

Motor Training

BLDC (Brushless DC Motor)

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01

ANSYS RMxpert를 이용한 BLDC 설계

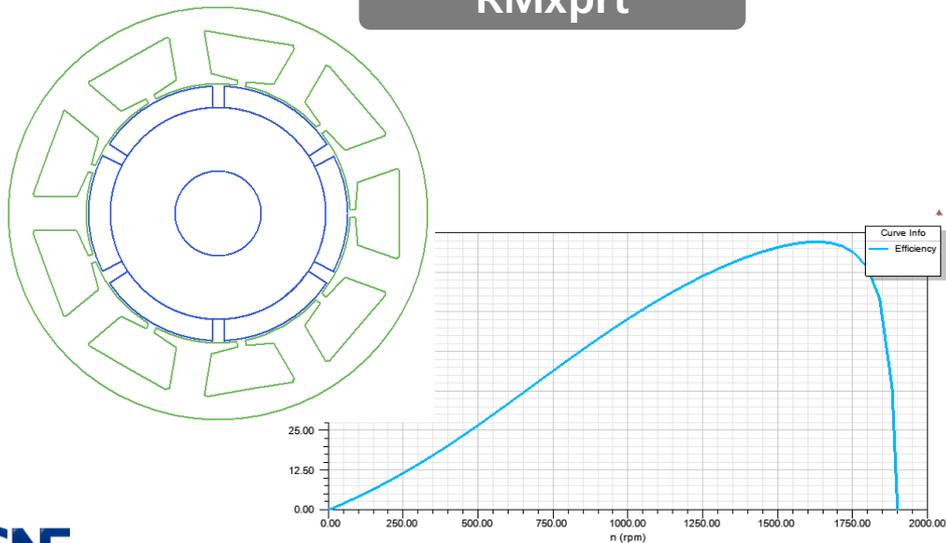
Equivalent Circuit 해석

Introduction

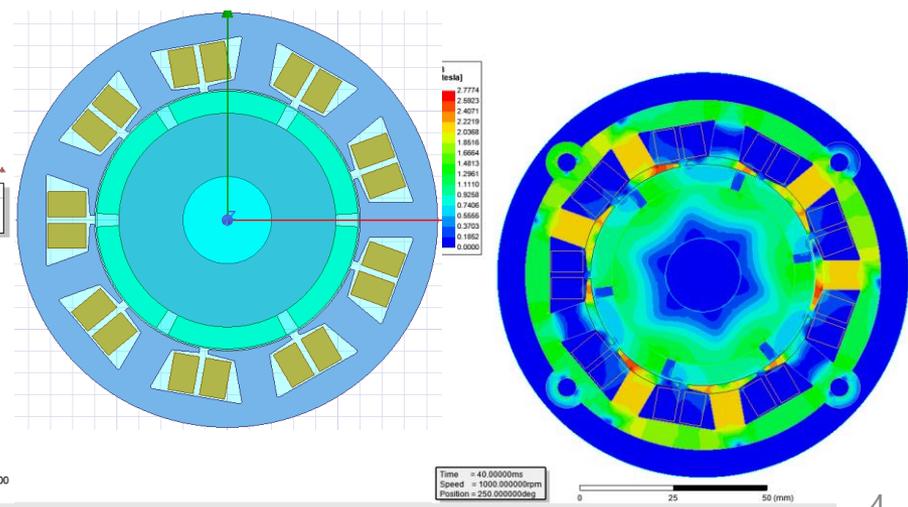
- 해석 모델
 - BLDC (Brushless Permanent Magnet DC Motor)
- 목적
 - RMxpert를 이용한 BLDC의 설계 및 등가회로 해석
 - Maxwell 2D를 이용한 FEM 해석
- 출력
 - 토크, 전압, 전류, 손실, 효율

Motor Specification	
모터 종류	BLDC
극수	6
슬롯수	9
외경사이즈	95mm
최대출력	900W
최대토크	20Nm
최대속도	1,900rpm
전압제한	42V

RMxpert

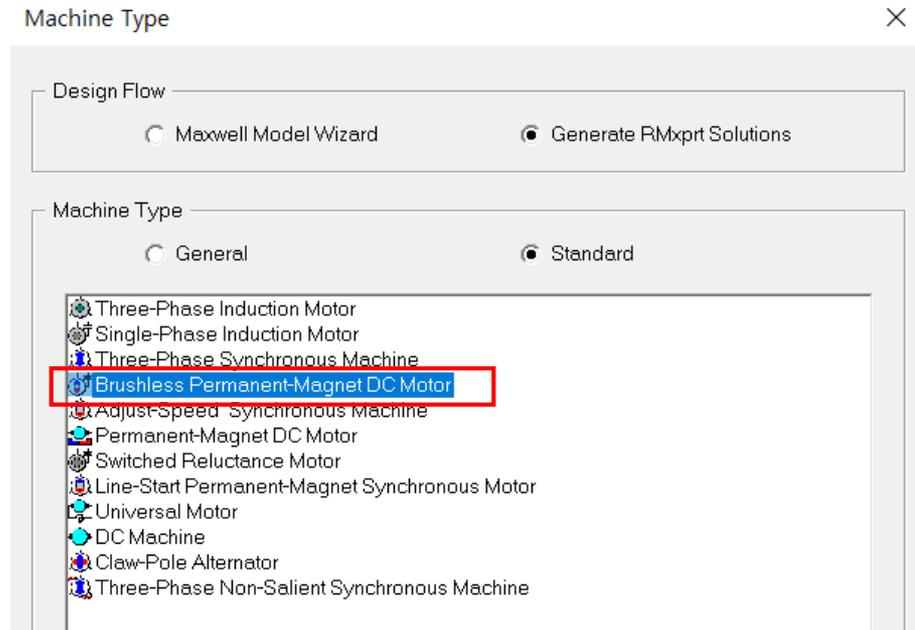
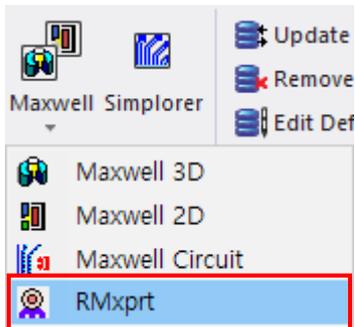


Maxwell 2D



RMxprt 실행 및 Machine Type 선택 (RMxprt)

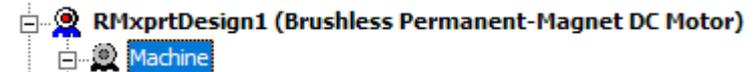
- RMxprt project 만들기
 1. Electronics Desktop 실행
 2. Project 저장 : BLDC.aedt
 3. Insert RMxprt Design
 4. Brushless Permanent-Magnet DC Motor 선택



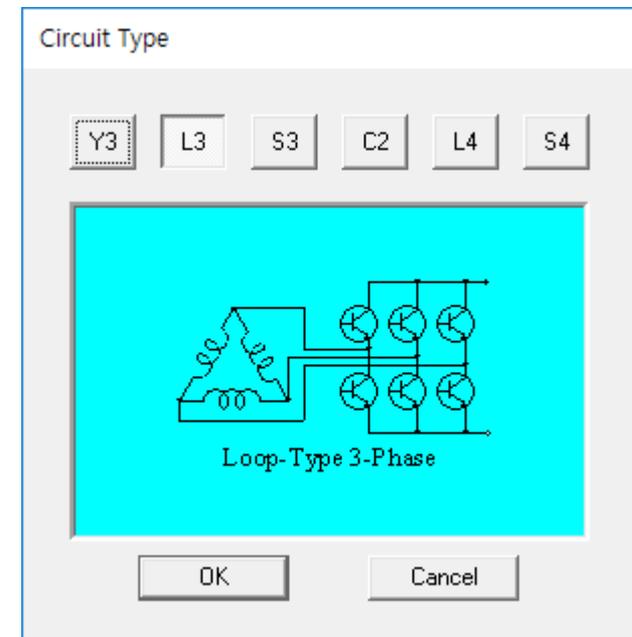
Machine 정보 입력 (RMxprt)

