

工學碩士 學位論文

2

*A Study on the Inverter for Photovoltaic Power System Using
a Two-phase Boost Converter*

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A Study on the Inverter for Photovoltaic Power System Using a Two-phase Boost Converter

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Abstract

Photovoltaic(PV) power system converts infinite solar energy directly into electrical energy. PV system has been considered to be the most reliable renewable energy source, because it supplies green energy without emitting greenhouse gases like CO₂. However, the high initial installation cost prevented its usage from terrestrial applications except an installation for special purpose such as pilot plant and local power plant.

It is important to reduce the harmonic component of inverter output with solar-cell in an utility-connected inverter system. In order to reduce the output harmonics, various methods such as using a output L-C filter, and a PWM switching pattern, etc., are currently being investigated.

This paper proposes a new PWM(Pulse Width Modulation) method which is derived by shifting its phase at a conventional

SPWM(Sinusoidal Pulse Width Modulation) on-off time. The PWM on-off time was calculated from simultaneous equation induced fourier series.

To verify a validity of the proposed algorithm, computer simulation and experimental test has been implemented. The experimental result showed that the ratio of each harmonics to the fundamental component are decreased by the proposed PWM, and the 3rd harmonic is decreased from 30.15[%] to 10.5[%]. Also it is confirmed that the output current waveform comes to be nearly a sinusoidal waveform.

1.

가

[1] [3]

가

[4],[5]

DC

AC

DC

AC

가 가 10
 15[%] 가 가 가
 가 [6],[7]
 , 3가
 ,
 , 가
 , 가 가
 , 가
 [8] [10]
 , DC DC-link
 2 ,
 SPWM PWM
 . 2
 . 3
 ,
 .
 PWM . 4
 PSpice
 ,

2.

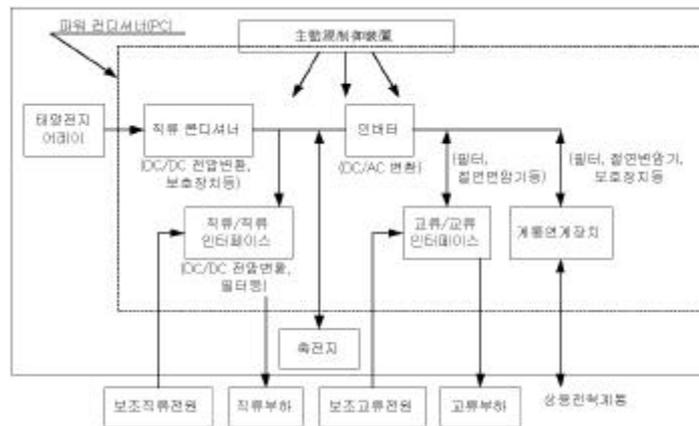
2.1

(主監視制御装置)

가 가

PWM

가 [10], [11]



2.1

2.1

가 ,
[kW]
[MW] 가 .
가
()
가 ()
가 PWM ,

() ,
3가 .

2.1.1 PWM

PWM(pulse width modulation)

PWM .
PWM ,
가 .
가 ,
가 .
가 .
가 가 .
PWM 가 가 .

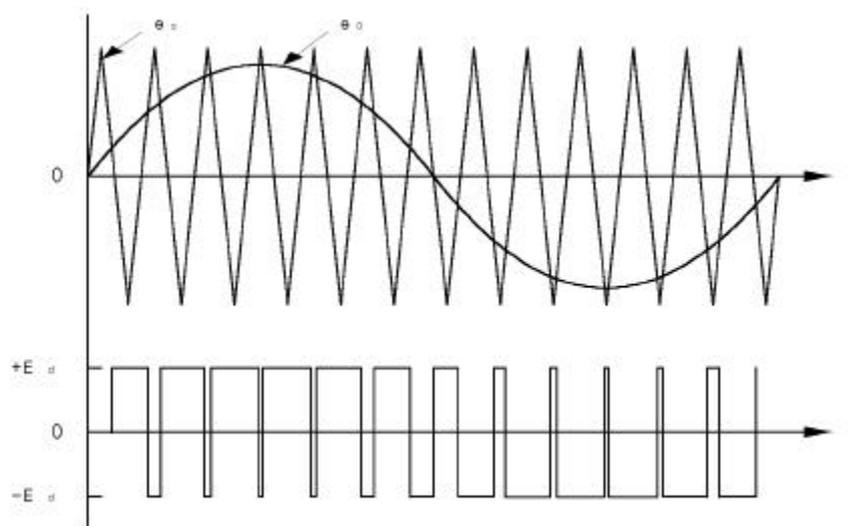
2.2 e_s 가 , e_0 가

PWM

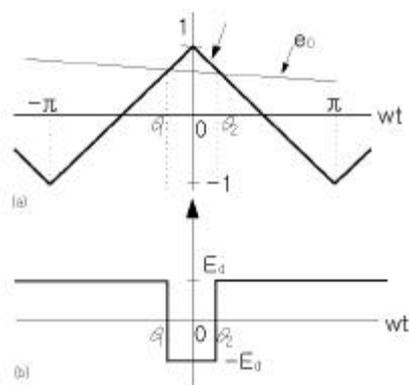
$e_0 \geq e_s$ S_3 S_6 on +

E_d e_0 e_s S_4 S_5 가 on

- E_d .



2.2 PWM



2.3 PWM

2.3 , PWM

2.3(a) e_s e_0

2.3(b) PWM v_o

$$e_0 \geq e_s, \quad \omega_s t \leq \theta_1 \quad \omega_s t \geq \theta_2$$

$$v_o = E_d$$

$$e_0 < e_s, \quad \theta_1 < \omega_s t < \theta_2$$

$$v_o = -E_d$$

가 , p , (2.6)

[12],[13]

$$V_o = \left[\frac{2p}{2\pi} \int_{(\pi/p - \delta)/2}^{(\pi/p + \delta)/2} V_s^2 d(\omega t) \right]^{1/2} \quad (2.6)$$

δ_m m

$$V_o = V_s \left(\sum_{m=1}^p \frac{\delta_m}{\pi} \right)^{1/2} \quad (2.7)$$

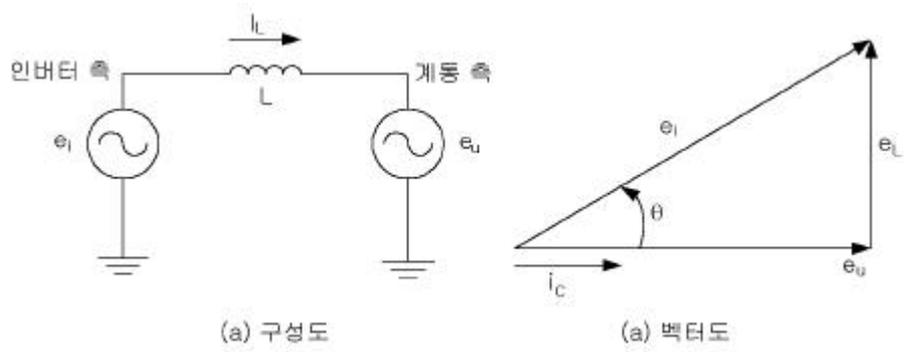
Fourier

$$v_o(t) = \sum_{n=1,3,5,\dots}^{\infty} B_n \sin n\omega t \quad (2.8)$$

B_n

$$B_n = \sum_{m=1}^p \frac{2V_s}{n\pi} \sin \frac{n\delta_m}{2} \left[\sin n \left(\alpha_m + \frac{\delta_m}{2} \right) - \sin n \left(\pi + \alpha_m + \frac{\delta_m}{2} \right) \right] \quad (2.9)$$

2.1.2



(a) 구성도

(a) 벡터도

2.4

2.4

e_i , e_u , e_L

가

2.4(b)

L

PWM

i_c

e_c

e_L

i_C

90°

2.1.3

3가

가

(60[Hz])

가

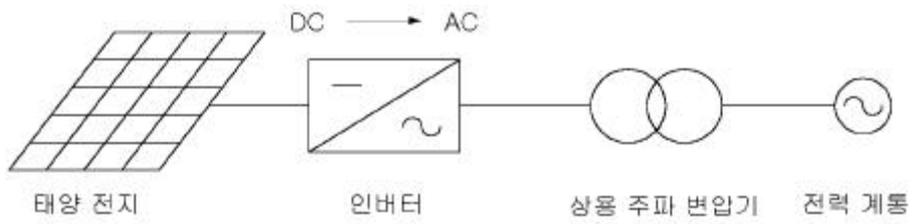
가

DC-DC

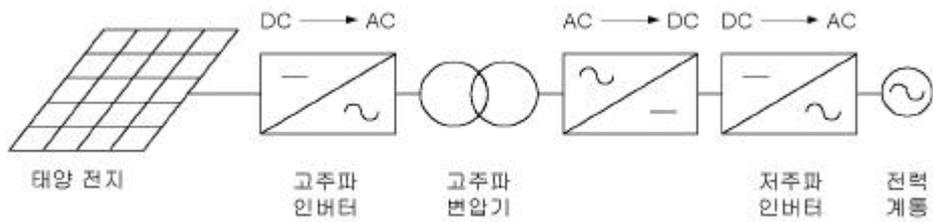
가

가 가

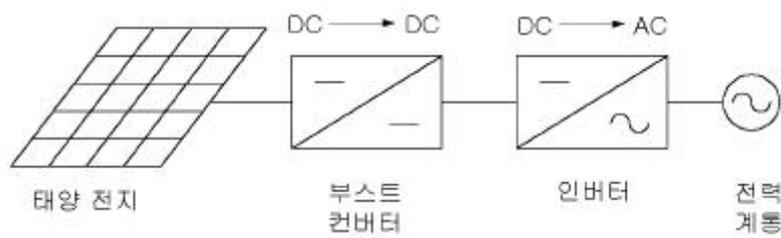
2.5



(a)



(b)



(c)

2.5

3.

