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Increase of operation speed of digital measuring elements of microprocessor protection of electrical installations

Abstract. *The article presents the digital measuring elements of microprocessor protection, which use combined digital filters to determine the controlled signal during a time equal to a quarter of the period of fundamental frequency. The model of the proposed digital measuring body is implemented in the Matlab-Simulink system. Analysis of the results of computational experiments confirmed the correct functioning of the digital measuring element that had been proposed.*

Streszczenie. *W artykule przedstawiono cyfrowe elementy pomiarowe zabezpieczenia mikroprocesorowego, które wykorzystują połączone filtry cyfrowe do określania kontrolowanego sygnału w czasie równym jednej czwartej okresu częstotliwości podstawowej. Model proponowanego cyfrowego elementu pomiarowego jest zaimplementowany w systemie Matlab-Simulink. Analiza obliczeniowych wyników potwierdziła prawidłowe działanie zaproponowanego cyfrowego elementu pomiarowego.* ***(Zwiększenie prędkości działania cyfrowych elementów pomiarowych mikroprocesorowej ochrony instalacji elektrycznych)***

Keywords: relay protection, digital measuring element, digital filters, orthogonal components, observation window, model, current transformer, Matlab, Simulink
Słowa kluczowe: ochrona przekaźnika, cyfrowy element pomiarowy, filtry cyfrowe, elementy ortogonalne, okno obserwacyjne, model, przekładnik prądowy, Matlab, Simulink

Introduction

There are two factors that influence on the performance of digital measuring elements (DME) of microprocessor protection of electrical installations. The first is associated with the appearance – when there is damage – of aperiodic and harmonic components in the measured signals, due to transients and nonlinearity of the elements of the electrical installation. The second factor is the inertia of information processing algorithms, in particular, such ones as analog and digital filtering.

One of the ways to increase of operation speed of DME is the use of flexible digital filtering that is emerged in the event of damage [1]. It is based on the use of digital filters with a small observation window when damage is detected [2]. An observation window can be equal, e.g., half of the base frequency period. Over time, the observation window can remain unchanged or increase, and when the specified time is reached, it takes the initial value.

The implementation of such an algorithm assumes the presence of a starting element that gives a start to flexible filtering, and differs from the classical algorithm, primarily in the fact that with the change of the observation window, new values of the filter coefficients are used. When a certain point in time is reached, that is, e.g., equal to the base frequency period, the filter adjustment is stopped and further filtering is being performed with the initial constant coefficients.

The presence of the starting element and the need to adjust the output vector when changing the observation window complicate the implementation of flexible filtering.

Taking into account the above, to increase the operation speed and simplify the implementation, it is proposed to form the output signal of the DME in the form of an equivalent signal, which is a function of the correction factor k_{kn} and orthogonal components (OC) of the signal being controlled.

The main part

Various algorithms of construction of digital filters (DF) with constant coefficients can be used to obtain the OC of the controlled signal coming to the input of the DME. The algorithms are: the method of least squares, discrete Fourier transform (DFT), as well as OC generators (OCG) [3], [4]. The allocation of cosine u_{cn} and sine u_{sn} OC basic harmonic by the constructed filters are specified by the following expressions:

$$u_{cn} = \sum_{n=1}^{N} a_{cn} u_{in}(n); \quad u_{sn} = \sum_{n=1}^{N} a_{sn} u_{in}(n), \tag{1}$$

where a_{cn}, a_{sn} are the coefficients of the cosine and sine DF, respectively, $u_{in}(n)$ are the samples of the controlled signal.

The amplitude of the fundamental harmonic signal for an arbitrary sample of n is defined as

$$U_{m1n} = \sqrt{u_{sn}^2 + u_{cn}^2}\,, \tag{2}$$

Formation of the OC of equivalent signal u_{eqcn}, u_{eqsn} is carried out by multiplying u_{cn}, u_{sn} by the correction factor k_{kn}

$$u_{eqcn} = k_{kn} u_{cn}; \quad u_{eqsn} = k_{kn} u_{sn}., \tag{3}$$

The numerical value of k_{kn} for an arbitrary sample of n is calculated by the following expression obtained from the analysis of the studies performed by the method of computational experiment

$$k_{kn} = m\frac{U_{m\,in\,n} - U_{m1n}}{U_{m1n}} + 1\,, \tag{4}$$

where m is a constant coefficient, $U_{m\,in\,n}$ is an amplitude of the controlled signal for sampling of n.

