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RELIABILITY FUNCTIONAL RELATIONSHIP ANALYSIS ON THE POWER CIRCUIT IN INDUCTION INSTALLATION USING FAULT TREE METHOD

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Abstract: *Reliability prediction for a system of elements functioning jointly concerns determining the causes for failures in this system and also detecting the elements that can cause failures. This type of prediction is known as a fault tree analysis and consists of determining the failure rate at a lower level of the system examined. Such an analysis will be applied in the reliability study of a thyristor converter for induction heating.*

Key Words: ***Reliability, Failure rate, Fault tree Analysis, Thyristor converter, induction heating.***

1. INTRODUCTION

The application of complex technical systems often requires solving problems, which are related to their reliability and maintenance, e.g. what kind of failures or combinations of them produce a defined reliability of the system and which is the lowest-price maintenance for the system.

The subject of the present article is an induction heating installation used in a forge shop for heating steel work pieces. The basic blocks of the induction heating installation are: thyristor converter - SMK UB 2F2 630/1.5/0.6-R and a mass heating machine for steel parts - ITO 631/1-A-L. The main parameters are: operating voltage across the load – 600 V; operating frequency within the range – (750 – 1500) Hz; rated power – 630 kVA;

The thyristor converter SMK UB 2F2 630/1.5/0.6-R consists of (fig.1) :

- ❖ **Two controllable three-phase rectifiers** working in parallel, according to a Larionov circuit. The thyristors in the rectifiers are: Th1÷Th12 → TV967-400-20;
- ❖ **Input choke**
- ❖ **Starting circuit** with basic elements: Diodes, D1÷D4 → DR856-250-20; Thyristors, Th21÷Th22 → TR967-260-12; Capacitors battery C2÷C4 → POAJN-0,75/440
- ❖ **Two bridge current inverters** working in parallel. The thyristor in inverters are: Th13÷Th20 → TR967-400F-12

The mass heating machine ITO 631/1-A-L for steel parts consists of:

- ❖ **Inductor** 80-630 DK or 100-630 DK
- ❖ **Load capacitors battery** C1→ FRJJK 1-95

Each failure in one of these elements will cause a failure in the system and the task is to predict how the system failure rate is distributed in the presence of these elements.

The choice thyristors in the power converters and the design of these blocks are not a topic of the current paper. The work aims to determine the operating reliability of the induction installation and the lowest-price maintenance for the work time. The aim can be formulated as follows:

Compose the „fault tree" for power circuit of an induction installation and define its reliability and maintenance parameters.

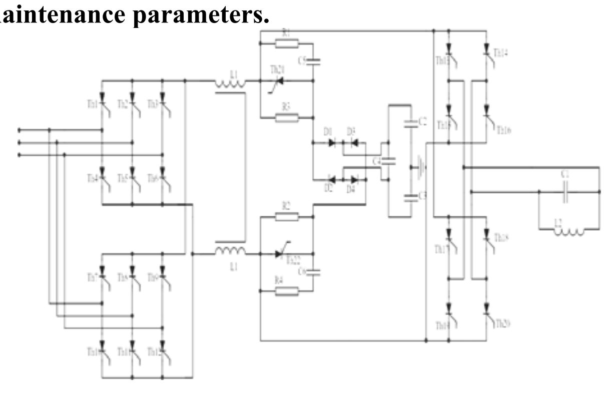

Fig. 1. *Power circuit of the basic blocks of the induction heating installation*

2. PRESENTATION

The "fault tree" analysis (FTA) technique [1, 2] is a method for block diagramming constituent lower level on the reliability of elements. It determines, in a logical way, which failure modes at a certain level produce critical failures at a higher level in the system. To build a “failure tree”, the undesired output event is set and the reasons causing it are analyzed. The reason for the occurrence of the event at the output may graphically be presented in a logic hierarchic structure, where the events are modeled by symbols and logic elements represent the relationships between them. When one or more elements in the “failure tree” are connected by an **OR** operator, this means that in order for the object to fail one of the elements must fail, and in order for the object to operate, all elements must operate. When one or more elements are connected by an **AND** operator, this means that in order for the object to fail all elements used must fail, and in order for the object to operate at least one of the elements must operate.

