Chap. 9 시변자계 및 Maxwell 방정식

- 전류 I $\underset{\text{1831, Faraday}}{\overset{\text{1820, Oersted}}{\rightleftarrows}}$ 자계 $\vec{H}$

- 자계의 변화 $(\frac{\partial \vec{B}}{\partial t})$ $\xrightarrow{\text{1831, Faraday}}$ 전계 생성 $(\vec{E})$
  자계 생성 $(\vec{H})$ $\xleftarrow{\text{Maxwell 전자파예언}}$ 전계의 변화 $(\frac{\partial \vec{D}}{\partial t})$

9.1 Faraday 법칙

- 유도 기전력 (Induced Electromotive Force)

$\boxed{\mathrm{emf} = -\frac{d\Phi}{dt}\ \mathrm{V}}$: 자계의 변화는 기전력 (Electromotive Force, emf)를 발생시킨다.

$$emf = \oint \vec{E} \cdot d\vec{L} = -\frac{d}{dt}\int_S B \cdot d\vec{S}$$

$$\int_S \nabla \times \vec{E} \cdot d\vec{S} = \int_S -\frac{\partial \vec{B}}{\partial t} \cdot d\vec{S}$$

$$\therefore \boxed{\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}}$$: Faraday 법칙

✓ N Turn : $\boxed{\mathrm{emf} = -N\frac{d\Phi}{dt}}$

✓ Electrostatic : $\oint \mathbf{E} \cdot d\mathbf{L} = 0 \qquad \nabla \times \mathbf{E} = 0$

✓ Lentz 의 법칙 :
유도기전력에 의한 자계는 원 자속과 반대방향으로 발생한다.
즉 $\frac{d\Phi}{dt}$ 가 만드는 기전력은 Φ 의 변화를 억제하는 방향.

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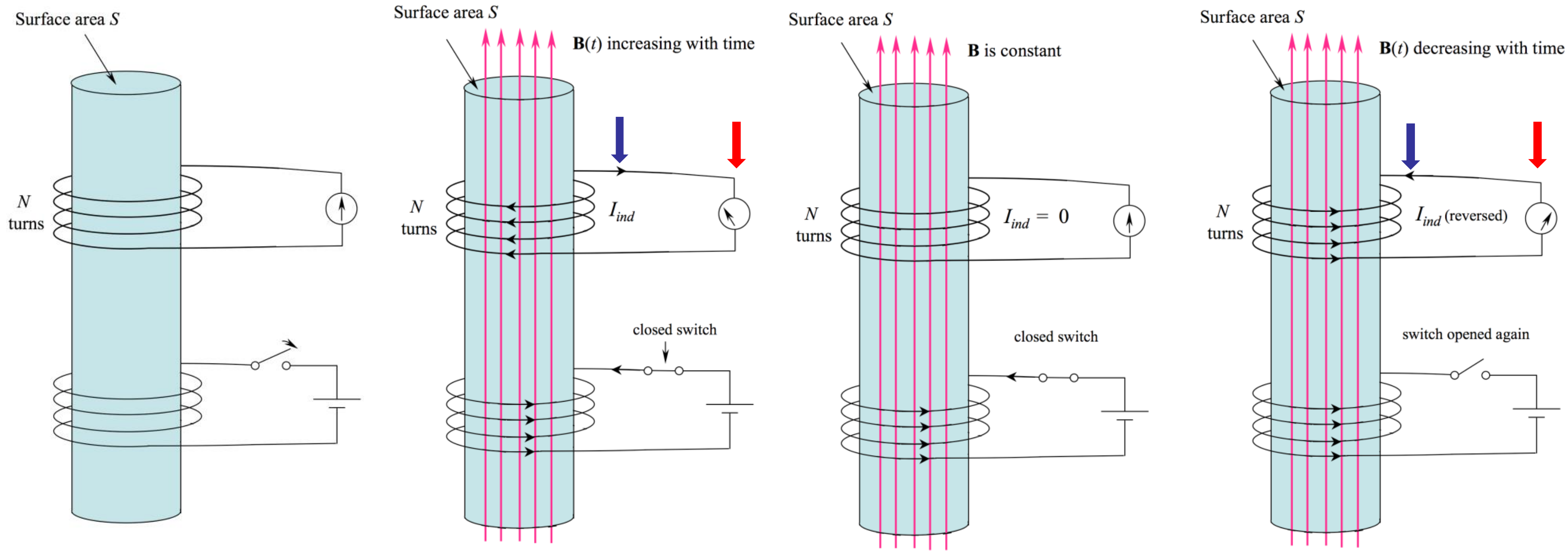
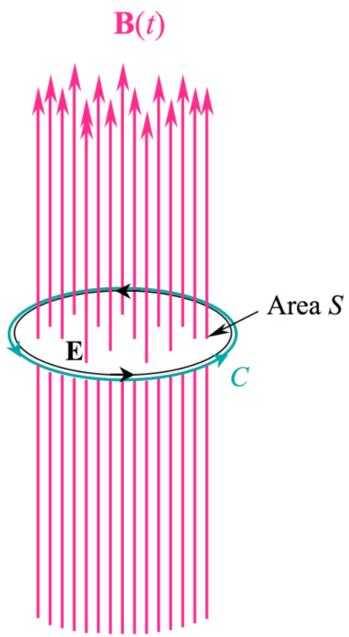
$$emf = -\frac{d\Phi}{dt}\,[V]$$



$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$



✓ The flux varies with time.

→ The ***electromotive force***, or ***emf***, is defined as the closed path integral of **E** about C:

→ A current, I_{ind} , is generated in the wire loop as a result of the changing magnetic flux.

$$\text{emf} = -\frac{d\Phi}{dt}$$

$$\oint_C \mathbf{E} \cdot d\mathbf{L} = -\frac{d}{dt}\int_S \mathbf{B} \cdot \mathbf{n}\, da$$

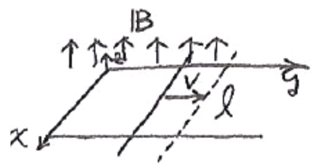
(Ex) Uniform (but time-varying) field: $\mathbf{B} = B_0 e^{kt} \mathbf{a}_z$

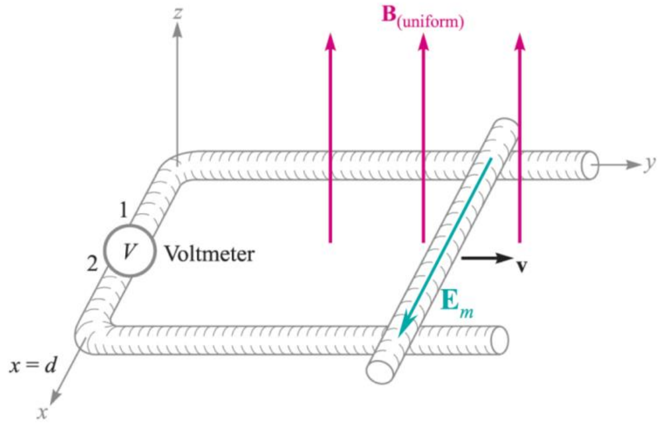
$$\oint_C \mathbf{E} \cdot d\mathbf{L} = -\frac{d}{dt}\int_S \mathbf{B} \cdot \mathbf{n}\, da \qquad \left[\begin{array}{l} \text{emf} = \oint \mathbf{E} \cdot d\mathbf{L} = 2\pi a E_\phi \\ \text{emf} = -\int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} = -k B_0 e^{kt} \pi a^2 \end{array}\right] \longrightarrow \begin{array}{c} 2\pi a E_\phi = -k B_0 e^{kt} \pi a^2 \\ \boxed{\mathbf{E} = -\tfrac{1}{2} k B_0 e^{kt} \rho \mathbf{a}_\phi} \end{array}$$

