CONTRIBUTIONS TO RELIABILITY MODELLING AND EVALUATION OF AUTOMATION STRUCTURE SUBSYSTEMS IN URBAN MEDIUM VOLTAGE ELECTRIC NETWORKS

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Abstract: The paper is structured in five parts. The first part is evoked the importance of the topic and current concerns. In the second part are presented the general pattern of reliability of the relay - the core of the automation subsystem (SSA). In the third part are given the models for the proposed development reliability evaluation in SSA, based on the general model, for a given structure of SSA and their functions in urban medium voltage electric networks (UMVEN). In part four are given the results of operational reliability evaluation for SSA as in the last part of the analysis the conclusions are presented.

Keywords: modelling, reliability protection system, electrical network.

1. INTRODUCTION

Reliability analysis and automatic protection system (APS) in structure of UMVEN are subordinated to the objectives of maximizing the availability of energy and UMVEN security. By maximizing the availability of energy is also obtained the maximizing of economic efficiency of UMVEN. Sometimes there is a tendency to minimize the importance of APS of UMVEN performance, because they are more reliable than the primary equipment (RPE). In fact, as it is shown analytically [1, 2, 3, 4, 5], APS and its elements are at a higher level plan in which the RPE and its equipment, the position that "intended" and if necessary, "occur" within the meaning of correct operation of the RPE and all UMVEN.

In a schematic form, a suggestive UMVEN of APS integration can be as in Fig. 1.

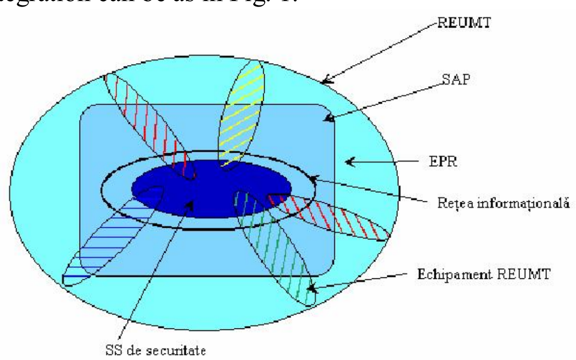

Fig. 1. Schematic representation of UMVEN and its components

Although APS and its components by its position in UMVEN (tracking and intervention) involves some features and treatment of reliability approach, by making the tests should be considered the interference between components of the RPE and APS (Fig. 1) and decisive impact of this reality on the UMVEN performances.

A reliability study requires a comprehensive approach of the APS related issues. The reliability is treated, from simple to complex as [6]:

- simple relay, as part of itself;
- complex relay consisting of several simple relays;
- protection subsystem (SSP) or subsystem automation (SSA), composed from one or more relays in connection with the complex measuring transformers, current sources and elements of the actuator;
- SSP or SSA and the actuator plus switching device (switch);
- protected element / automated and two cells, which is connected to power system;
- protected element, including "n" cells whose switching equipment, is controlled by APS.

The main specificities in reliability analysis of APS from UMVEN structure result from the operation and features of failure:

- need to operational request (intermittent);
- by unexpected power failure or refuse of operation.

The modelling of APS in reliability study of UMVEN may be made only by locating the correct line diagrams of their schemes and correct analysis of the effects of their operation or malfunction.

SSP notifies a failure occurring, fault locating and triggering control switches, which makes the connection between the primary elements of integrity and failure.

Two categories of indicators recommended for APS components [7, 8]:

a) Classical indicators (mainstream);

- Probability of good service (safety time): R (t);
- Mean time between the failures: MTBF;
- The probability of rejection (risk of not responding to the request):

$$q(\tau)=\frac{\lambda\cdot\tau}{2}+\gamma\;;\tau\;\hat{=}\;MTTR \qquad (1)$$

γ – probability of failure upon request

- Average number of unanswered requests during the "T":

$$\nu(T) = \nu_{EPR}(T) \cdot q(\tau) \qquad (2)$$

Classical indices can't fully characterize the reliability of APS and its components, whereas only refer to refusals ($\overline{RC}$) and quantifies their effect unexpected operation (INT ≡ false).

b) Complementary indicators

These indicators are intended for full characterization, (along with the classical one) the reliability of APS and its components.

