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A NEW METHOD FOR DEVELOPING AND TESTING OF COMPUTER RELAYING ALGORITHMS FOR POWER SYSTEM PROTECTIONS

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Abstract

Problems associated with the tests of protective devices have been of interest to power system protection engineers for many years. Conventional test methods include artificial short-circuits on the primary power network, which is a costly and dangerous method, or the secondary tests, when appropriate voltage and current signals have to be injected to the protective device. The problem of this second method is the modelling of the primary transient phenomena with considerable power. The microprocessor based protection represents an advanced technology in the power systems. Their development and testing needs an advanced technology as well. The transient signals are calculated off-line by a computer simulation, then the results are converted to analogue signal and put into the relay's input. In this way the new protection can be tested using transient signals, but special power amplifiers are needed as well. Our new method uses the communication capability of the computer relay. The transient signals are computed off line by a special EMTP program, then these numerical values are sent directly to the CPU of the protection, passing by the analogue circuits using the standard RS232 connection. Our system leads to a general improvement in the development process of new protection's algorithms and it helps efficiently in teaching power system transients and power system protection as well. The use of the new method is illustrated by practical examples of a digital, transformers differential protection.

Keywords: protection, computer relaying, transformer.

1. Microprocessor Based Power System Protection

In case of any power system fault the concentrated high energy can cause further damages not only in the faulted element, but in every part of the system delivering the energy to the fault location, and the environment. In worst case even human life can be in danger as well. To avoid all these effects, the faulty element must be disconnected by circuit breakers from the energy system as quickly as possible. The modern protective devices can selectively find the location of the fault and give commands to the appropriate circuit breakers within 10–20 ms. The trend in development of power system protection led to the microprocessor based relays, which have many advantages as compared to the older electro mechanical relays, and their capabilities can be even better than the broadly used electronic devices. Their first advantage is the self-test and self-diagnosis capability, which improves the reliability of the protective system. They have capability to communicate with a central computer, which can supervise the operation of the relay, can check the correct setting, the results of the self-test, collects the measured and calculated current and voltage values stored in the digital memory, and can get the sequence of events and recorded transient waveforms. The analysis of these data in a central computer helps monitoring the state not only of the relay, but the power system as well.

All these advantages resulted in the quick spreading of microprocessor-based technology. All the big relay manufacturers have developed their own relay family, but the possibilities are not exploited yet. New measuring algorithms based not only on conventional steady-state approach, but using numerical methods to solve differential equations of the power system, or new digital filtering techniques, or perhaps sensing the travelling wave generated transients can lead to improvement of the protective system. The operational demands placed on modern power system protection creates specific requirements to test the relays.

2. Generalized Hardware Structure of Digital Protective Device

In order to explain our new test method it is necessary to summarize the normal structure and operation of the protection itself.

2.1 Hardware

Fig. 1 shows the dedicated hardware for a digital protective device (PETRI, 1987; PETRI, 1988). The three-phase voltages and currents of the high voltage network are transformed to measurable level signals by voltage and current transformers, and these values are connected to the input of the relay. The transformers inside the unit provide the necessary galvanic isolation and match the signal levels to the internal A/D converter. The low-pass filter — called anti-aliasing filter — is required to avoid the well-known aliasing phenomena, which is a basic consequence of sampling in any numerical algorithm. After analog to digital conversion the sampled digital values of the currents and voltages are stored in the RAM. The program — which controls the sampling, processes the data, makes the decisions for switching off the circuit breakers and performs all the necessary and