Machine Specification

- Number of Poles (극 수) : 6
 - 6극 모터라는 것은 N-S-N-S-N-S를 의미.
즉, pole pair 는 3
- Rotor Position (회전자 위치) : Inner Rotor
 - 회전자가 내부에 있는 모터
- Friction Loss (마찰 손실) : 0 Watt
 - 보통은 정격 출력의 2~3 % 가량의 손실 있음
- Windage Loss (풍손) : 0 Watt
- Reference Speed : 1,000 rpm
 - 측정 시 rpm 을 입력하는 것이지만,
이 경우는 정격 속도와 같은 값을 입력
- Control Type (제어 방식) : DC
 - DC 제어
- Circuit Type (권선 방식) : delta3
 - 3상 delta 결선 이용



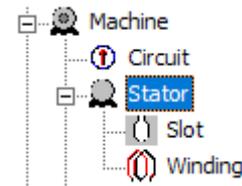
Name	Value	Unit
Machine Type	Brushless Permanent-M...	
Number of Poles	6	
Rotor Position	Inner Rotor	
Frictional Loss	0	W
Windage Loss	0	W
Reference Speed	1000	rpm
Control Type	DC	
Circuit Type	L3	



Stator 정보 입력 (RMxpert)

Stator 의 크기, slot 수, slot 모양, 재질, skew 등 입력

- Outer Diameter (Stator 의 외경) : 95 mm
- Inner Diameter (Stator 의 내경) : 60 mm
- Length (Stator 의 축방향 길이) : 30 mm
- Stacking Factor (적층률) : 0.95



➤ 와전류 손실을 방지하기 위하여 보통 모터의 Stator 와 Rotor 는 강판을 적층하여 사용. 강판과 강판 사이에 공간이 형성되는데 전체 축방향 길이 중에서 강판이 차지하는 비율을 입력 0.95 는 95% 를 의미

- Steel Type (강판 재질) : JFE_Steel_50JN470
- Number of Slots (Slot 수) : 9
- Slot Type (Slot 모양) : 3
 - 적합한 slot 모양을 선택하여 치수를 변경 Slot 형태를 사용자가 지정할 수 있음
- Skew Width (Skew 폭) : 0

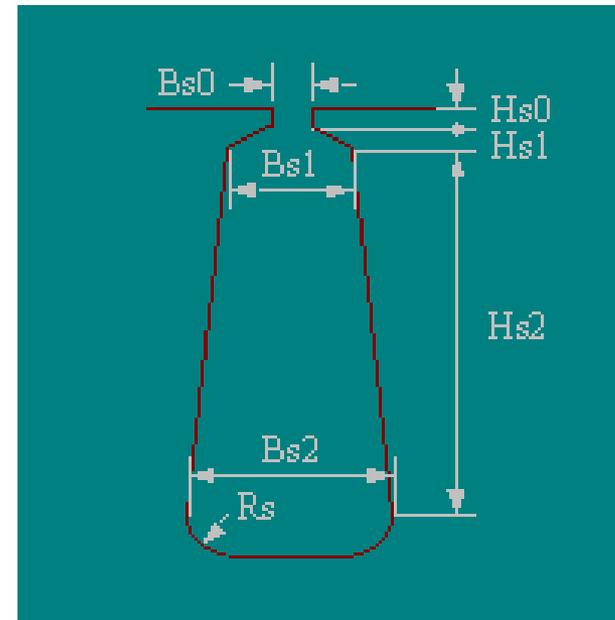
Name	Value	Unit	Evaluated V...
Outer Diameter	95	mm	95mm
Inner Diameter	60	mm	60mm
Length	30	mm	30mm
Stacking Factor	0,95		
Steel Type	JFE_Steel_50JN470		
Number of Slots	9		
Slot Type	3		
Skew Width	0		0

- 제일 윗쪽의 강판과 제일 아래쪽의 강판이 얼마만큼의 slot 수 차이를 입력
- 0 은 skew 가 없다는 의미
- 0.5 는 반 slot 만큼 skew 가 있다는 의미
- 1 이면 한 slot 만큼 skew 가 있다는 의미

Slot 정보 입력 (RMxpprt)

- Slot 의 치수 입력
 - Auto Design 을 check 하지 말 것
 - (Auto Design 을 선택하면 RMxpprt 가 권선에 stator 의 크기에 맞추어서 slot 형상을 결정함)
 - Parallel Tooth 를 check 하지 말 것

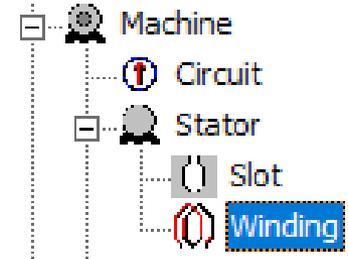
Properties		
Name	Value	Unit
Auto Design	<input type="checkbox"/>	
Parallel Tooth	<input type="checkbox"/>	
Hs0	1	mm
Hs1	0.5	mm
Hs2	9	mm
Bs0	2	mm
Bs1	14.405	mm
Bs2	20.956	mm
Rs	0.5	mm



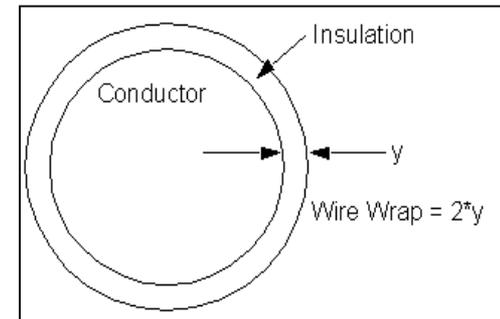
Stator Winding 설정 (RMxprt)

Winding (권선 설정)

- Winding Layers : 2
 - 1은 단층권, 2는 2층권
- Winding Type : Whole-Coiled
 - Half-Coiled, 또는 사용자가 직접 지정하는 Edit 도 있음
- Parallel Branches (병렬 회로수) : 1
 - 직렬 방식의 경우는 1을 입력
- Conductors per Slot (Slot 당 도체수) : 100
 - 2층권이므로 1 layer 당 50개의 도체
- Coil Pitch : 1
 - 1개 Tooth에 감는것을 의미
- Number of Stranded : 1
 - 한 Conductor 가 몇 개의 소선으로 이루어졌는지를 의미
- Wire Wrap : 0 mm
 - 도선을 싸고 있는 절연층 두께,
 - 0 을 입력하면 RMxprt 에서 wire library 중 자동선택
- Wire Size : Diameter:0.9mm
 - AWG Gauge 번호를 선택 및 User가 직접 입력 가능
 - 0 을 입력하면 자동으로 설정



