

본 사이트에서 수업 자료로 이용되는 저작물은 **저작권법 제25조 수업목적저작물 이용 보상금제도에** 의거, **한국복제전송저작권협회와 약정을 체결하고** 적법하게 이용하고 있습니다. 약정범위를 초과하는 사용은 저작권법에 저촉될 수 있으므로 **수업자료의 대중 공개·공유 및 수업 목적 외의 사용을 금지합니다.**

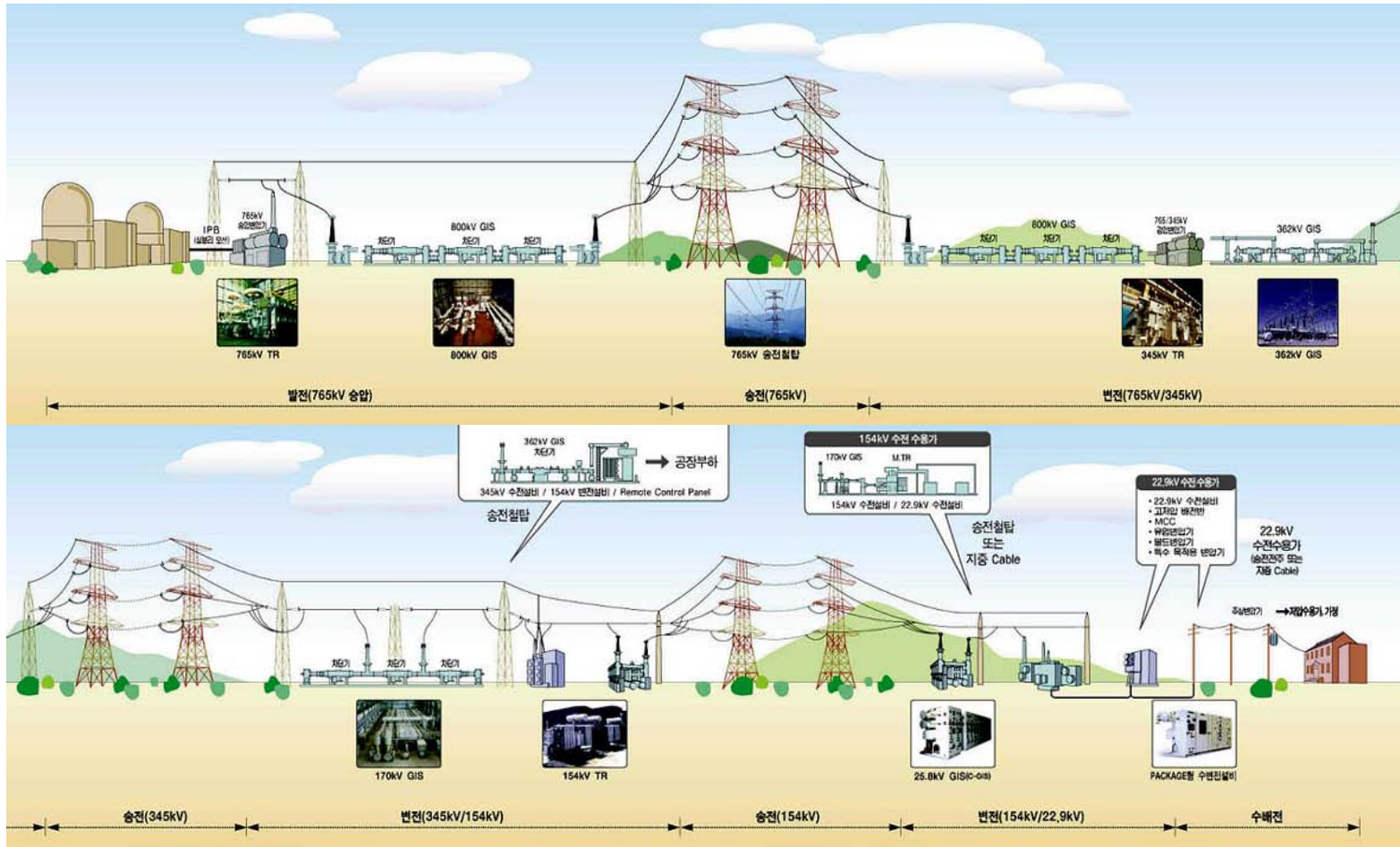
2014. 03. 24.

동아대학교·한국복제전송저작권협회

변압기

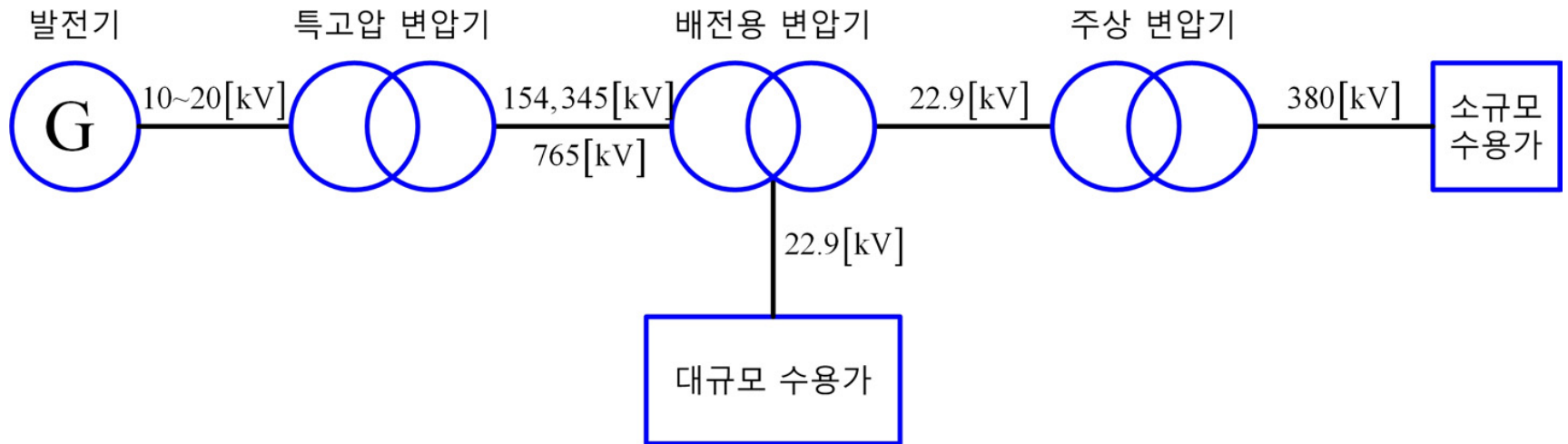
1. 개요 (introduction)
2. 이상변압기 (ideal transformer)
3. 실제변압기 (real transformer)
4. 변압기 특성 (characteristics of transformer)
5. 손실과 효율 (loss and efficiency)
6. 3상 변압기 (three phase transformer)

1. 개요



전력시스템 (power system) : 전기에너지 발전(generation), 송전(transmission), 배전 (distribution), 부하(load)

❖ 변압기(Transformers)



※ 전력전송에서 전압이 높을수록 효율적인 이유 ?

$$\begin{aligned} \text{저항손실} &= I^2 R = I^2 \left(\frac{\rho L}{A} \right) = \frac{\rho L I^2}{A} \cdot \frac{V^2}{V^2} = \frac{\rho L P^2}{A V^2} \\ &\propto \frac{1}{V^2}, \frac{1}{A} \end{aligned}$$

$$\begin{aligned} \text{전압강하} &= IR = \frac{\rho L I}{A} \cdot \frac{V}{V} = \frac{\rho L P}{A V} \\ &\propto \frac{1}{V}, \frac{1}{A} \end{aligned}$$