- incorrect operation intensity (ER) of components / subsystems of APS is expressed as:

$$\lambda_{ER} = \lambda_{\overline{RC}} + \lambda_{INT} \qquad (3)$$

where,

$\lambda_{\overline{RC}}$ - intensity events "refusal response to commands" ($\overline{RC}$);

λ_{INT} - intensity of transmission of unexpected orders (false).

- The risk of events appearing ($\overline{RC}$, INT):

$$q_j(t) = 1 - e^{-\int_0^t \lambda_j(t)dt} \quad j = \{ \overline{RC}, \text{INT} \} \qquad (4)$$

- The statistics made about the reliability of APS and its components, will refer to variables of:

t_j – operating time without the variables "j"

$\nu_{i(T)}$ – number of events of "j" type during "T", period, where, j={ $\overline{RC}$, INT, ER}

- intensity of failure on ensemble:

$$\lambda_{ANS} = \lambda_{EPR} + \lambda_{\overline{RC}} + \lambda_{INT} \qquad (5)$$

The relay is the core of the SSP, for which modelling and reliability evaluation of the SSP, respectively, APS is necessary to start from opinions about the reliability of the relay which are generally divided between two different issues pertaining to safety and security [9]. To improve both security and safety tests must be conducted to ascertain appropriate and protection system [10].

Modern digital relays are normally equipped with devices and monitoring of self. Impact on relay performance and expected benefits from the use of these devices are discussed in various papers [11, 12, 13].

There are many methods which can be used to improve the reliability of relay. These include different operating principles, redundancy in the relay, local safety methods and distance. Redundancy method is generally applied because too high costs and its complexity [14]. Reliability of a relay can also be improved by including in the design, monitoring of embedded devices and of self.

2. GENERAL MODEL OF RELAY RELIABILITY FROM APS STRUCTURE OF UMVEN (R-APS)

For R-APS is a general pattern of reliability suitable containing five states, presented in Fig. 2, taking into account the two main modes of failure of protective relay, i.e. lack of response ($\overline{RC}$), operation when needed and when not needed (INT).

In major part of life R-APS is in energized but static state. In this state, the relay is "healthy" (works properly), and monitories an RPE. This state (S_1) can be named as "unnecessary and functional relay. The term "functional" refers on the fact that it is ready and able to perform its function.

In state S_2, the "functionally necessary" R-APS operates successfully when called upon. In this state, the relay is operating normally and responds to any irregular condition associated with protected components. Probability associated with this condition is the reliability of the relay.

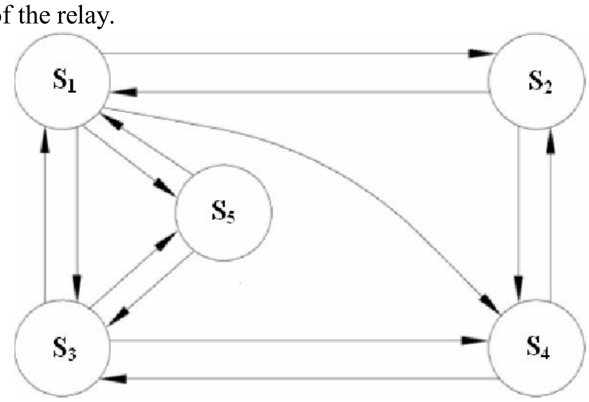

Fig. 2. General model of reliability of relay

In state S_3, the "unnecessary and unworkable", R-APS is neither requested nor prepared to work. Not required because there has been no damage. Not ready for the relay is either failed or it is subjected to a routine test or inspection of self. This condition can be called state of "unavailability of R-APS.

The S_4 state is called as "necessary and inoperative relay, the relay does not fulfil the function of ($\overline{RC}$). In this case, failure occurs when the relay is unavailable.

In state S_5, "operation necessary, when the relay operates when doesn't require to operate (INT). A high probability of being in this state indicates a low safety relay.