3.1

가

2

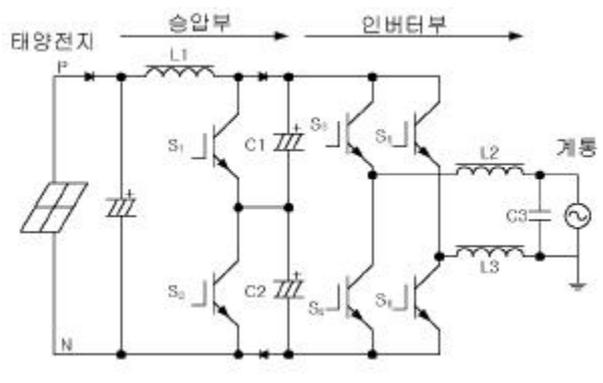
2 (Two-phase)

2

(S_1, S_2)가 180°

2

(L_2, L_3)



3.1

3.1

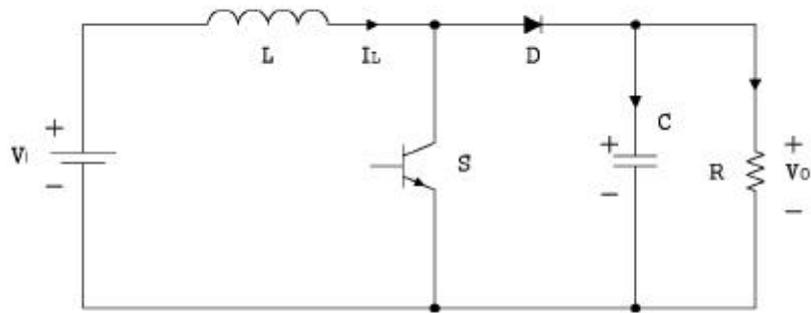
3.1.1

DC-DC

Buck , Boost , Buck-Boost

Boost

Boost 1 Boost 3.2
S가 L 가 , S가 L
가 Boost PWM 가 가



3.2

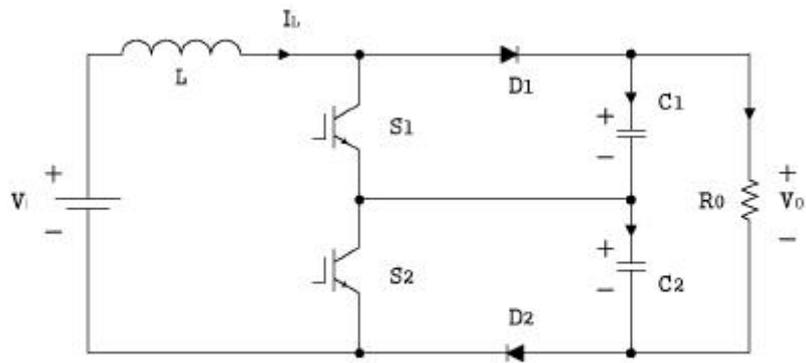
DC-DC

(L)가

2

3.3

(L), S_1 (IGBT 1) S_2 (IGBT 2), D_1 D_2 ,
 C_1 C_2
 180° on-off
 1



3.3 2 DC-DC

(L)

$C_1 \quad C_2$

1/2

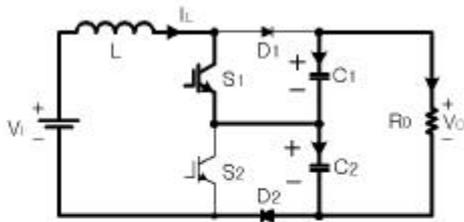
2

$S_1 \quad S_2 \quad \text{on-off}$

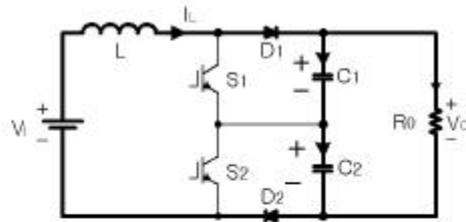
4가

3가

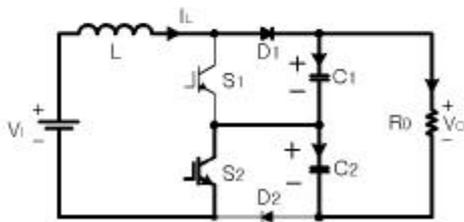
3.4



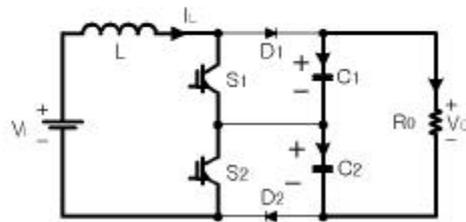
(a) 모드 1



(b) 모드 2



(c) 모드 3



(d) 모드 4

3.4 2

1

(a)

$S_1 \quad \text{on}, \quad S_2 \quad \text{off}$

(L)

$d < 0.5$

, $d > 0.5$

2 (b) S_1 S_2 가
 off L 가
 L
 3 (c) S_1 S_2 가 on
 1 , 1
 4 (d) S_1 S_2 가 on
 L
 L

$$(d = \frac{T_{on}}{T})$$

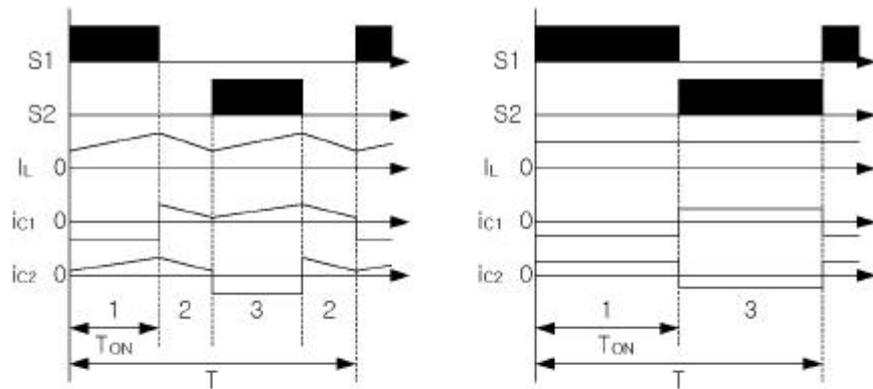
3.1 3가

3.2 2

(, ,)

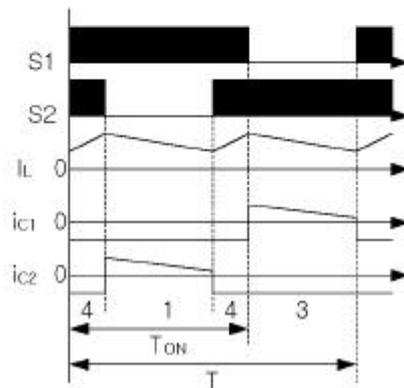
	1 2 3 2
	1 3
	4 1 4 3

가 $1/2$ ($1 < V_o / V_I < 2$)
 S_1 on (T_{on}) L 가



(a) 동작모드 사이클 I

(a) 동작모드 사이클 II

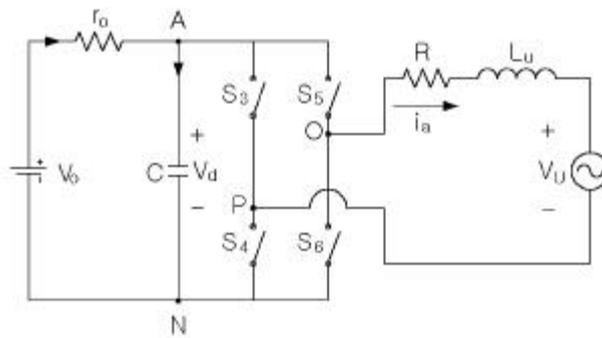


(a) 동작모드 사이클 III

3.1.2

PWM 가 () () on-off ,
 . 4
 (IGBT) PWM
 가 , L_u
 가

3.6



3.6

3.1.3

on
DC-DC
가

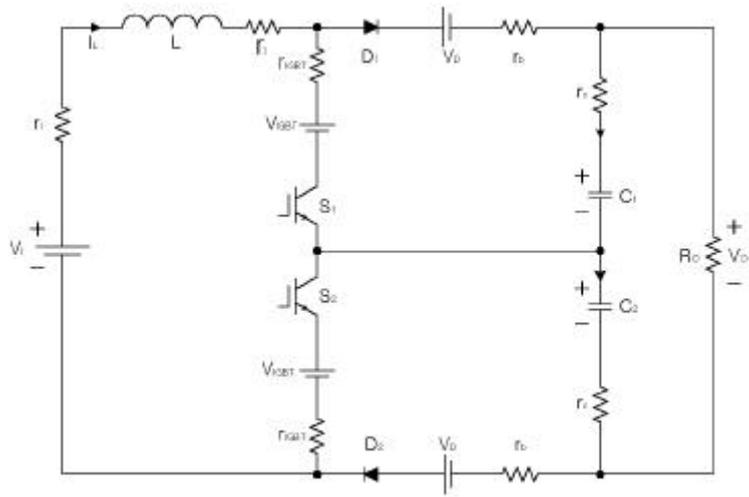
on
가

ESR(Equivalent Series Resistance)
가

2
2
2

DC가

3.7
가



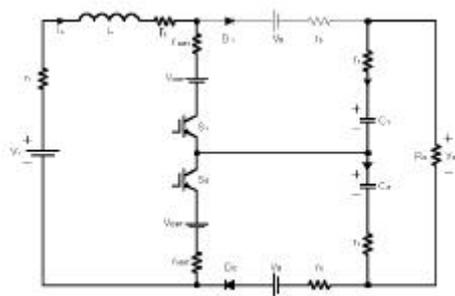
3.7

2

1)

)

1



3.8

1

1

$$\begin{aligned}
& - V_i + r_i i_L + L \frac{di_L}{dt} + r_L i_L + r_{IGBT} i_L + V_{IGBT} + V_T + R_T i_L + r_D i_L + V_D \\
& = 0
\end{aligned} \tag{3.1}$$

(3.1)

$$\begin{aligned}
\frac{di_L}{dt} = & - \left(r_{P1} + \frac{(R_o + r_c)r_c}{R_o + 2r_c} \right) \frac{1}{L} i_L + \frac{r_c}{R_o + 2r_c} \frac{1}{L} v_{C1} \\
& - \frac{R_o + r_c}{R_o + 2r_c} \frac{1}{L} v_{C2} + V_i \frac{1}{L} - V_{IGBT} \frac{1}{L} - V_D \frac{1}{L}
\end{aligned} \tag{3.2}$$

$$r_{P1} = r_i + r_L + r_{IGBT} + r_D$$

(3.3)

$$V_{C2} + r_c i_{C2} = - v_{C1} + i_{C1}(R_o + r_c) \tag{3.3}$$

$$i_L = i_{C1} + i_{C2}, \tag{3.3}$$

$$V_{C2} + r_c(i_L - i_{C1}) = - v_{C1} + i_{C1}(R_o + r_c) \tag{3.4}$$

$$(3.4) \tag{3.5}$$

$$i_{C1} = \frac{r_c}{R_o + 2r_c} i_L + \frac{1}{R_o + 2r_c} v_{C1} + \frac{1}{R_o + 2r_c} v_{C2} \tag{3.5}$$

$$i_{C1} = -C \frac{dv_{C1}}{dt} \quad , \quad (3.5) \quad (3.6)$$

$$\frac{dv_{C1}}{dt} = - \frac{r_c}{C(R_o + 2r_c)} i_L + \frac{1}{C(R_o + 2r_c)} v_{C1} + \frac{1}{C(R_o + 2r_c)} v_{C2} \quad (3.6)$$

v_{C2}

$$\frac{dv_{C2}}{dt} = \frac{(R_o + r_c)}{C(R_o + 2r_c)} i_L + \frac{-1}{C(R_o + 2r_c)} v_{C1} + \frac{-1}{C(R_o + 2r_c)} v_{C2} \quad (3.7)$$

