A study on the usage of CDA in EMTP simulations

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***Abstract* – The numerical integration scheme used in EMTP is the Trapezoidal rule, and it enables to treat an inductance and a capacitance with an equivalent conductance and an equivalent current source in the difference equation. Though the Trapezoidal rule is a stable numerical integration method, but this modeling method causes numerical oscillation of current in an inductor and voltage in a capacitor to a circuit topology change caused by on/off switch operation. This paper discuss about the influences of numerical oscillation to the behavior of power electronics circuit having plural switch elements in it and of power system with a synchronous generator. The instantaneous current commutation and the numerical oscillation suppression by CDA are studied to a power electronics circuit. Both the counter measurement cannot fully compensate the difficulty, but they can compensate complementary. Therefore, they should be used concurrently in a power electronics circuit. A power system simulation also has numerical oscillation difficulty, and its adverse affect is discussed by comparing a three phase system simulation result with a stability analysis simulation result. It shows that the numerical oscillation caused by a circuit breaker operation can be avoided by adopting CDA, and the calculated result can meet with the stability analysis simulation result. The instantaneous current commutation is provided in ATP, and CDA is implemented in Simpass.**

Keywords – Trapezoidal rule, numerical oscillation, CDA, instantaneous current commutation, ATP, Simpass

I. INTRODUCTION

There are many kind of numerical simulation analysis method for an analogue electrical circuit, whose state value, such as voltage or current, changes continuously in the circuit. The Trapezoidal rule used in EMTP type simulation software as the numerical time integration method is one of the stable and accurate calculation method which has wide A-stable region. When the configuration of circuit topology changes by a switch operation in a circuit, the circuit shows discrete state characteristics. This discrete state characteristic becomes severe to a power electronics system having plural switches, because its circuit behavior is largely dominated by switch operation. Moreover, just a simple switch operation, such as circuit breaker operation, may affect on the power system analysis, whose primary objective of the analysis is not studying the short time transient response after the circuit breaker operation at the instant of fault occurrence, but the long term dynamic response after recovering the fault.

The inductor and capacitor modeling method used in EMTP is suitable for managing with the Trapezoidal rule, but it cannot take into account of discrete change in the circuit configuration in normal procedure, and it induces numerical oscillation by a switch operation[1]. This difficulty is quite different from the conventional simulation time step problem in the analogue circuit, for it cannot be settled by fining the time step. The installation of numerical snubber circuit is one solution to cope with this discrete characteristic, but it is just a calculation technique and is not an essential solution for it does not coincide with the actual physical phenomena in an electrical circuit.

There has been proposed several counter measurement to cope with this switching difficulty, such as interpolation and re-initialization, etc[2,3,4,5]. Though, they focus on essential switching phenomena its self, but they are rather sophisticated procedure and require dedicated software. The objective of this paper is coping with this switching difficulty by minimum program update of conventional type EMTP (ATP), which secures the reasonableness of circuit behavior. This paper studied about the ability of CDA (Critical Damping Adjustment)[6] in suppressing numerical oscillation of state values after switch state change, and the performance of instantaneous current commutation[7] to a power electronics circuit in avoiding discontinuous circuit sequence. This paper also discuss about the suitability of these procedures in the analysis from the view point of actual physical phenomena in an electrical circuit.

Though, the instantaneous current commutation is implemented in ATP as GIFU switch, but CDA is not implemented in the current version of ATP (EMTP-V3 DCG has), therefore authors implemented CDA into prototype software called Simpass, which is a subset of ATP and it was used in the development of type-58 synchronous machine in ATP[8].

II. COUNTER MEASUREMENT FOR TRANSIENT PHENOMENA ENTAILED TO SWITCH OPERATION IN EMTP

A. Numerical oscillation occurrence and its elimination by CDA[6]

The Trapezoidal rule used in EMTP type simulation software as numerical integration method gives numerically high accurate result and it shows excellent numerical stability in studying an electrical circuit whose state values changes continuously in time domain. The differential equation of current for an inductor and of voltage for a capacitor is expressed as equation (1) respectively. It must be transformed and expressed as a difference equation to perform numerical integration with a digital computer as given in equation (2).