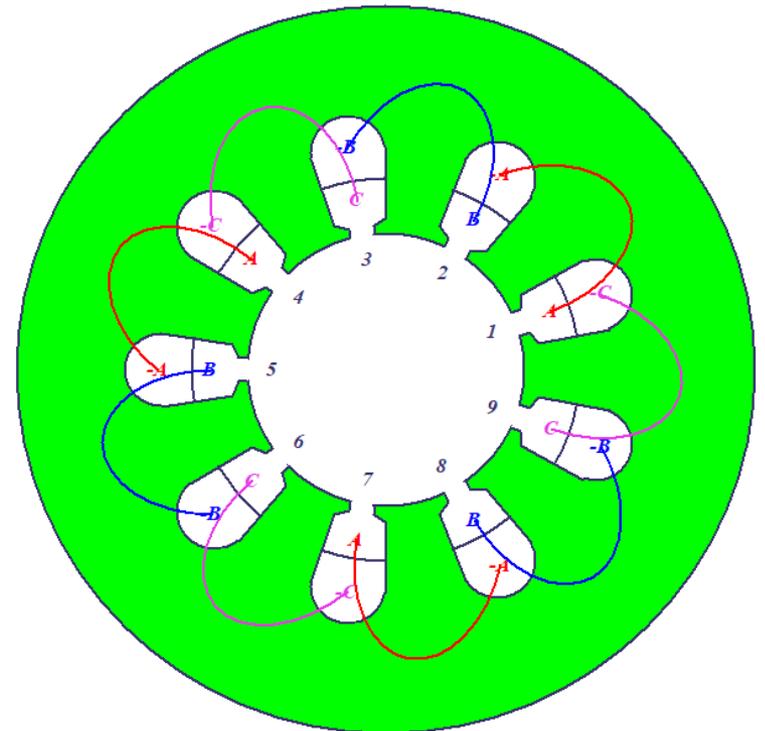
Name	Value	Unit
Winding Layers	2	
Winding Type	Whole-Coiled	
Parallel Branches	1	
Conductors per Slot	100	
Coil Pitch	1	
Number of Strands	1	
Wire Wrap	0	mm
Wire Size	Diameter: 0,9mm	



Stator Winding 설정 (RMxprt)

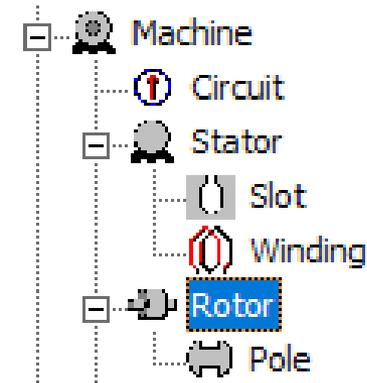
- 권선 정보
 - 나머지 부분은 주기적으로 반복함
 - T 는 Rotor 에 가까운 Layer
 - B 는 Rotor 에서 먼 Layer
 - Coil_1 은 A 상이고 50 turn 으로 이루어졌으며
 - 1번 Slot 안쪽에서 2 번 Slot 바깥쪽으로
 - 연결되어 있음을 의미

	Phase	Turns	In Slot	Out Slot
Coil_1	A	50	1T	2B
Coil_2	B	50	2T	3B
Coil_3	C	50	3T	4B

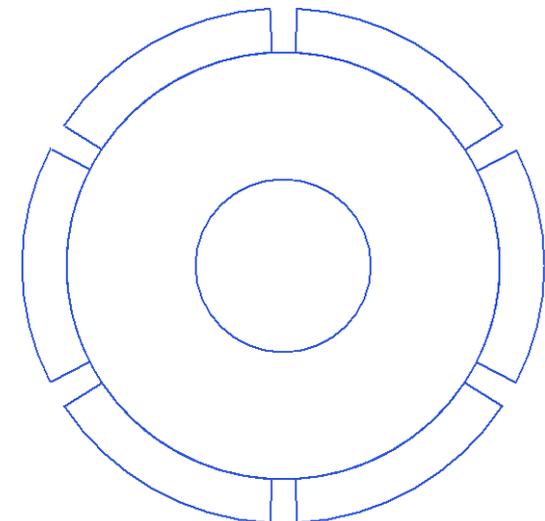


Rotor 정보 입력 (RMxpprt)

- Rotor 의 크기와 재질, 자석 종류 등을 입력
 - Outer Diameter (Rotor 의 외경) : 59 mm
 - Inner Diameter (Rotor 의 내경) : 20 mm
 - Length (Rotor 의 축방향 길이) : 30 mm
 - Steel Type (강판 재질) : JFE_Steel_50JN470
 - Stacking Factor (적층률) : 0.95
 - Pole Type (자석의 형태와 착자 방향 선택) : 1 (Radial 착자)



Name	Value	Unit
Outer Diameter	59	mm
Inner Diameter	20	mm
Length	30	mm
Steel Type	JFE_Steel_50JN470	
Stacking Factor	0,95	
Pole Type	1	

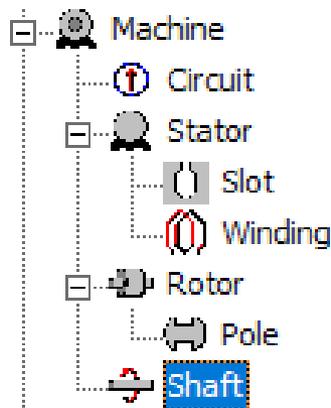


자석 및 Shaft 설정 (RMxpert)

- 자석의 크기, 재질 등을 입력
 - Embrace : 0.9
 - 자석이 차지하는 비율
 - Offset : 0 mm
 - Pole-arc 의 원점과 Rotor 의 원점간의 거리
 - Magnet Type : NdFe30
 - Magnet Thickness : 5 mm (자석 두께)

Properties			
Name	Value	Unit	Evaluated V...
Embrace	0.9		0.9
Offset	0	mm	0mm
Magnet ...	NdFe30		
Magnet ...	5	mm	5mm

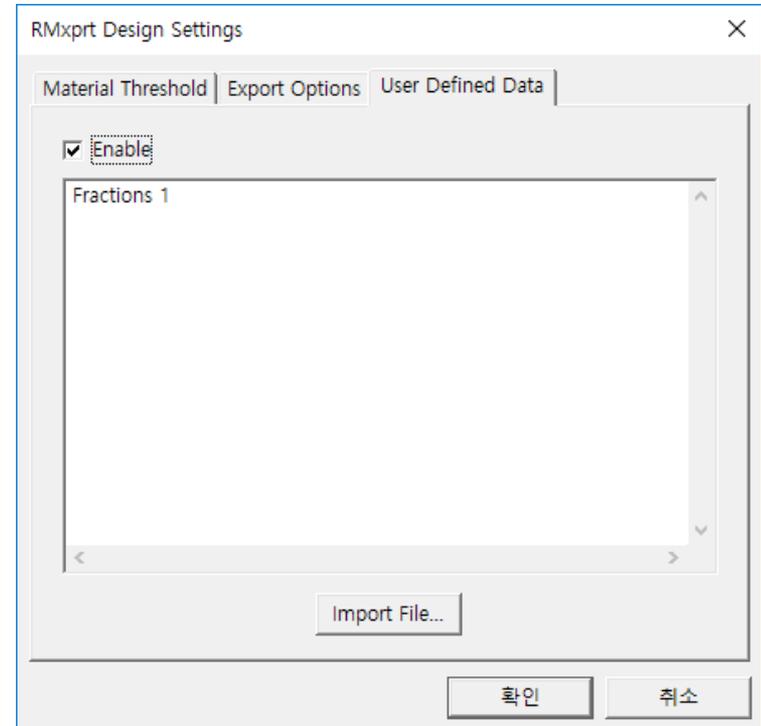
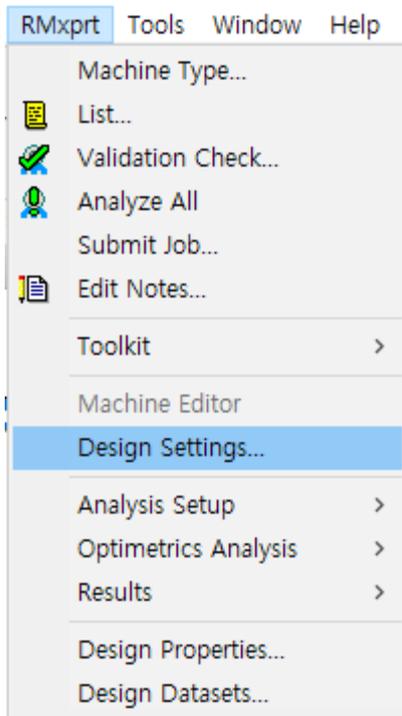
- Shaft 의 재질을 결정
 - Magnetic Shaft : Uncheck
 - Shaft 재질이 자성체이면 check, 비자성체이면 uncheck