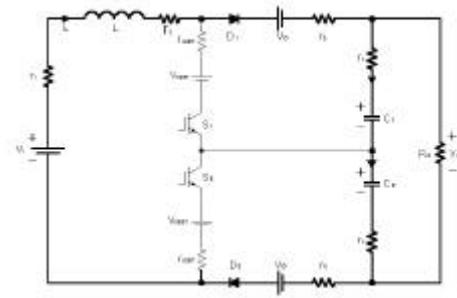
$$(3.2), (3.6), (3.7) \quad , \quad (3.8)$$

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = A_1 x + B_1 v_i + B_1 (-V_{IGBT} - V_D) \quad (3.8)$$

$$A_1 = \begin{bmatrix} - \left(r_{p1} + \frac{(R_0 + r_c)r_c}{R_0 + 2r_c} \right) \frac{1}{L} & \frac{r_c}{(R_0 + 2r_c)L} & \frac{-(R_0 - r_c)}{(R_0 + 2r_c)L} \\ \frac{-r_c}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} \\ \frac{R_0 + r_c}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix}, \quad x = \begin{bmatrix} i_L \\ v_{C1} \\ v_{C2} \end{bmatrix}, \quad r_{p1} = r_l + r_i + r_{IGBT} + r_D \quad .$$

) 2



3.9 2

1 2

(3.9) .

$$- V_i + r_i i_L + L \frac{di_L}{dt} + r_l i_L + v_D + r_D i_L + \frac{R_o(v_{C1} + v_{C2})}{R_o + 2r_c} + \frac{2R_o r_c}{R_o + 2r_c} i_L + v_D i_L + v_D = 0 \quad (3.9)$$

(3.9)

(3.10)

$$\begin{aligned} \frac{di_L}{dt} = & - \left(r_{P2} + \frac{2R_o r_c}{R_o + 2r_c} \right) \frac{1}{L} i_L - \frac{R_o}{(R_o + 2r_c)L} v_{C1} - \frac{R_o}{(R_o + 2r_c)L} v_{C2} \\ & + \frac{1}{L} (v_i - 2v_D) \end{aligned} \quad (3.10)$$

(3.11)

$$2r_c i_1 + v_{C1} + v_{C2} = R_o i_2 \quad (3.11)$$

$$i_L = i_1 + i_2 \quad (3.11) \quad (3.12)$$

$$\begin{aligned} \frac{dv_{C1}}{dt} &= \frac{dv_{C2}}{dt} \\ &= \frac{R_o}{(R_o + 2r_c)C} i_L - \frac{1}{(R_o - 2r_c)C} v_{C1} - \frac{1}{(R_o + 2r_c)C} v_{C2} \end{aligned} \quad (3.12)$$

(3.10)

(3.12)

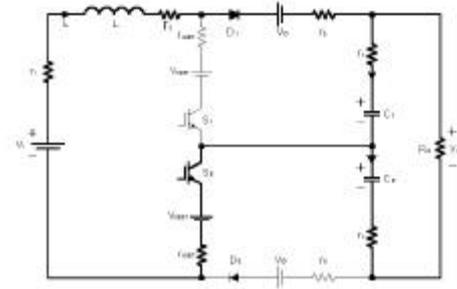
(3.13)

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = A_2 x + B_2 v_i + B_2 (-2V_D) \quad (3.13)$$

$$A_2 = \begin{bmatrix} \left(-r_{p2} + \frac{2R_0 r_c}{R_0 + 2r_c}\right) \frac{1}{L} & \frac{-R_0}{(R_0 + 2r_c)L} & \frac{-R_0}{(R_0 + 2r_c)L} \\ \frac{R_0}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} \\ \frac{R_0}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} \end{bmatrix}$$

$$B_2 = \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix}, \quad x = \begin{bmatrix} i_L \\ v_{C1} \\ v_{C2} \end{bmatrix}, \quad r_{p2} = r_l + r_i + 2r_D$$

) 3



3.10 3

$$\begin{aligned} & -V_i + r_i i_L + L \frac{di_L}{dt} + r_L i_L + v_D + r_D i_L + R_L i_L + v_T + v_{IGBT} + r_{IGBT} i_L \\ & = 0 \end{aligned} \quad (3.14)$$

$$R_T = \frac{r_c(R_0 + r_c)}{R_0 + 2r_c}, \quad v_T = \frac{(R_0 + r_c)v_{C1} - r_c v_{C2}}{R_0 + 2r_c} .$$

$$\begin{aligned} \frac{di_L}{dt} = & -\frac{1}{L} \left(r_{P3} + \frac{r_C(R_o + r_C)}{R_o + 2r_C} \right) i_L - \frac{R_o + r_C}{L(R_o + 2r_C)} v_{C1} + \frac{r_C}{L(R_o + 2r_C)} v_{C2} \\ & + \frac{1}{L} (v_i - v_D - v_{IGBT}) \end{aligned} \quad (3.15)$$

$$v_{C1} + r_C i_1 = (R_o + r_C) i_2 - v_{C2} \quad (3.16)$$

$$i_L = i_1 + i_2 \quad (3.17)$$

$$v_{C1} + r_C i_1 = (R_o + r_C)(i_L - i_1) - v_{C2} = (R_o + r_C) i_L - (R_o + r_C) i_1 - v_{C2} \quad (3.17)$$

$$i_1 = \frac{(R_o + r_C)}{R_o + 2r_C} i_L + \frac{-1}{R_o + 2r_C} v_{C1} + \frac{-1}{R_o + 2r_C} v_{C2} \quad (3.18)$$

$$i_1 = C \frac{dv_{C1}}{dt} \quad i_1$$

$$\frac{dv_{C1}}{dt} = \frac{R_o + r_C}{C(R_o + 2r_C)} i_L + \frac{-1}{C(R_o + 2r_C)} v_{C1} + \frac{-1}{C(R_o + 2r_C)} v_{C2} \quad (3.19)$$

$$V_{C2} \quad ,$$

$$\frac{dv_{C2}}{dt} = - \frac{r_c}{C(R_o + 2r_c)} i_L + \frac{-1}{C(R_o + 2r_c)} v_{C1} + \frac{-1}{C(R_o + 2r_c)} v_{C2} \quad (3.20)$$

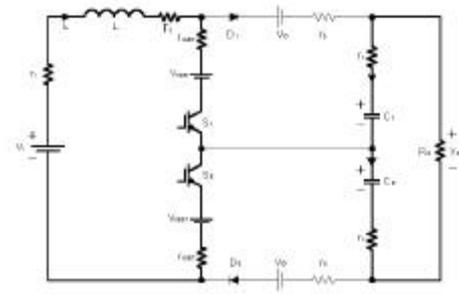
$$, \quad (3.15), (3.19), (3.20)$$

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = A_3 x + B_3 v_i + B_3 (-V_{IGBT} - V_D) \quad (3.21)$$

$$A_3 = \begin{bmatrix} - \left(r_{P3} + \frac{(R_o + r_c)r_c}{R_o + 2r_c} \right) \frac{1}{L} & \frac{(-R_o + r_c)}{(R_o + 2r_c)L} & \frac{r_c}{(R_o + 2r_c)L} \\ \frac{R_o + r_c}{(R_o + 2r_c)C} & \frac{-1}{(R_o + 2r_c)C} & \frac{-1}{(R_o + 2r_c)C} \\ \frac{-r_c}{(R_o + 2r_c)C} & \frac{-1}{(R_o + 2r_c)C} & \frac{-1}{(R_o + 2r_c)C} \end{bmatrix}$$

$$B_3 = \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix}, \quad x = \begin{bmatrix} i_L \\ v_{C1} \\ v_{C2} \end{bmatrix}, \quad r_{P3} = r_l + r_i + r_{IGBT} + r_D \quad .$$

) 4



3.11

4

4

(3.22)

$$-v_{i+} r_i i_L + L \frac{di_L}{dt} + r_i i_L r_{IGBT} i_L + V_{IGBT} + V_{IGBT} + r_{IGBT} i_L = 0 \quad (3.22)$$

$$\frac{di_L}{dt} = -\frac{r_{P4}}{L} i_L + \frac{1}{L} (V_i - 2V_{IGBT}) \quad (3.23)$$

$$r_c i + r_c i + v_{C1} + v_{C2} + R_o i = 0 \quad (3.24)$$

$$, i = -\frac{v_{C1} + v_{C2}}{R_o + 2r_c}$$

$$i = C \frac{dv_{C1}}{dt} = C \frac{dv_{C2}}{dt}$$

$$\frac{dv_{C1}}{dt} = \frac{dv_{C2}}{dt} = \frac{-1}{C(R_0 + 2r_C)} v_{C1} + \frac{-1}{C(R_0 + 2r_C)} v_{C2} \quad (3.25)$$

. (3.23), (3.25)

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = A_4 x + B_4 v_i + B_4 (-2 V_{IGBT}) \quad (3.26)$$

$$A_4 = \begin{bmatrix} -\frac{r_{P4}}{L} & 0 & 0 \\ 0 & \frac{-1}{(R_0 + 2r_C)C} & \frac{-1}{(R_0 + 2r_C)C} \\ 0 & \frac{-1}{(R_0 + 2r_C)C} & \frac{-1}{(R_0 + 2r_C)C} \end{bmatrix}$$

$$B_4 = \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix}, \quad x = \begin{bmatrix} i_L \\ v_{C1} \\ v_{C2} \end{bmatrix}, \quad r_{P4} = r_l + r_i + 2r_{IGBT}$$

2)

)

