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Detecting development scenarios of dynamic events in electric power networks smart-grid Part 1 "Method"

Vitaliy Fedorovich Sivokobylenko[1)]
ORCID: https://orcid.org/0000-0002-7720-0540; svf1934@gmail.com. Scopus Author ID: 6603906155 and 55553493200
Andrey Petrovich Nikiforov[2)]
ORCID: https://orcid.org/0000-0002-3724-430; a.p.nikiforov@i.ua. Scopus Author ID: 57191825673
Ivan Vadimovich Zhuravlov[3)]
ORCID: https://orcid.org/0000-0003-4879-4666; ivanvzhuravlov@gmail.com
[1)] Donetsk National Technical University, 2, Shybankova Square, Pokrovsk, Donetsk region, 85300, Ukraine
[2)] Education and Research Institute of Energetics, Automation and Energy Efficiency,
National University of Life and Environmental Sciences of Ukraine, 12, Heroiv Oborony, Str. building 8, Kyiv, 03041, Ukraine
[3)] SICAME SAS France, 39 Av. du Midi, St. Sornin Lavolps, France

ABSTRACT

A method for constructing a semantic S-detector for the senior hierarchical level of pattern recognition in dynamic objects is proposed. The S-detection method is based on a uniform synthesis of all hierarchically subordinate detectors and information preparation schemes, based on the tasks of the upper hierarchical level of recognition of scenarios for the development of processes in an object. The method can be used to solve problems of relay protection, emergency control automation, to identify rare events in impulse, short-term input signals when implementing the concept of developing of electric power smart-grid. The synthesis of the S-detector of scenarios for the development of transient processes was the result of the development of a structural-information SI-method for processing information components. A mathematical SI-model is presented that allows you to control the mutual correspondence of the structure of the formation tree in the object and the device recognition tree. The task is to improve the stability of the device recognition algorithm. The Part 1 describes the theoretical provisions of the application of the recognition method. It is proposed to unify the trees for generating recognition scenarios in the industry, similar to the IEEE high-voltage network diagrams. The S-detector algorithm based on the formation of a semantic signal and on the selective search for the required amount of information for automatic decision-making is presented. The facts of the appearance of elementary information events in the input signals of the detector are controlled by Ξ,Η-selectivity windows, which are sequentially opened depending on the previous development of events. The block diagram of the S-detector of the scenario is presented, which can be synchronous, multichannel, with a high signal processing speed, without losing rapidly changing information when slow and infraslow information is detected. Combines useful properties of instantaneous and inertial detection algorithms. The output of the S-detector is a series of responses with different weights. This allows elementary detectors to be combined into sequential chains at different hierarchical levels of recognition. Part 2 provides an example of the application of the scenario detection method to solve the problem of increasing the stability of the operation of a selective protection relay against single-phase earth faults based on medium-frequency signals in 6-35 kV networks with an arc suppression Petersen's coil. The results of modelling the operation of the S-detector algorithm on the signals of real emergency files recorded by high-frequency recorders of transient processes in the network are presented.

Keywords: Relay protection; automation; smart grid; single-phase; earth faults; semantic signal; structural-information

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INTRODUCTION

When implementing the smart-grid concept in the electric power industry, several multidirectional trends began to emerge – from liberal to conservative, from centralized to local, from the operation of the control and protection facility (OCP) in modes from normal to emergency, and others. The parameters and characteristics of the equipment are being rapidly improved, as well as the provisions of the legislative framework are changing [1].

As a result, mathematical models become necessary, operating with *SceN* scenarios for the development of semantic *SN* situations, where *N*=1, 2, ... in which the OCP can be located. Such mathematical models can be used to control the operating modes of the electric power smart-grid network based on the control of elementary information components, for example, to take into account the operating conditions of the equipment of control objects, automation devices, relay protection, as well as when they are implemented in real, local, specific operating conditions [2].

An important property of the information mathematical model of the network operating *SceN*, *SN* is to take into account the change in the parameters of inertia of the network equipment, taking into account the reaction to rapid changes in the operating modes of the network (chargedischarge processes of batteries of energy storage devices, operating modes of energy carriers of sources) [3]. Controlling the response of equipment to rapid changes open the way for the emergence of new modes of operation and new circuit configurations of the smart-grid network [4].

The tasks of relay protection and automation (RPA) [5], diagnostics [6], self-control [7], economics [8] and others are reduced to the management of such a group of dynamic OCP. The tasks of recognising the semantic events *SN*, and *SceN* are characterized by irregularity, discontinuity of changes in time of development of transient processes [9, 10]. The tasks of increasing the stability of the work of local sections of the network are solved by modelling in CAD. This will make it possible to control the required response speed of the equipment to changes in the network operation modes within the permissible limits in real time [11, 12].

ANALYSIS OF LITERARY DATA

There are known problems of parametric adjustment of the OCP in the control loop, which operate under conditions of steady-state processes [13]. However, the application of methods for solving control and protection problems under conditions of development of transient processes (in case of damage, switching, etc.) does not ensure the stability of the operation of RPA devices [14, 15].

Further, we will consider dynamic OCPs during the development of short-term semantic events in the changing internal structure of OCPs (Fig. 1) [5].

According to the developed structural-information (SI) method, sources of shock effects in the OCP (damage, operational switching, etc.), during their development, modulate the carrier industrial frequency ω of the network, forming information components [9, 10]. The transient signals in the OCP are detected by RPA devices according to the generalised OCP structural model [10, 11]. The interrelationships of elementary information events in the internal structure of the OCP are described by the generalised equivalent structure (GES) scheme [11, 12]. The terminal (TS), and non-terminal (NTS) symbols, *SN* situations, and *SceN* scenarios can be considered such events. They develop sequentially in steps *n*, *n+1*, *N* located on the time axis *t*. All elements of the GES scheme are involved in the formation of a selective semantic signal *S(t)=KS*Selectivity(t)–KB*Blocking(t)*, which takes into account two groups of information components “For” and “Against” the formation of the recognition result using the corresponding significance coefficients *KS*, and *KB*.

The flow of information in a dynamic OCP can be interrupted and resumed for various reasons. This property of the OCP during operation can lead to instability of the RPA devices, and, consequently, the entire system of the automatic stabilization of normal operation (ASNOM) of such OCP (Fig. 1) [5].

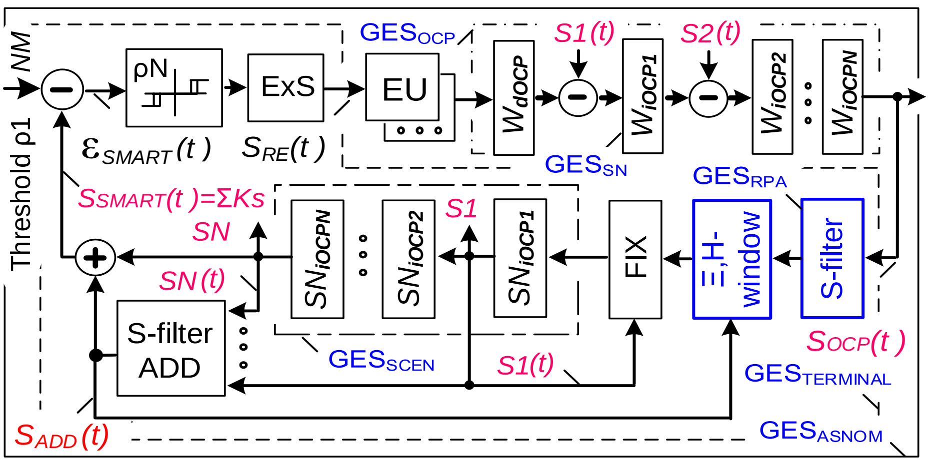

Fig. 1. **System the automatic stabilisation ASNOM of the normal mode “NM” of the OCP for the semantic signals $S_{TS}(t)$, $S_{RPA}(t)$, $S_{T\text{-}RPA}(t)$, $S_{SMART}(t)$, $S_{DISPATCHER}(t)$, and $S_{SCADA}(t)$.**
Source: **compiled by the authors**