(1) 에너지 변환



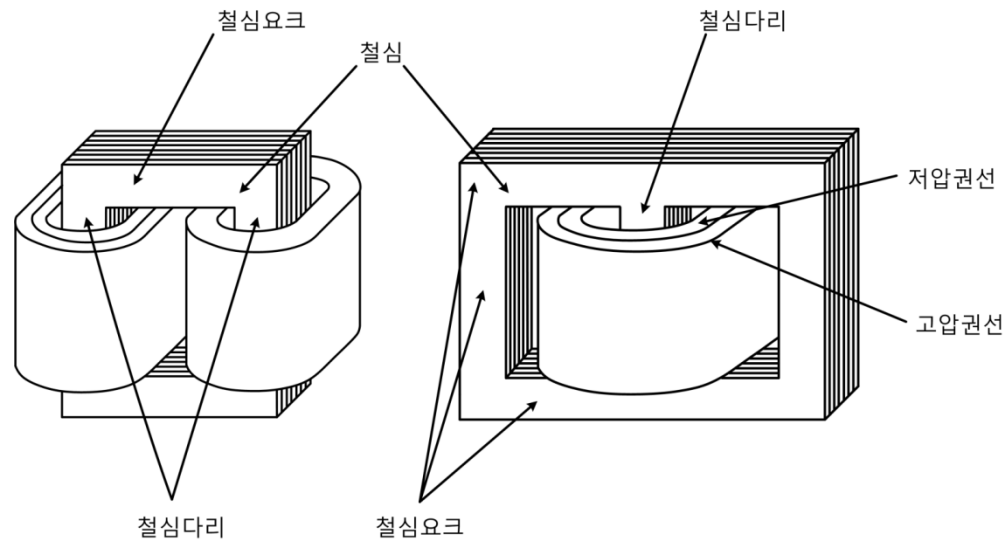
(2) 변압기 분류

용도	전압	코일	냉각방식	절연방식	주파수	코어	절연종별	
<p><계통></p> <p>전력용 배전용</p>	<p>저압 (~600V)</p> <p>고압 (6.6KV) (3.3KV)</p> <p>특고압 (22.9KV)</p> <p>초고압 (154KV) (345KV) (765KV)</p>	<p><구조></p> <p>단권선 2 권선 3 권선 다권선 Zigzag 3 상 다상 단상</p>	<p><건설식></p> <p>자냉 풍냉</p>	<p><건설식></p> <p>Dry VPI</p>	<p>상용주파 - 60 Hz - 50 Hz</p> <p>고주파</p>	<p><구조></p> <p>내철형 외철형 원형 각형 권철심 적철심</p>	<p>A 종 (105°C) E 종 (120°C) B 종 (130°C) F 종 (155°C) H 종 (180°C)</p>	
<p><설치장소></p> <p>옥내용 옥외용 주상용 Pad Mount 지중형 Class 1E 선박용 갱내용</p>			<p><유입식></p> <p>자냉 풍냉 수냉</p>	<p><Mold></p>				<p><유입식></p> <p>광유 실리콘유</p>
<p><부하></p> <p>정류기 인버터 VFD</p>			<p><Gas봉입></p> <p>SF₆ Gas</p>	<p><재질></p> <p>Silicon Steel - 일반형 - High - B - 자구미세화 규소강판 Amorphous</p>				

(3) 변압기 구조

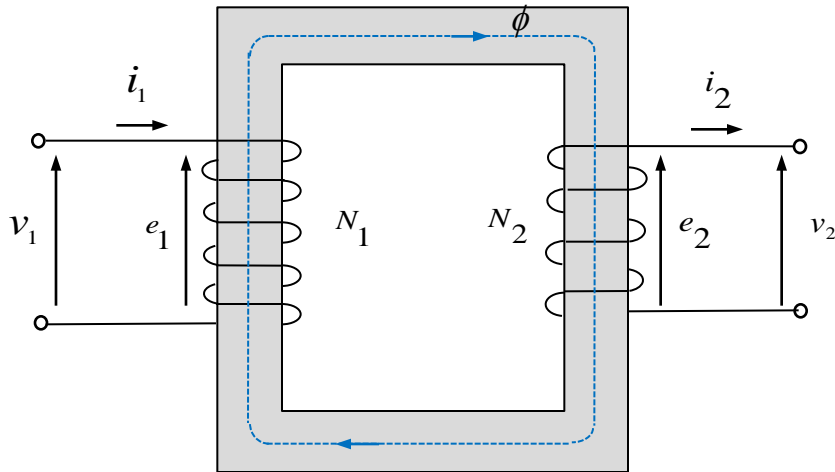
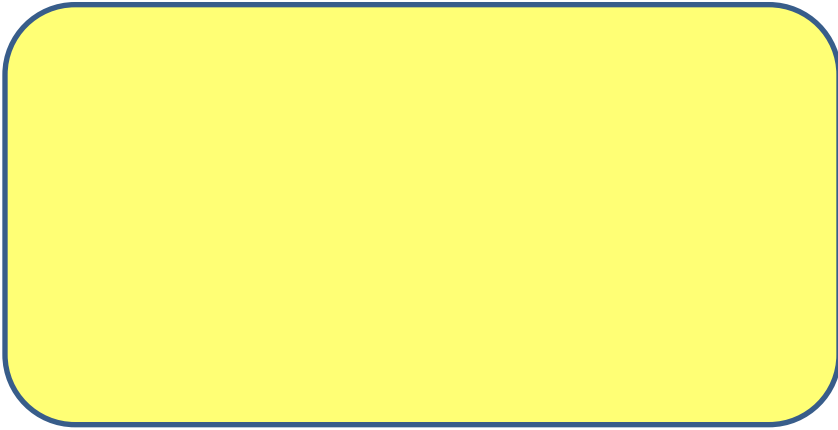
① Core type (내철형)

② Shell type (외철형)



2. 이상변압기

1) 가정



① 공급전압

$$\begin{cases} v_1 = e_1 = N_1 \frac{d\phi}{dt} \\ v_2 = e_2 = N_2 \frac{d\phi}{dt} \end{cases}$$

$$\therefore \frac{v_1}{v_2} = \frac{e_1}{e_2} = \frac{N_1}{N_2} = a : \text{턴수비 (turns ratio)}$$

② 전류

$$v_1 i_1 = v_2 i_2 \quad \text{입력전력} = \text{출력전력}$$

$$\therefore \frac{i_1}{i_2} \left(= \frac{v_2}{v_1} \right) = \frac{N_2}{N_1} = \frac{1}{a}$$

③ 임피던스

$$\frac{z_1}{z_2} = \frac{v_1}{i_1} \div \frac{v_2}{i_2} = \frac{v_1}{v_2} \times \frac{i_2}{i_1} = a^2$$

$$\therefore z_1 = a^2 z_2$$

2) 유도전압 (induced voltage)

$$e_1 = \frac{d\lambda}{dt} = N_1 \frac{d\phi}{dt} \quad (\lambda = N\phi)$$

$$= N_1 \frac{d}{dt} \phi_m \sin \omega t$$

$$= \omega N_1 \phi_m \cos \omega t$$

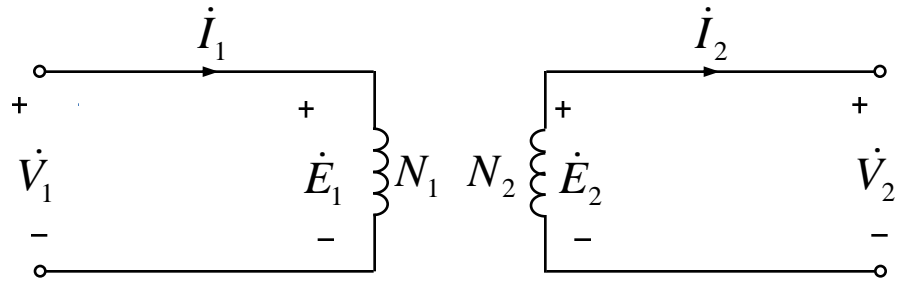
$$= 2\pi f N_1 \phi_m \cos \omega t$$

$$E_1 = \frac{2\pi}{\sqrt{2}} f N_1 \phi_m$$

$$= 4.44 f N_1 \phi_m \text{ [Vrms]}$$

$$\left[\begin{array}{c} E_1 \\ N_1 \\ \phi_m \\ f \end{array} \right]$$

3) 이상변압기의 등가회로



4) 여자전류 (exciting current)

$$v_1 = e_1 = \frac{d\lambda}{dt} = L \frac{di_0}{dt} \quad (\lambda = Li)$$

$$v_1 = \sqrt{2}V_1 \cos \omega t = L \frac{di_0}{dt} \quad (i_0 : \text{여자전류})$$

$$i_0 = \frac{\sqrt{2}V_1}{L} \int \cos \omega t dt = \frac{\sqrt{2}V_1}{\omega L} \sin \omega t$$

