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The real-time simulation of an electric systems – the simulation stability

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The paper presents the results of a research of the impact of numerical integration algorithm and the method of solving the system of linear equations for the stability of the simulation of electric circuit in steady states and transient states. Stability criteria was explained. Mathematical modeling algorithm of the electric power line (steady states and transient states) was presented with elements of concurrent computing. The goal is to create a mathematical model of the electric circuit that will meet the requirements of the models used in simulators working in real time.

KEYWORDS: simulator working in real-time, DSP processor, multicore system, concurrent computing simulation of electrical system

1. Introduction

The author's previous papers present the conception of a digital simulator working in real time based on multicore TMS320C6678 processor [1]. Results of a simulation of some operating conditions of a medium-voltage power line, with the use of a simulator based on platform with aforementioned processor [2] and algorithm with concurrent computing was also explained [3]. Hardware platform of the simulator based on conception explained in [1] was constructed. Due to this, carrying out a simulation research became possible for circuit with three structural elements and three circuits nodes [1] next for MV power line with seven structural elements and ten circuit nodes with sequential [2] and concurrent computing [3].

In this article the author analyzes the subject of the stability of real time simulation of exemplary electric circuit. Mathematical model of this circuit was described in detail in [2]. Except for a few articles concerning mainly the stability of the simulation in computer games, it is difficult to find publications in the field of technical sciences.

2. Description of the modeling electric circuit

In Figure 1 the schematic of the analyzed circuit was presented. Part of the distribution medium voltage electrical power network was analyzed. This is overhead power line with total length equal to 9.0 km, which is connect to one of the bay in HV/MV transformer substation. This line directly supply MV/LV transformer substation which supply devices of production factory. In Figure 1 was shown the mutual location of the line wires on poles (flat formation).

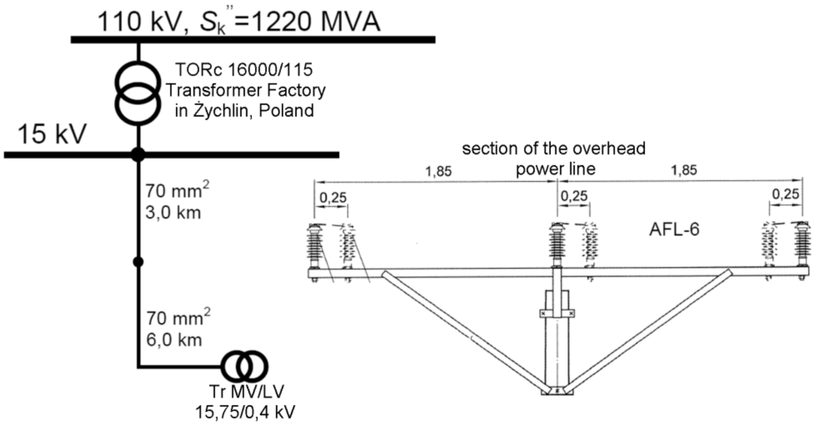

Fig. 1. Schematic of the analyzed circuit [3]

In Figure 2, an equivalent schematic of circuit analyzed with partition for specific structural elements SE 1 – SE7 was presented. Electric power system (voltage 110 kV and higher) was replaced by three phase real voltage source (equivalent generator). Equivalent generator and HV/MV transformer station are modeling by structural element SE1. Two-sectioned MV power transmission line is presented by structural elements SE2 – SE6. Three phase equivalent load of the factory was replaced by structural element SE7.

The power line model is the classical model of type π, with RL longitudinal branches and C transverse branches. In model developed serially with capacitors using for representing capacitance to ground and capacitances between phase wires was inserted in series connected resistors and inductors.

In Table 1, parameters of elements of electric circuit (Fig. 2) which are used in experimental research, were combined.

