Handling of Switching Transient and GIFU Switch Ability on the IEE-J's Power Electronics Benchmark Circuits

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Abstract - **There is a one-calculation time step lag between the open/close state change decision and its state change in the circuit calculation in EMTP, when using a switching device in a diode or in a valve mode. Also, a switching transient causes a numerical oscillation at inductance adjacent to the switching device, which is unavoidable when using the trapezoidal rule as the integration algorithm. Therefore, the calculation accuracy of ATP is estimated by simulation analysis of the benchmark models of power electronics circuits, i.e. a three-phase PWM inverter and DC-DC converter. The calculated results compare well with other EMTP type software. Moreover, the artificial numerical oscillation difficulty in simulating power electronics converter circuits with EMTP type software caused by the trapezoidal rule, unnatural results which do not coincide with practical circuit behavior, and the usefulness of GIFU switching logic in ATP to cope with switching difficulties are discussed.**

Keywords: Power Electronics Converter, Modeling, Benchmark, Switching, ATP, GIFU switch.

I. INTRODUCTION

Advances in semiconductor device are regularly widening the field of power electronics and introducing more and more links of power electronics apparatuses to utility systems. Then, not only the study of the behavior of power electronics circuits, but also the study of their interactions with other linked power system apparatuses are required. The operation of power electronics apparatuses is based on switch state changes of power semiconductor devices, such as diodes, thyristors, GTOs and IGBTs, etc. The switching action is affected by a feedback signal of the control system and by the internal condition of the apparatus. The power electronics apparatus consists of an analogue - digital mixed hybrid system as a whole, which is made up of power converters, electric machinery and an analogue and/or digital control system. On the other hand, many conventional circuit behavior or electro magnetic transient analysis programs were developed and are convenient for studying steady and transient states of a circuit or a power system, which is an entirely analogue system. The difference in the element managing characteristics between an entirely analogue circuit and a power electronics circuit must be taken into account when applying these programs to simulation studies of power electronics apparatuses. This paper presents some example of fundamental and basic power electronics systems as benchmark models and discusses the difficulties in modeling power electronics systems on EMTP. Some indices to evaluate the obtained results are also given.

II. FEATURES AND DIFFICULTIES IN DIGITAL SIMULATION OF POWER ELECTRONICS SYSTEMS

The following listed difficulties must be taken into account when studying power electronics systems by digital simulation.

1) Hybrid characteristics of a system: A power electronics system consists of the power conversion circuit, the load, the power source and the control system. The power semiconductor device in the power conversion circuit is treated as a switch device having two states of open and close, whose state is decided by the assorted logic depending on the internal condition. Therefore, it can be said that the power conversion circuit is also a hybrid system, which combines conventional electrical circuits and logic circuits. The hybrid characteristics can also be applied to the load system and the control system. In another words, the power electronics system is a hybrid system in the sense of having elements of physically different features of switching devices, electronics circuits, electrical machinery and analogue - digital mixed control systems. As shown above, it is not easy to formularize a power electronics circuit to study its response because of its hybrid nature.

2) Nonlinear characteristics of the system: Power semiconductor devices in the power electronics circuit cause nonlinear characteristics of the system. Not only the precisely described behavior model of the device, but also the ideal model having only open/close states show nonlinear characteristics for the switch state is decided by the internal condition of the device and the system. In addition to this, nonlinearity of the control system and a nonlinear load cause nonlinear characteristics of the whole system. How to study and implement the nonlinear characteristics in a simulation have been important subjects.

3) Difficulties caused by switching action: The switching action of the switch devices in a power electronics circuit raises the following difficulties:

a) Change of circuit topology;
b) Detection of switching state change timing; and
c) Occurrence of discontinuity, impossibility of acquisition, and uncertainty of the state value in the formularized system under some conditions.

The state equations of the system model must be

modified in accordance with the circuit topology change induced by the switching. The accuracy of the calculated results for the switching period affects the correctness and reliability of the entire simulation result. Moreover, the discontinuous transition of the system state variable at the instant of a switch state change induces impulsive noise on to other state variables or makes it impossible to solve equations or gives uncertain solutions.

4) Stiffness of the system: The time duration of state changing action of the switch device is considerably faster than the time constant of the whole system response from a macroscopic viewpoint. The higher switching frequency becomes, the more the controllability of the converter, which is attained. On the other hand, it makes the difference in the time constant between the switching transient and the whole system response more, and then the stiffness of the system becomes more severe. A stiff system cannot be simulated stably and accurately unless the simulation time step is made quite small compared to the whole system response rate. Therefore, a huge number of calculation steps is required for the stiff system when studying the response of the whole system from the macroscopic viewpoint.