A, B

$$A_{av.} = A_1 d + A_2 (1/2 - d) + A_3 d + A_2 (1/2 - d) \quad (3.27)$$

$$B_{av.} = B_1 d + B_2 (1/2 - d) + B_3 d + B_2 (1/2 - d) \quad (3.28)$$

$$A_{av.} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (3.29)$$

(3.29)

$$A_{11} = - \frac{1}{L} \left\{ r_i + \frac{2R_o r_c (1-d) + 2r_c^2 d}{R_o + 2r_c} \right\} \quad (3.30)$$

$$r_i = r_i + r_i + 2r_{IGBT} d + 2r_D (1-d)$$

$$A_{12} = - \frac{R_o (1-d)}{(R_o + 2r_c)L}, A_{13} = - \frac{R_o (1-d)}{(R_o + 2r_c)L}, A_{21} = \frac{R_o (1-d)}{(R_o + 2r_c)C}$$

$$A_{22} = \frac{-1}{(R_o + 2r_c)C}, A_{23} = \frac{-1}{(R_o + 2r_c)C}, A_{31} = \frac{R_o (1-d)}{(R_o + 2r_c)C}$$

$$A_{32} = \frac{-1}{(R_o + 2r_c)C}, A_{33} = \frac{-1}{(R_o + 2r_c)C}$$

(3.31), (3.32)

$$A_{av.} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (3.31)$$

$$A_{11} = -\frac{1}{L} \left\{ r_i + \frac{2R_o r_c (1-d) + 2r_c^2 d}{R_o + 2r_c} \right\}$$

$$A_{12} = -\frac{R_o(1-d)}{(R_o + 2r_c)L}, \quad A_{13} = -\frac{R_o(1-d)}{(R_o + 2r_c)L}$$

$$A_{21} = \frac{R_o(1-d)}{(R_o + 2r_c)C}, \quad A_{22} = \frac{-1}{(R_o + 2r_c)C}, \quad A_{23} = \frac{-1}{(R_o + 2r_c)C}$$

$$A_{31} = \frac{R_o(1-d)}{(R_o + 2r_c)C}, \quad A_{32} = \frac{-1}{(R_o + 2r_c)C}, \quad A_{33} = \frac{-1}{(R_o + 2r_c)C}$$

$$r_i = r_l + r_i + 2r_{IGBT}d + 2r_D(1-d) \quad .$$

$$\begin{aligned} B_{av.} &= \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} d + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} \left(\frac{1}{2} - d\right) + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} d + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} \left(\frac{1}{2} - d\right) \\ &= \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} \end{aligned} \quad (3.32)$$

)

A,B

$$A_{av.} = A_1 d + A_3 d \quad (3.33)$$

$$B_{av.} = B_1 d + B_2 d \quad (3.34)$$

$$A_{av.} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (3.35)$$

$$A_{11} = - \left(r_t + \frac{2(R_o + r_c)r_c}{R_o + 2r_c} \right) \frac{1}{L} d, \quad A_{12} = A_{13} = \frac{-R_o}{(R_o + 2r_c)L} d \quad (3.36)$$

$$r_i = 2r_l + 2r_i + 3r_{IGBT} + r_D$$

$$A_{21} = A_{31} = \frac{R_o}{(R_o + 2r_c)C}, \quad A_{22} = A_{23} = A_{32} = A_{33} = \frac{-2d}{(R_o + 2r_c)C}$$

$$(3.37), (3.38)$$

$$A_{av.} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix}$$

$$= \begin{bmatrix} - \left(r_t + \frac{2(R_o + r_c)r_c}{R_o + 2r_c} \right) \frac{1}{L} d & \frac{-R_o}{(R_o + 2r_c)L} d & \frac{-R_o}{(R_o + 2r_c)L} d \\ \frac{R_o}{(R_o + 2r_c)C} & \frac{-2d}{(R_o + 2r_c)C} & \frac{-2d}{(R_o + 2r_c)C} \\ \frac{R_o}{(R_o + 2r_c)C} & \frac{-2d}{(R_o + 2r_c)C} & \frac{-2d}{(R_o + 2r_c)C} \end{bmatrix} \quad (3.37)$$

$$B_{av.} = \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} d + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} d = \begin{bmatrix} \frac{2}{L} \\ 0 \\ 0 \end{bmatrix} \quad (3.38)$$

$$r_i = 2r_l + 2r_i + 3r_{IGBT} + r_D \quad .$$

)

A,B

$$A_{av.} = A_4(d - 1/2) + A_1(1 - d) + A_4(d - 1/2) + A_3(1 - d) \quad (3.39)$$

$$B_{av.} = B_4(d - 1/2) + B_1(1 - d) + B_4(d - 1/2) + B_3(1 - d) \quad (3.40)$$

.

$$A_{av.} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (3.41)$$

$$A_{11} = -\frac{1}{L} \left\{ r_i + \frac{2R_o r_c (1 - d)}{R_o + 2r_c} + \frac{2r_c^2 (1 - d)}{R_o + 2r_c} \right\} \quad (3.42),$$

$$r_i = r_l + r_i + 2r_{IGBT}d + 2r_D(1 - d) \quad .$$

$$A_{12} = A_{13} = -\frac{R_o(1 - d)}{(R_o + 2r_c)L}, \quad A_{21} = A_{31} = \frac{R_o(1 - d)}{(R_o + 2r_c)C}$$

$$A_{22} = A_{23} = A_{32} = A_{33} = \frac{-1}{(R_o + 2r_c)C}$$

(3.43), (3.44)

$$A_{av} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (3.43)$$

$$A_{11} = -\frac{1}{L} \left\{ r_t + \frac{2R_o r_c (1-d) + 2r_c^2 - 2r_c^2 d}{R_o + 2r_c} \right\}$$

$$A_{12} = -\frac{R_o(1-d)}{(R_o + 2r_c)L}, \quad A_{13} = -\frac{R_o(1-d)}{(R_o + 2r_c)L}$$

$$A_{21} = \frac{R_o(1-d)}{(R_o + 2r_c)C}, \quad A_{22} = \frac{-1}{(R_o + 2r_c)C}, \quad A_{23} = \frac{-1}{(R_o + 2r_c)C}$$

$$A_{31} = \frac{R_o(1-d)}{(R_o + 2r_c)C}, \quad A_{32} = \frac{-1}{(R_o + 2r_c)C}, \quad A_{33} = \frac{-1}{(R_o + 2r_c)C}$$

$$r_t = r_l + r_i + 2r_{IGBT}d + 2r_D(1-d)$$

$$\begin{aligned} B_{av} &= \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} \left(d - \frac{1}{2}\right) + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} (1-d) + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} \left(d - \frac{1}{2}\right) + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} (1-d) \\ &= \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} \end{aligned} \quad (3.44)$$

$$A, B, r_c, 2, \quad (3.31)$$

$$(3.43), \quad (3.32), \quad (3.44)$$

A_{av}, B_{av} .

$$A_{av} = \begin{bmatrix} - \left(r_l + \frac{2R_0 r_c (1-d)}{R_0 + 2r_c} \right) \frac{1}{L} & \frac{-R_0(1-d)}{(R_0 + 2r_c)L} & \frac{-R_0(1-d)}{(R_0 + 2r_c)L} \\ \frac{R_0(1-d)}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} \\ \frac{R_0(1-d)}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} & \frac{-1}{(R_0 + 2r_c)C} \end{bmatrix} \quad (3.45)$$

$$B_{av} = \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} \quad (3.46)$$

$$r_i = r_l + r_i + 2r_{IGBT}d + 2r_D(1-d) \quad .$$

$$A_{av}, B_{av} \quad \begin{matrix} 2 & 3 \\ 1 \end{matrix} \quad ,$$

$$\begin{aligned} \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_{C1}}{dt} \end{bmatrix} &= \begin{bmatrix} - \left(r_l + \frac{2R_0 r_c (1-d)}{R_0 + 2r_c} \right) \frac{1}{L} & \frac{-2R_0(1-d)}{(R_0 + 2r_c)C} \\ \frac{R_0(1-d)}{(R_0 + 2r_c)C} & \frac{-2}{(R_0 + 2r_c)C} \end{bmatrix} \begin{bmatrix} i_L \\ v_{C1} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_i \\ &- \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} (2d V_{IGBT} + 2(1-d) V_D) \\ &= A x + B v_i - B (2d V_{IGBT} + 2(1-d) V_D) \end{aligned} \quad (3.47)$$

$$y = [0 \quad 2] \begin{bmatrix} i_L \\ v_{C1} \end{bmatrix} = C x \quad (3.48)$$

$$d = D + \hat{d}, \quad i_L = I_L + \hat{i}_L, \quad v_{C1} = V_{C1} + \hat{v}_{C1}, \quad v_i = V_i + \hat{v}_i \quad (3.49)$$

(3.47), (3.48)

$$\begin{aligned} \left[\begin{array}{c} \frac{d(I_L + \hat{i}_L)}{dt} \\ \frac{d(V_{C1} + \hat{v}_{C1})}{dt} \end{array} \right] &= \left[\begin{array}{c} \frac{dI_L}{dt} \\ \frac{dV_{C1}}{dt} \end{array} \right] + \left[\begin{array}{c} \frac{d\hat{i}_L}{dt} \\ \frac{d\hat{v}_{C1}}{dt} \end{array} \right] \\ &= \left[\begin{array}{cc} - \left(r_T + \frac{2R_o r_C (1-D)}{R_o + 2r_C} \right) \frac{1}{L} & \frac{-2R_o(1-D)}{(R_o + 2r_C)L} \\ \frac{R_o(1-D)}{(R_o + 2r_C)C} & \frac{-2}{(R_o + 2r_C)C} \end{array} \right] \left[\begin{array}{c} I_L \\ V_{C1} \end{array} \right] \\ &+ \left[\begin{array}{cc} - \left(2r_{IGBT} \hat{d} - 2r_D \hat{d} + \frac{-2R_o r_C \hat{d}}{R_o + 2r_C} \right) \frac{1}{L} & \frac{2R_o \hat{d}}{(R_o + 2r_C)L} \\ \frac{-R_o \hat{d}}{(R_o + 2r_C)C} & 0 \end{array} \right] \left[\begin{array}{c} I_L \\ V_{C1} \end{array} \right] \\ &+ \left[\begin{array}{c} \frac{1}{L} \\ 0 \end{array} \right] [V_i] + \left[\begin{array}{c} \frac{1}{L} \\ 0 \end{array} \right] [\hat{v}_i] \\ &- \left[\begin{array}{c} \frac{1}{L} \\ 0 \end{array} \right] [2DV_{IGBT} + 2\hat{d}V_{IGBT} + 2(1-D)V_D - 2\hat{d}V_D] \quad (3.50) \end{aligned}$$

(DC)

x가

X₀

$$\frac{dx(t)}{dt} = 0 \quad (3.51)$$

(3.50)

$$\begin{aligned} 0 &= \begin{bmatrix} - \left(r_T + \frac{2R_o r_c (1-D)}{R_o + 2r_c} \right) \frac{1}{L} & \frac{-2R_o(1-D)}{(R_o + 2r_c)L} \\ \frac{R_o(1-D)}{(R_o + 2r_c)C} & \frac{-2}{(R_o + 2r_c)C} \end{bmatrix} \begin{bmatrix} I_L \\ V_{C1} \end{bmatrix} \\ &+ \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_i - \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} (2D V_{IGBT} + 2(1-D) V_D) \\ &= A_S X_o + B_S V_i - B_S (2D V_{IGBT} + 2(1-D) V_D) \end{aligned} \quad (3.52)$$

$$r_T = r_l + r_i + 2r_{IGBT}D + 2r_D(1-D)$$

(3.50) 2

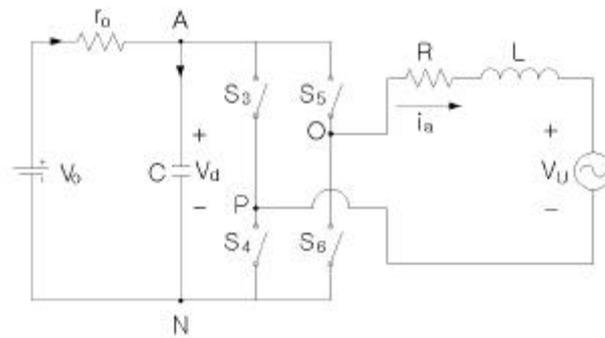
$$\begin{aligned} \begin{bmatrix} \frac{d\hat{i}_L}{dt} \\ \frac{d\hat{v}_{C1}}{dt} \end{bmatrix} &= \begin{bmatrix} - \left(r_T + \frac{2R_o r_c (1-D)}{R_o + 2r_c} \right) \frac{1}{L} & \frac{-2R_o(1-D)}{(R_o + 2r_c)L} \\ \frac{R_o(1-D)}{(R_o + 2r_c)C} & \frac{-2}{(R_o + 2r_c)C} \end{bmatrix} \begin{bmatrix} \hat{i}_L \\ \hat{v}_{C1} \end{bmatrix} \\ &+ \begin{bmatrix} \frac{1}{L} \left(-2(r_{IGBT} - r_D)I_L + \frac{2R_o(r_c I_L + V_{C1})}{(R_o + 2r_c)} - 2(V_{IGBT} - V_D) \right) \\ \frac{-R_o I_L}{(R_o + 2r_c)C} \end{bmatrix} \hat{d} \\ &+ \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \hat{v}_i \end{aligned} \quad (3.53)$$