FORMULATION OF THE PROBLEM. RELEVANCE OF DETECTING *SCEN* ARIES IN DYNAMIC OBJECTS

The need to recognise *SceN* scenarios was driven by the tasks of ensuring the stability of the algorithms when detecting rare events in the short-term U_{IN} input signals of RPA devices. According to previous studies carried out by the SI-method, the properties of dynamic objects in the electric power industry include the insufficient amount of information for making a decision, which appears due to the instability of the development of transient processes, the possibility of incomplete development of information components, passing through a variety of scenarios [15, 16]. Insufficient amount of information *Q* is the cause of detection errors during recognition [5, 15].

It is known that operating with the durations of the circular frequency ω, used for continuous, regular, repetitive information components or parts of the circular frequencies, significantly limit the possibility of reducing the total recognition time for short-term, irregular events. It is also known that with inertial signal processing methods, the amplitude (AFD), and synchronous (CFD) detectors generate a zero component. Such inertial detection methods turn out to be too wasteful for the considered tasks of processing short-term irregular signals.

The developed method of dynamic recognition is based on the principle of formation and control of the corresponding sequences in the chains of short-term open Ξ,H-windows selectivity (Fig. 2). The windows reflect the internal structure of the OCP and set the correctness of the appearance of the elementary information components TS, and NTS.

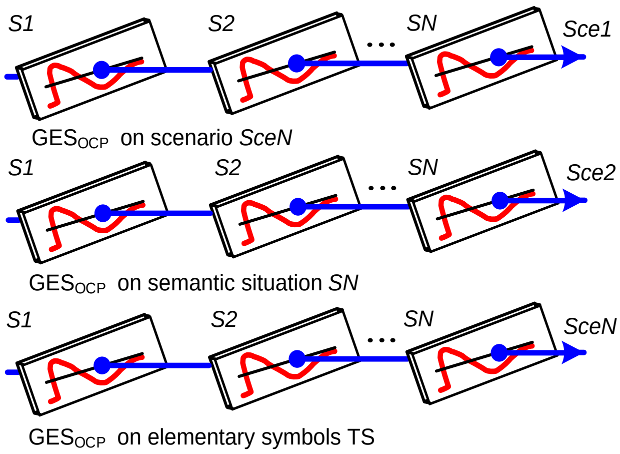

Fig. 2. **Situational, and scenario dynamic stages determined by Ξ,H-selectivity windows**
Source: **compiled by the authors**

The main function of the windows is to protect the recognition algorithm from interfering *SceN*, *SN* “by meaning”, which are structurally located in the U_{IN} input signals, and they cannot be eliminated by signal filters in the information channels of U_{IN} devices.

Each component is formed by the amplitude “Ξ” and time “H” parameters of the U_{IN} signals. The initial amplitude Ξ-window starts when the initiating TS1 appears, which is known for a specific transient recognition problem [7, 8]. The result of each Ξ,H-window triggering has its own significance *KN* coefficient. Decision-making can be carried out on the fact that the threshold ρN is exceeded and with the duration “H” of this fact for a given time by the semantic signal $S(t) \geqslant \rho N$ (Fig. 1).

Let us divide the recognition process in the RPA devices into situational, and scenario dynamic stages, determined by their Ξ,H-windows of selectivity (Fig. 2). At the situational stage, the movements in the oscillatory circuits OCP are recognised by detecting the values of the parameters A, ω, φ of the signals of the input coordinates U_{IN}. The *SN* situation is movement in the oscillatory circuits of the OCP. It can be the simplest, for example, consisting of one TS or consisting of all elementary information components. Such recognition is performed by Ξ,H-windows of selectivity of the semantic situation *SN*.

At the scenario stage, logical sequences of changes in the values of these parameters in time *t* are recognised, as well as the change of one *SN* situation by another *SN* at successive steps *n*, *n+1*, *N*, *t*. That is, the amount of information *Q* is accumulated sequentially step by step. The *SceN* script can be elementary, consisting of two consecutive TS, different *SNs*, or be “complex” corresponding to the $G_{SCE}N \rightarrow (TS, S1, S2, \ldots, SN)$, grammar describing the structure of the $GES_{SCE}N$ tree schema. This scenario recognition $SceN=\Sigma SN$ is performed by the logical Ξ,H-window selectivity. According to monitoring in real OCPs, the number of *SceN* scripts can be a limited number, for example, *N*=25 pieces. Consequently, there is a problem of recognising the presence of *SN* situations and the sequence of their development in the scenarios $SceN=\Sigma SN$.

OBJECTIVES OF THE STUDY

The aim of the work is to develop a method for improving the *SceN* scenario recognition algorithms based on selective search (SP) of sequentially developing information components to fill the volume of information *Q* with automatic decision making at each hierarchical recognition level. To compose a joint mathematical SI-model of the OCP, and RPA devices for solving problems of analysis, synthesis, and construction of the algorithms for obtaining additional information step by step as the selective, and blocking information components develop. Propose ways to solve the problem of increasing the stability of the selective relay against earth faults in the electric power networks of a smart grid with a Petersen's coil with a voltage of 6-35 kV on the basis of the developed method.

Let's focus on solving the problem of increasing the stability of the RPA devices. The solution will make it possible to synthesise, improve the algorithms for the operation of devices and maintain the efficiency of using devices in specific places of their placement over long intervals of time, taking into account specific operating modes.

In previous works, a name was given to each elementary information component of TS, and NTS, semantic *SN* situations, and *SceN* scenarios [5], [9, 10], [11, 12], [14, 15]. This will further develop the proposed mathematical SI-model $GES_{OCP} \approx GES_{RPA}$ for the hierarchical level of *SceN* scenario recognition.

Based on the SI-method, recognition algorithms are divided into three hierarchical levels – morphological, syntactic, and semantic. For each level, a GES scheme is synthesised. Accordingly, to build an S-detector for recognising *SceN* scenarios, it is necessary to build an OCP the SI-model with hierarchically subordinate script trees $GES_{SCEN} = \Sigma GES_{SCEN} = GES_{TS}$, where each *SceN* tree consists of the subordinate trees of semantic situations GES_{SN}, and each *SN* tree consists of elementary TSNs, where *N*=1,2, … (Fig. 4). Thus, there is a subordination of grammars G_{TS}=(TS,NTS,S), G_{SN}=(TS,NTS,S,SN) and G_{SCEN}=(TS,NTS,S,SN,SceN).

The recognition task associated with RPA, and OCP management is characterized by the intersection of *SN*, and *SceN*. Generally speaking, in order to increase the robustness of the RPA algorithms for each *SN*, and *SceN* overlap area, it is desirable to define its own TS information sensor. For this, according to information theory, it is necessary to supply an excess amount of information for the purposes of rechecking, determining errors, recovering information in case of errors [15, 16], [17, 18]. In practice, this important property is not implemented in the RPA devices. This also leads to recognition errors.

