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직류송전 인버터의 필터 최적설계를 위한 해석 및 목적함수의 선정

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Analysis of HVDC Inverter and Application of Objective Functions for the Optimal Filter Design

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요 약

본 논문은, HVDC 시스템의 인버터 제어기 및 고조파 필터의 설계를 위하여 동특성 및 정상상태 특성을 해석하는 방법을 제시한다. EMTP 시뮬레이션을 이용하면, 동특성 분석이 가능하며, 정상상태 특성의 분석은 필터와 부하를 고려한 조류해석을 수행함으로써 가능하다. 또한 본 논문은 HVDC 시스템의 정적 및 동적 특성 분석이 가능한 단상 등가회로를 제안한다. 이 단상 등가회로에서 인버터는 스위치의 소호에 따른 전류원으로 취급된다. 또한 필터설계에 사용되고 있는 각종 목적함수를 단상 등가회로를 이용하여 구할 수 있다. 본 논문은 전압의 고조파 성분 및 필터의 전력손실을 고려한 목적함수를 이용하여 필터를 최적화하는 과정이 제시되어 있다.

ABSTRACT

This paper proposes several methods to analyze dynamic and static characteristic of HVDC inverter system. The characteristic analysis is essential for the controller and filter design of the HVDC inverter system. Dynamic characteristic can be analyzed with EMTP simulation and static characteristic can be obtained by solving newly proposed load flow equation which includes the filter and load characteristic. New simple per-phase-equivalent circuit is also proposed. In this circuit, HVDC inverter is considered as a current source depending on the on-off status of switch. Dynamic and static characteristic can be analyzed by the proposed per-phase-equivalent circuit. For the optimal filter design, various performance criteria are proposed. The performance index, based on the per-phase-equivalent circuit, is calculated. Voltage harmonics and filter power loss are selected as criteria. Optimization procedure is explained to find optimal passive filter parameters.

Key Words : HVDC, Inverter, Passive filter, Harmonics, Optimization

1. Introduction

HVDC transmission has many advantages in environmental and economic aspects comparing with AC transmission. HVDC transmission system imporves the stability and the reliability of power system. However, harmonic currents are generated by HVDC inverter and reactive power should be compensated. HVDC inverter converts DC power to AC power. Conversion process is mostly done by thyristor switching and line commutation. Therefore, the voltage of AC bus should be stable for the DC/AC inversion.

In order to reduce the harmonics, passive filters are widely used due to their simple structures and economical merit. Recently with the development of high-voltage power-switching devices, the use of active filter is considered. Active filter has excellent harmonic characteristics during load variation.

However, the implementation of active filter in actual power system requires further research.

In order to design passive filter for the HVDC system., the characteristics of AC/HVDC system should be analyzed first with various methods.

Transient and steady-state characteristics of AC/HVDC system can be studied with EMTP simulation. In order to perform EMTP simulation, nominal parameters such as voltage magnitude and phase angle at voltage buses and thyristor firing angle should be known first.

In order to get nominal values, AC/HVDC load flow concept is proposed. If the operating point is changed, new nominal value should be calculated first, New nominal value can be obtained by solving nonlinear equation. This method is widely used in power system and it is called as load flow calculation. HVDC inverter should be included in load flow calculation.

Particularly, performance index such as system harmonics to optimize system capacity should be defined and it can be calculated with equivalent circuit. Optimal filter parameters can be varied depending on performance index. Selection of performance index is very difficult due to its nonlinear characteristics. For optimization, application of analytic function has limitation.

Among available performance index which is adopted in various design procedure, voltage harmonics comparing with ac reference voltage and power loss are selected as performance index.

Performance index is calculated with proposed per phase equivalent circuit and optimal parameters are obtained by optimization technique. Dynamic characteristics are also analyzed with proposed equivalent circuit.

Particularly system harmonics or performance index to optimize system capacity should be defined and it can be calculated with equivalent circuit.