States S_3, S_4 and S_5 are considered undesirable and failure states. The main objective is, to minimize the probabilities associated to these three states and maximize the protection or operation of probabilities associated with states S_1 and S_2. It is noted that the probabilities associated with S_2 state depend mainly on the rate of failure and recovery time when the fault is isolated RPE.

Typically, statistics on operational reliability of R-APS refers on states that reflect its failure when it would be necessary (S_4, S_5).

Reliability analysis in the context of R-APS functions that refer on UMVEN RPE, leads to the development of reliable detailed model of R-APS operation involving 17 states [10].

3. Modelling the reliability of SSA from a UMVEN structure

For a relative complex system as APS, respectively SA and SP, from UMVEN, are possible many reliability modelling skills:

- modelling basing on the functions of UMVEN starting from the state graphs;
- analysing the modes of failure, basing on the tree of events and damages;

Here will be given the model to evaluate the previsional reliability of AAR, RAR, and DAS starting from its functions in frame of UMVEN, taking into account the general states (figure 2) and using trees of events and failures.

3.1. Modelling the provisional reliability of AAR

The domain of application and the operating function of the systems AAR (of relays) are well known [15, 16, 17]. The block diagram of the system AAR is given in fig. 3.

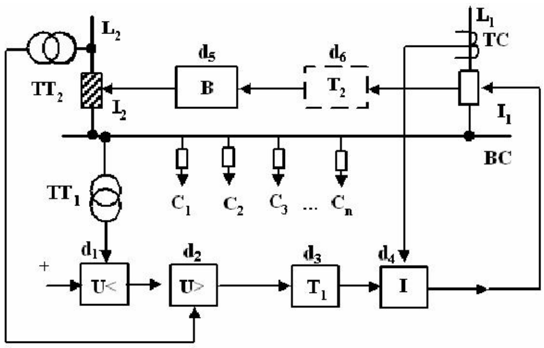

Fig. 3. Block diagram of an AAR system

The following AAR functions are distinguished:
f_1 – anomalous status notification of the power system and enabling the AAR;
f_2 – logical processing of information and security decision;
f_3 – proper power control equipment.

The AAR referral and activation is made in the following circumstances:

- increasing under a pre-stabilized value (U_{rez}) of the voltage in the bar [TT_1, d_4];
- initiating one switcher through which is realized the normal supplying (the basic) [TC, d_4].

The logical processing of the information and the decision's securing implies in principal:

- if at the action of AAR appears a failure on the supplying bars through AAR and occurs the protection, the AAR installation mustn't operate for the second time;
- AAR must be ensured that the intervention does not result in an extension of the damage;
- During the AAR is allowed taking into account two conflicting requirements imposed on the one hand short time for engines connected to the AAR can reboot, on the other hand, enough time to ensure selective disconnection through protection of damaged item (or line power source).

These conditions are assured through: d_2, d_3, TT_2, d_4, d_5 and I_1 (open) elements.

The elements d_5 assures to realize the functions f_3, as d_6, allowing to complete the specific AAR functions with those that characterizes RAR.

The correspondence between specific states of general reliability model (fig. 2) and structural elements of AAR states are shown in Table 1.

Table 1. Impact of AAR element states on AAR general elements state

General states of AAR		States of EPR
Marking	Significance	State structural elements witch causing general state of a AAR
S_1	Necessary and functional	$U > U_{rez}$ Current in L_1 ($I_{L1} > 0$). Elements : TT_1, d_1, TT_2, d_2 and d_4.are in operation The other elements are functional.
S_2	Necessary and functional (in operation)	$U < U_{rez}$ or $I_{L1} = 0$ All elements operate.
S_3	Necessary and unfunctional	$U > U_{rez}$ and $I_{L1} > 0$ Any element may be damaged (unfunctional).
S_4	Necessary and unfunctional	$U < U_{rez}$ or $I_{L1} = 0$ Any element may be damaged (unfunctional).
S_5	Unexpected operation	$U > U_{rez}$ and $I_{L1} > 0$ Parametric damage of TT_1, d_1, d_4 or $d_5$elements.