In the real OCP, there are third-party processes that are not associated with typical *SN* situations and *SceN* scenarios [18, 19], [2, 21]. They can be present for a long time; they are registered by some TS in the RPA. They need to be detected; a named list should be formed and taken into account when making decisions as rules for *PB* blocking.

The more qualitatively it is necessary to determine the current *SN*, and *SceN*, the more TS should be included in the structure of recognition automata A. The criterion for optimizing the solution

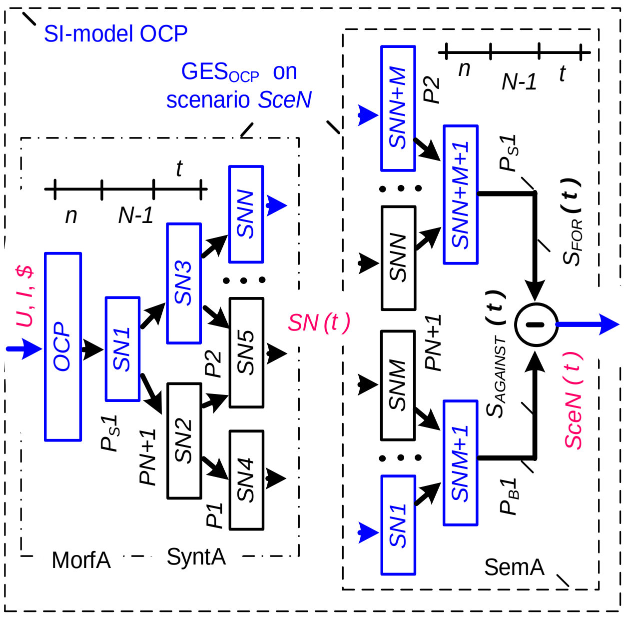

Fig. 3. **SI-model OCP. Scenario tree *SceN* in the dynamics of the development of the semantic signal *S(t)*. Formation of two information flows "For–Against" in steps *n*,…, *N-1, t***
Source: **compiled by the authors**

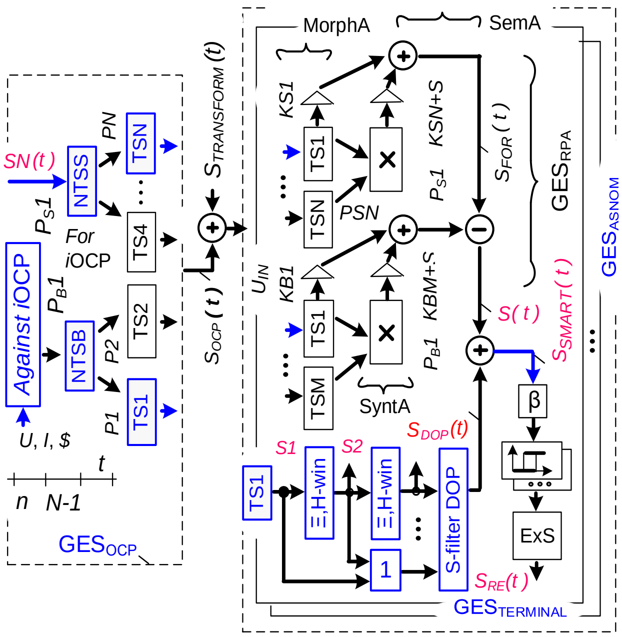

Fig. 4. **Joint SI-model OCP, and RPA. Scenario tree *SceN* in the dynamics of the development of the semantic signal *S(t)* inside the OCP object**
Source: **compiled by the authors**

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of the problem is to minimize the number of elementary information components used. This optimization criterion is the ultimate task of constructing a mathematical SI-model of the OCP.

Consequently, specifying the task at hand, we propose below a method for synthesising an S-detector specifically for algorithms for recognising dynamic irregular sequential patterns that operate on instantaneous information components while maintaining the cumulative performance criteria. The dynamic recognition tasks should be performed based on the final result of the *SceN* script recognition. To ensure the stable operation of the S-detectors *SceN*, should be uniformly synthesised for each hierarchical level of recognition devices, namely, information sensors, relays, terminals, and SCADa systems (Fig. 5).

To solve this problem, it is necessary to build an information SI-model that mutually reflects the structures of the OCP, and RPA devices. In view of the universality of the concept of information, the SI-model can be proposed for unification in the industry, similar to the IEEE high-voltage network diagrams. This will allow using the SI-model to control the stability of the operation of different recognition algorithms.

MATERIALS AND RESEARCH METHODS. SI-SCENARIO RECOGNITION METHOD IN DYNAMIC OBJECTS STUDY

The SI-method being developed is based on two theorems "On the presence of a semantic signal in relay protection and automation devices" and "On the unity of description of structural diagrams in relay protection and automation devices" [9, 10]. The SI-method allows you to implement the stages of analysis, synthesis, improvement of stably working algorithms for the implementation of concepts for the development of the electric power industry – "Smart-Grid", "Digital substation", and "Services outsourcing" [5], [11, 12], [15].

According to the SI-method, the parameters of electrical signals are only carriers of elementary information components in *SN*, and *SceN*. The characteristic features of the input coordinates U_{IN} of the RPA algorithms are the natural space-time sequence of consideration of elementary information components.

In the ASNOM system, different hierarchical levels of recognition can be distinguished — relay, terminal, and SCADa (Fig. 1). For subsequent higher hierarchical recognition levels, the generated symbol S is the initial TS elementary information component. The amount of information *Q* for automatic decision making on the issuance of each the resulting symbol S is made up of elementary information components. Internal relationships in the structures of the OCP, and RPA devices are represented, respectively, by the GES_{OCP} shaping tree and the GES_{RPA} recognition tree (Fig. 3 and Fig. 4). $GES_{OCP} \approx GES_{RPA}$ schemes are described by grammars G_O = (TS, NTS, K, P, RS), where O is MorphA, SyntA, and SemA for TS, RPA, OCP, and ASNOM. The combined SI-model is built mutually reflecting the structure and grammar $G_{OCP} \approx G_{RPA}(TS,NTS,S,SN,SceN)$ with the corresponding elementary information components (Fig. 4) [5], [11, 12], [14, 15].

Further, in the work, the SI-method is improved as applied to the recognition of *SceN* scenarios for the development of information events in the OCP. The problem arises of recognising or dividing the information set *SceN*, and *SN*.

The GES_{SCEN} scenario tree consists of a number of *SNs* replacing one another logically sequentially in time *t* as the transition process develops (Fig. 1). Each *SN* characterizes the corresponding known (classical) state of the OCP. The transient process in the OCP consists of elementary *SceN*, and *SN*. The semantic situations *SN* also consist of the TS, and NTS chains, arranged stepwise (*n*, *n+1*, *N*). The *SN* situation is described by the grammar G_SN=(TS,NTS,S), where N=1, 2, ... The sequential formation of a chain of recognised *SNs* determines the scenario $SceN=\Sigma SN$ and, accordingly, is described by the grammar $G_{SCE}N$=(TS,*S1*,*S2*,*S2*,*SN*,S). That is, the *SceN* scenario is one of the paths according to the GES_{SCEN} scenario tree, which displays the direction of changing *SN* situations (Fig. 3). Among the *SceN* scenarios there can be elementary ones, which developed into one *SN*, with a duration of one-time interval (step) *n+1*, and complex ones, with multiple changes in undeveloped *SNs*. The duration of the formation of elementary information components (the terminal symbols TS, and nonterminal NTS) is different, but its beginning and completion are due to the regularity of transient processes in the OCP (Fig. 3).

