Reliability of microprocessor-based relay protection devices - myths and reality Part I

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This first article in a two-part series examines four basic theses about the ostensibly high reliability of microprocessor-based relay protection (MP) touted by supporters of MP.

Through detailed analysis based on many references it is shown that the basis of these theses are widespread myths, and actually MP reliability is lower than the reliability of electromechanical and electronic protective relays on discrete components.

Malfunction of relay protection is one of the main causes of the serious failures that periodically occur in power systems all over the world. According to the North American Electric Reliability Council [1] in 74 % cases the reason for heavy failures in power systems was the incorrect actions of relay protection in trying to avoid the failure. Thus the reliability of a power system depends on the reliability of relay protection in many respects.

It is a fact that intensive research and development in the field of electromechanical protective relays (EMRs) have been completely frozen for the past 30 - 35 years and all efforts of developers have been redirected to development of electronic, and then microprocessor-based protective devices (MPDs). Meantime EMRs provided and continue to provide reliable protection of all objects in the electric power industry. The reason for the disappearance of EMRs and transition to MPDs is not the inability of EMRs to carry out the functions, but something else. Due to the massive expenditure by leading MPD-manufacturers in promoting the MPD, the development of new materials and technologies have not affected the EMRs in any way. After tens of years in operation, today's EMRs have worn out and become outdated and, consequently, are a cause of a fair amount of discontent amongst protective relays experts. On the other hand, demounting EMR and transition to MPD in the electric power industry is connected with the necessity for investing significant amounts of money, not only for purchasing MPDs, but also for computers and special expensive test equipment, as well as for the replacement of expensive MPD failed units, which cannot be repaired. Significant capital investments are required as well for reconstruction of grounding systems of substations, for training of the relay personnel, etc. All this essentially disrupts the process of transition to MPD. According to [2], in 2002 Russian power systems had in operation 98,5% EMR and only 1,5% of various electronic devices of relay protection. According to [3] MPD constitutes about 0,12% of the total quantity of relay protection devices in Russia. In the West rates of replacement of relay protection in working power objects is also not so high (excluding newly erected power stations, of course). According to [4] at existing rates it will take about 70 years to replace all old protective relays with microprocessor-based. Such low rates for updating protective relays in working power stations all over the world causes intensive advertising activity of MPD-manufacturers and their distributors.

One of the main reasons usually presented in the vindication of MPD advantages is its considerably higher reliability, ostensibly, in comparison with electromechanical and electronic relays. This thesis is represented as being so obvious that it usually does not cause objections and frequently is repeated by managers and even by technical specialists of the power engineering companies. However, in a deeper analysis it appears that the basis of this thesis is made with a whole set of widespread myths about microprocessor protection [5].

Myth 1: MPD reliability is higher than EMR reliability because MPD does not contain moving internal elements [6].

EMR malfunction is usually associated with ageing and damage of wiring insulation (wear, drying), corrosion of the screws and terminal clips, deterioration of the mechanical parts of the relay. However, the number of operation cycles (i.e., movement of mobile parts) over the entire EMR service life under real operating conditions in power systems does not exceed several hundreds. So to speak about mechanical deterioration of EMR mobile parts, for all practicality, it is only in the case of evident defects of the factory-manufacturer or use of improper materials for these purposes. As for

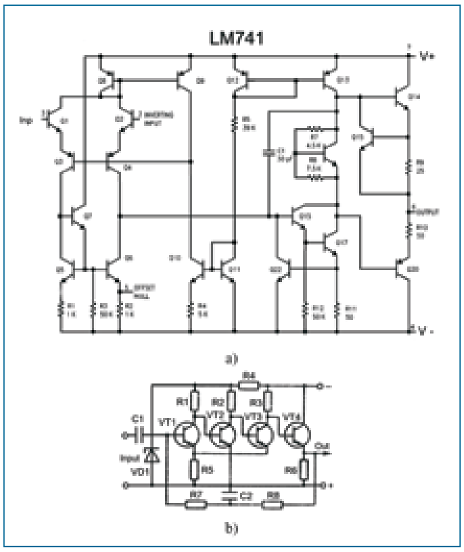

Fig. 1: Circuit diagrams of two amplifiers: at the top of a widely used IC LM741 type containing 20 transistors; below - the amplifier on the discrete elements with same parameters, containing only four transistors.