✓ Another way ; use: $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ where $\mathbf{B} = B_0 e^{kt} \mathbf{a}_z$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \left[\begin{array}{l} (\nabla \times \mathbf{E})_z = \frac{1}{\rho}\frac{\partial(\rho E_\phi)}{\partial \rho} \\ -\frac{\partial \mathbf{B}}{\partial t} = -k B_0 e^{kt} \pi a^2 \end{array}\right] \longrightarrow \begin{array}{c} -\tfrac{1}{2} k B_0 e^{kt} \rho^2 = \rho E_\phi \\ \boxed{\mathbf{E} = -\tfrac{1}{2} k B_0 e^{kt} \rho \mathbf{a}_\phi} \end{array}$$

$$emf = -\frac{d\Phi}{dt}\,[V]$$





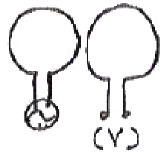
- ✓ Induced emf from a Moving Closed Path
- ✓ Finding the Direction of E
- ✓ Motional EMF
- ✓ ??

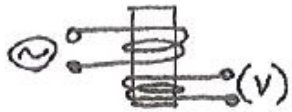
$$\text{emf} = \oint \mathbf{E}\cdot d\mathbf{L} = \underbrace{\underbrace{-\int_S \frac{\partial \mathbf{B}}{\partial t}\cdot d\mathbf{S}}_{\textbf{Transformer emf}} + \underbrace{\oint (\mathbf{v}\times\mathbf{B})\cdot d\mathbf{L}}_{\textbf{Motional emf}}}_{-\frac{d\Phi}{dt}}$$

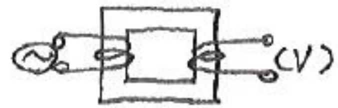
$$emf = -\frac{d\Phi}{dt}\,[V]$$

◎ $\frac{d\Phi}{dt} \rightarrow \frac{\partial \vec{B}}{\partial t}$, or and $\frac{\partial \vec{S}}{\partial t}$

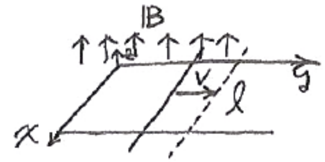
- $\frac{\partial \vec{B}}{\partial t}$:







- $\frac{\partial \vec{S}}{\partial t}$:



$$\Phi = \int \vec{B} \cdot d\vec{S} = B\ell y$$

$$emf = -\frac{d\Phi}{dt}\,[V] = -B\ell\frac{dy}{dt} = -B\ell v$$

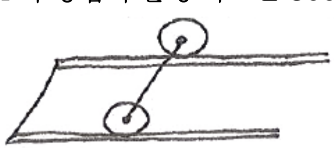
✓ <u>운동 기전력 (Motional emf)</u> : $\vec{E}_m = \vec{v} \times \vec{B} \; (= \frac{\vec{F}}{Q})$

$$emf = \oint \vec{E}_m \cdot d\vec{L} = \oint (\vec{v} \times \vec{B}) \cdot d\vec{L} = \int_L^0 v \cdot B\, dx = -BLv$$

- 일반적으로 : $emf = \oint \vec{E} \cdot d\vec{L} = -\int_S \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S} \quad + \quad \oint (\vec{v} \times \vec{B}) \cdot d\vec{L} = -\frac{d\Phi}{dt}$

(→ 기전력 = 자속변화 기전력 + 운동 기전력)

(Ex) KTX 의 상업적 운행 속도는 300 km/H 이다. 이 경우 1.5m 인 두바퀴 축에 유기되는 기전력은?



$\vec{B} = 0.5\,\hat{a}_z\,[G]$

$$emf = B \cdot \ell \cdot v = 0.5 \times 10^{-4} \times 1.5 \times \frac{300 \times 10^3}{3600}$$
$$= 6.25\ mV$$

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9.2 변위전류

- $$\nabla\times\vec{E}=-\frac{\partial\vec{B}}{\partial t},\quad \nabla\times\vec{H}=\vec{J}+\frac{\partial\vec{D}}{\partial t}\ (?)$$

$$\nabla\times\vec{H}=\vec{J},\quad \nabla\cdot\nabla\times\vec{H}\equiv 0=\nabla\cdot\vec{J}\ (\neq-\frac{\partial\rho}{\partial t})$$

$$put\ \nabla\times\vec{H}=\vec{J}+\vec{G},\quad then\ \nabla\cdot\nabla\times\vec{H}\equiv 0=\nabla\cdot\vec{J}+\nabla\cdot\vec{G}$$

$$\nabla\cdot\vec{G}=-\nabla\cdot\vec{J}=-(-\frac{\partial\rho}{\partial t})=\frac{\partial\rho}{\partial t}=\frac{\partial}{\partial t}(\nabla\cdot D)=\nabla\cdot\frac{\partial\vec{D}}{\partial t}\,!$$

$$\therefore\quad \vec{G}=\frac{\partial\vec{D}}{\partial t}$$

$$\therefore\quad \boxed{\nabla\times\vec{H}=\vec{J}+\frac{\partial\vec{D}}{\partial t}}$$: Ampere

$$\nabla\times\mathbf{H}=\mathbf{J}+\mathbf{J}_d$$

✓ *displacement current density.* $\mathbf{J}_d=\frac{\partial\mathbf{D}}{\partial t}$

◎ 전류의 종류 :

(i) 전도전류 (Conduction Current)

$$\vec{J}=\sigma\vec{E}$$: net charge density → 0   ex) 전자(정공) pain

(ii) 대류전류 (Convection Current)

$$\vec{J}=\sigma\vec{V}$$: net charge density → 0

(iii) 변위전류 (displacement Current)

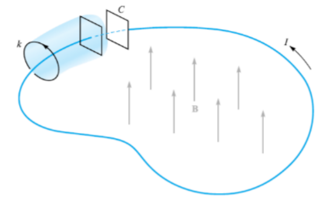
$$\boxed{\vec{J}_d=\frac{\partial\vec{D}}{\partial t}}\qquad \nabla\times\vec{H}=\vec{J}+\frac{\partial\vec{D}}{\partial t}$$ 에서 $\vec{J}=\vec{J}_{(i)}+\vec{J}_{(ii)}$

- 변위전류 (I_d) & 전도전류 (I)