가 ,
 (3.52) DC gain G_V .

$$\begin{aligned}
 G_V &= \frac{V_0}{V_i} = \frac{2V_{C1}}{V_i} \\
 &= \frac{1}{1-D} \frac{R_0(1-D)^2 \left(1 - \frac{2DV_{IGBT} - 2(1-D)V_D}{V_i}\right)}{r_T + \frac{2R_0r_c(1-D)}{R_0+2r_c} + \frac{R_0^2(1-D)^2}{R_0+2r_c}} \quad (3.54)
 \end{aligned}$$

가 .

L .
 DC Link DC .



3.12

가

$$V_{PO} = R i_a + L \frac{di_a}{dt} + V_u \quad (3.55)$$

$$(3.78) \quad \text{O-P}$$

$$L \frac{di_a}{dt} = (V_{NO} - V_{NP}) - R i_a - V_u \quad (3.56)$$

$$\begin{aligned} & S_3, S_4 \quad d_1, d_1' \\ & , \quad S_3 \text{가 on} \quad S_4 \text{가 off} \quad , \quad S_3 \\ & \quad d_1 = 1 \quad S_4 \quad d_1' = 0 \end{aligned}$$

$$V_{NP} = V_d \quad .$$

$$\begin{aligned} & S_3 \text{ off} \quad , \quad S_4 \text{가 on} \\ d_1 = 0 \quad d_1' = 1 \quad , \quad V_{NP} = 0 \quad \text{가} \quad . \end{aligned}$$

$$\begin{aligned} & , \quad S_5, S_6 \quad d_2, d_2' \\ & \quad , \quad S_5 \text{가 on} \quad S_6 \text{가 off} \\ , \quad S_5 \quad d_2 = 1 \quad S_6 \end{aligned}$$

3.3

$S_3 = ON, S_4 = OFF$	$d_1 = 1, d_1' = 0$	$V_{NP} = V_d$
$S_3 = OFF, S_4 = ON$	$d_1 = 0, d_1' = 1$	$V_{NP} = 0$
$S_5 = ON, S_6 = OFF$	$d_2 = 1, d_2' = 0$	$V_{NO} = V_d$
$S_5 = OFF, S_6 = ON$	$d_2 = 0, d_2' = 1$	$V_{NO} = 0$

$$d_2' = 0 \quad V_{NO} = V_d \quad .$$

S_5 off , S_6 가 on

$$d_2 = 0 \quad d_2' = 1 \quad , \quad V_{NO} = 0 \quad \text{가} \quad .$$

(3.56)

$$L \frac{di_a}{dt} = - R i_a - (d_1 - d_2) V_d - V_u \quad (3.57)$$

3.12 A

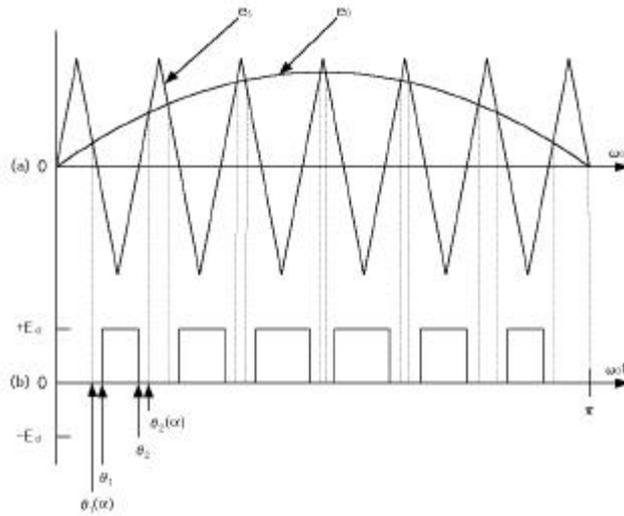
$$C \frac{dV_d}{dt} = (d_1 - d_2) i_a + \frac{V_d - U}{r_o} \quad (3.58)$$

(3.57) (3.58)

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{dV_d}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{d_1 - d_2}{L} \\ \frac{d_1 - d_2}{C} & \frac{1}{Cr_o} \end{bmatrix} \begin{bmatrix} i_a \\ V_d \end{bmatrix} + \begin{bmatrix} -1 & 0 \\ 0 & -\frac{1}{r_o} \end{bmatrix} \begin{bmatrix} V_u \\ V_d \end{bmatrix} \quad (3.59)$$

3.2

DC ,
 , V/F 가 . 가
 (PWM) .
 가 SPWM(Sinusoidal Pulse Width Modulation)
 ,
 .
 ,
 가 . PWM
 .
 3.13 PWM . e_s ,
 e_0 . SPWM (e_0)
 (e_s) , $\theta_1(\alpha)$, $\theta_2(\alpha)$, ...
 on-off ,
 3.14(b)
 θ_1 , θ_2 , ... on-off
 , $+E_d$ $-E_d$ PWM .



3.13 SPWM

3.13(b)

$$p = 2L$$

$$f(x) = a_0 + \sum_{k=1}^{\infty} \left(a_k \cos \frac{k\pi}{L} x + b_k \sin \frac{k\pi}{L} x \right) \quad (3.60)$$

$$a_0 = \frac{1}{2L} \int_{-L}^L f(x) dx \quad (3.61)$$

$$a_k = \frac{1}{L} \int_{-L}^L f(x) \cos \frac{k\pi x}{L} dx \quad (3.62)$$

($k = 1, 2, \dots$)

$$b_k = \frac{1}{L} \int_{-L}^L f(x) \sin \frac{k\pi x}{L} dx \quad (3.63)$$

($k = 1, 2, \dots$)

3.13(b) PWM 가 , (3.64) 가

$$f(\omega_0 t) = -f(-\omega_0 t)$$

$$f(\omega_0 t) = -f(\omega_0 t - \pi)$$
(3.64)

$$\omega_0 \quad . \quad (3.64) \quad a_0$$

a_k 가 ,

3.13(b) PWM 1/4

E_d , on-off
 $\theta_1, \theta_2, \dots, \theta_n$, b_k .

$$b_k = \frac{4E_d}{\pi} \left\{ \int_{\theta_1}^{\theta_2} \sin k\omega_0 t d(\omega_0 t) + \dots + \int_{\theta_{n-1}}^{\theta_n} \sin k\omega_0 t d(\omega_0 t) \right\}$$

$$= \frac{4E_d}{k\pi} (\cos k\theta_1 - \cos k\theta_2 + \cos k\theta_3 - \dots + \cos k\theta_{n-1} - \cos k\theta_n)$$

$$= \frac{4E_d}{k\pi} \sum_{j=1}^n (-1)^{j-1} \cos k\theta_j$$
(3.65)

$$k = 1, 3, 5, \dots$$

p . f_s ,

$$f_0$$

$$p = \frac{1}{2} (f_s/f_0 - 1)$$
(3.66)

, PWM

e_c

$$e_c = \sum_{k=1,3,\dots}^{\infty} b_k \sin k\omega_0 t \quad (3.67)$$

(3.65)

b_1

$$b_1 = \frac{4E_d}{\pi} (\cos \theta_1 - \cos \theta_2 + \cos \theta_3 - \dots - \cos \theta_6) \quad (3.68)$$

$\theta_1, \theta_2, \dots, \theta_6$

3

11

$b_3, b_5, \dots,$

b_{11}

0

6

,

SPWM on-off

$\theta_1(\alpha), \theta_2(\alpha), \dots, \theta_n(\alpha)$

4.

PSpice
2

PWM

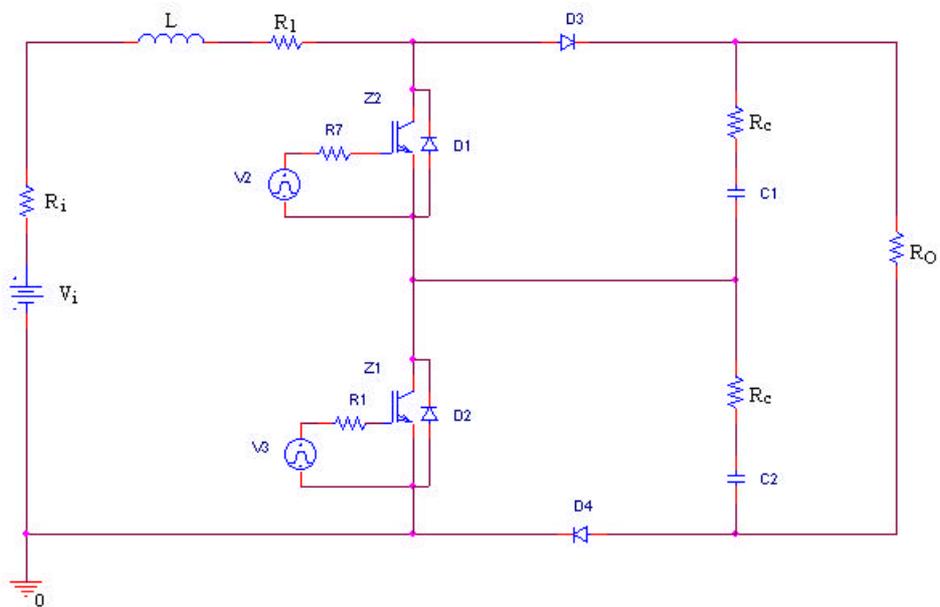
4.1

3가

4.1

50[V], 110[V], 180[V]

220[V]