For the power grids, the causes of *SN* situations are shock or asymmetric changes in the existing industrial parameters (amplitude A, frequency ω, phase φ). The relative change in the parameters occurs due to the components of the movements in the oscillatory circuits of the OCP (high, medium, industrial low-frequency, low-frequency envelopes).

The development of *SceN*, and *SN* in the OCP makes it possible to extract additional information by the P_{ADD} re-recognition rules. The P_{ADD} automaton controls the sequence of *SN* situations in the chains of the script G_{SCEN} grammar. This leads to the formation of a makeweight ΔP_{ADD} with a certain weighting K_{ADD} coefficient. Further, the appendage ΔP_{ADD}, according to Fig. 1, either increases or decreases the overall semantic signal $S(t)=S(t)\pm S_{ADD}(t)$, depending on whether the *SceN* scenario is recognised as selective or as blocking.

At any time, stage in the development of the *SceN* scenario, the transient process in the OCP can stop and the sequence of filling the volume *Q* is interrupted. Therefore, the correspondences of the components for different parts of the OCP, recognised at the current time moment *t*, form their part of the value of the additional weight ΔP_{ADD}, which changes the current signal level *S(t)*. This makes it possible to separate the signal levels *S(t)* for the damaged and undamaged sections of the network as the transient process develops in the OCP.

For each the hierarchical level of recognition, the decision to issue the resulting root symbol S is performed by the corresponding P_{ADD} rules (Fig. 1). In the formation of the general semantic signal $S_{SMART}(t)=S(t)\pm S_{ADD}(t)$, P_{ADD} are involved, corresponding to each hierarchical level — the $P_{ADD\text{-}TS}$ rules for the very initial level TS, the $P_{ADD\text{-}RPA}$ rules for the relay level, $P_{ADD\text{-}TERMINAL}$ for terminal level, $P_{ADD\text{-}ASNOM}$ for system level (Fig. 1).

The P_{ADD} rules for correcting *SN* situations apply similarly, when the initially blocked S-filter, while continuing the development of the transient process in the OCP, accumulates a sufficient amount of information *Q* to make a decision on unblocking or to issue a resulting signal.

RESULTS OF STUDIES. ADVANTAGES OF CONSTRUCTING THE DETECTOR OF THE UPPER RECOGNITION LEVEL

In cases where the development of the transient process in the OCP stops, the internal elements of the RPA devices contain information that forms a certain residual signal level *S(t)*. Such information can be analyzed at higher levels of recognition. This is important when recognising "complex" *SNs*, *SceNs*, their prehistory, breaks and terminations of intermediate states, interference, and more.

Based on obtaining the final result, the developed method of S-detection can be called as follows – "Dynamic recognition of *SceN* scenarios of *SN* semantic situations based on the control of the optimal amount of information *Q* for making a decision by a multi-threshold element ρN by means of a semantic signal *S(t)* and Ξ,Η-windows selectivity".

The advantage of the developed method for detecting *SceN* consists in giving a result about a specific chain of development of the transient process according to the OCP SI-model. We will consider two options for issuing the result. The first option is performed by forming *SN* chains corresponding to each *SceN* scenario, therefore, requires a memory block in the ExS expert system (Fig. 1). The output of the *SceN* detector is an indication of the name of a specific scenario *SceN*, selected from the list of answers *N*=1, 2, ..., laid down at the stage of training the recogniser. Another variant of issuing the result by the recognition algorithm is performed by means of a single semantic signal *S(t)*, the trajectory of the change of which is formed by the accumulation of the volume of information *Q* at all hierarchical levels. In this case, the result will be one of a number of known responses – "Normal mode" or "NM", "NotNM", "Pre alarm", "Alarm". These answers are widely used in the practice of operating RPA devices – relay, terminal, SCADa-system and are a sufficient result for most application tasks [11].

CONSTRUCTION OF A JOINT DYNAMIC SI-MODEL OF THE OBJECT AND RECOGNITION DEVICES

To synthesise the structural diagram of the P_{ADD} additional recognition block, we will compose the SI-model of the OCP (Fig. 1). Let us put the correspondence between the recognising and forming parts of the *SceN* recognition tree in OCP (Fig. 3). The formative part in OCP generates the development of the transient during the development of the *SceN* scenario. The *SN* chains are divided into two parts "For" and "Against" in relation to the end result – identification of the damaged OCP site. The part "Against" includes the chains *SN* "Unrecognisable", *SN* "Mismatch", *SN* "Interference", *SN* "Intact section". Thus, with a long-term qualitative development of transient processes at the output of the *SceN* detector, the value of the resulting signal *S(t)* of the damaged and non-damaged OCP sections will diverge with respect to the initial level. This allows you to accumulate the necessary amount of information *Q* for making a decision.

The scenario formation tree is made up of situations formation trees according to $GES_{SCEN}=\Sigma GES_{SN}$. The stable state of the OCP parameters can be distinguished and named *SN*. When viewed dynamically, the SI-model OCP is initially in the *S1* "NM" semantic situation. That corresponds to the steady-state values of the internal parameters of the OCP (operator outputs, NTS symbols, *P* rules).

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A) DESCRIPTION OF THE OCP STRUCTURE BY TREES OF FORMATION GES$_{SCEN}$ AND GES$_{SN}$

A working OCP in the power industry can only be divided into operatively detachable sections, therefore, its internal structure is largely unobservable.

Among the semantic *SN* situations, and *SceN* scenarios, the following can be distinguished:

a) formed only by the GES$_{TS}$ scheme;

b) starting with incomplete development of all elementary information components;

c) starting with the formation completely by the GES scheme and further develop until the complete completion of the transients in OCP, etc.

According to the SI-method, the concept of a semantic *SN* situation means the appearance of a reaction ΔU_{OUT} of the OCP structural scheme to a change in Δ in any OCP coordinate. It also understands the structural, logical relationship of individual TS control points in the SI-model of the OCP or equipment, which form the signals of the transient process (Fig. 5). And also, under *SN* is meant a part of the OCP formation tree with activated root symbols *PS*, and *PB*, then NTS, and TS. Situation *SN* template means the sequence of symbols *PS*, *PB*, TS, and NTS of the OCP tree established for this *SN*, which is formally described by the G$_{OCP}$ grammar.

These definitions of the *SN* situation are based on the description of the OCP, and based on the RPA devices they are introduced in the form of an analogy – each *SN* corresponds to a sequence of filled Ξ,H-selectivity windows (Fig. 4) and (Fig. 5). The OCP generation tree can be planned using the TSN/SN table. The table is filled based on the emergency files, as well as when calculating OCP models and GES$_{RPA}$ schemes in CAD [5], [12], [15].

Specifying the problem posed, we will focus on the further synthesis of the mathematical SI-model of the OCP in order to obtain an additional amount of information *Q* and use it in the GES$_{RPA}$ recognition tree to increase the stability of the RPA algorithms.

The synthesis of the script recognition tree GES$_{SCEN}$ is performed deductively according to the templates GES$_{SCEN}$=ΣGES$_{SN}$=ΣGES$_{TS}$. The GES$_{SCEN}$ tree is synthesised as follows. On posters with the reaction of the recognition algorithm, a search for new elements of grammars G = (TS, NTS, *K*, *P*, S) is performed in the interrelationships of signals obtained during modelling in CAD as additional ones [14, 15]. It is necessary to get the largest number of additional elements in the G$_{OCP}$≈G$_{RPA}$ grammars.