corrosion of the metal elements or drying out of the insulation, this is a consequence of using poor-quality materials by the relay manufacturer. Such defects are typical for EMR of Russian manufacture and do not come close to meeting the products of the leading Western companies which have been in operation for 30 - 40 years – even in a tropical climate [7]. Thus, to speak of EMR as an insufficient mechanical resource, as a kind of relay, is unreasonable. On the other hand, if the moving elements of the EMR move only at the moment of operation (pick ups) of the relay, the thousands of electronic components in the MPD are constantly at work: signal generators, numerous transistor switches, amplifiers, comparators, timers, counters, logic elements, voltage stabilisers, constantly works; the microprocessor constantly exchanges signals with elements of memory, the analogue-digital converter constantly conducts processing input signals, etc. Many elements are constantly under the influence

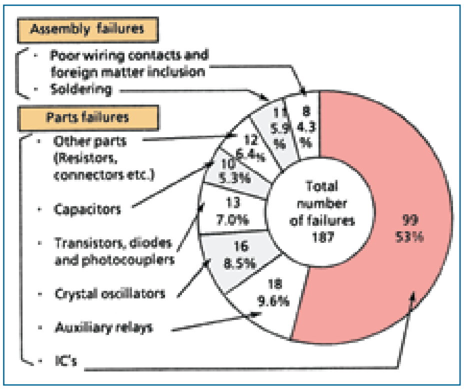

Fig. 2: The statistical data on damaged MPD based on investigations by leading Japanese companies [18].

of a high working voltages (120 - 250 V) and voltage spikes which periodically arise in the input circuits and external power supply circuits; as well as constant power dissipation (that is, they are heated), etc. In especially heavy work in MPD conditions, switching power supplies is very frequently the reason for MPD malfunction.

Myth 2: Reliability of semi-conductor (solid state) relays on discrete components is higher than reliability of electromechanical relays [8]. Reliability of electronic protective devices based on integral microcircuits (ICs) with a high degree of integration is higher than reliability of devices on discrete electronic components [8]. Reliability of microprocessor-based relays is higher than reliability of electronic non-microprocessor devices.

The unconditional statement about the greater reliability of semi-conductor relays over electromechanical relays is a popular mistake [9]. Semi-conductor relays possess increased reliability only at very large number of switching cycles (hundreds of thousand, millions) or at high switching frequencies. In many other cases reliability of semi-conductor relays is essentially lower than electromechanical relays [10].

Discrete electronic elements have much higher capability for withstanding voltage spikes and other adverse influences than integrated microcircuits [11]. According to [12] 75 % of all damages to microprocessor devices are the result of voltage spike impact. Voltage spikes with amplitudes from tens of volts up to several kilovolts, arising from switching transients in circuits [13] or the impact of electrostatic discharges, are "fatal" for internal microcircuits and processor microcells. According to [12] normal transistors (discrete elements) can withstand a voltage of electrostatic discharges almost 70 times higher than, for example, a microchip of memory (EPROM) in a microprocessor system. The most calamitous of temporary failures caused by electromagnetic noise that occur in microprocessor functioning can be [14], spontaneous changes of the operative memory (RAM) and registers contents, and internal damages can have the latent character [15]. These kinds of damage do not come to light in any tests and can appear unexpectedly.

In [16] it is mentioned that in connection with low stability of transients and voltage spikes the MPD demands especially rigid requirements for the protection level against electromagnetic influences. Attempts to use an MPD without strengthened electromagnetic protection frequently lead to use their malfunctioning [16, 17]. Electronic devices with discrete components contain fewer components than similar devices on ICs, (Fig. 1.) This does not seem to promote higher reliability of ICs.

The statistics on damages of MPD elements, collected by engineers of some MPD manufacturers, (Fig. 2) [18], very persuasively denies the myth about higher reliability of ICs.

According to the statistics submitted in [8], it is very obvious that the protective relays with electronic elements have three times the damageability of electromechanical relays, and microprocessor-based relays 50 times the damageability!

Reliability of the microprocessors of manufacturers such as Intel and AMD can be very high, and in fact the microprocessor, though not big, is a very important part of the MPD which contains many ICs. In [19] it is clear that the main processor unit (that is the printed-circuit-board with the microprocessor, memory, the analog-to-digital converter, library of programs and all auxiliary elements) part of MPD is the most likely to malfunction.

