Reliability and Survivability Models of Integrated Drone-Based Systems for Post Emergency Monitoring of NPPs

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Abstract—This paper presents the approach to research integrated drone-based systems for post emergency monitoring of NPPs as systems with a multi-level degradation. Reliability block diagrams of the systems are built. Degradation levels, conditions which determine them and formulae for calculating the reliability functions of the systems on these levels are proposed. The possibility of using developed models for research systems with a multi-level degradation and using drones are shown

Keywords—reliability block diagram; reliability function; degradation level; drone; redundancy

I. INTRODUCTION

Nuclear power is currently one of the most powerful and clean energy sources [1]. However, constant control and monitoring of the power unit equipment parameters and components within premises and adjacent areas is held to ensure stable work of Nuclear Power Plant (NPP). Solving this problem requires the use of several thousand sensors combined into networks using measurement modules [1-4]. Negative experiences in the Fukushima NPP accident [5] requires an increase of reliability and survivability of monitoring tools, because during the accident a part of data channels will inevitably fail and it will be necessary to look for ways for redirecting of the information flows. To overcome this situation, additional wireless channels [4, 6] should be used. These wireless channels can be part of the drones’ equipment. Nowadays, drones are able to provide the necessary data flow in minutes after the accident occurred and are the most profitable platform where repeater modules can be placed [7-9].

The aim of this work is to develop and research reliability and survivability models based on a concept of NPP integrated system for both post-emergency monitoring and decision support, considering such system as systems with a multi-level degradation.

II. A CONCEPT OF INTEGRATED DRONE-BASED SYSTEMS FOR POST EMERGENCY MONITORING OF NPPs

The following principles of the system functioning are proposed [10]:

a) A communication network of the system for the NPP post-emergency condition monitoring is put in the drones group (fleet), that located permanently at a considerable distance from the NPP. The communication network is deployed after the accident, when drones are flying into the accident zone.

b) Drones fleet is divided by the role and equipment into: repeaters, that work together on a principle of “one leader” and if the “leading drone-repeater” (Master) is damaged then other drone-repeater takes Master functions; observers (equipped with a TV camera), that enable to run the continuous visual monitoring of the accident location; additional sensors, that can be located in drones or be dropped down in certain places). Drones should be able to change their role by upgrading equipment at the location base.

c) Measurement and control modules are equipped with backup batteries, blocks of wireless communication, as well as, self-testing and self-diagnostic systems.

d) To meet the system requirements the self-adaptability, self-testing and self-healing procedures are used.

Short structural scheme of integrated drone-based systems for post emergency monitoring of NPPs Based on the proposed concept are shown in Fig 1.
III. RELIABILITY MODELS

A. Reliability block diagram of the systems and Formulae for Calculating the Reliability Function of Them

According to the proposed concept and short structural scheme of integrated drone-based systems for post emergency monitoring of NPPs (Fig. 1) the three systems of post-emergency monitoring systems (S1, S2, S3) and reliability block diagrams (correspondingly: RBD1 (Fig. 2), RBD2 (Fig. 3) and RBD3 (Fig. 4) have been developed.

Each system has a general way for increasing the system reliability, which includes sliding redundancy in SS, DR and DM – any failed element of the main chain ((S1- S2- ∙∙∙-Sk) for SS, (R1- R2- ∙∙∙-Rq) for DR and (M1- M2- ∙∙∙-Mg) for DM) can be replaced by means of any element of the redundancy chain ((Sr1- Sr2- ∙∙∙-Sr) for SS, (Rr1- Rr2- ∙∙∙-Rp) for DR and (Mr1- Mr2- ∙∙∙-Mrp) for DM). Moreover, each system has a possibility to replace the failed main chain by means of the redundancy chain: (CD-DR-DM) by means of (CW-WS) for S1, (DR-DM) by means of WS for S2, (WS1-WS- ∙∙∙-WSn) by means of ((DR-DM)1-(DR-DM)2- ∙∙∙-(DR-DM)m) for S3.

Based on the proposed reliability block diagrams we can obtain the following formulas for calculating the reliability function (RF) per each of these systems:

\[
P_{S1} = p_{SS} \cdot p_{PCS} \left[ 1 - \left( 1 - p_{CD} \cdot p_{DR} \cdot p_{DM} \right) \cdot \left( 1 - p_{CW} \cdot p_{WS} \right) \right] \cdot p_{CC},
\]

where \( p_{SS} = \sum_{i=0}^{m} C_{m+k} \cdot \left( 1 - p_{S} \right)^{i} \cdot p_{S}^{m+k-i} \);

\[
P_{DR} = \sum_{j=0}^{P} C_{p+q} \cdot \left( 1 - p_{R} \right)^{j} \cdot p_{S}^{p+q-j} ;
\]

