Dynamic Wireless EV Charging System

[너와 나의 연결고리]
2016024102 윤지원
2017083309 원윤재
2016033736 이정현

Idea Sketch

- Wireless Charging

FEM Analysis

- Modeling in Comsol

COMSOL MULTIPHYSICS®

System Design

- Simulink & LTspice

MATLAB® & SIMULINK®

Result Analysis

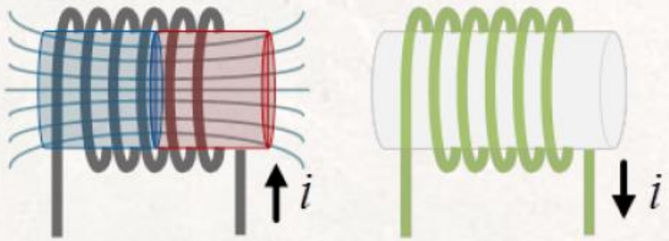
- Change in SOC versus Velocity

Idea Sketch

Idea Sketch : Dynamic Wireless Charging

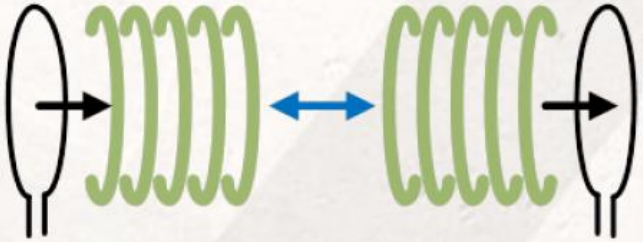
Wireless Charging Methods

자기 유도 방식



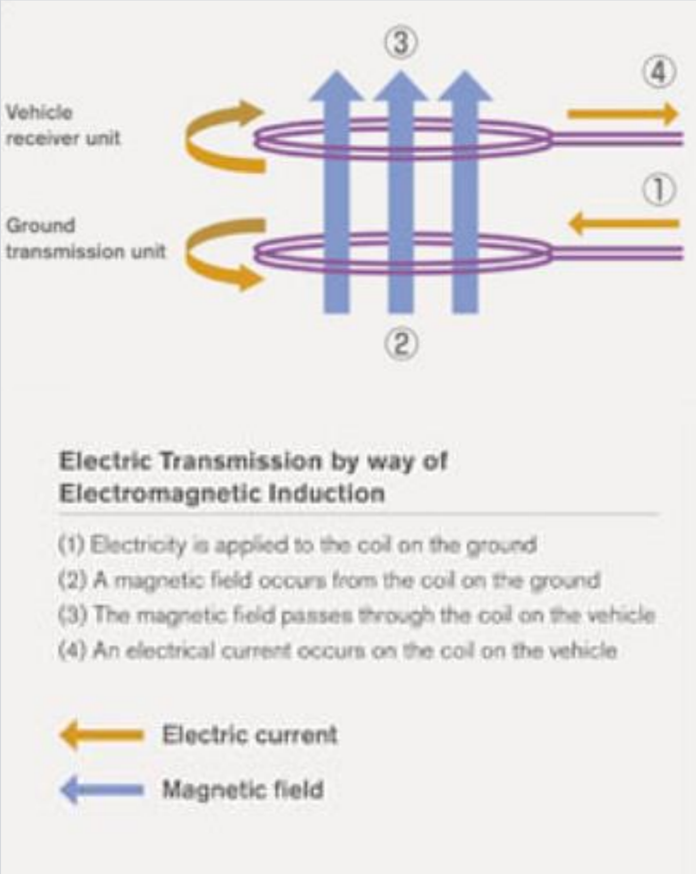
- 송수신 코일 간의 자기유도 현상 이용
- 충전 효율 좋음
- 전자파의 영향 낮음
- 무선 충전 거리가 짧음

자기 공진 방식



- 송수신 공진기 간 자기공진 특성 이용
- 원거리 충전 가능
- 물리적 위치에 따른 전력 손실
- 인체에 유해한 전자파 발생

Faraday's Law of Electromagnetics



Nissan Global

- 전자기 유도
- 유도 기전력

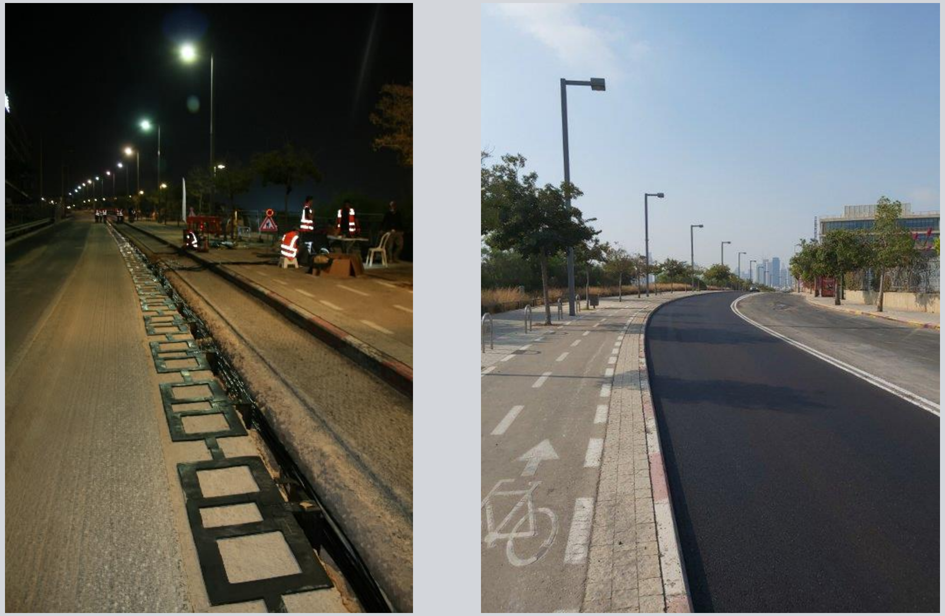
$$\mathrm{emf} = -N\frac{d\emptyset}{dt} \text{ [V]}$$

- 유도 전류

GM Chevrolet

Shared Energy Platform : Electreon

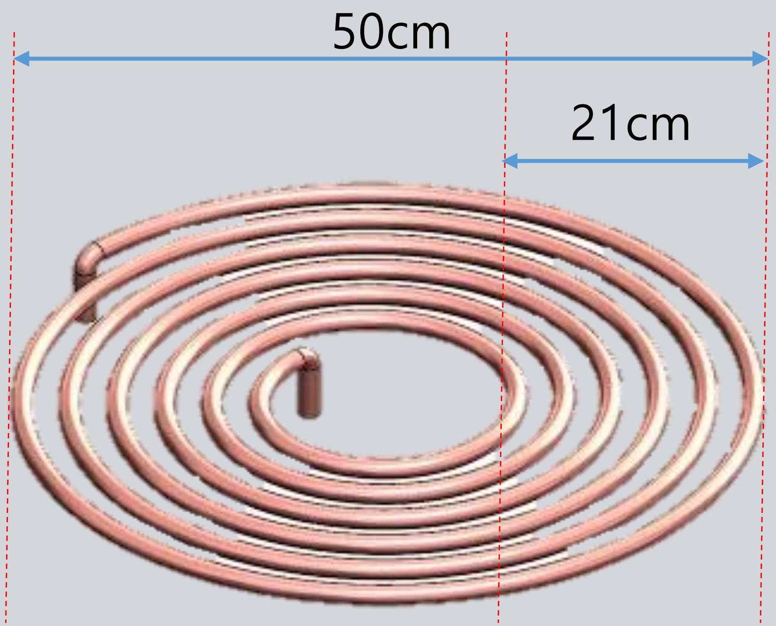
Wireless Charging Roads Example

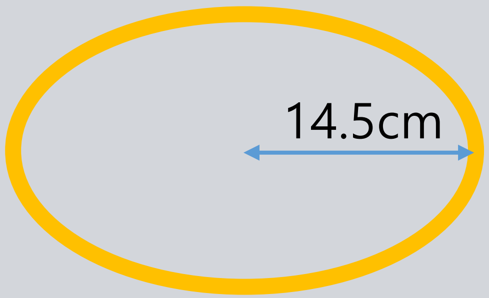


Tel Aviv, Israel
Electreon

Daejeon, South Korea
KAIST

Coil Parameter Decision





Number of Turns : 15

Current through wire : I

Average Winding Radius : 14.5cm

Current through wire : 15 * I

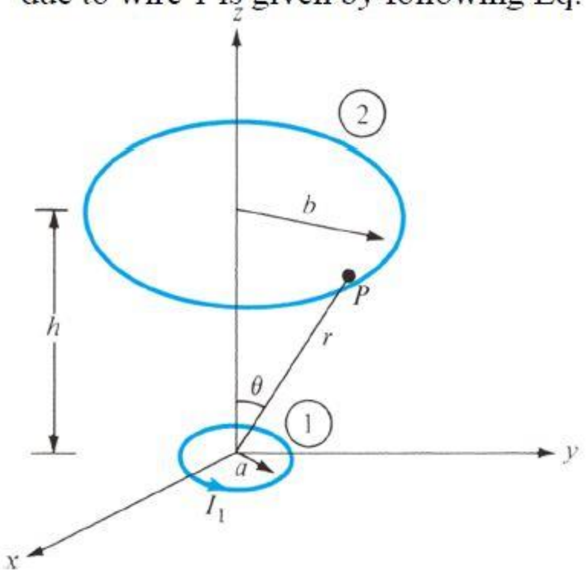
Finding Mutual Inductance

Example 8.13

Two coaxial circular wire of radii a and $b(b>a)$ are separated by distance $h(h>>a,b)$ as shown in Figure. Find the mutual inductance between the wires.

Solution :

Let current I_1 flow in wire 1. At an arbitrary point P on wire 2, the magnetic vector potential due to wire 1 is given by following Eq.



$$\mathbf{A} = \frac{\mu I_1 a^2 \sin\theta}{4r^2}\mathbf{a}_\phi = \frac{\mu I_1 a^2 b}{4[h^2+b^2]^{3/2}}\mathbf{a}_\phi$$

If $h>>b$ $\quad \mathbf{A}_1 = \frac{\mu I_1 a^2 b}{4h^3}\mathbf{a}_\phi$

Hence,

$$\Psi_{12} = \oint_L A_1 \cdot dl_2 = \frac{\mu I_1 a^2 b}{4h^3}\cdot 2\pi b = \frac{\mu \pi I_1 a^2 b^2}{2h^3}$$

$$\therefore \quad M_{12} = \frac{\Psi_{12}}{I_1} = \frac{\mu \pi a^2 b^2}{2h^3}$$

Choosing Values of L & M & k

$$L_1 = \frac{a^2 N^2}{8a + \pi w} = 260(\mu H)$$

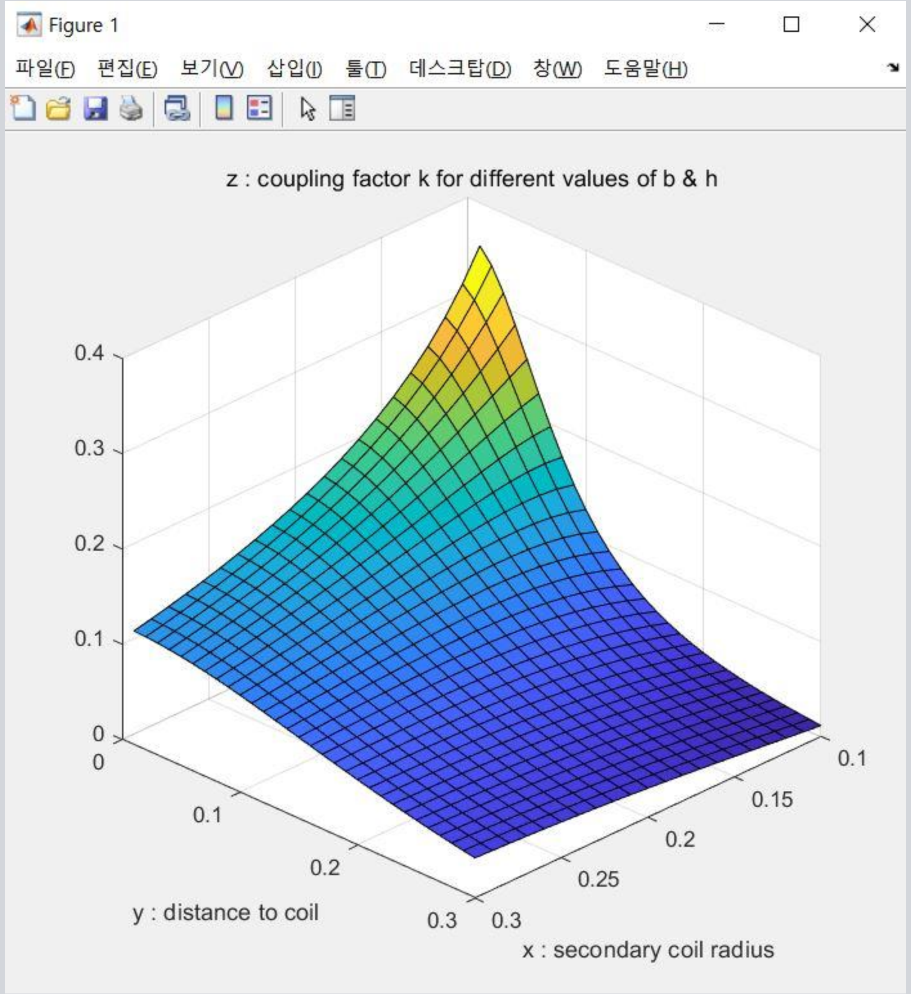
$$L_2 = \frac{b N^2}{8b + \pi w}$$

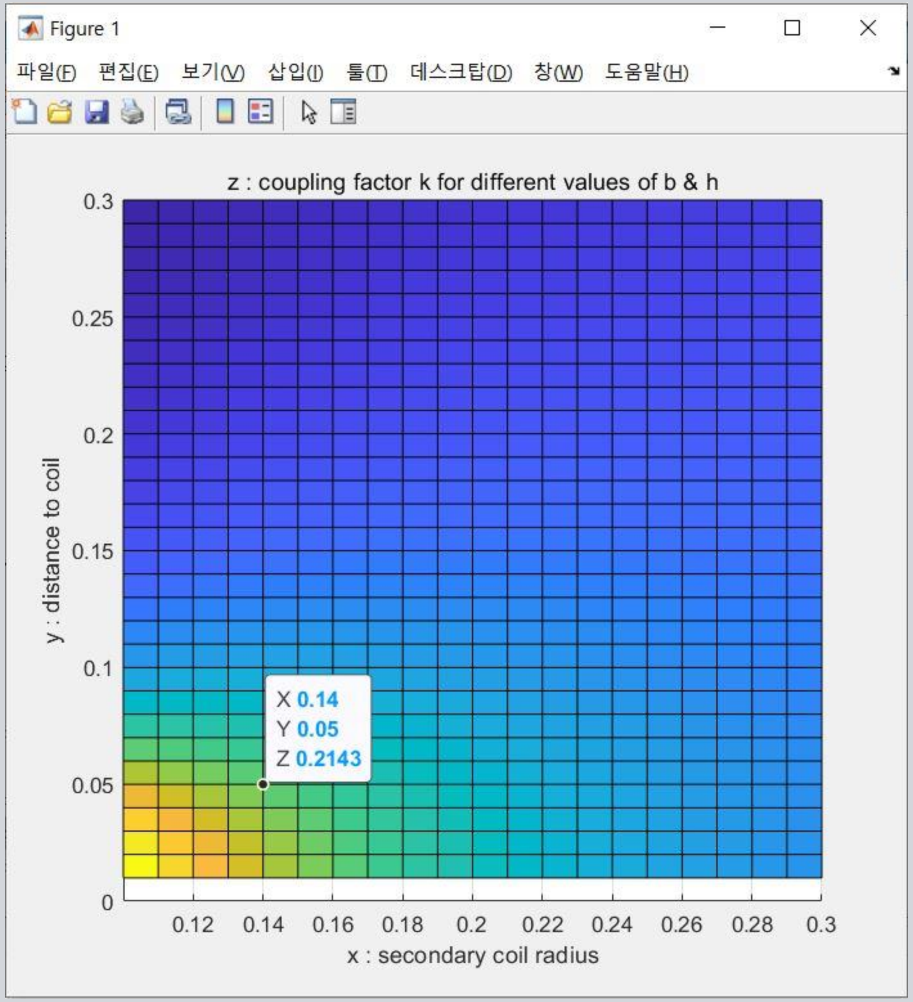
$$M = \frac{\mu_0 \pi a^2 b^2 N^2}{2(b^2 + h^2)^{\frac{3}{2}}}$$