$$\begin{cases} v_L(t) = L\frac{d}{dt}i_L(t) \\ i_C(t) = C\frac{d}{dt}v_C(t) \end{cases} \quad (1)$$

$$\begin{cases} \frac{v_L(t)+v_L(t-\Delta t)}{2} = L\frac{i_L(t)-i_L(t-\Delta t)}{\Delta t} \\ \frac{i_L(t)+i_L(t-\Delta t)}{2} = C\frac{v_L(t)-v_L(t-\Delta t)}{\Delta t} \end{cases} \quad (2)$$

The difference equation of an inductor and a capacitor can be transformed into equation (3) of numerical calculation expression, which is consisted from equivalent resister R_L and R_C, historical value of equivalent current source of $J_L(t\text{-}\Delta t)$ and $J_C(t\text{-}\Delta t)$, and the presenting voltage $V_L(t)$ and $V_C(t)$. The merit of using this numerical calculation model is that all the node voltage in the circuit can be calculated by solving the algebraic nodal equation in real number matrix operation $V=Y^{-1}I$. This transformation of the differential equation makes the most of superior feature in the Trapezoidal rule.

$$\begin{cases} i_L(t) = \frac{v_L(t)}{R_L} + J_L(t-\Delta t) \\ i_C(t) = \frac{v_C(t)}{R_C} + J_C(t-\Delta t) \end{cases} \quad (3)$$

here, $R_L = \frac{2L}{\Delta t}$, $J_L(t-\Delta t) = \frac{v_L(t-\Delta t)}{R_L} + i_L(t-\Delta t)$,

$R_C = \frac{\Delta t}{2C}$, $J_C(t-\Delta t) = -\frac{v_C(t-\Delta t)}{R_C} - i_C(t-\Delta t)$.

The state value of current in an inductor and voltage in a capacitor numerically oscillate in integral calculation to a circuit topology change by a switch operation for the sake of discontinuous change in the historical voltage term of equivalent current source $J_L(t\text{-}\Delta t)$ and $J_C(t\text{-}\Delta t)$.

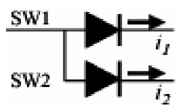
CDA is the numerical integration technique, which can extinguish the inadequate numerical oscillation caused by a switch operation in the circuit. It eliminates the impact of historical voltage term $v_L(t\text{-}\Delta t)$ and $v_C(t\text{-}\Delta t)$ in the equivalent current source with adopting the backward Euler method as given in equation (4). The influence of the discontinuous change of historical voltage term in the equivalent current source can be completely eliminated by applying equation (4) for two calculation steps.

$$\begin{cases} i_L(t) = \frac{v_L(t)}{R_L} + i_L(t-\Delta t) \\ i_C(t) = \frac{v_C(t)}{R_C} + i_C(t-\Delta t) \end{cases} \quad (4)$$

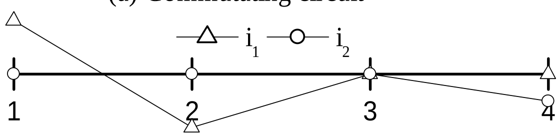
Though CDA calculation requires two calculation steps to remove the influence of discontinuous change, but it can bring this two time step with equivalent one calculation step of conventional trapezoidal rule, when adopting the equivalent resistance value of R_L and R_C in equation (4) same as the value used in equation (3). Because, the equivalent resistance value becomes comparable to the numerical integration with half the calculation time step of $\Delta t/2$.

B. Instantaneous current commutation of GIFU switch in ATP[7]

A power electronics system has plural switching devices in it by its nature and its operating characteristics are determined by the combination of switch states in the circuit. The current flowing through one switch moves to succeeding switch without current interruption by either switch operation is called commutation in power electronics circuit. The passive operation of a switch device, such as on and off operations of a diode or turn off operation of a thyristor, is determined by the state values of voltage impressed on the device or current flowing through it. The conventional state change decision of a passively operated switch takes effect in the next calculation step in EMTP

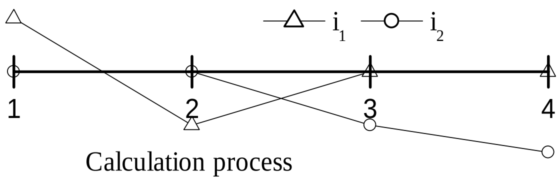


(a) Commutating circuit



Calculation process
t=2 numrical integration
fullfil the condition for SW1-OFF
t=3 numrical integration with SW1-OFF
fullfil the condition for SW2-ON
t=4 numrical integration with SW2-ON