Table 1. Parameters of structural elements [2]

Structural element	Type	*R* [Ω]	*L* [mH]	*C* [nF]
SE1	ERL	0,195	6,21	-
SE2	RLC	0,01	1,00	36,5
SE3	RL	1,32	3,63	-
SE4	RLC	0,01	1,00	72,0
SE5	RL	2,64	7,26	-
SE6	RLC	0,01	1,00	36,5
SE7	RL	104	141	-

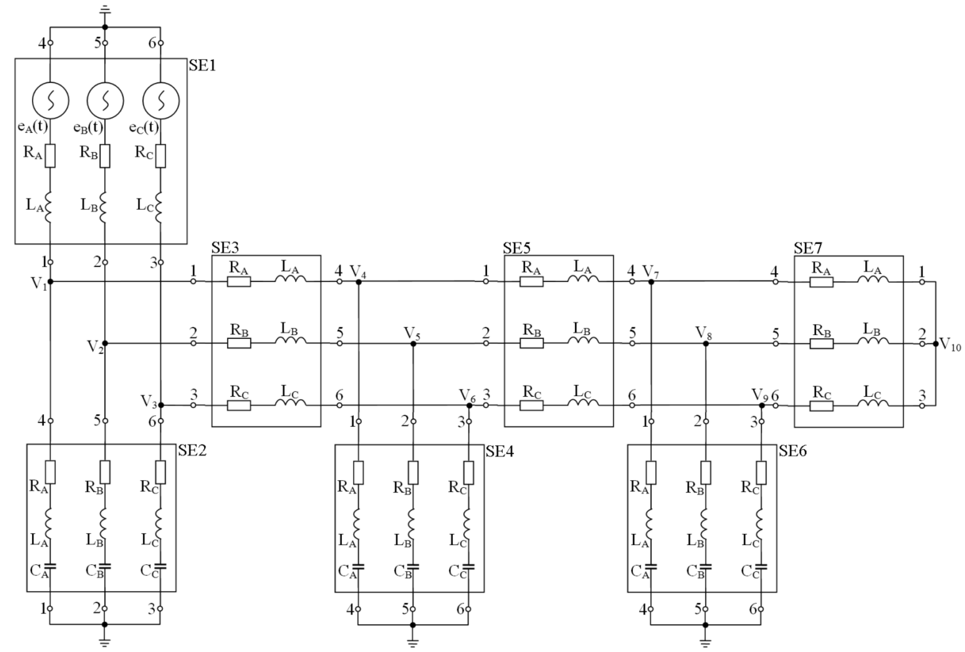

Fig. 2. Equivalent schematic diagram of analyzed circuit [2]

Based on the parameters from Table 1 it can be concluded that the analyzed circuit is symmetrical. Whereas parameters of voltage sources inside the SE1 element were shown in Table 2.

Table 2. Parameters of voltage sources of element SE1 [2]

E_m [V]	f [Hz]	φ_A [rad]	φ_B [rad]	φ_C [rad]
12247	50,00	0	-2,094	2,094

This parameters meet the conditions in three phase balanced networks of medium voltage and frequency 50 Hz.

3. Simulator of the electric circuit

In the carried out research, a hardware platform constructed by the author and described in papers [1, 2] was used. A simplified block diagram of a simulator based on the digital signal processor is shown in Figure 3. In hardware platform of the simulator there can be distinguished main element, which is eight-core TMS320C6678 DSP processor in the development module TMDSEVM6678L from Texas Instruments [4]. The computational power of a single core is 20 GFLOPS at a core clock frequency of 1.25 GHz. The parallel computing is supported here, including the classical support of the shared memory and hardware synchronization mechanisms [5].

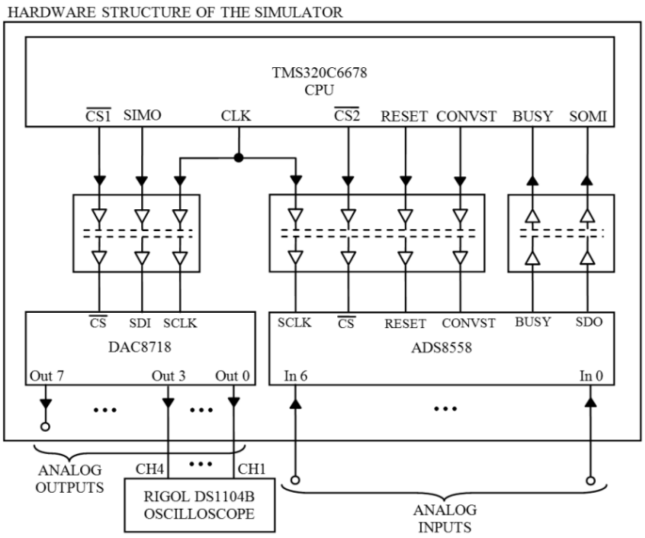

Fig. 3. Simplified block diagram of the simulator [3]