Properties	
Name	Value
Magnetic Shaft	<input type="checkbox"/>

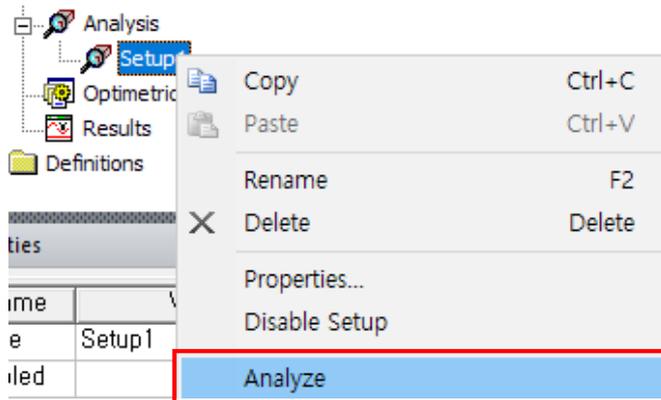
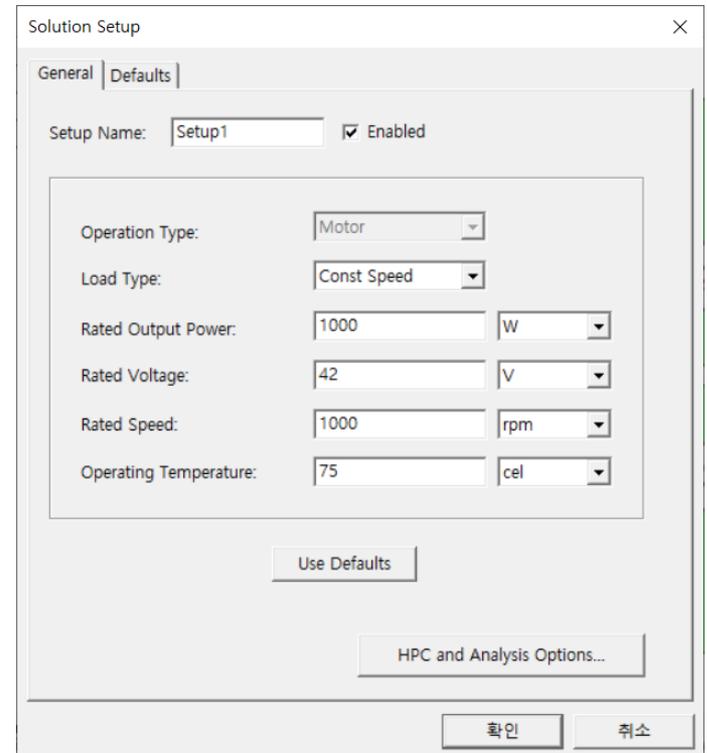
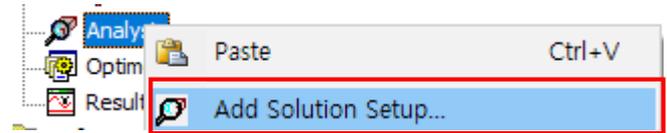
Maxwell 만들 때 Full Model로 설정 (RMxpert)

- 형상을 Full model로 설정
 - 아래 설정을 하지 않고, Create Maxwell Design을 하면 자동으로 분할 모델로 해줌
 - 진동 소음 해석을 하려면 Full Model에 대한 Force 데이터를 넘겨야 함 (Fractions 1)



Setup 설정 및 Analyze (RMxpert)

- Analysis 에서 RMB > Add Solution Setup 클릭
 - Operation Type : Motor 선택
 - Load Type (부하 조건) : Constant Speed
 - Rated Output Power (정격 출력) : 1000W
 - Rated Voltage (정격 전압) : 42V
 - Rated Speed (정격 속도) : 1000rpm
 - Operating Temperature (동작 온도) : 75 cel
 - "확인"
- Setup1 에서 RMB > Analyze 클릭



결과 확인 (RMxprt)

- 결과 확인
 - 상단메뉴 RMxprt > Results > Solution Data
(반응이 없는 경우 프로그램 종료 후 다시 열기)

The screenshot shows the RMxprt software interface. The top ribbon has tabs for Desktop, View, Simulation, Results, and Automation. The 'Results' tab is active, and the 'Solution Data' icon is highlighted with a red box. Below the ribbon, a window titled 'Solutions: BLDC - RMxprtDesign1' is open. It shows simulation settings for 'Setup1' and 'Performance'. The 'Design Variation' field is empty with a green checkmark icon. The 'Performance' tab is selected, and the 'Data' dropdown is set to 'FEA Input Data'. A table displays the following data:

	Name	Value	Units	Description
1	Armature Parallel Branches	1		
2	Equivalent Model Depth	30	mm	
3	Equivalent Stator Stacking Factor	0.95		
4	Equivalent Rotor Stacking Factor	0.95		
5	Equivalent Br	1.1	tesla	
6	Equivalent Hc	838000	A_per_meter	
7	Region Depth	49.3135	mm	
8	Unit Fractions	3		

결과 Data 확인 (RMxpert)