To do this, the path of shock impacts is traced from their place of origin to the exit through the OCP coordinates to the input of the recognition

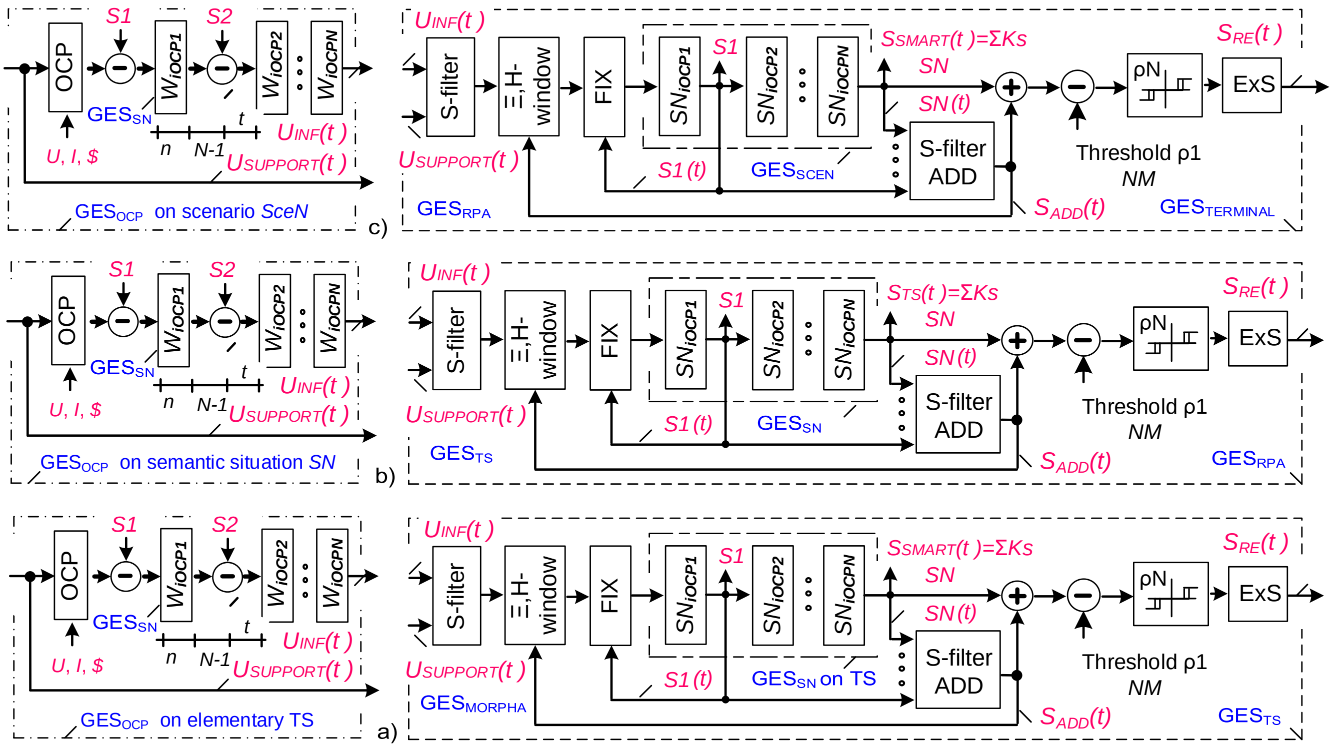

Fig. 5. **Joint OCP and RPA circuits at different hierarchical levels of SN(t) chip formation: a – GES$_{TS}$ sensor; b – GES$_{RPA}$ relay; c – terminal GES$_{TERMINAL}$**

***Source:* compiled by the authors**

system and then according to GES patterns to the desired output of the control system (Fig. 3 and Fig.4) determine a tree of possible developments *SceN* and a list of scenarios *N*. Each path of passage along steps *n* of the time axis t of an elementary information component of interest is fixed in the structures of templates, which are GES_{OCP}, GES_{SN}, and GES_{ASNOM} schemes, individual *SN* situations, and *SceN* scenario.

To synthesise the mathematical SI-model of the recogniser in the RPA devices, the unobservable structure OCP is replaced by the tree of equivalent generators GN [10]. Then, the internal structure of OCP becomes observable and formalized $GES_{OCP} \approx GES_{GN} = GES_{RPA}$. For example, when replacing elements covered by feedbacks in Fig. 1 and Fig. 2, one transfer function results in a more general OCP scheme in the form of a unidirectional *SN*→TS formation tree (Fig. 1). The scheme allows solving modelling problems and information problems of the smart-grid [14, 15].

The dynamic control of GN generators simulates signals corresponding to the transient signals detected in real OCPs. According to the signals of transient processes, it is possible to mutually equivalent and compare the internal elementary information components. It is possible to recover the cause of damage development based on transient signals in real emergency files. This allows you to synthesise a recogniser with the highest recognition rate and the best stability.

The SI-model of the OCP is implemented in CAD based on functional modelling, taking into account real emergency files [22, 23], [24, 25], [26, 27]. Taking into account the individual characteristics of specific OCPs will be reserved for the tasks of adapting or improving structures [28, 29], [30, 31], [32]. The general solution of the problem is achieved by modelling the recognition process on the training and control samples of signals from real emergency *SNs* [14, 15].

The SI-model of OCP or individual equipment will allow solving the following tasks:

a) it is possible to introduce situational information events from signal sources at a certain moment of the transient process, interfering with the current situation *SN* "NM". For example, such actions as disconnecting, changing parameters, short-circuiting or shunting a single element, a series of elements in the SI-model of the OCP (Fig. 8);

b) the minimum information for building the SI-model of the OCP is two elements of the information part of the *i*OCP – selective TS or blocking TS (Fig. 3). In the $S_{OCP}(t)$ limit, a single *SN* can be specified. This allows you to reduce the time of a single calculation when modelling a mathematical model in CAD. Also, the minimum OCP model will be a couple – a signal source $S_{OCP}(t)$ and a controlled generator GN. The generator can have amplitude, frequency, phase modulation of the output signal from the super-LFC–HFC range, depending on the problem being solved. Such SI-models of OCP minimize the time of a single calculation;

c) the algorithm for recovering the $S_{OCP}(t)$ signal from the OCP SI-model can be used to analyze the accumulated emergency files (Fig. 1 and Fig. 2). For this, the models of the expert system ExS and the generator of diagnostic messages are used (Fig. 4).

B) DESCRIPTION OF DEVICES WITH SCENARIO RECOGNITION TREES GES_{SCEN}, GES_{SN}

One of the tasks of RPA algorithms is to recover *SceN* scenarios that occurred at the highest semantic recognition level. The filling of the volume of information *Q*, necessary for the recognition stability, is based on multi-point and multiple detection of the parameters of information components by a number of the amplitude AD and the synchronous SFD elementary detectors, on the recognition of *SN*, and *SceN*.

To solve this problem, it is possible to create a SI-model of RPA devices based on hierarchically subordinate *SN* trees (Fig. 4 and Fig. 5). At this level of recognition, a significant part of the non-selective operation of devices occurs due to the limited or lack of appropriate *PN* rules in their algorithms.

Trees are described by the "GES_{OCP} by *SN* situation" scheme (Fig. 5). It is possible to distinguish schemes "GES_{OCP} on oscillatory circuits" to consider the issues of separation of movements and the scheme "GES_{OCP} on semantic situations *SN*", which shows movement in terms of meaning, in *SN* situations. The task of optimizing the construction of the SI-model is to describe the OCPs that return all possible relationships in the synthesis trees *SN*, *SceN*. They are typical for OCP, and should have their own names (for example, *SceN* "Intermittent arc", *SceN* "Self-liquidating multiple breakdowns".