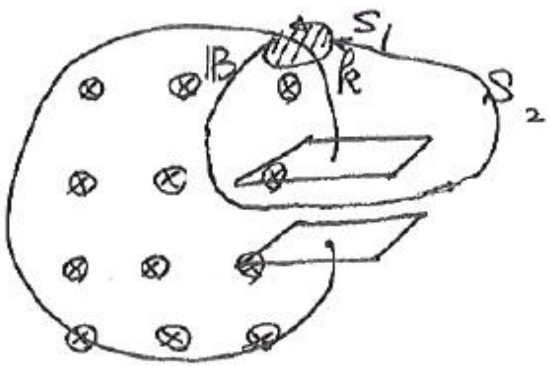
$$I_d = \int_S \mathbf{J}_d \cdot d\mathbf{S} = \int_S \frac{\partial \mathbf{D}}{\partial t} \cdot d\mathbf{S}$$

$$\int_S (\nabla \times \mathbf{H}) \cdot d\mathbf{S} = \int_S \mathbf{J} \cdot d\mathbf{S} + \int_S \frac{\partial \mathbf{D}}{\partial t} \cdot d\mathbf{S}$$

$$\boxed{\oint \mathbf{H} \cdot d\mathbf{L} = I + I_d = I + \int_S \frac{\partial \mathbf{D}}{\partial t} \cdot d\mathbf{S}}$$



➢ <u>$\vec{B}$ 변화에 의한 기전력 발생 :</u>



(i) 전도전류 : $emf = V_0 \cos wt$

$$I_C = C\frac{dv}{dt} = -wCV_0 \sin wt \;\; = \underline{-w\frac{\varepsilon\, S}{d} V_0 \sin wt} \qquad (\because C = \varepsilon \frac{S}{d})$$

＊ Loop k 에서 S_1을 관통하는 전류, 전도전류

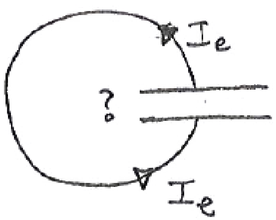
(ii) 변위전류 :

$$I_d = \frac{\partial D}{\partial t} \cdot S \;\; , \;\; D = \varepsilon\, E \, , \;\; \varepsilon = \frac{V}{d}$$

$$\therefore D = \varepsilon\, E = \; \varepsilon \frac{V_0}{d} \cos wt$$

$$\rightarrow I_d = \frac{\partial D}{\partial t} \cdot S = \underline{-w \cdot \frac{\varepsilon\, S}{d} V_0 \sin wt} \qquad \boxed{I_C = I_d}$$

＊ Loop k 에서 S_2을 통과하는 전류

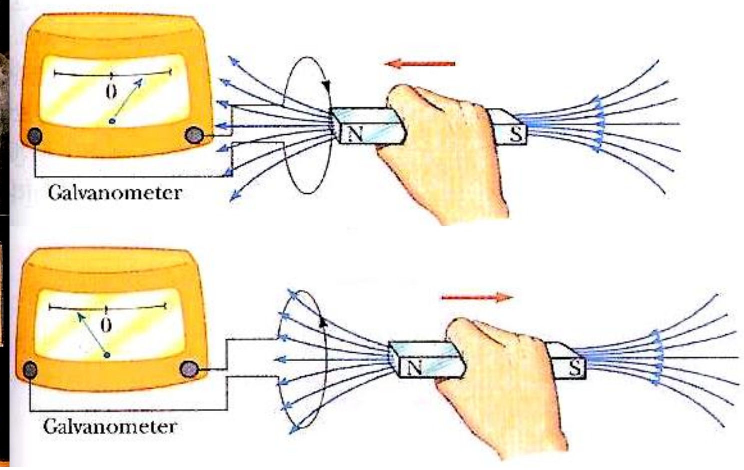


$$\oint_k \vec{H} \cdot d\vec{L} = I_k = \begin{cases} S_1 : I_C \\ S_2 : I_d \end{cases}$$

- **Faraday' Law**

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \longrightarrow e = -\frac{d\Phi}{dt}$$

$$\int (\nabla \times \mathbf{E}) \cdot d\mathbf{S} = -\frac{\partial}{\partial t}\int \mathbf{B} \cdot d\mathbf{S} \xrightarrow[Stokes]{} \int E \cdot dL = -\frac{d\Phi}{dt} \qquad e = -\frac{d\Phi}{dt}$$



9.3 미분형 Maxwell 방정식 / 9.4 적분형 Maxwell 방정식

◎ Maxwell Equation

	미분형	적분형	비고
Gauss	$\nabla \cdot \vec{D} = \rho$	$\oint_S \vec{D} \cdot d\vec{S} = Q$	전계발생
Faraday	$\nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t}$	$\int_S \vec{E} \cdot d\vec{L} = -\int_S \dfrac{\partial \vec{B}}{\partial t} \cdot d\vec{S}$	전자유도
	$\nabla \cdot \vec{B} = 0$	$\oint_S \vec{B} \cdot d\vec{S} = 0$	
Ampere	$\nabla \times \vec{H} = \vec{J} + \dfrac{\partial \vec{D}}{\partial t}$	$\int \vec{H} \cdot d\vec{L} = I + \int_S \dfrac{\partial \vec{D}}{\partial t} \cdot d\vec{S}$	자계발생

- 매질에서 : $\vec{D} = \varepsilon_0 \vec{E} + \vec{P}$, 분극 $\vec{P} = \chi_e \varepsilon_0 \vec{E}$, $\vec{D} = \varepsilon_0 (1 + \chi_e) \vec{E} = \varepsilon_0 \varepsilon_r \vec{E}$ $\qquad \vec{D} = \varepsilon \vec{E}$(유전체)

  $\vec{B} = \mu_0 (\vec{H} + \vec{M})$, 자화 $\vec{M} = \chi_m \vec{H}$, $\vec{B} = \mu_0 (1 + \chi_m) \vec{H} = \mu_0 \mu_r \vec{H}$ $\qquad \vec{B} = \mu \vec{H}$ (자성체)

➢ Lorentz Force : $\vec{f} = \rho [\vec{E} + \vec{v} \times \vec{B}]$ (단위체적당 전하에 작용하는 힘)

➢ 전류 :

$\vec{J} = \sigma \vec{E}$: 전도전류

$\vec{J} = \rho \vec{V}$: 대류전류

$\vec{J} = \dfrac{\partial \vec{D}}{\partial t}$: 변위전류

- <u>Boundary Condition :</u>

$$\begin{bmatrix} E_{t1} = E_{t2} & , & D_{n1} - D_{n2} = \rho_s \\ H_{t1} = H_{t2} & , & B_{n1} - B_{n2} = k_s \end{bmatrix}$$

- **<u>완전도체 :</u>** ($\sigma = \infty , \vec{J} \rightarrow$ finite value, ex 초전도체)

① ohm 법칙으로부터 $\vec{E} = 0$, 즉 도체 내부에서 $\vec{E} = 0$, V=constant

$$(\because \vec{J} = \sigma \vec{E}, \vec{E} = \frac{\vec{J}}{\sigma} \rightarrow \frac{C}{\infty})$$

② Faraday 법칙으로부터 $\vec{H} = 0$, 즉 도체 내부에서 $\vec{H} = 0, \vec{B} = 0$

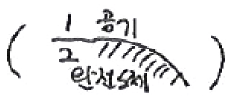
$$(\because \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} , \frac{\partial \vec{B}}{\partial t} = 0 , \vec{B} = const. \rightarrow 0)$$

③ Ampere 법칙으로부터 $\vec{J} = 0$, 즉 도체 내부에서 $\vec{J} = 0$

$$(\because \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} , \vec{J} = 0)$$

→ 완전 도체 내부에서 $\vec{J} = 0 , \vec{E} = 0 , \vec{H} = 0.$ 표면전류만 존재! 