The following expression can be used for determining $U_{m\,in\,n}$:

$$U_{m\,in\,n} = \sqrt{\frac{2}{N}\sum_{n=1}^{N} a_{cn} u_{in}^2(n)}\,, \tag{5}$$

The constant coefficient m, which is included in (4), determines the speed of formation of the OC of the equivalent signal, which increases with the increase of the speed. In addition, m has a significant impact on the maximum value of the correction factor. Besides, m has a significant impact on the maximum value of the correction factor.

As the k_{kn} increases, the non-uniformity of the transient response of the OC-equivalent signal increases, which is to be taken into account when choosing numerical values for *m*.

In transient conditions, when the U_{m1n} values are small, the OC of the equivalent signal that is being generated can grow uncontrollably by increasing the k_{kn}. To avoid it, the amplitude of the equivalent signal $U_{m\ eq\ n}$, which is determined by u_{eqcn}, u_{eqsn} using (2), ought to be limited at the amplitude level of the controlled signal $U_{m\ in}$.

When $U_{m\ eq\ n} > U_{m\ in}$, $U_{m\ eq\ n} = U_{m\ in}$ is taken and the values of the equivalent signal of OC are specified

$$(6)\qquad \begin{aligned} u_{eqcn} &= \frac{u_{cn}}{U_{m1n}} U_{m\ eq\ n}; \\ u_{eqsn} &= \frac{u_{sn}}{U_{m1n}} U_{m\ eq\ n}. \end{aligned},$$

In transient conditions, the amplitude of the controlled $U_{m\ in}$ signal can be fixed by implementing the high-speed peak detector function.

It should be noted that the frequency characteristics of the considered method of forming an equivalent signal correspond to the similar characteristics used to segregate the OC of the main frequency of the DF.

The main condition for the successful feasibility of this method is that the transient characteristic of the algorithm for obtaining the amplitude of the controlled signal was steeper and located above the corresponding characteristic of the DF, which segregates the OS of the first harmonic.

DME implementation

The DMT model has been developed in the Matlab-Simulink dynamic modeling environment. The basis of its construction is the DMT model [5], which consists of the following elements (Fig. 1):

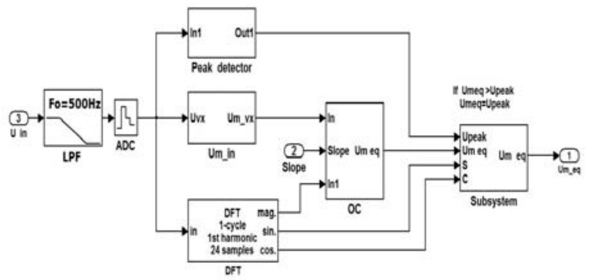

Fig. 1. The DMT model

The lowpass filter of the 2nd order (the "LPF" block) is represented by the block of the model of the *"2nd-Order Filter"* and is designed to suppress such components the frequency of which exceeds half the sample rate.

The analog-to-digital converter (the "ADC" block) is represented by the "Zero-Order Hold" block and is designed to discretize the output continuous signal of the "LPF" block.

Basic-type digital filter (block "DFT") is used to evaluate the OC of the main harmonic of the signal being monitored according to the expression (1).

The implementation of the DF is based on the use of DPF and is represented by two library blocks of "Digital Filter" models, the parameters of which are pre-calculated coefficients for the cosine u_{cn} and sine u_{sn} of orthogonal components, by which, in accordance with the expression (2), the value of the amplitude of the fundamental harmonic of the controlled signal is determined [6].

