Artículo de investigación

Testing of hidden defects in interconnections

Тестирование скрытых дефектов в соединениях

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Abstract

Electronic instrumentation has a constant growth density layout and functionality. This entails an increase in the density of interconnection elements by increasing their number and reducing the size of it. The growing cost of interconnection structures (printed circuit boards, printing and wired mounting) associated with their complexity and increase of their reliability requirements, result in the search of new and improved non-destructive diagnostic methods and means of control. However, the existing methods do not allow control interconnects with sufficient certainty to identify a significant number of hidden defects. This class of defects can be diagnosed by means of non-destructive testing of interconnections, based on the detection of controlled circuit reaction to a current. The paper describes the principles for calculating the current to exercise that control.

Keywords: Current determination for testing, diagnostic non-destructive testing, electrical interconnects, electronic assembly, printed circuit boards.

Аннотация

Электронное приборостроение находится в состоянии постоянного роста плотности компоновки и функциональности. Это влечет за собой рост плотности элементов межсоединений за счет увеличения их количества и уменьшения размеров. Возрастание стоимости конструкций межсоединений (печатных плат, печатного и проводного монтажа), связанное с их усложнением и возрастанием требований к надежности, обуславливает поиск новых и совершенствование существующих неразрушающих диагностических методов и средств контроля. Однако, существующие методы контроля межсоединений не позволяют с достаточной достоверностью выявить значительную часть скрытых дефектов. Такие дефекты могут быть диагностированы при помощи неразрушающего контроля соединений, основанного на регистрации реакции контролируемых цепей на воздействие импульса тока. В статье описываются принципы расчета параметров импульса тока и способ реализации такого контроля.

Ключевые слова: диагностический неразрушающий контроль, печатные платы, расчет токовой нагрузки, электрические межсоединения, электронные сборки.

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Introduction

The process of development of electronic instrumentation is characterized by a constant increase in the density of the arrangement of active elements by about 75% per year (Armstrong, 2001; IEC 60194, 2006), and this, in turn, leads to the need to increase the density of interconnect elements due to a significant reduction in printed wiring elements: width of the conductors and gaps, holes and contact pads, spatial (layer-by-layer) distribution of interlayer transitions through the use of through and blind holes in mounting substrates (printed circuit boards) (Pfeil, Holden, 2007). Compaction of the layout of the blocks, increasing the requirements for the overall dimensions of the on-board equipment, leads to the complication of interblock switching, reducing the "margin of safety" with which its connections are made.

The increased density of the group of elements, the increase in the number of connections and the decrease in size complicates the ensuring of the quality and reliability of the equipment, and requires further improvement of control methods based on the use of high-performance automatic tools.

Theoretical basis

The need to use of such control is dictated by the increase in the number of inevitable defects as the density of the layout and the level of integration of microcircuits increase. As the number of components in the printing unit grows without increasing its size, there is a rise in the number of defects that need to be detected, localized and eliminated by known repair methods (Karpov, 2010). Statistics of real production shows the inevitability of defects in the approximate quantities (Table 1). But the main problem is to find them for further elimination (Vorunichev, Zasovin, 2019). If on single-sided and double-sided printed circuit boards conductors are available for inspection and detection of defects, then in multilayer structures (multilayer printed circuit boards - MPCB) they are inaccessible for visual inspection. In this regard, there is a need for techniques for searching for defects in compounds, and non-destructive methods (Medvedev, 1986; Rasika, Gautami, Swati, Mayuri, Archana, 2016).

Table 1. Number of defects depending on the saturation of printed circuit boards with interconnects in the MPCB

Number of components on the board	Number of connecting elements	Average number of defects
20	350	0,1
50	900	0,3
100	1500	0,6
150	3000	1,4
300	10000	2,0
1000	50000	3,0

There are functional, parametric and diagnostic methods for monitoring compounds (Lulina, Medvedev, Mylov, Semenov, Serzhantov, 2009). While using functional control (identification of wires), when only the correctness of connections and disconnections is checked, a significant part of latent defects that can subsequently lead to failures remain undetected. Therefore, functional control is used only in a well-organized sustainable production of simple installation products. It is distinguished by the simplicity and very high performance of automatic controls, which gives functional control a well-known advantage over other types of control.