Another strike against microcircuits lies not only in physical damage of the microprocessor, but also software failures - damages not known earlier for electromechanical and electronic relays. As it is pointed out in [19], program bugs are not always detected during MPD testing. An additional source of problems is the necessity for periodically upgrading the MPD program versions. Frequently during this process software-to-hardware incompatibilities [19] appear. Such problems can show up during the most unexpected moments and can lead to very serious consequences for a power network. As is known, one of the reasons for failures in a power supply system in the USA and Canada in August, 2003 was a computer-related problem, a "lag" of a computer control system in a power company "First Energy" [20].

Myth 3: Reliability of MPD is much higher than reliability of all other types of the protective relays due to the presence of built-in self-diagnostics. With the self-diagnostics in MPD, 70 - 80 % of all internal MPD's elements are covered [21, 30]

This idea is widespread and is found in practically all publications devoted to MPD advantages. We shall consider features of this self-diagnostics more in detail.

Analogue-digital converter (ADC)

This device transforms an input analogue signal from CTs and VTs in binary code, transmitted through special filters to processing in the microprocessor. All ADC work by sample of input values through the fixed intervals of time and thus will transform a sine wave signal to a set of the fixed amplitudes. As can be seen from Fig. 3, this is a rather complex device carrying out a complex algorithm and containing a sizable set of internal units.

Some modern ADCs are so complex that they include even a small microprocessor to manage their work. The ADC is actually the principal unit of the measuring device, and, as in any complex measuring device, there are various errors in the transformation of input values present in the ADC. These are errors

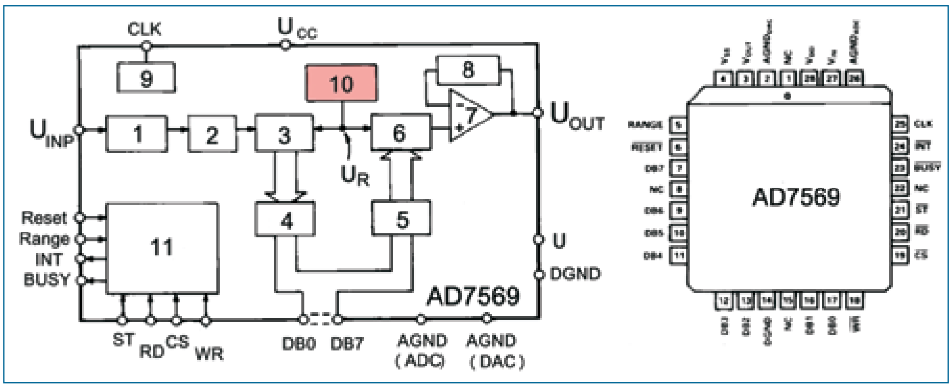

Fig. 3: Structure of the analogue digital converter AD7569 type. 1 – range network; 2 - unit of tracking/holding; 3 – analogue digital converter (ADC); 4 – ADC latch; 5 – DAC register; 6 – digital analogue converter (DAC); 7 - the amplifier; 8 – range network; 9 – synchronising clock; 10 – reference power supply.

in quantisation, additive and multiplicative errors, differential and integrated nonlinearity of the transfer characteristic, an aperture error, aliasing, etc. How it is possible to supervise the proper functioning of such complex devices during the continuous change of input values when there is only a single element storing a constant level of a signal during ADC functioning as the reference voltage source 10 (see Fig. 3). The so-called "self-diagnostics" ADC is based on this reference voltage monitoring [21]. The efficiency and usefulness of such "self-diagnostics" can be imagined.

Memory

MPD employs two kinds of memory: ROM (read only memory) intended for storing the managing program and setting, and RAM (random access memory) intended for temporary storage of the results of input values measurement and intermediate calculations. The managing algorithm is a set of certain numerical codes. A certain control sum, which is remembered in a separate cell of memory, is made of these codes. During MPD functioning, the pre-recorded control sum is periodically compared with the actual sum. A mismatch of these sums should specify malfunction of a ROM [21]. Clearly, the process of calculation of the actual control sum and its comparison with a pre-recorded sum is a discrete process, performed within certain intervals. And what happens if a malfunction occurs at a time between the intervals of comparison of the control sums? Won't there be a false operation of the protective relay and switching-off of a power network? The question is not completely hypothetical: such real cases which not were detected by of self-diagnostics algorithm are described in [19].

