Spurious Inductor Loss of High Switching Power Converter in EMT Simulation Study

J. Na, H .Kim, C. Lee, K. Hur

***Abstract*—This research investigates the spurious inductor loss encountered in electromagnetic transient (EMT) simulation of high switching power electronic devices such as a voltage sourced converter (VSC) with high voltage direct current (HVDC). This spurious loss due to numerical integration substitution of the EMT modeling of passive elements, especially an inductor. It occurs when the applied voltage across the inductor is not sinusoidal. This research thus unveils the mechanism of the spurious inductor loss associated with converter parameters such as inductance, DC voltage, modulation index, and switching frequency, and simulation parameters such as the solution time step. Therefore, care must be taken of the spurious inductor loss contribution on top of conventional switching and conduction loss when EMT simulation including a converter is conducted. In addition, the converter parameters usually cannot be changed because it is designed parameters. However, the simulation parameter can be changed and directly affects the spurious inductor loss. The spurious inductor loss increases the possibility of misleading the simulation results. Therefore, the smaller solution time step is recommended to reduce the spurious inductor loss, but it increases computational burden, which leads to extremely slow run in EMT simulation. In this paper, we discuss the trade-off relationship between the simulation run time and the spurious inductor loss.**

***Keywords*: EMT, high switching power converter, converter loss, spurious inductor loss.**

I. Introduction

TRADITIONAL electrical systems are only concerned with electromechanical transients, then the analysis can use voltage and current phasors in the frequency domain during steady-state operation. However, the number of switching devices has been growing up in the power systems, steady-state analysis is no more effective approach. The switching event belongs to high frequency band phenomena. Therefore, it is necessary to analyze electromagnetic transients (EMT) [1]. The simulation tool using computer named electromagnetic transients program (EMTP) was developed to find a time-domain solution. EMTP has its origin in the work by Frey and Althammer [2]. In EMTP, computer simulates continuous transient phenomena using discretization methods such as forward rule, backward rule, and trapezoidal rule. The basic algorithm of the EMTP is Dommel's algorithm. This algorithm is based on the trapezoidal rule because it has a better accuracy than other methods [3]. Dommel's algorithm in EMTP is based on the assumption that any change of parameters is linear at every fixed solution time step. This assumption and switching event with inductor could cause implement interpolation and chatter between time steps. To overcome this issue, interpolation technique and chatter remove methods are introduced in [4], [5].

The power converter is a device which transfers power with signal properties such as frequency, amplitude, and phase [6]. A voltage-sourced converter (VSC) is a kind of the high switching power converter. It converts AC voltage to DC voltage and vice versa using high frequency switching control. Two-level VSC, three-level converter, and a multilevel converter are the representative high switching power converters. A two-level VSC applies either positive or negative DC voltage at the AC side voltage depending on which switch cell is on. A multilevel converter applies stairs wave at AC-side using divided DC voltage. This operation is controlled based on a pulse-width modulation (PWM) or other switching methods to produce fundamental AC component [7]. When any system with a high switching power converter is simulated, unexpected higher power conversion loss could be observed. The converter power losses consist of switching loss, conduction loss, and AC side resistance loss [8]. However, there is an additional loss component, which may be encountered in the EMTP only, i.e. the spurious inductor loss. It does not occur when an ideal AC voltage source is applied across inductor nodes, but it occurs in the non-sinusoidal voltage. Particularly, the spurious inductor loss of a VSC with RL filter would be salient. Therefore, it is possible to mislead analysis by the spurious inductor loss in Dommel's algorithm for EMTP because a real inductor has no spurious loss.

This paper investigates the spurious inductor loss in high switching power converter in EMT simulation. Also, the EMT representation of a capacitor model may lead to the spurious power loss.