Unlike functional, parametric control of compounds by quality criteria (for example, resistance of compounds) allows not only to identify a significant part of defects, but also to identify violations of technological discipline in production. However, even after parametric control, a significant group of hidden defects remains undetected, the presence of which does not affect the results of the control of the controlled circuit. The defects in connections that are not detected by parametric control determine the level of decrease in the operational reliability of electronic equipment.

Local weakening of compounds occurs mainly under extraordinary impacts. The reactions of the controlled element to them are analyzed by means of "diagnostic" control. The use of such a control principle allows predicting the resistance of compounds to extreme impacts or to conditions of long-term operation, which is accompanied in time by deep processes of aging of materials, which proceed most quickly in places of heterogeneity or defects. Timely detection of such defects and subsequent repair with a repeat of the diagnostic control can reduce the level of defective connections (Danilova, Kochegarov, Yurkov, Miheev, Kante, 2018).

The physical basis of diagnostic control methods is the study of the physical characteristics of the object and the detection, therefore, of the imperfection of its structure. These methods are based on the results of studies of physical processes leading to connection failures.

The development of practical methods for the diagnostic control of connection elements is connected, first of all, with the solution of the problem of electrical switching of many circuits using special programs developed by computer technology. A large number of controlled circuits in the MPCB makes it necessary to use high-performance methods of thermal excitation and to detect the reaction of the elements of compounds to this excitation. The requirements for high reliability of control of compounds and the urgent need to automate control operations are the basis for the predominant use of electrical verification methods (Chaudhary, Dave, Upla, 2017).

The simplest type of control is the electrical identification of circuits (functional control of correct installation). This type of control reveals only design errors and gross manufacturing defects. Its advantages consist in the possibility of using transistor switches in the switching system of controlled circuits and, as a result, in large control performance.

A more reliable assessment of the quality of the compounds is carried out by monitoring the resistance chains. However, the most dangerous types of joint defects are not detected when monitoring targets for electrical resistance, since the changes introduced by such attenuation into the overall resistance of the circuit are many times smaller than possible changes in resistances caused by permissible technological changes in the geometry of the elements. Such defects are: for MPCB, local thinning of printed conductors, ring cracks in the metallization of holes in printed circuit boards, defects in internal connections in the MPCB (for example, hair cracks in conductors); for interblock connections, weakening of contacts, kinks of wires, “hauling” of wires, local thinning of wires.

In addition, in accordance with the well-known theoretical concepts, an electrically “reliable” contact is created not only when the contacted surfaces are in full contact, but also in the case of partial contact of quasimetal surfaces coated with thin layers of oxides and / or an adsorbed gas film several molecules thick. At low values of the transition resistance in the defect, it is practically impossible to obtain trustful information about the reliability of the connection element. Even the methods of nonlinear distortion and signature analysis do not allow solving this problem, since with a large number of tunneling zones the signal distortions are so small that they cannot be detected by standard means.

The disadvantages of existing connection control methods can be circumvented by checking the circuit resistance to current load. The essence of the method consists in loading the controlled compound with current, recording the heating temperature by incrementing the voltage drop and evaluating its quality by the nature of the development of the thermodynamic process of heating the compound. This method has a diagnostic character and high reliability of the quality assessment of compounds (Medvedev, 1986). According to this method, a single current pulse is passed through a controlled connection, in accordance with the increment of voltage drop, the heating temperature is recorded on it, when a predetermined temperature level is reached, the current is turned off, thereby providing a non-destructive mode of diagnostic control of the connection. The need to automate connection control processes requires the use of rapid quality assessment methods. In this case, this requirement is satisfied by the use of short (millisecond) current pulses, the energy of which is selected from the conditions of rapid heating of the controlled circuits.

Diagnostic automated control of connections in the onboard equipment of aircraft has an important role for the timely diagnosis of latent defects, which, developing, lead to the failure of nodes and blocks. The most dangerous types of joint defects that are not detected by existing control methods are:

- For multilayer printed circuit boards (MPCB): local thinning of printed conductors, ring cracks in the metallization of the holes of printed circuit boards, defects in internal connections in the MPCB (for example, hair cracks in conductors);
- For interconnects: weakening of contacts, kinks of wires, “hauling” of wires, local thinning of wires (Lulina, Medvedev, Mylov, Semenov, Serzhantov, 2009).