✓ 완전도체에서의 경계조건 :



$E_{t1} = 0$: 도체 표면에서 $E_{t1} = 0$ 

$E_{t1} = k$

$D_{n1} = \rho_s$

$B_{n1} = 0$: 도체 표면에서 B_t *only* 

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9.5 지연포텐셜 (Retarded Potential)

$$*\begin{pmatrix}\rho,\ \varepsilon\\ \vec{J},\ \mu\end{pmatrix} \rightarrow V, \vec{A} \rightarrow \vec{E}, \vec{B} \rightarrow \vec{F}$$

◎ 정전하 분포에서 :

$$\begin{bmatrix} V = \int_v \frac{\rho dv}{4\pi\varepsilon R} & \nabla^2 V = -\frac{\rho}{\varepsilon} \\ \vec{A} = \int_v \frac{\mu \vec{J} dv}{4\pi R} & \nabla^2 \vec{A} = -\mu \vec{J} \end{bmatrix} \qquad \begin{matrix} \vec{E} = -\nabla V \\ \vec{B} = \nabla \times \vec{A} \end{matrix}$$

◎ Time Varying Potential 과 $\vec{E}$

- $\vec{E} = -\nabla V \qquad \nabla \times \vec{E} = -\nabla \times (\nabla V) \Rightarrow 0\ always \qquad but\ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ 이므로 모순 !

- 가정 : $\vec{E} = -\nabla V + \vec{N} \qquad \nabla \times \vec{E} = \nabla \times (-\nabla V) + \nabla \times \vec{N} = 0 + \nabla \times \vec{N} = -\frac{\partial \vec{B}}{\partial t} \qquad \therefore\ \vec{N} = -\frac{\partial \vec{A}}{\partial t}$

$$\therefore\ \nabla \times \vec{N} = -\frac{\partial \vec{B}}{\partial t} = -\frac{\partial}{\partial t}(\nabla \times \vec{A}) = -\nabla \times \frac{\partial \vec{A}}{\partial t}$$

즉 $\boxed{\vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t}} \qquad cf.\ \vec{B} = \nabla \times \vec{A}$

※ 시변계에서 $\vec{E}$ 및 $\vec{A}, V$

$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$	$\nabla \cdot \vec{D} = \rho$
$\frac{1}{\mu} \nabla \times \nabla \times \vec{A} = \vec{J} + \varepsilon(-\nabla \frac{\partial V}{\partial t} - \frac{\partial^2 \vec{A}}{\partial t^2})$	$\varepsilon(-\nabla \cdot \nabla V - \frac{\partial}{\partial t} \nabla \cdot \vec{A}) = \rho$
$\nabla(\nabla \cdot \vec{A}) - \nabla^2 \vec{A} = \mu \vec{J} - \mu\varepsilon(\nabla \frac{\partial V}{\partial t} + \frac{\partial^2 \vec{A}}{\partial t^2})$	$\nabla^2 V + \frac{\partial}{\partial t}(\nabla \cdot \vec{A}) = -\frac{\rho}{\varepsilon}$

✓ $\frac{\partial}{\partial t} \rightarrow 0$ 일 경우는 시 불변

- 정전계 및 전자계에서 $\nabla\cdot\vec{A}=0\ :\ -\nabla^2\vec{A}=\mu\vec{J}\ ,\ \nabla^2 V=-\dfrac{\rho}{\varepsilon}$, 앞 장식과 동일
- $\vec{A}$에 대하여 $\nabla\times\vec{A}=\vec{B}.\quad \nabla\cdot\vec{A}=?$, for uniqueness put $\nabla\cdot\vec{A}=-\mu\varepsilon\dfrac{\partial V}{\partial t}$

$$\text{then}\ \left\{\begin{array}{l}\nabla^2\vec{A}=-\mu\vec{J}+\mu\varepsilon\dfrac{\partial^2\vec{A}}{\partial t^2}\\[2ex] \nabla^2 V=-\dfrac{\rho}{\varepsilon}+\mu\varepsilon\dfrac{\partial^2 V}{\partial t^2}\end{array}\right.$$

→ 파동 방정식으로 !

- Sum : from Potential to Field :

$$\left\{\begin{array}{l}\vec{B}=\nabla\times\vec{A}\\[2ex] \vec{E}=-\nabla V-\dfrac{\partial\vec{A}}{\partial t}\end{array}\right.\qquad \nabla\cdot\vec{A}=-\mu\varepsilon\frac{\partial V}{\partial t}$$

$\rho \longrightarrow v$

: 점전하에 의한 전계는

$\rho(t_0)$ 가 아니라

$\rho(t_{-1})$ 전하에 의하여 결정된다.

$*\,v=\dfrac{1}{\sqrt{\mu\varepsilon}}\cong 3\times10^8\ m/s$ (t_{-1} :두 점 사이를 전자기가 전파하는 시간만큼의 전시간)

$[\rho]$의 $t'=t-\dfrac{R}{v}$: retarded Time

➢ retarded Potential :

$$\left[\begin{array}{l}V=\displaystyle\int_v\frac{[\rho]}{4\pi\varepsilon R}dv\\[2ex] \vec{A}=\displaystyle\int_v\frac{\mu[\vec{J}]}{4\pi R}dv\end{array}\right]$$

Static Potentials		**Retarded Potentials**
$V=\displaystyle\int_{\mathrm{vol}}\frac{\rho_v dv}{4\pi\epsilon R}$	⟹	$V=\displaystyle\int_{vol}\frac{\rho_v(t-R/v_p)}{4\pi\epsilon R}dv$
$\mathbf{A}=\displaystyle\int_{\mathrm{vol}}\frac{\mu\mathbf{J}\,dv}{4\pi R}$	⟹	$\mathbf{A}=\displaystyle\int_{vol}\frac{\mu\mathbf{J}(t-R/v_p)}{4\pi R}dv$