Module of the analog outputs use a 16-bit, 8-channel Digital/Analog D/A DAC8718 type converter. In contrast, analog inputs were created through a 16-bit, six-channel analog/digital (A/D) ADS8558 type converter. Sections of D/A and C/A converters are connect to processor TMS320C6678 by SPI interface (Serial Peripheral Interface) with four channel optical isolator ISO7242M.

In Figure 4a the computer simulation algorithm used for sequential computings is shown. Detailed description of sequential calculations is presented in [1].

Mathematical model used in construction of the simulator (like shown in Fig. 4a) is based on electrical multipoles as structural elements. Essential feature of such method is decomposition possibility of the model. Due to decomposition, concurrent computing can be performed in some parts of the model. Furthermore mathematical model without LC elements was used [6]. Algebraization of the differential equations is perform by trapezoidal algorithm. For comparison purposes the Gear's II order algorithm was also implemented.

A.1 block is used for input data. It means the memory is initialized by values relating to parameters and physical quantities inside structural elements. Block A.2 realizes calculating values which are constant in the simulation process. It is necessary to distinguish differences between calculating time and software integration step. First is the time of executing calculating blocks from A.4 up to A.11. Second is the integration step of differential equations of mathematical model of electric circuit, which obviously depend of summing calculating time and time consumption for communicating with D/A converter. A.3 block is used for the configuration of the processor and peripheral devices.