(b) Conventional switch operation in EMTP



Calculation process
t=2 numerical integration
fullfil the condition for SW1-OFF
t=3 numerical integration with SW1-OFF
fullfil the condition for SW2-ON
iteration ↕ abort the calculated results
numerical integration with SW1-OFF
and SW2-ON
no more switch state change-> proceed to next step
t=4 usual numerical integration

(c) Instantaneous commutation

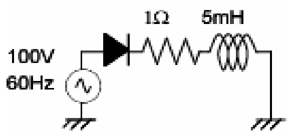
Fig. 1 Instantaneous commutation

type simulation. There is one time step delay between timing of the switch should be operated and actually operated, which is shown in Fig. 1(b). Then, the calculating circuit condition is inaccurate for that delaying one period, which does not exist in the actual circuit and it induces abnormal result, such as the over voltages or the numerical oscillations, for the continuity of the circuit is not preserved at the commutation. The numerical snubber circuit can mitigate this difficulty[9,10], but it is not the fundamental solution for it cannot fill up the blank period. The instantaneous current commutation method implemented in ATP as GIFU switch preserves the continuity of the circuit at commutation, whose operation is triggered by detecting a condition for state change of the specified switch. It iterates circuit calculation with staying at the pending time step by expiring the calculated value and going backward for one time step before, whose recalculation is performed with changing switch state to a new value and continues until no more switch state change occurs. This iteration procedure can fill in the discontinuous circuit operation caused by one step delay of switch operation as given in Fig. 1(c), and it can maintain the successive characteristics of a circuit.

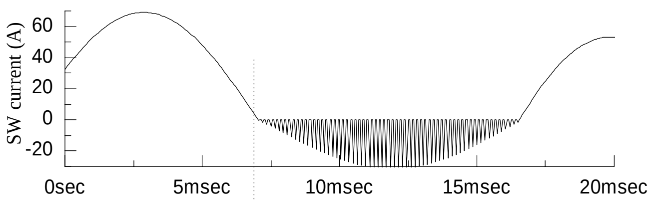
III. Power electronics circuit simulation

A. Switching difficulty in simple configuration

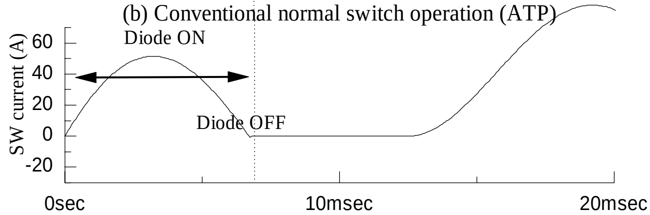
Power electronics circuits has multiple switch devices in it by its nature, whose on and off states are actively controlled by gate signals or passively determined by circuit conditions of impressed voltage on it or flowing current through it. There is little difficulty of unexpected circuit behavior in power electronics circuit analysis, when all the on and off states of the switches are actively controlled by the gate signal. The difficulty in analyzing power electronics circuit shown up when it has the switch device whose on and/or off states are determined by the circuit conditions, such as diodes or thyristors. Fig.2(a) gives the simplest power electronics circuit of half-wave rectification, which has one diode connected AC voltage source to supply dc current of an inductive load. A diode element in conventional EMTP software requires passive RLC element next to it to determine both the node voltages of diode terminal. The diode becomes off soon after the next time step of forward direction current becomes less than 0. There is some backward direction residual current in the diode at the time step of the diode became off. Therefore, it induces numerical oscillation at the isolated circuit element by the switch off operation as given in Fig.2(b). This numerical oscillation difficulty is unavoidable for EMTP which has fixed calculation time step, because it cannot obtain the accurate timing of current or voltage becoming 0. Fig.2(c) gives the result when CDA is applied to the diode switching operation. The residual current in the diode at the time step of the diode becomes off is numerically damped out by the numerical process of backward Euler method in CDA, and the installation of numerical snubber circuit can be avoided. This result proved that CDA process can work properly to a simple power electronics circuit.