(Ex). $\rho=e^{-r}\cos wt,\quad [\rho]=e^{-r}\cos w(t-\dfrac{R}{v})$

◎ Sum : Source, Field, Potentail

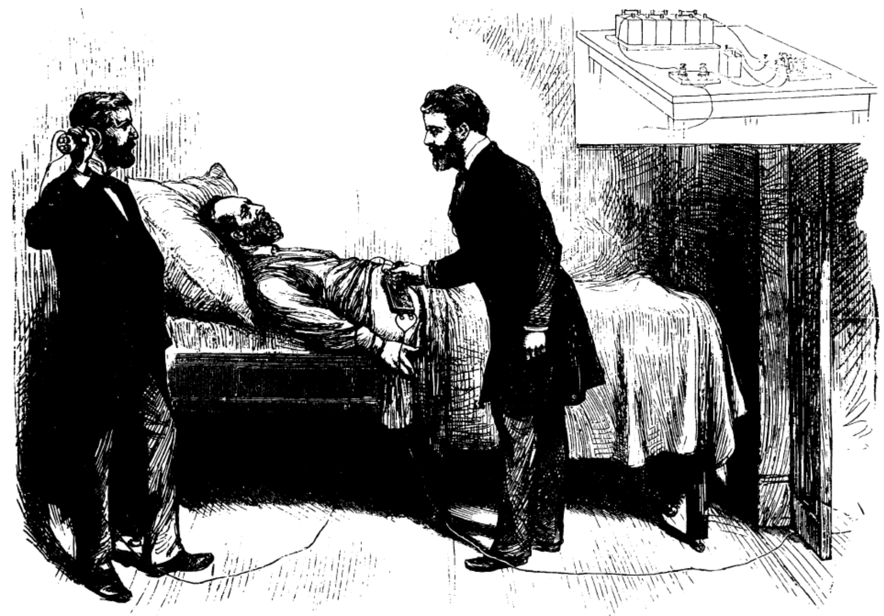
$$\begin{pmatrix} \rho \\ \vec{J} \end{pmatrix} \longrightarrow \begin{bmatrix} V = \int_v \frac{[\rho]}{4\pi\varepsilon R} dv \\ \vec{A} = \int_v \frac{\mu[\vec{J}]}{4\pi R} dv \end{bmatrix} \longrightarrow \begin{bmatrix} \vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t} \\ \vec{B} = \nabla \times \vec{A} \end{bmatrix}$$

OR

$$\begin{pmatrix} \rho \\ \vec{J} \end{pmatrix} \longrightarrow \begin{bmatrix} \vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t} \\ \vec{B} = \nabla \times \vec{A} \\ \nabla \cdot \vec{A} = -\mu\varepsilon \frac{\partial V}{\partial t} \\ \text{로 정의하면} \end{bmatrix} \longrightarrow \begin{bmatrix} \nabla^2 V = -\frac{\rho}{\varepsilon} + \mu\varepsilon \frac{\partial^2 V}{\partial t^2} \\ \nabla^2 \vec{A} = -\mu\vec{J} + \mu\varepsilon + \frac{\partial^2 \vec{A}}{\partial t^2} \end{bmatrix}$$

전기와 자기의 관계

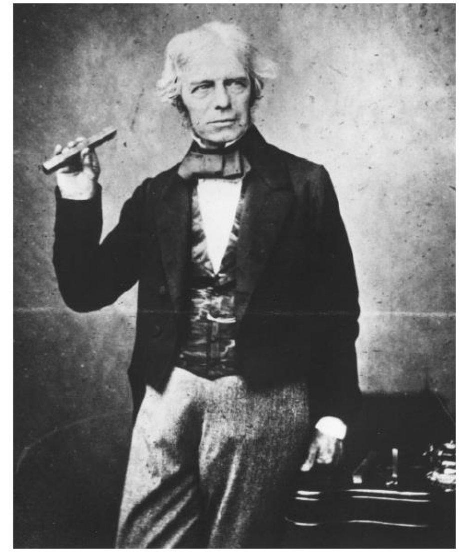
- 자기가 만드는 전기
  - Alexander Graham Bell (1847~1922)
    - 1881년 미국 대통령 James A. Garfield의 몸 속에 있는 총알을 찾기 위한 시도
    - 자기유도 및 와전류 이용



- 자기가 만드는 전기
  - 전자기 유도 현상
    - 도선 고리 주위에 자기의 변화를 주어 도선에 전류가 흐르는 현상
    - 유도전류 : 도선에 흐르는 전류
    - 유도기전력 : 유도전류를 흐르게 만드는 전자기 유도에 의해 발생되는 가상 전지의 전압
  - Heinrich Lenz (1804~1865)
    - Lenz's Law
    - 유도전류는 항상 유도전기를 일으키는 원인인 자기 다발의 변화에 저항하는 방향으로 흐른다.
  - 와전류 (Eddy Current)
    - 맴돌이 전류
    - Jean Bernard Leon Foucault (1819~1900)가 처음으로 증명
    - 푸코전류(Foucault Current)
  - David Edward Hughes (1831~1900)
    - Alexander Graham Bell (1847~1922)이 1876년에 발명한 전화기이용
    - 1879년에 두 개의 코일을 이용하여 두 개의 동전을 비교
    - 동전의 닳아 있는 정도 및 온도의 차이에 따른 변화 감지
    - 구리의 전도도를 기준으로 다른 물질의 전도도를 구리에 대한 상대적인 값으로 측정
    - IACS (International Annealed Copper Standard)

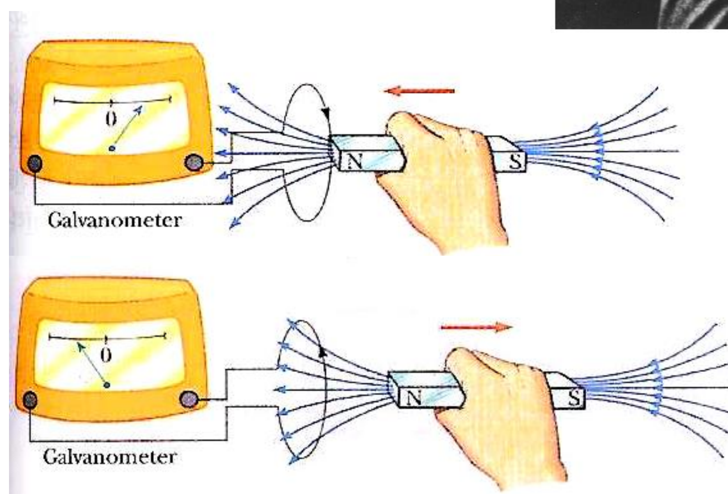
Faraday' Law

- 자기가 만드는 전기
  - 1831년 여름 Michael Faraday (1791~1867, 영국)
  - 자석과 코일 사이에 상대적인 운동이 검류계 회로에 전류 생성
  - 회로에 전지가 없을지라도 그 회로에 전류가 생성



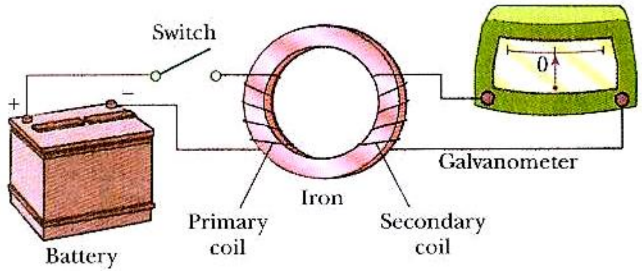
- 자기장의 변화에 의해 전류가 만들어 짐
  - Henry와 거의 동일한 실험을 수행하여 똑같은 발견을 함.
  - 논문으로 발표
  - Faraday's Law of Electromagnetic Induction