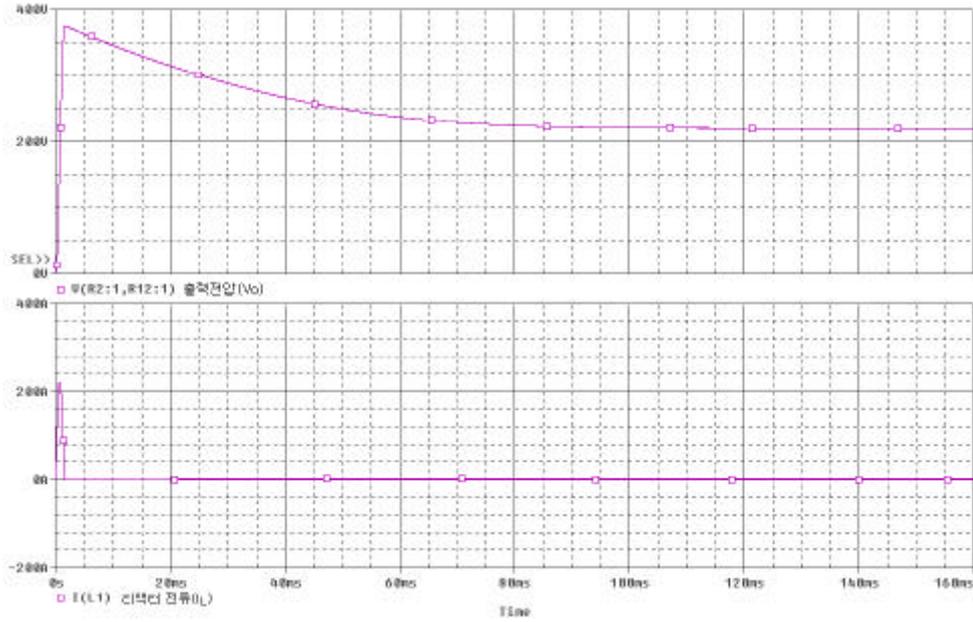
4.1 2

4.1

		160 [ms]
	[kHz]	9.9 [kHz]
	(V_o)	220 [V]
	(R_i)	0.005 [Ω]
	(L)	360 [mH]
	(R_l)	0.036 [Ω]
	(C_1, C_2)	1000 [μ F]
	(R_c)	0.002 [Ω]

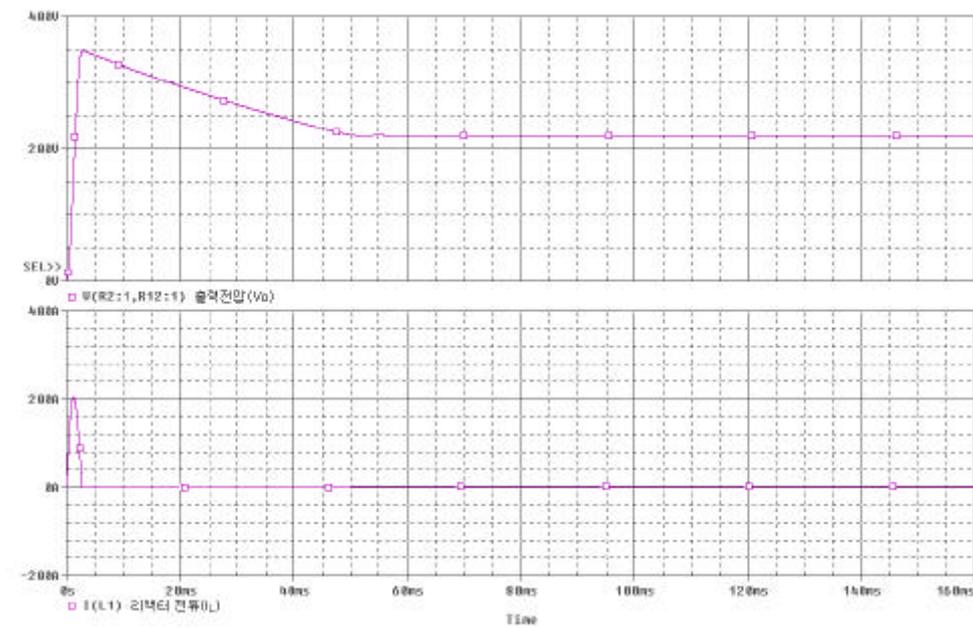
4.2 (a), (b), (c) 2

(V_o) (I_L)
 $d=0.144,$
 $d=0.52,$ 0.772 .
 $55[\text{ms}]$ 가 ,
 $120[\text{ms}]$,
 $45[\text{ms}]$ 가 .
 . 4.2



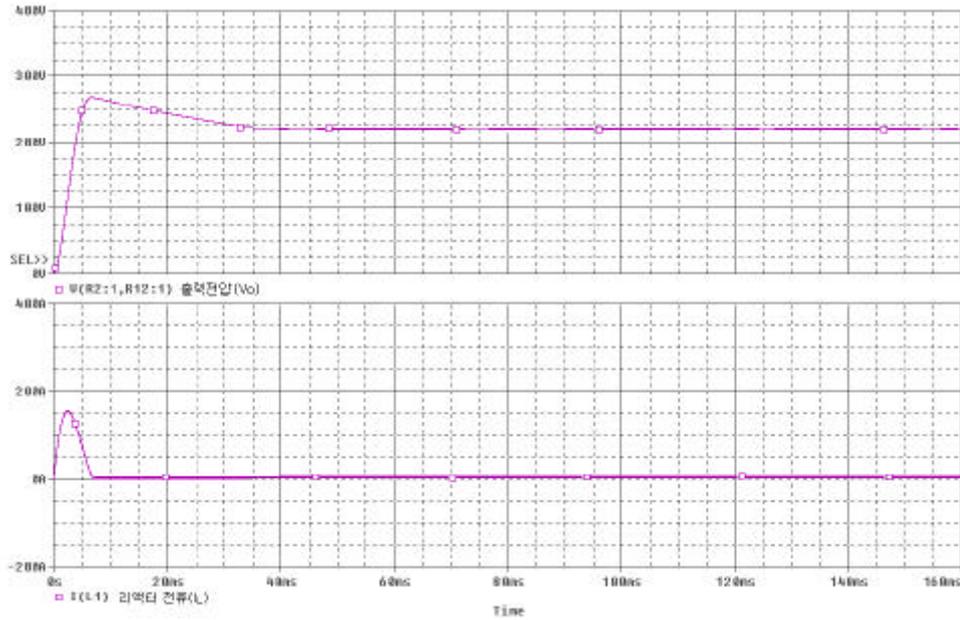
(a)

(d=0.144)



(b)

(d=0.5)



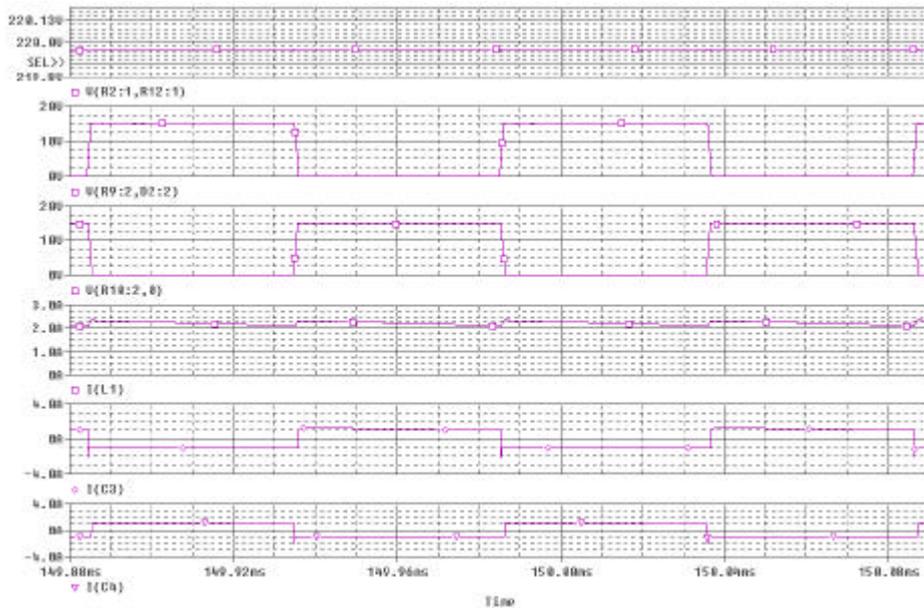
(c) $(d=0.772)$
4.2 2

4.3

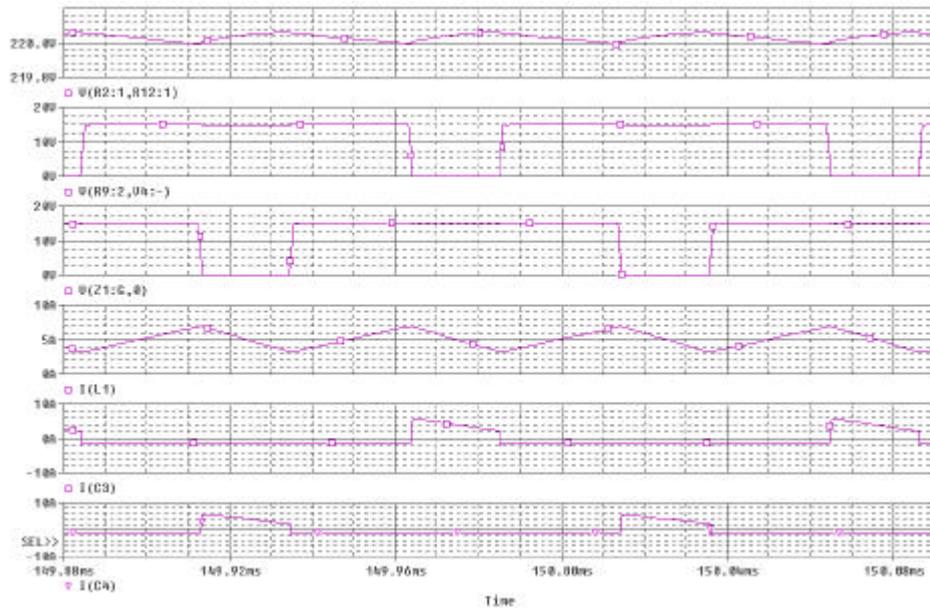
$(V_o), \quad 1 (S_1)$
 $, \quad 2(S_2), \quad , \quad (I_L),$
 $1 \quad (I_{C1}), \quad 2 \quad (I_{C2})$
 2
 $, \quad 1/2$
 $1/2$



(a)



(b)



(c)

4.3

4.4

50[V]

가

9.9[kHz],

780[Hz]

(L_u) 1[mH]