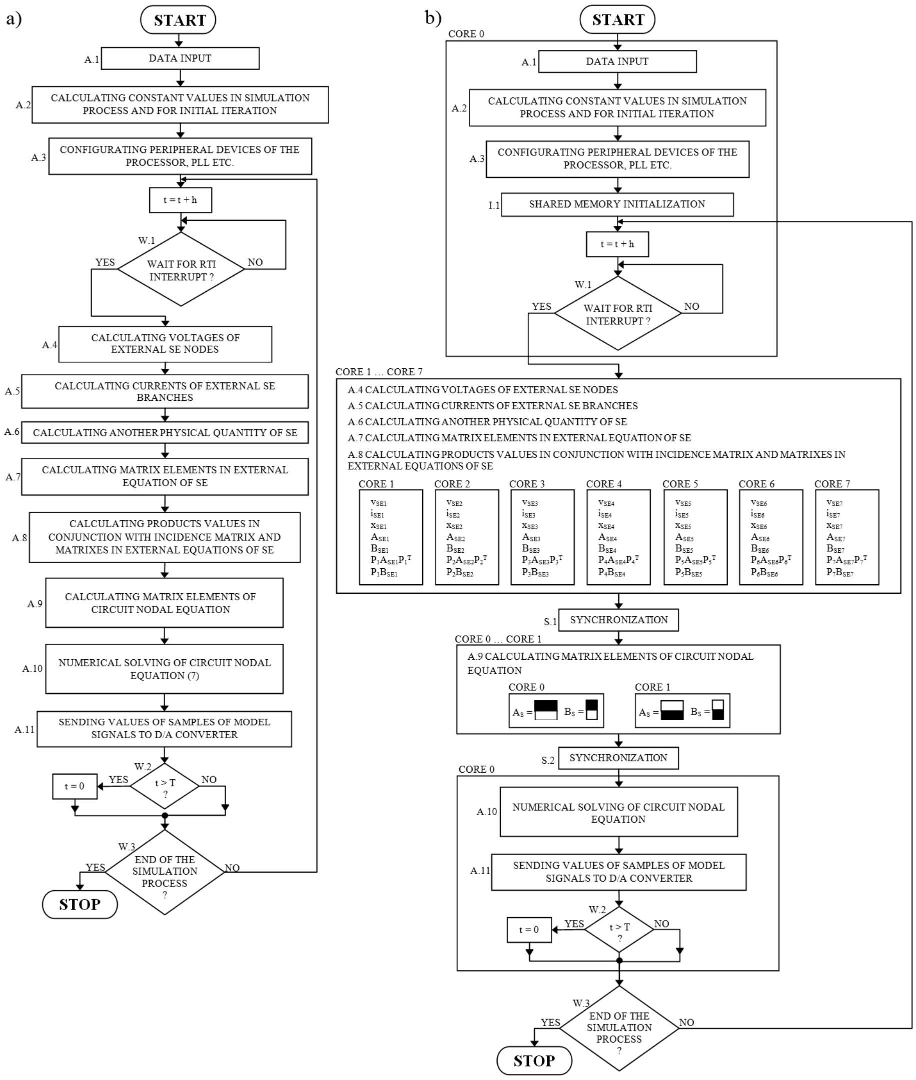

Fig. 4. Mathematical modeling algorithm of electric circuit, a) sequential computing, b) concurrent computing [1, 3]

The time variable t is increasing in each iteration by value of software integration step h. RTI module (Real Time Interrupt) inside the structure of used processor is responsible for the software integration step. This module was configured for periodically interrupts every h time (conditional operation W.1).

There is a global variable set up in the subroutine of this interrupt. It causes the start of calculation inside main loop of program.

Afterwards, blocks A.4 – A.10 which are responsible for calculating variables values for each iteration are realized. In computing block A.6 internal physicals quantities of SE are determined, such as voltages on capacitors and inductors. A.7, A.8 and A.9 blocks are responsible for calculating elements of matrixes $\boldsymbol{A}_S$ and $\boldsymbol{B}_S$ in circuit nodal equation of the analyzed electric circuit.

Calculating block A.10 is used for numerical solving of that linear equation system. Fast convergence iterative Conjugate Gradient method and other iterative Gauss-Seidel method was used here. The article [2] demonstrated advantage of iterative methods with reference to the classical methods. Iterations methods calculates only an approximate solution [7]. Therefore, for reference purposes the Gaussian elimination method with partial pivoting was also implemented.

The last of blocks is A.11. It is responsible for sending signals of instantaneous values the specified signals of model to the D/A converter (simulator communication with external environment).

In Figure 4b, mathematical modeling algorithm with partially concurrent computing in specified model sections was shown. Description in more details about concurrent activities was presented in [3]. The core 0 is distinguished here as a supervisory unit (master). Calculating block A.1, A.2, and A.3 was realized in a similar way to the previous case inside core 0 of the processor. Due to implementation of the concurrent computing it is necessary to introduce additional block I.1 which is responsible for initializing shared memory.

Inside cores form 1 to 7 concurrent computing was realized in specified parts of the model for individual structural elements (multipoles). Calculations in blocks A.4 - A.8, previously were realized sequentially but in this case it is concurrent. Decomposition this part of the model by algorithm previously presented is possible due to independent this calculations to each other. The calculation result depends only on the value of the potential nodes which are stored in shared memory [6].

Important subject in concurrent computing is synchronization – blocks S.1 and S.2. It is synchronization activities realized inside cores from 1 to 7 with actions realized inside core 0. Because of this, the information about end of calculations is transmitted from cores 1 – 7 to core 0. Next, but concurrently only inside the cores 0 and 1, calculations are realized for block A.9. Decomposition of the model is based on such a distribution of computational operations that, for the first five rows of the matrix $\boldsymbol{A}_S$ and $\boldsymbol{B}_S$ calculations are performed in the core 0, and the remaining rows in the core 1. Functionality of synchronization block S.2 is the same as in block S.1. Additional function here is to combine fragments previously calculated matrix $\boldsymbol{A}_S$ and $\boldsymbol{B}_S$.

Blocks A.10 and A.11 are realized in a sequential way.