$$\boxed{\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}}$$

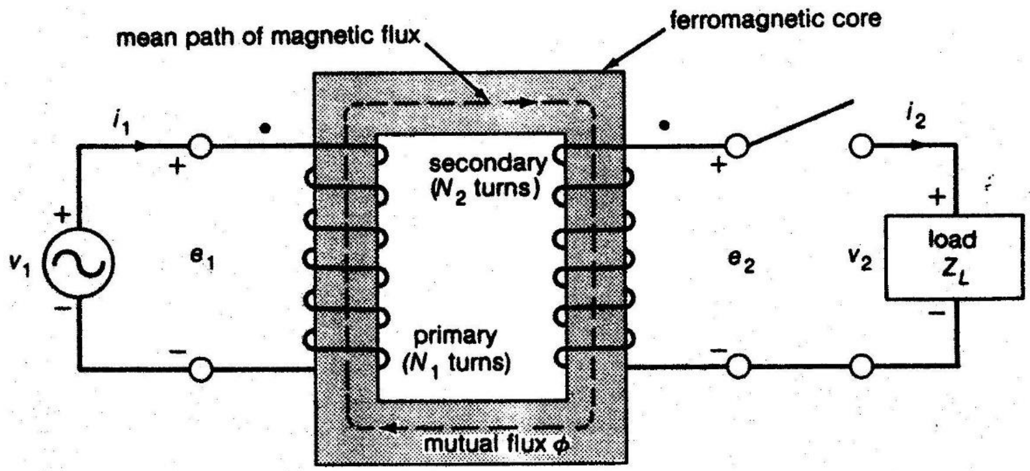


Faraday' Law

- 페러데이 실험



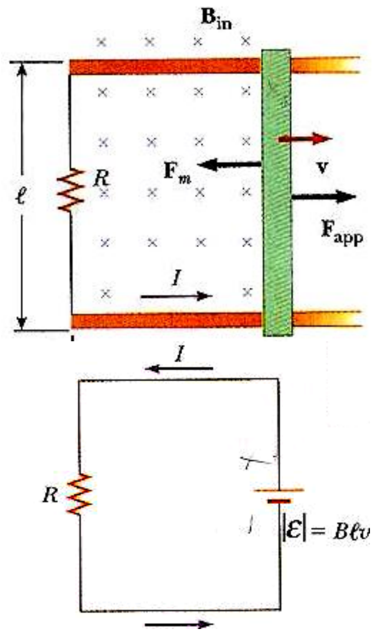
- 왼쪽 1차 스위치가 닫힐 때, 오른쪽 2차 회로의 검류계는 순간적으로 움직임



- 변압기 (Transformer)
  - 전자기 유도 현상
  - 전기에너지를 전기에너지로 변환
  - 권수비에 비례하여 전압 크기 변경
  - 권수비에 반비례하여 전류 크기 변경

운동 기전력

- 면적의 변화에 의한 기전력



- 회로의 면적이 lx이므로 $\Phi_B = Blx$
- 유도 기전력 : $\mathrm{E} = -N\dfrac{d\Phi_B}{dt} = -\dfrac{d}{dt}(Blx) = -Bl\dfrac{dx}{dt},$
- 유도전류의 크기 : $I = \dfrac{|\mathrm{E}|}{R} = \dfrac{Blv}{R}$

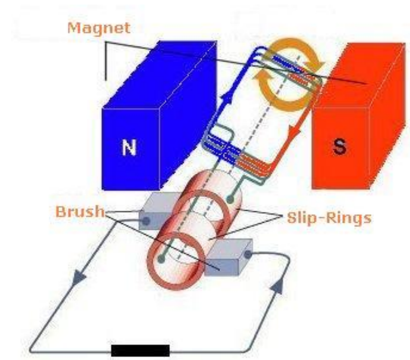
$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \longrightarrow e = -\frac{d\Phi}{dt}$$

$$\int(\nabla\times\mathbf{E})\cdot d\mathbf{S} = -\frac{\partial}{\partial t}\int\mathbf{B}\cdot d\mathbf{S} \xrightarrow[Stokes]{} \int E\cdot dL = -\frac{d\Phi}{dt} \qquad e = -\frac{d\Phi}{dt}$$

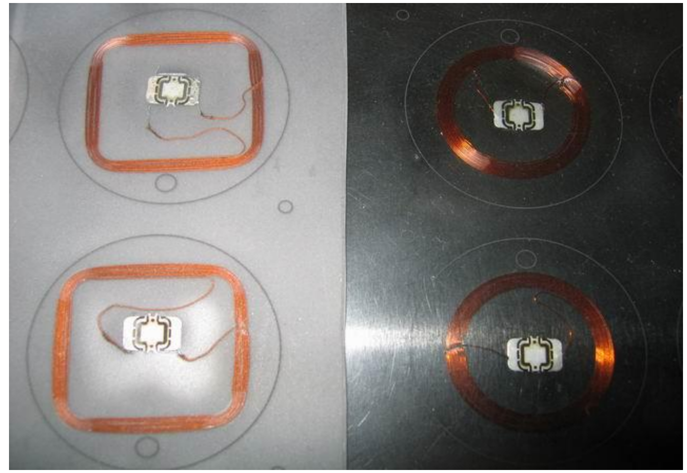
- 교류 발전기

$$\Phi_B = BA\cos\theta = BA\cos\omega t$$

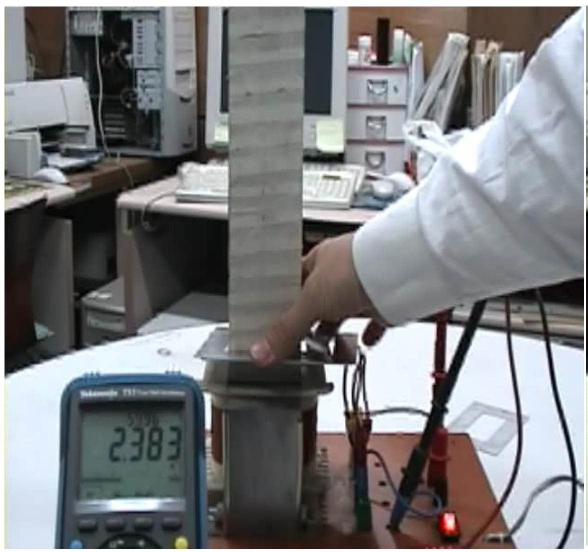
$$\mathrm{E} = -N\frac{d\Phi_B}{dt} = -NAB\frac{d}{dt}(\cos\omega t) = NBA\omega\sin\omega t$$