Earlier (Medvedev, Vasiliev, Sokolsky, 2013), the principles of diagnostic non-destructive testing of aircraft on-board equipment connections based on recording the response of controlled circuits to a pulsed current load are considered. To create equipment that implements these principles, it is necessary to consider the physical processes taking place in the conductor under the influence of electric current.

The limit value of the current that a printed conductor and its surrounding insulation can withstand without noticeable physical and chemical changes and, moreover, without destruction, depends on a large number of factors, including the thermal conductivity of the dielectric, the size, shape and spatial position of the conductors in a multilayer printed circuit board (MPCB). To take into account all the factors affecting the kinetics of heating conductors with current, we present the following physical model: a conductor element of mass m with specific heat capacity C has resistance R_0 in the initial state at temperature T_0. When passing through the current conductor I, the power P is allocated at the resistance R_0. The temperature of the conductor rises by $\Delta T=(T-T_0)$, , the conditions of heat transfer from the conductor are determined by the thermal resistance $r_т$, heating of the conductor causes an additional increase in resistances corresponding to the temperature coefficient of resistance α (for copper— 0,004 K^{-1}) (Webb, 2006; Medvedev, Vasiliev, Sokolsky, 2013).

The relationship of the thermodynamic heating process can be described by a system of equations:

$P(t)=I^2R_0[1+\alpha\Delta T(t)]$ - power released on the resistance of the conductor, depending on the superheat temperature $\Delta T(t)$;

$\Delta T(t)=T(t)-T_0$ - conductor overheating relative to ambient temperature T_0;

$T(t)=Q(t)/C$ - conductor temperature;

$Q(t)=\int_0^t P(t)dt$ - amount of heat accumulated in the conductor;

$\Delta P(t)=P(t)-P_{out}(t)$ - the difference between the emitted $P(t)$ (Joule heat) and the power withdrawn by $P_{out}(t)$, causing a change in the temperature of the conductor;

$P_{out}(t)=\Delta T(t)/r_т$ - power withdrawn from the conductor through thermal resistance $r_т$.

The equation linking the allocated power with the accumulated (due to heat capacity - $Q(t)$ and output (due to dispersion - $P_{out}(t)$), is as follows:

$$I^2R_0[1+\alpha\Delta T(t)]dt = mCd[\Delta T(t)]+[\Delta T(t)/r_т]dt \qquad (1)$$

The solution of differential equation (1) has the form:

$$\Delta T(t) = (T\infty - T_0)(1-\exp(-t/\tau)); \qquad (2)$$

where $T\infty$ is the steady state conductor temperature, T_0 is the initial conductor temperature and τ is the time constant of the thermodynamic heating process:

$$\tau = mCr_т/(1-I^2R_0\alpha r_т) \qquad (3)$$

Qualitative characteristics of the thermodynamic processes of heating compounds for characteristic current loading modes are shown in Figure 1 (Medvedev, Vasiliev, Sokolsky, 2013).

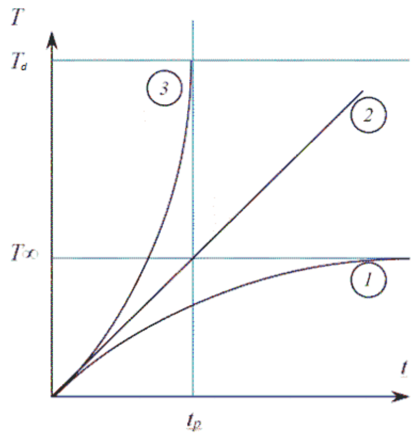

Figure 1. Qualitative characteristics of circuit loading by current (td — destruction of the conductor by current)

Initial rate of temperature rise

$T(t)|t\to 0 = \{d[T(t)]/dt\}|t\to 0 = (mC)\text{-}1I2R_0t$ (4)

that is, in the initial stage, the heating of the conductor by current is an adiabatic process, independent of the characteristics of the environment surrounding the conductor.