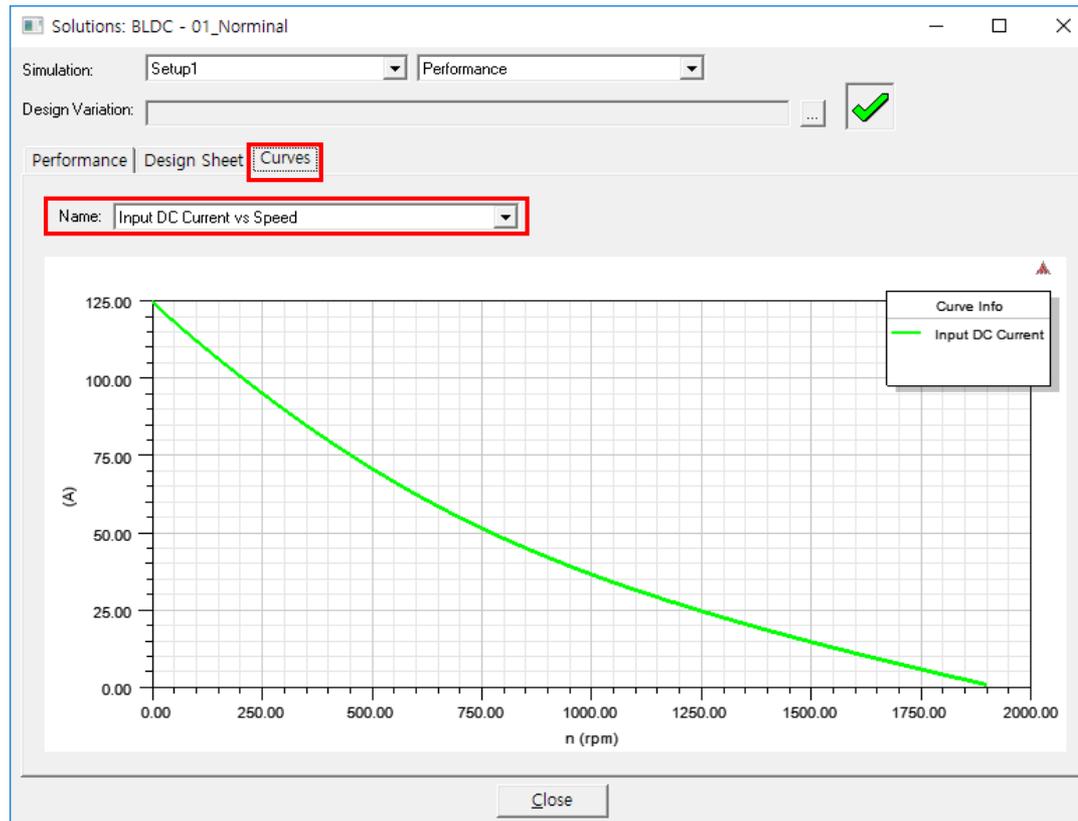
- Performance tab > Data: Full-Load Operation

The screenshot shows the 'Performance' tab in the RMxpert software. The 'Data' dropdown menu is set to 'Full-Load Operation'. The table below lists various performance metrics with their values, units, and descriptions. Red arrows on the left side of the image point from Korean labels to specific rows in the table.

	Name	Value	Units	Description
DC 전류	1 Average Input Current	36305.7	mA	DC current from the source
AC 전류(1개 Phase)	2 RMS Armature Current	19984.8	mA	AC current through the winding
자성체 철손	7 Iron-Core Loss	19886.6	mW	
전기자 동손	8 Armature Copper Loss	604634	mW	
기계적 출력	16 Rated Torque	8.59743	NewtonMeter	
전기적 출력	12 Output Power	900321	mW	
효율	14 Efficiency	59.0436	%	
속도	15 Rated Speed	1000	rpm	
토크	17 Locked-Rotor Torque	20.5445	NewtonMeter	
	19 Maximum Output Power	934100	mW	

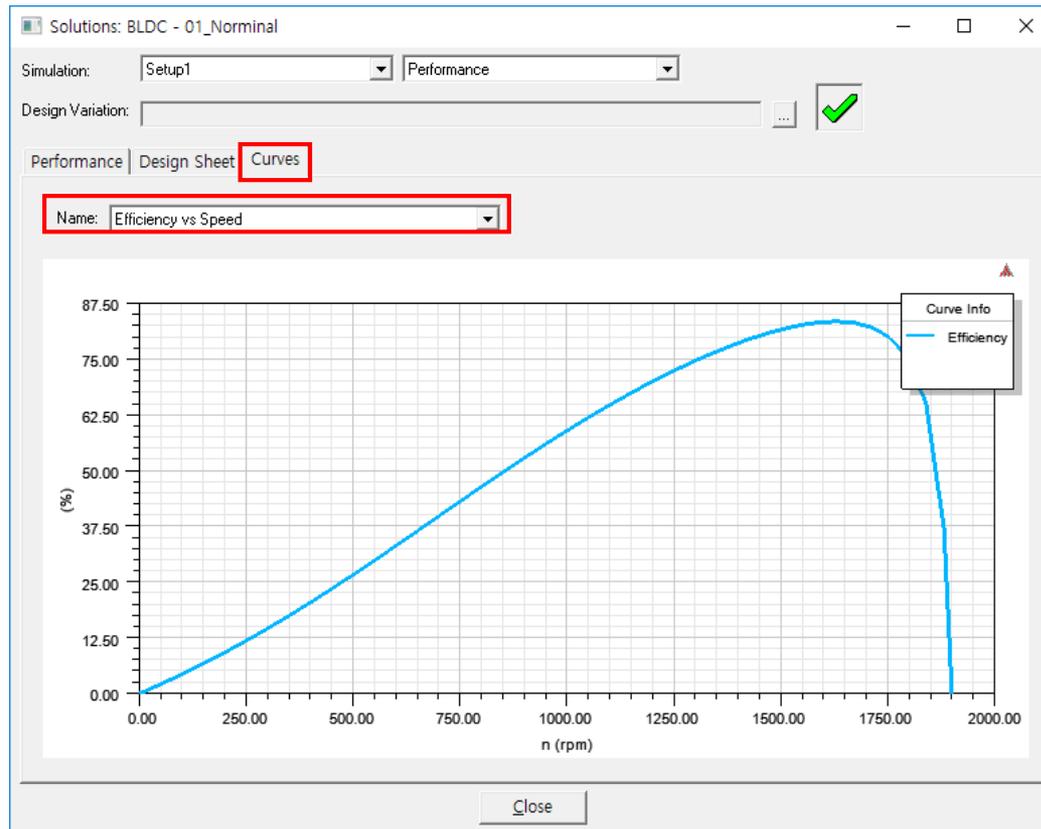
결과 Curve 확인 (RMxpert)

- Curves tab
 - Name : Input DC Current vs Speed
 - 속도에 따른 DC 전류
 - 초기 전류 약 125Adc / 최대 속도 1900rpm



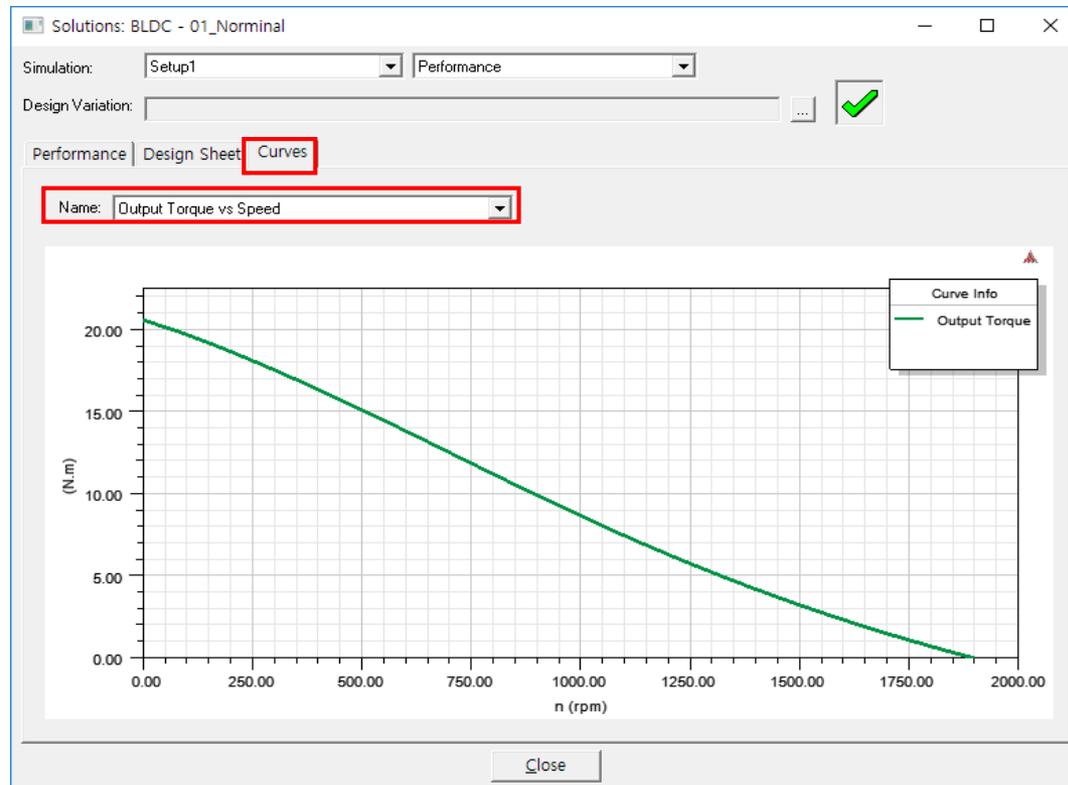
결과 Curve 확인 (RMxprt)