III. SWITCH DEVICE ON EMTP AND GIFU SWITCH

The simulation software, EMTP, was first developed for analysis of power transmission systems [1]. It has generator models, the electromotor models and transmission line models. Moreover, switch (circuit breaker) models were implemented from the beginning to study surge phenomena on power lines. The TACS (Transient Analysis of Control Systems) routine makes it easy to describe a control system which uses transfer functions, etc., and recently, the simulation language MODELS makes it possible to study complex digital control systems. Then, EMTP has come to be used to study power electronics systems, linked to power systems. Prof. N.Mohan had the lecture of power electronics system modeling on EMTP [2].

EMTP is based on the Schnider-Bergeron scheme to get easy calculation for surge phenomenon on transmission lines. The trapezoidal rule, which is an implicit scheme of numerical integration, is used for the calculation. The calculation is performed with a given fixed time step, and it cannot take into account the switch timing which occurs between the calculation time intervals. An ideal switch describes the power semiconductor device and a series resister must be connected to determine the imposed voltage on the switch, when studying the diode or thyristor whose open/close state change is determined by the state value. Numerical oscillation occurs for the inductor adjacent to the switch device at the instant of current interruption induced by switch action, and it must be suppressed by connecting a damping resistor in parallel to the inductance. The DCG version of EMTP adopts the CDA (Critical Damping Adaptation) scheme [3], which uses the Backward Euler scheme for only a two-calculation time step after the switch state transition to cope with the numerical oscillation difficulty. EMTDC implements on and off resistance of the switch device and snubber circuit in the switch device as a default, and it estimates an adequate switch timing and approximates it while varying the calculation time step with an interpolation algorithm.

Another difficulty of EMTP is the one time step lag of the circuit topology change in the calculation for the switch open/close state change decision, which depends on the circuit condition or TACS order of the firing signal. This lag may give an unusual circuit topology, which would never occur in a real circuit, and it outputs an unexpected wrong calculation result. GIFU switch was proposed by Prof. Murai to manage this difficulty. The switch operation logic can be described as follows [4].

One or more experimental steps are taken for any time instant where a GIFU switch changes status. At the end of this step, diodes are checked for illegal forward voltage or reverse current. If any is found, the step will be repeated with modified switching. The new logic will switch a maximum of two diodes/valves on any such step: 1) the diode with the largest forward voltage; and 2) the diode/valve with the largest reverse current. Only when all diodes/valves are operating legally will the experimental step be accepted, and the simulation allowed continuing. This is provided by GIFU switches (named after the request word that appears in columns 61-64 of a switch card). But the effect of GIFU switching logic has not been sufficiently studied yet. This paper precisely studies about the applicability of GIFU switch logic action to the power electronics circuit behavior.

IV. IEE-J's BENCHMARK MODELS FOR POWER ELECTRONICS CIRCUITS

The power electronics benchmark circuits have the following items to distinguish them from other electric circuits.

a) Having open/close switch state changes.
b) Having circuit topology changes in accordance with circuit operation modes.
c) Involving the converter main circuit, load and control system of the converter in the same simulation.
d) Having a quite large difference in the time constant between switching transient phenomena and whole system response.

The IEE-Japan working group on power electronics simulation made two benchmark models for power electronics circuits, which satisfy the listed conditions. They are the three-phases, six-pulse bridge PWM inverter in Fig. 1 and the DC-DC step-down converter in Fig. 2 [5].

The benchmark model of circuit I in Fig. 1 is a three-phase, six-pulse bridge PWM inverter that is one representative power electronics circuit that poses moderate circuit complexity. The load consists of simple R and L constant impedances. The inverter is controlled by an open loop system for which the switching signal is generated by comparing the sinusoidal wave signal with the triangle wave carrier. The ratings of the inverter are given in Table 1.