II. Power loss of passive elements in EMT simulation

A high switching power converter uses RL filter to eliminate high frequency harmonic in output current [7]. A power converter produces non-sinusoidal voltage at inductor node of RL filter, then it causes the spurious inductor loss. Although there is no chance to observe the spurious loss in converter simulation with capacitor model because the series capacitor is not used with converters, the spurious loss phenomenon of capacitor model also exists due to that the basic formula is

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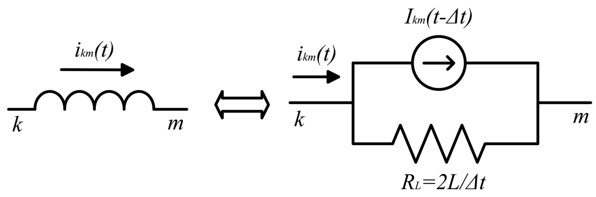

Fig. 1. The equivalent circuit of inductor in EMT simulation

the same as an inductor. In this section, we calculate spurious power loss with both of an inductor model and a capacitor model.

A. Inductor spurious loss

According to Dommel's algorithm, an inductor component are modeled using an ideal current source and resistor [3]. Fig. 1 shows the equivalent circuit of an inductor in EMT simulation. According to [3], inductor current could be described as (1).

$$i_{km}(t) = I_{km}(t-\Delta t) + \frac{\Delta t}{2L}(V_k(t-\Delta t) - V_m(t-\Delta t)) \quad (1)$$

where

$$I_{km}(t-\Delta t) = i_{km}(t-\Delta t) + \frac{\Delta t}{2L}(V_k(t-\Delta t) - V_m(t-\Delta t))$$

and Δt is a discrete time interval named a solution time step.

The instantaneous power is defined that it is the product of instantaneous voltage and current. Consider a voltage is any function of t and current is (1) and assuming $V_m(t)$ is zero. The instantaneous power of inductor is

$$\begin{aligned} P(t) = {} & V_k(t)i_{km}(t-\Delta t) + \frac{\Delta t}{2L}V_k(t)V_k(t-\Delta t) \\ & + \frac{\Delta t}{2L}(V_k(t))^2 \end{aligned} \quad (2)$$

It could be separated three parts:

$$P_{\Delta t}(t) = V_k(t)i_{km}(t-\Delta t) \quad (3)$$

$$P_{R_L,\Delta t}(t) = \frac{\Delta t}{2L}V_k(t)V_k(t-\Delta t) \quad (4)$$

$$P_{R_L}(t) = \frac{\Delta t}{2L}(V_k(t))^2 \quad (5)$$

To demonstrate that an ideal AC voltage cannot create the spurious inductor loss, assume that there are an ideal single phase AC voltage source and an inductor. Therefore,

$$V_k(t) = V cos(\omega t + \delta) \quad (6)$$

$$i_{km}(t) = \frac{V}{\omega L}cos(\omega t + \delta - \frac{\pi}{2}) \quad (7)$$

where ω is the fundamental frequency of system and δ is voltage angle. One solution time step Δt can make the angle delay of voltage and current phasors. That angle delay is $\omega\Delta t$. In that case, we have

$$\begin{aligned} P_{\Delta t}(t) = {} & \frac{V^2}{2\omega L}[cos(\frac{\pi}{2} + \omega\Delta t) \\ & + cos(2(\omega t + \delta) + \frac{\pi}{2} - \omega\Delta t)] \end{aligned} \quad (8)$$

$$P_{R_L,\Delta t}(t) = \frac{V^2\Delta t}{4L}[cos(\omega\Delta t) + cos(2(\omega t + \delta) - \omega\Delta t)] \quad (9)$$

$$P_{R_L}(t) = \frac{V^2\Delta t}{4L}[1 + cos(2(\omega t + \delta)] \quad (10)$$

which could be simplified with averaging and used sum and difference formulas of trigonometric function, as well as a small-angle approximation. Δt is small enough value to use a small-angle approximation. Finally, the average value of each parts are

$$\overline{P}_{\Delta t}(t) \approx -\frac{V^2\Delta t}{2L} \quad (11)$$

$$\overline{P}_{R_L,\Delta t}(t) \approx \frac{V^2\Delta t}{4L} \quad (12)$$

$$\overline{P}_{R_L}(t) = \frac{V^2\Delta t}{4L} \quad (13)$$

$$\overline{P} = \overline{P}_{\Delta t} + \overline{P}_{R_L,\Delta t} + \overline{P}_{R_L} \approx 0. \quad (14)$$

Therefore, an ideal AC system does not represent inductor power loss.

