Simulation and Control of Harmonics in Ship Networks

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***Abstract*-- This paper describes the simulation for two very different networks on board of ships with diesel-electric propulsion. The first simulation refers to a cruise vessel with 34 MW propulsion power, eight thyristor inverters (LCI) and several generators and consumers. The result of the simulation shows that the expected distortion is below the limiting value, but for some unusual operation conditions higher order harmonics could be critical with respect to the limits.**

The thyristors are modeled as ideal switches so that a set of hybrid differential equations – one set of ordinary differential equations and one set of discrete transition functions – has to be solved. Because the continuous part of the system is in most cases nearly linear, the standard Runge-Kutta-Merson algorithm is convenient and efficient to solve the differential equations. In the paper it is described how the discrete transition functions are handled in state machines, how the state machines select the actual valid set of differential equations and how they control the Runge-Kutta-Merson algorithm to calculate the exact time of each transition with reasonable accuracy.

A second simulation refers to a small service vessel. Bi-directional pulse-with modulated (PWM) inverters are used to connect a permanent magnet excited synchronous motor/generator with the grid. There is the unexpected result that a commutation choke can cause an increase of the harmonics.

***Keywords*: Ship network, harmonics, frequency converters, simulation, power electronics, hybrid differential equation.**

I. The Problem of Harmonics

Many passenger vessels or special purpose vessels today are equipped with diesel-electric propulsion. In most plants all consumers and the propulsion drives are connected in parallel to the main switchboard and two or more diesel generator sets supply the mains. The propulsion drives are supplied via frequency converters. Pulse-with modulated (PWM) inverters with DC voltage links with uncontrolled bridge rectifiers are quite common today, but for high power demands like for the propulsion of cruise vessels also line controlled inverters (LCI) with DC current links and thyristor bridge rectifiers are built. The non-sinusoidal current of the rectifiers and particularly the commutation of the thyristor rectifier cause a harmonic distortion of the voltage at the mains. In addition, interharmonics could be induced. The distortion must not exceed certain limiting values defined in the referring regulations, e. g. [1]. There are different ways to control the harmonics. With respect to reliability and cost it is desired to avoid harmonic filters, duplex chokes or active front-ends as far as possible. This requires a careful design of the system and simulations are essential.

II. Simulations of Power Electronics in Networks

A. Simulation of Continuous Systems

Networks with elements like resistors, inductivities, transformers and capacitors are typically described by a set of ordinary first order differential equations (ODEs)

$$\text{implizit: } g(\frac{dx}{dt}, x, u(t)) = 0 \quad \text{or explicit: } \frac{dx}{dt} = f(x, u(t))$$

where x is the state vector (the variables), t is the time, $u(t)$ is the input vector and f and g are any functions. Many different methods and algorithms are known and implemented in the available simulation systems [2, 3, 4, 5] to solve such ODEs numerically. In the field of system simulation, mostly the explicit form and an explicit solver are used. In principle, the state vector $x(t+\Delta t)$ is approximated from $x(t)$. The linear extrapolation starting at $x(t)$ with the slope given by the derivative $dx/dt(t)$ is the simplest method. Most solvers use extrapolation of higher order which requires the calculation of the derivatives to more than one state vector. It is obvious that the time step Δt is important for the accuracy of the solution (and for the convergence). If Δt is too big, then the approximation of $x(t+\Delta t)$ from $x(t)$ is too inaccurate, if it is too small, then not only a long computing time is needed but also rounding errors occur. It is worth to note that the ratios between the time step Δt and the time constants (given by the eigenvalues) of the system are the significant quantities for these effects. Many solvers use a variable time step. A convenient time step is estimated from the differences between the derivatives used for the approximation of $x(t+\Delta t)$ and for mostly one additional state vector. These differences give a measure for the curvature of the found approximation with respect to the time step. If the time step is too big with respect to the curvature, it is reduced and the calculation is repeated. If it is low enough with respect to a specific exact criterion, then the time step is increased for the next calculation. Many algorithms are available, Runge-Kutta [6] and DASSL [2] are examples.