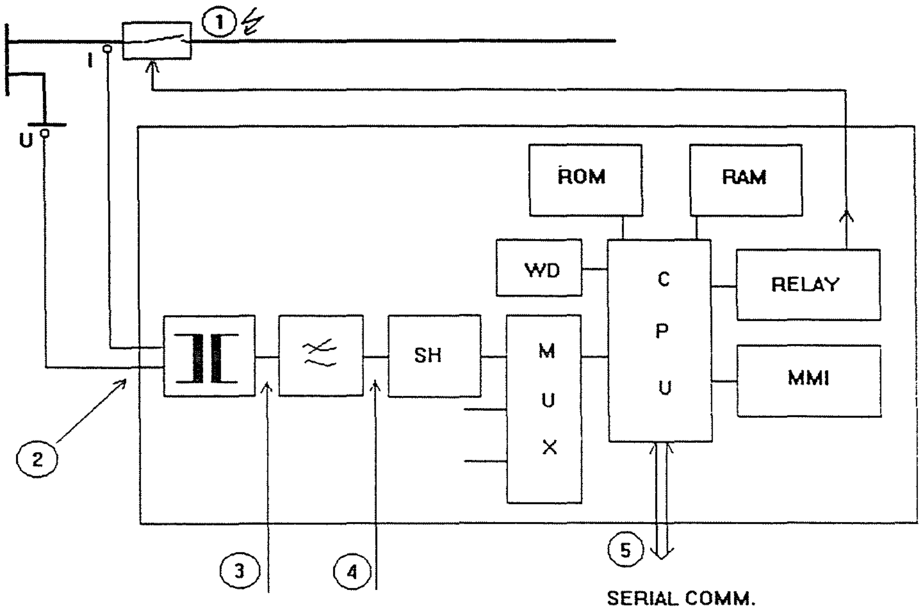

Fig. 1. The scheme of a numerical protection

possible service functions — is stored in EPROM. The peripheral devices of the protection are the relay contacts and the man-machine setting interface. The independent watch-dog circuit can try to reset the program in case of any serious failure of the program flow. An additional part is the communication unit, which enables a serial data transfer between the protection and the supervising computer on a higher hierarchical level. In this construction the communication unit, which under normal operating conditions, performs data acquisition from the protection unit, makes it possible to transmit information from a supervising computer to the protection as well, which is utilized in our method for testing the programmed algorithm.

2.2 Software

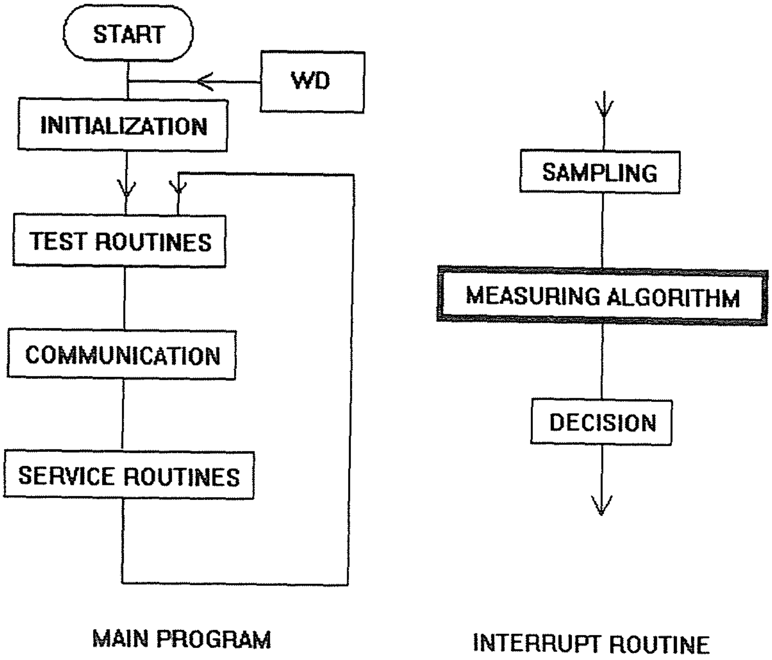

Fig. 2. The flowchart of a protection's software

The software structure consists of two independent units shown in *Fig. 2*. The main program, after the necessary initiation, gets in an infinite loop, where the routines perform the self-tests, the settings of the protection and the communication. The other software unit is the interrupt routine, which determines the properties and the behaviour of the relay, is activated by a programmable timer hardware circuit. Its functions are the control of data sampling and the calculation of the quantities (effective values, reactances, resistances, etc.), which can be compared with the setting values of the relay by the decision routines and the handling of the watch-dog circuit as well. In practice, the frequency of the activation of this interrupt routine is in the range of 0.5–2 kHz. During its time period all calculations for all three phases of the energy system must take place. It means that the calculation must be very quick and effective. The development of this algorithm is a tiresome process. Making its testing easier is the aim of our research, the process and results of which are summarized in this publication.

3. Relay Operation Testing Methods

Returning to *Fig. 1*, the locations are marked with numbers, where operation tests can be initiated.

The first possibility is the evaluation of relays operation by field trials on the real power system. It is an obviously adequate method, but very costly and dangerous one. It cannot be repeated many times, so for an exhaustive investigation, especially before filtering out all the possible bugs of the program in the development phase it can not be applied.