However, if the high switching power converter output voltage applied at inductor node, it should make real power loss. For simplicity, starting from the simplest case. Assume that a two-level VSC with sinusoidal voltage command. Since two level VSC can generate only two levels of terminal voltage, then the voltage and current consists of fundamental component which following voltage command and other components from PWM. In addition, assume that the chatter problem which is caused when switches and inductors are connected had already solved by using interpolation [4]. Then, we can assume terminal voltage and current.

$$\begin{aligned} V_k(t) &= \frac{MV_{DC}}{2}cos(\omega t + \delta) + V_{other} \\ &= \begin{cases} \frac{V_{DC}}{2} & \text{if } m(t) \geq c(t) \\ -\frac{V_{DC}}{2} & \text{if } m(t) \leq c(t) \end{cases} \end{aligned} \quad (15)$$

$$i_{km}(t) = \frac{MV_{DC}}{2\omega L}cos(\omega t + \delta - \frac{\pi}{2}) + i_{other} \quad (16)$$

where $m(t)$ is the modulation index, $c(t)$ is the carrier signal for PWM, M is peak value of $m(t)$, V_{DC} is DC voltage of VSC, V_{other} is non-fundamental component of voltage at node k, and i_{other} is non-fundamental component of current between node k and m.

In this case, the average power loss of a inductor is

$$\overline{P}_{\Delta t}(t) \approx -(\frac{MV_{DC}}{2})^2\frac{\Delta t}{2L} - \overline{P}_{other} \quad (17)$$

$$\overline{P}_{R_L,\Delta t}(t) = \begin{cases} (\frac{V_{DC}}{2})^2\frac{\Delta t}{2L} & \text{if } V_k(t) = V_k(t-\Delta t) \\ -(\frac{V_{DC}}{2})^2\frac{\Delta t}{2L} & \text{if } V_k(t) \neq V_k(t-\Delta t) \end{cases} \quad (18)$$

$$\overline{P}_{R_L}(t) = (\frac{V_{DC}}{2})^2\frac{\Delta t}{2L} \quad (19)$$

$\overline{P}_{\Delta t}(t)$ has a negative real power which is composed with real power of fundamental and other components. The other part $\overline{P}_{other}$ depends on various variables such as magnitude of current and switching frequency. $\overline{P}_{R_L,\Delta t}(t)$ has a negative

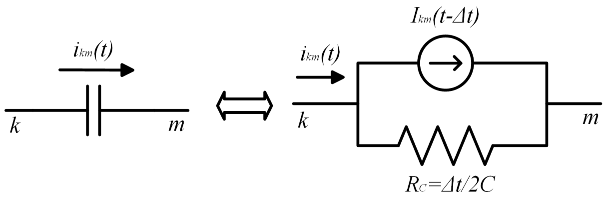

Fig. 2. The equivalent circuit of capacitor in EMT simulation

value only when the value of the previous time step is different from the value of the current time step, and has a positive value in the other cases. Accordingly, $\overline{P}_{R_L,\Delta t}(t)$ will be reduced as the switching state changes frequently. Finally, average power loss of an inductor is

$$\overline{P} = -\overline{P}_{other} + (1 - M^2 + a)(\frac{V_{DC}}{2})^2 \frac{\Delta t}{2L} \tag{20}$$

where *a* is the parameter that varies depending on how often the switching occurs.

Typically, the solution time step always smaller than switching time period, parameter *a* should be positive number. In addition, the magnitudes of harmonics are smaller than fundamental components, then it could be negligible. M is modulation index, then it always smaller than 1. Therefore, (20) has positive value.

$$\overline{P} = \overline{P}_{\Delta t} + \overline{P}_{R_L,\Delta t} + \overline{P}_{R_L} > 0 \tag{21}$$

In EMT simulation, the fact that an inductor consumes real power called the spurious inductor loss when a non-sinusoidal voltage at the node is applied is shown in (21).