(a) Studied circuit



(b) Conventional normal switch operation (ATP)



(c) Switch operation with CDA (Simpass)

Fig. 2 Half-wave rectification circuit

B. Switching difficulty in commutation

The switch behavior discussed in the previous section is limited to a single switch operation and the phenomenon is induced from self contradiction in a circuit state generated by the numerical oscillation in the Trapezoidal rule. This section discuss about the commutation between two switch devices, the influences of numerical oscillation in the Trapezoidal rule and switch state change decision logic of EMTP type simulation software. Fig. 3 gives the studied step down chopper circuit. SW1 is a gate controlled self extinguishable switch device, such as IGBT or FET, which is expressed by Type-14 TACS controlled switch. The device current commutates between SW1 and SW2 take place by the state change of SW1. Though a commutation of current flowing through SW1 to SW2 is always take place by changing the state of SW1 from on to off, but a commutation from SW2 to SW1 does not always take place by the state change of SW1 from off to on, for which depends on the circuit condition. This commutation occurs when load current flowing through SW2 does not fall off to zero during the SW1 off period, which is called the continuous current mode operation. On the contrary, a commutation does not occur when load current falls off to 0 during SW1 off period, which is called a discontinuous current mode operation. Fig. 4 and Fig. 5 gives the simulation result of the continuous current mode and the discontinuous current mode respectively. Fig. 4(a) give the simulated result when conventional ATP switch state changing logic is adopted. SW1 state change from on to off triggers the numerical oscillation of the current flowing through load reactor, and it induces abnormal state value oscillation keeping in step with the 1 time step delay of switch state change. This commutation difficulty given in Fig. 4(a) can also be said to discontinuous current mode of Fig. 5(a).

The installation of numerical snubber circuit to SW1 is one solution, but its element values are highly dependent on the circuit property and simulation parameters. The essential counter measurement to settle this commutation difficulty is a instantaneous current commutation, which is served as “GIFU” switch option in ATP. The instantaneous current commutation in ATP is realized by going backward to the previous calculation time step, when state change occurs at a switch having the checked property of “GIFU” in data cards and iterates the calculation time step with using the changed switch conditions. Fig. 4(b) gives the result when instantaneous current commutation is applied to the continuous current mode. Both the commutation of SW1 from on to off (at 25μsec) and off to on (at 75μsec) properly functions with the assistance of instantaneous current commutation and no numerical oscillation occurs. However, instantaneous current commutation becomes inoperative to the discontinuous current mode. Fig. 5(b) shows that the commutation at SW1 from on to off works properly, but when the current of SW2 diode becomes lower than 0, numerical residual error current in the diode does not have any switch to commutate, for the circuit condition is discontinuous current mode. Therefore, it generates switch state oscillation of SW2 at t=50μsec. The instantaneous current commutation cannot become universal solution for power electronics circuit simulation for its many variations of circuit conditions.

Fig. 4(c) gives the result when CDA is applied to suppress the numerical oscillation at the switch operation. Though CDA can effectively suppresses residual error current at the instant of switch off, but it also diminishes the commutating current at the instant of SW1 changes from on to off, and the commutation fails. This can also be said the discontinuous current mode result given in Fig. 5(c). Fig. 5(d) is the case when both CDA and instantaneous current commutation is applied. It can be concluded that the instantaneous current commutation and CDA must be suitably combined to realize adequate commutation and numerical oscillation free result.

IV. POWER SYSTEM SIMULATION

This section discuss about the numerical oscillation suppression effect by CDA in a power system simulation. The objective of CDA usage in a power system analysis in this paper is to obtain the result, which coincide with the stability analysis simulation results. (The stability analysis simulation used in this paper solves the power system calculation in positive sequence of d-q coordinate system.) Fig. 6 gives the studied system, which has one machine and infinite bus with double circuit transmission line. The generator used in the ATP simulation is the novel reliable Type-58 phase domain synchronous machine model. The given disturbance to the system is 3 phase line ground fault at one transmission line circuit (1cct. 3LG at 0.2sec) and one circuit open to clear the fault (1cct. 3LO at 0.3sec). 3LG fault in ATP is modeled by three time controlled switches whose one terminal is grounded.