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

```
clc; clear all
a = 0.145;
w = 0.21;
mu0 = 4*pi*10^-7;
N = 15;
h = [0.01:0.01:0.3];    % choosing displacement between TX~RX (h)
b = [0.1:0.01:0.3];     % choosing RX coil radius (b)
L1 = (a^2*N^2)/(8*a+pi*w)*10^-4;
L20 = (b(1)^2*N^2)/(8*b(1)+pi*w)*10^-4;

x = length(b);
y = length(h);

L2 = L20 * ones(x,1);

for i = 1:x
    L2(i) = (b(i)^2*N^2)/(8*b(i)+pi*w)*10^-4;
end

M0 = (mu0*pi*a^2*b(1)^2*N^2)./(2*(h(1)^2+b(1)^2)^1.5);
M = M0*ones(y,x);

for j = 1:y
    for i = 1:x
        K(j,i) = ((mu0*pi*a^2*b(i)^2*N^2)/(2*(h(j)^2+b(i)^2).^1.5))/sqrt(L1*L2(i));
    end
end

surf(b,h,K)         % coupling factor K
axis on
xlabel('x : secondary coil radius');
ylabel('y : distance to coil');
title('z : coupling factor k for different values of b & h');
grid on
```

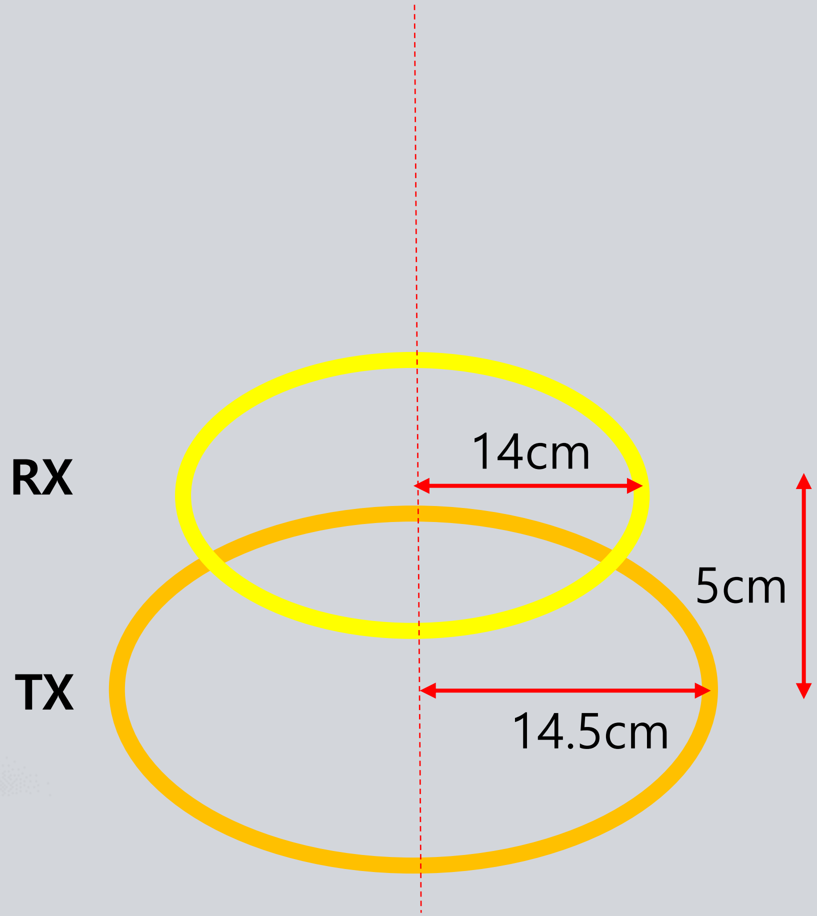
Choosing Values of L & M & k





Coil Radius : 14cm, Distance between Coils : 5cm, Coupling Coefficient k = 0.2143