The situation with the self-testing of the RAM is much more difficult as the contents of the RAM constantly change at a high frequency in the random mode during MPD operation. It is difficult to understand how, in general, it is possible to test the memory cells which constantly re-record at a high frequency during operation, that is, to diagnose so-called "dynamic failures". MPD manufacturers have decided not to trouble themselves with solving this problem and to test the RAM in an automatic mode by periodic recording of the certain constant number in especially reserved memory cells and periodically reading this number with the subsequent comparison of these two numbers. If these numbers match, according to the manufacturers, this ostensibly confirms serviceability of the RAM [21], though it is not absolutely clear how it is possible to estimate serviceability of all RAM in the proper storing of the information in several cells of memory only. Besides it is well-known that

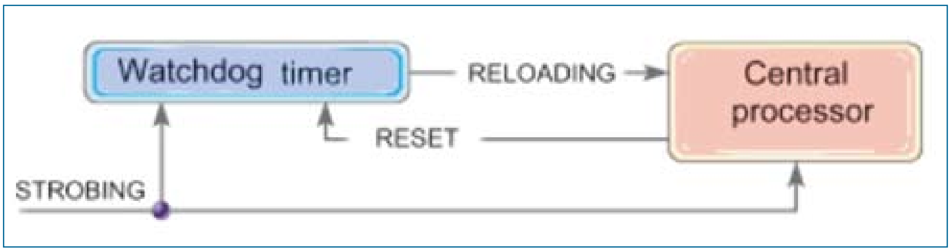

Fig. 4. A principle of the serviceability monitoring of of the microprocessor with the help of the watchdog timer.

absence of the static errors in memory does not guarantee occurrence of dynamic errors [22, 23], that is, the errors arising directly during record and reading process.

The problem with reliability of the MPD memory elements is actually much more complex. It appears that memory elements are subject to random unpredictable failures, not connected to physical damage of memory cells. Such random, temporary malfunctions caused by spontaneous changes of the contents in memory cells are referred to as "soft-failures" or "soft errors" (not to be confused with program failures - "software programming errors"). Such errors were not known earlier for the electronic devices based on discrete semiconductor elements or on usual microcircuits. Progress in the last years in the area of nanotechnology has led to a dramatic reduction in the sizes of semiconductor elements (along the order of microns and even parts of a micron), reduction of thickness of layers in semiconductor and insulation materials, reduction of working voltage, increase in the working speed (working frequency), reduction of electric capacity of separate memory cells, increase in density of placement of elementary logic cells in single chip. All this taken together has led to a sharp increase in the sensitivity of memory to ionising radiation [24, 25]. This sensitivity became so high that usually the radiating background at sea level became dangerous to memory cells. Streams of the high-energy elementary particles coming from space are especially dangerous. Even one such particle that hits a memory cell gives rise to secondary streams of electrons and ions causing spontaneous switching of