B. Capacitor power loss

The capacitor is modeled in the same way as the inductor [3]. Fig. 2 shows the equivalent circuit of a capacitor in EMT simulation.

$$i_{km}(t) = I_{km}(t-\Delta t) + \frac{2C}{\Delta t}(V_k(t-\Delta t) - V_m(t-\Delta t)) \tag{22}$$

where

$$I_{km}(t-\Delta t) = -i_{km}(t-\Delta t) - \frac{2C}{\Delta t}(V_k(t-\Delta t) - V_m(t-\Delta t))$$

The same way as inductor, consider a voltage is any function of *t* and current is (22) and assuming $V_m(t)$ is zero. The instantaneous power of a capacitor is

$$\begin{aligned} P(t) \, &= -V_k(t)i_{km}(t-\Delta t) - \frac{2C}{\Delta t}V_k(t)V_k(t-\Delta t) \\ &+ \frac{2C}{\Delta t}(V_k(t))^2 \end{aligned} \tag{23}$$

It could be separated three parts:

$$P_{\Delta t}(t) = -V_k(t)i_{km}(t-\Delta t) \tag{24}$$

$$P_{R_C,\Delta t}(t) = -\frac{2C}{\Delta t}V_k(t)V_k(t-\Delta t) \tag{25}$$

$$P_{R_C}(t) = \frac{2C}{\Delta t}(V_k(t))^2 \tag{26}$$

Assume that there are an ideal single phase AC voltage source and a capacitor. Therefore,

$$V_k(t) = V cos(\omega t + \delta) \tag{27}$$

$$i_{km}(t) = \omega CV cos(\omega t + \delta + \frac{\pi}{2}). \tag{28}$$

In that case, we have

$$\begin{aligned} P_{\Delta t}(t) \, &= -\frac{\omega CV^2}{2}[cos(-\frac{\pi}{2} + \omega\Delta t) \\ &+ cos(2(\omega t + \delta) + \frac{\pi}{2} - \omega\Delta t)] \end{aligned} \tag{29}$$

$$P_{R_C,\Delta t}(t) = \frac{CV^2}{\Delta t}[cos(\omega\Delta t) + cos(2(\omega t + \delta) - \omega\Delta t)] \tag{30}$$

$$P_{R_C}(t) = \frac{CV^2}{\Delta t}[1 + cos(2(\omega t + \delta)] \tag{31}$$

which could be simplified as

$$\overline{P}_{\Delta t}(t) \approx -\frac{C\omega^2 V^2 \Delta t}{2} \tag{32}$$

$$\overline{P}_{R_C,\Delta t}(t) \approx -\frac{CV^2}{\Delta t} + \frac{C\omega^2 V^2 \Delta t}{2} \tag{33}$$

$$\overline{P}_{R_C}(t) = \frac{CV^2}{\Delta t} \tag{34}$$

$$\overline{P} = \overline{P}_{\Delta t} + \overline{P}_{R_C,\Delta t} + \overline{P}_{R_C} \approx 0. \tag{35}$$

Therefore, an ideal AC system also does not represent capacitor power loss.

As same as an inductor case, we could derive average power formula when two-level VSC has a series connection with a capacitor.

$$\begin{aligned} V_k(t) \;\; &= \;\; \frac{MV_{DC}}{2}cos(\omega t + \delta) + V_{other} \\ &= \;\; \begin{cases} \frac{V_{DC}}{2} & \text{if } m(t) \geq c(t) \\ -\frac{V_{DC}}{2} & \text{if } m(t) \leq c(t) \end{cases} \end{aligned} \tag{36}$$

$$i_{km}(t) = \frac{\omega CMV_{DC}}{2}cos(\omega t + \delta + \frac{\pi}{2}) + i_{other} \tag{37}$$

$$\overline{P}_{\Delta t}(t) \approx -(\frac{MV_{DC}}{2})^2 \frac{\omega^2 C\Delta t}{2} - \overline{P}_{other} \tag{38}$$

$$\overline{P}_{R_C,\Delta t}(t) = \begin{cases} (\frac{V_{DC}}{2})^2 \frac{2C}{\Delta t} & \text{if } V_k(t) = V_k(t-\Delta t) \\ -(\frac{V_{DC}}{2})^2 \frac{2C}{\Delta t} & \text{if } V_k(t) \neq V_k(t-\Delta t) \end{cases} \tag{39}$$

$$\overline{P}_{R_C}(t) = (\frac{V_{DC}}{2})^2 \frac{2C}{\Delta t} \tag{40}$$

$$\overline{P} = -\overline{P}_{other} + (\frac{2}{\Delta t} - \frac{\omega^2 M^2 \Delta t}{2} - \frac{2a}{\Delta t})(\frac{V_{DC}}{2})^2 C \tag{41}$$