Additional DF for determining the amplitude of the controlled signal (block "*Um in*") is represented by the block of the "Digital Filter" model, which is implemented according the expression (5).

In ***the "OC" composite block*** the OC of the equivalent signal is being formed according to the expression (3), as well as the value of the correction factor is being formed according the expression (4). A constant coefficient *m* is fed to the *Slope* input.

The unipolar peak detector (the "Peak detector") is implemented according the expression $Up=|u_{in\ n}|_{max}$, and serves to limit the amplitude of the equivalent signal.

In ***the "Subsystem"*** composite block the values of the OC of the equivalent signal are specified after their limitation according to (6), and the amplitude value of the equivalent signal $U_{m\ eq}$ is formed.

Modelling

The test of functioning of the DME developed in Simulink was conducted by feeding to the input of the two types of test actions, viz., a sinusoidal signal of unit amplitude with the frequency of 50 Hz, and also the current transformer (CT) close to a real signal of the secondary current at short circuit.

Harmonic effect. One of the criteria according to which the filtration rate is determined is the setting time of the DF output signal.

In this study, we compared the performance of the proposed DF, which form the output signals U_{meq1} and U_{meq2} and which the coefficients *m* are 4 and 6, respectively, with similar parameters of the DF based on the DFT at the sinusoidal input action (Fig. 2). The constant coefficient *m* increases the speed of determination of amplitude values of signals equivalent to U_{meq1} and U_{meq2}, but leads to the emergence of significant overshot of them. As it was mentioned above, in such cases, the output of the DF is limited to the peak detector at the U_p level.

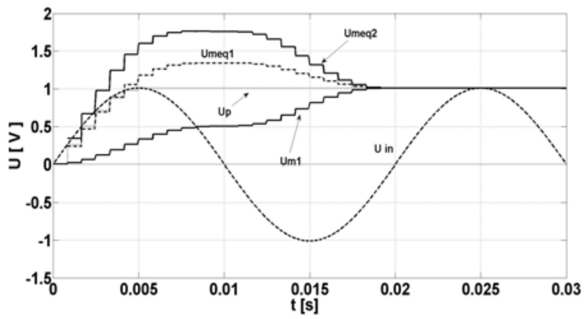

Fig. 2 Transition characteristics in DF at different coefficients *m*

Fig. 3 presents the results of the functioning of the proposed models of CF and filter models based on DFT. The settling time of the equivalent U_{meq} signal at the selected coefficients *m* is 0.25 of the fundamental frequency period, which is 4 times higher than that of the DFT-based DF (U_{m1} curve).

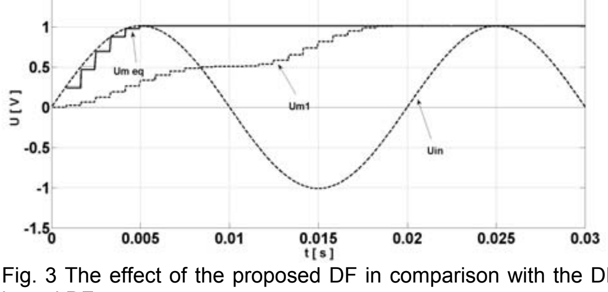

Fig. 3 The effect of the proposed DF in comparison with the DPF-based DF

A similar effect, with a sinusoidal input impact, can be achieved with the use of digital filters when a observation window is small. But, as it will be shown below, the effectiveness of their work is achieved only under harmonic influences.

Complex input effect

Information about the parameters of the operation of the power system is transmitted to the relay protection devices through the measurement current transformers. Therefore, it is advisable to test the performance of the CF by the signal close in its form to the emergency secondary current of the CT. The signal can be obtained using mathematical simulation methods.

For this purpose, the pattern of the structure shown in Fig. 4 has been designed. The pattern includes the Simulink-SimPowerSystems [7] implemented models of power systems, CT, load and short circuit unit implemented.