The present paper considers the initial stage of the application of the “failure tree” method, i.e. the definition of the reliability indicators of the induction installation only regarding the reliability of the elements in the power circuit. The next stage will be the definition of the failure rates of all elements in the system and the probability of the system's failure-free operation, respectively.

For the most frequently used operating modes of the induction installation, a data base has been created, with the operating parameters of all ellements (of the power and regulating blocks). For example, the operating modes of the rectifier and the inverter during heating of steal elements (ø 100 mm) at a rate of 50 sec are shown in the following oscilograms (fig.2 - fig. 7).

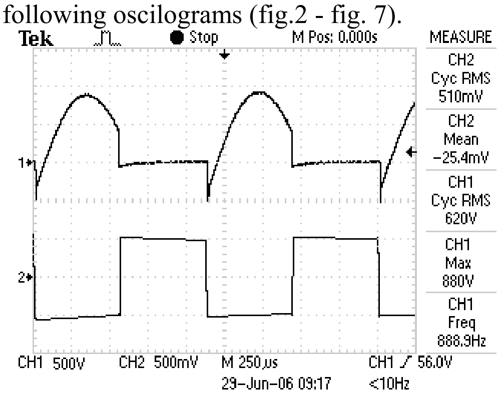

Fig. 2. *Voltage and current of the inverter thyristors*

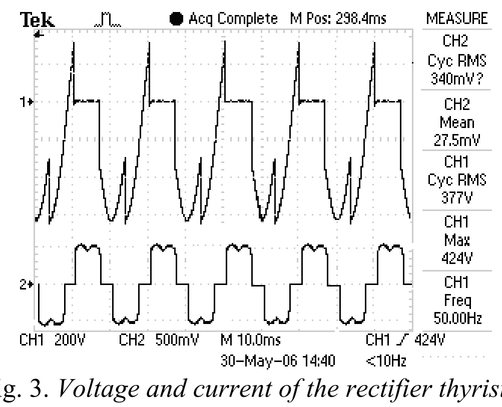

Fig. 3. *Voltage and current of the rectifier thyristors*

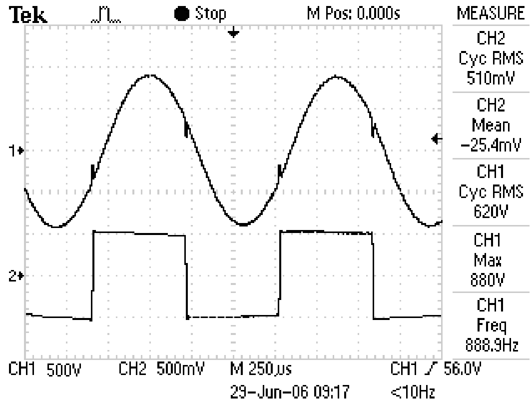

Fig. 4. *Voltage of the load capacitors*

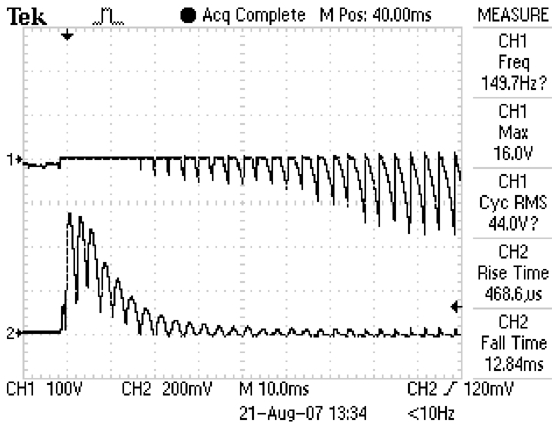

Fig. 5. *Voltage and current of the start thyristors*

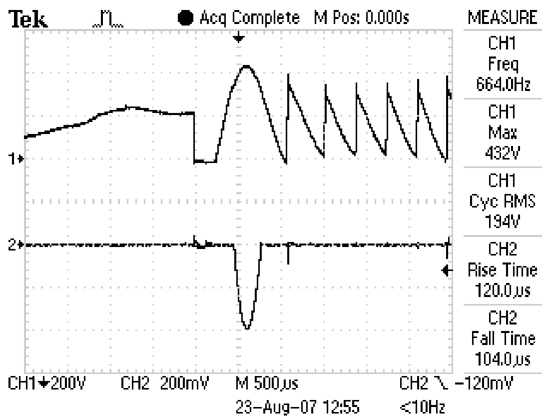

Fig. 6. *Voltage and current of the start diodes*

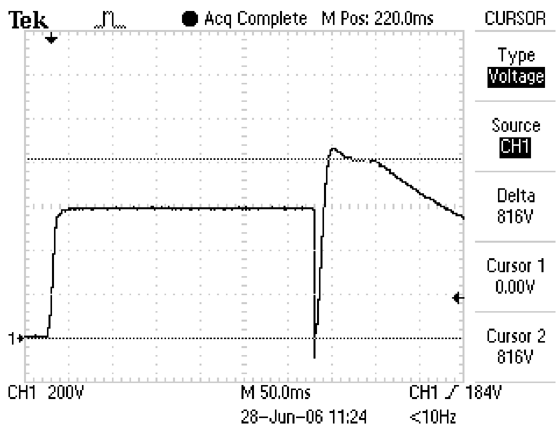

Fig. 7. *Voltage of the start capacitors*

Note that for the same operating mode, the **Failure Rates – λ (FR)** of the thyristors in the rectifiers and the inverters (fig.1), have been calculated[4,5] as follows:

- for the thyristors used in the two rectifiers - $\lambda_1 = ... = \lambda_{12} = 1246 FIT$ **;**

- for the thyristors used in the two inverters – $\lambda_1 = ... = \lambda_8 = 6116 FIT$