The GES_{RPA} tree is built based on the initial and final states of the normal *SN* "NM" operation of the OCP. *SN* "NM" situation is used for relative comparison of emerging *SN*, and *SceN* with normal OCP mode.

SN "NM" includes:

a) start *SN* "NM start";
b) terminating *SN* "NM termination";
c) *SN* "Processes not related to the task";
d) *SN* "Neutral offset".

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These *SNs* are caused by exceeding the normalized levels of the low-frequency components (LFC) and are the result of the operation of the technological equipment of the distribution network. The although *SN* "NM" does not belong to the reasons for the appearance of the transition process in the OCP, it is with it that the analysis of the processes into structural information components begins and ends (Fig. 3) and (Fig. 4).

The characteristic *SN* situations are distinguished as different stages of the transient process (Fig. 4 and Fig. 5). For example, the initial breakdown (the first *SN* in the OCP until the moment of a clearly pronounced OCP reaction), then the OCP reaction to the initial *SN*, subsequent *SNs* and recovery *SN* "NM completion" after the elimination of the *SceN* scenario, a particular case of which is a single-phase earth fault (OPG). These named elementary *SNs* constitute the GES formation tree "GES$_{OCP}$ by *SN* situation", and hence the RPA device recognition tree [5], [9, 10], [14, 15].

SYNTHESIS OF SCENARIO DETECTION METHOD BASED ON THE Ξ,H-WINDOWS OF SELECTIVITY

To synthesise the method, let's bring together the requirements for the implementation of the S-detector in the RPA device based on the tasks of the upper level of *SceN* recognition:

a) determination of the type of the entire transient process. That is, receiving a response about the ultimate reason for the elimination of the event in the OCP;

b) implementation of the recognition method based on the control of the amount of information *Q* for making a decision;

c) change of the initial state of the S-detector from the initial blocked to the working one and vice versa in cases of determining the situations *SN* "Unrecognizable", *SN* "Interference", *SN* "Third-party processes";

d) formation and transmission of information about elementary information components for higher hierarchical levels of recognition;

e) increasing the stability of the device when some *SN* are replaced by others, interrupting the development of *SN* "Interference", *SN* "Unrecognisable" and *SN* "Unrelated to damage";

f) building a queue of favorites of the OCP sections to disconnect the damaged section in case of complex damage development;

g) redefining the damaged area of the OCP to another area in the event of self-destruction of the damage site and the occurrence of damage in other areas of weakened insulation;

h) formation of the device operation protocol for the subsequent analysis of the accident and the stability of the algorithm.

According to the SI-method, single events in the OCP develop within a small section of the trajectories of the considered dynamically moving point *Attr* (point attractor) according to the signal of the transient process in the OCP (Fig. 6). Therefore, the S-detector algorithm also allows you to control the entire structure of transient processes using the Ξ,H-selectivity windows at the final hierarchical recognition level. The development of events in the signal *S(t)* is controlled by the amplitude "Ξ" during a certain interval of selectivity "H".

The operation of the S-detector circuit is considered as a sequence of dynamic steps *N*=1, 2, ... of information processing at the control points of the constituent algorithms of its automata A.

The morphological automaton MorphA is the initial hierarchical level. The recognition process is considered as the passage of elementary information components through the elements of the OCP circuit and, then, leading to the appearance of recognition results at the control points of the S-detector.

The middle hierarchically subordinate level is the syntax level SyntA. Performs structural analysis (grammatical analysis) of information received from

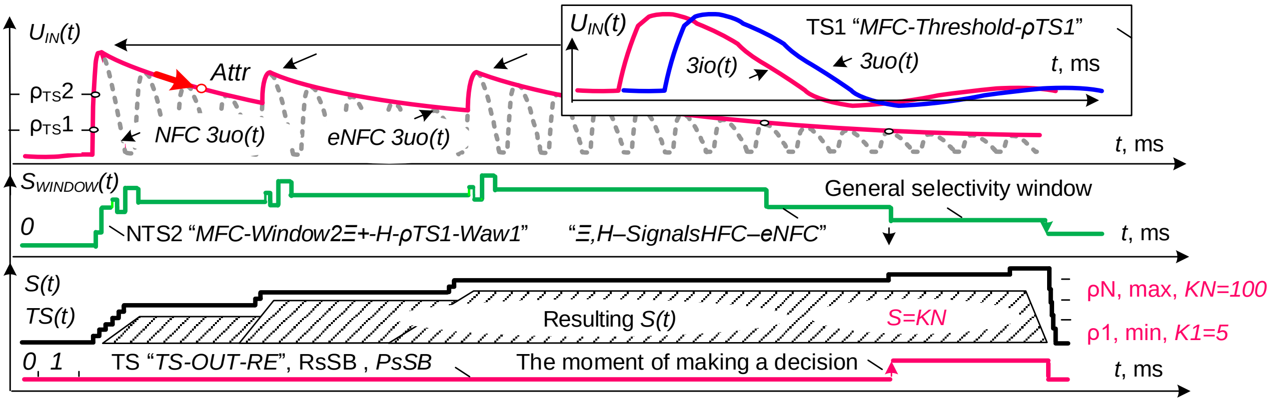

Fig. 6. **Synthesised common Ξ,H-window in the dynamics of *SceN* development**
***Source:* compiled by the authors**

the output of the second hierarchical level. In other words, a decision is made whether the TS strings are syntactically correct or not according to the given grammar G.

The S-detection method for *SceN* scenarios is applied uniformly to each hierarchical level of information processing when recognising dynamic patterns.

ALGORITHM OF SENSE DETECTION *SCEN* BASED ON Ξ,H-WINDOWS OF SELECTIVITY

Three hierarchical levels of recognition are involved according to the schemes $GES_{TS} \rightarrow GES_{SN} \rightarrow GES_{SCEN}$ (Fig. 5).

The recognition algorithm based on Ξ,H-selectivity windows is as follows:

A) *Step n* "Initial unlocking". It is the initial step in the sequential queue of recognition steps *n*, *n+1*,…, *N*. The initial Ξ,H-window "*GES_{SN}* Initialization" is opened (cocked) upon the appearance of an initiating event in the U_{IN} input signal. The initiating event is highlighted by the threshold element ρTS1 and triggers the initial Ξ,H-selectivity window. This is the initial stage of the GES_{RPA} recognition tree (Fig. 3 and Fig. 7). Further, during the duration of a certain waiting interval of the current H-window, the fact of occurrence of an event in the input signal U_{IN} is checked. Then the H-window is closed upon the appearance of the expected desired event.

As a result, the corresponding symbol TS1 "Initialize GES_{SN}" is generated. If the expected event in the U_{IN} signal did not appear during the operation of the H-window, then at the end of the waiting interval the H-window closes on its own and the TS1 symbol is not issued.

Further, if a corresponding information event appears in the U_{IN} signals, subsequent Ξ,H-windows are launched according to the GES_{RPA} scheme and the FIX fixation block is activated (Fig. 1), which leads to the sequential accumulation of elementary information components and the formation of a semantic signal *S(t)*.