The conditioning of structural elements state function of AAR system is given in table 2.

Table 2. Correlation functions structure for AAR

Function	Structural elements
f_1	SS1 ≡ { TT_1, d_1, TC, d_4.}
f_2	SS1 ∧ SS2 SS2 ≡ { d_2, d_3, d_4, d_5, TT_2, TC, I_1 (open)}
f_3	SS1 ∧ SS2 ∧ SS3 SS3 ≡ { d_5, d_6}

Considering the above evoked functions may be represented the graph of the AAR system state (fig. 4a and b).

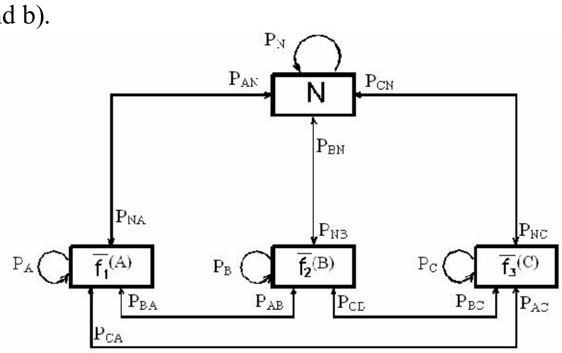

Fig. 4 a. The AAR graph of states rated to its function as indicator uses the state probability and transition (N – normal state; $\overline{f_i}$ - relative unsuccessful states of "f_i" functions)

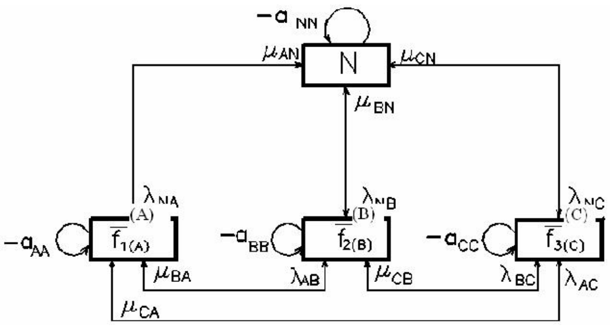

Fig. 4 b. The AAR graph of states rated to its functions utilizing as indicators the damage intensities and recurrence (N – normal state; $\bar{f}_i$ - unsuccessful relative states at "f_i" function)

To develop the analyze and the probability state assessment, taking into account the impact of some elements on many functions will be introduced the following notations:

$1 \equiv TT_1 \wedge d_1$
$2 \equiv TT_2 \wedge d_2$
$3 \equiv d_3$
$4 \equiv TC \wedge d_4$
$1 \equiv d_5 \wedge d_6$
$6 \equiv I_1$

To facilitate the formalization of analysis of failure states ($\bar{f}_i$, i = 1,3) were marked with initials (A, B, C) too.

The expressions of state probabilities and transitions are expressed in function with the probabilities of operation and maintenance of the implied subsystems. To express the probabilities of nominated states in fig. 4a and of transitions between these states, it is considered the fact that these corresponds to some composed events, resulted from combining of elementary events. In this case, will be considered the elementary events (E_i), regarding the operation or the damage of (i) subsystem of AAR.

There are two typical expressions [18] for the composed events probability, applied in this case:

$$\text{Prob}(E_1 \cap E_2 \cap \ldots \cap E_m) = \text{Prob}(E_1) \cdot \text{Prob}(E_2) \cdot \ldots \cdot \text{Prob}(E_m) \quad (6)$$

$$\text{Prob}(E_1 \cup E_2 \cup \ldots \cup E_m) = \sum_{j=1}^{m} \text{Prob}(E_j) - \sum_{j=2}^{m} \sum_{i=1}^{j-1} \text{Prob}(E_i E_j) + \sum_{j=3}^{m} \sum_{i=2}^{j-1} \sum_{k=1}^{i-1} \text{Prob}(E_i E_j E_k) + \ldots + (-1)^{m-1} \text{Prob}(E_1 E_2 \ldots E_m) \quad (7)$$

The number of terms NT of expression (7) increases rapidly with increasing of "m" [18].