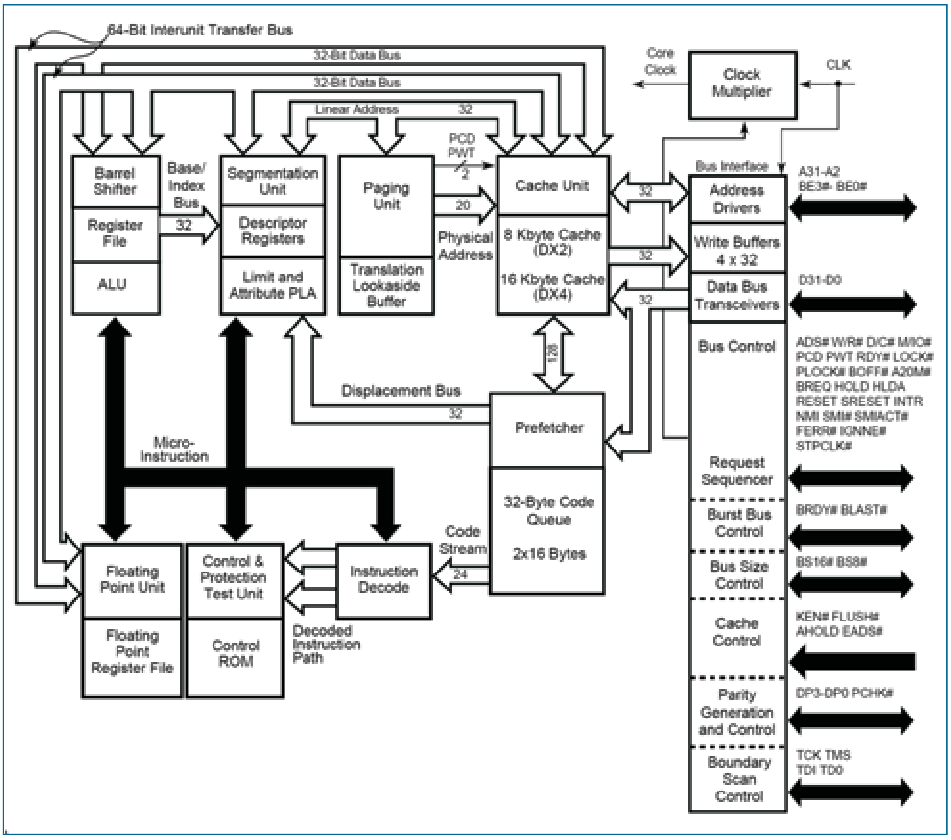

Fig. 5: Intel 486 SX block diagram.

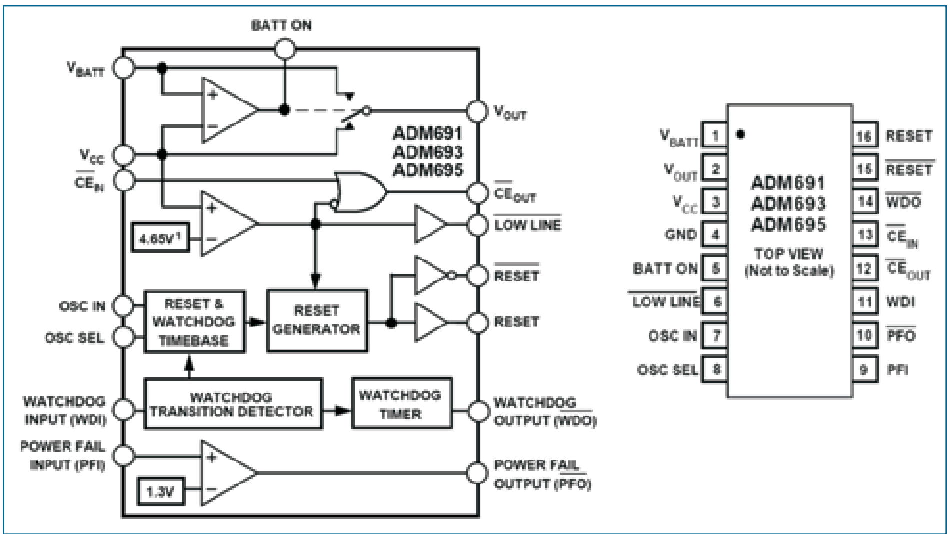

Fig. 6: Series ADM691 - ADM695 watchdog timer, manufactured by Analog Devices Co.