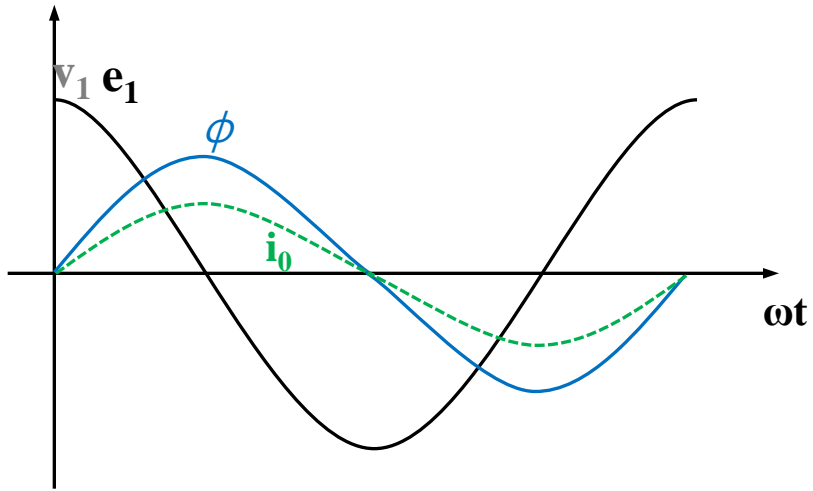
$$L = \frac{N_1^2}{\mathfrak{R}_m} = \frac{N_1^2 \mu A}{l} \quad [\text{H}] \quad \left(\begin{array}{l} A : \text{철심의 단면적} \\ l : \text{철심자로의길이} \end{array} \right)$$

$$i_0 = \frac{l\sqrt{2}V_1}{\mu AN_1^2 \omega} \cos \left(\omega t - \frac{\pi}{2} \right) = I_0 \cos \left(\omega t - \frac{\pi}{2} \right) \quad [\text{A}]$$

(I_0 : 여자전류의 최대치)

5) 페이저표시 (phasor)

① 시간축 상의 전원전압, 자속, 여자전류, 유도기전력

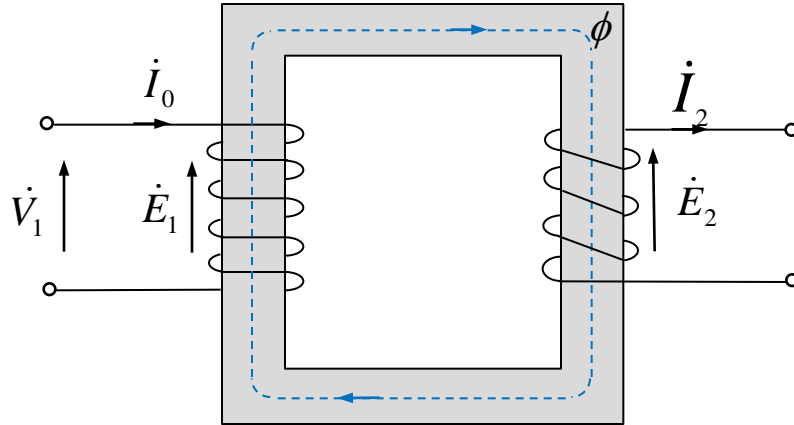


$$v_1 = \sqrt{2}V_1 \cos \omega t = e_1$$

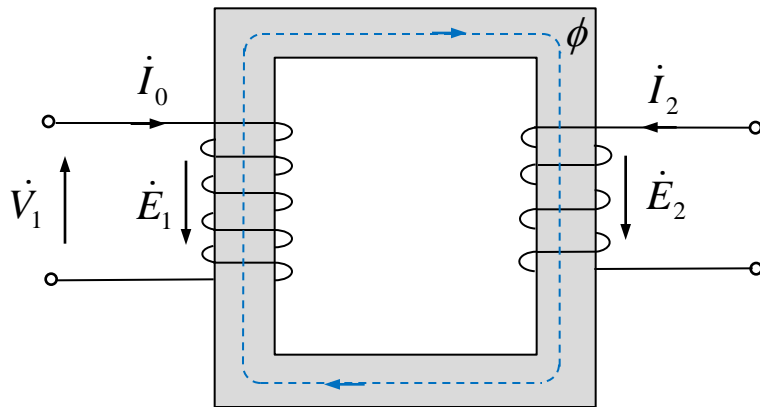
$$i_0 = \frac{\sqrt{2}V_1}{\omega L} \cos\left(\omega t - \frac{\pi}{2}\right)$$

$$\phi = \frac{\sqrt{2}V_1}{\omega N} \cos\left(\omega t - \frac{\pi}{2}\right)$$

② 전압과 유도기전력의 방향이 같은 경우 (페이지도)



③ 전압과 유도기전력의 방향이 다른 경우 (페이지도)

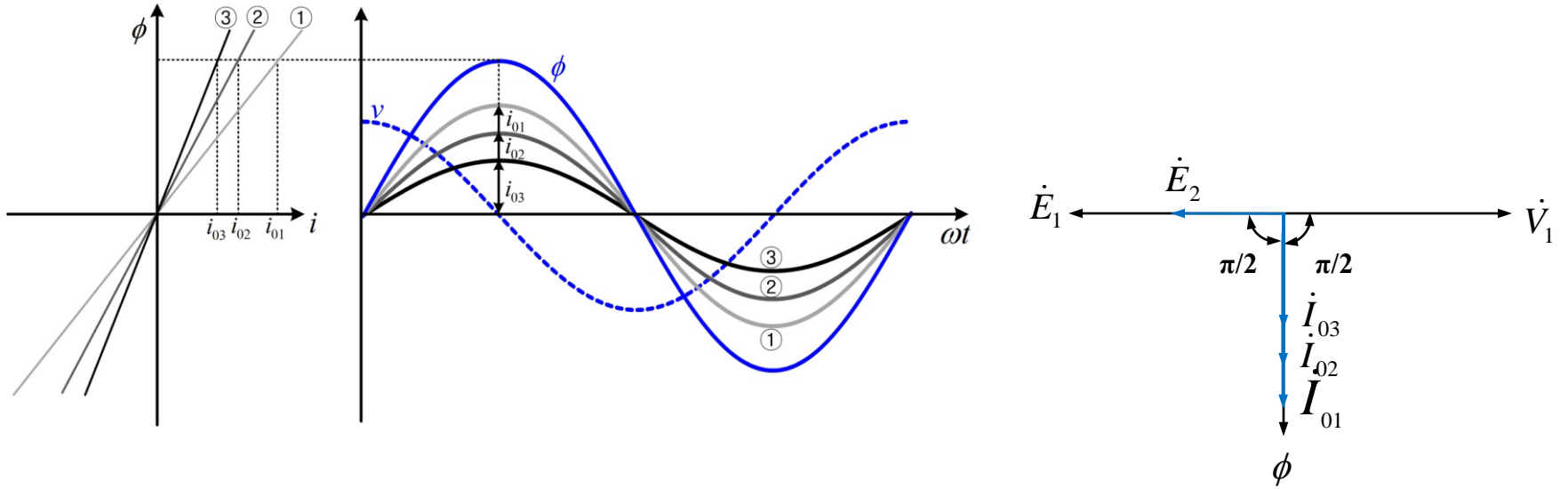


6) 자성체에 따른 여자전류

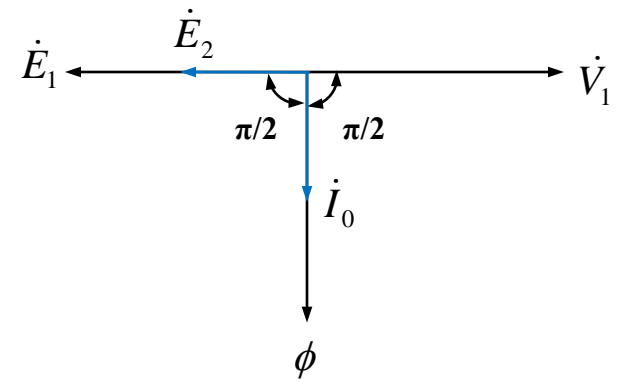
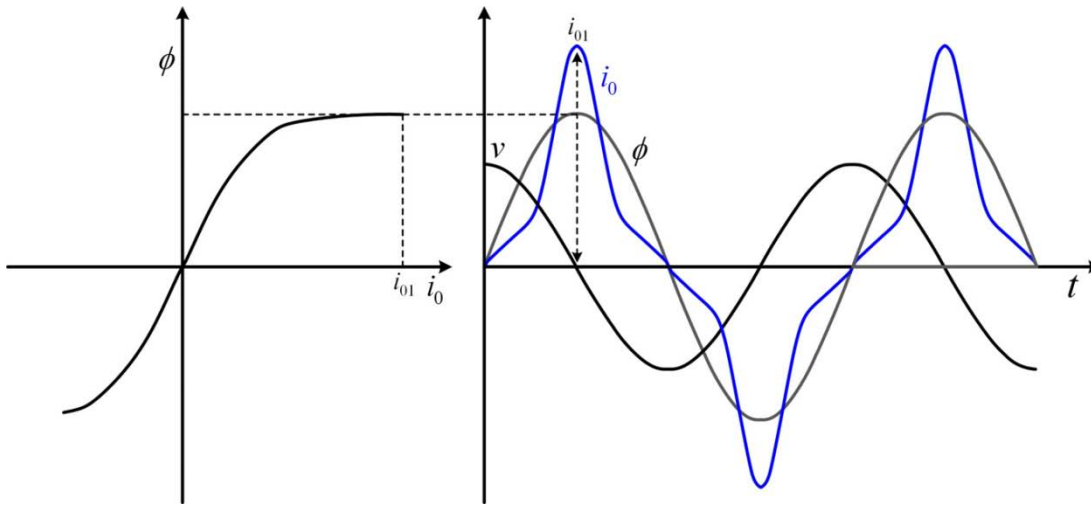
$$\begin{aligned}i_0 &= \frac{\sqrt{2}V_1}{\omega L} \cos\left(\omega t - \frac{\pi}{2}\right) \\&= \frac{\sqrt{2}V_1}{\omega} \left(\frac{\mathfrak{R}_m}{N^2}\right) \cos\left(\omega t - \frac{\pi}{2}\right) \\&= \frac{\sqrt{2}V_1}{\omega} \left(\frac{1}{N^2} \frac{l}{\mu A}\right) \cos\left(\omega t - \frac{\pi}{2}\right)\end{aligned}$$