The nature of the further development of the heating process depends on the sign of the root of equation (1):

$p = 1 - I^2R_0\alpha r_T$ (5)

for $p>0$ the process reduces to a steady-state value (curve 1 in the Figure 1):

$T\infty = lim[\Delta T(t)]|_{t\to\infty} = I^2R_0r_{T\infty}/(1-I^2R_0r_{T\infty})$ (6)

where $r_{T\infty}$ - is the thermal resistance in the steady state heating;
and the change in temperature over time is:

$\Delta T(t) = I^2R_0r_T\ (1\text{-}I^2R_0\ r_T)[1\text{-}exp(\text{-}t/T)];$ (7)

at $p<0$, the temperature of the conductor increases unlimitedly until the current is turned off (curve 3);

at p=0, the heating process is characterized by a linear increase in temperature $T(t) - I^2R_0t/mC$ in time (curve 2). The linear mode is the boundary between the stable and unstable heating modes. Therefore, it defines the critical current value (as the boundary value between the modes).

If the current is not limited in time and exceeds the I_{KP}, value, then the connection is destroyed.

The process of cooling the conductor at I=0 is characterized by a time constant $\tau_0 = mCr_T$ and is determined by the expression

$T(t)|_{I=0} = T_{max}\exp(-t/\ \tau_0),$ (8)

where T_{max} - is the maximum temperature of the conductor overheating with the current from which it cools.

The thermal resistance r_T and the specific heat C are related to the geometry of the conductor, the characteristic of the environment, and the nature of the heating process. In transition mode, thermal resistance and heat capacity change over time. At the initial moment of time, after turning on the current, the thermal resistance of the heat sink is determined by the heat transfer resistance from the heated conductor to the dielectric region located in close proximity to its surface. At this moment, the conductor's body is mainly heated, i.e. the heating process is close to adiabatic (image 1 in Figure 2). Over time, more and more large masses of material are heated around the conductor, the boundaries of the heat sink are moved away, therefore, the values of heat capacity C and thermal resistance r_T change (image 1 in Figure 2. When heat release and heat transfer are balanced at a temperature corresponding to T∞, the thermal resistance is mainly associated with the resistance of heat transfer from the surface of the board to the environment, since the thermal resistance of the dielectric in this heat transfer circuit is minimal (image 3 in the Figure 2).

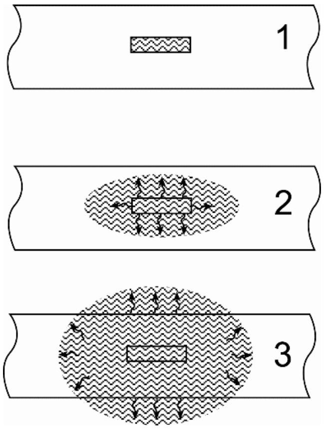

Figure 2. Stages of heating a current conductor

Among the nondestructive testing methods studied, the most acceptable is the method of thermal excitation of interconnect chains. Therefore, a single current pulse is passed through the monitored connection to the method, the heating temperature is recorded on it in increments of the voltage drop, when the predetermined temperature level is reached and the current is turned off, thereby providing a non-destructive mode for the diagnostic control of the connection. The need to automate connection control processes requires the use of rapid quality assessment methods. In this case, this requirement is satisfied by the use of short (millisecond) current pulses, the energy of which is selected from the conditions of rapid heating of the controlled circuits (Remesh Kumar, Shreekrishna Kumar, 2019).

We introduce the concept of linear values of physical constants: $M = \gamma Sl$ *(г)*, $r'_T = r_T / l$ *(K·cm/W)*, $R_0 = \rho_0 l/S$ *(Ohm·cm)*, $I = JS$ *(A/cm²)*, $C = cm$ *(J/g·K)*, where M, l, S, γ and c are weight, length, cross-section, density and specific heat of the conductor material; r'_T, the linear thermal resistance of the conductor material in the initial state; J, the current density. Then expression (7) takes the form

$$T(t) = J^2\rho_0 r_T S\,(1 - J^2\rho_0 r_T S\,)^{-1}\,\{l\text{-}exp[-\,(l - J^2\rho_0 r_T S)(\,\gamma_0 r_T S\}^{-1} \quad (9)$$

An analysis of this relationship shows that the greatest sensitivity to heterogeneities of the elements of compounds is ensured at $J^2\rho_0 r_T S\alpha \rightarrow 1$.