\[
P_{DM} = \sum_{l=0}^{G} C_{h+g} \cdot \left( 1 - p_{M} \right)^{l} \cdot p_{S}^{h+g-l} ;
\]

\[
P_{S2} = p_{SS} \cdot p_{PCS} \left[ 1 - \left( 1 - p_{CD} \cdot p_{DR} \cdot p_{DM} \right) \cdot \left( 1 - p_{CW} \cdot p_{WS} \right) \right] \cdot p_{CC},
\]

\[
P_{S3} = \left( p_{SS} \cdot p_{PCS} \right)^{m} \left[ 1 - \left( 1 - \prod_{i=1}^{n} p_{WS_{i}} \right) \cdot \left( 1 - p_{DR} \cdot p_{DM} \right)^{m} \right] \cdot p_{CC}.
\]
TABLE I. Degradation Levels Characteristics of the Sensor System

<table>
<thead>
<tr>
<th>Number of the Degradation Level</th>
<th>Condition that Determines the Degradation Level and Formula for Calculating the Reliability Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>m+1</td>
<td>All elements of the main chain (S1-S2-...Sk) are functioning, all elements of the redundancy chain (Sr1-Sr2-...SrM) are functioning;</td>
</tr>
<tr>
<td></td>
<td>[ \sum_{i=0}^{m} C_{m+k}^i \cdot (1 - P_S)^i \cdot P_S^{m+k-1} ]</td>
</tr>
<tr>
<td>m</td>
<td>All elements of the main chain (S1-S2-...Sk) are functioning, one element of the redundancy chain (Sr1-Sr2-...SrM) is failed, or it is functioning instead of a failed element of the main chain;</td>
</tr>
<tr>
<td></td>
<td>[ \sum_{i=0}^{m-1} C_{m+k-1}^i \cdot (1 - P_S)^i \cdot P_S^{m+k-2} ]</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>i</td>
<td>All elements of the main chain (S1-S2-...Sk) are functioning, m elements of the redundancy chain (Sr1-Sr2-...SrM) are failed, or they are functioning instead of failed elements of the main chain;</td>
</tr>
<tr>
<td></td>
<td>[ \sum_{i=0}^{0} C_{m+k}^i \cdot (1 - P_S)^i \cdot P_S^{m+k} = P_S^k ]</td>
</tr>
<tr>
<td>0</td>
<td>At least one of the elements of the main chain (S1-S2-...Sk) is failed, m elements of the redundancy chain (Sr1-Sr2-...SrM) are failed or they are functioning instead of failed elements of the main chain;</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

TABLE II. Degradation Levels Characteristics of the Drone Transmission System

<table>
<thead>
<tr>
<th>Number of the Degradation Level</th>
<th>Condition that Determines the Degradation Level and Formula for Calculating the Reliability Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+1</td>
<td>All elements of the main chain (R1-R2-...Rq) are functioning, all elements of the redundancy chain (Rr1-Rr2-...Rrp) are functioning;</td>
</tr>
<tr>
<td></td>
<td>[ \sum_{j=0}^{p} C_{p+q}^j \cdot (1 - P_R)^j \cdot P_R^{p+q-1} ]</td>
</tr>
<tr>
<td>p</td>
<td>All elements of the main chain (R1-R2-...Rq) are functioning, one element of the redundancy chain (R1-R2-...Rrp) is failed or it’s functioning instead of a failed element of the main chain;</td>
</tr>
<tr>
<td></td>
<td>[ \sum_{j=0}^{p-1} C_{p+q-1}^j \cdot (1 - P_R)^j \cdot P_R^{p+q-2} ]</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1</td>
<td>All elements of the main chain (R1-R2-...Rq) are functioning, p elements of the redundancy chain (R1-R2-...Rrp) are failed or they are functioning instead of failed elements of the main chain;</td>
</tr>
<tr>
<td></td>
<td>[ \sum_{j=0}^{0} C_{p+q}^j \cdot (1 - P_R)^j \cdot P_R^{p+q} = P_R^q ]</td>
</tr>
<tr>
<td>0</td>
<td>At least one of the elements for the main chain (R1-R2-...Rq) is failed, p elements of the redundancy chain (R1-R2-...Rrp) are failed, or they are functioning instead of failed elements of the main chain;</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