These kinds of solvers could perform rather bad or could

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even fail for systems with a big ratio between the biggest and smallest time constants (so called stiff system). For such systems some implicit solvers (on basis of trapezoidal integration or a backward differentiation formula BDF) perform better and avoid instability. Electric circuits could be very stiff systems in this sense, especially if discrete components like chokes or transformers with long time constants and details of the switching of switches or semiconductors with short time constants are simulated. Referring simulation programs like SIMPLORER [3], EMTP [4] or SPICE [5] or therefore mostly use solvers of this kind.

Beside the fact that for non-stiff systems explicit solvers tend to have a better performance than implicit solvers [7], the algorithms are more compact.

The analysis of the eigenvalues for the examples below shows smallest time constants of 5 µs (Figure 5) and 3 µs (Figure 8). With respect to the period of the voltage in the net, these values are high enough that stiffness is no problem.

B. Simulation of Systems with Switches

Figure 1 shows as an example a typical rectifier circuit with six thyristors connected via chokes with the three-phase network.

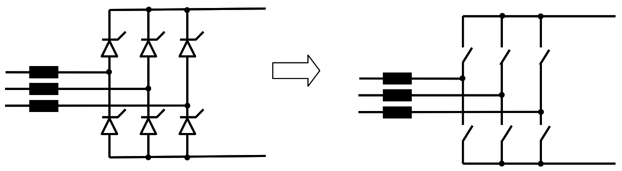

Figure 1: Left: typical rectifier circuit with thyristors and chokes. Right: Thyristors modeled as switches (not shown: Optional with resistors and voltage sources in series)

Many simulation programs use the characteristic $u(i)$ of the thyristor for the simulation. The off-state in this case is represented by a very high resistor. This causes a very small time constant in the system that could require a very small time step in the simulation. It may be even impossible to solve the equations at all. Because the rated voltage of the network is by far higher than the forward voltage of the thyristors and the time delay in the thyristors is much shorter than the period of the voltage in the network, it is adequate to replace a thyristor by a switch, optional with resistor and a voltage source in series according to the on-characteristic of the thyristor. The switch closes if the forward voltage is higher than the typical voltage drop (typ. 2 V) and a firing pulse is supplied. It opens if the current is zero or reverses. Simulation programs using this method mostly require a capacitor (sometimes called snubber) in parallel with the switch in order to get a continuous system. This could also require very short time steps for the simulation. Even though, there might be a snubber device in the actual circuit, but the purpose of it is to control the switching operation and this can not be simulated by replacing the device by a simple switch. Therefore, the only purpose of the snubber is to assist the numerical solver. In principle, all this is also applicable, if there are diodes or transistors (IGBTs) instead of thyristors only the switching condition is changed for these devices.

The DEVS formalism [8], [9] is a new complete other approach to solve the equations describing the system with switches. The basic idea is to quantize the state vector instead of the discretisation of time. The algorithms are very efficient. Only a few simulation tools are available and it is difficult to include existing models made for usual solvers on base of discretisation of time.

Due to the deficits in the usual solvers in the application on discrete systems a standard solver on base of the Runge-Kutta-Method is extended for the handling of discrete states and events in a set of hybrid differential equations, as follows.

III. Simulation on Base of a State Transition System

A. Selection of a set of Equations with a State Machine

As an example, for the system in figure 1 it can be calculated that there are $2^6 = 64$ different combinations of the states of the 6 switches. Only 13 from these are applicable in practice, in the other 51 combinations either the DC capacitor is shorted or there are closed switches without a closed circuit.

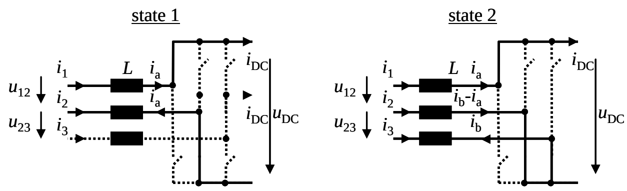

Figure 2: Two states of the bridge rectifier in Figure 1 at a three-phase network. The dotted lines are passive paths in the shown states.