In the analyzed case m ≤ 6, therefore the state transition probability expression AAR as the graph of fig. 4 is possible to reach a number of terms $NT = \sum_{i=0}^{6} 2^i = 63$.

The numerical significance of the terms in expression (7) decreases with implied similar events number. Under these conditions may appear simple and overlap between multiple events. Given these aspects, will be taken into account the expressions only with single events.

There is illustrate further the expression of status and transition probabilities for some cases

- Probability of states „N":

$$P_N(t) = \text{Prob}(1 \cap 2 \cap \ldots \cap 6) = \prod_{i=1}^{6} R_i(t) \quad (8)$$

- Probability of states „A":

$$P_A(t) = \text{Prob}\left[\left(\bigcap_{i=\{2,3,5,6\}} i \quad \bigcup_{j=\{1,4\}} \bar{i}\right)\right] = \left[F_1(t) + F_4(t)\right] R_2(t) \cdot R_3(t) \cdot R_5(t) \cdot R_6(t) \quad (9)$$

where:

i ≡ equivalent element "i" in operation;
$\bar{i}$ ≡ equivalent element "i" is failed.

- Probability of some transitions:

$$P_{NA}(t) = \text{Prob}(\bar{1} \cup \bar{4} \cong F_1(t) + F_4(t) \quad (10)$$

$$P_{CB} = \text{Prob}\left[t_M(5) \le T_M(5)\right] = M_5(t_M) \quad (11)$$

T_M – pre-established value of the maintenance works.

Similarly, there are expressed the state probabilities and transitions between the other defined states.

A frequently applied method in reliability studies [2, 7, 19, 20], applicable also in AAR case, is the assessment of provisional reliability indicators basing on the events tree and failure. It is given an example on this method, referring on the undesirable events: "parametrical failure of AAR" (fig.5), respectively, "non realizing of referral function for anomalous state of power subsystem and activation of AAR (fig.6).

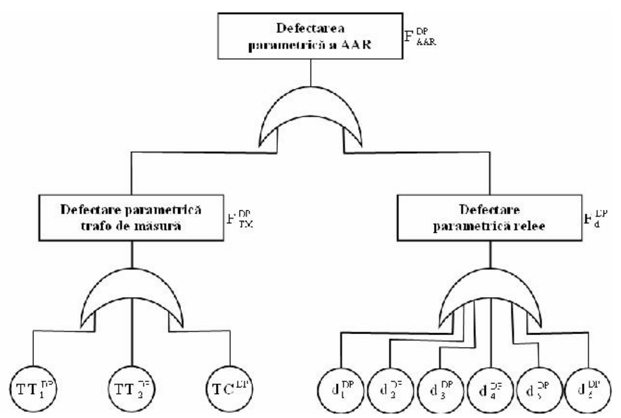

Fig. 5 – Tree of events for AAR referring on the undesired events "parametrical failure" (DP) of AAR"

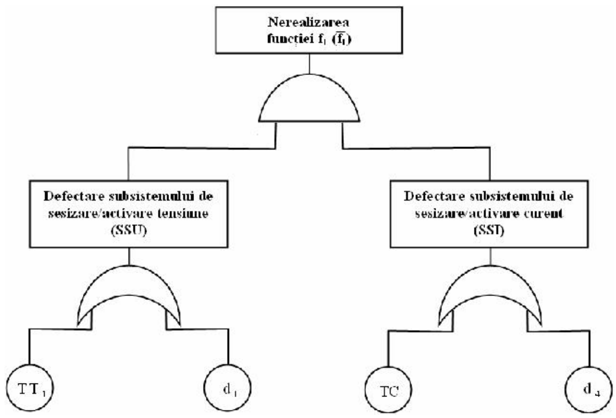

Fig. 6. Tree of events of AAR referring on undesired events "non realization of function f1"