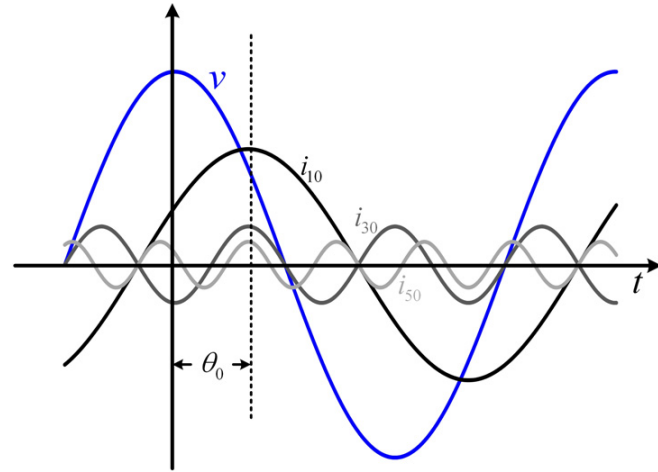
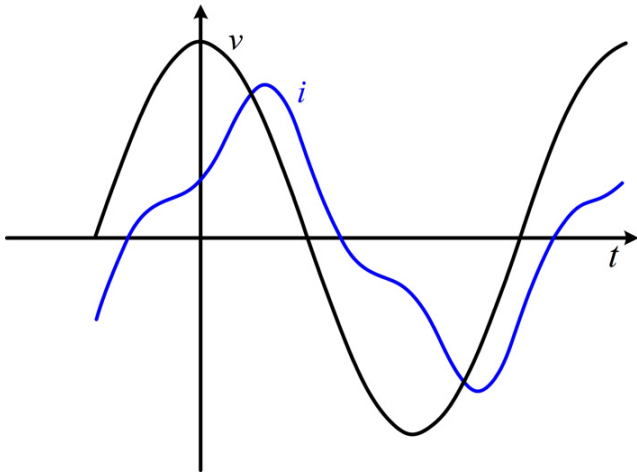
① 자성체 투자율이 **무한대**인 경우

② 자성체 투자율이 선형인 경우



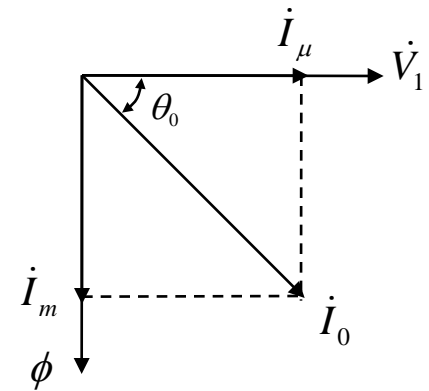
③ 자성체 투자율이 비선형인 경우





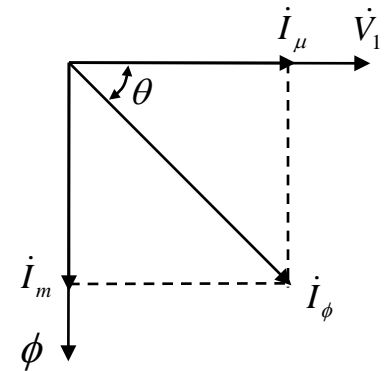
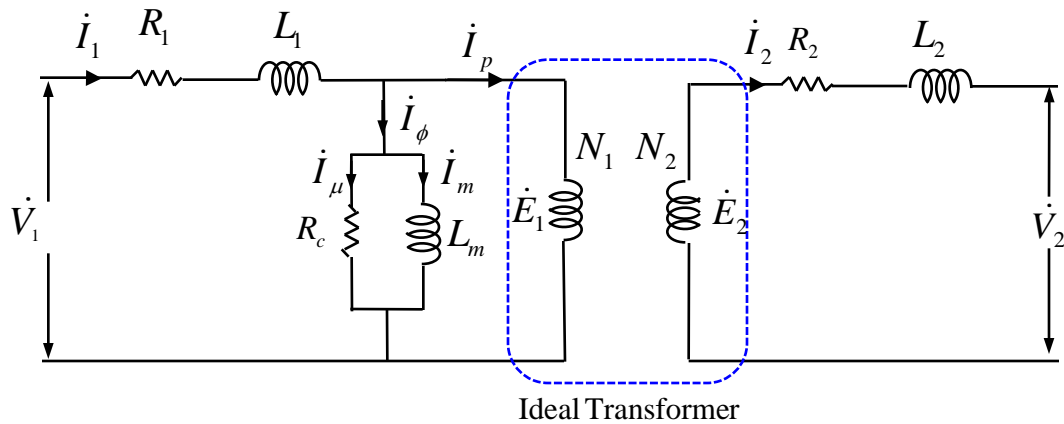
철손분 전류 : $\dot{I}_\mu = \dot{I}_0 \cos \theta_0$

자화 전류 : $\dot{I}_m = \dot{I}_0 \sin \theta_0$



3. 실제 변압기 (real transformer)

- ① resistance in winding
- ② leakage flux \Rightarrow leakage inductance
- ③ finite permeability \Rightarrow magnetizing inductance
- ④ core losses \Rightarrow core-loss resistance



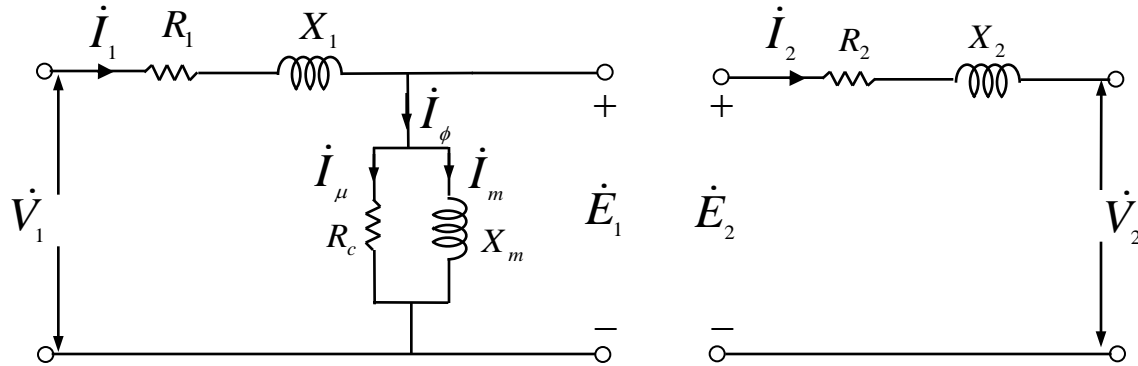
$$\dot{I}_\phi = \dot{I}_\mu + \dot{I}_m$$

$$\left(\dot{I}_\mu = \frac{\dot{E}_1}{R_c} \quad \dot{I}_m = \frac{\dot{E}_1}{j\omega L_m} \right)$$

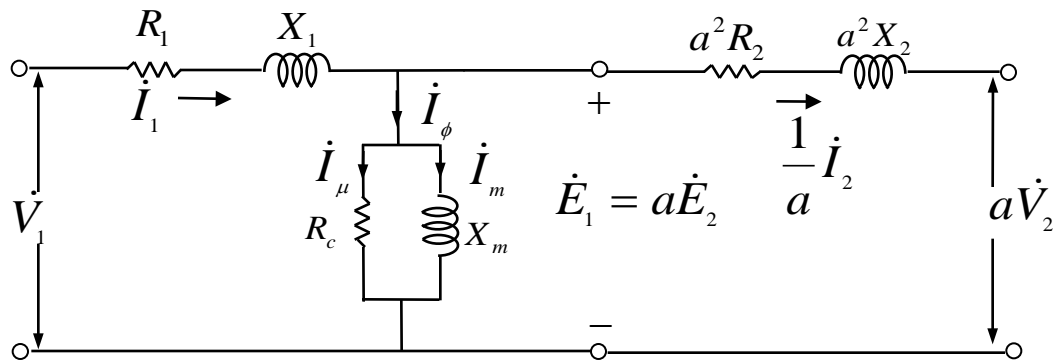
$$\begin{cases} \dot{E}_1 \dot{I}_\mu : \text{손실 유효전력} \\ \dot{E}_1 \dot{I}_m : \text{손실 무효전력} \end{cases}$$