TABLE I
EQUATIONS TO THE TWO STATES SHOWN IN FIGURE 2

	state 1	state 2
State vector to currents	$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_{DC} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 0 & 0 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \end{bmatrix}$	$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_{DC} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \end{bmatrix}$
ODEs $\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \end{bmatrix} =$	$\frac{1}{2 \cdot L} \cdot \begin{bmatrix} 1 & 0 & -1 \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} u_{12} \\ u_{23} \\ u_{DC} \end{bmatrix}$	$\frac{1}{3 \cdot L} \cdot \begin{bmatrix} 2 & 1 & -2 \\ 1 & 2 & -1 \end{bmatrix} \cdot \begin{bmatrix} u_{12} \\ u_{23} \\ u_{DC} \end{bmatrix}$

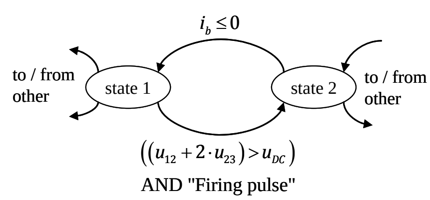

Figure 3: State machine to the states shown in Figure 2 with the equations from Table I.

As an example, figure 2 shows 2 of the 13 states of a thyristor controlled rectifier-bridge, table I shows the corresponding ODEs. (The voltage source and resistor to model the voltage drop in on-state are omitted to get more clear equations. Both components give simply additional terms at the right hand side of the equations.)

A state machine with all possible states is used to control firstly, which set of ODEs is applicable for a certain condition and secondly, which relationship between the state vector and the currents is to be used. Figure 3 shows the excerpt of the state machine with the two states shown in Figure 2 and table I. The condition for a transition from "state 1" to "state 2" is derived from the equation in table I. It implies the requirement, that the on-state for the thyristor is only possible, if $di_b/dt > 0$ after firing.

B. Solving the Equations

For most systems, the set of ODEs for each state of the system is linear or are at least "nearly" linear. "Nearly" in this sense means that not a special kind of solver is needed for the numerical solution of the system. For the studies below a Runge-Kutta-Merson algorithm 4th order [6] with automatic time step control is used. It works in principle as described in Section II. A.

Two extensions are needed for the application in the actual case: Firstly, during the automatic time step control it happens that the calculation of the new state vector $x(t+\Delta t)$ from $x(t)$ causes the time step control to reduce the time step to $\Delta t_{new} = 1/2 \cdot \Delta t$. With this, the calculation is repeated with $x(t+\Delta t_{new})$ from $x(t)$. If there was a change of the state (of the switches) in the time between t and $t+\Delta t$, then also the switches have to be set to the previous states at $x(t)$. Especially for bi-stable devices like thyristors or devices with hysteresis, the state depends not only on the values at the actual time but also of the state in the previous time step. To overcome this problem, either the state machine has to monitor the time and in case of a step back it has to restore the last valid state, or the solver has given access to the states in the state machine and has to do the work. The latter is much easier and it also has an advantage in the automatic time step control as follows.

Secondly, it is clear from the equations in Table I that the variables in the state vector are continuous, but their derivatives are not. As mentioned in chapter II. A, the change of the derivative of a variable in the state vector is used to control the time step. If the derivative is not continuous, then the solver will reduce the time step until it is so small that the rounding error covers the discontinuity. Typical solvers increase the time step rather slow, this results in a long computing time and also in non acceptable rounding errors.

Because the solver has control over the states of the state machine, it can detect that a required reduction of the time step is caused by a change of a state in the state machine. This gives the opportunity to save the current value of the time step, then reduce the time step again and again as described above, and finally after the state has changed, restore the time step with the saved value (Figure 4). Because the result of a calculation with two half steps might be slightly different from the result calculated with one full step, an extra step is required to ensure that the saved time step is not overwritten before the state has changed. A lower limit for the time step has to be defined to avoid a reduction down to the limit given by the rounding error. A value in the range of some ns is convenient for simulations in a power network. (Values down to by far not reasonable $50 \cdot 10^{-18}$ s have been monitored in some simulations without this limit.)

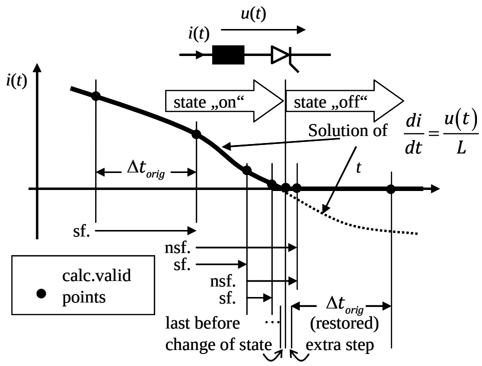

Figure 4: Control of time step taking into account a change of a state in the state machine. The current time step Δt_{org} is saved, when a change is detected and it is restored after a successful change.