The probability of apparition of undesired events "parametrical failure of AAR" is expressed:

$$F_{AAR}^{DP} = \Pr ob\left(\overline{TM} \cup \overline{d}\right) = F_{TM}^{DP} + F_{d}^{DP} - F_{TM}^{DP} \cdot F_{d}^{DP} \qquad (12)$$

Taking into account only the simple effects:

$$\begin{cases} F_{TM}^{DP} = F_{TT_1}^{DP} + F_{TT_2}^{DP} + F_{TC}^{DP} \\ F_{d}^{DP} = \sum_{i=1}^{6} F_{d_i}^{DP} \end{cases} \qquad (13)$$

The evaluation of the apparition probability of the above mentioned events implies the operation referring on all structural elements of AAR, but with "parametrical" failure.

Basing on AE, from fig. 6, may be expressed the apparition probability of undesired events "non realizing by AAR of the normal function of power system.

$$P\left(\overline{f}_1\right) = \Pr ob\left(\overline{SSU} \cap \overline{SSI}\right) = F_{SSU} \cdot F_{SSI} \qquad (14)$$

where:

$$\begin{cases} F_{SSU} = F_{TT_1} + F_{d_1} - F_{TT_1} \cdot F_{d_1} \\ F_{SSI} = F_{TC} + F_{d_4} - F_{TC} \cdot F_{d_4} \end{cases} \qquad (15)$$

Knowing the indicator of P $(\overline{f}_1)$ may be determine the other indicators of interest R$(\overline{f}_1)$, β$(\overline{f}_1)$.

3.2. Modelling the previsional reliability for RAR

The applicability and the operating mode of the RAR system (relays) are widely described in the technical literature [15, 16, 17, 21, 22].The bloc diagram is given in fig. 7.

RAR has the same functions as AAR:

f_1 – trigger referral breaker (I) and RAR activation;
f_2 – processing the information and securing of decisions;
f_3 – control of switcher (I).

Activation of RAR is made by the staring element (d_1), when the switcher is activated (I) on one from the ways:

a – non-correspondence between the control key position and switcher position (I, CC);
b – action the protection through the relay (TC, d_5).

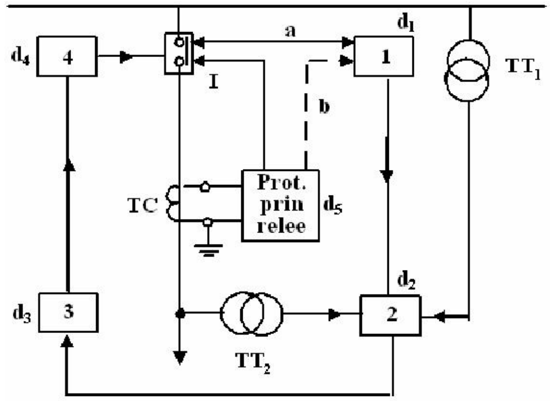

Fig. 7. Block diagram of a RAR system

The logical processing of the information and assuring the decision, implies in principal, to satisfy the following operation condition of the ensemble SP-RAR:

- RAR must occur to trigger switching and protection caused by the disconnection does not occur manually (controlled) thereof, or the onset of the protection immediately after the actuator;
- RAR must allow the blocking of resetting when the releasing is provoked by some protections;
- RAR must be used with any type of protection and eventually failure, appeared in the device of RAR or its extract from operation, should not impede the proper functioning of protection;
- RAR scheme should allow rapid extension step distance protection scheme and choice of RAR single phase or three phase, to be made easier to service with keys or shoulders, the regime chose to be visible to operating personnel;
- the actuator given by RAR device must be enough long to ensure the release of the switcher.

These conditions are assured by elements of: TT_1, TT_2, d_2 and d_3. Element d_4 is destined to realize the function f_3. In table 3, is given the correspondence between the states that are specifically to the general model of the reliability (fig. 2) and the states of structural states of RAR.