The second location in the scheme labelled by 2 is the secondary injection method. In this case there are more possibilities to carry out the test. The 'static' method uses slowly increasing injected 50 Hz currents or decreasing voltages to find the border points of the relay characteristic. The method does not investigate the transient behaviour of the relay, which is important during the development. The transient test needs a multi-channel power amplifier for voltages and currents and an appropriate source which produces wave forms simulating the original transients. The problem of the amplifier is the required broad frequency characteristic on a high power, which makes this method costly. The source can be a recorded primary transient, or a simulated one made by a network model or a computer program. The high power requirement can be abandoned if bypassing the built-in isolation transformer we put the simulated waveforms directly to the anti-aliasing filter's input. This possibility is noted by number 3. The source of the signal can be any of the previously mentioned methods.

There is a possibility to leave out the filter as well, if we want to test for example the influence of the different level low pass filtering on the behaviour of the relay, and we do not want to realize but only model the filter. The connection point is denoted in the figure by number 4. In most cases the model of the primary network is a digital algorithm which results in digitally stored waveforms. They need to be converted into analogue form, and the next step in the signal flow is an analogue digital conversion inside the relay. As this second conversion is a conventional step, it need not be tested again and again. So the duplicate conversion from digital to analogue and back from analogue to digital form can be left out of the signal flow, if the digitized values can be passed directly into the memory of the digital protective device. This is the basic idea of our method, and the details are discussed in the next chapter.

4. The Scheme of the New Test Method

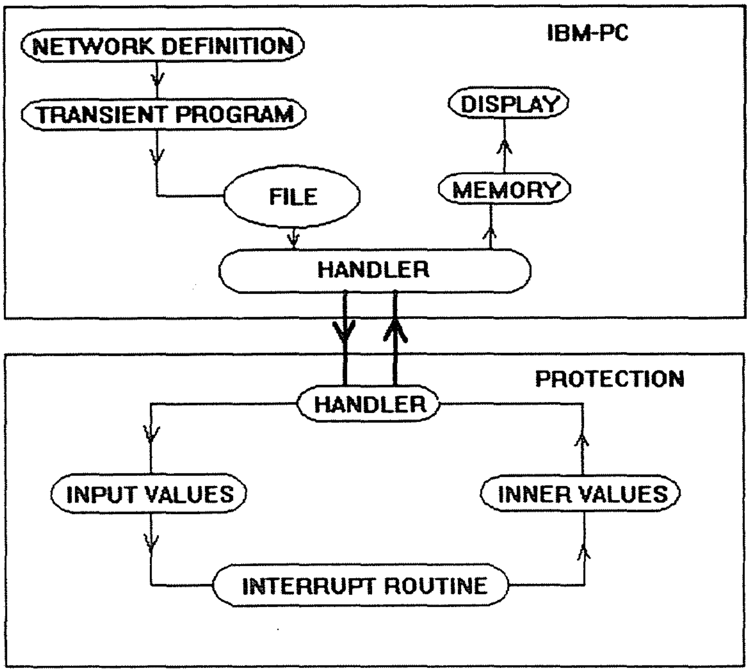

Fig. 3. The scheme of the testing system

Fig. 3 shows the scheme of the new test method. The two units, the protection and the supervising IBM-PC are connected with a bidirectional data communication channel. This is the same communication channel, through which a central computer installed on an electric power substation can collect data from the relay. In the laboratory it can be used for test purposes as well.

4.1 Changes in the Protective Device

The general hardware of the protection is fully unchanged. The required software modification is plotted in *Fig. 3*. The interrupt routine is the part of the program to be tested. It contains the calculation algorithm, the behaviour of which must be optimized to get an effective and exact protection. Instead of getting the stored data produced by the A/D converter, the 'handler routine' delivers them and puts them into the appropriate memory locations. These are the input values of the calculation algorithm. They must be of the same form, as if they were sampled by the A/D converter.

The algorithm calculates the required results from sampled voltages and/or currents (effective values, Fourier components, resistances, reactances, etc.). These results — on the figure called as 'inner values' — are stored in the memory. The decision routine uses these values for deciding whether the power system's circuit breaker should be opened or not.

The other task of the handler is to collect all the data from the memory of the protection unit, which are required by the supervising program running on the IBM-PC, and then to pass them through the communication line. The whole memory area is accessible, so not only the final results are at disposal, but with the help of intermediate results the whole calculation process can be followed as well. A big advantage of this method is that the calculation process does not have to run in real-time. In the real-life situations the interesting part of the process happens within some milliseconds, so the steps of the calculation were not accessible. In our method the timed interrupt is disabled, the interrupt routine is triggered by the handler routine. This is the only required change in the program, the calculation routine fulfils its duties regularly. After the successful test the handler routine can be removed, the interrupt must be enabled, and the bug-free program can be burned in EPROM.