The benchmark model of circuit II in Fig. 2 is a step down DC-DC converter, which is a basic power converter circuit. Though the circuit is simple, but the existence of a continuous current mode and a discontinuous current interruption mode of the load circuit, which depends on the

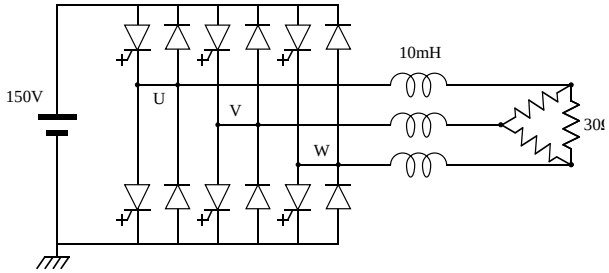
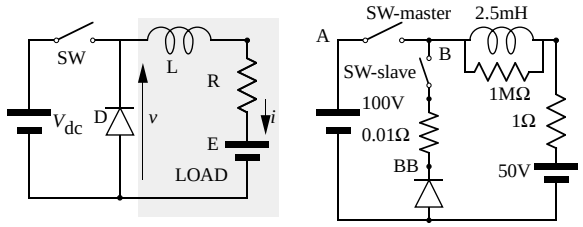


Fig. 1. Three-phase, six-pulse bridge PWM inverter (IEE-J's power electronics benchmark circuit I).

Table 1. Ratings of the inverter (benchmark circuit I).

PWM carrier frequency	5kHz
Output frequency	100Hz
PWM modulation ratio	0.8
Switching dead time	5μs



(a) Base model (b) Used circuit in the simulation

Fig. 2. DC-DC step down converter (IEE-J's power electronics benchmark circuit II).

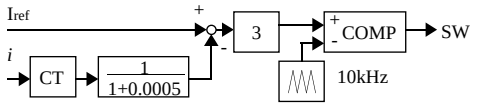


Fig. 3. Control block feedback loop system for DC-DC step down converter.

load condition, affects the simulation results through the switch device modeling. This circuit is controlled by the feedback loop system given in Fig. 3.

The benchmark models were utilized to compare results among several simulation programs, e.g. EMTP, SPICE, SABAR and MATRAB/SIMULINK. But in the working group report, the EMTP type programs (BPA, ATP, ETP, EMTDC) were all treated together, and so simulation differences between them were not discussed and no simulation results for ATP were shown [6]. Therefore, this paper gives some results for ATP regarding these benchmark circuits.

V. RESULTS FOR CIRCUIT I

The arm of the inverter valve is modeled as in Fig. 4 for ATP analysis. The parallel and series resisters connected to the diode of the switching device are necessary for determining the switch state of the diode when changing from the open condition to the close condition in accordance with the node voltage value. The self-turn off switch device is modeled using the TACS controlled switch and series connected diode to prevent reverse current flow.

Fig. 5 shows simulation results of circuit I with 1 μs calculation time step. The calculated inverter output voltage and current in Figs. 5(a)(b) are almost sinusoidal wave for the filter reactor suppression of the greater part of the harmonics generated by the switching. The inverter output line-to-line voltage shows PWM waveform, which consists of a rectangular pulse train. There is no impulsive voltage occurrence at the switching transient in Fig. 5(c). On the other hand, a big reverse current flows through the anti parallel diode at the instant of closing the self-turn off device in the other arm in Fig. 5(d). Expanded scale drawings of these phenomena are given in Figs. 5(e)(f). The reverse over current occurs when the current flows through the anti parallel diode of the open arm at the end of the dead time of 5 μs, but it does not occurs when the current is not flowing through the diode at that time. In the reverse over current occurrence case, the current does not flow through the self-turn off device when an off signal is given to it, but it flows through the anti parallel diode and it continues to flow during the given dead time of 5 μs. The antiparallel diode conducts the reverse current for one time step after the dead time when the closing signal is given to the self turn off device in the other arm for the one time step delay of the diode conduction state change. Also the conducting self turn off device of the other arm causes an excessive forward current flow. The dead time which is adapted in the practical circuit to prevent a short circuit of self-turn off devices between their arms because of their slow insulation recovery time, does not have any effect on this kind of difficulty. Then, the dead time, which is prepared for a non-ideal switch device, does not suit the ideal switch in this case.

A. Adaptation of GIFU switch

Prior studies show that one simulation difficulty for this kind of circuit lies in the open and close decision process in the switch device when used as a diode. The GIFU switching logic in ATP, which takes the present calculating time back to one time step before the switch state change occurred, was developed to manage this switching difficulty. However, the simulation cannot be done for the first switching transient occurrence which gives the error message "Overflow temporary limit of 10 GIFU diode iterations", when the GIFU option is applied to the data cards. Though the GIFU switching logic may work correctly in some conditions, it does not work correctly under this configuration. Therefore, further improvement in GIFU switch logic is necessary.