- Curves tab
 - Name : Efficiency vs Speed
 - 속도에 따른 효율
 - 1500rpm~1750rpm 사이에서 효율이 가장 좋음



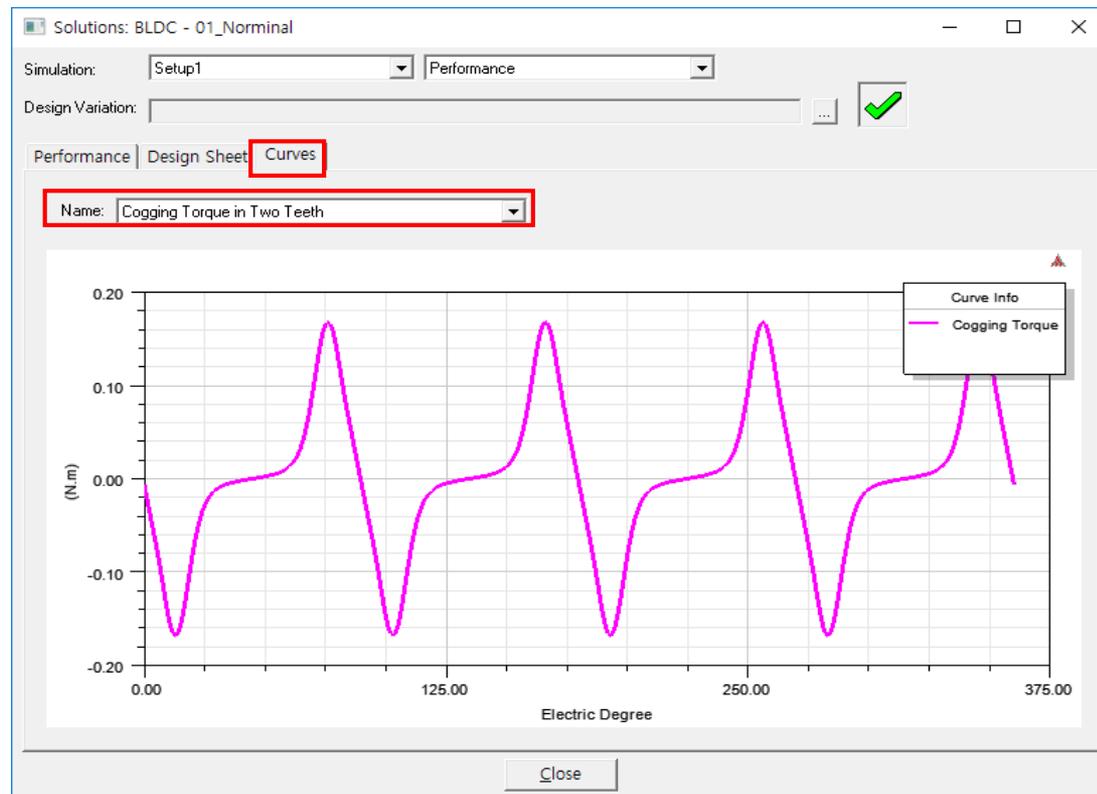
결과 Curve 확인 (RMxpert)

- Curves tab
 - Name : Output Torque vs Speed
 - 속도에 따른 토크 (전류와 같은 추세, $T=K\Phi$ 관계)
 - 초기 토크 약 20.5Nm / 최대 속도 1900rpm



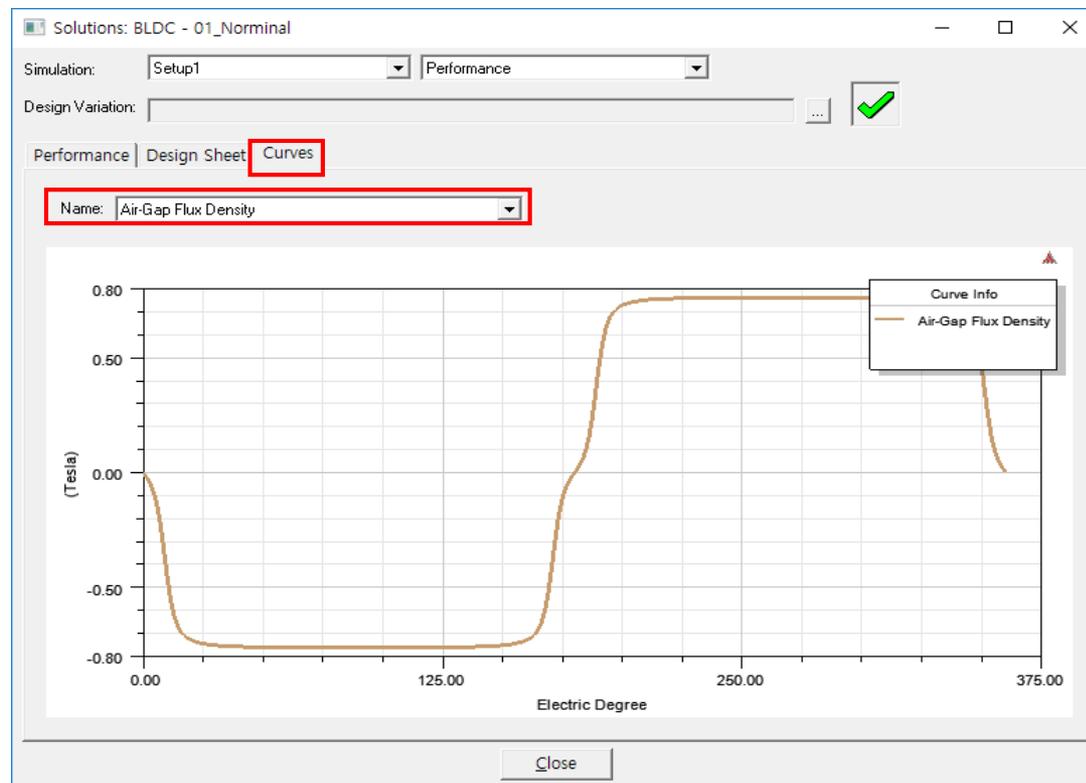
결과 Curve 확인 (RMxpert)