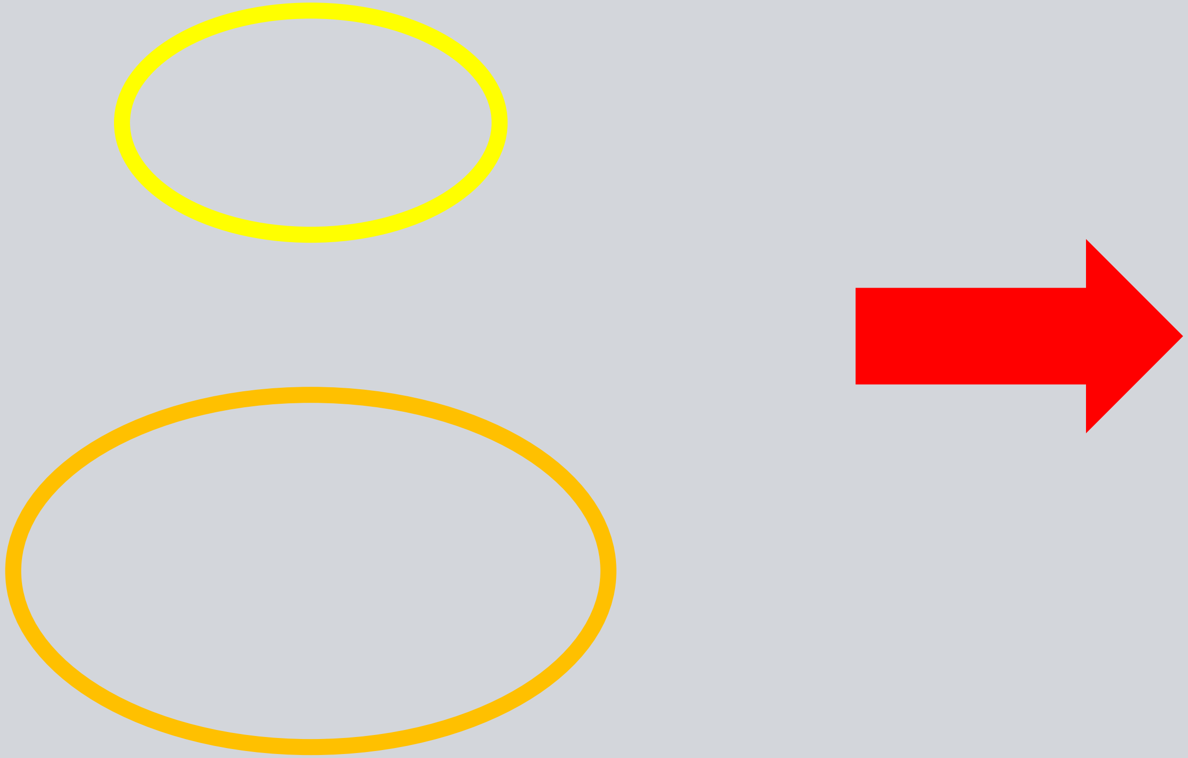
Coil Design



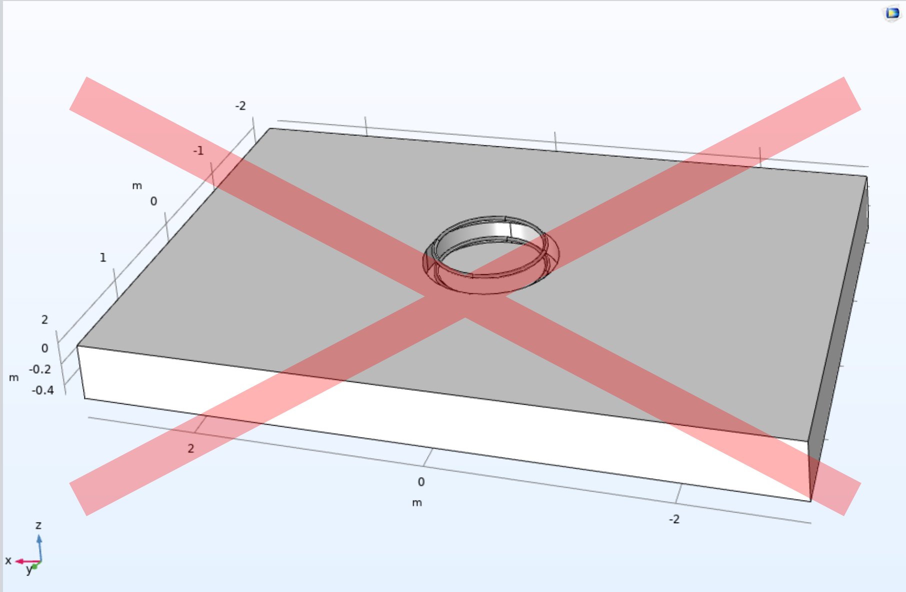
Coupling Coefficient k = 0.2143

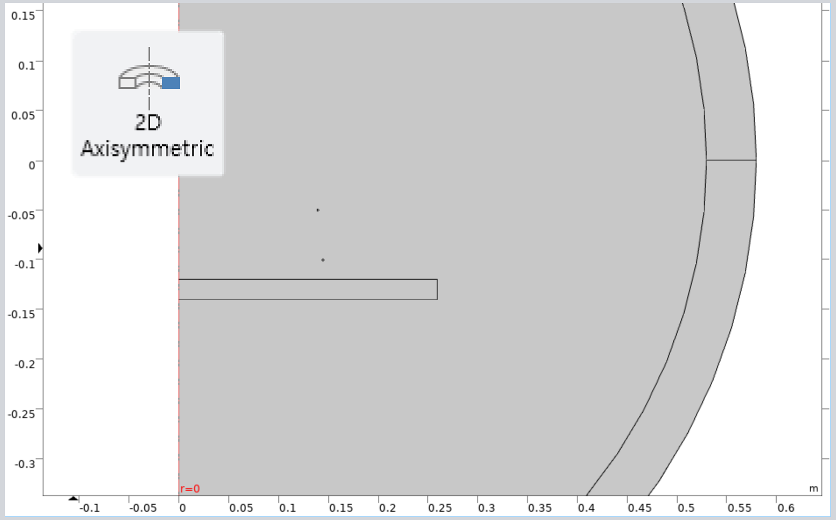
FEM Analysis

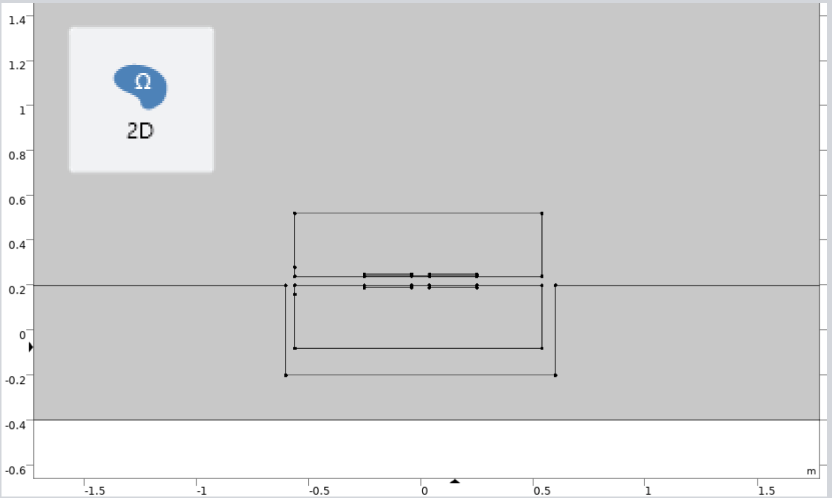
Charging Coil Modeling



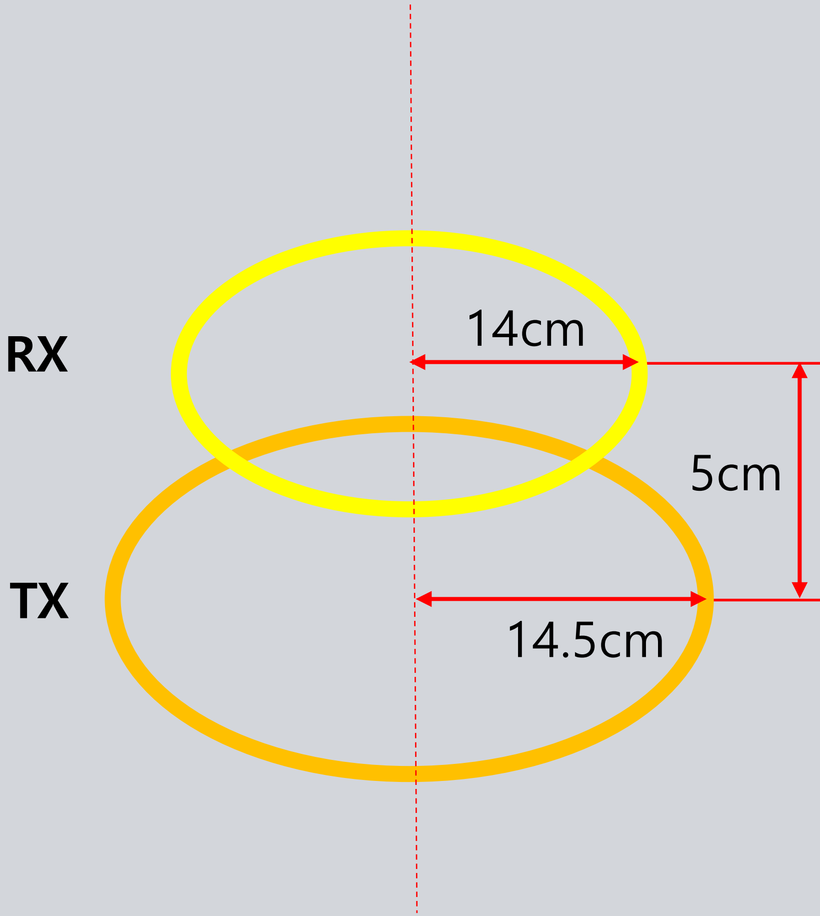
Charging Coil Modeling

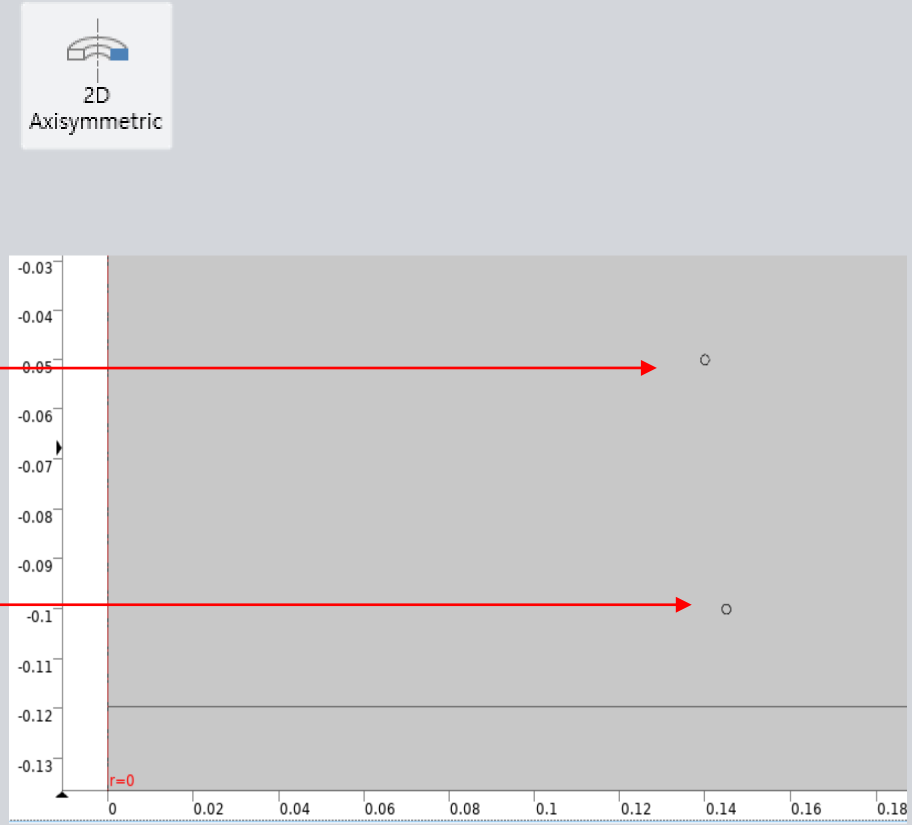


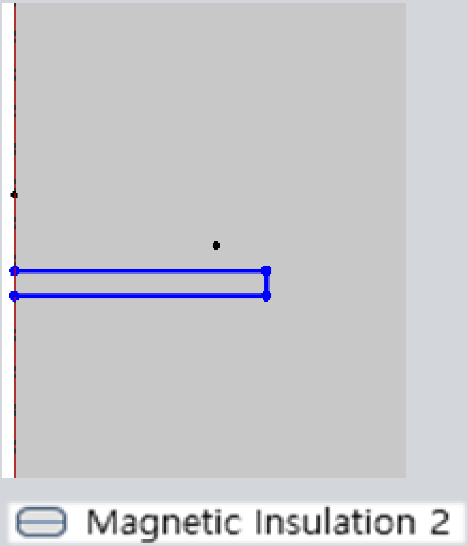




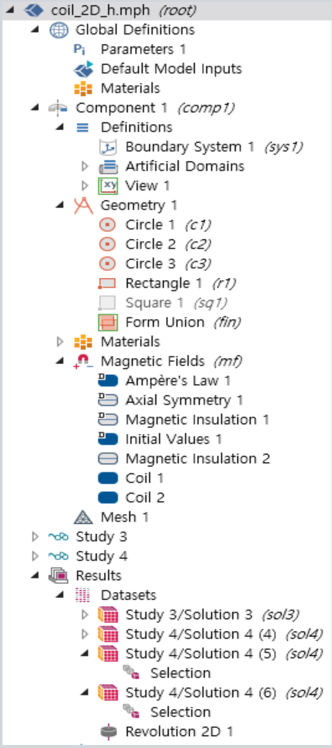
Charging Coil Modeling : Coil Spacing

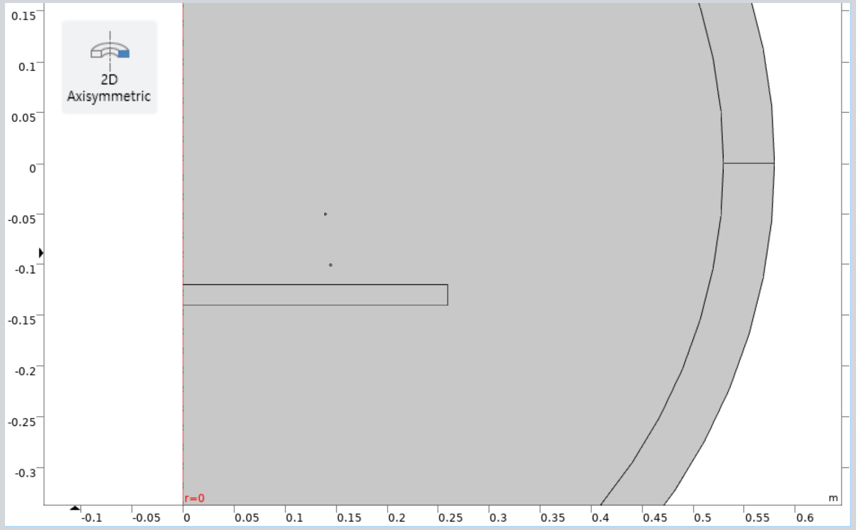


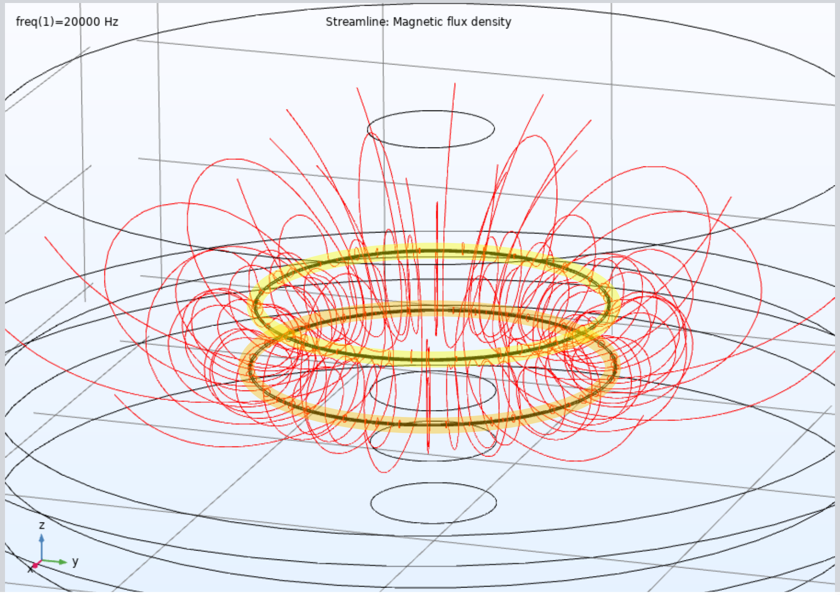


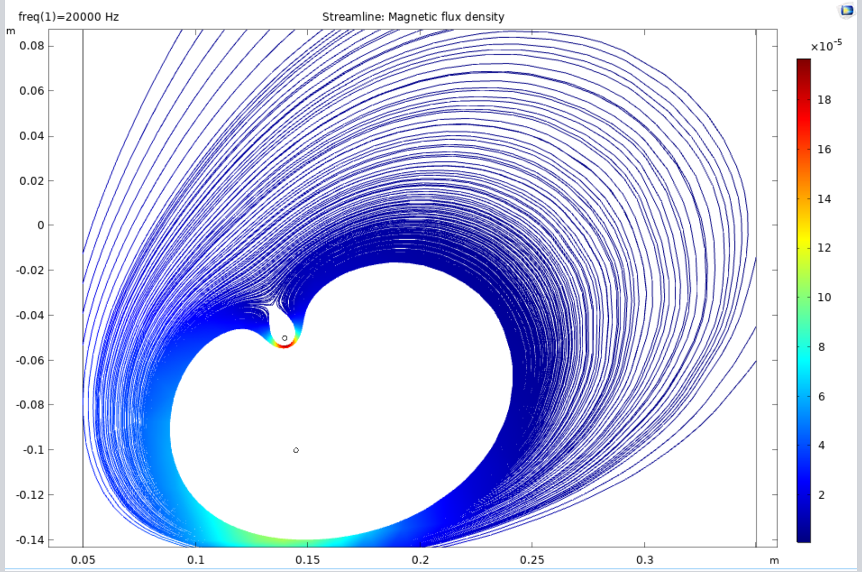


Charging Coil Modeling : Coil Spacing

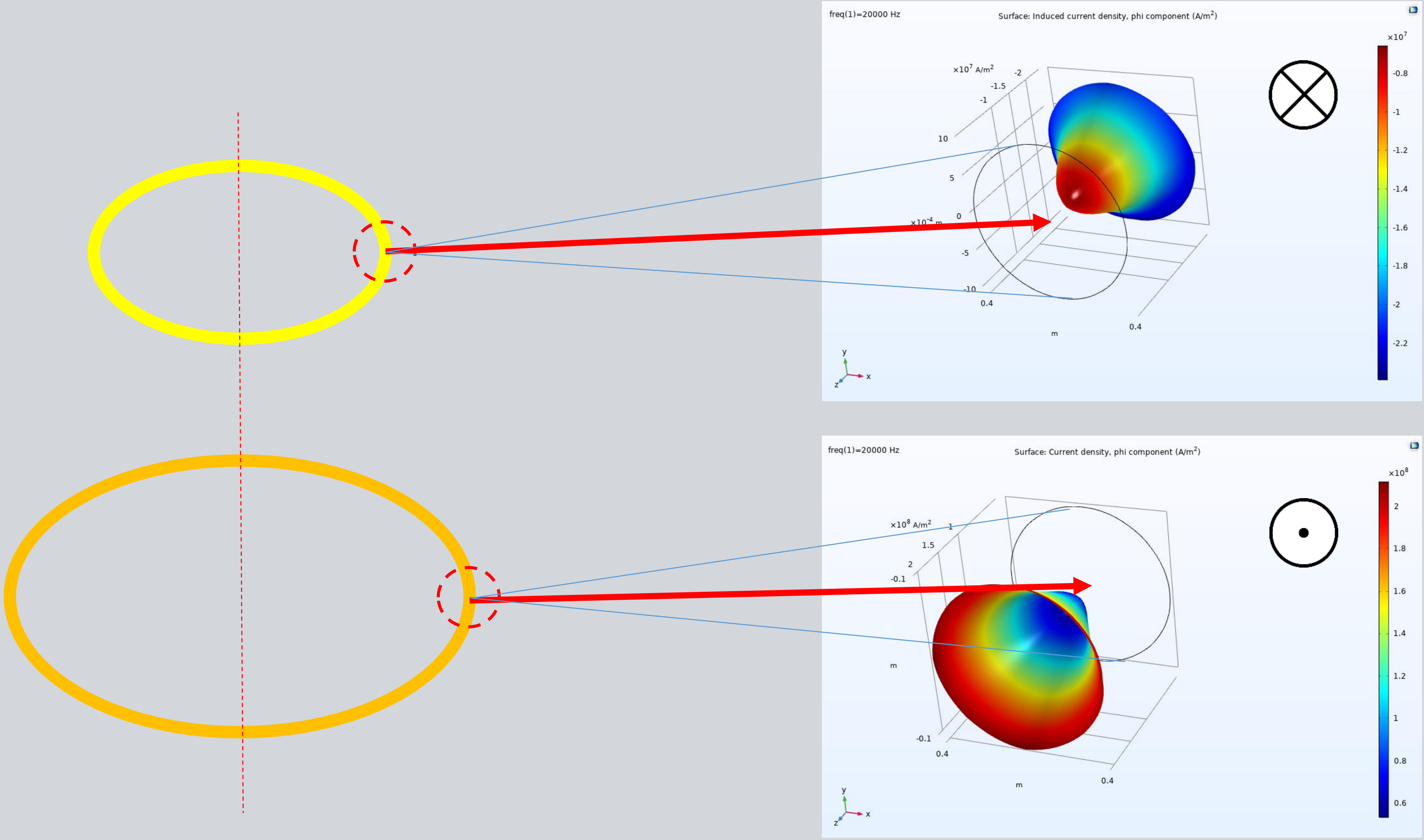




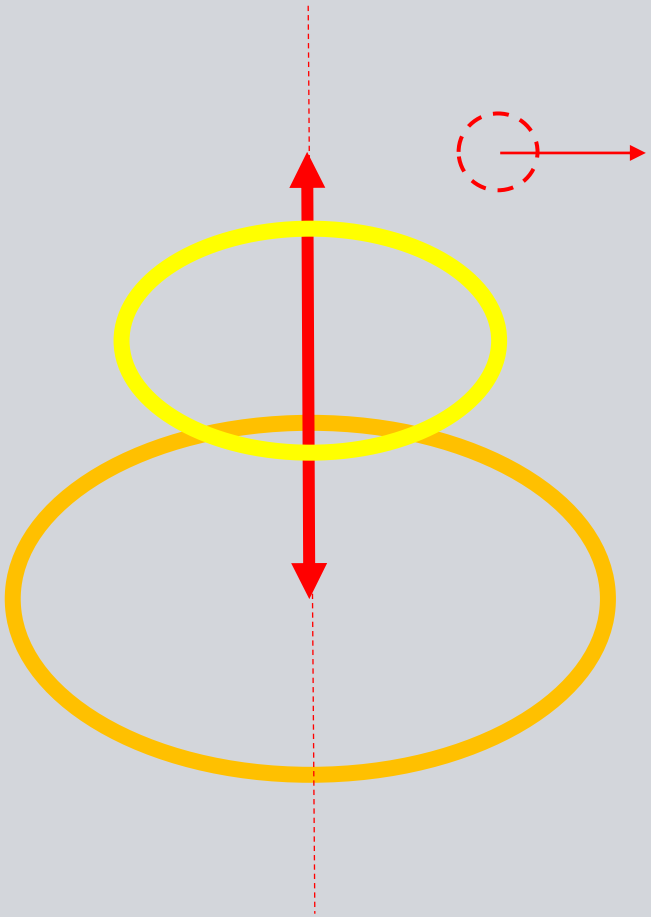




Charging Coil Modeling : Coil Spacing

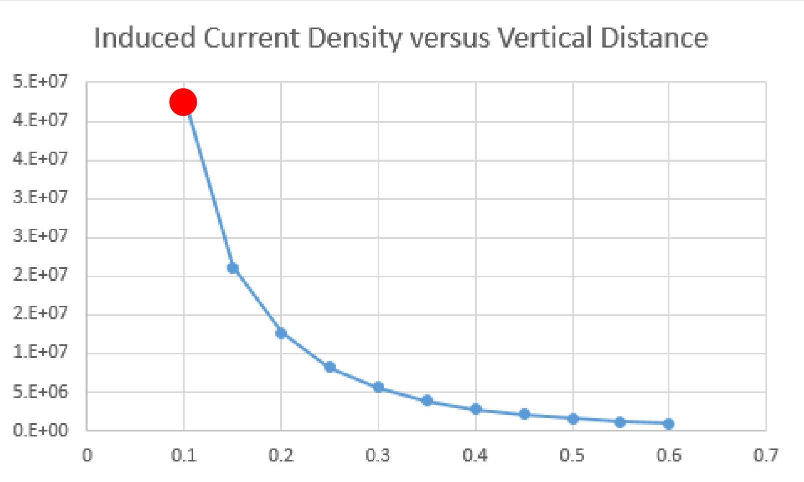


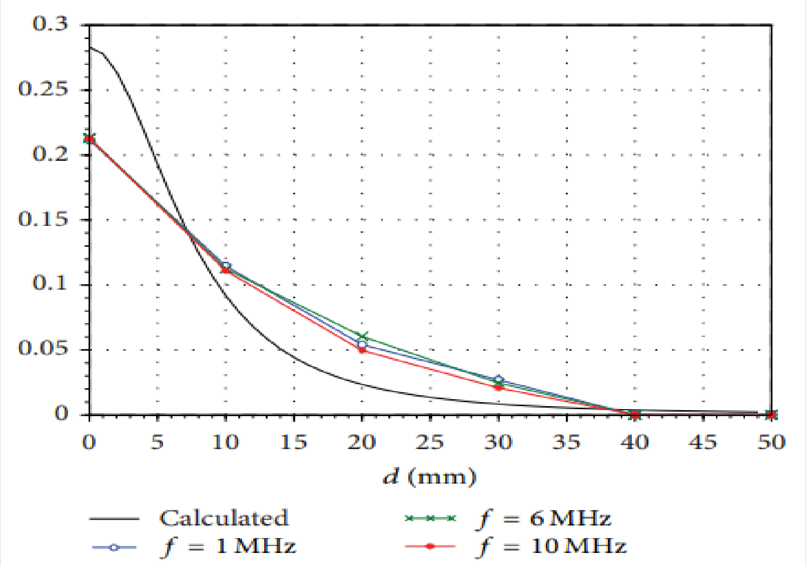
Charging Coil Modeling : Coil Spacing



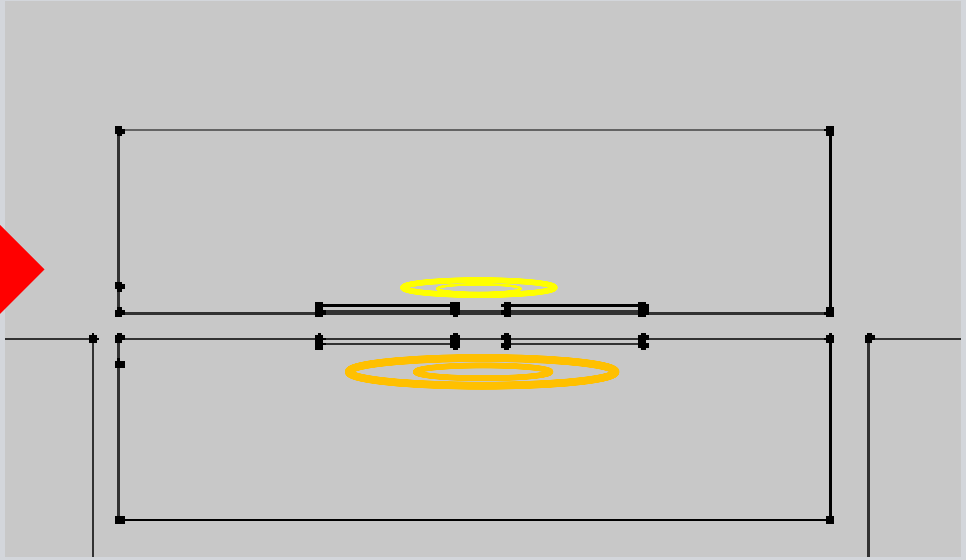