sf.: successful step, no reduction of time step required

nsf: not a successful step, reduction of time step required

IV. Control of Harmonics in Ship Networks

A. Network in a large Cruise Vessel

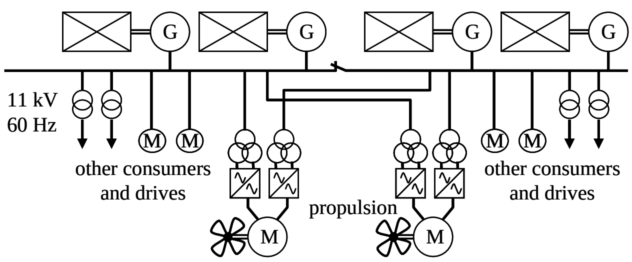

Figure 5: Typical network on a large cruise vessel with diesel-electric propulsion

Large cruise vessels are frequently equipped with a diesel-electric propulsion system. The total power of the propulsion is in the range of 30 - 40 MW. The propulsion is by far the biggest consumer in the network. In a current project there was the question, if there are any resonances in the system due to the capacities of the cabling and if it is sure that the total harmonic distortion (THD) of the voltage in the network is below given limits.

Figure 5 shows the network which is typical for cruise vessels of this kind. In this case, line controlled inverters (LCI) with DC current links and thyristor-bridge rectifiers are used to supply the propulsion drives. There are in total eight controlled rectifiers supplied via transformers with eight different vector groups. In case of a symmetrical load at both drives, the 48th order (equal 2880 Hz) is the lowest harmonic to be expected. In case of an unsymmetrical load, also the 24th is excited.

The level of harmonics depends mainly on the number and the power of the propulsion drives and on the number of generating sets in operation. There is the question if THD is below the limits in all load cases. Furthermore, it was not clear if an additional filter to suppress the higher harmonics has any benefit. These questions should be analyzed by simulations.

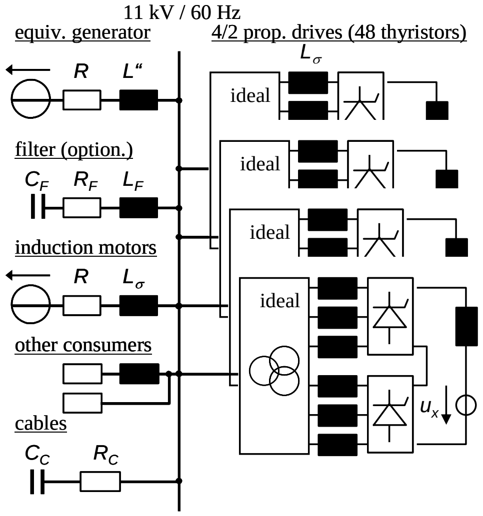

Figure 6: Model for simulation of the network shown in Figure 5.

11 steady-state load cases and 3 transient conditions have been defined for the evaluation. Figure 6 shows a model used for the simulation. The figure is a single line diagram, but for the simulation, all three phases are included:

- For the transformers, the standard model with only the leakage inductivity as a series impedance is used, the vector group is taken into account. The rectifiers are modeled by ideal switches, the firing angle is calculated from the voltage demand of the drive which depends on the speed of the referring propeller.
- All generators are replaced by one equivalent generator. Subtransient impedances and voltages are used in the model.
- All induction motors are replaced by one equivalent motor, the subtransient parameters are used for the model.
- Other consumers (minor influence, because the power is much lower than from all other) are a resistor and an inductance in series and a resistor in parallel
- The capacity of the cables and the damping resistance of the cables are modeled by a series connection of capacitor and resistor.
- There is an optional filter for the suppression of high order harmonics.

The data used are listed in Appendix VI. A.

One important question to be answered with the simulation is, if an additional filter to suppress high order harmonics has benefit or would it change things to worse in some low order harmonics. The results for the 11 defined load cases are shown in Figure 7. The positive effect of the additional filter for the high order harmonics is in evidence. There is the disadvantage in particular for load cases 5 and 9, where there is an increase in the low harmonics. This is clear, because the filter is capacitive for low frequencies and thus reduces the lowest resonance frequency of the system. The critical load case 9 is a very unusual situation: There are failures in both drives and only one half winding of each drive is operated. The simulation is done for those two remaining windings giving the maximum harmonics. Furthermore, the remaining windings are operated with full torque, but with only one half motor, the speed of a propeller is lower than the rated speed. It follows, that also the power is lower than rated.