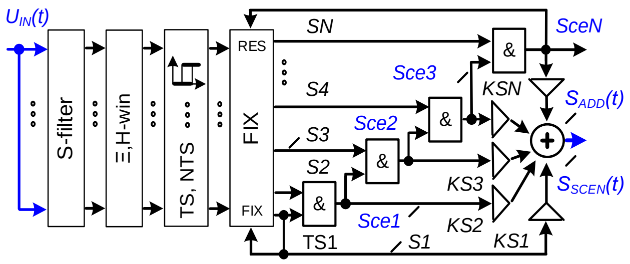

Fig. 7. **Block diagram of the S-detector *SceN*. Recognition of the top hierarchical level of dynamic pattern recognition**
Source: **compiled by the authors**

In cases of occurrence of inappropriate events in U_{IN} signals, other threshold elements of ρTSN are checked by the next Ξ,H-selectivity window that the next desired event has appeared in U_{IN} signals.

If the development of U_{IN} signals is not confirmed by the next opened Ξ,H-window, the FIX block will be disabled and the signal *S(t)* will then cease to be generated. In this case, during the duration of the H-window, there will be information about the symbol TS1, which means the semantic situation *S1* "Interference";

B) *Step n+1* "Recognising *SN* situations". Each Ξ,H-window at the recognition step *n+1* launches the next Ξ,H-window or several different windows according to the dynamic sequence of NTS in the trees for recognising GES_{TS} symbols, GES_{SN} situations and, accordingly, the hierarchically superior script tree GES_{SCEN} (Fig. 3 and Fig. 7).

So, upon the appearance of a certain symbol TS or NTS in the chain of symbols, upon the triggering of the corresponding threshold element ρTSN, the fact of the appearance of a certain desired event in the next Ξ,H-window is checked. If the monitored event appears in the U_{IN} signal, the current Ξ,H-window is closed within the duration of the waiting interval "H" set for this window. If the required event does not occur in the U_{IN} signal, then the window closes on its own after the duration of the H-window time has elapsed. Closing the Ξ,H-window leads to the formation of NTS, which opens the next window. In this case, the controlled pieces of information in the U_{IN} may appear in another window, then the recognition will go in a different direction in the GES_{SN} recognition tree. If the required events do not appear in the U_{IN} in any of the windows of the GES_{SN} tree, the recognition process ends (Fig. 3, Fig. 4 and Fig. 5);

C) *Step N* "Recognising Scripts". The scenarios *SceN* are recognised, which in turn consist of the semantic situations *SN* according to the GES_{SCEN} recognition tree. The presence of a number of sequences of opening of Ξ,H-windows is formed in the GES_{SCEN} scheme (Fig. 3 and Fig. 7). The appearance of certain windows in the tree depends on the specific dynamic development of transient signals. Thus, the appearance of real U_{IN} signals in the initial windows of the GES circuits leads to the control of the fact of synchronization between the windows. This fact triggers the appearance of new windows (see Fig. 7, arrows of the line "General form of the selectivity window for HFC–MFC").

As a result, the *SceN* scenario for the passage of Ξ,H-windows is recognised (Fig. 6). Each fact of such events is recorded as new NTS symbols with weights *KN*. As a result, a semantic signal is formed *S(t)*.

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APPLICATION OF THE METHOD IN DETECTING DEVICES AT DIFFERENT HIERARCHICAL LEVELS

To implement the set tasks, it is necessary to delegate the ability to recognise *SceN* scenarios to the lowest hierarchical recognition level when preparing elementary information components, that is, to the level of the GES_{TS} sensor circuit. This will lead to the implementation of the structures of sensors, relays, and SCADa, the synthesis of their schemes $GES_{SCADA}=\Sigma GES_{RPA}=\Sigma GES_{TS}$ in a uniform way and to the unification of this approach to improve devices and measurement systems.

Preferred is a relative detection method that compares the input reference signal $U_{PIVOT}(t)$ with the output information signal $U_{INF}(t)$ passed through the OCP (Fig. 5). The S-detector detects the difference between these signals. If the reference signal is unavailable, it is necessary to build detectors according to the absolute method of obtaining information. It is known that this detection method has a drawback – all changes in the signal, including interference, extraneous signals will also be detected and penetrate to the output. In view of the fact that these two principles are fundamental, we will further orient ourselves in the synthesis of the semantic S-director to, first of all, the synchronous SFD modifications of the relative detection method and, forcedly, to the amplitude AFD at all the hierarchical levels of recognition.

We will consider two interrelated ways of implementing the recognition algorithm. The simplest way of implementation is to add/decrease the value of the semantic signal *S(t)*. A more capacious way of implementation is storing the recognised elements of the grammar G in the memory elements in the fixation FIX block (Fig. 1, Fig. 5 and Fig. 7).

A) APPLICATION OF THE METHOD IN DEVICES AT THE INITIAL HIERARCHICAL LEVEL "SENSOR"

At this level, the *SceN* scenario means sequences of elementary internal information structural blocks of sensors, which are control points or outputs of structural elements of the GES_{TS} tree circuit (Fig. 5 and Fig. 7) [5]. The GES_{TS} scheme is characterized mainly by the sequential appearance of the elementary information selective and blocking components. The development of one *SN* situation can stop and resume at any time. With the further development of the transient process in the OCP, at the output of the S-detector, the TS symbol will give a signal about the recognition of the *SN* corresponding to this hierarchical level, hence, *SceN*. Information at the TS level in the form of various "simple" *SceNs* of the least complexity must be prepared for use at higher hierarchical levels.

B) APPLICATION OF THE METHOD AT THE HIERARCHICAL LEVEL OF THE "RELAY", "TERMINAL" DEVICES

The input information of this recognition level is TS prepared at the outputs S in the sensor structure of the previous hierarchical level [11].

The GES_{RPA} tree scheme is characterized mainly by the parallel formation of the selective and blocking components (Fig. 5 and Fig. 7). This is due to the preliminary preparation of TS by all sensors. The outputs of the internal elements of the GES_{RPA} circuit go to the corresponding fixing FIX block in the GES_{RPA} block diagram, from where the trigger data can be used for recognition.

A number of outputs about the indication of the recognised *SceN* scenario can be implemented in the GES_{RPA} circuit or in the circuit for connecting a relay, a terminal to the OCP. With the software implementation of a relay, terminal on microcontrollers, data is issued about the triggering of each symbol of the TS, NS, S, *SN*, and *SceN* over the local network and/or, if necessary, upon request from the senior hierarchical level of recognition devices. The main way of accounting for information is formed by means of the signal *S(t)*.

C) APPLICATION OF THE METHOD AT THE FINAL HIERARCHICAL LEVEL "SCADA"

The most difficult *SceN*, and *SN* are recognised [14, 15]. The GES_{SCADA} scheme is also characterized by the parallel formation of the selective and blocking components (Fig. 1, Fig. 7 and Fig. 6). The task of the SCADa is to provide information on the essence of transient processes in the OCP, on the result of recognising the existing *SceN*, and *SN* in the OCP operation, forming recommendations for operating personnel, emergency files for analysing the accident, commands for localizing accidents, blocking personnel wrong actions, diagnosing malfunctions [33, 34], [35, 36] and monitoring the current the state of the OCP with and without the participation of operating personnel [37, 38], [39, 40]. It is implemented graphically on the SCADa screen in the form of a widget with filled active places on semantic messages prepared to help operational personnel.

CONCLUSIONS

1. A method for recognising scenarios of development of transient processes in dynamic objects "Dynamic recognition of the *SceN* scenarios

of the semantic *SN* situations based on control of the optimal amount of information *Q* for making a decision by a multi-threshold element ρN by means of a semantic signal *S(t)* and Ξ,H-windows of selectivity" is proposed. The method is based on delegation of scenario recognition uniformly to all hierarchical recognition levels – sensor, relay, terminal, and SCADa. Allows to build an SP-algorithm for selective search of the required amount of information for automatic decision-making. Examples of the application of the proposed method for different hierarchical levels of recognition in the electric power smart-grid networks are given.