Calculations with elements of concurrent computing (Fig. 4b) and sequential (Fig. 4a) are performed to end of simulation. It is schematically shown as W.3. block. It can be associated with specified end of calculations time in block A.2.

4. Research results of the stability in steady and transient states

In Figure 5 photography of the created measurement station is shown. It consists of power supply module (1), TMDSEVM6678L development kit, D/A (2) and A/C converters modules (3 and 4). Oscilloscope Rigol DS1104B (5) is a measurement equipment for observing and registrating simulation results. Modules (1) - (4) are included in hardware structure of the simulator (Fig. 3).

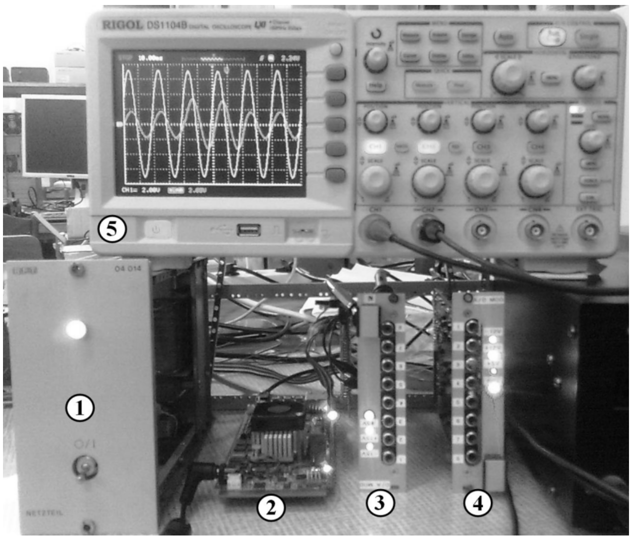

Fig. 5. Photography of created measurement station [3]

Simulation stability was studied by analyzing the instantaneous values of the nodal voltage potentials in each iteration. Due to the use of medium voltages potentials of the nodes cannot exceed the maximum voltages, i.e. 12247 V (Tab. 2). Stability criterion is based on absolute values of the nodal voltages. This voltages cannot be raised about 10% than magnitude of supply voltages. So threshold value is equal to 13472 V. Figures 6 and 7 illustrates stability issue and justify validity of criterion. Such criterion was chosen due to dependence of all model's variable on nodal voltages of the circuit [6]. It was shown also on Figure 7.

Figure 7 shows oscillograms of currents of external branches structural element SE1 at a time stability loss.

Figure 8 shows some of the waveforms nodal voltages in case stability loss with threshold values marked by dotted lines.

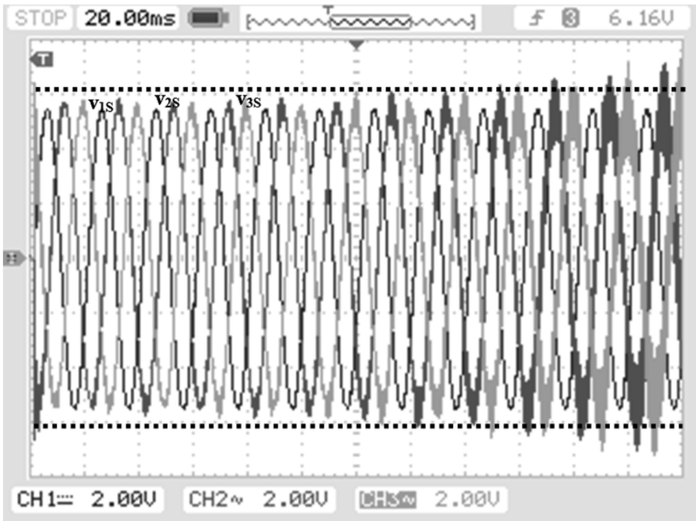

Fig. 6. Waveforms of some of the nodal voltages at a time of stability loss (4400 V/div)