1) 1차측으로 환산한 Equivalent Circuit

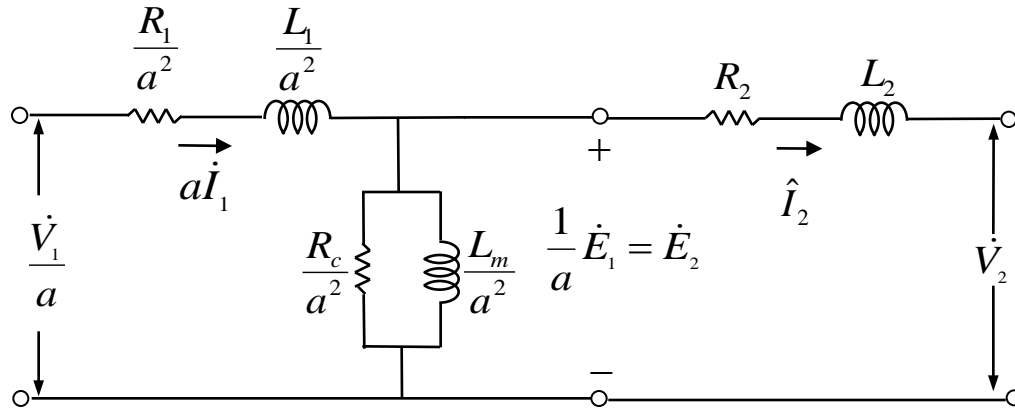
- 1차측과 2차측이 전기적으로 분리
 - 2차측의 전기적인 회로정수를 전원전압으로 나타내기 어려움
 - 1,2차측의 임피던스 환산을 통해 등가회로로 표현가능



$$\dot{E}_1 = a\dot{E}_2, \quad \dot{I}_1 = \frac{1}{a}\dot{I}_2, \quad \dot{Z}_1 = a^2\dot{Z}_2$$



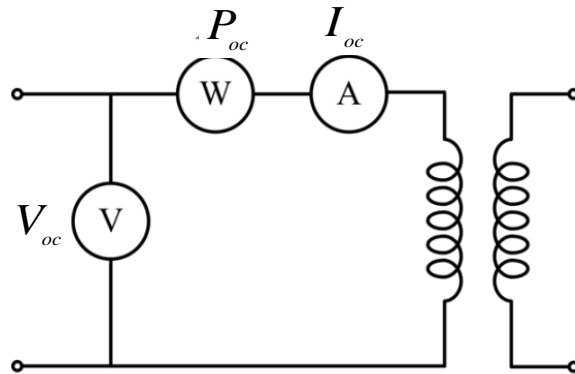
2) 2차측으로 환산한 Equivalent Circuit

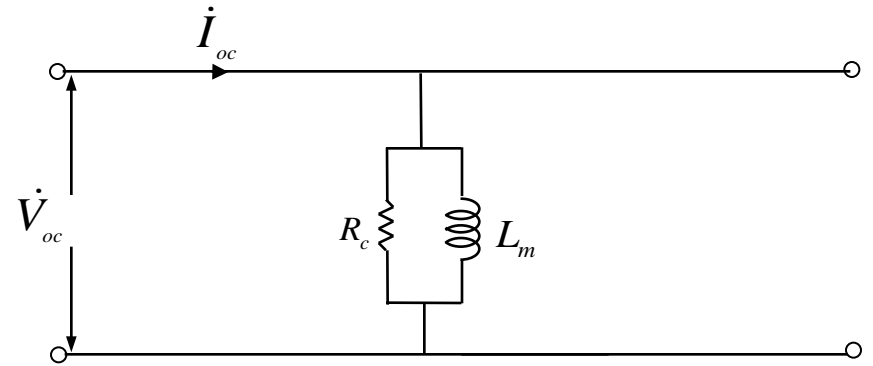
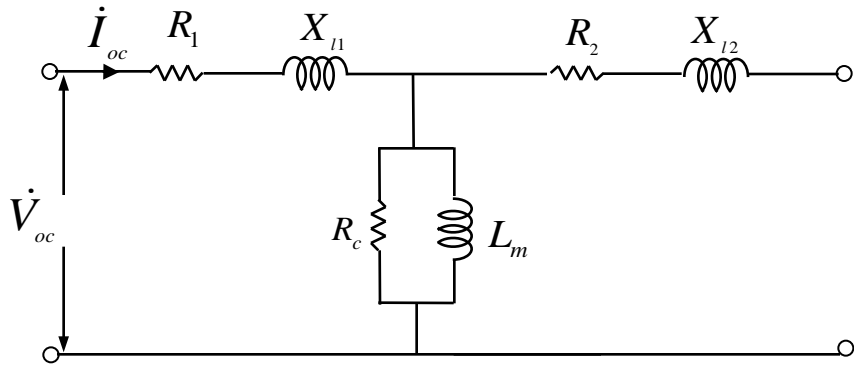


4. 변압기 회로정수 산정(Determination of transformer parameter)

1) 개방시험 (open-circuit test)

- 2차측을 개방한 상태에서 1차측 단자에 정격주파수의 정격 전압을 인가
- R_1, X_{l1} 은 R_c, X_m 에 비해 매우 작은 값이므로 무시
- 측정항목 : V_{oc}, I_{oc}, P_{oc}
- 산정항목 : R_c, X_m





$$Z_{oc} = R_1 + jX_{l1} + Z_{\phi} = R_1 + jX_{l1} + \frac{R_c(jX_m)}{R_c + jX_m}$$



$$Z_{oc} \approx Z_{\phi} = \frac{R_c(jX_m)}{R_c + jX_m}$$

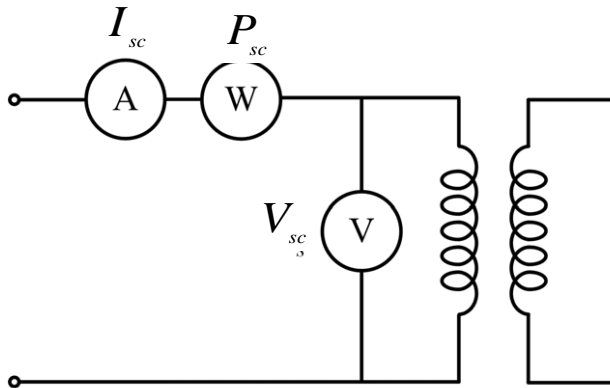
$$\therefore R_c = \frac{V_{oc}^2}{P_{oc}}$$

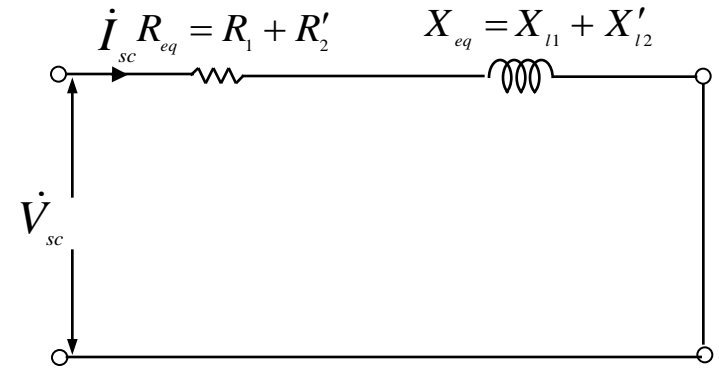
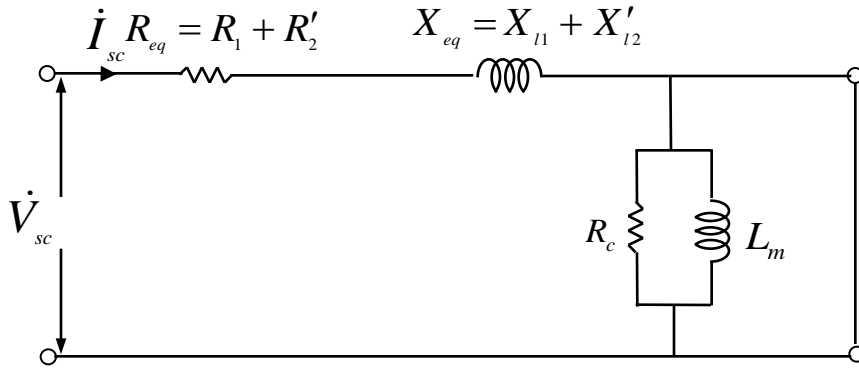
$$|Z_{\phi}| = \frac{V_{oc}}{Z_{oc}}$$

$$\therefore X_m = \frac{1}{\sqrt{\left(\frac{1}{|Z_{\phi}|}\right)^2 - \left(\frac{1}{R_c}\right)^2}}$$