The mathematical calculation of the failure rates for the next elements in the power circuit of the induction installation (fig.1) assumes that the objects consist of electronic elements in an operational period for which an exponential law of distribution of random variables applies. At nominal operating and temperature modes and at ambient conditions, λ_{EL_i} of these elements have been calculated as follows:

➢ **Total failure rate of the Load capacitors battery** ($\lambda_{CAP_{LOAD}}$)

The failure rate for a single **capacitor in the Load capacitors battery** (λ_{CAP}) is:

$$\lambda_{CAP} = \lambda_{bcap}.\pi_T.\pi_C.\pi_V.\pi_{SR}\pi_Q.\pi_E \qquad (1)$$

Values for the *π-factors* in Eq. 1 can be choused according operating mode, temperature and at ambient conditions[3] as follows:

- $\lambda_{bcap} = 0,5\ FIT$.- Base failure rate for the capacitor style CKR

- π_T → Factor ambient temperature

$$\pi_C = C^{0,23} = 2,9 \text{ at T} = 50^0\text{C} \qquad (2)$$

- π_C → Capacitance factor

$$\pi_C = C^{0.09} = 96^{0,09} = 1,5 \qquad (3)$$

- π_V →Voltage stress factor

$$\pi_V = \left(\frac{Opetaning\ voltage}{0,6.Rated\ voltage} \right)^3 + 1 = 4\,. \qquad (4)$$

The capacitor's operating voltage in the nominal mode can be determined from Fig. 4 as U_C = 620V.

- π_Q → Quality factor for the capacitor

$$\pi_Q = 0.1, Established\,\mathrm{Re}liability\ StyleR3 = 3 \qquad (5)$$

- π_{SR} → Series resistance factor

$$\pi_{SR} = \frac{ESR(by1000Hz)}{ESR_{nom}} = 1 \qquad (6)$$

- π_E → Environment factor for the capacitor:

π_E = 10 for the ground fixed;

Using the data above:

$\lambda_{CAP} = 174\ FIT$.