Fig. 7 gives the calculated result of phase A voltage at the generator output terminal. It shows there is no difficulty in the calculation during the sound condition

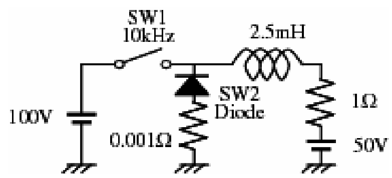
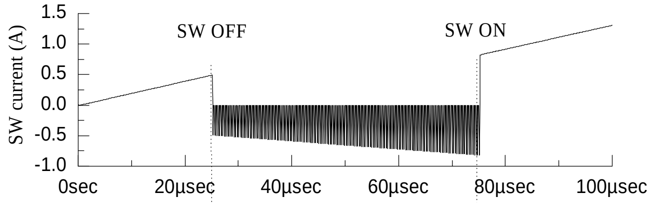
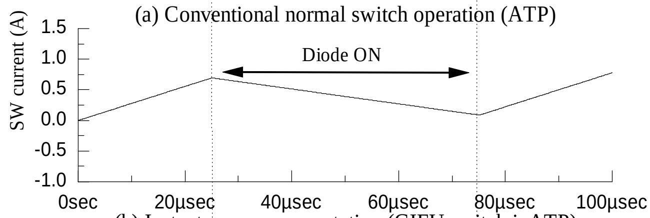


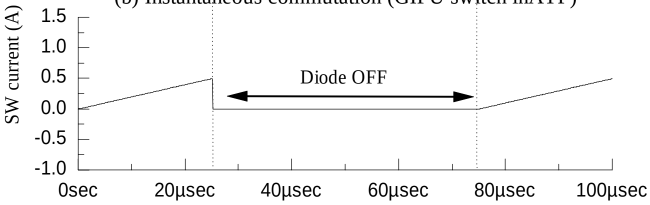
Fig. 3 Studied chopper circuit



(a) Conventional normal switch operation (ATP)

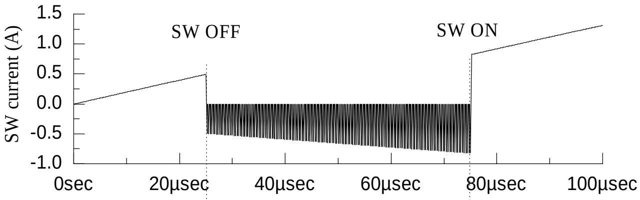


(b) Instantaneous commutation (GIFU switch inATP)

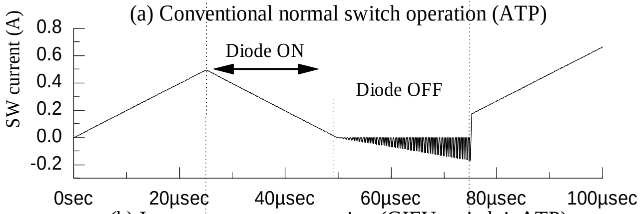


(c) Switch operation with CDA (Simpass)

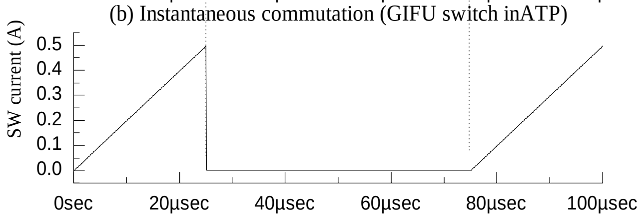
Fig. 4 Chopper circuit operation in continuous current mode



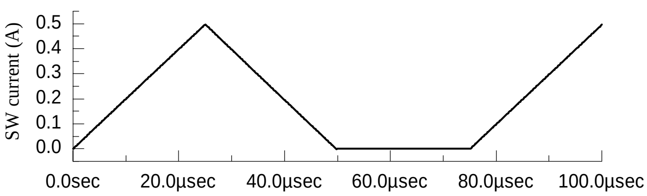
(a) Conventional normal switch operation (ATP)



(b) Instantaneous commutation (GIFU switch inATP)



(c) Switch operation with CDA (Simpass)



(c) Switch operation with CDA and instantaneous commutation (GIFU switch implemented in Simpass)