Then

$$\Delta T(t) = (1 - \exp(1 - J^2\rho_0 r'_T S\,\alpha)\,t \quad (10)$$

The absence in expression (10) of the dependence of $\Delta T(t)$ on thermal resistance is a sign of the adiabaticity of the process, i.e. at large current densities, the conductor heating process is so fast that heat transfer to the environment does not occur. Under this condition, the thermal conductivity of the environment has a weak effect on the results of the control of connections by current loads, which is the second significant advantage of this control mode.

The duration of the process of destruction of compounds t_d when passing current is determined by the time of their heating to the temperature of destruction of T_d. Solving (10) with respect to t, we obtain:

$$t_p = \gamma c\, ln(1+\alpha\Delta T_p)/(J^2\rho_0\alpha)$$

Copper conductors 0.3 mm wide and 0.035 mm thick: S = 0.01 $mm^2 = 10^{-4}\ cm^2$; $\gamma = 8.9\ g/cm^3$; $\Delta T_d = 1063$ K (difference from room temperature to melting point); $c = 0.45\ J/g\cdot K$; $\rho_0 = 1.72\cdot 10^{-6}\ Ohm\cdot cm$; $\alpha = 0.004$ K^{-1}; under current load 30 A ($J = 3\cdot 10^5\ A/cm^2$) burn out for 10 ms. In non-destructive testing mode with the current turned off when it is heated to 50 °C , the heating time is 1 ms.

Thus, the condition for non-destructive testing of compounds is to limit the heating temperature to values that do not cause irreversible processes of destruction of the «conductor-insulator» composition.

Methodology

The control equipment developed according to these principles (Medvedev, Vasiliev, Sokolsky, 2013) contains a control element that, when the temperature limit is reached, turns off the load current. Let us denote the upper limit of the heating of the compounds under current loading through T_m. Each normal element of the connection will correspond to a time interval from the moment the current is turned on until it is turned off when the temperature T_m is reached. We call this interval the cutoff time t_0. In the above calculations, this time corresponds to 1 ms. Having agreed that $\Delta T_m = T_m - T_0$, we express t_0 in terms ΔT_m:

$$t_0 = [\gamma_0 c ln(1+\alpha\Delta T_m)]/(J^2\rho_0\alpha) \text{ or } t_0 = \tau_н\, ln(1+\alpha\Delta T_m)$$

where $\tau_н = \gamma_0 c/J^2\rho_0\alpha$

If, for example, for a copper conductor without defects, ΔT_m = 50°C, is taken, we obtain the numerical value of the cutoff time $t_0 = 10^8/J^2$.

The circuit for assessing the quality of circuit elements when loading it with current consists in the fact that a current source is connected to the current probes C - C of the connecting device (Figure 3). Voltage at potential probes P - P:

$$u(t) = IR_0[1+\alpha\Delta T(t)] = IR_0 + IR_0\, \alpha\Delta T(t).$$

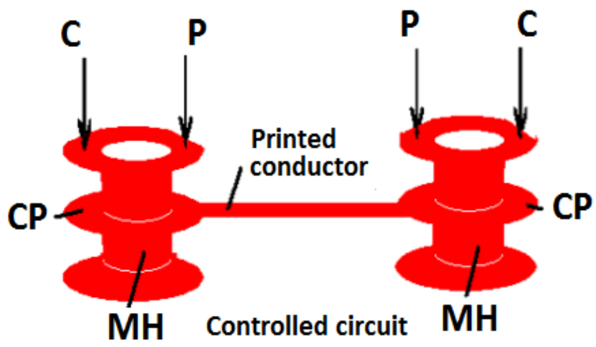

Figure 3. The scheme of connecting the probes to the controlled circuit of the printed circuit board: C and C – current probes – i(t), P and P – potential probes - u(t), CP – contact pads metallized holes (MH) of the printed circuit board

The maximum voltage increment ΔU_m, upon reaching which the corresponding device disconnects the load current, we find from the relation $\Delta U_m = U_0\alpha\Delta T_m$. For the selected cutoff temperature, $\Delta U_m = k\ U_0$. For example, for ΔT_m = 50°C $\Delta U_m = 0.2U_0$ (Figure 4).