- Curves tab
 - Name : Cogging Torque in Two Teeth
 - 2개 Teeth에 따른 코깅토크 파형
 - Max. = 0.17Nm, Peak-to-Peak = 0.34Nm



결과 Curve 확인 (RMxpert)

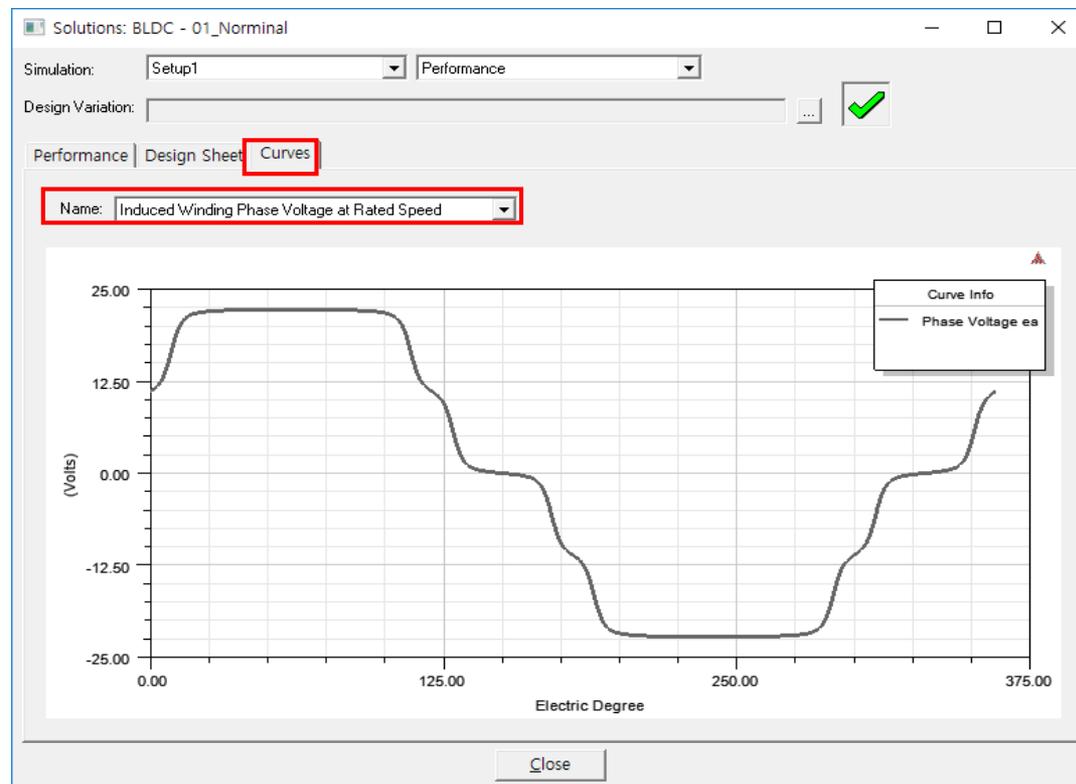
- Curves tab
 - Name : Air-Gap Flux Density
 - 전기적인 360deg에 대한 공극 자속밀도
 - 최대 자속밀도 = 약 0.76[Tesla]



결과 Curve 확인 (RMxpprt)

Curves tab

- Name : Induced Winding Phase Voltage at Rated Speed
- 1000rpm에서의 상 역기전력
- max. = 약 22.2V , rms = 약 17.1V



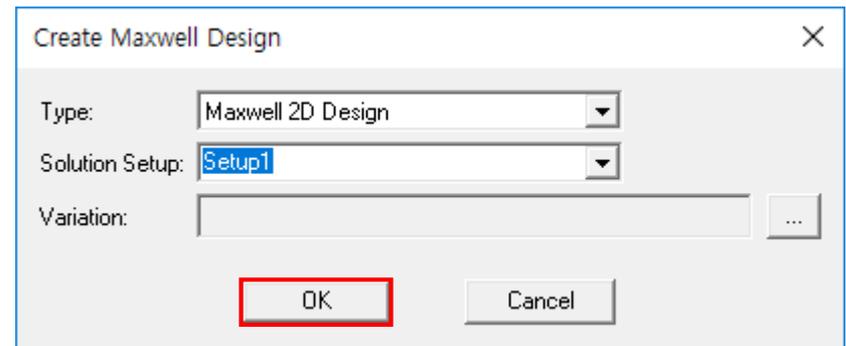
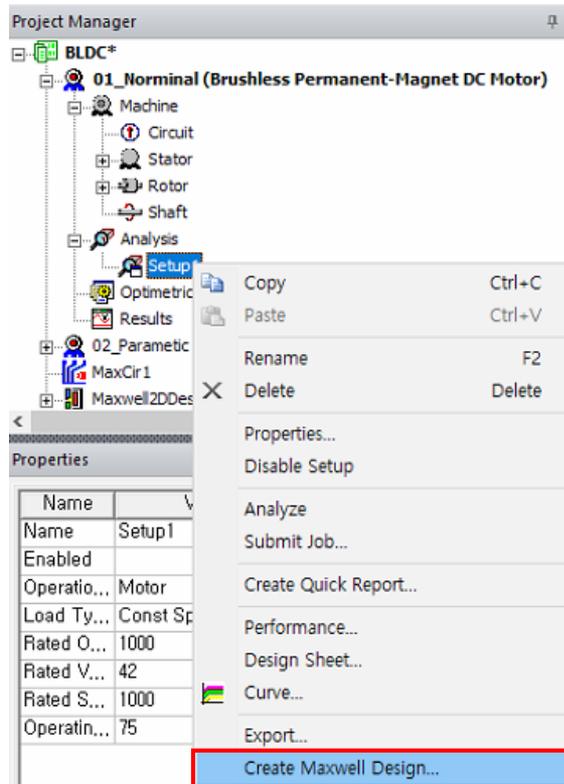


ANSYS Maxwell을 이용한 FEM 해석

무부하 해석

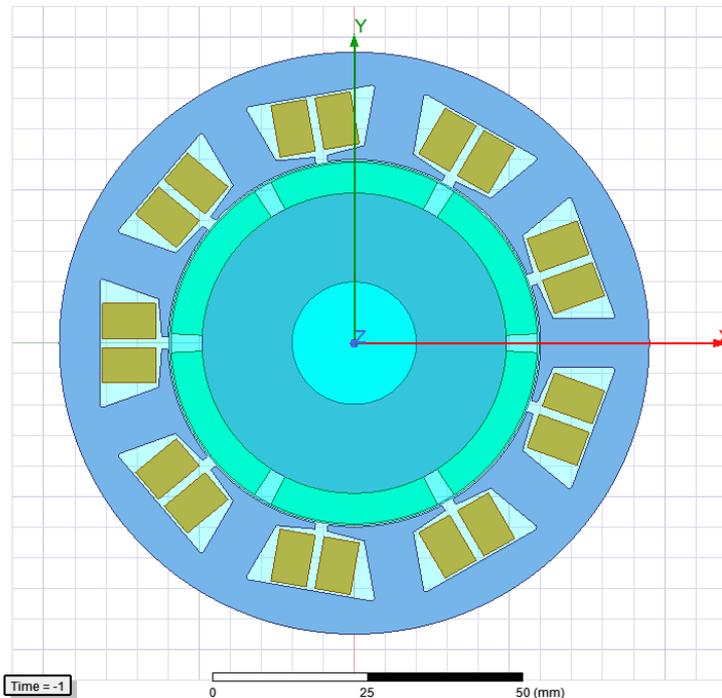
Create Maxwell Design (RMxpprt)