Optimal filter parameters can be varied depending on performance index. Selection of performance index is very difficult due to its nonlinear characteristics. For optimization, application of analytic function has limitation.

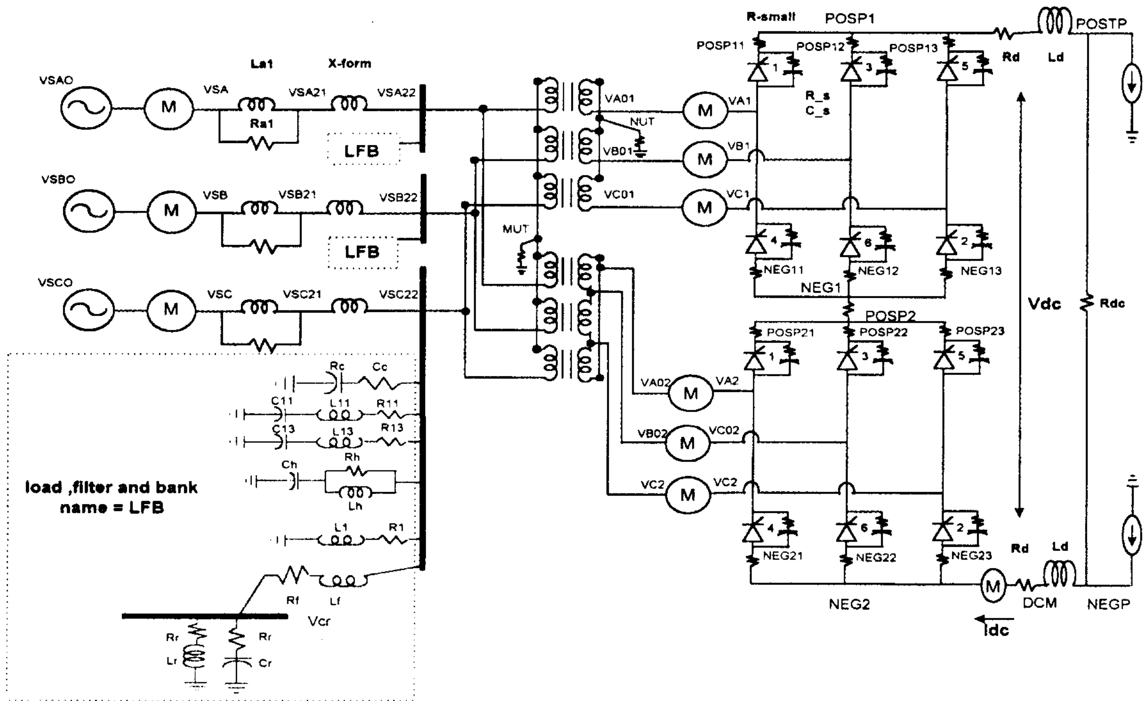

Fig. 1 The circuit diagram of 12 pulse HVDC inverter system connected to a simple AC power system

2. Chracteristics of AC/HVDC system

2.1 AC/HVDC system

Fig. 1 shows the 12 pulse HVDC system connected to an AC power system, which consists of 12 pulse thyristor inverter, snubbers, Y-Y and Y-Δ transformer, capacitor bank for reactive power compensation and filter to remove harmonic currents. Generators are represented with voltage sources and internal impedances. Transmission line and load are modelled with resistors and inductors.

2.2 Load flow calculation of AC/HVDC system

HVDC system connected to an ac power system can control the real power flowing into the AC power system. However, the amount of the real power flow depends on the thyristor-firing angle, α, the voltages in ac power system, the impedance of the transmission line and load.

In order to perform the EMTP simulation study, the nominal parameters such as the magnitudes and the phase angles at voltage buses and the thyristor-firng angle should be defined first. In order to get nominal values, the load flow equation of the AC/HVDC system should be derived as a function of the thyristor-firing angle, α.

Fig. 2 shows the single-phase equivalent circuit of AC/HVDC system. In Fig. 2, Z_s represents impedance between terminal and infinite buses. Z_l represents various load, harmonic filter and capacitor bank. Z_x represents equivalent impedance of Y-Y, Y-Δ connected transformer.