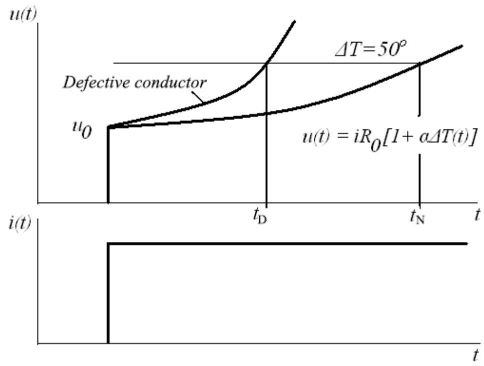

Figure 4. Plots of voltage and current load on the controlled circuit: t_D - current cutoff time in the presence of a defect in the circuit; t_N is the current cutoff time for a normal circuit when a temperature increase of 50 °C is reached.

The constant component of voltage U_0 contains information about the length of the circuit L and its initial state, since $U_0 = R_0 I = \rho_0 LI/S$. Therefore, the cutoff voltage is set automatically taking into account the length of the circuit.

The criterion for the quality of the controlled connection by this control method is the cut-off time t_0, set for each design of the printed circuit board according to the minimum allowable width of the conductor. At the same time, a sign of a weakening of the connection will be considered to be a decrease in the current cutoff time relative to that set for the minimum permissible conductor width.

Results

The implementation of this method is as follows.

A sufficient current pulse is supplied to the contact pads between which the controlled conductor is located, for heating the conductor at 50 ... 550 °C. When heated, metals increase their electrical resistance and, therefore, when a constant current flows through a conductor, the voltage drop increases on it. The rate of increase in voltage drop across a defective conductor will be greater than on a defect-free conductor, since in the places of defects the electrical resistance will cause more intense local heating. By fixing the difference in the rate of change of current, we can draw conclusions about the suitability of the conductor and, according to the results of a general check, the MPCB.

For practical implementation of the proposed method, a device (Medvedev, Vasiliev, Sokolsky, 2013) was developed, the functional diagram of which is shown in the Figure 5.

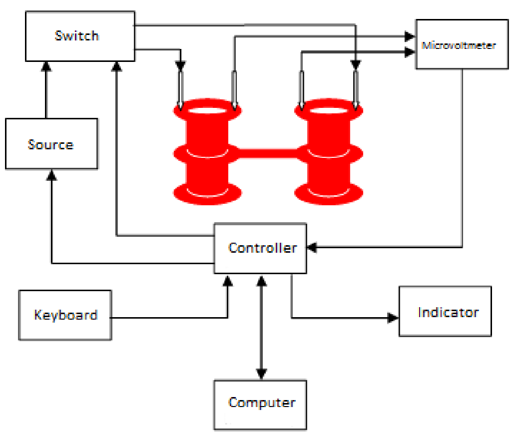

Figure 5. Functional diagram of the diagnostic stand

The stand consists of the following functional parts:

- The controller in which the program and the algorithm of the stand are stored;
- Current source;
- A switch to create a pulse of a certain duration;
- Microvoltmeter for measuring the voltage drop across the conductor;
- Keyboards to control the controller;
- An indicator used to visualize information about the work of the stand;
- A computer (any IBM compatible with a USB controller) that stores information about all the conductors of the printed circuit board.