Thus, the failure rate of the load capacitors battery, composed of 24 capacitors in parallel is:

$$\lambda_{CAP_{LOAD}} = \sum_{i=1}^{24} \lambda_i = 4176 FIT \qquad (7)$$

➢ **Failure rate of the capacitor in the Starting circuit (** λ_C^{SC} **)**

$$\lambda_C^{SC} = \lambda_{bcap}.\pi_T.\pi_C.\pi_V.\pi_{SR}\pi_Q.\pi_E \qquad (8)$$

$\lambda_{CAP}^{SC} = 540 FIT$

➢ **Failure rate of the diodes in the Starting circuit** (λ_D)

$$\lambda_D = \lambda_{bD}.\pi_Q.\pi_T.\pi_S.\pi_E \qquad (9)$$

where

λ_{bD} → Base failure rate for the diode

π_Q → Quality factor for the diode

π_S →Power stress factor

π_T → Factor ambient temperature

π_E →- Environment factor for the diode

After a calculation by (9) is obtained:

$\lambda_D = 550\ FIT$

The number of diodes in the starting circuit is 4. Therefore:

$$\lambda_D^{SC} = \sum_{i=1}^{4} \lambda_i = 2200\ FIT \qquad (10)$$

➢ **Failure rate of the thyristors in the Starting circuit**

$$\lambda_{Th} = \lambda(T,U).\pi_R.\pi_Q.\pi_E \qquad (11)$$

where

$\lambda(T,U)$ - Base failure rate for the thyristor according to work temperature and voltage – fig.5.

$$\lambda(T,U) = \lambda_b(T_b, U_b).\left(\frac{U}{U_{RRM}}\right)^\gamma.\exp\left[Ea(1/T_{JM} - 1/T_0)/k\right] \qquad (12)$$

- π_R - coefficient depending on the working mode;

- π_Q → Quality factor for the thyristor

- π_E → Environment factor

$\lambda_{Th} = 4670 FIT$

For two thyristors in the Starting circuit:

$$\lambda_{Th}^{SC} = \sum_{i=1}^{2} \lambda_i = 9340,\ FIT \qquad (13)$$

In the following, the "fault tree" analysis (FTA) will be used to calculate the reliability indicators of an induction heating installation. The probability for the whole system to fail depends on several basic blocks. Their configuration in the fault tree depends on the interconnections between the block elements and the operating modes of the system. The method consists of composing a fault tree for the power elements in the induction installation and determining their reliability indicators. The use of the method consists of composing a fault tree for the power elements in the induction installation and determining its reliability indicators.

A failure in the induction installation will be the result of a failure in the following important elements: 1) in the thyristors of the rectifier block; 2) in the inverter block or the starting scheme; 3) in one of the capacitors or the inductors in the load circuit; 4) in the control boards or the protection of these blocks; 5) in the supply voltage, or in the connections between the blocks. Therefore, the calculation of the probability of failure for the whole system can be reduced to determining the **Failure rate – λ (FR)** and the **Probability of failure Q (t)** of the basic elements in the power circuit. Respectively, the fault tree contains the elements of the power circuit – thyristors, diodes and capacitors of the **starting and load circuits** (fig. 8).

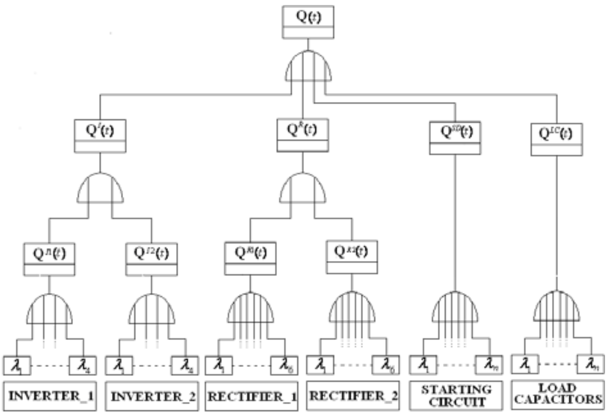

Fig. 8. *Fault tree for the power circuit of a induction installation*

A failure in the Inverter and the Rectifier blocks can be presented by their respective **Probability of Failure:**

(Q) → $Q^{I_1}(t)$, $Q^{I_2}(t)$, $Q^{R_1}(t)$ and $Q^{R_2}(t)$ will occur.