The phase angle of infinite bus V_s is assumed as 0. Therefore, V_s is written as

$$V_s = |V_s| \angle 0 \tag{1}$$

AC voltage V_l at the inverter terminal is

$$V_l = |V_l| \angle \delta \tag{2}$$

Therefore, the power flows from V_l to V_s and from V_l to load Z_l are written as

$$P_s + jQ_s = 3V_l I_l^* = 3V_l \left(\frac{V_l - V_s}{Z_s}\right)^* \tag{3}$$

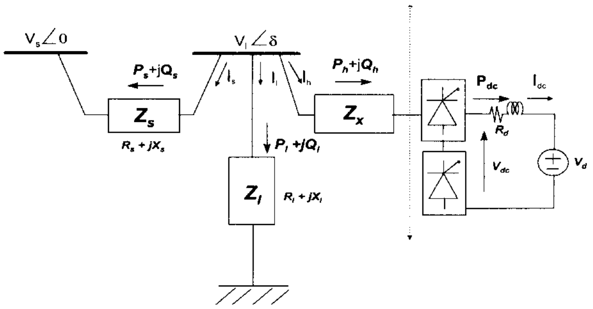

Fig. 2 Load flow model for AC/HVDC system

$$P_l + jQ_l = 3V_l I_l^* = 3\frac{|V_l|^2}{Z_l^*} \tag{4}$$

AC current from bus V_l to HVDC inverter is

$$I_h = |I_h| \angle \phi \tag{5}$$

Therefore, power flow flowing into HVDC inverter is written as

$$P_h + jQ_h = 3V_l I_h^* = 3V_l \angle \delta \cdot I_h \angle -\phi \tag{6}$$

In Fig. 2, V_d is DC voltage controlled at rectifier terminal, which is considered as DC voltage source.

V_{dc} is the output voltage of 12 pulse thyristor inverter. Relation of V_{dc} and V_d is as follows,

$$V_{dc} = I_{dc} R_d + V_d \tag{7}$$

Relation of thyristor firing angle α and V_{dc} is

$$V_{dc} = \frac{6\sqrt{2}}{\pi} a \, |V_l| \cos\alpha - \frac{6}{\pi} X_c I_{dc} \tag{8}$$

Relation between I_{dc} and rms value I_h is

$$I_h = \frac{2\sqrt{6}}{\pi} I_{dc} \tag{9}$$

If the power loss of the transformer is negligible, the relation between P_h and P_{dc} is

$$P_h = P_{dc} = 3|V_l I_h| \cos(\delta - \phi) = V_{dc} I_{dc} \tag{10}$$

Power flow equations at inverter bus are

$$P_s + P_l + P_h = f_1(|V_l|, \delta, \phi) = 0 \tag{11}$$

$$Q_s + Q_l + Q_h = f_2(|V_l|, \delta, \phi) = 0 \quad (12)$$

$$P_{dc} = f_3(|V_l|, \delta, \phi) = P_{sch} \quad (13)$$

In order to find V_l, δ, Φ, in Eq. (11), (12) and (13), Newton Raphson method is used. System parameters of the AC/HVDC system and results of the load flow calculation are listed in Table 1, 2 respectively. Fig. 3 shows the flow chart of the load flow calculation.

Table 1 System parameters for load flow calculation and EMTP simulation.