The average power of the capacitors also varies depending on the system parameters such as peak value of modulation index, fundamental frequency, and soultion time step etc.

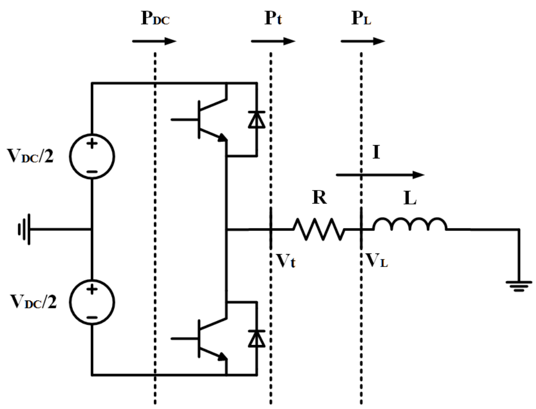

Fig. 3. The two-level VSC system configuration

TABLE I
SYSTEM PARAMETERS FOR BASE CASE

Parameter	Value
R	0.5m Ω
L	5mH
V_{DC}	1.25kV
M	0.3
Δt	50us
f_s	3140Hz

TABLE II
AVERAGE POWER OF EACH BRANCH IN THE VSC SYSTEM

Branch	P_{DC}	P_t	P_L
Spurious Loss (kW)	5.0436	4.9740	4.9716

III. CASE STUDY WITH PSCAD/EMTDC

According to (20), the spurious inductor loss is related to the following parameters.

- Inductance
- DC voltage
- Modulation index
- Switching frequency
- Solution time step

This case study proceeded by adjusting each parameter to confirm that the parameters affects the spurious inductor loss with PSCAD/EMTDC. The case study used two-level converter, and it makes terminal voltage V_t with cosine modulation index

$$m(t) = Mcos(2\pi f_s t) \tag{42}$$

where f_s is system frequency.

This test system configuration is described in Fig. 3. For comparison, there should be base case, and its parameters are shown at Table I.

In this case study, only the inductor case is considered except for the capacitor case, because typically high switching power converter uses the RL filter. The spurious inductor loss was measured by $V_L(t) \cdot I(t)$.

Before looking at the impact of parameter adjusts, we first compare the average power at each point in the converter system. The average power was averaged over the data measured during one cycle.

TABLE III
THE SPURIOUS POWER LOSS OF ALL CASES

Chainging Factor	**Spurious Loss (kW)**
Base case	4.972
Inductance (5mH to 50mH)	0.497
DC voltage (1.25kV to 0.625kV)	1.239
Modulation index (0.3 to 0.15)	4.112
Switching frequency (3140Hz to 6280Hz)	4.730
Solution time step (50us to 5μs)	1.323

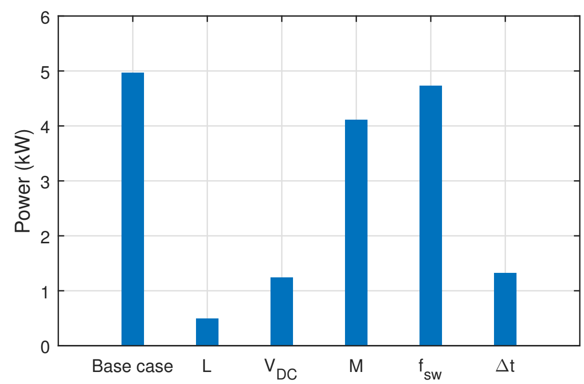

Fig. 4. The spurious power loss of all cases

A. Power loss of each branch

The instantaneous power was measured at three points, the DC port, the output terminal of the VSC, and the front of the inductor as shown in Fig. 3. Then, the results which are averaged shown in Table II. In the Table II, P_{DC}, P_t, and P_L show slight differences, the difference between P_{DC} and P_t is the switching and conduction loss, and the difference between P_t, and P_L is the loss in resistance. Since there is a ground after the inductor, P_L is a real power flow through the inductor, it means inductor consumes real power loss.