The **Probability of Failure Q (t)** for a single block**,** when the operational time is set to $t = 5000$ *hours,* (ca 1 year) has been already calculated [4].

- For Inverter I_1: $Q^{I_1}(t) = 0{,}1152$
- For Inverter I_2: $Q^{I_2}(t) = 0{,}1152$
- For Rectifier R_1: $Q^{R_1}(t) = 0{,}0367$
- For rectifier R_2: $Q^{R_2}(t) = 0{,}0367$

The **Probability of Failure Q (t)** on the inverter and the rectifier is already too calculated [4] when the operational time set $t = 5000$ *hours.*

- For Inverter I: $Q^{I}(t) = 0{,}217$
- For Rectifier R: $Q^{R}(t) = 1 - P^{R}(t) = 0{,}07$

The **Probability of Failure Q (t)** for the **thyristors, diodes and capacitor from the Starting circuit** when the operational time set $t = 5000$ *hours* or approximately 1 year, is obtained:

- For thyristors:

$$Q_{Th}^{SC}(t) = 1 - \ell^{-\lambda_{Th}^{SC}.t} = 0{,}045 \quad (14)$$

- For diodes:

$$Q_{D}^{SC}(t) = 1 - \ell^{-\lambda_{D}^{SC}.t} = 0{,}01 \quad (15)$$

- For capacitor:

$$Q_{CAP}^{SC}(t) = 1 - \ell^{-\lambda_{CAP}^{SC}.t} = 0{,}003 \quad (16)$$

The **Probability of Failure Q (t)** for the **Starting circuit**

$$Q^{SC} = Q_{Th}^{SC}.Q_{D}^{SC}.Q_{CAP}^{SC} \quad (17)$$

$$Q^{SC} = 0.0574$$

The **Probability of failure** from the load capacitors battery when the operational time set $t = 5000$ *hours* is obtained:

$$Q_{CAP_{LOAD}}(t) = 1 - \ell^{-\lambda_{CAP_{LOAD}}.t} \quad (18)$$

$$Q_{CAP_{LOAD}} = 0{,}015$$

With such probabilities obtained it is possible to move forward to the definition of the final event – a system failure caused by a single blocks failure in the induction installation. The **Probability of Failure Q (t)** for the final event is obtained as a product of the probability of the failure-free operation of the single blocks (**OR** operator): rectifier, inverter, starting circuit and load capacitor battery:

$$R(t) = \left[1 - Q^{I}(t)\right]\left[1 - Q^{R}(t)\right]\left[1 - Q^{SC}(t)\right]\left[1 - Q_{CAP}(t)\right] \quad (19)$$

$$R(t) = 0{,}674 .$$

The **Probability of failure** from the induction installation when the operational time set $t = 5000$ *hours* is obtained:

$$Q(t) = 1 - R(t) = 0{,}326 \quad (20)$$

The probability of failure, as has been obtained above, represents the weak points of the power system with respect to its reliability. The blocks with the highest Failure rate and Probability of failure-free operation, respectively can be clearly defined.

According to the ‘failure tree’ (fig. 8), and the calculations of the reliability indicators, the inverter thyristors are the elements with the highest Probability of Failure in the power system. Moreover, a failure can be expected in both blocks with parallel working inverters. The other elements of the power system for which a failure can be expected are the start thyristors – they show the second highest failure rate and probability of failure, respectively.

The results from the reliability research have been confirmed by a practical exploration of the induction installation presented in this paper. It has been restored and set to exploitation conditions for a period of 5000 hours (ca 1 year). For that period, the failure data was mainly related to a failure in the thyristors within the inverter or in the starting circuit.

3. CONCLUSION

In conclusion, it can be pointed that there is a match between the theoretical and the experimental results on the reliability of the presented induction installation. The method „Fault Tree" presents clearly the weak system's points by recognizing the failure probability of each single block. This method is applicable for complicated technical systems, where it is difficult to predict the origin of failure and its relation to the reliability of the whole system.

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