R_a	15Ω	R_l	100ohm	L_{13}	54mH
L_{a1}	27mH	L_l	88mH	R_h	166Ω
L_{a2}	54mH	R_{11}	1Ω	L_h	9mH
R_f	12Ω	L_{11}	50mH	C_h	1.5uF
L_f	200mH	R_{13}	1Ω	C_c	17.6uF
R_r	300ohm	L_r	284mH	C_r	4uF
R_d	12Ω	L_d	100mH	L_{TR}	37mH
V_s	141kV	V_{dc}	-300kV	P_{dc}	300MW

Table 2 Results of load flow calculation

V_l	116.7kV	δ	-4.2°	V_{dc}	-287.5kV
I_h	1043A	Φ	125.9°	I_{dc}	1032A
P_h	-300MW	P_s	-183MW	P_l	483MW
Q_h	484MVar	Q_s	-282MVar	Q_l	-202MVar

2.3 EMTP simulation study

In order to study of the transient and steady-state characteristics of the HVDC system and to prove the load flow calcultion, the computer simulations using EMTP are performed. HVDC system supplies 300MW to the AC power system and V_{dc} is 300kV.

The infinite bus voltage, V_s, is 141kV. The thyristor firing angle, α, is 117.5°, which is a solution of the load flow equation. This value is used as the value of thyristor-firing angle in EMTP simulation.

Fig. 4 shows the waveforms of P_{dc} and P_s, in EMTP simulation, using the firing angle obtained by the load flow calculation. The steady-state performance of HVDC system in EMTP simuation agrees with the result of the load flow calulation.

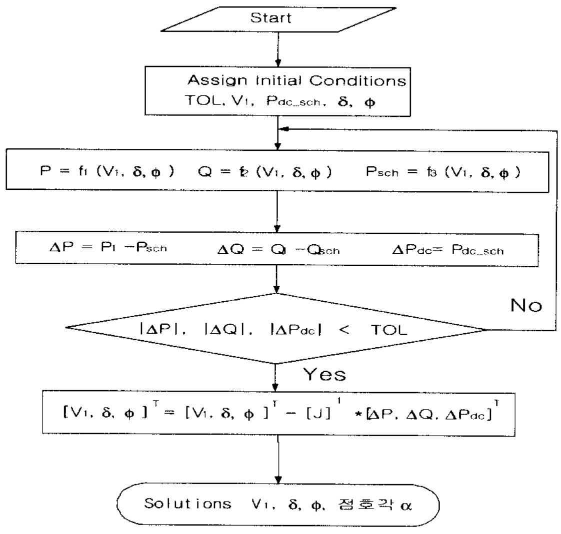

Fig. 3 Flow chart of the load flow calculation

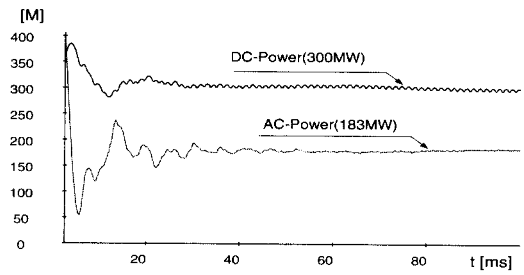

Fig. 4 The waveforms of P_{dc} and P_s

3. Problem caused by harmonics

During inverter operation, voltage and current harmonic exist both AC and DC side. If the number of pulse of converter is p, it generates pq_th and (pq±1)_th harmonics(q=1,2,3…). The amplitude of harmonic is decreased as the order of harmonic is increased. In 12 pulse HVDC system, harmonic component of AC side is n=11,13,23,25…[1]. In order to decrease harmonics, ac harmonic filter should be used. In most cases, AC filter is installed in source side of transformer.

Parameters which effects on harmonic generation are as follows: (1) Converter delay angle, (2) Converter control strategy, (3) Electrical load, (4) Capacitor bank, (5) AC/DC link stiffness.[2]

Many techniques to reject harmonics are proposed. Variation of filter configuration is one of them.

Gilsig[5] proposed a filter configuration which replaces resistor of each filter with one resistor.

Even though filter loss can be decreased, harmonic component is almost the same.

For the stable converter operation, detecting source voltage of converter is necessary. Since actual source voltage is not perfect sinusoidal, direct sensing is difficult due to the voltage drop of the reactance. Compensation is needed.

4. Selection of performance index

In order to eliminate harmonics, passive filter is widely used due to its simple structure and economical merit. Recently as high voltage power switching devices developed, use of active filter is considered. Active filter has excellent harmonic characteristic during load variation. However, implementation of the active filter in actual power system requires further research.