Surface Integration 4

Distance	Induced J_Avg
0.1	4.E+07
0.15	2.E+07
0.2	1.E+07
0.25	8.E+06
0.3	6.E+06
0.35	4.E+06
0.4	3.E+06
0.45	2.E+06
0.5	2.E+06
0.55	1.E+06
0.6	9.E+05





Charging Coil Modeling : Lateral Misalignment



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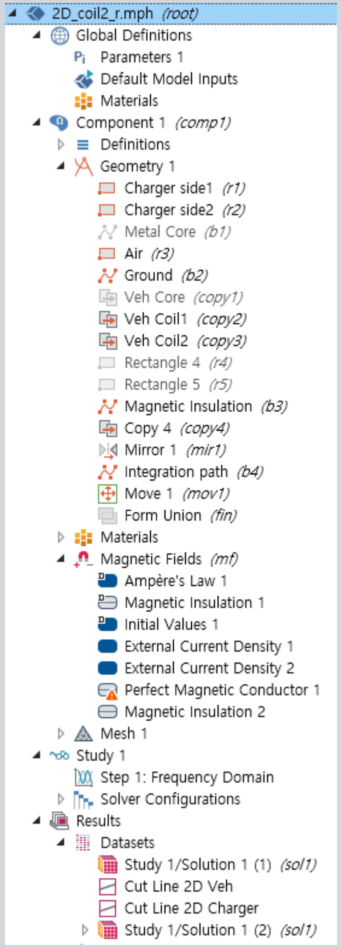
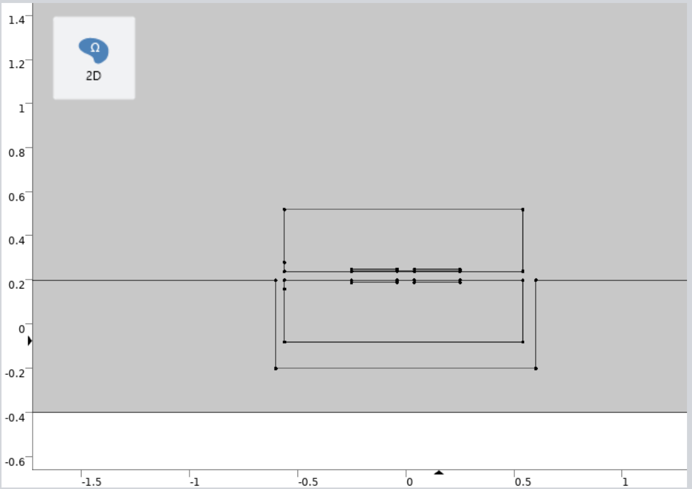
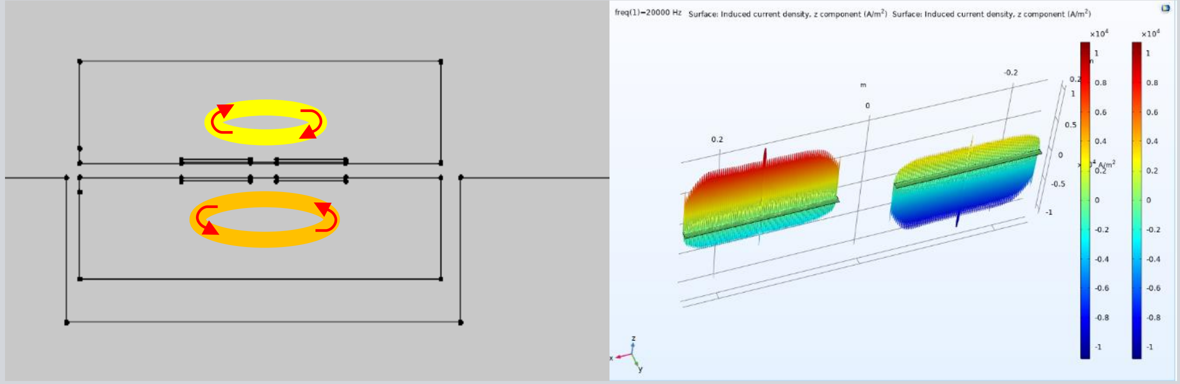
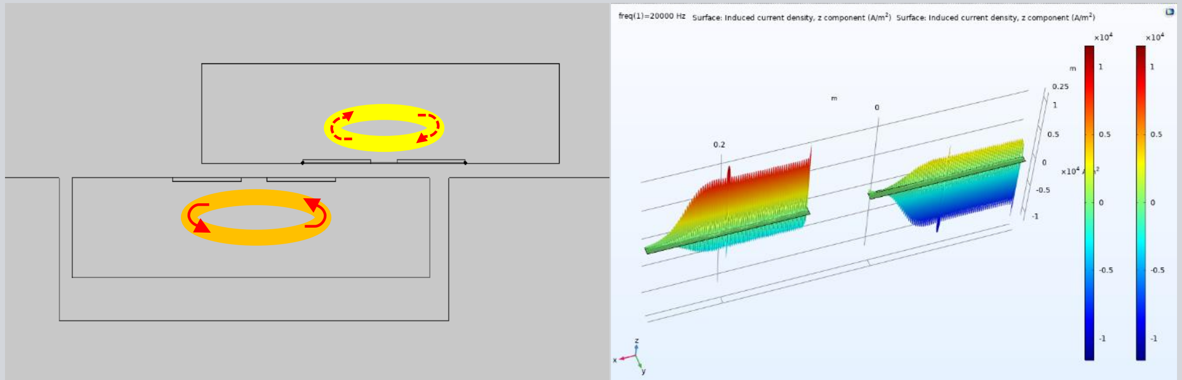
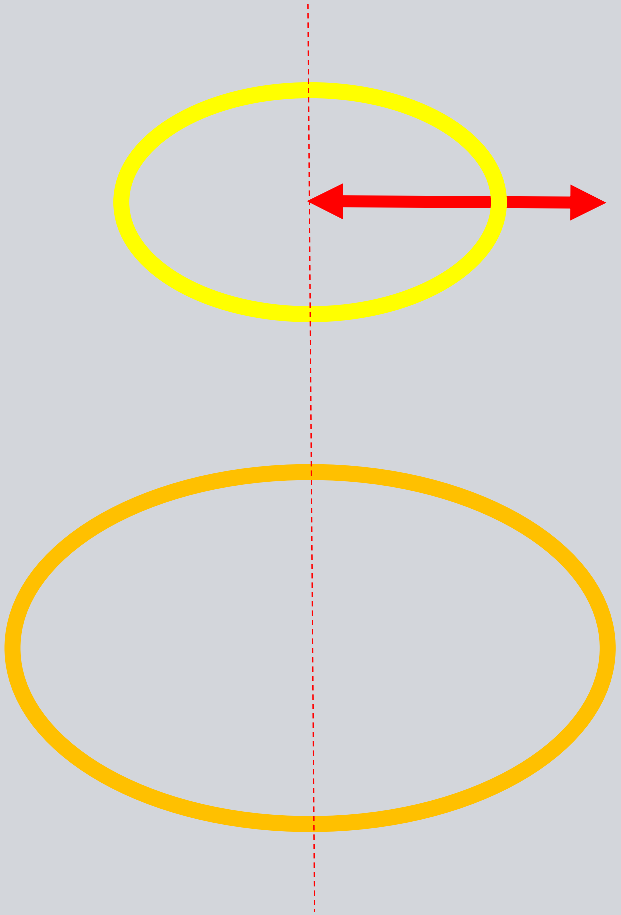




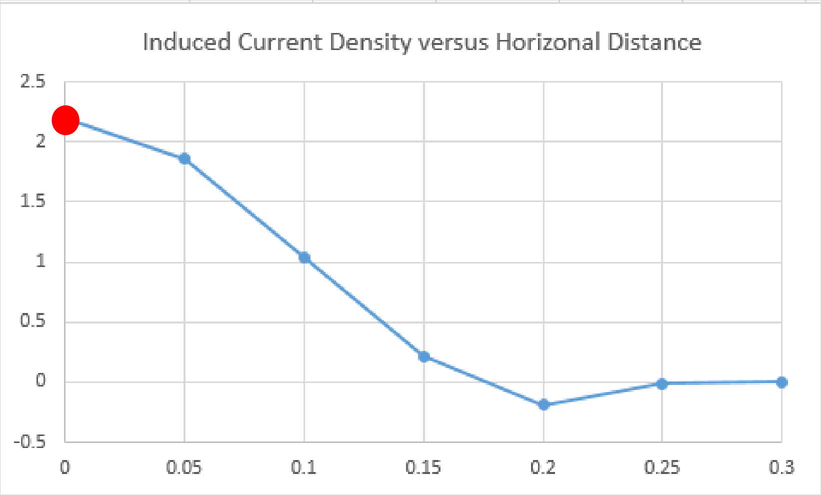




Charging Coil Modeling : Lateral Misalignment



Misalignment	Induced J_Integrated
0	2.1977
0.05	1.8574
0.1	1.0432
0.15	0.21424
0.2	-0.18734
0.25	-0.010736
0.3	-0.000109
0.35	5.2328E-06
0.4	2.112E-07
0.45	-2.8234E-07
0.5	-7.7771E-07



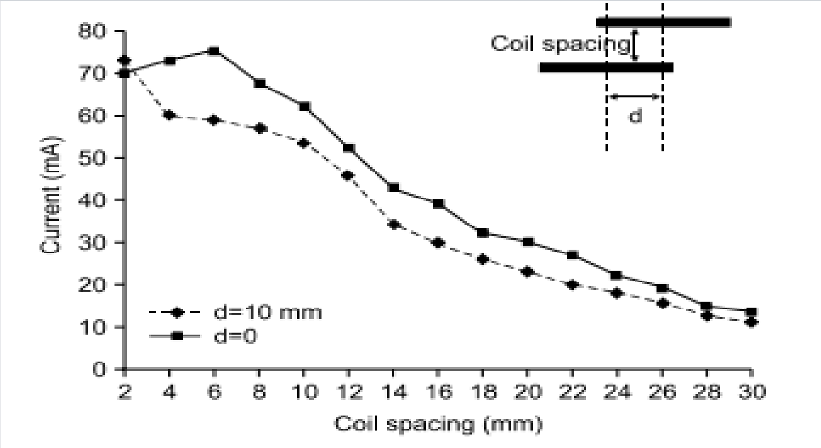


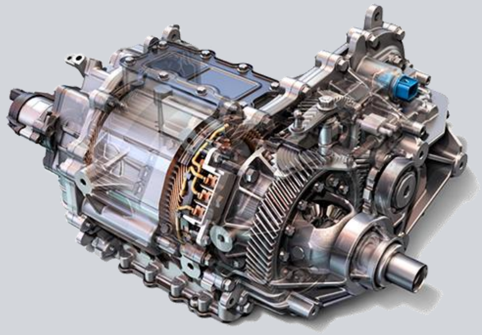
Fig. 7. Variation of transmitter current against spacing for lateral misalignment.