2) 단락 시험 (short-circuit test)

- 2차측을 단락하고 1차측 전류가 정격전류에 도달할 때까지 전압을 상승시킴
- 입력전압이 낮기 때문에 여자전류가 거의 흐리지 않아 R_c , X_m 을 무시
- 측정항목 : V_{sc} , I_{sc} , P_{sc}
- 산정항목 : R_{eq} , X_{eq}





$$Z_{sc} = R_1 + jX_{l1} + \frac{Z_\phi (R_2 + jX_{l2})}{Z_\phi + R_2 + jX_{l2}} \quad \xrightarrow{Z_\phi \gg Z_{eq}} \quad Z_{sc} \approx R_1 + jX_{l1} + R_2 + jX_{l2} = R_{eq} + jX_{eq}$$

$$Z_{eq} = Z_{sc} = R_{eq} + jX_{eq} \quad \therefore R_{eq} = R_{sc} = \frac{P_{sc}}{I_{sc}^2}$$

$$\left| Z_{eq} \right| = \left| Z_{sc} \right| = \frac{V_{sc}}{I_{sc}} \quad \therefore X_{eq} = X_{sc} = \sqrt{\left| Z_{sc} \right|^2 - R_{sc}^2}$$

5. 손실과 효율 (Loss and Efficiency)

- 부하손 : 동손 (copper loss)

$$P_c = R_1 I_1^2 + R_2 I_2^2 \text{ [W]}$$

- 무부하손

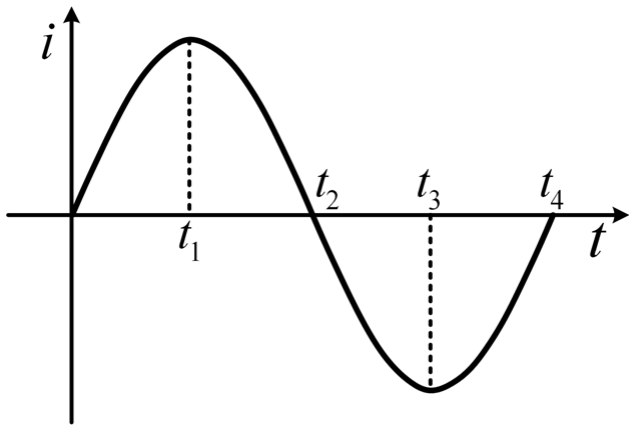
- 철손 (iron loss)

- ① 히스테리시스손 (hysteresis loss)

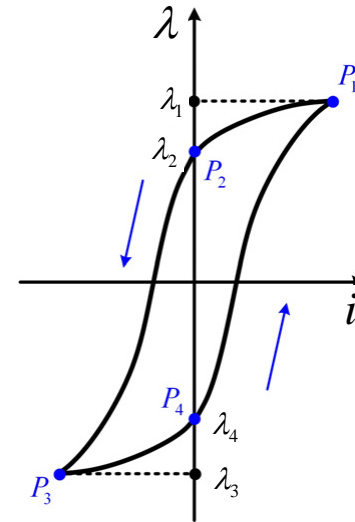
- ② 와전류손 (eddy current loss)

- 표류부하손 (stray load loss)

① 히스테리시스 손실



(a) 한 주기 전류 파형



(b) 히스테리시스 현상이 있을 때 전류-자속의 관계

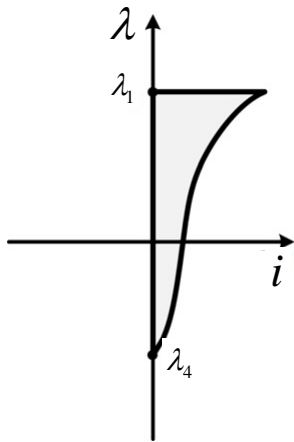
▪ 한 주기 동안 전류가 변할 때 철심에서의 전력관계

- 0 ~ t1 사이에서의 소비되는 전력

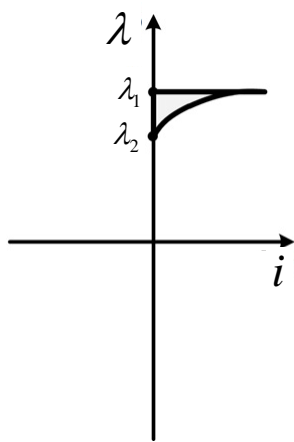
$$W = \int_0^{t_1} p dt = \int_0^{t_1} e \cdot i dt = \int_0^{t_1} i d\lambda \quad [J] \quad \left(\because e = \frac{d\lambda}{dt} \right)$$

- 전류가 1주기 변할때 소비되는 전력

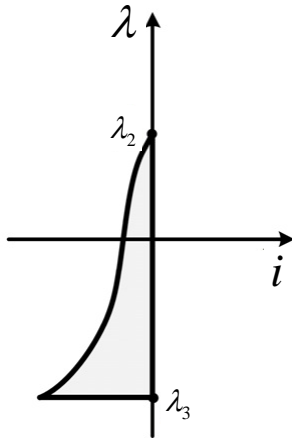
$$W = \oint i d\lambda = \int_{\lambda_4}^{\lambda_1} i d\lambda - \int_{\lambda_2}^{\lambda_1} i d\lambda + \int_{\lambda_2}^{\lambda_3} i d\lambda - \int_{\lambda_4}^{\lambda_3} i d\lambda$$



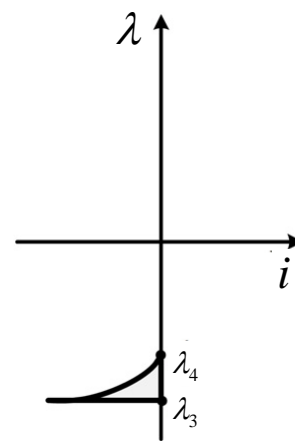
0 ~ t₁



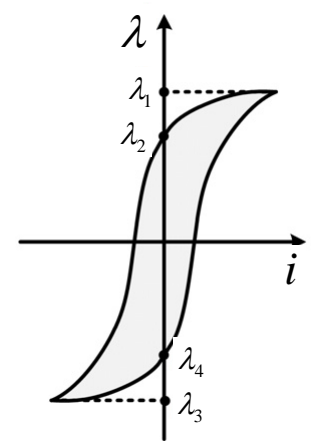
t₁ ~ t₂



t₂ ~ t₃



t₃ ~ t₄



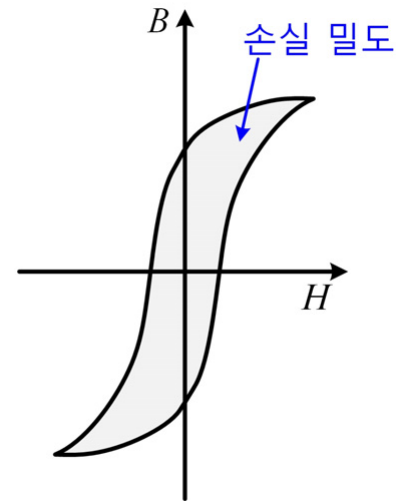
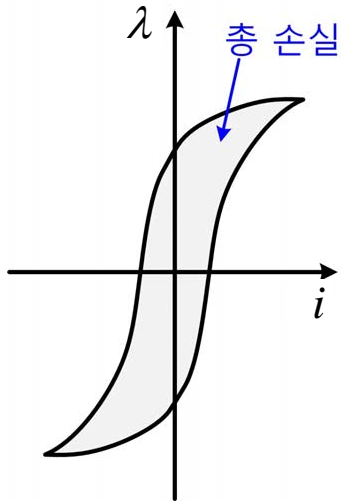
전류의 한주기 변화에 따른 소비전력

