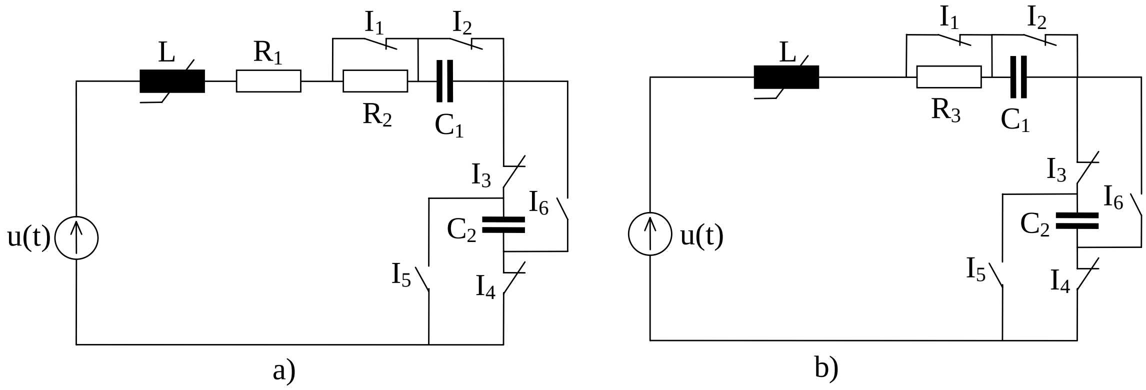

Fig.5 Electrical circuits for simulation of mechanical system for closing operation a), for opening operation b)

The electrical circuits which model the mechanical system of circuit breaker are used in numerical simulations which offer us information about the kinematic parameters of circuit breaker, simulations realised in EMTP/ATP software, [18]. These models have been validated using some experimental tests, fact that has allowed the usage of numerical results obtained through simulation for the training of artificial neural networks considered. In Fig.6 is given the travel of movable contact during the closing operation obtained experimentally, respectively with RLC model. After more experimental and numerical tests, the errors between the parameters obtained through both possibilities are:

- ± 1.15%, for total travel;
- ± 0.85% for travel in contact;
- ± 4.25%, for movement's duration;
- ± 3.2%, for maximum velocity.

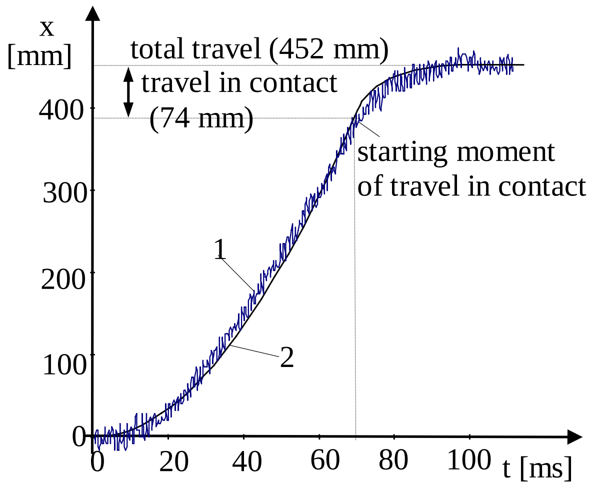

Fig.6 Travel of movable rod during the closing operation experimental (curve 1) and numeric (curve 2) determinated, respectively

In conditions in which the equipment manufacturer gives for kinematic parameters the variation ranges of those values, even at the maximum errors given by the model, the numerical values of the kinematic parameters have been found in these variation domains.

4 The analysis of the kinematics characteristics using ANN

The architecture of artificial neural network (ANN) has three layers complete connected; the input layer receives the monitored parameters, one or many hidden layers, while the output layer provides the estimation of desired parameters, Fig.7.

The used learning algorithm is the backpropagation, [3].

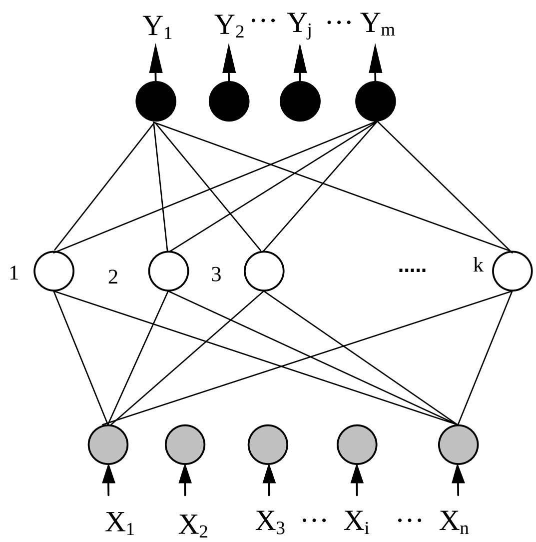

Fig.7 The architecture of artificial neural network

The convergence criterion is carried out when the global error into a cycle decrease under a certain value. The training data, which satisfy the other convergence criterion, are not used in the weight update; some training data, which can be easily learned, are excluded from the weight update sequence. This criterion is defined by the absolute maximum error between desired and actual output.