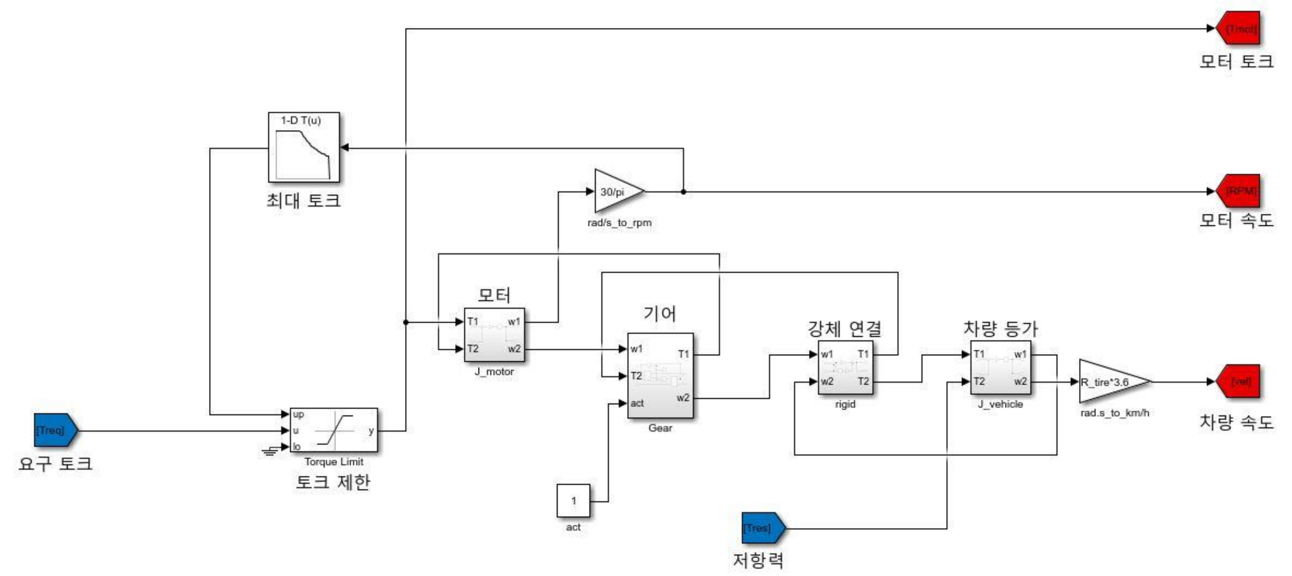
System Design

Reference Vehicle Model : GM Bolt EV

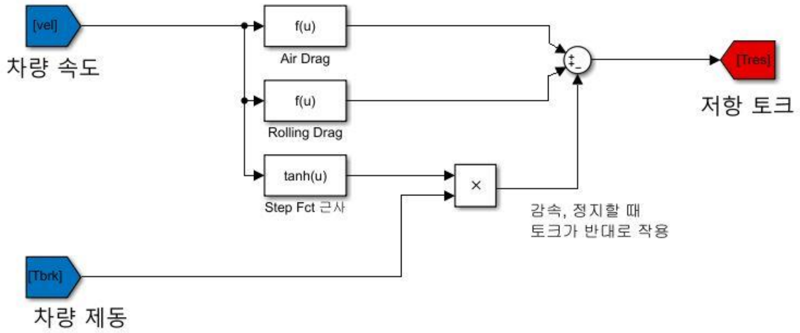
```
%% Input data
rho_air = 1.226; % Air density [kg/m^3]
g = 9.81; % Gravitational acceleration [m/s^2]
Kp = 500; Ki = 100; % Driver gain
FGR = 7.05; % Gear ratio
R_tire = 0.323; % Tire radius [m]
m_veh = 1625; % Vehicle mass [kg]
J_mot = 0.1; % Motor inertia [kg*m^2]
mu_roll = 0.01; % Rolling resistance
A = 2.397; Cd = 0.308; % Air resistance
tau_filter = 0.1;
brk_tq = 1000; % Brake capacity [N*m]
tq_regen = 250; % Regenerative brake capacity [N*m]
Tm = 360; % Motor spec.: maximum torque [N*m]
Pm = 150000; % Motor spec.: maximum power [W]
RPMm = 8800; % Motor spec.: maximum speed [rev/min]
SOC_init = 50; % Initial SOC [%]
C_nom = 60/350 * 1000; % rate capacity [Ah]
```