B. Power loss with adjusting parameters

There are five cases which adjusting parameters. The simulation result of all cases is shown at Table III and Fig. 4, and the base case has about 5kW spurious inductor loss. In the first case is that inductance was changed to 50mH. Its change is ten times the previous value, then the spurious inductor loss is reduced to one tenth of the base case value which is 0.497kW. That result is equal to the observation that inductance is the denominator in (20).

The second case is DC voltage changing case that V_{DC} was changed 0.625kV. Since the spurious inductor loss is proportional to the square of the DC voltage according to (20), a quarter of the base case should come out in this case where the voltage is halved. The result shows the value 1.239kW.

The third case is that the peak value of modulation index is changed to 0.15. As well as the fourth case is that switching frequency is changed to 6280Hz. According to (20), the

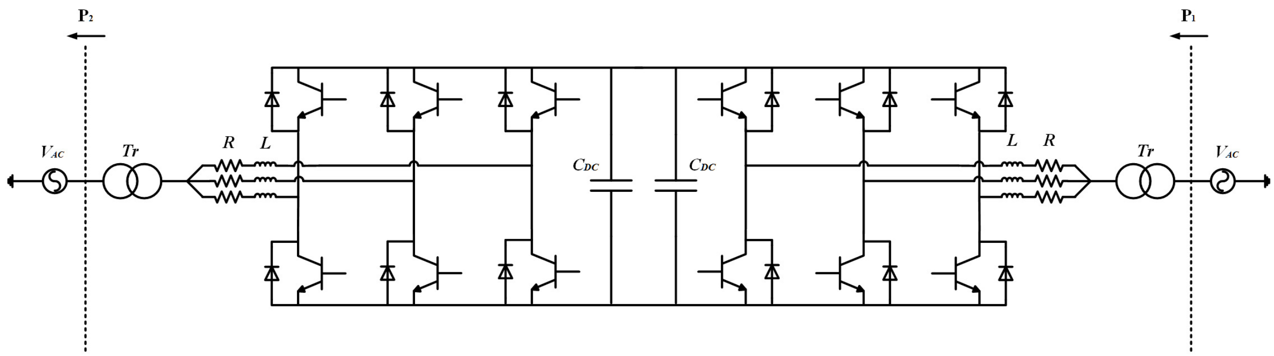

Fig. 5. The two level three phase back-to-back VSC-HVDC system configuration

TABLE IV
SYSTEM PARAMETERS FOR HVDC SYSTEM

Parameter	Value
$V_{AC,\ L\text{-}L}$	138kV
Transformer rating	10MVA
Transformer turns ratio	138kV/15kV
R	0.5m Ω
L	5mH
C_{DC}	131.58μF
V_{DC}	40kV
f_{system}	60Hz
$f_{switching}$	1680Hz
Transfer Power Reference	1MW
Duration of Run	2s

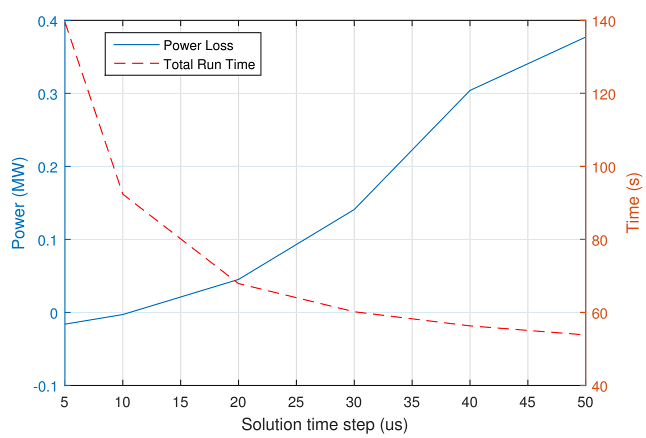

Fig. 6. Trade-off relationship of back-to-back HVDC case

decrease in M and the increase in f_s should lead to an increase in spurious inductor loss, nevertheless, both of the cases shows results that are reduced. Further investigation is needed on this point.