0.78

3 가

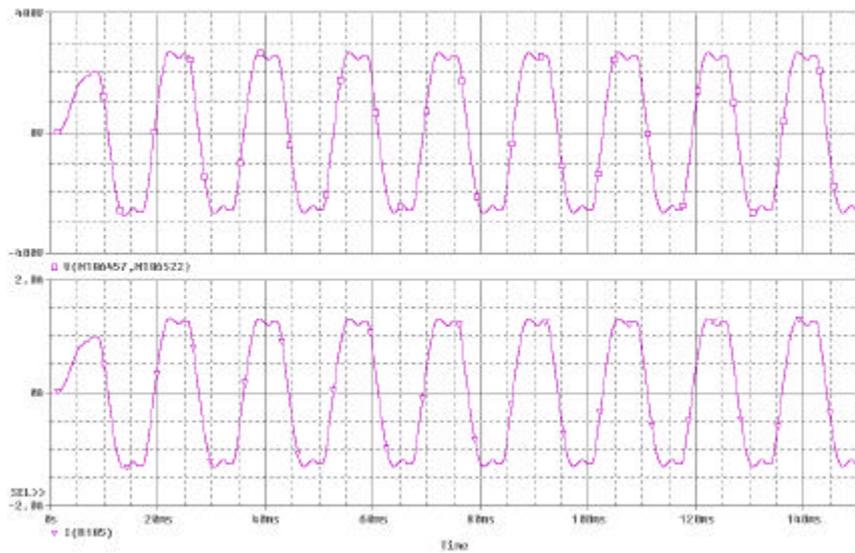
가

4.4

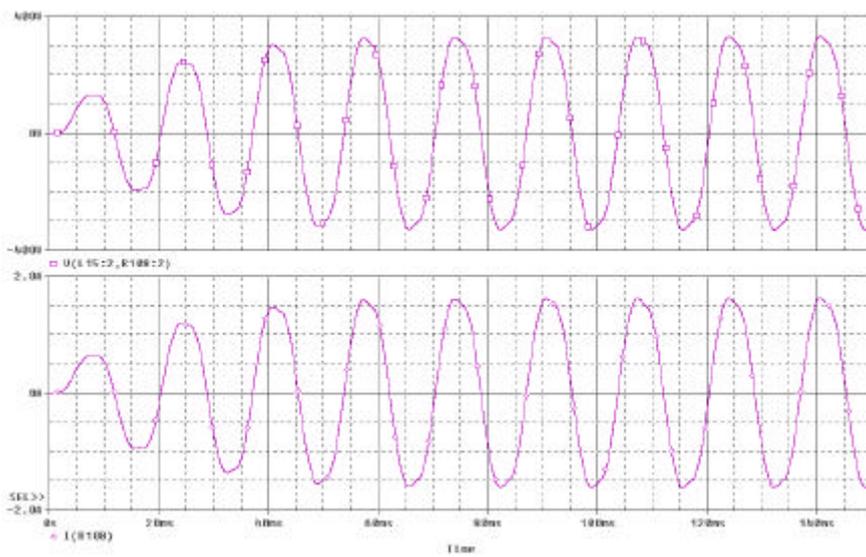
1 . 4.5

, 가

, 4.5(a)
 SPWM 3 가 16.7[%], 5 가 5[%], 7
 가 1.7[%], 9 가 1.3[%], 11 가 0.8[%] .
 4.5(b) SPWM , 3 가 5.9[%], 5 가
 1.8[%], 7 가 0.9[%], 9 가 0.4[%], 11 가
 0.1[%] .
 SPWM ,
 , 4.4(b)
 가 .



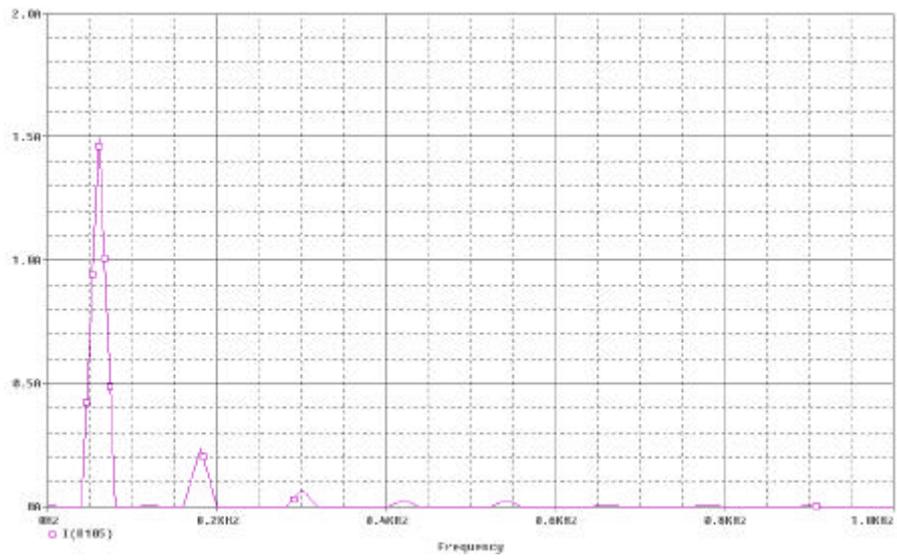
(a) SPWM



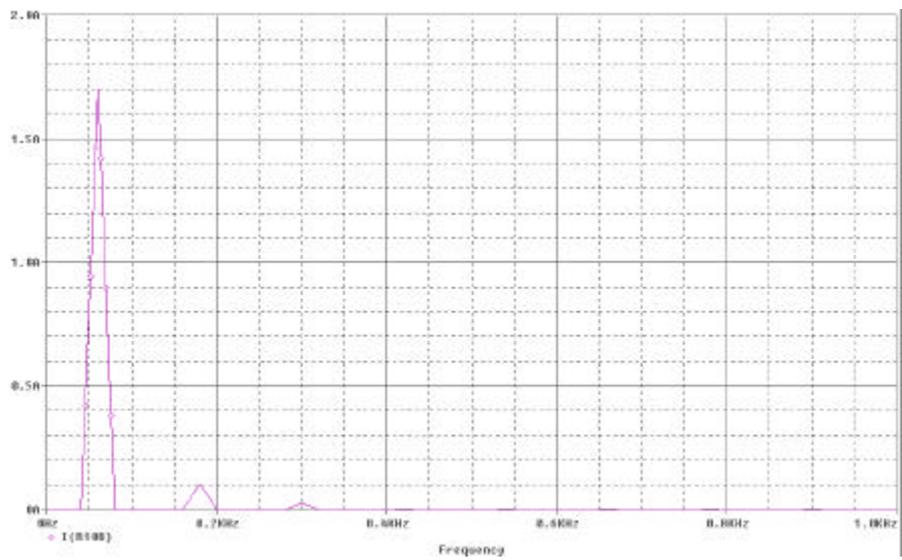
(b) SPWM

4.4

(.)



(a) SPWM



(b) SPWM

4.5 FFT

4.6

IGBT (2MBI50L-060, 50[A], 600[V])

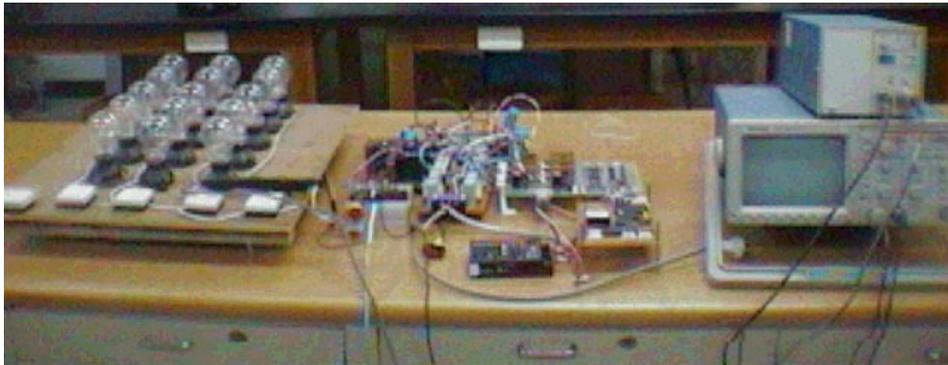
IGBT

EXB-841

8031

(360[mH])

1[mH]



4.6

50[V], 110[V], 180[V]

4.7

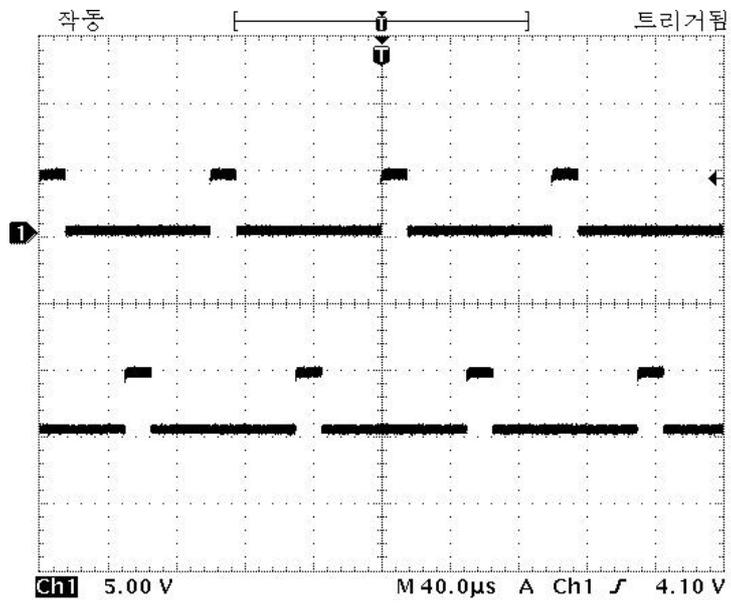
180 °

가

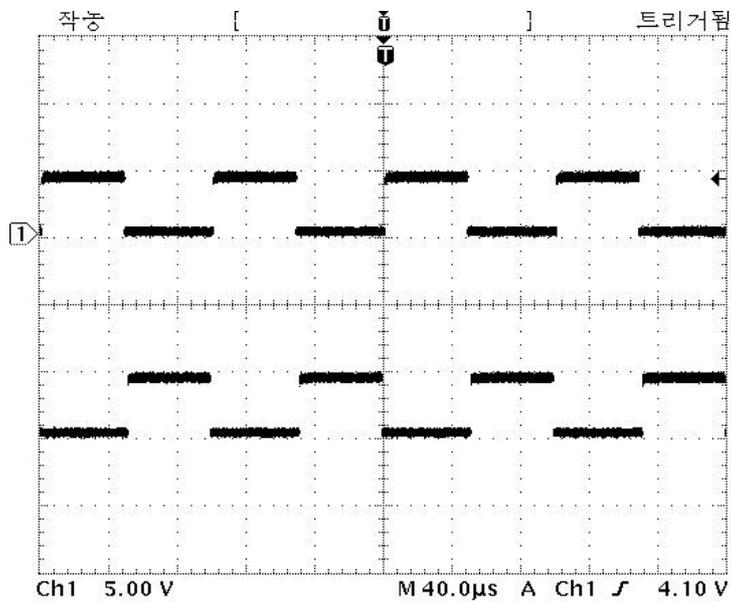
0.15,

0.5,

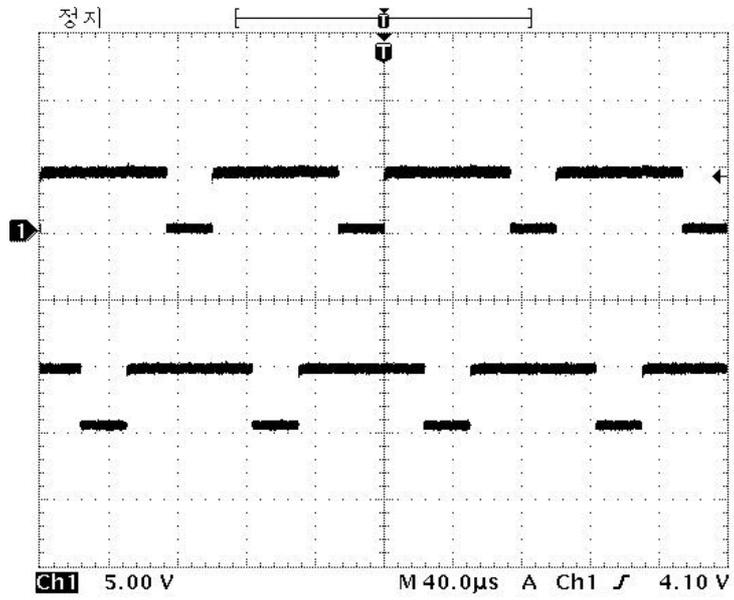
0.77



(a) ($V_i = 180[V]$)