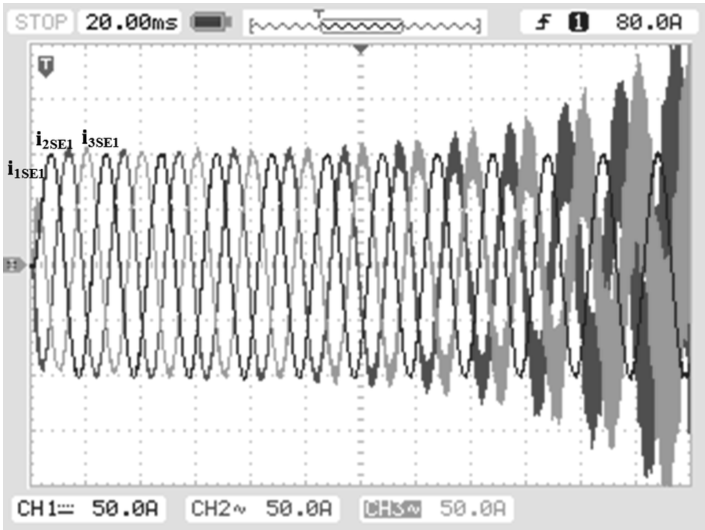

Fig. 7. Waveforms of currents of external branches of structural element SE1
at a time of stability loss (50 A/div)

Stability studies are initiated after 60 ms from start of the simulation. It is due to presence of transient states in the early moments of time (Fig. 6). When reaching the threshold value, calculations are interrupted. The final measure of the stability is the number of iterations of main loop through which the simulator has worked stable.

4.1. Stability simulation in steady states

The study of simulation stability was carried out based on previously specified criteria. In Table 3 the number of iterations by which the simulation works stable for discrete mathematical model related to trapezoidal algorithm is shown. Presented results are related to solving of linear equation system by Conjugate Gradient method and Gauss-Seidel method.

Table. 3. Combination of the simulation stability in steady state

Iteration number for improving initial solution	Numerical method for solving linear equation					
	h = 110 μs		*h* = 95 μs		*h* = 80 μs	
	Conjugate Gradient method	Gauss-Seidel method	Conjugate Gradient method	Gauss-Seidel method	Conjugate Gradient method	Gauss-Seidel method
1	0	0	0	0	0	0
2	0	0	2	0	1	0
3	15287	0	20018	0	31063	0
4	53893	0	91877	0	stable	0
5	267529	0	458473	0	stable	0
6	stable	0	stable	0	stable	0
7	stable	2	stable	0	stable	4
8	stable	14	stable	83	stable	522
9	stable	470	stable	964	stable	97563
10	stable	1833	stable	21701	stable	stable
11	stable	23197	stable	stable	stable	stable
12	stable	stable	stable	stable	stable	stable

Impact of the number of iterations was included here to improve the initial solution in iterative methods and length of software integration step *h*. Simulation works stable when iteration number for improve initial solution is grater or equal to 6 for Conjugate Gradient method for *h* equal to 110 μs and 95 μs. Whereas for *h* equal to 80 μs only 5 iterations are needed to reach stability. In case of Gauss-Seidel method minimal number of iteration is equal to 12 for stability reached with *h* equal to 110 μs. In relation to other values of software integration step *h* smaller number of iterations to improve initial solution is needed.

Results related to Gear II order method was not presented because simulation works stable with this method. In case of Gauss elimination method with partial pivoting simulation works stable independently by integration algorithm. Moreover for concurrent computing (Fig. 4b) results are the same like in sequential computing (Fig. 4a).

4.2. Stability of the simulation in transient states

In this case, single phase short circuit in phase A of SE7 element (Fig. 2) was analyzed. Shorting the circuit was repeated periodically at the programmed time. Short circuit duration was equal to 40 ms. Time between individual shorts was equal to 300 ms. In this case R_{AES7} = 2.00 Ω and inductance L_{AES7} = 141 mH. Also in this case, the stability of the simulation was tested based on the criteria listed above. Table 4 shows a number of iterations by stable working simulation for discrete mathematical model related to trapezoidal algorithm. Analogically to the previous case, the presented results are related to solving of linear equation system by Conjugate Gradient and Gauss-Seidel methods.