Fig. 5 Chopper circuit operation in discontinuous current mode

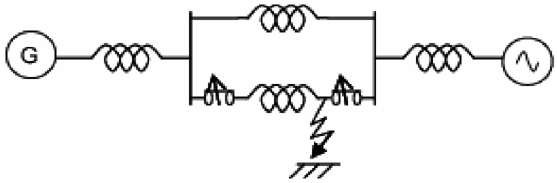
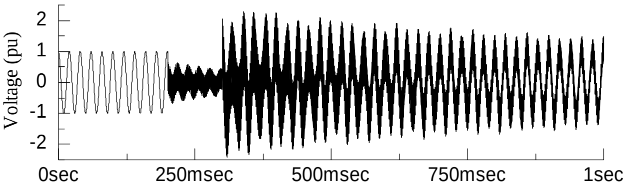
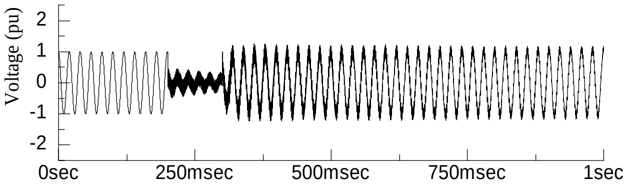


Fig. 6 Studied one machine and infinite bus power system model

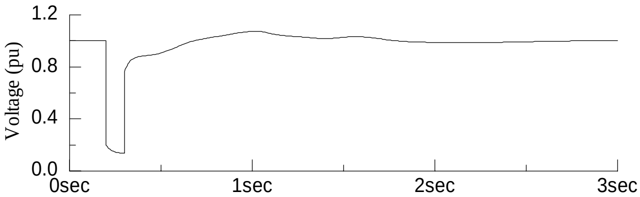


(a) Conventional normal switch operation (ATP)

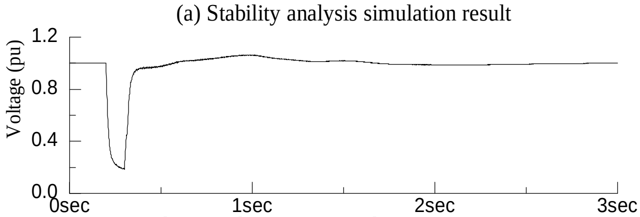


(b) Switch operation with CDA (Simpass)

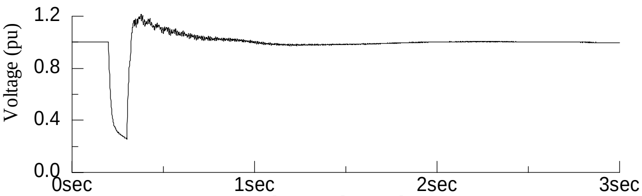
Fig. 7 AC voltage at the generator terminal (Phase A)



(a) Stability analysis simulation result

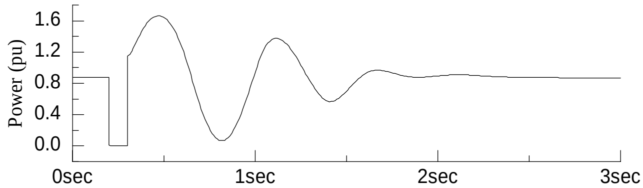


(b) Switch operation with CDA (Simpass)

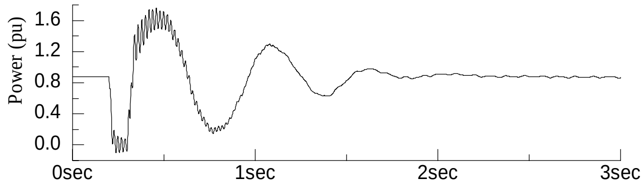


(c) Conventional normal switch operation (ATP)

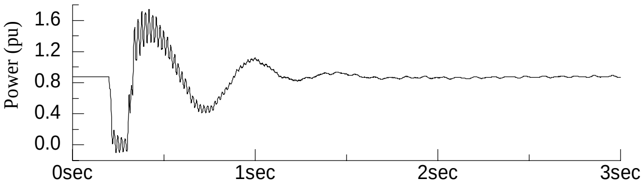
Fig. 8 RMS value of ac bus voltage at generator terminal



(a) Stability analysis simulation result

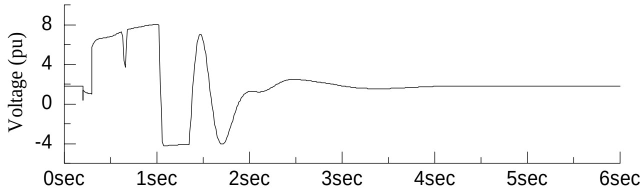


(b) Switch operation with CDA (Simpass)