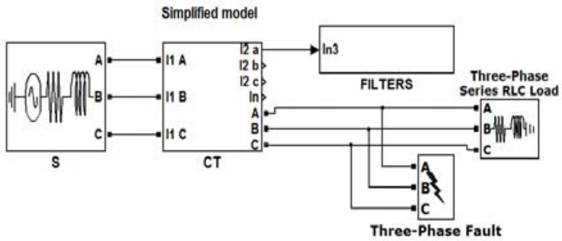

Fig.4 Testing model

The power system (block *"S1"*) is represented by the model block of the three-phase voltage source *“3-Phase Source”* from the SimPowerSystems (SPS) library. The main parameters that require additional calculation are: the own resistance of the source R_s (source resistance), Ω and the own inductance of the source L_s (source inductance), H. Using these parameters, the value of the damping time constant of the aperiodic component of the short-circuit currents $T_s= L_s/R_s$ is determined, the value of which has a determining effect on the shape of the secondary CT current.

The WYE-connected current transformers (Block "CT"). Since the CT library block is absent in the SPS library, out of the from the standard Simulink blocks simplified CT models Simulink were created and debugged, that had secondary nominal current of 5 A, a secondary winding accuracy class of 10P and an average magnetization characteristic of the steel of the magnetic circuit. All the geometric parameters necessary for the simulation of CT is calculated according to the data resented in its registration certificate [8]. The system of equations describing a simplified model of a three-phase CT group generally takes the following form:

$$(7)\quad \begin{cases} \dfrac{dB_{mj}}{dt} = \dfrac{83.34\cdot\left[(0{,}0004\, I_{1nom}+R_{2j})\cdot i_{2j}+R_0\cdot i_0\right]}{K_{nom}\cdot(0{,}0004\, I_{1nom}+R_{nomj})}, \quad j=A,B,C \\ i_{2j}=\dfrac{5\cdot i_{1j}}{I_{1nom}}-2{,}25\cdot 10^{-4}\cdot K_{nom}\cdot H_j; \\ B_{mj}=f(H_j); \\ i_0=i_{2A}+i_{2B}+i_{2C}. \end{cases},$$

where I_{1nom} is rated primary CT current; K_{nom} is rated CT ratio; R_{nom} is the nominal resistance of the secondary CT load; R_2 is the valid active resistance of the secondary CT load; R_0 is the the resistance of the neutral wire; i_0 is instantaneous value of the current flowing in the CT neutral wire; B_m=*f*(*H*) is he average magnetization characteristics of electrical-sheet steel; i_1 и i_2 are instantaneous values of primary and secondary CT current TT respectively.

Load (the “Load” block) is represented by the *“3-Phase Series RLC Load”* model block from the *SPS* library.

Short circuit (the “SC” block) is represented by the *"3-Phase Fault"* model block from the *SPS* library, which simulates a three-phase device closing the phases on each other as well as on the ground.

In the composite block "Filters" the model of DME is placed (Fig.1), at the input of which the secondary current of the CT model is fed.

Fig. 5 represents the results of calculations obtained using the presented model.

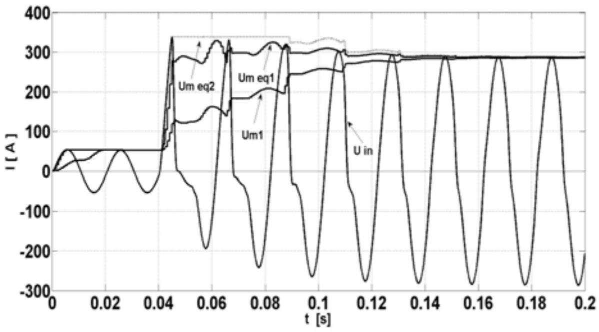

Fig.5 Simulation results of the proposed DF

The pre-emergency mode, in which the secondary CT current (controlled signal) is sinusoidal, is modeled in the time interval *t* = 0.00–0.04 s. At the time *t* = 0.04 s three-phase short-circuit occurs, i.e. the emergency mode, in which the form of the secondary CT current is distorted (curve U_{in}).