The block diagram of the algorithm of the stand is shown in the Figure 6

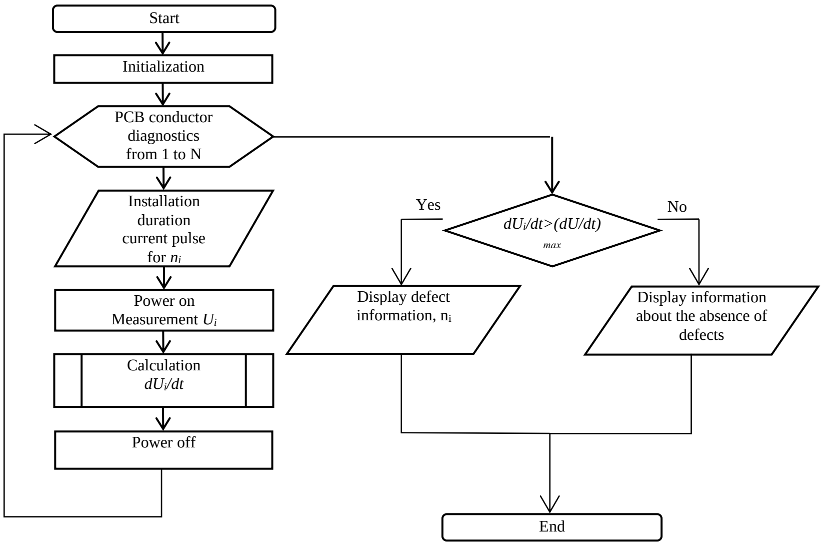

Figure 6. Block diagram of the algorithm of the stand

The diagnostic stand of printed circuit boards (PCB) works as follows.

After switching on from the keyboard, a command is given to “initialize the PCB”, that is, download information about the PCB conductors to the controller from the computer via USB. Next, the magnitude and duration of the current pulse are set. Then, four-point probes are connected to the PCB pads (in a predetermined sequence), and a voltage drop with a sampling frequency of 1 MHz is measured for each conductor and the derivative dU/dt, is calculated, which is compared with the previously calculated value stored in the connection table. If the calculated value is greater than the tabular one, a decision is made to reject a particular conductor. Information on the progress of diagnostics and its results is written to a file on the computer.

Figure 7 shows a circuit diagram of a current source for the diagnostic control of electrical connections on a Microchip PIC 18F2550 microcontroller. This device has 6 analog and 2x8 digital inputs / outputs, a 10-bit ADC, a built-in USB controller and an operating frequency of up to 48 MHz. The microcontroller program is written in assembly language and is intended for compilation in the MPLAB environment. Since the volume of the article is limited, no listing has been submitted.

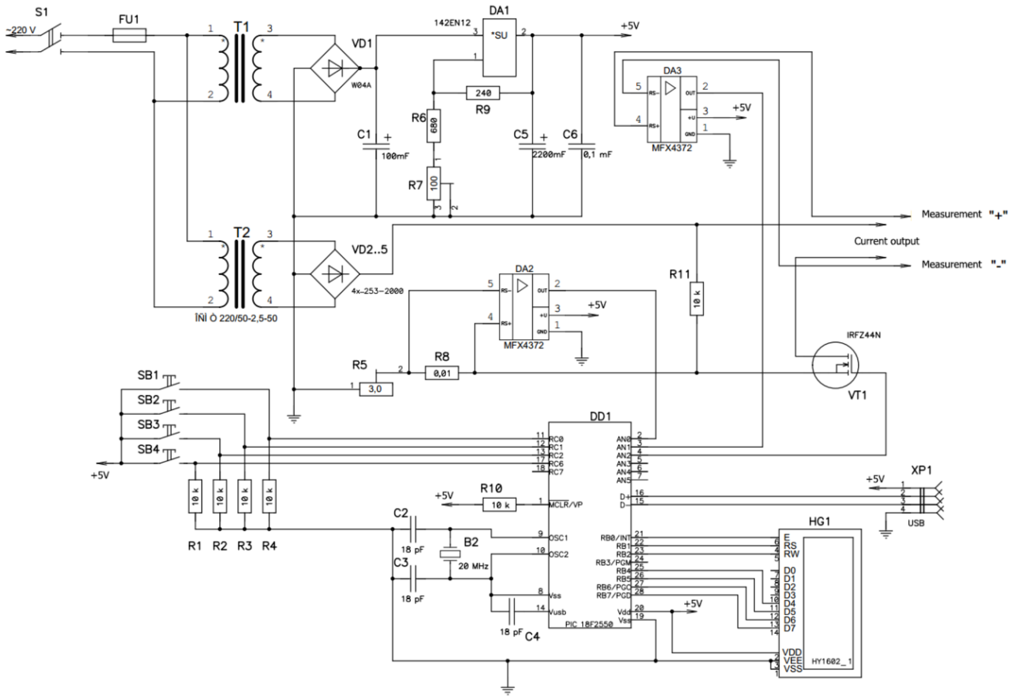

Figure 7. Current source for diagnostic monitoring of electrical connections

The current source is implemented on a T2 transformer, a VD2 ... 5 diode bridge and R5 rheostat (3.0 Ohm 100 W); the switch, on a powerful MOSFET transistor VT1 (IRFZ44N); the controller, on a DD1 microcontroller (Microchip PIC 18F2550); the microvoltmeter, on the DA3 current sensor (MAX4372F); the keyboard, on the SB1 ... 4 buttons; the indicator, on the HG1 (16 character 2-line LCD indicator HY1602). The current is set by the rheostat R5 and is controlled by the DA2 current sensor (MAX4372F) on the resistor R8. To power the microcircuits, a stabilized DC source is used: a transformer T1, a diode bridge VD1 (W04A) and a stabilizer DA1 (LM317T).