(b) ($V_i = 110[V]$)



(c) ($V_i = 50[V]$)

4.7

4.8

100[V]/div, 가

10[ms]/div 4.9

0.5[A]/div, 가

10[ms]/div

(a)

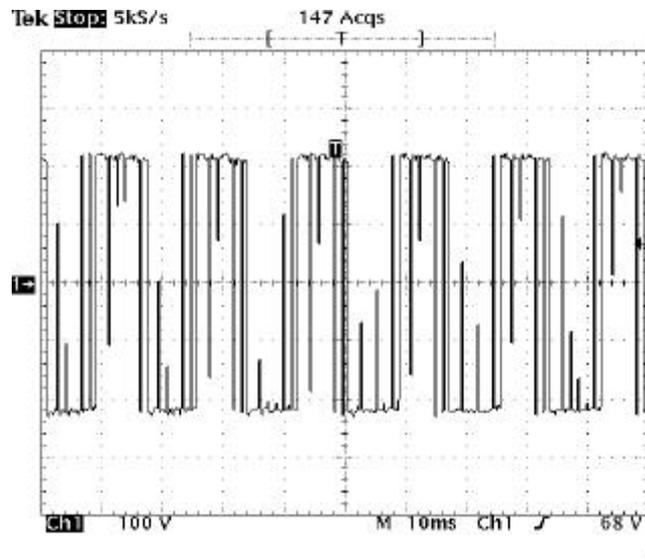
(b)

4.9(a)

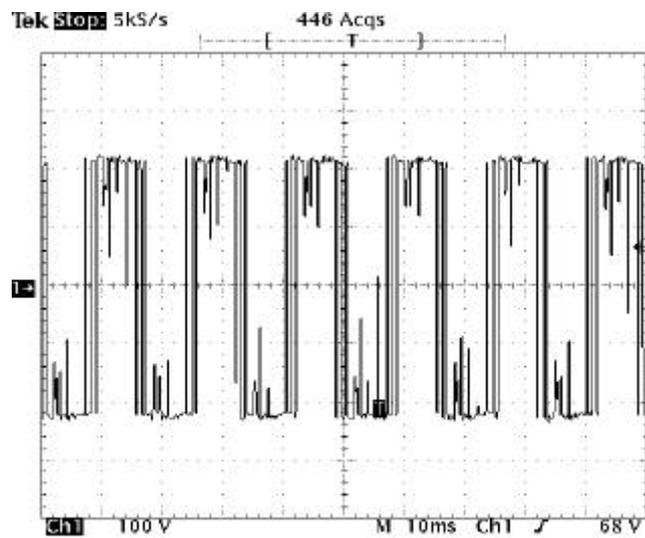
SPWM

4.9(b)

. 4.10 FFT
 . 4.10
 13 .
 3 가 30.15[%] 10.5[%] ,
 5 가 9.9[%] 5.4[%], 7 가 6.9[%] 5.1[%],
 9 가 5.4[%] 2.7[%], 11 7.8[%]
 1.5[%]
 , SPWM
 .
 가 .
 가 .
 ,
 .

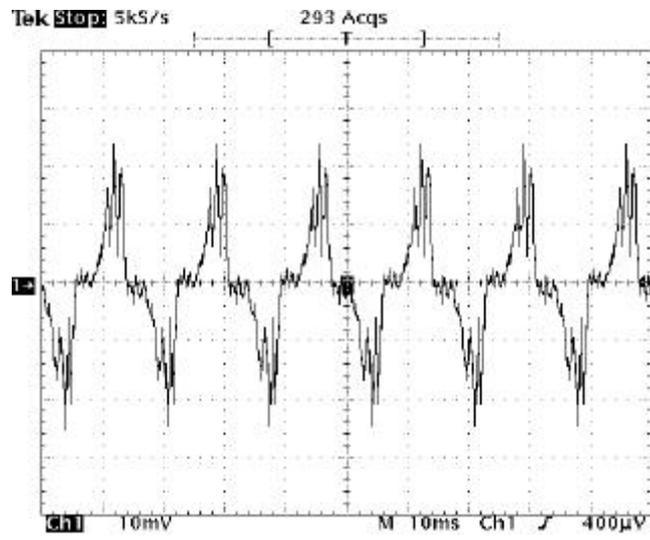


(a) SPWM

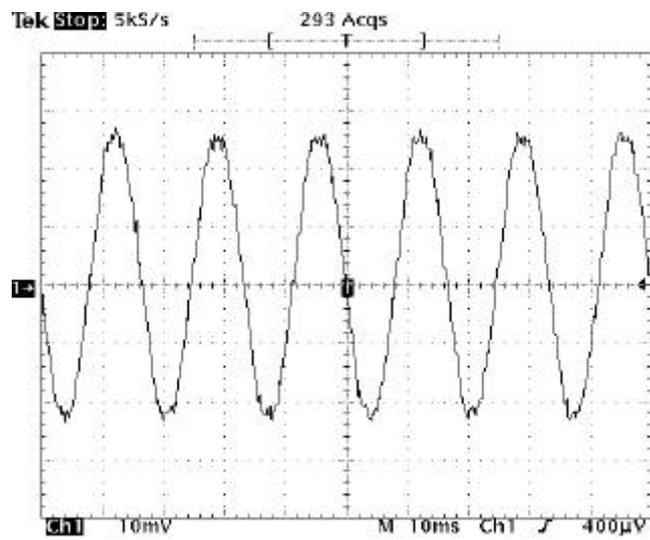


(b) SPWM

4.8

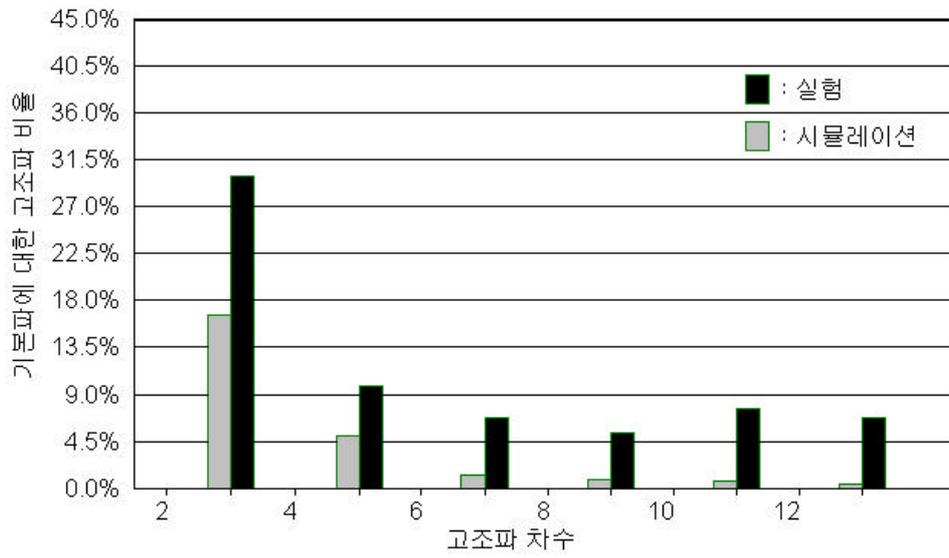


(a) SPWM

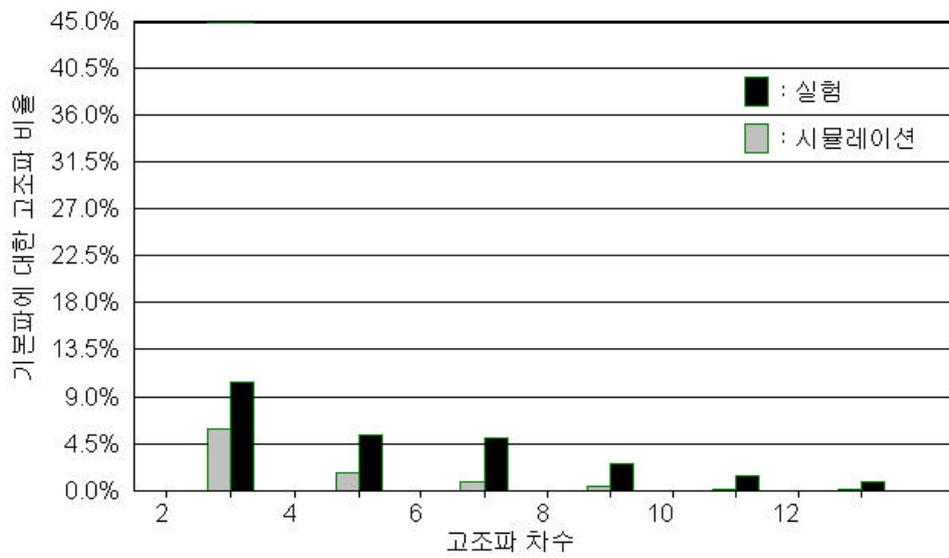


(b) SPWM

4.9



(a) SPWM



(b) SPWM

4.10 FFT

5.

가

2

2

1/2

가

가 가

1/2

가

가

가 가

SPWM

on - off

PWM

PWM

0

on - off

on - off

PWM

3 가 30.15[%]

10.5[%]

5 가 9.9[%]

5.4[%]

7 가 6.9[%]

5.1[%]

9 가 5.4[%]

2.7[%]

11

7.8[%]

1.5[%]

가

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