2. A method for the synthesis of a combined mathematical SI-model of an object, and the devices based on elementary generators is proposed, which makes it possible to build recogniser models for the objects with incomplete information. The SI-model will help build recognisers with a high recognition rate for all the hierarchical levels. Individual features of objects are taken into account separately by additional the adaptation rules.

3. Examples of the application of the joint mathematical SI-model of the object, and devices, the method of dynamic recognition of the *SceN* scenarios for all the hierarchical levels of information processing – sensor, relay, terminal, and SCADa are shown.

The main example of application in the work is the problem of ensuring the stability of the operation of the algorithms of the ASNOM system of protection against single-phase earth faults in the medium voltage networks of 6-35 kV with an arc-suppressing Petersen's coil.

4. An algorithm for dynamic recognition of scenarios for the development of transient processes in an object is compiled on the basis of a tree, grammars, Ξ,H-selectivity windows, weights of multi-threshold elements. The S-detector algorithm for *SceN* scenarios of semantic situations *SN* is implemented at each hierarchical level of recognition in the system for automatic stabilization of the normal operation of the network.

5. Two types of structural schemes of the S-detector of *SceN* recognition scenarios based on the formation of a semantic signal, taking into account additional elementary information sensors of the dynamic recognition, are given.

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Детектування сценаріїв розвитку динамічних подій у електроенергетичних мережах смарт-грид Частина 1 «Спосіб»

Віталій Федорович Сивокобиленко[1)]
ORCID: https://orcid.org/0000-0002-7720-0540; svf1934@gmail.com. Scopus Author ID: 6603906155 and 55553493200
Андрій Петрович Нікіфоров[2)]
ORCID: https://orcid.org/0000-0002-3724-430; a.p.nikiforov@i.ua. Scopus Author ID: 57191825673
Іван Вадимович Журавльов[3)]
ORCID: https://orcid.org/0000-0003-4879-4666; ivanvzhuravlov@gmail.com
[1)] Donetsk National Technical University, 2, Shybankova Square. Pokrovsk, Donetsk region, 85300, Ukraine
[2)] Education and Research Institute of Energetics, Automation and Energy Efficiency,
National University of Life and Environmental Sciences of Ukraine, 12, Heroiv Oborony, Str. building 8. Kyiv, 03041, Ukraine
[3)] SICAME SAS France, 39 av. du Midi, St. Sornin Lavolps, France

АНОТАЦІЯ

Пропонується спосіб побудови смислового S-детектора для старшого ієрархічного рівня розпізнавання образів в динамічних об'єктах. Спосіб S-детектування заснований на однаковому синтезі всіх ієрархічно підлеглих детекторів і схем підготовки інформації, виходячи із завдань верхнього ієрархічного рівня розпізнавання сценаріїв розвитку процесів в об'єкті. Спосіб може застосовуватися для вирішення завдань релейного захисту, протиаварійної автоматики, виявлення рідкісних подій в імпульсних, короткочасних вхідних сигналах при реалізації концепції розвитку смарт-грид електроенергетичних мереж. Синтез S-детектора сценаріїв розвитку перехідних процесів став наслідком розробки структурно-інформаційного SI-методу обробки інформаційних складових. Наведено математичну SI-модель, що дозволяє контролювати взаємну відповідність структури дерева формування в об'єкті та дерева розпізнавання пристроїв. Ставиться завдання підвищення стійкості роботи алгоритму розпізнавання пристроїв. У Частині 1 наведено опис теоретичних положень застосування способу. Пропонується уніфікувати в галузі дерева формування сценаріїв розпізнавання, аналогічно схемам високовольтних мереж IEEE. Наведено алгоритм S-детектора, заснований на формуванні смислового сигналу і на селективному пошуку необхідного обсягу інформації для автоматичного прийняття рішень. Факти появи елементарних інформаційних подій у вхідних сигналах контролюються Ξ,Η-вікнами селективності, що послідовно відкриваються в залежності від попереднього розвитку подій. Наведено структурну схему S-детектора сценарію, який може бути синхронним, багатоканальним, із великою швидкістю обробки сигналу, без втрати швидкоплинної інформації при детектуванні повільної і понад повільної інформації. Поєднує корисні властивості миттєвих та інерційних алгоритмів детектування. Виходом S-детектора є ряд відповідей із різними ваговими коефіцієнтами. Це дозволяє об'єднувати елементарні детектори в послідовні ланцюжки на різних ієрархічних рівнях розпізнавання. У Частині 2 наведено приклад застосування способу детектування сценаріїв для вирішення завдання підвищення стійкості роботи селективного реле захисту від однофазних замикань на землю на основі середньо частотних сигналів в мережах 6-35 кВ із дугогасною котушкою Петерсена. Наведено результати моделювання роботи алгоритму S-детектора на сигналах реальних аварійних файлів, записаних високочастотними реєстраторами перехідних процесів в мережі.

Ключові слова: релейний захист; автоматизація; інтелектуальна мережа; однофазні замикання; семантичний сигнал; структурно-інформаційний

ABOUT THE AUTHORS

Vitaliy F. Sivokobylenko – Dr. Sci. (Eng), Professor, professor Department of “Electrical Engineering” Donetsk National Technical University, 2, Shybankova Square. Pokrovsk, Donetsk region, 85300, Ukraine

ORCID: https://orcid.org/0000-0002-7720-0540; svf1934@gmail.com. Scopus Author ID: 6603906155 and 55553493200

***Research field*:** Math modelling; transient processes; increasing the reliability; own needs of power plants; relay protection

Віталій Федорович Сивокобиленко – доктор технічних наук, професор, професор кафедри «Електрична інженерія» ДонНТУ, пл. Шибанкова, 2. Покровськ, 85300, Україна

Andrey P. Nikiforov – Dr. Sci. (Eng), Associate Professor, Associate Professor Department of “Power Supply” of Education and Research Institute of Energetics, Automation and Energy Efficiency. National University of Life and Environmental Sciences of Ukraine. 12, Vul. Heroyiv oborony. Kyiv, 03041, Ukraine

ORCID: https://orcid.org/https://orcid.org/0000-0002-3724-430; a.p.nikiforov@i.ua Scopus Author ID: 57191825673

Research field: Relay protection; capacitive current compensation; smart grid; single-phase earth faults; distribution networks; pattern recognition

Андрій Петрович Нікіфоров – доктор технічних наук, доцент, доцент кафедри Електропостачання Навчально-наукового інституту енергетики, автоматизації та енергоефективності Національного університету біоресурсів та природокористування України, вул. Героїв оборони, 12. Київ, 03041, Україна

Ivan V. Zhuravlov – Product manager (Eng). Duties: Product Lifecycle Management, Global market strategy development, Gathers and analyses market and competition research data, New product development assistant

SICAME SAS France, 39, av. du Midi, St. Sornin Lavolps, France

ORCID: https://orcid.org/0000-0003-4879-4666; ivanvzhuravlov@gmail.com

Research field: Relay protection; smart grid; single-phase earth faults; distribution networks

Іван Вадимович Журавльов – Менеджер із продукту. Обов’язки: управління життєвим циклом продукту, розробка глобальної ринкової стратегії, збір та аналіз даних із дослідження ринку та конкуренції, помічник у розробці нових продуктів. SICAME SAS Франція, пр. дю Міді, 39, місто Сент-Сорнен Лавольпс, Франція

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