B. Another counter measurement

Current flowing in the upper and lower arms of the inverter changes reciprocally to the other arm by switch signal. Here, an ideal switch is installed in series to the anti parallel diode to prevent reverse over current as shown in Fig. 6. The additional ideal switch opens and closes contrary to the signal of the self-turn off switch in the other arm. Therefore, switching devices in upper and lower arm can maintain the master and slave relation with each other.

Fig. 7 shows simulated results of this case. This arm model modification does not affect the inverter output voltage as shown in Figs. 7(a)(b)(c). The additional ideal

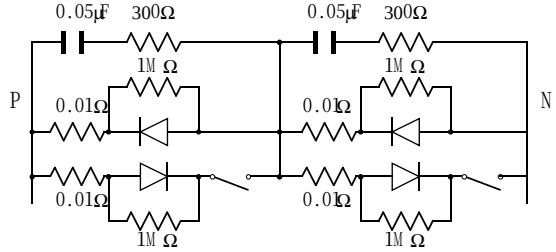


Fig. 4. Inverter arm equivalent circuit.

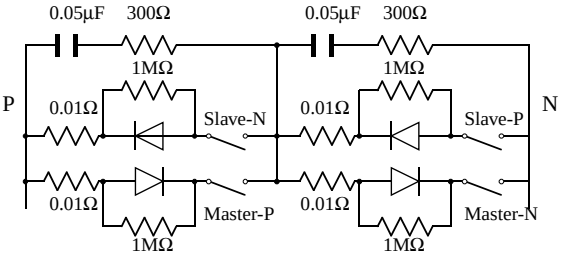


Fig. 6. Inverter arm equivalent circuit (modified).

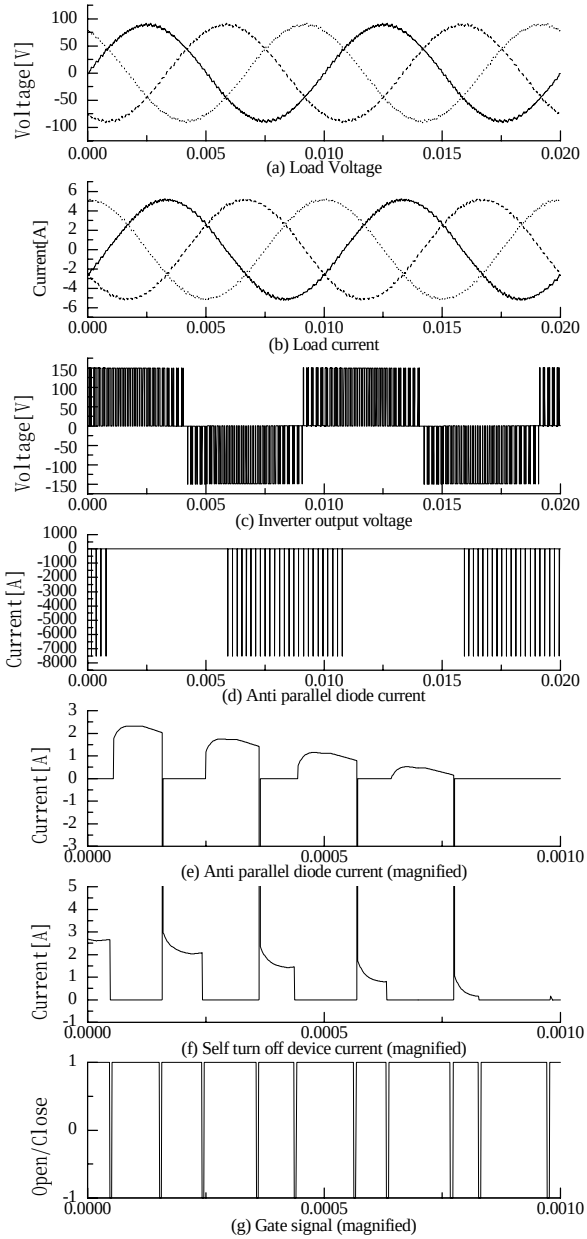


Fig. 5. Simulation results for circuit I.