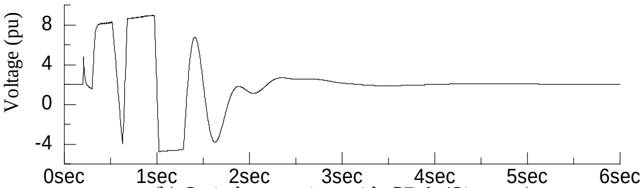


(c) Conventional normal switch operation (ATP)

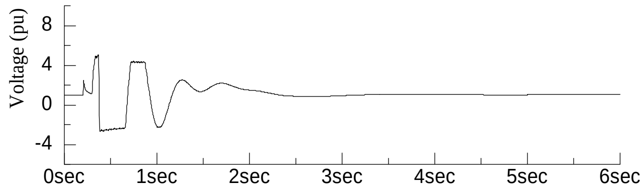
Fig. 9 Generator output power



(a) Stability analysis simulation result



(b) Switch operation with CDA (Simpass)



(c) Conventional normal switch operation (ATP)

Fig. 10 Exciter voltage of generator (Thyristor type)

(t<0.2sec). The switch state change operation for fault occurrence and circuit breaker operation causes discrete change of circuit topology, and this circuit breaker operation lead to numerical oscillation occurrence.

Fig. 7(a) shows that the switch operation for fault does not affect on the simulation result so much, for it does not create any floating node in the circuit, but the switch opening operation for circuit breaker to clear fault induces large over voltage caused by the numerical oscillation occurrence. This transient over voltage caused by numerical oscillation gives different result when comparing the generator output voltage in RMS value from 3 phase voltage to the stability analysis simulation result as given in Fig. 8(a) and (c). The over voltage caused by the unnecessary numerical oscillation at the instant of the circuit breaker opening operation cannot meet with the actual power system phenomena and it is unsusceptible. Therefore this unexpected numerical oscillation must be settle down by the usage of CDA. The effect of numerical oscillation elimination by CDA can be confirmed as in Fig. 8(c). The calculated RMS value to the CDA applied case is obtained as given in Fig. 8(b), which quite agree with the stability simulation result given in Fig. 8(a). The transient over voltage caused by the numerical oscillation also affects the AVR operation of the generator and the output power. Fig. 9 gives the result of generator output power to the respective simulation, and it shows that the power swing of the generator is affected by the unexpected transient over voltage and CDA is inevitable for obtaining adequate result to meet with the stability analysis simulation.

AVR output given in Fig. 10 indicates that the over voltage caused by the numerical oscillation induces unexpected AVR response. The recent high power generator equips with high speed exciter and AVR. They dominantly affects on the power system stability, therefore the accuracy of the simulation is inevitable. Moreover, the error of calculated power swing may affects on the power system planning and on the design of control equipments which stabilize power system fluctuations.

VI. Conclusions

This paper discussed about a numerical transient phenomena in a simulated electrical circuit induced by switch operation and tested its counter measurements.

The combination of the Trapezoidal rule and the modeling scheme of inductor and capacitor with an equivalent resistance and an equivalent current source for numerical integration is convenient, accurate and numerically stable for electrical circuit calculation so long as the circuit topology remain unchanged. But, this calculation method has difficulty in handling a circuit, whose topology changes discretely, though the practical analysis is required to handle the circuit topology change caused by switching devices in a power electronics circuit or a circuit breaker operation in power system. This difficulty arises from the historical term of equivalent current source used in the numerical integration model of trapezoidal rule and from the one time step delay of switch operation. They are tested and studied with taking a chopper circuit as a power electronics circuit and a one machine and infinite bus system as a power system for example. The counter measurement of CDA and instantaneous current commutation to this difficulty was proposed and tested to the above mentioned systems. The studied results show that CDA can diminish the numerical oscillation of voltage and the error of power swing in the power system simulation. But, the individual CDA and instantaneous current commutation cannot completely manage the difficulty in the power electronics circuit.

It can be concluded that the suitable combination of CDA and instantaneous current commutation is required to manage the difficulties regarding with the switch operation.

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