TABLE III. Degradation Levels Characteristics of the Drone Monitoring System

<table>
<thead>
<tr>
<th>Number of the Degradation Level</th>
<th>Condition that Determines the Degradation Level and Formula for Calculating the Reliability Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>h+1</td>
<td>All elements of the main chain (M1-M2-...Mg) are functioning, all elements of the redundancy chain (Mr1-Mr2-...Mrp) are functioning;</td>
</tr>
<tr>
<td></td>
<td>[ \sum_{l=0}^{h} C_{h+g}^l \cdot (1 - P_M)^l \cdot P_M^{h+g-1} ]</td>
</tr>
<tr>
<td>h</td>
<td>All elements of the main chain (M1-M2-...Mg) are functioning, one element of the redundancy chain (Mr1-Mr2-...Mrp) is failed, or it’s functioning instead of a failed element of the main chain;</td>
</tr>
<tr>
<td></td>
<td>[ \sum_{l=0}^{h-1} C_{h+g-1}^l \cdot (1 - P_M)^l \cdot P_M^{h+g-2} ]</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1</td>
<td>All elements of the main chain (M1-M2-...Mg) are functioning, h elements of the redundancy chain (Mr1-Mr2-...Mrp) are failed, or they are functioning instead of failed elements of the main chain;</td>
</tr>
<tr>
<td></td>
<td>[ \sum_{l=0}^{0} C_{h+g}^l \cdot (1 - P_M)^l \cdot P_M^{h+g} = P_M^g ]</td>
</tr>
<tr>
<td>0</td>
<td>At least one of the elements of the main chain (M1-M2-...Mg) is failed, h elements of the redundancy chain (Mr1-Mr2-...Mrp) are failed, or they are functioning instead of failed elements of the main chain;</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Based on the proposed TABLE I-III we can build the degradation diagram (DD) for systems S1-S3. Example of the DD for the drone monitoring system (S3) are shown in Fig. 5

Figure 5. DD for the drone monitoring system when h=2: \( t_0 \) – moment, when all elements of the main chain (M1-M2-...Mg) are functioning, all elements of the redundancy chain (Mr1-Mr2-...Mrp) are functioning; \( t_1 \) – moment, when all elements of the main chain (M1-M2-...Mg) are functioning, one element of the redundancy chain (Mr1-Mr2-...Mrp) is failed, or it’s functioning instead of a failed element of the main chain; \( t_2 \) – moment, when all elements of the main chain (M1-M2-...Mg) are functioning, two elements of the redundancy chain (Mr1-Mr2-...Mrp) are functioning, two elements of the redundancy chain (Mr1-Mr2-...Mrp) are failed, or they are functioning instead of failed elements of the main chain.

D. Main results of using proposed models

Using the data from TABLE I-III and assuming that devices CS, CD, CW, WS, CC are characterized by a two-
level degradation (these devices have only 1 and 0 degradation level), we can determine levels and provide characteristics per each of them per each of the systems S1, S2, S3 correspondingly. For example, in the TABLE IV the characteristics of the given degradation level \(a\) for the system with common sensors S1 are shown, and in TABLE V the characteristics of the lowest degradation level for the system S1 are shown too.

**TABLE IV. CHARACTERISTICS OF THE GIVEN DEGRADATION LEVEL FOR SYSTEM WITH GENERAL SENSORS (S1) ACCORDING TO DEGRADATION LEVELS OF DEVICES, WHICH THIS SYSTEM INCLUDES**

<table>
<thead>
<tr>
<th>Number of the Degradation Level</th>
<th>Shorthand Names for the Devices, their Degradation Levels and Formula for Calculating the Reliability Function of the System</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>(m_{p1} h_{l1} 1 1 1 0 0 1)</td>
</tr>
</tbody>
</table>

Increasing the number of zones, controlled by the system with separated zones of sensors and drones, reduces the value of the reliability function of this system from 0.9625 to 0.9580 when number of the elements under redundancy of the drone monitoring system = 15 and from 0.9627 to 0.9583 when number of the elements under redundancy of the drone monitoring system = 9 (Fig. 8).

**TABLE VIII. DEGRADATION LEVELS WITH CORRESPONDING VALUES OF THE RELIABILITY FUNCTION OF THE DRONE TRANSMISSION SYSTEM WHEN NUMBER ELEMENTS UNDER REDUNDANCY = 15**

<table>
<thead>
<tr>
<th>Number of the Degradation Level</th>
<th>Value of the Reliability Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m=3)</td>
<td>(m=4)</td>
</tr>
<tr>
<td>(m=5)</td>
<td>(m=6)</td>
</tr>
<tr>
<td>7</td>
<td>0.9999999</td>
</tr>
<tr>
<td>6</td>
<td>0.9999930</td>
</tr>
<tr>
<td>5</td>
<td>0.9999207</td>
</tr>
<tr>
<td>4</td>
<td>0.9998977</td>
</tr>
<tr>
<td>3</td>
<td>0.9988656</td>
</tr>
<tr>
<td>2</td>
<td>0.9986784</td>
</tr>
<tr>
<td>1</td>
<td>0.9984280</td>
</tr>
<tr>
<td>0</td>
<td>0.9984280</td>
</tr>
</tbody>
</table>

We can make the following conclusions based on the analysis of the proposed dependencies:

a) A significant increase the value of the reliability function of the drone transmission system is observed with an increase in the number of redundant elements from 3 to 4 (Fig. 6).

b) the same trend has continued for the system with general sensors(Fig. 7).

c) The best value of the reliability function of both the drone transmission system and the system with general sensors is provided when the number of the elements under redundancy is 9 and the number of redundant elements is 6 (Fig. 6, 7).

d) The worst value of the reliability function of both the drone transmission system and the system with general sensors is provided when the number of the elements under redundancy is 15 and the number of redundant elements is 3 (Fig. 6, 7).