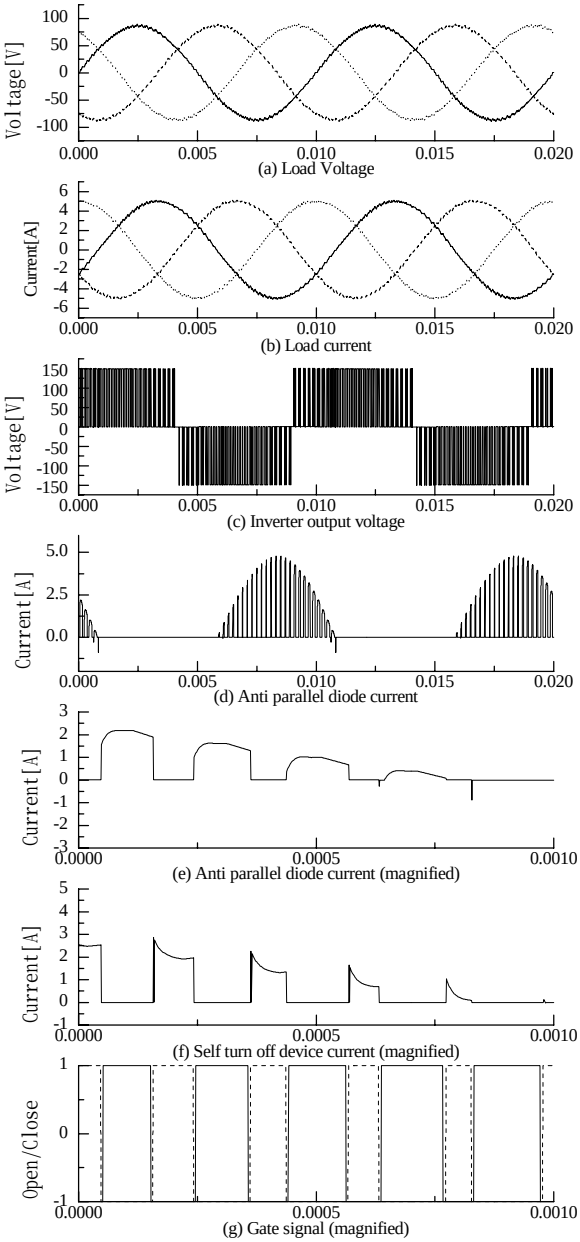


Fig. 7. Simulation results for circuit I (modified arm).

switch can prevent reverse over current in the diode and forward over current in the ideal switch as shown in Figs. 7(d)(e)(f). However, in some conditions reverse current still flows for one time step. The adaptation of the slave ideal switch makes the simulation give a warning for floating node occurrence, because the slave ideal switch forcibly opens the current path before the diode attached to the master switch changes its state to closed. The simulation results are somehow improved, but not significantly. It can be said that explicit expression of the master and slave ideal switch and diode must be used with care, and certain improvement of the GIFU switch logic and its speed up is necessary.

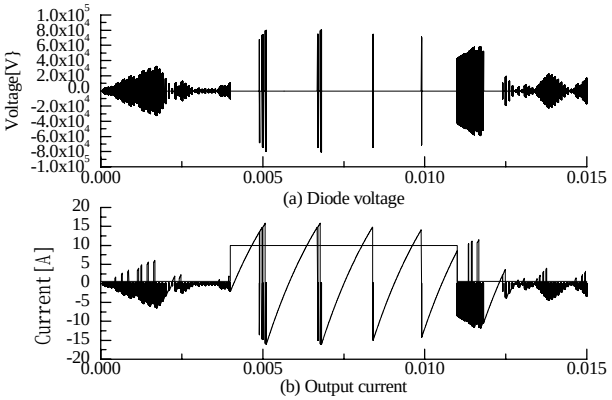


Fig. 8. Simulation results for circuit II (Δt=1μs).

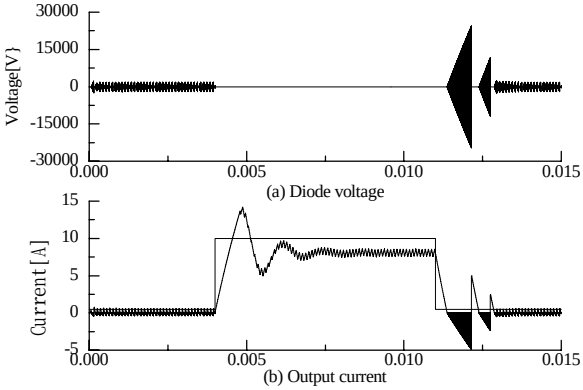


Fig. 9. Simulation results for circuit II (GIFU, Δt=1μs).