$$P_h = k_h f B_{\max}^{1.5 \sim 2.5} \cdot V \text{ [W]}$$

k_h

f

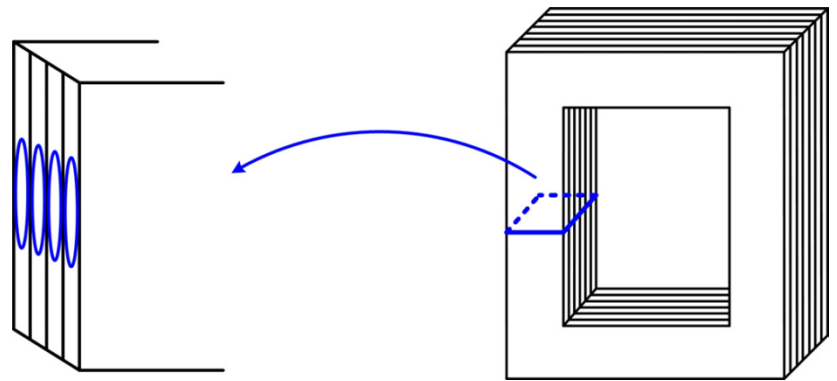
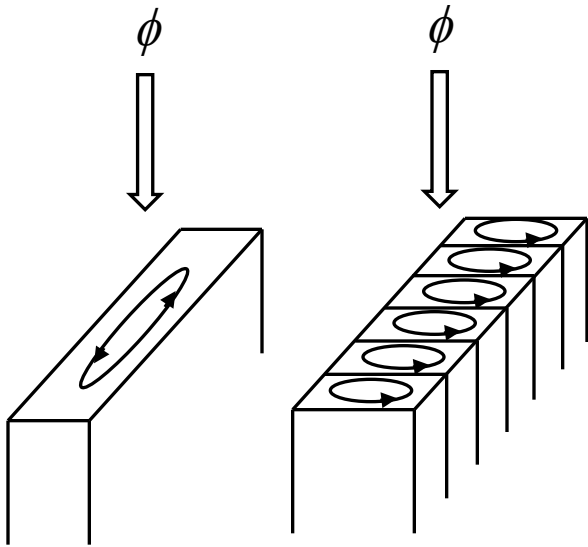
B_{\max}



② 와전류 손실

$$P_e = k_e (f B_{\max} \cdot d)^2 \cdot V \text{ [W]}$$

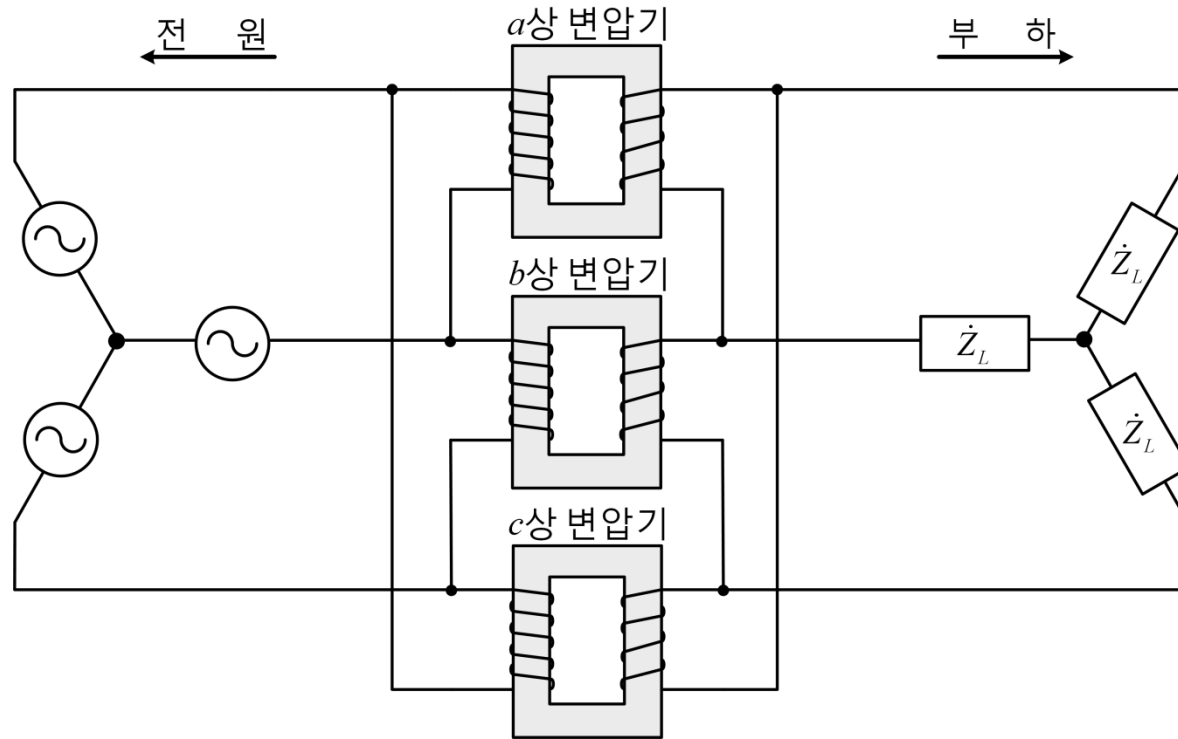
d



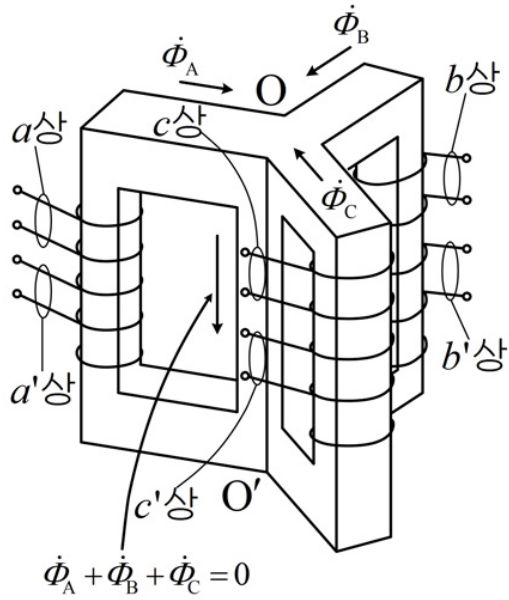
6. 3상 변압기 (three-phase transformer)

(1) 3상 변압기 구조

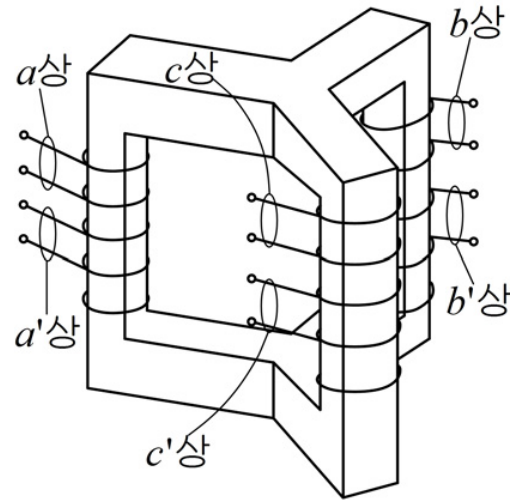
1) 3 single-phase transformer (transformer bank)