In order to increase the sensitivity of the measurement circuits on the resistor R8 and the controlled conductor, maximum voltage amplification is necessary. For this purpose, specialized microcircuits can be used, the so-called current sensors, manufactured by various companies. In the proposed device we used chip MAX4372F (DA3) of the company Maxim.

Conclusion

This technique of diagnostic nondestructive testing of electrical connections allowed to automate the process of MPCB control and at the stage of production (and not operation) to diagnose hidden defects that, developing, lead to failure of components and units.

The installation of non-destructive diagnostic control of connections, created on the basis of the described principles, will make it possible to detect defective connection elements without destruction, thereby increasing the reliability of monitoring and reliability of interconnects, increasing the yield of suitable MPCBs by more than 7%, and expanding the range of quality control due to the possibility of detecting defects and other weaknesses in all dissimilar elements of controlled circuits of on-board equipment of aircraft and other special-purpose equipment.

The experiments showed the efficiency of the methodology and the correctness of preliminary calculations.

References

IEC 60194: (2006). Printed board design, manufacture and assembly. Terms and definitions. 120.
Armstrong K. (2001). Advanced printed circuit boards design and Layout for EMC. Part 6. Transmission Lines. 3rd. EMC & Compliance Journal, 1-30.

Chaudhary V., Dave I.R., Upla K.P. (2017). Automatic visual inspection of printed circuit board for defect detection and classification. 2017 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET), Chennai, 732-737.

Danilova E., Kochegarov I., Yurkov N., Miheev M., Kante N. (2018). Models of Printed Circuit Boards Conductive Pattern Defects. Applied Computer Systems. 2(23), 128-134.

Karpov S. (2010). Criteria in assessing the quality of manufacture of printed circuit boards. Technology in the electronics industry. 8.

Lulina V.I., Medvedev A.M., Mylov G.V., Semenov P., Serzhantov A. (2009). Production of flexible and flexible-rigid boards. Part 6. Special means of control and testing of printed circuit boards. Technology in the electronics industry. 1, 11-21.
.
Medvedev A.M. (1986). Reliability and quality control of printed circuit boards. Moscow: Radio and communication.

Medvedev A.M., Vasiliev F.V., Sokolsky M.L. (2013). Current source for the diagnostic control of electrical connections in avionics. Practical Power Electronics. 3(51), 54-56.

Medvedev A.M., Vasiliev F.V., Sokolsky M.L. (2013). Diagnostic control of electrical connections in avionics. Practical power electronics. 1(49), 42-44.
Webb S. (2006). Design Basics of High Speed PCBs. EDA Expert. 10(113), 81-83.

Medvedev A.M., Vasiliev F.V., Sokolsky M.L. (2013). Calculation of current load for diagnostic control of electrical connections in avionics. Practical Power Electronics. 2(50), 45-48.

Pfeil C., Holden H. (2007). HDI Layer Stackups for Large Dense PCBs. www.mentor.com/pcb. 11.

Rasika R., Gautami D., Swati A., Mayuri B., Archana S. (2016). Quality Control of printed circuit boards using Image Processing. International Journal of Computer Applications. 141(5), 28-32.

Remesh Kumar K. R., Shreekrishna Kumar K. (2019). Testing of Current Carrying Capacity of Conducting Tracks in High Power Flexible Printed Circuit Boards. Journal of Electronic Testing. 2 (35), 131-143.

Vorunichev D.S., Zasovin E.A. (2019). Metallographic Analysis during Multilayer Printed Circuit Board Production Quality Assurance with Interlayer Connections Composed of Radio-Electronic Systems. Journal of Communications Technology and Electronics. 2(64), 182-185