For the general filter design, practical criteria is to keep certain harmonic component under certain value. Harmonic current and voltage can be criteria.

Harmonic voltage is widely used in filter design since limitation on voltage harmonic is much easier than limitation on current harmonic of ac network due to impedance variation.

In filter design, current source, filter admittance and system admittance should considered in detail.

Current source is changed by load variation and firing angle variation.

To decrease voltage harmonic, total admittance of filter should be increased. Also, increase of voltage harmonic effects on the voltage sensing which is needed to determine reference point of firing angle.

It also effects on system stability. The purpose to optimize filter is to minimize voltage harmonics at AC bus.

Another aspects in determining performance index is power loss generated in filter. If Q is large, following assumption is possible.

$$V_c = V_L + V_s \tag{14}$$

where V_c, V_L, V_s are capacitor, inductor, and supply voltage respectively.

Filter size is represented as follows.

$$SIZE, S = \frac{V_s^2}{X_c - X_L} \tag{15}$$

where, X_c, X_L are the fundamental reactance of capacitor and inductor.

If filter is tuned to n_th harmonic,

$$X_0 = nX_L = X_c/n \tag{16}$$

Therefore,

$$S = (V_s^2/X_c)[n^2/(n^2-1)] \quad [MVar] \tag{17}$$

and

$$V_c = [n^2/(n^2-1)]\,V_s \quad [kV] \tag{18}$$

Power loss of capacitor is the sum of fundamental and harmonic component. Fundamental component of power loss of capacitor is written as

$$V_c^2/X_c = (V_s^2/X_c)[n^2/(n^2-1)]^2 \tag{19}$$

Harmonic component of power loss of capacitor is written as

$$I_n^2(X_c/n) = [(I_n^2 V_s^2)/(Sn)][n^2/(n^2-1)] \tag{20}$$

And the total power loss of the filter is written as

$$K_{CL}[S + (I_n^2 V_s^2)/(Sn)][n^2/(n^2-1)] \quad [MVar] \tag{21}$$

where K_{CL} is capacitor loss factor (kW/MVAr).

Fundamental component of inductor loss is written as

$$V_L^2/X_L = (V_c/n^2)^2(n^2/X_c) = V_c^2/n^2X_C \quad [MVar] \tag{22}$$

Reactance at resonant frequency is the same as that of capacitor.

The above procedure is the conventional filter design procedure. Recently many performance criteria is used in various application. Saied et. al[3] used current THD(Total Harmonic Distortion) after calculation of each harmonic current on each harmonic impedance. Ashton et. al[4] proposed the concept of active power line conditioner and use RMS error between reference voltage and actual voltage. Grady et. al[6] proposed four performance indices as follows: (1) Total Harmonic Distortion (THD), (2) Telephone Influence Factor (TIF) (3) Motor Load Loss Function (MLL), (4) Single-Bus Sine Wave Correction. At certain bus k, the indices are represented as following equations.

$$THD_k = \frac{\sqrt{\sum_{h=2}^{H} |V_k^h|^2}}{|V_k^1|} \tag{23}$$

$$TIF_k = \frac{\sqrt{\sum_{h=1}^{H} (|V_k^h| W_h)^2}}{|V_k(rms)|} \tag{24}$$

$$(MLL_k)^2 = \frac{1}{|V_k^1|} \sum_{h=2}^{H} \frac{|V_k^h|^2}{h} \tag{25}$$

$$f(I_m) = \sum_{h=2}^{H} |V_m^h|^2 \tag{26}$$

In this paper, voltage harmonic and power loss are selected as performance index and optimization procedure is performed.

5. System modelling for the calculation of performance index

5.1 Equivalent circuit

With the result of load flow calculation, voltage at load bus and infinite bus can be calculated. Voltage at load bus is fed back to controller and it is used as reference voltage. Therefore harmonics contained in sensed voltage greatly affects on the stability of inverter. So, it is necessary to calculate total harmonics contained in sensed voltage compared with infinite bus.