The same figure shows the reaction to the complex non-sinusoidal effect of two types of DF. The lower curve U_{m1} reflects the operation of the digital filter based on DFT, and the curves U_{meq1} and U_{meq2} reflect the operation of the proposed digital filters with values of a constant coefficient m equal to 4 and 6, respectively. It should be noted that the curve U_{meq2} at the initial moments of the short circuit exceeds the maximum value of the input signal $U_{m\ in}$, so the peak detector limits the value of the equivalent signal at the level of $U_{m\ eq} = U_{m\ in}$.

As it is shown in Fig.5, the time of built up of the output signals of the filters under consideration to the level of response (taken, for example, equal to 200 A) occurs in the proposed filters at a time equal to 0.044 s, and in the classical Fourier DF–equal to 0.085 s, i.e. the latter is triggered about 2 periods of fundamental frequency later. At the same time, the proposed filters show high performance not only in comparison with the base DF, but also in absolute terms, viz., they are triggered 0.004 seconds after the onset of the short-circuit.

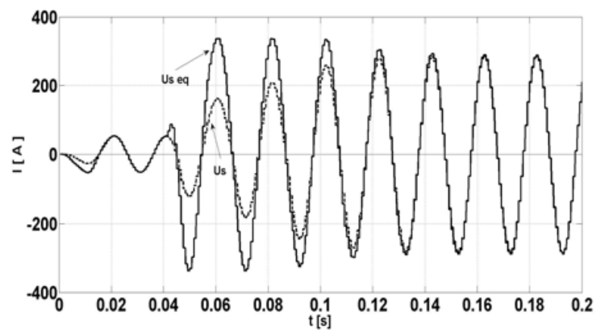

Fig.6 Sinus OC

To test the correctness of the determining phase of the equivalent signal, the sine OC of the latter u_{eqs} was compared with the DFT that is analogous to OS DFT u_s under the test exposure that is analogous to the one shown in Fig.5. In the pre-emergency mode, both OC are the same, and at the onset of the short circuit, their amplitudes differ the more the input effect differs from the sinusoidal one. (Fig.6).

Such a complex effect is advisable to be used for testing the performance of short-window filters. So, on behalf of the DF that determines a controlled signal according to the expression (5), two CFs were implemented, viz., the first $U_{m\ in1}$ with the window of observation equal to one period of fundamental frequency, and a second $U_{m\ in2}$ which window of observation is equal to half of the period of fundamental frequency. Moreover, under sinusoidal exposure the settling time of the first DF was 1 period of fundamental frequency, and as for the second one, the settling time was 2 times less. Fig.7 clearly demonstrates that the oscillativity of the $U_{m\ in2}$ makes it practically inoperable in real emergency modes.

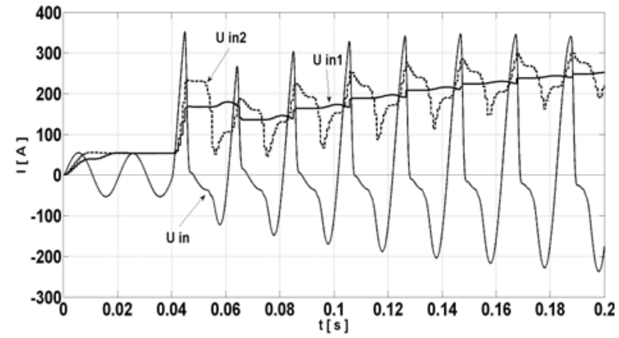

Fig.7 The effect of the DF with window of observation is equal to half of the period of fundamental frequency

Conclusions

1. The principle of implementation of high-speed DME is proposed.

2. In the Matlab-Simulink environment of dynamic simulation implemented a mathematical model of the developed DME has been implemented, as well as a model of the power system that allows forming the influences, close in their form to the emergency secondary CT current.

3. The conducted computational experiments, using harmonic test impact and the test impact close to real impact, revealed a significant (up to 4 times) increase in the operation speed of the proposed DME as compared to DME based on DFT, which are used in most modern microprocessor protections.

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