Reference Vehicle Model : GM Bolt EV

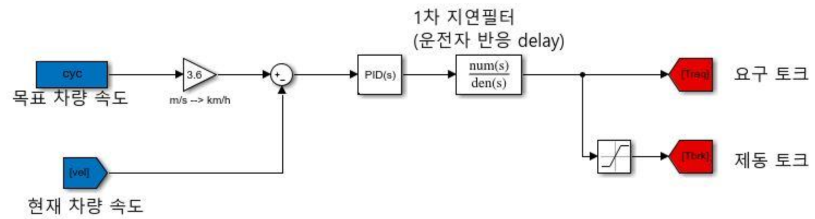




Powertrain

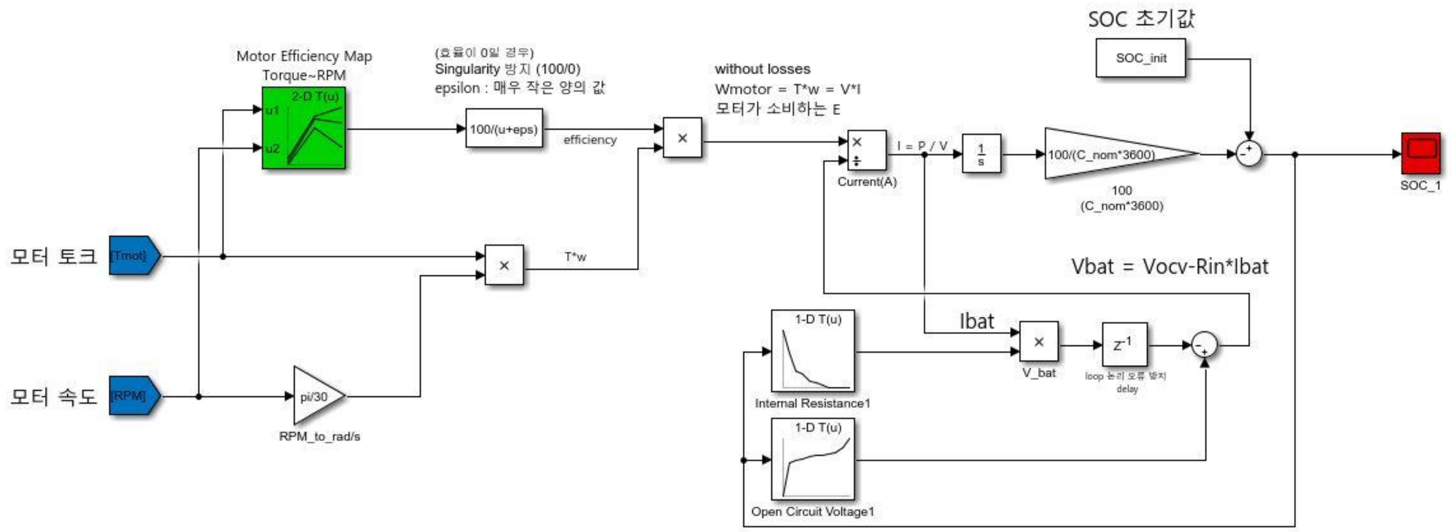


Drag Force

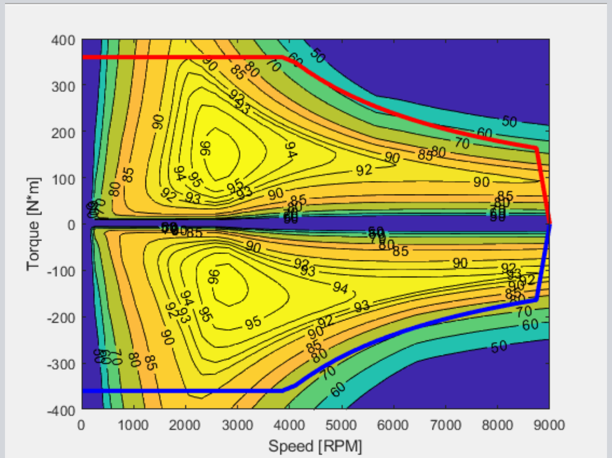


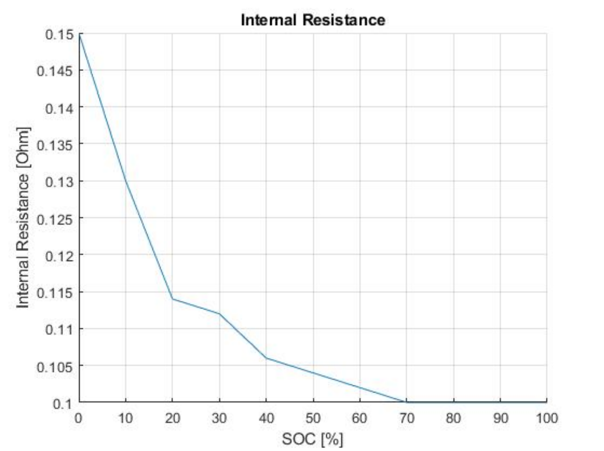
Driver Control

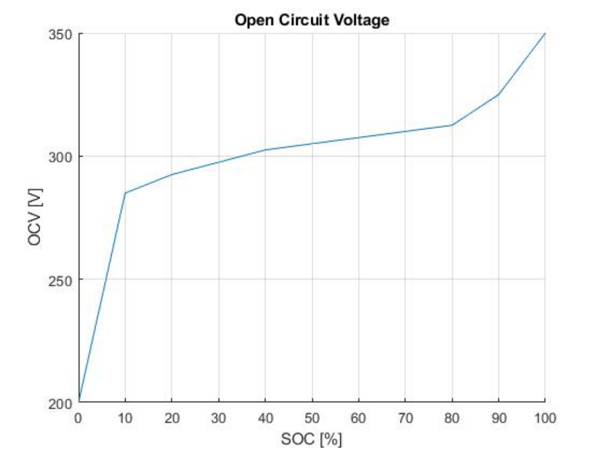
Reference Vehicle Model : GM Bolt EV



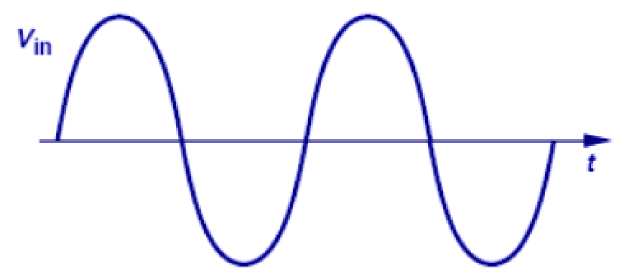
Battery SOC of Bolt EV

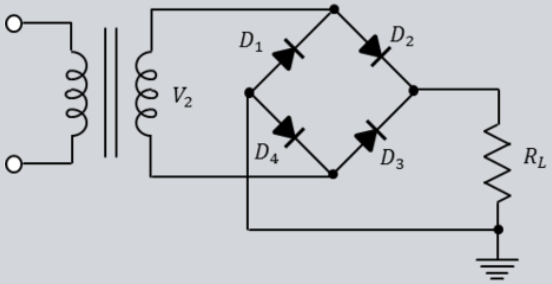


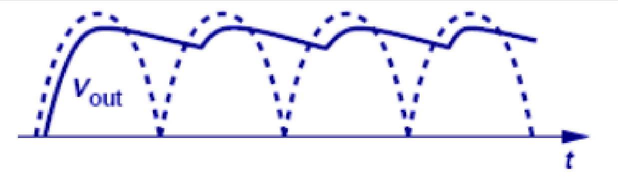


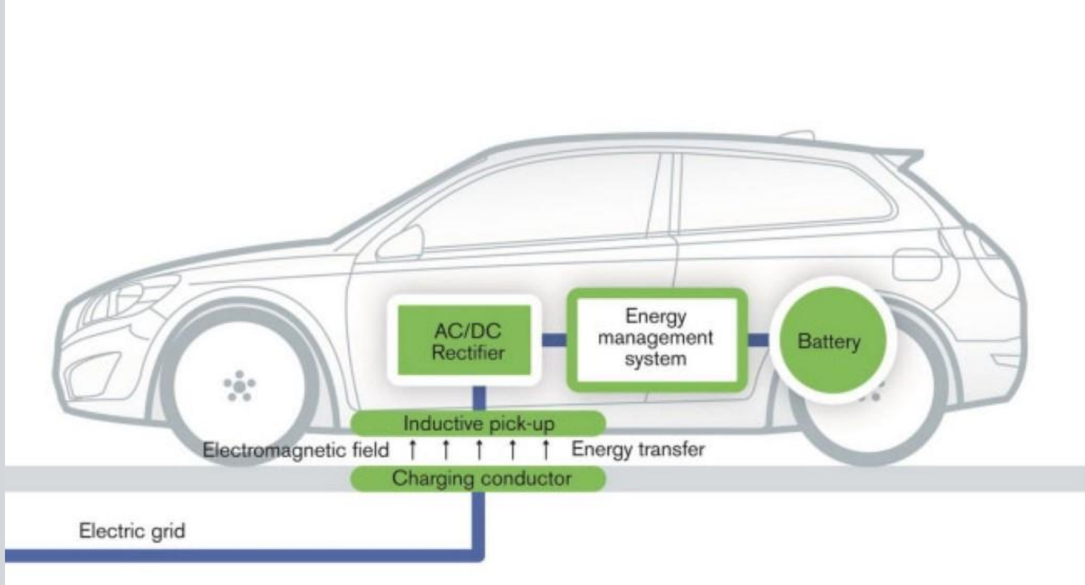


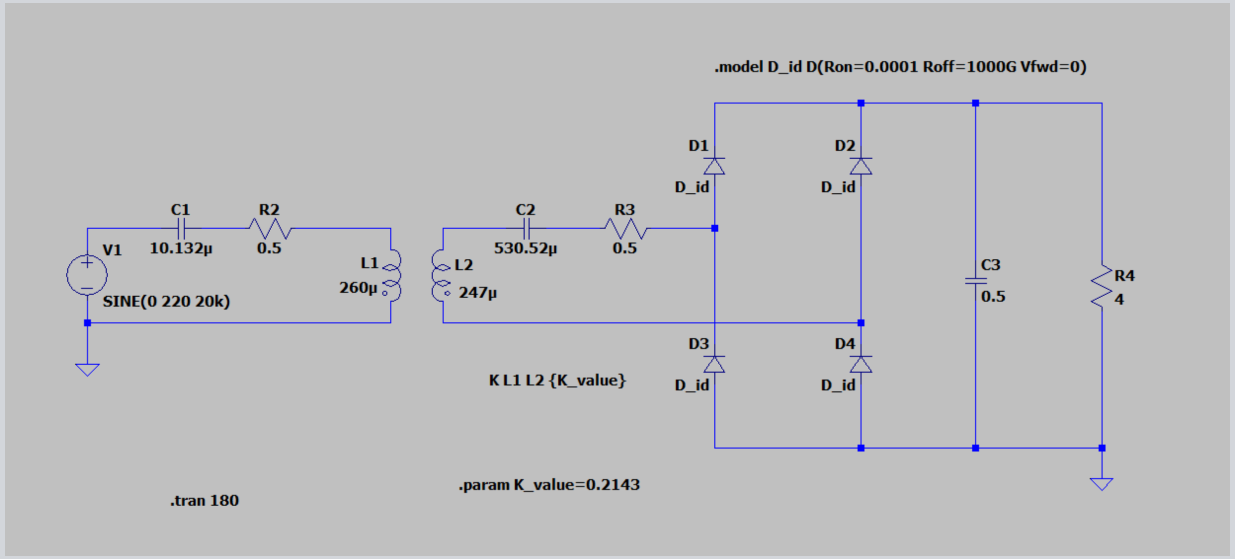
AC-DC Full Wave Rectifier



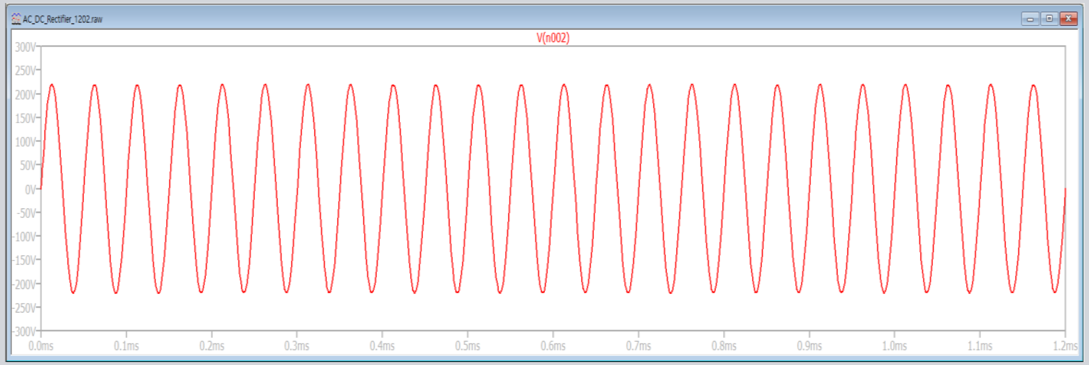


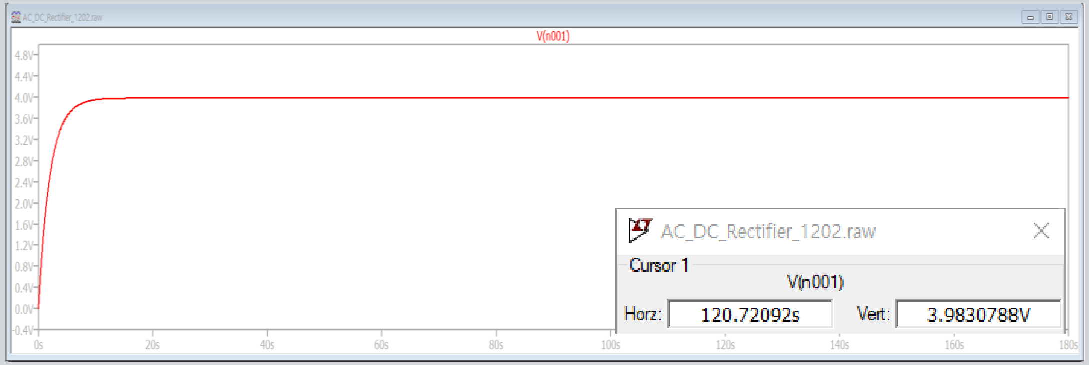


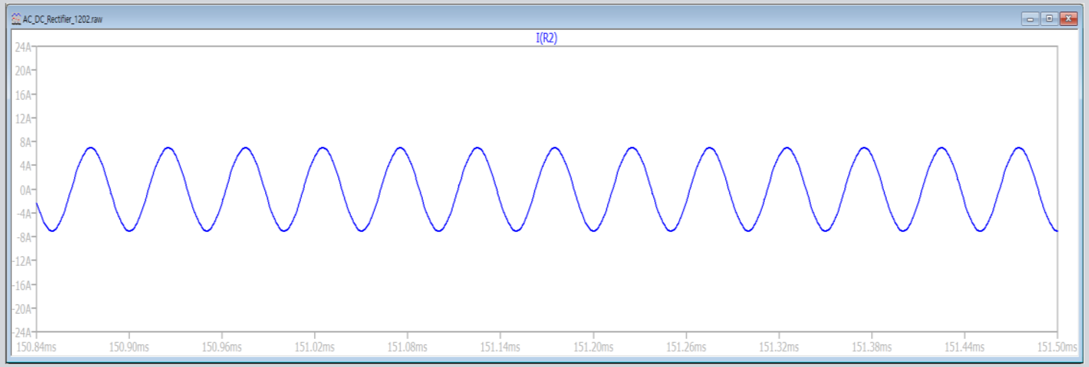


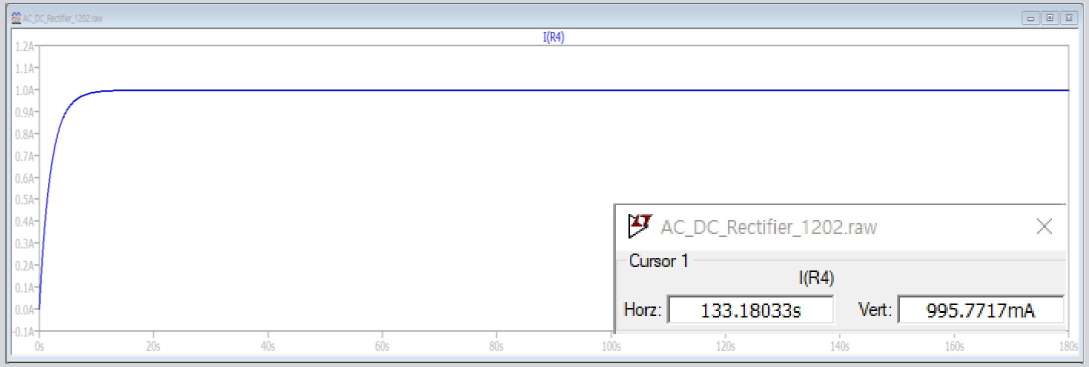


Simulation Results : LTspice

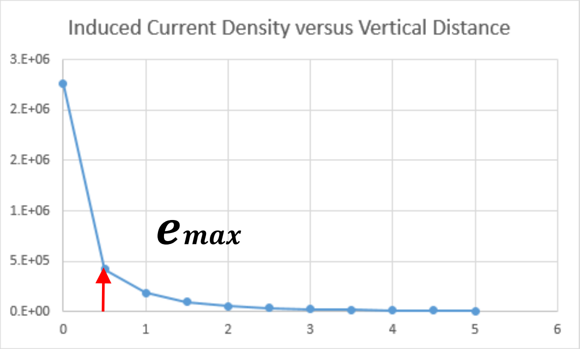


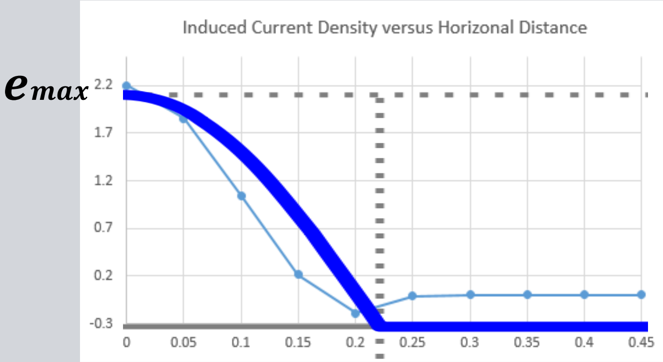




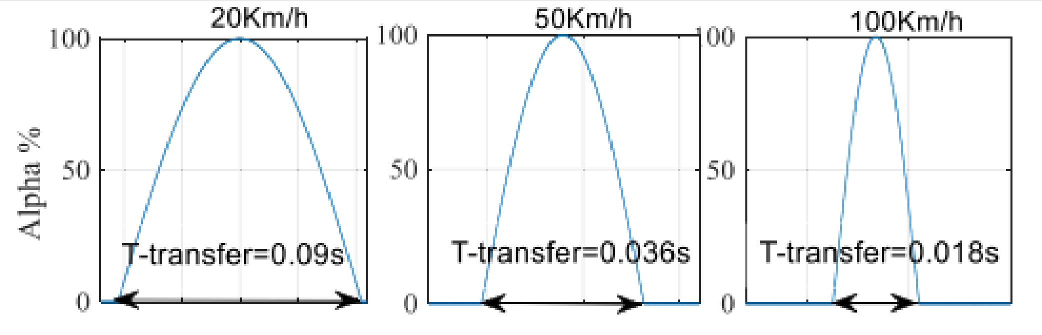


Charging System Model

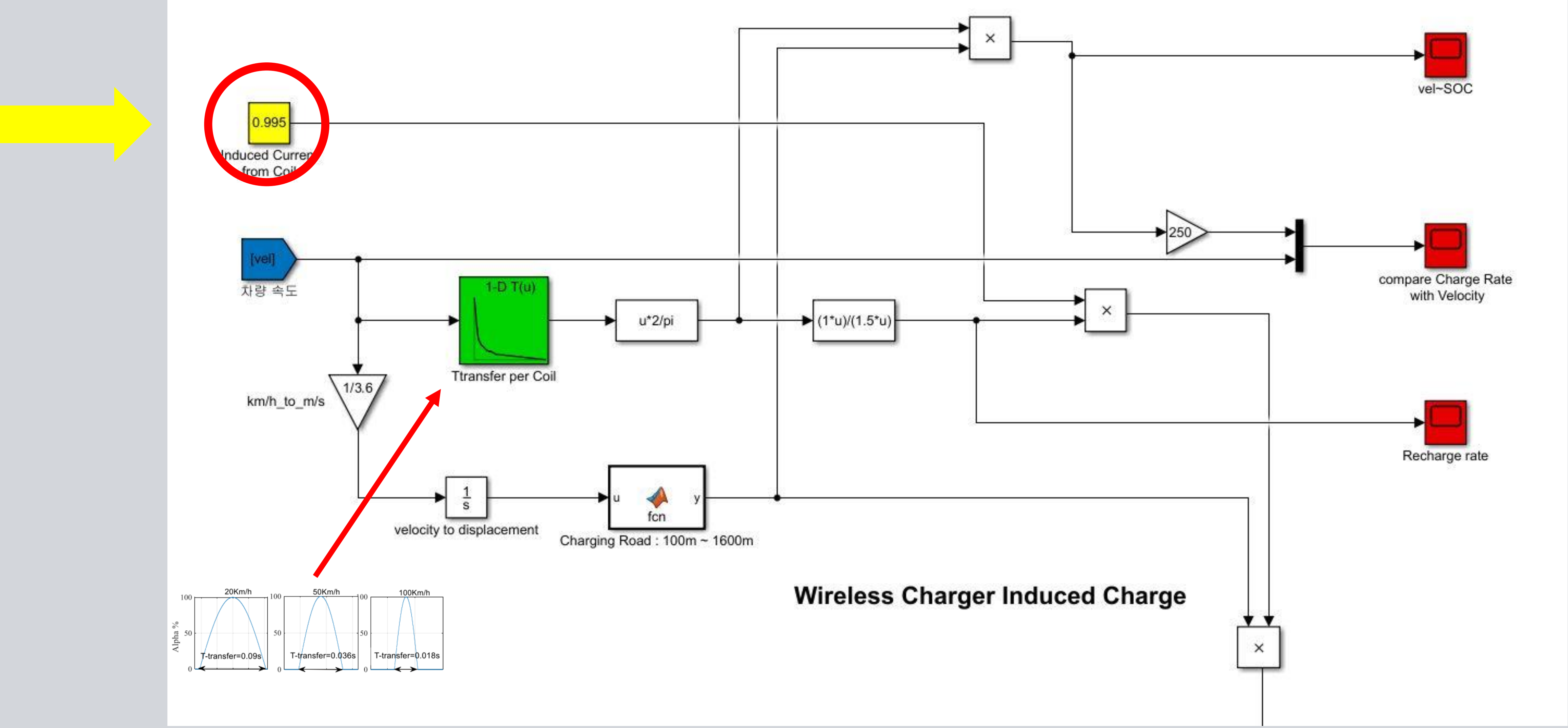




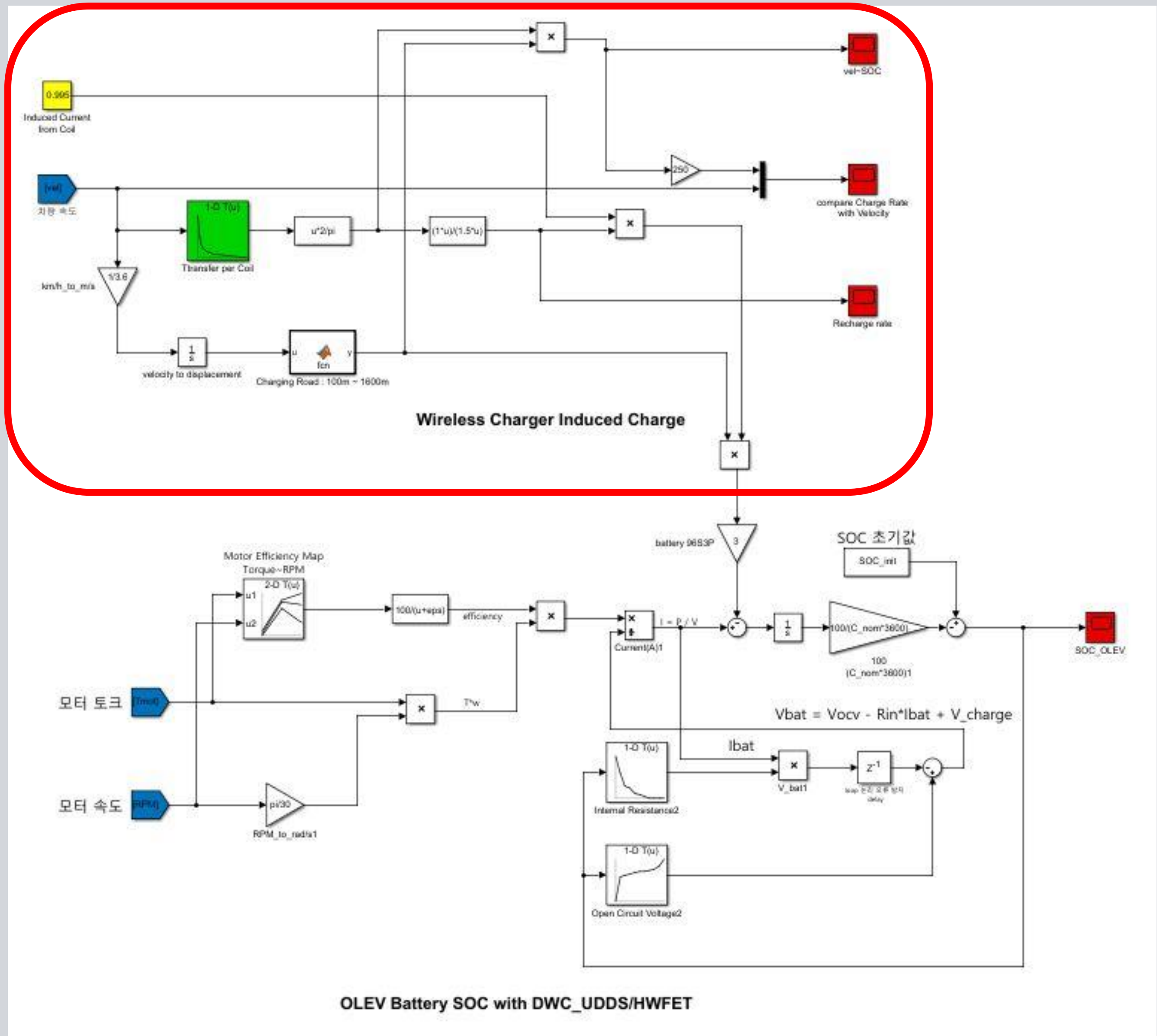
$$\alpha = \frac{e_x}{e_{max}} \times 100$$
$$\cong \sin(x)\ [\%]$$