Table 2. Propriety of GIFU logic expressions.

	Data card expression	Propriety
1	11 BB 13A B ... GATE	NG
2	11 BB ... GIFU 13A B ... GATE	NG
3	11 BB 13A B ... GIFU GATE	NG
4	11 BB ... GIFU 13A B ... GIFU GATE	NG
5	11 BB 13A B ... GIFU GATE	NG
6	13A B ... GATE 11 BB ... GIFU	NG
7	13A B ... GIFU GATE 11 BB ... GIFU	NG
8	13A B ... GIFU GATE 11 BB	OK

V. RESULTS FOR CIRCUIT II

The diode can work on the base model of simulation circuit II with open state for the voltage source or load voltage determines the node voltage to decide the open state of the diode. But, the simulation does not accept the diode close state and terminates the simulation abnormally for the voltage source is directly grounded when the difficulty of reverse conduction of diode occurs. There are two solutions to avoid this difficulty. The first is preventing reverse conduction of the diode; the second is inserting series connected impedance to the diode. The prior one cannot be done in the current version of the program as discussed in the

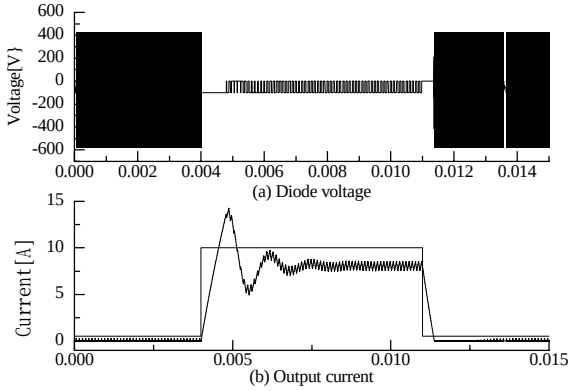


Fig. 10. Simulation results for circuit II (GIFU, Damping resister for inductance, Δt=0.1μs).

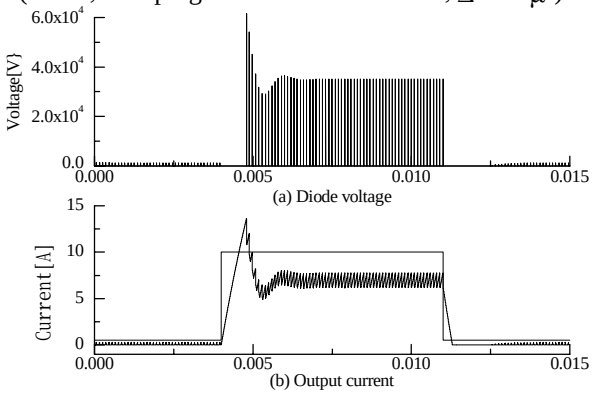


Fig. 11. Simulation results for circuit II (Snubber, Damping resister for inductance, Δt=0. 1μs).

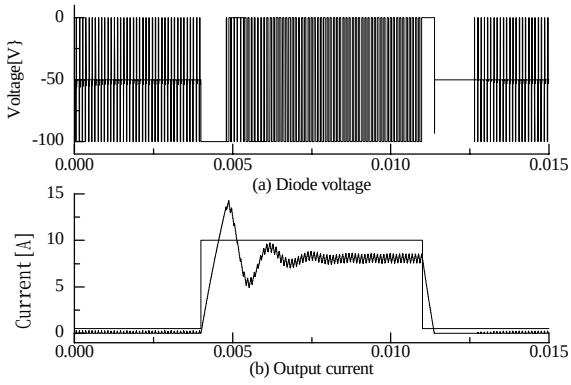


Fig. 12. Simulation results for circuit II (GIFU, Snubber, Damping resister for inductance, Δt=1μs).