The steps, which are performed during the training process, are the following, [4], [11]:

- *Initialisation of weights and thresholds*

The weights w_{ij} and thresholds θ_i from the network it initialises with small values, randomly.

- *Pattern introduction*

From learning set it chooses an desired input-output pattern, X_m - Y_m. For certain implementations, the extract of current pattern ca be randomly realised.

- *Forward propagation*

Vector X_m from the chosen pattern it applies at the network input and, using the current weights and thresholds, in order to determinate the real values at the network output, O_m.

- *Weights adjustment through back propagation*

It uses an iterative algorithm which, starting from output neurons, propagate the error gradient back, to input neurons realising the weights adjustment:

$$w_{ij}(t+1) = w_{ij}(t) + \eta \delta_j x_{mi}, \qquad (9)$$

where: w_{ij} are the weights of connections between hidden (or input) neuron i and output (or hidden) neuron j; x_{mi} is the output of hidden (or input) neuron i; η is learning rate; δ_j is error term assigned to neuron j.

If the neuron j is from output layer, then:

$$\delta_j = o_j(1-o_j)\cdot(y_{mj} - o_{mj}), \qquad (10)$$

where y_{mj} is desired value at the output of neuron j.

If the neuron j is from hidden layer, then:

$$\delta_j = x_{mj}(1-x_{mj})\sum_k \delta_k w_{jk}, \qquad (11)$$

where k represents the multitude of all neurons from superior layers referenced to current layer.

- *Convergence test*

The adjustment algorithm of the weights continues returning at step two, until the global error into a cycle decrease under a certain value.

In the analysis of the kinematics characteristics of the circuit breaker an ANN has been used with the architecture including three layers complete connected. The input layer receives the movable contact curve, *X(t)*, numerical determined using RLC model, but discretised in 30 points, while from the output layer it obtains the equipment's status (normal - abnormal). For the abnormal state the causes which have conducted to an incorrect operation are presented.

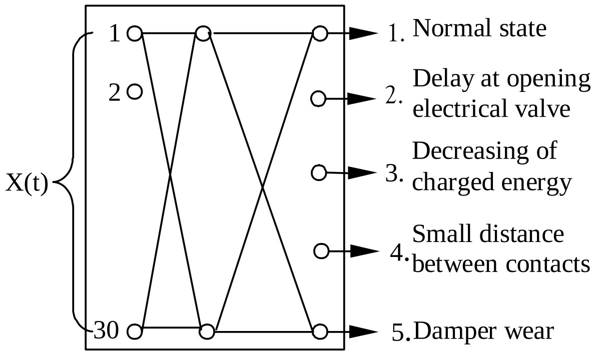

Fig.8 ANN architecture for the monitoring of kinematics characteristics

The used ANN, in this application, has the architecture described in Fig. 8, [1], [9].

In order to establish the optimum topology, many topologies have been tested, Table 3.

Table 3 The tested topologies

Topology	Training time	Square error	Relative errors on test data
30-30-5	3.7h	6.7e-8	3.49 %
30-40-5	5.2h	5.8e-8	1.08 %
30-50-5	6.4h	7.5e-9	0.68 %
30-60-5	8.5h	1.0e-8	0.80 %

The Fig. 9 shows the errors obtained on test set for ANN which have the topologies presented in Table 3.

The optimal topology of the ANN contains the input layer with 30 neurons, 50 on the hidden layer and, 5 on the output layer, respectively.

The technical state of the circuit breaker, looking from the point of view of kinematics characteristics, will be indicated at the ANN output through the neuron's activation in accordance with the respective state, by switching from 0 state in 1.

The learning data set has been generated using the electrical model of the mechanical system of movement transmission from circuit breaker, after the reducing of the mass and of the forces, this being simulated with the help of a RLC circuit, corresponding to the opening and closing operations.