Table 3. Impact of RAR elements state on general states of RAR

General state of RAR		State EPR
Marking	Significance	State of structural elements that provokes general state of RAR
S_1	Unnecessary and functional	Switcher (I) is closed. Elements: TT_1 and TT_2 are operating Other elements are functional
S_2	Necessary and functional l (in operation)	Switcher (I) a released. All elements operate.
S_3	Unnecessary and unfunctionar	Switcher (I) is closed. Any element is failed (unfunctional).
S_4	Necessary and unfunctional	Switchetr (I) is released.. Any element is failed (unfuncţional).
S_5	Unexpected operation	Switchetr (I) is closed. The control of the starting element on one of the two ways (a - failure CC, b – failure protection by relays) or Failure (unexpected): (d_1, d_2, d_3, d_4).

Basing on the above described function f_1, f_2, f_3, may be given for RAR to the previsional reliability analyze using the graph of states, similarly to the presented analyze for AAR. The evaluation of previsional reliability basing on the failure tree is very suggestive and efficient. This procedure will be given by an example, referring on the undesired event "unrealising the process functions of the information and the decision secreting" (f_2). AED adequate to this unwanted event $\bar{f}_2$, is given as in fig.8.
The probability of the unwanted event apparition $\bar{f}_2$ is expressed such as:

$$P(\bar{f}2) = \mathrm{Prob}(\overline{SSC} \cup \overline{d_3}) = F_{SSC} + F_{d_3} - F_{SSC} \cdot F_{d_3} \qquad (16)$$

Neglecting the multiple failures, may be written:

$$F_{SSC} = F_{TT_1} + F_{TT_2} + F_{d_2} \qquad (17)$$

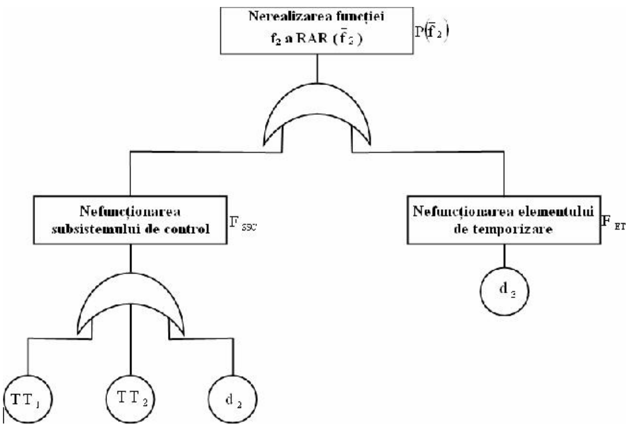

Fig. 8. Tree of RAR events referring on the unwanted event „unrealize the $\bar{f}_2$ function"

4. ASSESSMENT OF SOME SSA OPERATIONAL RELIABILITY

Monitoring in exploitation of APS, that serves the electric networks managed by SDEE Brasov, for a period of 6 month, were determined the indicators of operational reliability. In this frame is given a synthesis of the obtained results, evidencing the SSA specifications. In table 4, is given the synthesis of SSA behaviour in exploitation for functional and structural type.

Table 4. Analyzing the operation of automation

Action type / Tip SSA	Action total No.	Correct action No.	Incorrect action No.	No of refuse
RAR	963	911	14	38
AAR	36	29	4	3
DRRI	2	0	2	0
DAS_f	4	0	4	0
PRBM	2	0	2	0

In fig. 8, is given a comparison regarding the number and the type of the actions for RAR and AAR.

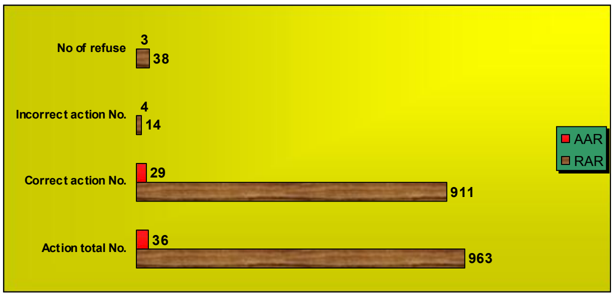

Fig. 8. The performances of RAR and AAR

In fig. 9 ÷ 12 are given the hierarchy of SSA in function with the number and type of actions.