Charging System Model



Charging System Model



Result Analysis

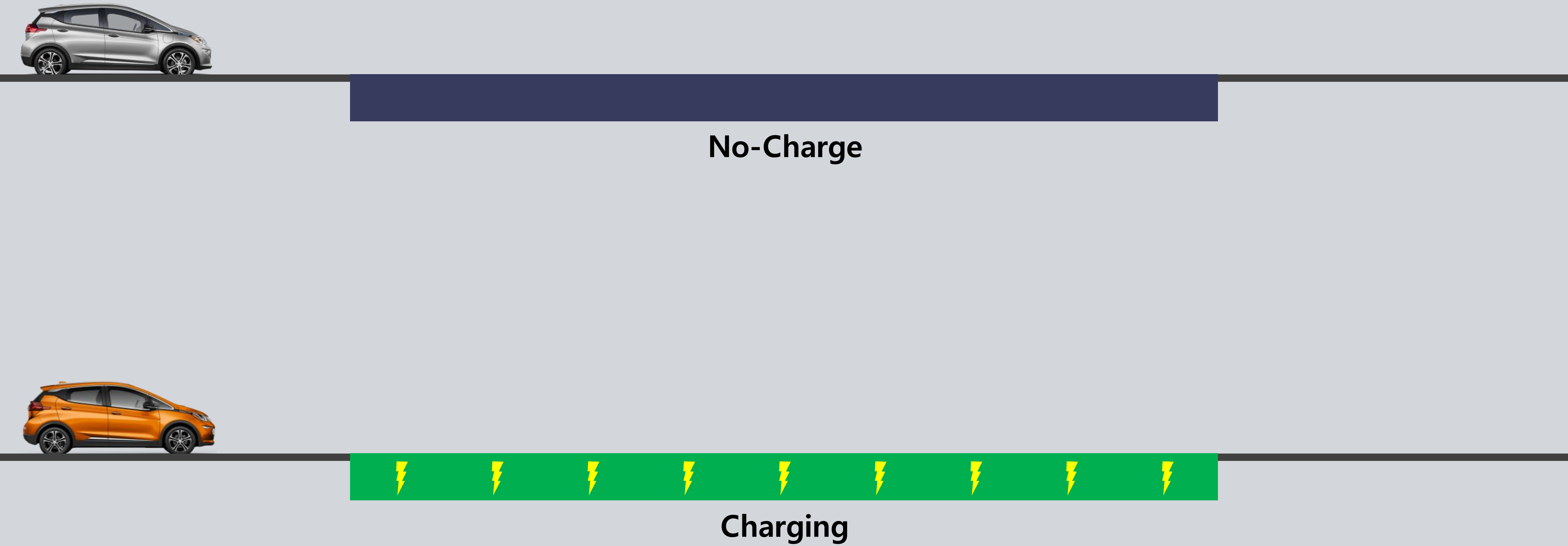
SOC Comparison : Bolt EV

Test 1. SOC Comparison with/without Dynamic Wireless Charging

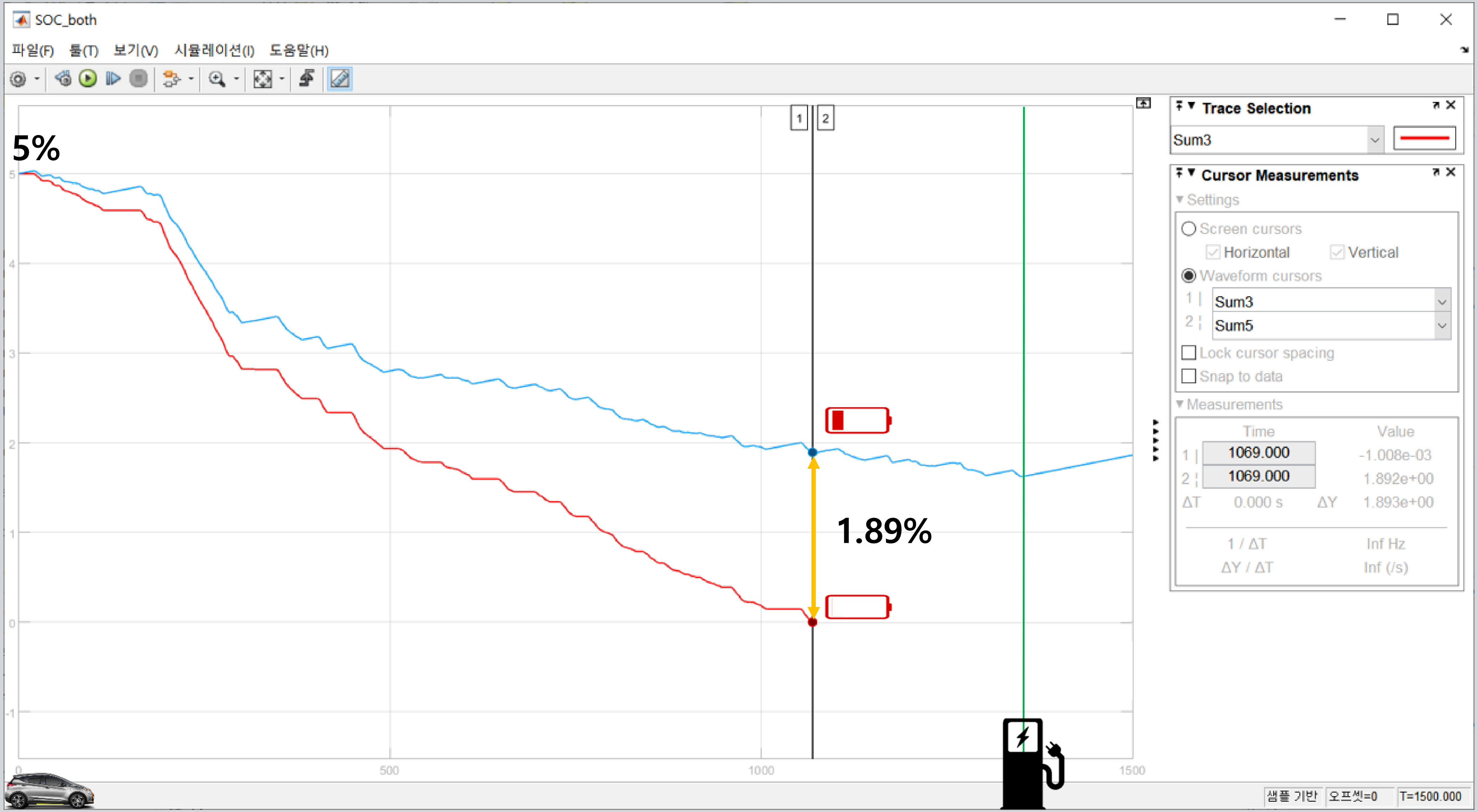
Test 2. SOC Comparison between Driving Conditions : UDDS vs HWFET

SOC Comparison : with/without Dynamic Wireless Charging

Test 1



Reaching a Charging Station

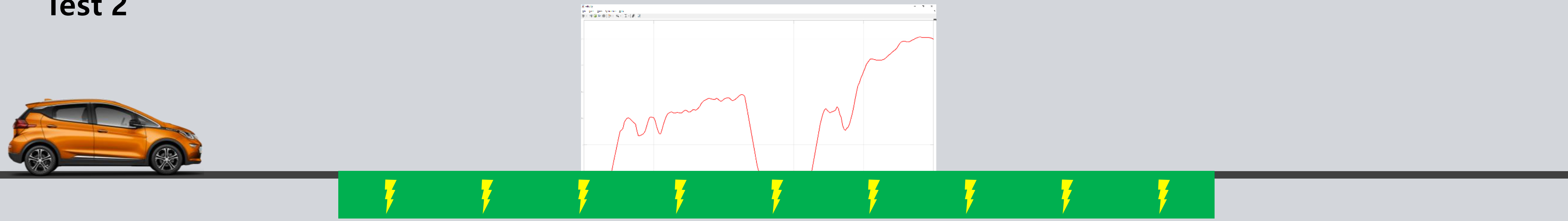


SOC Comparison : Driving Conditions UDDS vs HWFET

Charging Road

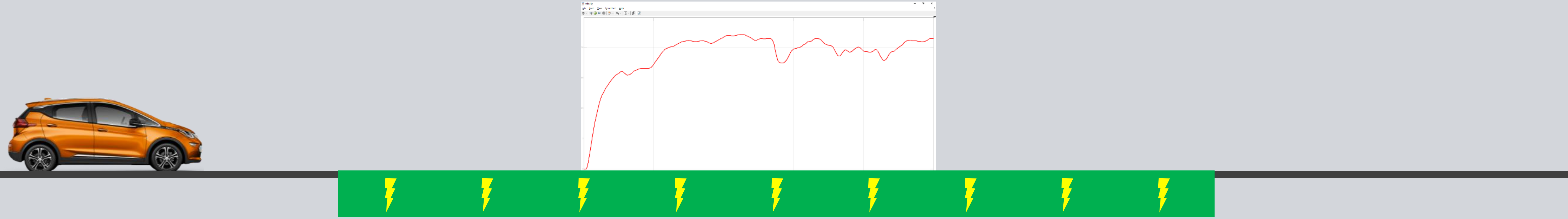
SOC Comparison : Driving Conditions UDDS vs HWFET

Test 2



강남대로(UDDS)

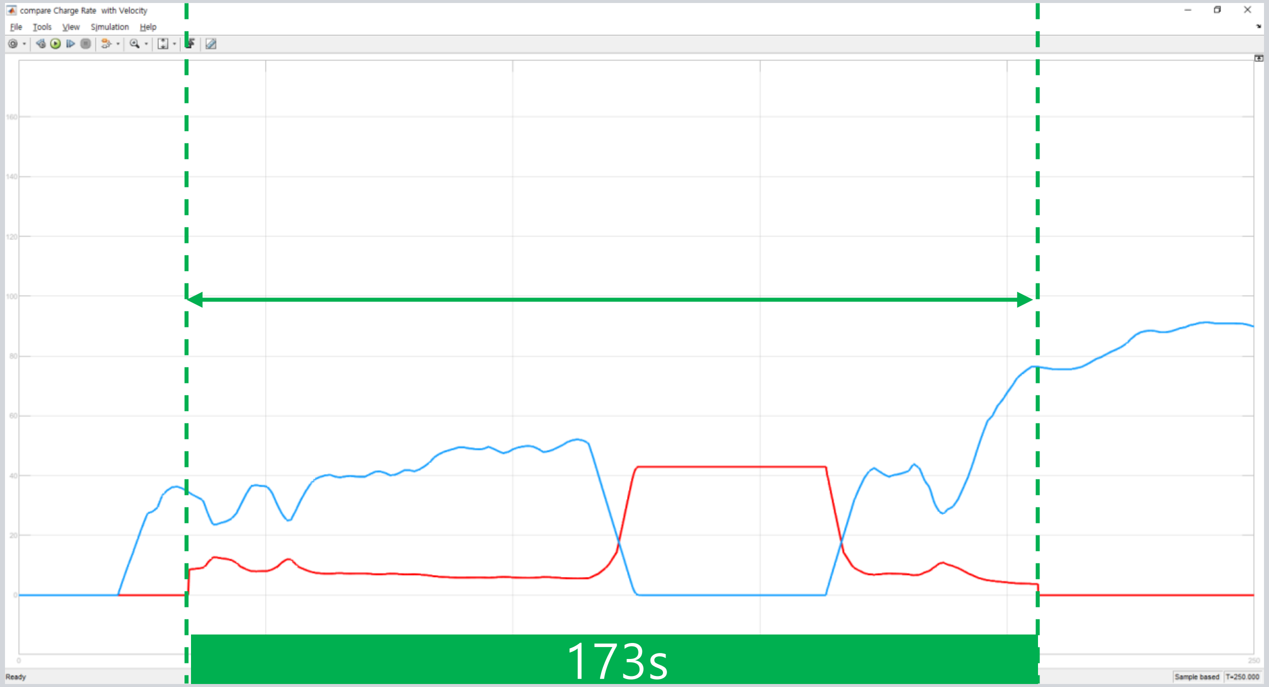
1500m



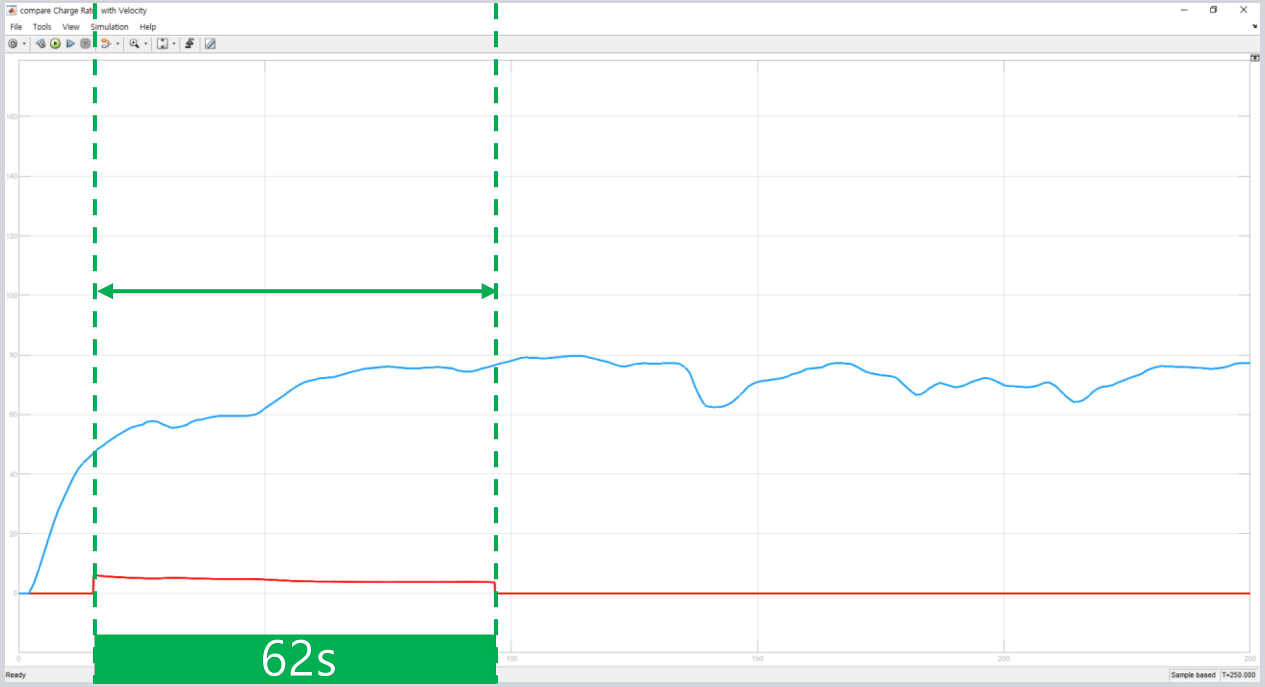
경부고속도로(HWFET)