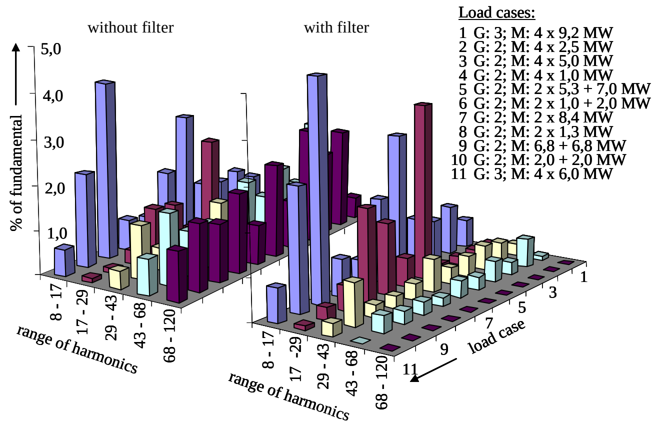

Figure 7: Results of the simulation of the distortion of the voltage in the network, for the cases with and without the optional filters (Figure 6). Labeling of the load cases: E. g. “G: 2; M: 2x5,3 + 7,0 MW” means: 2 generators in operation, one propulsion drive with 2 x 5,3 MW, the other with 7,0 MW, but only one set of windings operated.

Due to the efficient algorithm described in chapter III. only a few minutes are needed to do the simulation for all 22 cases (75 ODEs., 48 switches) with an usual PC.

B. Network in a Small Service Vessel

Small service vessels e. g. for the maintenance of offshore wind turbines or transportation of pilots on sea are sometimes equipped with a diesel-electric propulsion. Figure 8 shows an example of a plant which is very flexible with respect to power generation.

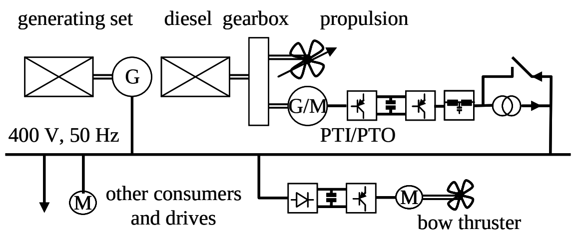

Figure 8: Network on a small service vessel; PTI/PTO: Power-take-in/Power-take-off Motor/Generator

In the most simple operation mode the generating set supplies electric power into the mains and the diesel engine drives the propeller. If the vessel is operated at low speed, then the diesel can be switched off and the propeller is driven by the electric motor/generator which is supplied via a frequency converter. The motor/generator can also work as generator and supply via a transformer the mains or work in parallel with the generating set. In total, there are six different modes of operation and a simulation shall prove that the THD is always below given limits. The input circuit of the converter for the bow thruster is a B6 rectifier-bridge. In order to save some weight in the vessel, it is planned to operate this rectifier without the usual commutation choke. The PTI/PTO is connected via a pulse-width modulated inverter (switching frequency 6 kHz) and a filter to the network. A transformer is used only in the generator mode (PTO).

The harmonics in the voltage at the main bus bar are listed in table II for different commutation chokes as an example of the simulation results for all operation modes. The PTI/PTO works as generator in parallel with the generating set, the bow thruster is operated at rated load. It is interesting and unexpected, that with a choke with a relative short-circuit voltage u_K = 3 % (typical values in those applications are u_K = 2 %...4 %) the harmonics are higher than in the case without any choke. A much bigger choke is required to improve the harmonics, but this would cause a high voltage drop and the DC-voltage may be too low to get nominal power. The simulation shows the reason for the increase of harmonics for a medium-sized choke: There is an oscillation between the DC-Link in the converter for the bow thruster and the filter of the PTO. Furthermore, the simulation shows that the current in the capacitors in the filter is much higher than designed, so the filter would be overloaded.