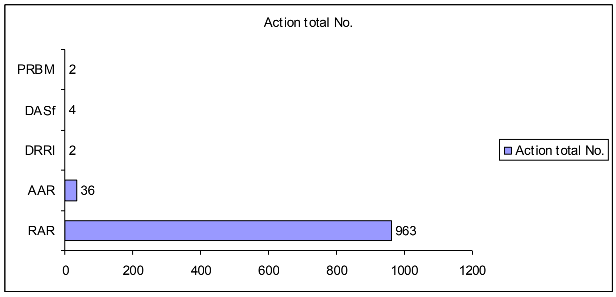

Fig. 9. Total number of actions for SSA types

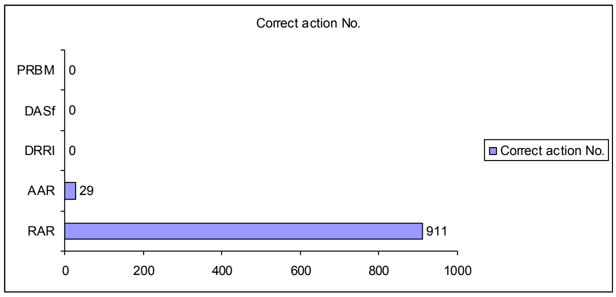

Fig. 10. Total number of correct actions of SSA types

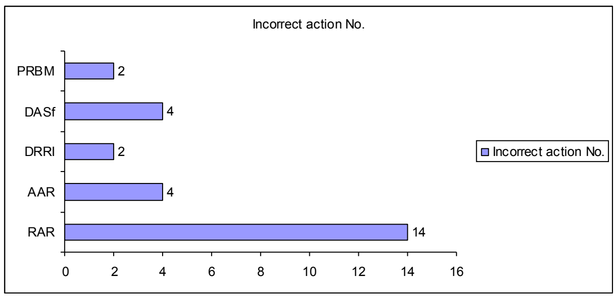

Fig. 11. Total number of false actions of SAA types

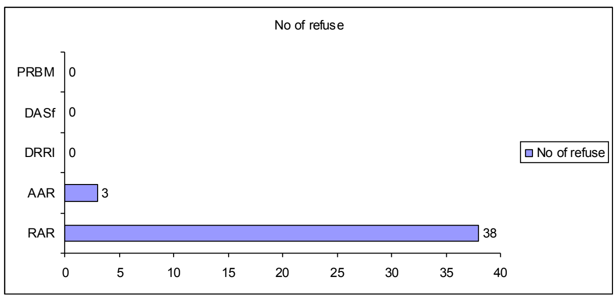

Fig. 12. Number of refuse of SAA types

4. CONCLUSIONS

For APS previsional reliability modelling we starts from the fundamental structure of the systems – relay.

Referring on the relay is given two analyzing level of previsional reliability:

- general model, are evidenced 5 states and the transitions between these;
- the detailed model, where are evidenced 17 states and the transitions between the states.

For APS from UMVEN are possible three variants (levels), of previsional reliability modelling:

- modelling basing on the structure, starting from the equivalent diagram of reliability;
- modelling basing on the functions in the frame of UMVEN, founded on the graph of states;
- analyzing the modes of failure, basing on the trees of events and failure.

For each type of SSA, SSP (maximal current, differential, of distance, etc.), may be established a correlation between the state of the components and general states of any type of relay, as well as between the state of components and satisfying degree of the SSP functions in UMVEN.

Regarding the SSA operational reliability analyze from the electric networks, managed by SDEE Brasov, reflects the followings:

- the highest number of actions were registered by RAR followed by AAR;
- for AAR from the total number of actions 94% were correct, 1,4% incorrect, and 3,9% were refused;
- for AAR of total number of actions were correct 80,5%, 11,1% incorrect and 8,3% were refused;
- at DRRI, DASf and PRBM the number of registered actions were very small for the monitoring period, in proportion of 100% incorrect;
- DRRI, DASf and PRBM are more reliable comparing with RAR and AAR.
- It is necessary to deep of operational reliability analyzes to evidence the damaged elements and of the damaging modes of SSA.

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