SOC Comparison : Driving Conditions UDDS vs HWFET

UDDS



HWFET

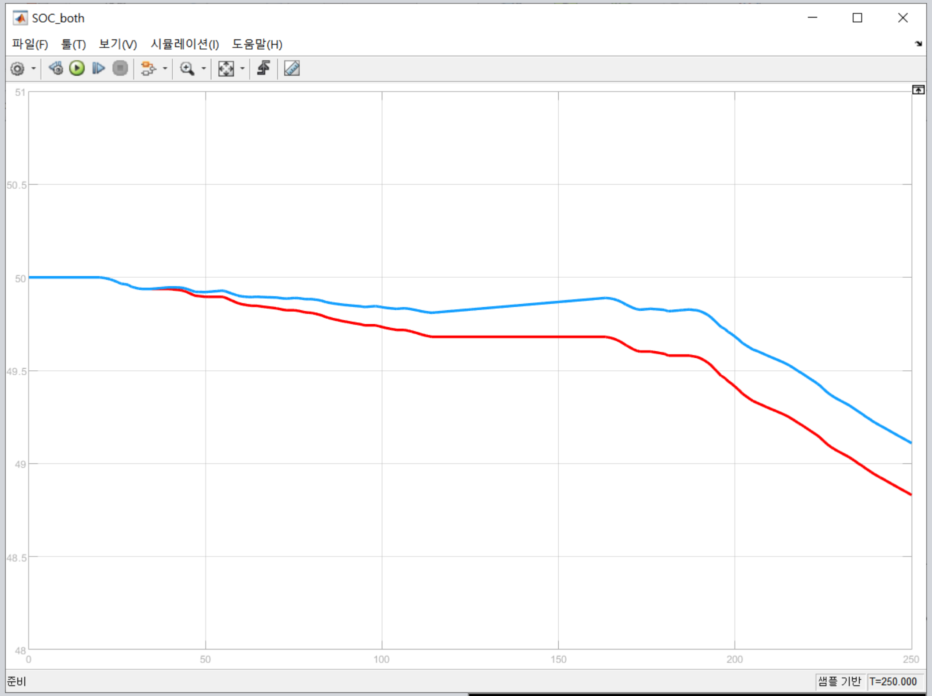


차량 속도

충전 효율

SOC Comparison : with/without Dynamic Wireless Charging

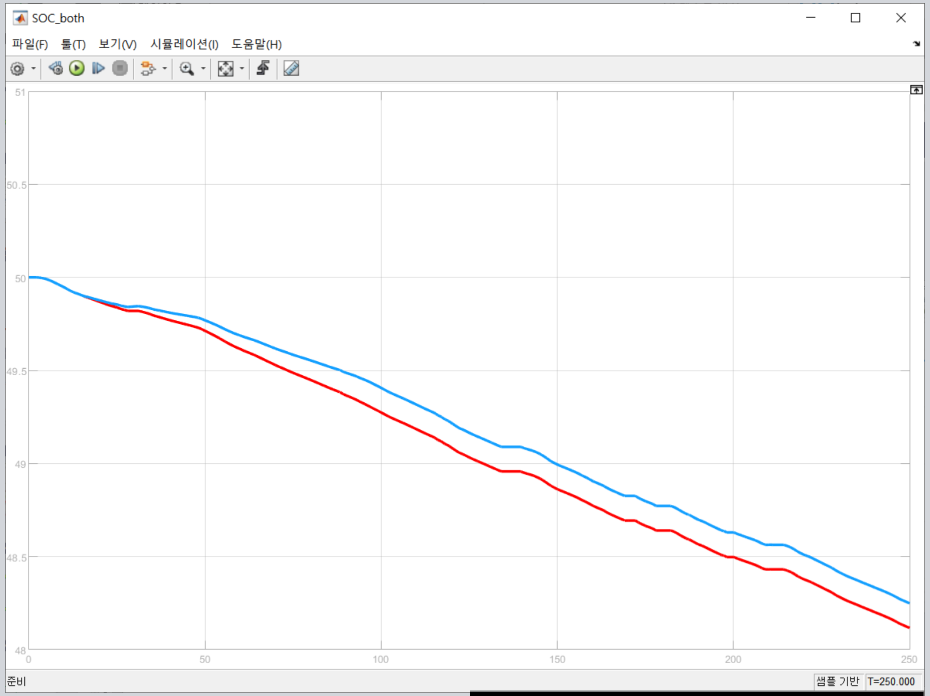
UDDS



	Time	Value
1	250.000	4.883e+01
2	250.000	4.911e+01
ΔT	0.000 s	ΔY 2.787e-01

0.2787%

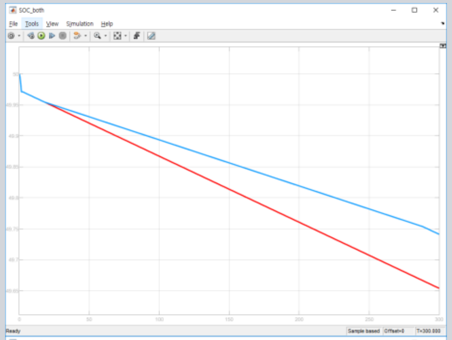
HWFET



	Time	Value
1	250.000	4.812e+01
2	250.000	4.825e+01
ΔT	0.000 s	ΔY 1.323e-01

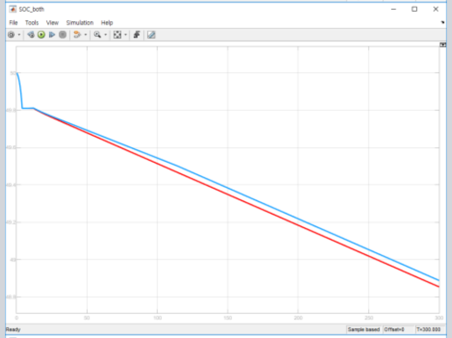
0.1323%

SOC Comparison : Constant Speeds



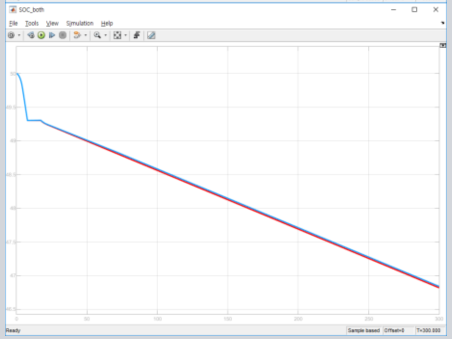
20km/h

0.3759%



50km/h

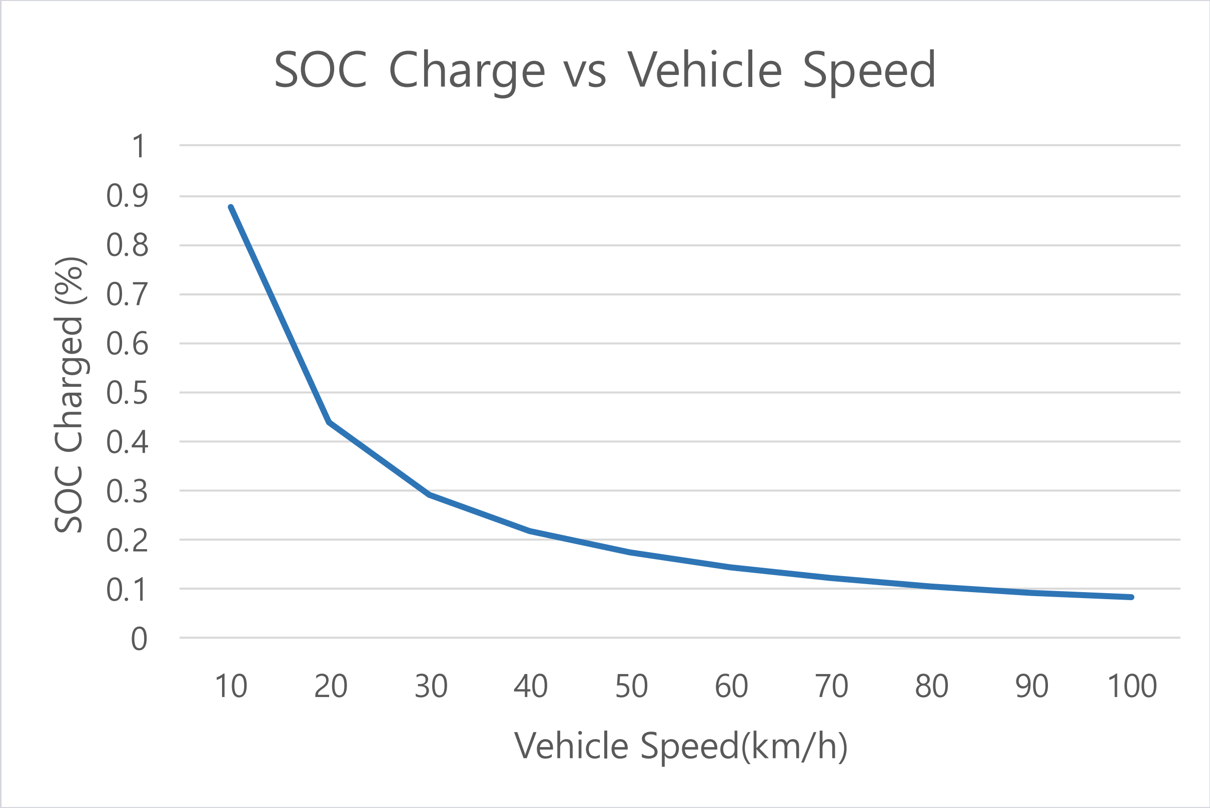
0.1738%



80km/h

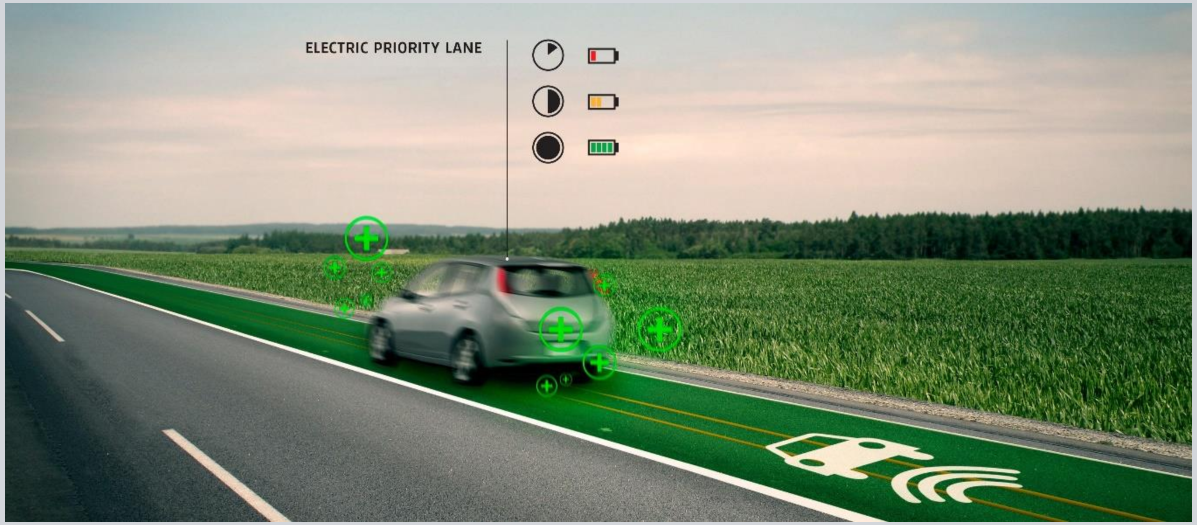
0.1068%

10	0.8755
20	0.4376
30	0.291
40	0.2182
50	0.1738
60	0.1448
70	0.1212
80	0.1068
90	0.09229
100	0.08117



차량의 속도가 빨라질수록, SOC 충전량은 급격히 감소

EV-Charging Roads in the Future



고찰

- 상용 무선충전 시스템에 대한 실험값 부족, 정확한 데이터 반영 X
  - 차량 탑재 Li-Ion 배터리(LG화학) 데이터시트
  - 충전회로 세부 Parameters (RLC)

- COMSOL 모델링의 한계 : 실제 모델 반영 어려움

- 주행 중 충전 효율(15%) 향상을 위한 시스템 개발 필요

References

- **Self Inductance and Mutual Inductance Between Single Conductors** (COMSOL)
- **전기자동차 비접촉식 충전시스템을 위한 20kHz 인버터 설계** - 한국전력공사 전력연구원
- **스마트 무선전력전송 기술** - KAIST 무선전력전송연구센터
- **Precise Analysis on Mutual Inductance Variation in Dynamic Wireless Charging of Electric Vehicle** – Ainur Rakhymbay, Anvar Khamitov, Mehdi Bagheri, Batyrber Alimkhanuly, Maxim Lu and Toan Phung
- **Analysis of Battery-EV State of Charge for a Dynamic Wireless Charging System** – Naoui Mohamed, Flah Aymen, Mouna Ben Hamed, Sbita Lassaad
- **Wireless Inductive Charging for Electrical Vehicles : Electromagnetic Modelling and Interoperability Analysis** – Mohammad Ibrahim
- **Analysis of the Coupling Coefficient in Inductive Energy Transfer Systems** – Rafael Duarte, Gordana Klaric
- **Wireless Power Transfer in Loosely Coupled Links: Coil Misalignment Model** – Kyriaki Fotopoulou, Brian W. Flyn

Thank You