In most of HVDC inverter, harmonic elimination is carried out by the passive filter. Voltage harmonics are influenced by filter characteristics. However, to calculate the voltage harmonics with EMTP simulation is not easy, since it is mainly used to analyze transient characteristic.

In most of optimal design procedure, performance criteria should be defined first. To get this performance criteria, analytic method is preferred. However, since circuit equation is varied depending on the ON-OFF state of each thyristor switch, to establish an analytic model for HVDC inverter is almost impossible. Therefore, in most cases simulation is used.

In this paper, per phase equivalent circuit is proposed, which can be used in performance calculation such as voltage harmonics. Per phase equivalent circuit is shown in Fig. 5 Characteristics of proposed equivalent circuit is as follows.

1) Thyristor converter is represented as a current source and depending on the gate pulse it supplies $+I_{dc}$, $-I_{dc}$ or 0, Gate pulse is determined by the delay angle and commutation overlap angle is neglected.

- Upper thyristor ON : $+I_{dc}$
- Lower thyristor ON : $-I_{dc}$
- Both thyristor OFF : 0

2) AC system is considered as voltage source and load is represented as series RL circuit.

3) Tuned filter is used. In case of 12 pulse converter, it represents 11th and 13th harmonic filter.

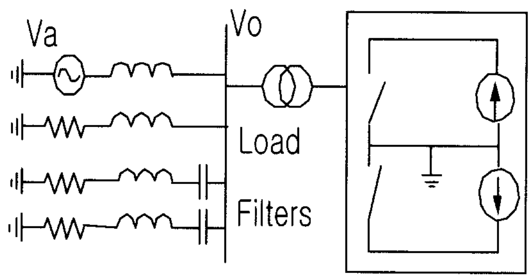

Fig. 5 Per Phase equivalent circuit

5.2 System simulation

Voltage and current waveform of system shown in Fig. 1 is simulated with the proposed per-phase equivalent circuit. System parameter used in this simulation is shown in Table 3.

Table 3 System parameters

V_s	141 KV
I_{dc}	1667A
load	R=100Ω, L=88.0 mH
11-th filter	R=1.0Ω, L=50mH, C= 1.163 uF
13-th filter	R=1.0Ω. L=53.5mH, C=0.778uF
delay angle	117.5°

In simulation, ACSL (Advanced Continuos Simulation Language) is used. In Fig. 6, infinite bus voltage and load voltage are shown. Phase shift between two voltages agrees with the load flow calculation which is about 4°.

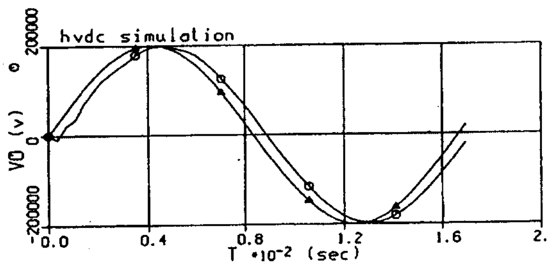

Fig. 6 Infinite bus voltage and load voltage

6. Filter parameter optimization

Voltage harmonics and filter power loss are selected as performance index. Once performance index is selected, optimization procedure shown in Fig. 7 can be used.

If the filter parameter is changed, voltage harmonics are also changed. Calculation of voltage harmonics can be easily done with the proposed equivalent circuit. It also has an effect on the performance of controller.

Voltage difference between detected voltage and infinite bus voltage is

$$e = V_o - V_s \tag{27}$$

Voltage harmonics can be defined as follows.

$$\varepsilon = E(e^2) = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\alpha+2\pi} e^2 d(wt)} \tag{28}$$

Eq. (28) is used as a performance criteria for the optimization. Search direction for the optimization is defined as follows.

$$\nabla = (\varepsilon_{k+1} - \varepsilon_k)/(L_{k+1} - L_k) \tag{29}$$

In Fig. 8, variation of voltage harmonics as a function of filter capacitor is shown. It is found that voltage hormonic is decreased as filter capacitance is increased with the same resonant frequency.