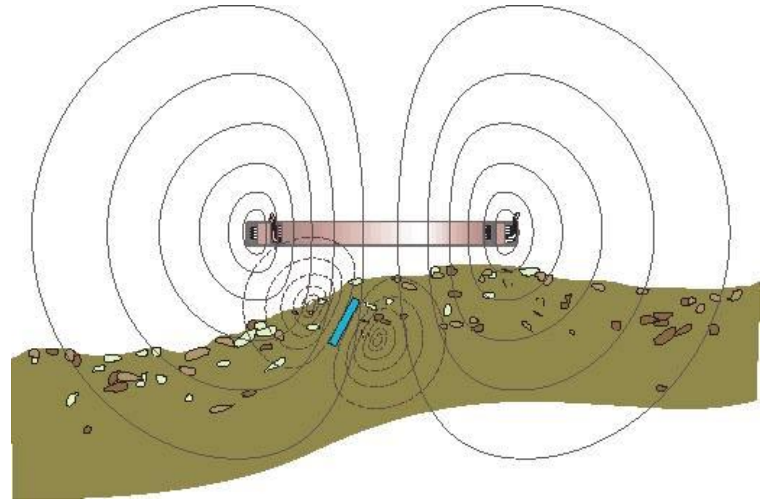
- RFID Card

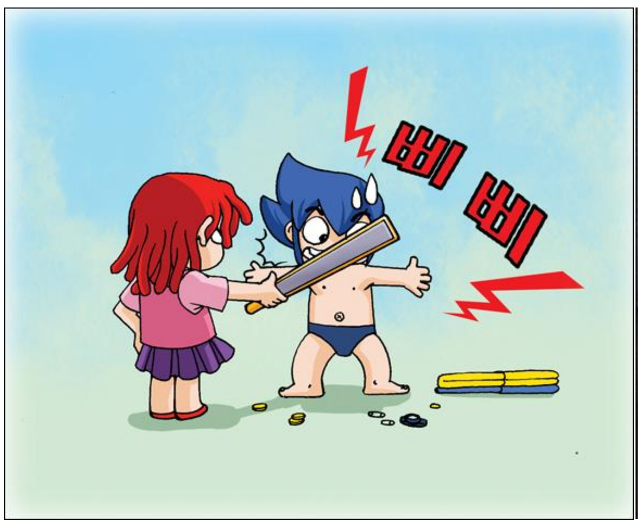


- EM Launcher



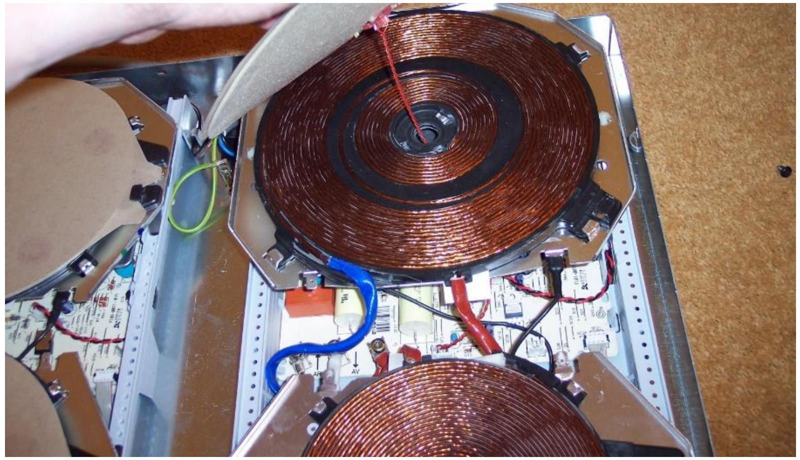
- 금속탐지기

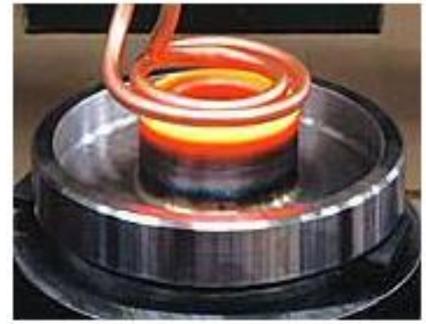




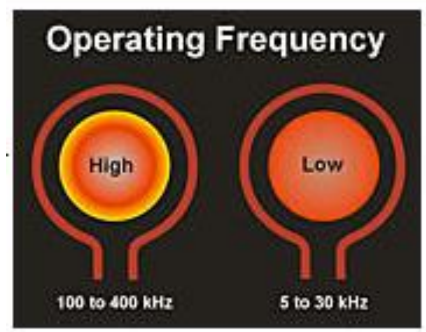
- 자기 브레이크 (Magnetic Brake)
  - 자이로드롭 제동 : 기계에너지 → 전기에너지

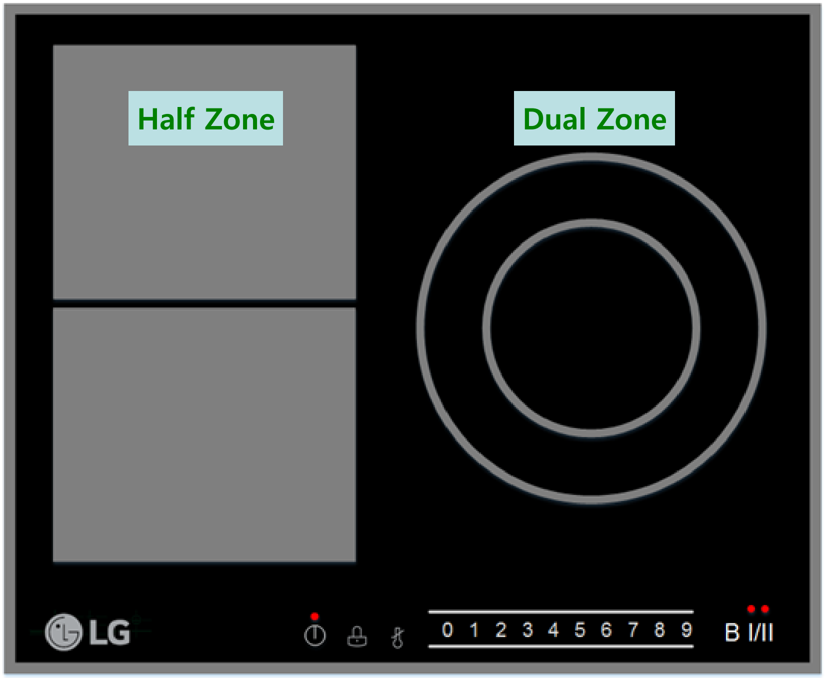
- Induction Cooker



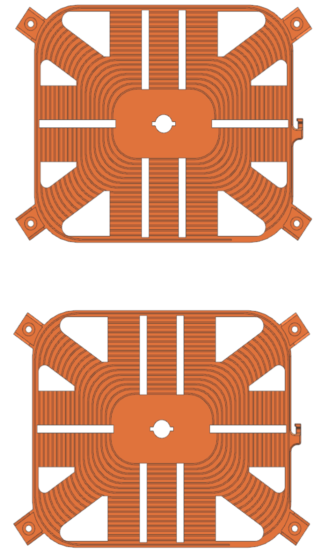


- IH (Induction Heating)