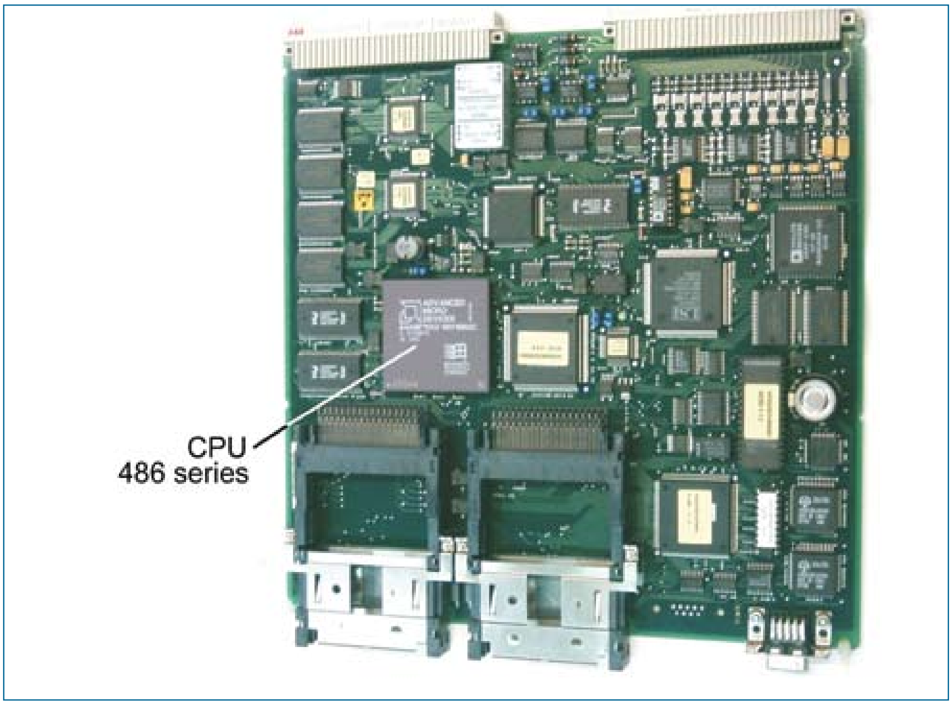

*Fig. 7: CPU of the of central processor unit of the MPD series RE *_316, manufactured by ABB.*

the elementary transistor or discharging the capacity in charge storage memory elements.

The problem is aggravated in modern microprocessor-based devices with the tendency toward the ever expanding use memory elements [25]. Many modern integrated microcircuits with high integration levels, included in the microprocessor-based device, contain the complex structures with embedded memory of such volume that serviceability, in general, is not supervised in any way. As shown in [26, 27], the problem of the sharp increase in sensitivity to ionising radiations is not only for memory, but also for high-speed logic elements, comparators, etc., that is, practically, for all modern microelectronics.

Central processor unit (CPU)

Compared to the complexities described above with the monitoring of memory serviceability, the self-diagnostics of the CPU looks simple enough, (Fig. 4).

It simply sends control cycling pulses with a period set to the so-called watchdog timer – the watchdog timer is reset to an initial condition with arrival of each new control pulse, and then begins a new cycle of time-reckoning. If at a certain moment the next control pulse from the CPU has not arrived, the timer starts the CPU reloads. A serious malfunction of the microprocessor and its "lag" during the reloading process which is found by the timer as the repeated absence of a control signal causes the locking of the CPU and transmitting a signal about CPU malfunction.

Process on tracking control pulses by the watchdog timer is synchronised with the help of external clock pulses (so-called "strobing"). Sometimes the watchdog timer is built directly in the microprocessor, and sometimes (which is preferable) it is an external specialised integrated microcircuits (IC). As an example of such devices the IC series ADM690 - ADM695, manufactured by Analog Devices can serve. This small chip contains not only the watchdog timer, but also the monitor of a voltage level of a CPU feeding. The pause between control pulses of the watchdog timer of this series can be 0,1 or 1,6 s.

It is abundantly clear that to check the serviceability of hundreds of thousands of transistor nanostructures of which any microprocessor consists is absolutely impossible. At best all that can be said is that it monitors only the general working ability of the CPU, in other words, checking if it is alive or dead. Given the very complex internal structure of the CPU, (Fig 5), containing many units (microcells; registers for temporal storage of the commands, the data and addresses; the arithmetic logic device; system management and synchronisation, etc.), the control signals from the CPU can continue to act on the watchdog timer even if part of the internal structure of the CPU is damaged.

It is obvious that damages of certain regions of the internal CPU structure (or parts of the internal managing program) can be detected only in an operating mode (upon activisation of these regions). If these regions of the CPU become active only at the input signals corresponding to emergency mode in an electric network, it means that the watchdog timer is of cold comfort.

In itself, the watchdog timer is a device made with the same technology as all other microelectronics devices, (Fig. 6), and is subject to malfunctioning and failures, as are all other microelectronic devices. Owing to its working algorithm, the watchdog malfunctioning during normal MPD operation can result in the locking of the CPU (i.e. locking of the whole MPD), or it will not notice "lag" of the CPU. In either case the relay protection will not work properly in emergency mode. Thus, the operational ability of the whole MPD appears to have a very strong dependence on the serviceability of one small chip named 'watchdog'.

One more important consideration is that the CPU is not an isolated element upon which correct functioning of MPD structure depends, it also depends on the serviceability of tens of other complex integrated microcircuits to which CPU is connected, but for which self-diagnostics is not stipulated. It's enough to look at the printed-circuit-board (PCB) of the central processor unit, (Fig. 7), to understand that serviceability of the CPU alone does not speak about serviceability of the entire PCB. Damage of any of numerous microelectronic (and not only!) components of this multilayered PCB will inevitably lead to infringement of correct MPD functioning and any watchdog here will not help, as proves to be true, judging from the data results in [19].

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