Fig. 9 shows the variation of filter power loss as a function of filter capacitor. In this figure, filter power loss is defined in eq. (21) and (22)

Power loss is calculated simultaneously during simulation and search direction is depending on the variation of power loss. It is also found that power loss is decreased as filter capacitance is increased with the same resonant frequency.

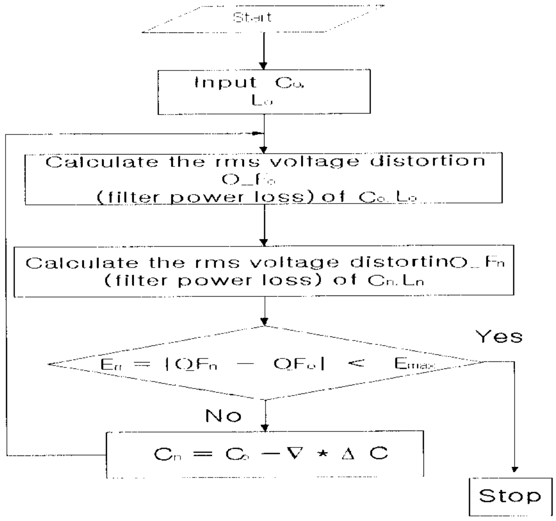

Fig. 7 Flow chart for filter optimization

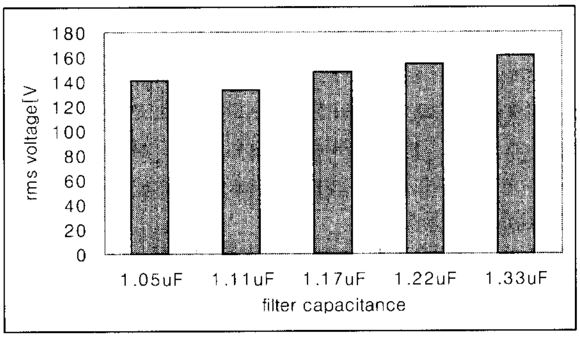

Fig. 8 Variation of voltage harmonics

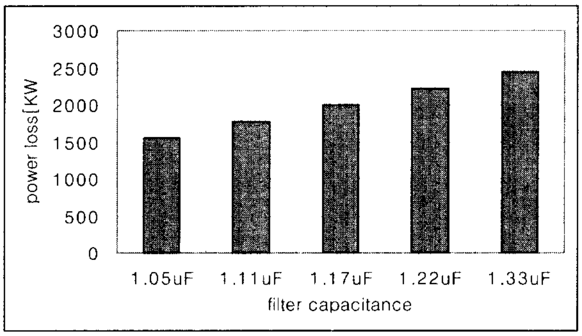

Fig. 9 Variation of power loss

7. Conclusion

For the stable HVDC inverter operation, harmonic component of load voltage should be minimized.

Passive filter is mainly used to reduce the voltage harmonic. In order to determine filter parameter, conventional method is used to get harmonics component and optimal value which minimizes voltage harmonic. On the other hand, power loss of filter should be considered for the economical reason.

For the optimal filter design, voltage harmonic and power filter power loss are selected as a performance index. However, to calculate analytically the performance index is almost impossible due to switching nature of inverter.

In this paper, a per-phase-equivalent circuit is used to analyze the characteristics of HVDC system. Also EMTP is used to get dynamic characteristics and AC/HVDC load flow is proposed to get the nominal values.

In the performance simulation with the per-phase equivalent circuit, ACSL program is used. The procedure to optimize the harmonic filter is also performed with ACSL.

Performance index such as the voltage harmonics and the power loss can be calculated as parameter changes and optimization procedure can be applied with per-phase-equivalent circuit. Optimal filter parameters are obtained.

Application of the proposed method to multi bus system is needed for the further research.

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