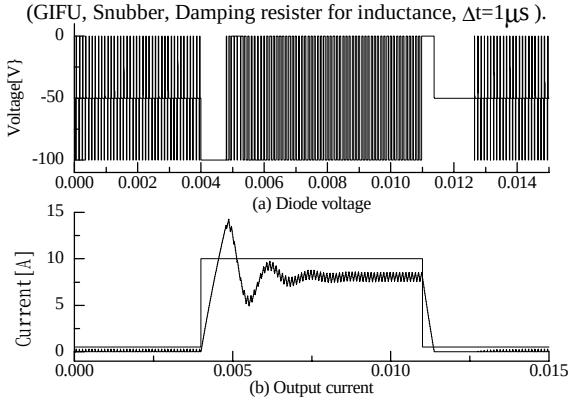


Fig. 13. Simulation results for circuit II (GIFU, Snubber, Damping resister for inductance, Δt=0.1μs).

last section even if GIFU switching logic works correctly, so the second solution must be chosen. The simulation results when the series low resister is connected to the diode are given in Fig. 8. This configuration cannot give adequate results, though the DCG version of EMTP can get tolerable results with the assistance of CDA. Also, EMTDC can get similar results with its interpolation function.

The main causes of the poor results are the disturbance induced by reverse conduction of the diode for one time step and the numerical oscillation in the discontinuous change of current at the inductor. Then, this paper applies GIFU switch logic to avoid reverse conduction of the diode. As shown in Fig. 9 the chopper outputs a satisfactory result to the reference of 1A of the current continuous conducting mode. On the other hand, the GIFU switch logic cannot work correctly and numerical oscillation occurs when the circuit operates under the discontinuous current mode with the current reference 0.05A. Shortening the calculation time step to 0.1μs cannot lower the numerical oscillation. Moreover, it becomes clear that there is a severe restriction in its expression when applying GIFU switch logic. Table 2 shows the propriety of the GIFU switch expression and its function.

Table 3. Simulation time comparison for circuit II.

Time step (μs)	Switch	Simulation time (sec)	Result
1.0	Normal	1.43	NG
0.1	Normal	14.28	OK
1.0	GIFU	101.83	OK
0.1	GIFU	114.68	OK

Fig. 10 shows simulation results when a dumping resistor is added to the inductor. The inductor in EMTP is modeled with equivalent resistance and current source instead of a conventional expression in the differential equation and it causes numerical oscillation to the discontinuous change of current. The 1M-ohm resistor is installed in parallel to the inductor to damp this oscillation. Because of this damping resistor, diverge of numerical oscillation is avoided, but still a stable result is not obtained for the discontinuous current mode since an illegal forward voltage exists on the diode for the numerical oscillation in that case. The numerical oscillation does not converge sufficiently before the next switching occurrence, therefore the oscillation continues.

Fig. 11 shows simulation results when a snubber circuit is added to the diode to reduce the dv/dt at the switching transient. The conventional diode outputs an undesired result for one time step delay of the open and close state decision in the diode. The snubber circuit cannot absorb this open/close delay influence. But the GIFU logic improves the results to really adequate values as shown in Figs. 12 and 13. The calculation time step seems to have little effect on the calculation results when GIFU logic is working correctly. The calculation time of the GIFU switch applied case does not differ so much in the time step since a large time step requires more iteration of GIFU logic than a small time step, which can be deduced from the required calculation time in Table 3.

VI. CONCLUSION

The switching phenomena of power semiconductor devices play the most important role in power electronics systems, unlike the situation for the conventional electric circuits. The switching phenomena make the system characteristics discrete and non-linear. The system behavior caused by these characteristics makes digital simulation study of power electronics systems difficult.

This paper discussed topics to be attended to in power electronics system study by digital simulation. Then, two examples of benchmark circuits were described which included notable features of power electronics system behavior and explained their modeling for EMTP, which has been used for power system analysis. The results showed that management of switching at the diode etc. must be done with care, the same as with other simulation software. An example of GIFU switching logic was given as a counter measurement for this difficulty.

The GIFU switching logic could suitably manage diode switching to a simple circuit as a DC-DC step down converter, though the restrictions in expressing the GIFU switch on the simulation data card were severe. The coordinated operation of the GIFU switch in the six-pulse bridge was difficult for implementing multiple switching device action.

The GIFU switching logic could not manage the numerical oscillation occurrence induced by discontinuous current interruption at an inductance, which is a peculiar difficulty of EMTP, when the discontinuous current mode existed for the configuration and condition of the circuit. Therefore, there was no way to manage the oscillation, except by adding a snubber circuit. There was a small difference in calculation time between a long calculation time step and a short time step, since GIFU switch logic in long time step required much more iteration time than the short time step.

It could be concluded that not only improvement of GIFU switching logic, but also suppression of numerical oscillation which accompanied the switch state change were necessary to use ATP easily in power electronics system analysis.

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