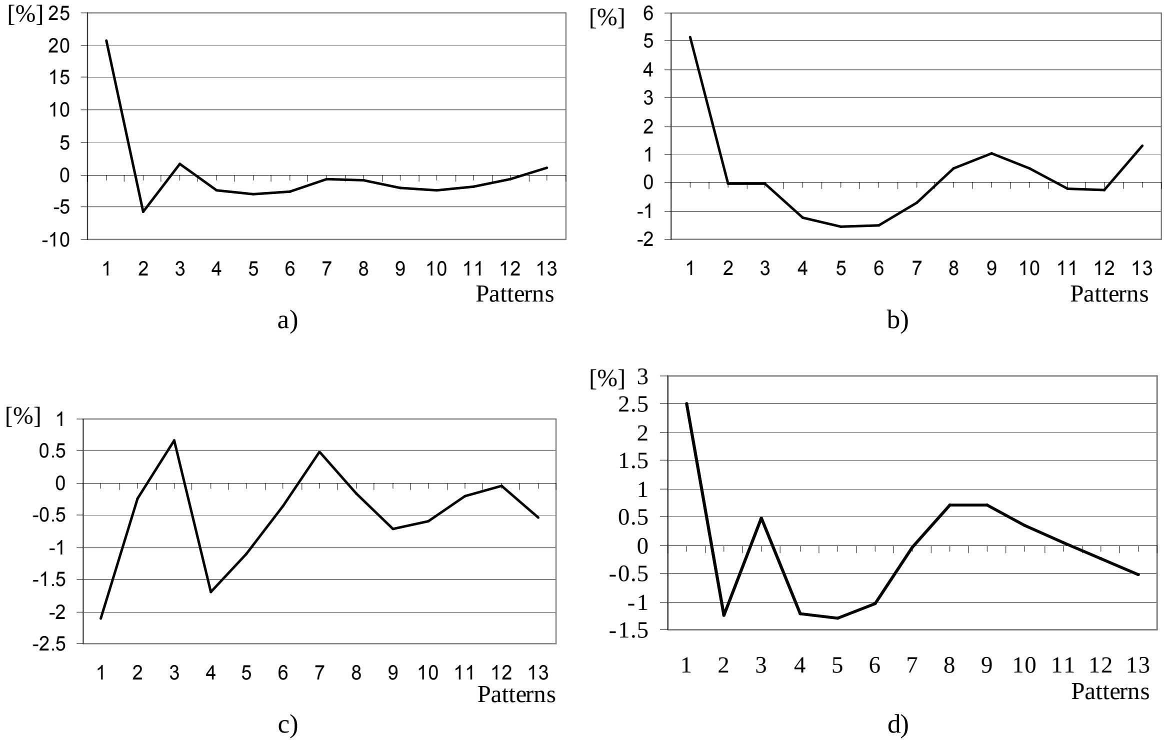

Fig.9 The errors obtained on test set for the following topologies: a) 30-30-5; b) 30-40-5; c) 30-50-5; d) 30-60-5

Through the repeated calculus and excluding the situations for which the technical restrictions are exceeded, it has obtained a learning data base which contains 350 input-output models. The ANN is trained using the training data obtained choosing different percents from the total of learning database.

After how it can see in Fig. 10, ten hours has been necessary for training of an ANN using 90% from the learning database. It consists that the training time necessary is linear according with the number of data used. Then, the ANN has been tested using the characteristics that haven't been used in the learning process.

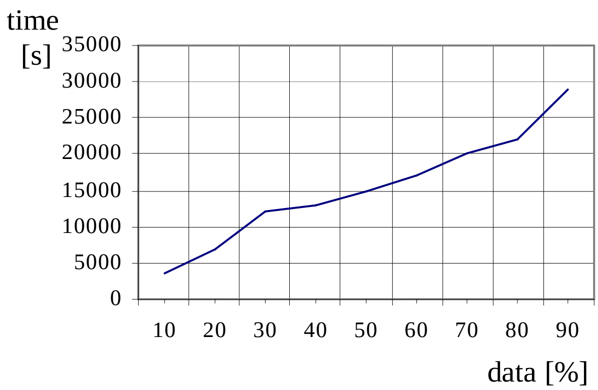

Fig.10 Learning time vs. used learning data

For example, applying a kinematics characteristic at the ANN input having the shape similar with that from Fig. 1a, the ANN has activated the output 2, Fig. 8, which corresponds with a delay of the opening electrical valve, given by the existence of some high frictions, those outputs remaining inactive.

It can appreciate that the ANN can be successfully used in the technical state diagnostic of the circuit breaker knowing the kinematics characteristics. Thus, through the analysis of the movable contact curve it can determinate various abnormal situations appeared in the kinematics system of circuit breaker.

5 Conclusions

The HV circuit breakers monitoring and diagnostic are orientated to their functions and constructive sub-ensemble (e.g. insulation, the switching function, the operating mechanism etc.), existing a big number of parameters that are used in these activities.

In the estimation of the circuit breakers technical state a great importance have their kinematics parameters. Thus, these strongly influence the contact electroerosions, puffer nozzle wearing (for the SF_6 circuit breakers), arc extinction chamber wearing and quality decreasing of insulation and ignition environment of electric arc, etc.

The ANN can be successfully used for diagnostic of circuit breakers technical state based on their kinematics characteristics. Thus, through the curve analysis of the movable contact it can determinates various failures appeared at the kinematics system of the circuit breaker like as: delays in the operation of electrical valves, too small distance between contacts, damper wearing, decreasing of charged energy, etc.

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