Table. 4. Combination of the stability simulation in transient states

Iteration number for improving initial solution	Numerical method for solving linear equation					
	h = 110 μs		h = 95 μs		h = 80 μs	
	Conjugate Gradient method	Gauss-Seidel method	Conjugate Gradient method	Gauss-Seidel method	Conjugate Gradient method	Gauss-Seidel method
1	0	0	0	0	0	0
2	0	0	2	0	1	0
3	11620	0	14328	0	17057	0
4	49497	0	75210	0	153185	0
5	86589	0	164685	0	293435	0
6	1607347	0	2423174	0	3009143	0
7	23983071	2	34168715	0	stable	4
8	stable	14	stable	83	stable	522
9	stable	470	stable	964	stable	27354
10	stable	1833	stable	18334	stable	stable
11	stable	23197	stable	stable	stable	stable
12	stable	stable	stable	stable	stable	stable

Also in this case, impact of the number of iterations was included to improve the initial solution in iterative methods and length of software h integration step. In this case, simulation works stable when iteration number for improved initial solution is grater or equal to 8 for Conjugate Gradient method. It is related to the case with integration step equal to 110 μs or 95 μs. For h equal to 80 μs 8 iteration is needed to reach stability, whereas for Gauss-Seidel method minimal number of iteration is equal to 12 for stability reached with h equal to 110 μs. Naturally for other values of software integration step h, lower number of iteration for improve initial solution is needed.

Something like in previous case results related to Gear II order method was not presented because simulation works stable with this method. In case of

Gauss elimination method with partial pivoting simulation works also stable independently by integration algorithm. Also like in previous case for concurrent computing (Fig. 4b) results are the same like in sequential computing (Fig. 4a).

5. Conclusions

The article presents the stability issue of a simulator working in real time based on DSP TMS320C6678 processor. Stability criteria was defined and results of experimental research were presented. The issue also factors affecting the stability of the simulation. Issue of determinant stability of the simulation was described. So impact of used integration algorithm and method for solving linear equation system was analyzed in this article. Moreover impact of iteration number for improve initial solution related to iterations methods and software integration step *h* was also described.

Table 5 shows the summary of combined results from the carried out research.

Table. 5. Combination summary of the research results

		Integration algorithm											
		$h = 110$ µs				$h = 95$ µs				$h = 80$ µs			
		Trapezoidal method		Gear II order method		Trapezoidal method		Gear II order method		Trapezoidal method		Gear II order method	
		Steady state	Transient states	Steady state	Transient states	Steady state	Transient states	Steady state	Transient states	Steady state	Transient states	Steady state	Transient states
Numerical method for solving linear equation	Gauss elimination method	Simulation works stable independently of the used integration algorithm for $h \leq 110$ µs in steady and transient states.											
	Conjugate Gradient method	Min. 6 iter. → stab.	Min. 8 iter. → stab.	Simulation works stable independently of iteration numbers.		Min. 6 iter. → stab.	Min. 8 iter. → stab.	Simulation works stable independently of iteration numbers.		Min. 4 iter. → stab.	Min. 7 iter. → stab.	Simulation works stable independently of iteration numbers.	
	Gauss-Seidel method	Min. 12 iteration → stable				Min. 11 iteration → stable				Min. 10 iteration → stable			

Table 5 shows that when using trapezoidal integration algorithm, the model is unstable in the steady state and transient states. It happens in the case of too low iteration number for improve initial solution for iteration method for solving linear equation systems. This problem does not occur when using the Gear II order method. Moreover, for smaller value of software integration step *h* mathematical model of the analyzed system (Fig. 2) is stable for a greater number of iterations. Due to that, using lower number to improve the initial solution in case of iterations methods for solving linear equation systems.

Simulator also works stable in the case of using non iteration Gauss elimination method with partial pivoting. Due to lower calculation time, iteration methods are better than classical methods [2]. Therefore, because simulator works in real time and stability is required, the best solution is the use of the Gear II order algorithm in conjunction with an iterative Conjugate Gradient method. It was also explained that the concurrent calculations have no effect on the simulation stability.

In case of transient states modeling stability loss occurs faster. It is due to extra errors of calculation. Therefore, a greater number of iterations should be used in order to improve initial solution for the iteration method.

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