The fifth case is that solution time step is changed to 5μs. The solution time step is proportional to the spurious loss in (20), however spurious loss is not reduced to a tenth accurately, because it is related to non-fundamental components.

C. Discussion of case study

The case study shows how each parameter affects the spurious inductor loss. This spurious loss lowers an accuracy of an EMT simulation, it must be decreased as much as possible. The most effective ways to lower the spurious loss are increasing inductance or reducing DC voltage and solution time step. Inductance and DC voltage are system parameter that is predetermined before proceeding with a simulation. Thus, system parameters could not be changed, then the simplest solution is choosing a small solution time step to lower the spurious loss.

The solution time step, which is simulation parameters, is the only parameter that can be modified to lower the spurious inductor loss. Therefore, the smaller time step is recommended. However, there is the trade-off relationship between the spurious inductor loss and the total simulation run time, since the smaller solution time step force to increase computational burden. We conduct more case study to show a trade-off relationship with PSCAD/EMTDC.

This case system consists of back-to-back HVDC with two-level VSC. The controls of HVDC are separated with inverter and rectifier. The inverter is controlled by 1MW power transfer reference and the rectifier is controlled by 40kV DC voltage reference. The system configuration is shown at Fig. 5 and parameters are shown at Table IV. The power loss was measured by subtracting P_2 from P_1 shown in Fig. 5. P_1 and P_2 was obtained by averaging the data that multiplying voltage and current for one cycle. The data for one cycle were measured during steady state operation and was measured at 1.5 seconds. The total computation time was measured using the time function of C language, as well as it is only meaningful to check tendency because it could be varied according to computer specification or operating environment. In addition, the channel plot step of PSCAD also affects the total computation time. In this case study, it was set to the same time as the solution time step.

The simulation result shows that spurious loss increases and total run time decreases as solution time step increases, as shown in Fig. 6. The result shows that there is a trade-off relationship between accuracy and total run time when running a simulation using a two-level VSC and that an appropriate solution time step should be chosen according to the situation.

IV. CONCLUSION

Typically, we only consider switching loss, conduction loss, and AC side resistance loss in converter simulations. However, there is a high probability of observing another loss in the EMT simulations. In this paper, it is defined as the spurious loss. The spurious loss does not occur when the applied voltage is a sinusoidal waveform. The spurious loss is only observed when the applied voltage is a non-sinusoidal waveform. Particularly, the spurious loss occurs prominently in the EMT simulation in the two-level VSC case which is analyzed intensively in this paper. Therefore, care must be taken of the spurious inductor loss contribution on top of conventional switching and conduction loss when EMT simulation including a high switching power converter such as two-level VSC is conducted.

The spurious loss is related to the parameters such as inductance, DC voltage, modulation index, switching frequency, and solution time step. The occurrence of the spurious loss is confirmed by a single-phase two-level VSC simulation using RL filter. In addition, it is confirmed, how each parameter affected the spurious loss in same simulation condition. The spurious loss is inversely proportional to the inductance and proportional to DC voltage and solution time step. If modulation index and switching frequency are reduced, the spurious loss is slightly reduced, but the change is less than the previous three parameters.

The spurious loss can lead to misleading when interpreting converter EMT simulation results. To reduce the spurious inductor loss, we can modify the converter parameters such as inductance, DC voltage, modulation index, and switching frequency. However, the converter parameters cannot be changed because it is designed parameters in the practical applications. Therefore, the changing solution time step, which is simulation parameter, can be the only solution to reduce spurious inductor loss. There is the trade-off relationship between the simulation time step and the spurious inductor loss. Therefore, this relationship should be considered for the accurate and not extremely slow simulation when choosing solution time step.

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