So the test process can be summarized from the point of view of the protection as follows: The handler receives the simulated sampled data from the supervising computer and puts them into the appropriate memory location. The interrupt routine is triggered, and results of its calculation are put regularly into the memory as well. Finally, the handler routine collects the required data and sends them back to the supervising computer.

4.2 The Program System in the Supervising Computer

Fig. 3 shows that the program system in the supervising computer has two branches. First of all the simulated sampled data must be produced. In our simplified diagram it is made by the 'transient program'. Then the results of the test must be visualized, which is the task of the 'display' program. The communication is controlled by the 'handler'. In this chapter these parts are presented in detail.

4.2.1 The Transient Program

As it was mentioned above, the source of the wave-forms can be a short-circuit transient recorded on the power network (or with the help of its model — a transient network analyzer) or the waveforms can be calculated with the help of a transient simulator software. To remain compatible with the first — very valuable — method, where the results are stored in a file drawn in *Fig. 3*, we have decided to store the results of the transient program in a similarly structured file as well. We could use the EMTP program system which is well known among electric power engineers, but a special software has been written instead for our purposes. The reason of it is that because the versatility of EMTP, its usage is very complicated, it requires special knowledge and practice. Our transient program is specially designed for short-circuit calculations on a single power system element. This element can be a transmission line or a transformer for example. The connected network is simulated in a simplified way. The simplification means that special high frequency components of the transient caused by the not faulty elements of the network are excluded. Their effect is added to the waveform during the 'sampling' as a random noise decreasing according to the damping of the faulty element. The most significant part of the network — in our case the faulty element — is modelled in appropriate details with its three-phase parameters. In this way all the possible fault types (single phase to ground, double phase, double phase to ground and three phase short circuits) can be calculated. The steady state of the network before the short circuit is calculated automatically, giving the starting conditions to the transient calculation. The phase angle at the moment of the fault inception is an input parameter for the program as well. Our transient program offers the possibility to model the frequency characteristic of the current transformer and the voltage transformer as well in addition to the calculation of the effect of the anti-aliasing filters built into the relay. To simulate the anti-aliasing filter we can use any types of digital filters. In the example below we modelled a 2nd order Chebysev low pass filter. We can investigate the effect of the sampling and the resolution of the A/D conversion as well. The method of calculation is the step-by-step solution of the differential system. All these effects can be adjusted in the 'network definition' part of the program. The dialog controlled by the algorithm makes it clear for the user how to define these data during the preparation process. The way the program is structured makes it possible to construct cycles in the investigation, where the parameters are changed automatically to analyze the effect of the individual factors on the protection's behaviour.

4.2.2 The 'Handler' in the IBM-PC Based Program System

The two tasks of the handler are to send the 'sampled' data to the protection subsystem via the communication channel step by step and to give commands to the protection's handler to collect the required results. To do this second step the map file produced by the compiler is needed. This map file contains the identifiers and addresses used in the protection's program, so to point to the results to be investigated does not require the knowledge of the memory allocation, only the identifiers of the calculation algorithm. The program automatically offers the choice to the user. The list of the pointed variables is saved in a separate file as well, so the series of investigation is simplified as much as possible. The data returned from the protection is stored for the whole investigation process, so retracing the time function is always possible.

4.2.3 The Display Program

The display program is a graphic tool for visualization of the input and output data driven by a menu system. The user has first to assign the file of the input data and the required results. Three graphic and ten numeric windows are defined, the use of which is explained in connection with the example later. The calculated values of the digital filters or of the algorithm can be chosen for graphical display. Counters, logical states, etc. can be displayed in the numeric window. With a simple cursor we can retrace the displayed graphs and can check the results step-by-step as well. This testing method can verify the operation of the software as thoroughly as no other testing method can. Errors in the program can be caught, and the faulty part of the program can be found easily, if it does not operate as we expected.