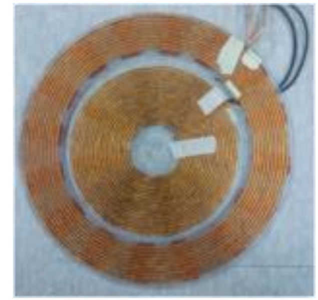


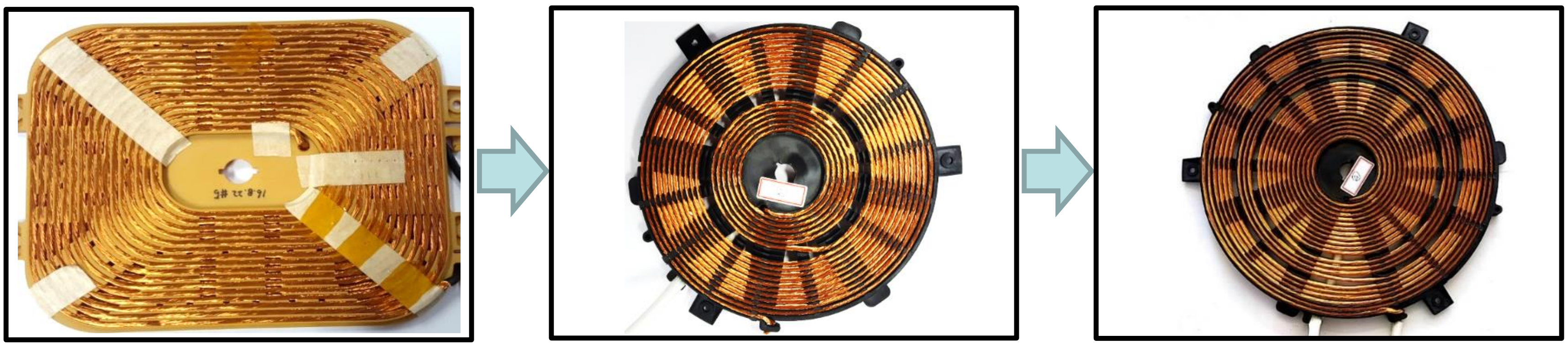


Half Zone



Dual Zone





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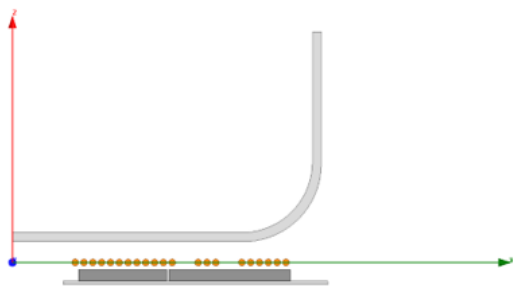
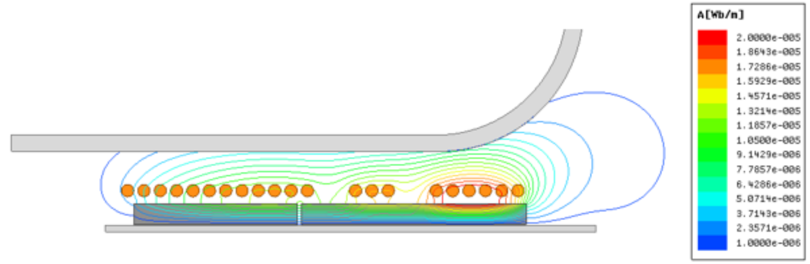
<tr><td>① Coil+Core+Shield</td><td></td><td>
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<tr><td colspan="2">P_{out}</td><td>2394W</td></tr>
<tr><td rowspan="3">loss</td><td>Coil</td><td>40.25W</td></tr>
<tr><td>Shield</td><td>15.28W</td></tr>
<tr><td>Case</td><td>.</td></tr>
<tr><td colspan="2">P_{in}</td><td>2449.53W</td></tr>
<tr><td colspan="2">η</td><td>97.7%</td></tr>
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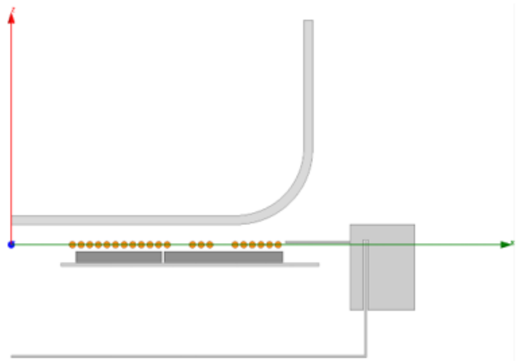
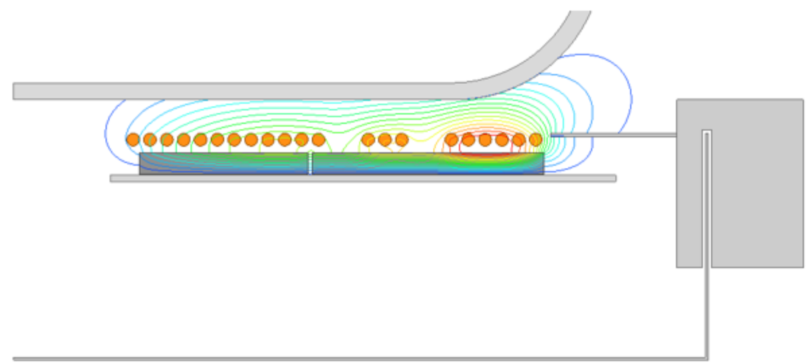
<tr><td>② Coil+Core+Shield+Case</td><td></td><td></td><td>
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<tr><td colspan="2">P_{out}</td><td>2348W</td></tr>
<tr><td rowspan="3">loss</td><td>Coil</td><td>40.25W</td></tr>
<tr><td>Shield</td><td>11.37W</td></tr>
<tr><td>Case</td><td>73.21W</td></tr>
<tr><td colspan="2">P_{in}</td><td>2461.46W</td></tr>
<tr><td colspan="2">η</td><td>95.4%</td></tr>
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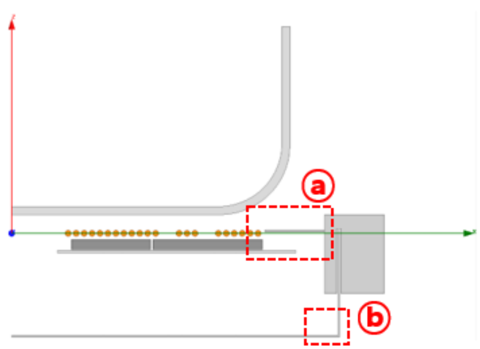
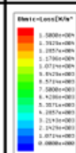
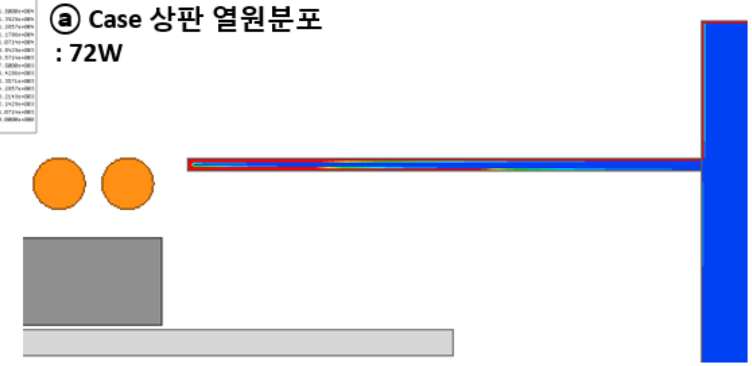
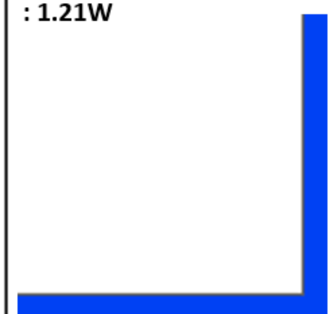
<tr><td colspan="2">※ ② Coil+Core+Shield+Case : 열원 분포

</td><td>
ⓐ Case 상판 열원분포
: 72W
</td><td>ⓑ Case 하판 열원분포
: 1.21W
</td></tr>
</table>

- <u>교류발전기 (AC Generator, Alternator)</u>
  - 기계에너지를 전기에너지로 변환

$$\Phi_B = BA\cos\theta = BA\cos\omega t$$

$$\mathrm{E} = -N\frac{d\Phi_B}{dt} = -NAB\frac{d}{dt}(\cos\omega t) = NBA\omega\sin\omega t$$