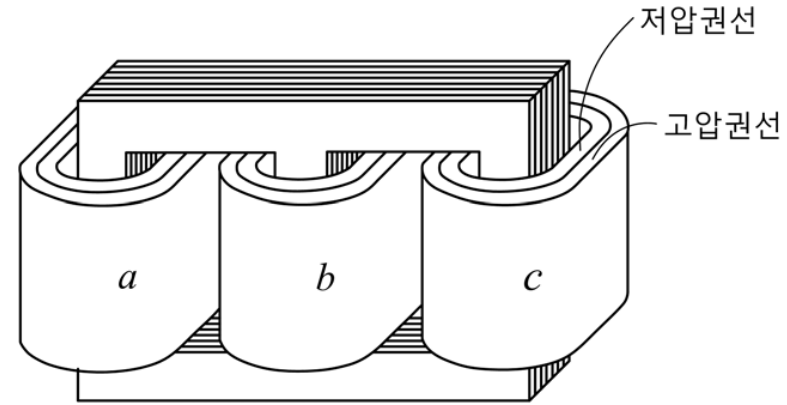
2) common-core device



(a) 단상 변압기 3대의 조합

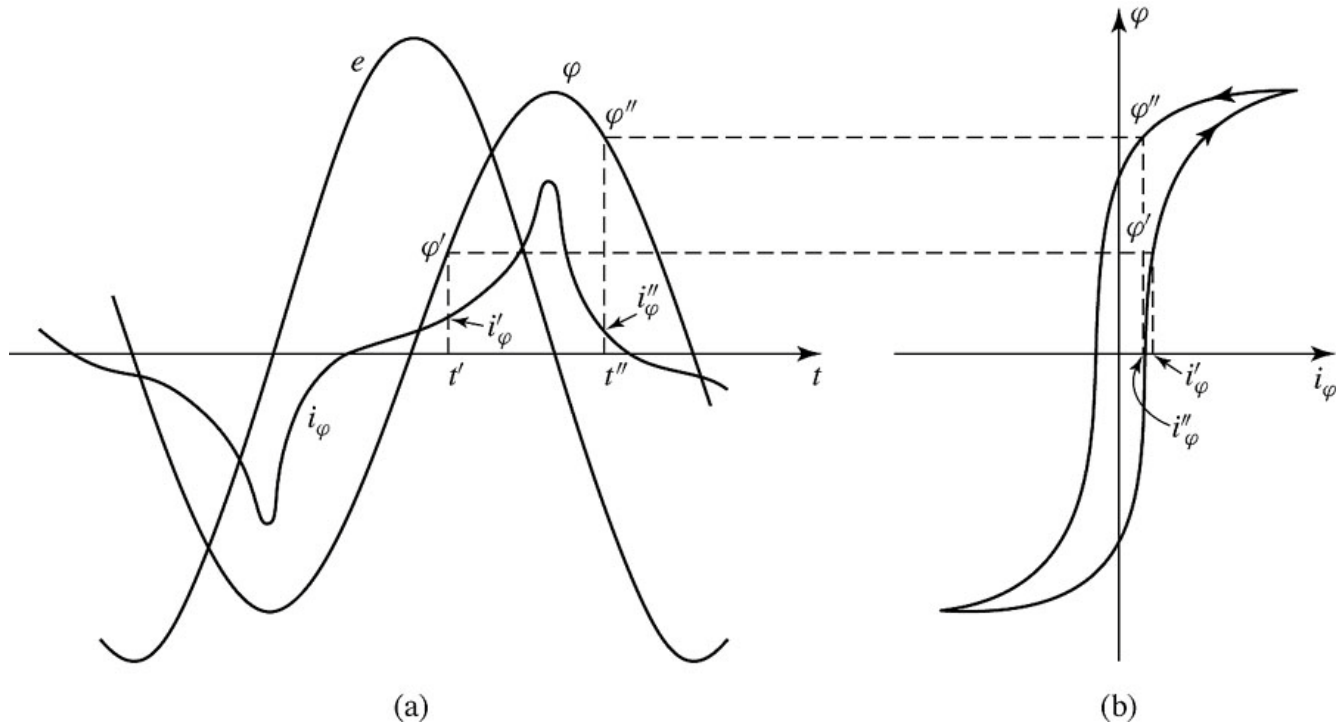


(b) OO'의 철심을 제거한 구조



(c) 직선형 구조

(2) 3상 변압기 결선과 고조파



$$i_{a0} = A_1 \sin \theta + B_1 \cos \theta + A_3 \sin 3\theta + B_3 \cos 3\theta + A_5 \sin 5\theta + B_5 \cos 5\theta + \dots$$

$$i_{b0} = A_1 \sin\left(\theta + \frac{2}{3}\pi\right) + B_1 \cos\left(\theta + \frac{2}{3}\pi\right) + A_3 \sin 3\left(\theta + \frac{2}{3}\pi\right) + B_3 \cos 3\left(\theta + \frac{2}{3}\pi\right) + \dots$$

$$i_{c0} = A_1 \sin\left(\theta + \frac{4}{3}\pi\right) + B_1 \cos\left(\theta + \frac{4}{3}\pi\right) + A_3 \sin 3\left(\theta + \frac{4}{3}\pi\right) + B_3 \cos 3\left(\theta + \frac{4}{3}\pi\right) + \dots$$

$$i_{a0} + i_{b0} + i_{c0} = A_1 \left[\sin \theta + \sin\left(\theta + \frac{2}{3}\pi\right) + \sin\left(\theta + \frac{4}{3}\pi\right) \right] \quad 0$$

$$+ B_1 \left[\cos \theta + \cos\left(\theta + \frac{2}{3}\pi\right) + \cos\left(\theta + \frac{4}{3}\pi\right) \right]$$

$$+ A_3 \left[\sin 3\theta + \sin 3\left(\theta + \frac{2}{3}\pi\right) + \sin 3\left(\theta + \frac{4}{3}\pi\right) \right]$$

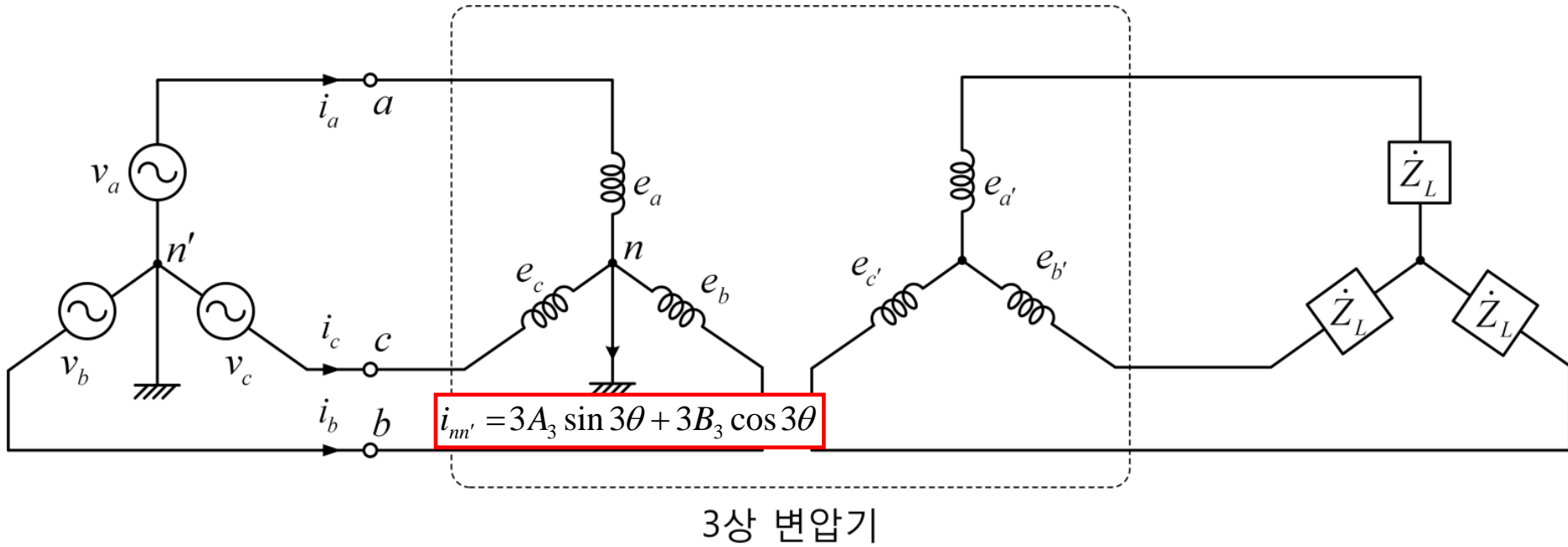
$$+ B_3 \left[\cos 3\theta + \cos 3\left(\theta + \frac{2}{3}\pi\right) + \cos 3\left(\theta + \frac{4}{3}\pi\right) \right]$$

$$3A_3 \sin 3\theta + 3B_3 \cos 3\theta$$

$$+ A_5 \left[\sin 5\theta + \sin 5\left(\theta + \frac{2}{3}\pi\right) + \sin 5\left(\theta + \frac{4}{3}\pi\right) \right] \quad 0$$

$$+ B_5 \left[\cos 5\theta + \cos 5\left(\theta + \frac{2}{3}\pi\right) + \cos 5\left(\theta + \frac{4}{3}\pi\right) \right]$$

1) 중성점을 접지시킨 3상 Y-Y 결선된 변압기



2) 중성점을 접지시키지 않은 3상 Y-Y 결선된 변압기

$$e_a = E_1 \sin \omega t + E_3 \sin 3\omega t = e_{a1} + e_{a3} \text{ [V]}$$

$$e_b = E_1 \sin(\omega t - 120^\circ) + E_3 \sin 3(\omega t - 120^\circ) = e_{b1} + e_{b3} = e_{b1} + e_{a3} \text{ [V]}$$

$$e_c = E_1 \sin(\omega t - 240^\circ) + E_3 \sin 3(\omega t - 240^\circ) = e_{c1} + e_{c3} = e_{c1} + e_{a3} \text{ [V]}$$

$$e_a + e_b + e_c = 3e_{a3} \text{ [V]}$$

3) Y- Δ 결선에서의 3고조파 순환전류