5. Example: Test of a Transformer's Differential Protection

The principle of any differential protection is simple. If the sum of currents flowing into and out of the protected element measured at the normal connections is not zero, then internal fault occurred, and the element must be disconnected from the network. The setting of the current limit can be small (above the maximal errors of the current transformers), and the operation can be expected without intentional time delay. In case of transformers, however, the open circuit magnetizing current must be taken into consideration as well, and during the energization process the normal 'inrush current' can disturb the measurement in a differential protection. This phenomenon can be explained as follows:

Before energization the circuit-breakers are open on both sides of the transformer. When they are switched on only from one side, the flux starts to build up, and increases until the polarity of the voltage does not change. In worst case this time can be a half period as well. If we take into consideration that the starting value of the flux — the so-called remanent value — can be high according to the hysteresis loop of the iron core and in polarity it can coincide with direction of the growth of the flux, we can reach very quickly the saturation value on the magnetizing curve. Above that value the current increases intensively, and high peak values can develop, the value of which can be in the short circuit range. This inrush current flows only from one side of the transformer resulting in a high differential current. This triggers the operation of the differential protection, so the transformer cannot be energized.

One of the best solutions against this phenomenon is the restraint with second harmonic current. The principle is simple: The inrush current is asymmetrical to the time axis (has high peaks in one polarity, and is flat on the other side). This is due to the even harmonic content, in which the second harmonic is dominant. It can easily be detected with a filtering method. In case of high current with high second harmonic content the relay must remain blocked, but in case of short circuits, when — as it can be proved — no second harmonic is present, the protection switches off the circuit breakers within a short time.

Fig. 4 shows our test method's application in case of energization. The three time diagrams show the input current, which has a typical inrush characteristic, its first harmonic content calculated by a simple Fourier algorithm programmed in the protection, and on the bottom the calculated second harmonic content is shown. The cornered shape of the curves shows the effect of the discreteness of the amplitude and time (in our case 600 Hz sampling frequency and a 10 bit resolution A/D converter were used). The upper right corner's zero numerical value shows for the programmer that no operation occurred.

In *Fig. 5* a high-current short circuit can be investigated. The last curve shows at the beginning a small calculated second harmonic content. This is because the theoretical Fourier decomposition needs a data window

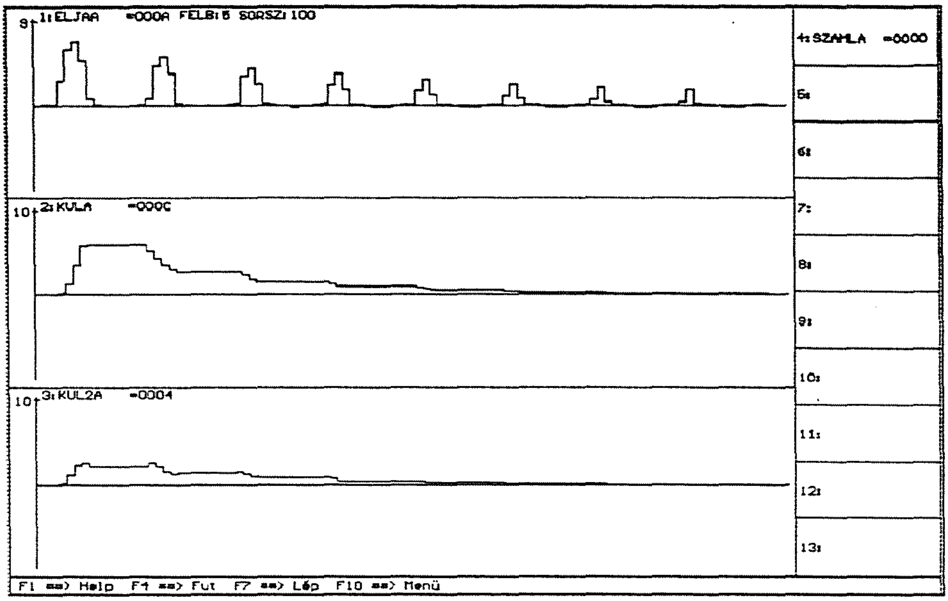

Fig. 4. Operation during inrush

of one period, and before this time this requirement is not fulfilled. The cursor line on the figure shows that the algorithm needed a little bit more than a half period to identify the short circuit and to give a three times checked command to the circuit-breaker to disconnect the transformer.

Fig. 6 shows a high impedance transformer fault resulting in a relatively small fault current with a relatively high decaying DC component in the current. The algorithm detected this fault correctly.