TABLE II
HARMONICS IN THE VOLTAGE AT THE MAIN BUS BAR (FIGURE 8) FOR DIFFERENT COMMUTATION CHOKES

commutation choke, $\boldsymbol{u_K}$	THD up to order 50 limit: 8 % [5]	order of max. level	max. level	limit [5]
0 %	7.6%	5	5.7 %	5.0 %
1 %	6.8%	5	4.6 %	5.0 %
3 %	9.6%	17	7.8 %	4.5 %
6 %	5.1%	5	3.2 %	5.0 %

The simulations shows that for the case without choke the limit is only slightly exceeded. An exemption in the rules [5] can be applied. It is also clear from the simulation that as for all systems with filters, the system is rather sensitive against changes or tolerances of the components. Measurements in the actual plant must be carried out to validate the simulation.

V. CONCLUSIONS

The harmonics in the networks of ships with rectifiers or frequency converters have to be controlled in the design phase. Simulation is an adequate method for this. The use of switches as models for e. g. thyristors or diodes is efficient and, contrary to other methods, avoids very small time constants. This saves computation time and avoids rounding problems. It is shown that a standard solver for ODEs works efficient for hybrid differential equations, if it is extended for the handling of the discrete states (of the switches) and events.

Filters and chokes are not universal remedies for harmonics. The example of the cruise vessel shows clearly how a filter may shift the problems from one frequency range to another range. It depends on details in the design of the plant and the planned operating condition if a filter has a benefit or makes things worse. A simulation for all relevant operation conditions and also for some emergency conditions is recommended.

The example of the service vessel shows that the system as a whole has to be analyzed. While commutating chokes at the input of a rectifier-bridge typically reduce the harmonics in the current and with this also the harmonics in the network, in this specific case they cause a critical resonance with components in a complete different device connected to the network.

VI. APPENDIX

A. Data to the Simulation in Figure 6

Generators, 4 pieces, each:

S_n = 19,5 MVA
(x_d" + x_q") = 16,4 %
T" = 37 ms

Transformers for propulsion, 4 pieces, each:

S_n = 2 x 5800 kVA
u_k = 14 %
vector groups: 8 x 45 ° (48 pulses)

Propulsion drives, 2 pieces, each

P = 18,4 MW
DC-Choke = 7,2 mH

Other drives, 1 piece (as sum of all)

R = 0,38 Ω
L = 5,4 mH

Ohmic consumers via transformers,1 piece (as sum of all)

P_n = 15 MW
u_k = 5 %

Optional filter, per generator:

C = 8 µF
L = 100 µH
R = 12 mΩ

Cables as sum:

C = 2 µF
R = 2 mΩ

VII. REFERENCES

[1] Germanischer Lloyd, Rules for Classification and Construction .- Ship Technology, I-Part 1, Chapter 3-Electrical Installations, Edition 2012, Section 1G2

[2] L. R. Petzold: A Description of DASSL: A Differential/Algebraic System Solver, *"IMACS World Congress, Montreal 1982";* Online available:www.osti.gov/bridge/servlets/purl/5882821-Fd1wBQ/5882821.pdf

[3] Ansoft Cooperation: Simulation Simplorer 6.0 User manual, Edition 2002

[4] Bonneville Power Administration, Oregon, USA: EMTP Theory Book, 1987

[5] Joel D. Hewlett, Bogdan M. Wilamowski: SPICE as a Fast and Stable Tool for Simulating a Wide Range of Dynamic Systems; International Journal of Engineering Education, Vol 27, No 2, pp217 – 224, 2011

[6] V.V. Pospelov (originator), "Kutta-Merson method", *Encyclopedia of Mathematics* - ISBN 1402006098; Online available: www.encyclopediaofmath.org/index.php/Kutta-Merson_method

[7] Liu, L.; Felgner, F.; Frey, G.: Comparison of 4 Numerical Solvers for Stiff and Hybrid Systems Simulation. Proceedings of the 15th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA 2010), DOI 10.1109/ETFA.2010.5641330, Bilbao, Spain, Sept. 2010.

[8] B. P. Zeigler, T.G. Kim, H. Praehofer, "Theory of Modelling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems" Academic Press 2000, ISBN-13: 978-0127784551.

[9] T. Beltrame, F. E. Celliert, "Quantised State System Simulation in Dymola/Modelica using the DEVS Formalism, "*The Modelica Association, Modelica 2006*, pp. 73-82