Using the TABLE I-III the reliability function of the drone transmission system on number of the redundancy elements for different values of number of the elements under redundancy are calculated and presented in TABLE VI-VIII. Others dependencies are shown in Fig. 6-8.

**TABLE VI. DEGRADATION LEVELS WITH CORRESPONDING VALUES OF THE RELIABILITY FUNCTION OF THE DRONE TRANSMISSION SYSTEM WHEN NUMBER ELEMENTS UNDER REDUNDANCY = 9**

<table>
<thead>
<tr>
<th>Number of the Degradation Level</th>
<th>Value of the Reliability Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m=3)</td>
<td>(m=4)</td>
</tr>
<tr>
<td>(m=5)</td>
<td>(m=6)</td>
</tr>
<tr>
<td>7</td>
<td>0.9999999</td>
</tr>
<tr>
<td>6</td>
<td>0.9999930</td>
</tr>
<tr>
<td>5</td>
<td>0.9999207</td>
</tr>
<tr>
<td>4</td>
<td>0.9998977</td>
</tr>
<tr>
<td>3</td>
<td>0.9988656</td>
</tr>
<tr>
<td>2</td>
<td>0.9986784</td>
</tr>
<tr>
<td>1</td>
<td>0.9984280</td>
</tr>
<tr>
<td>0</td>
<td>0.9984280</td>
</tr>
</tbody>
</table>

**TABLE VII. DEGRADATION LEVELS WITH CORRESPONDING VALUES OF THE RELIABILITY FUNCTION OF THE DRONE TRANSMISSION SYSTEM WHEN NUMBER ELEMENTS UNDER REDUNDANCY = 12**

<table>
<thead>
<tr>
<th>Number of the Degradation Level</th>
<th>Value of the Reliability Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m=3)</td>
<td>(m=4)</td>
</tr>
<tr>
<td>(m=5)</td>
<td>(m=6)</td>
</tr>
<tr>
<td>7</td>
<td>0.9999999</td>
</tr>
<tr>
<td>6</td>
<td>0.9999930</td>
</tr>
<tr>
<td>5</td>
<td>0.9999207</td>
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<td>1</td>
<td>0.9984280</td>
</tr>
<tr>
<td>0</td>
<td>0.9984280</td>
</tr>
</tbody>
</table>
The dependence of the reliability function of the drone transmission system on number of the redundancy elements for different values of number of the elements under redundancy

![Diagram](image1.png)

Figure 6. The dependence of the reliability function of the drone transmission system on number of the redundancy elements for different values of number of the elements under redundancy

The dependence of the reliability function of the system with general sensors on number of the redundancy elements for different values of number of the elements under redundancy

![Diagram](image2.png)

Figure 7. The dependence of the reliability function of the system with general sensors on number of the redundancy elements for different values of number of the elements under redundancy

The dependence of the reliability function of the system with separated zones of sensors and drones on number of the redundancy elements for different values of number of the elements under redundancy of the drone transmission system

![Diagram](image3.png)

Figure 8. The dependence of the reliability function of the system with separated zones of sensors and drones on number of the redundancy elements for different values of number of the elements under redundancy of the drone transmission system

IV. CONCLUSIONS

To assure safety of critical systems similar NPPs and to minimize sequences of emergencies we have proposed integrated drone-based system for monitoring of station in post-emergency time. A few variants of redundant structures and reliability models have been developed and researched. Main features of these models are possibility of their using for research integrated drone-based systems for post emergency monitoring of NPPs as systems with a multi-level degradation. Degradation levels, conditions which determine them and for formulae for calculating the reliability functions of the systems on these levels are proposed. A significant increase the value of the reliability function of the drone transmission system is observed with an increase in the number of redundant elements from 3 to 4. The same trend has continued for the system the system with general sensors. The best value of the reliability function of both the drone transmission system and the system with general sensors is provided when the number of the elements under redundancy is 9 and the number of redundant elements is 6. The worst value of the reliability function of both the drone transmission system and the system with general sensors is provided when the number of the elements under redundancy is 15 and the number of redundant elements is 3. Increasing the number of zones from 5 to 8, controlled by the system with separated zones of sensors and drones, reduces the value of the reliability function of this system from 0.9625 to 0.9580 when number of the elements under redundancy of the drone monitoring system = 15 and from 0.9627 to 0.9583 when number of the elements under redundancy of the drone monitoring system = 9.

REFERENCES