6. Use of the Test System in the Education

The elements in this test system can be used in the education as well. First the transient simulation program is applicable when explaining power system phenomena. Our example showed the typical time function of inrush current, but extreme influencing factors like current transformer saturation, filtering and other distorting factors can be modelled as well. The basic

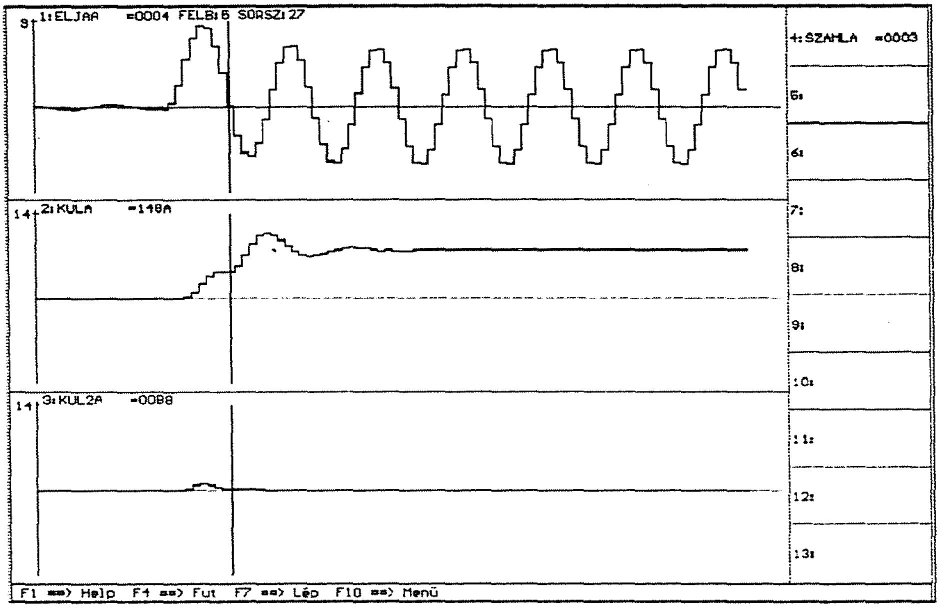

Fig. 5. Operation during high current short circuit

calculation of short circuit currents happens with the help of 'symmetrical component' method, which gives steady state voltage and current vectors. The presentation of time functions with this program helps understanding the different short circuit time functions and their relationships to vectors.

The further use is to display transient phenomena during short circuits as well, when the time functions differ considerably from steady state sinusoidal curves. This fact draws the attention to the difficulties of protection algorithms and any other (non microprocessor based) protections. The decision in quick relays based on 50 Hz values (RMS values, impedances, etc.) must be made during short circuit transients, when these values are theoretically not clearly defined.

The second element of our system is useful to investigate the reaction of different digital algorithms step-by-step. The use of microprocessor based protection is a brand new area in power system sciences. The visual presentation of their application need not be emphasized.

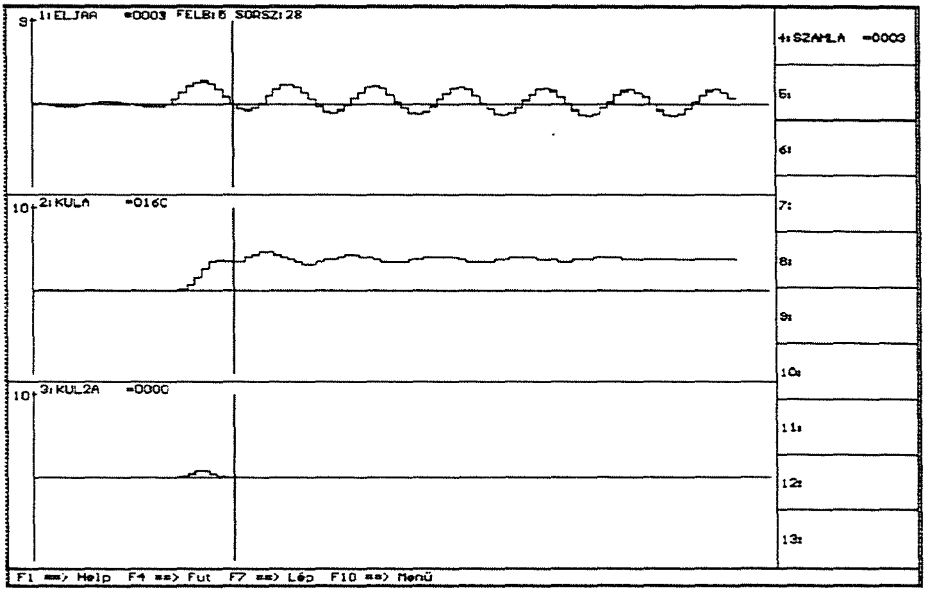

Fig. 6. Operation during low current short circuit

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