- 해석 목적
 - 무부하 해석을 통한 무부하 특성 확인
 - 무부하 해석은 입력 없이, 회전자만 회전시켜 "코깅토크", "역기전력" 특성을 확인
- 01_Nominal의 Setup1에서 RMB > Create Maxwell Design 클릭



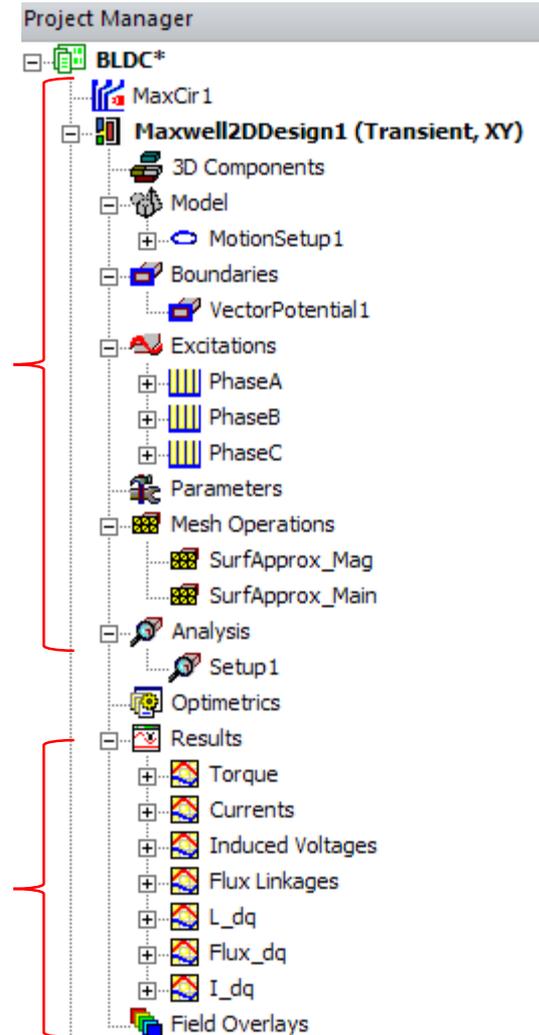
Maxwell Pre 및 Post 세팅 자동 완료 (Maxwell)

- RMxpert를 이용하여 Maxwell 2D 자동 생성
- 해석에 필요한 Pre-processing 자동 설정
- Motor해석 시 Post-processing으로 주로 보는 Results 자동 출력

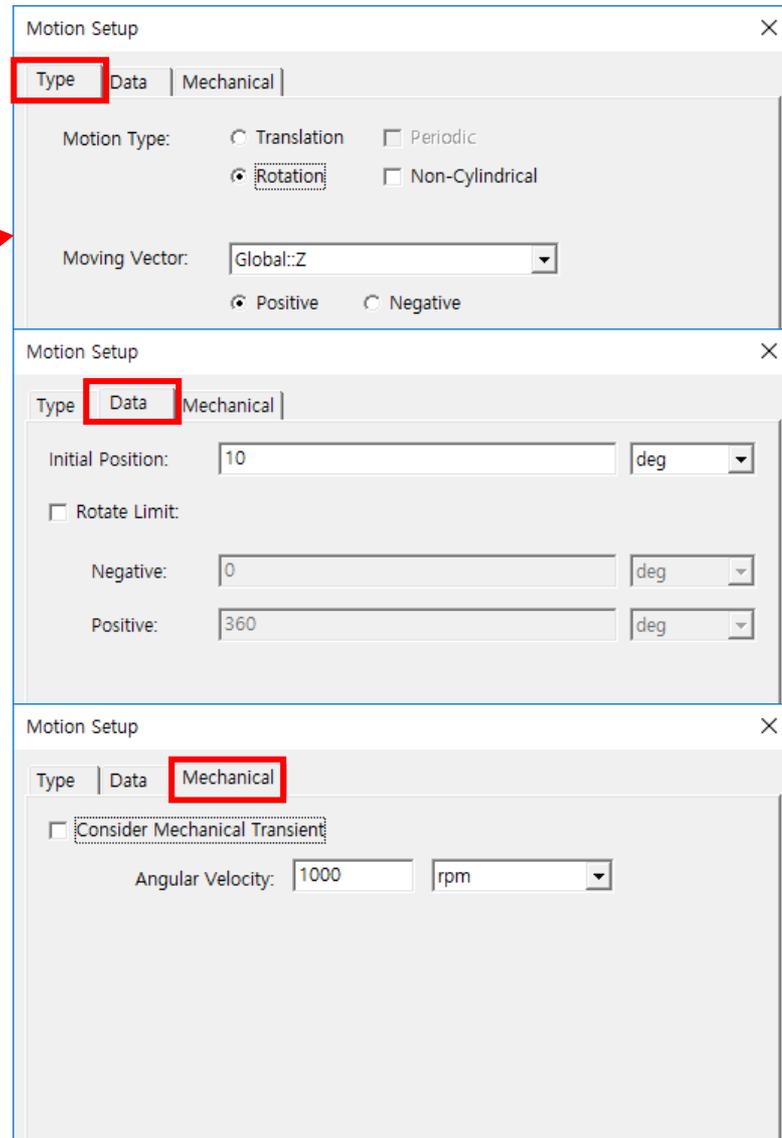
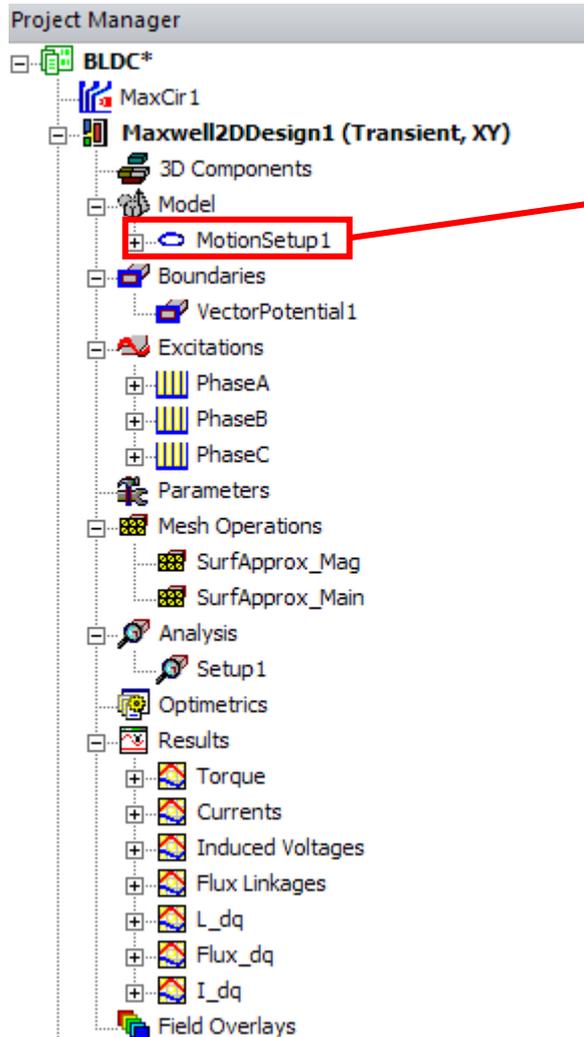


Pre-processing

Post-processing



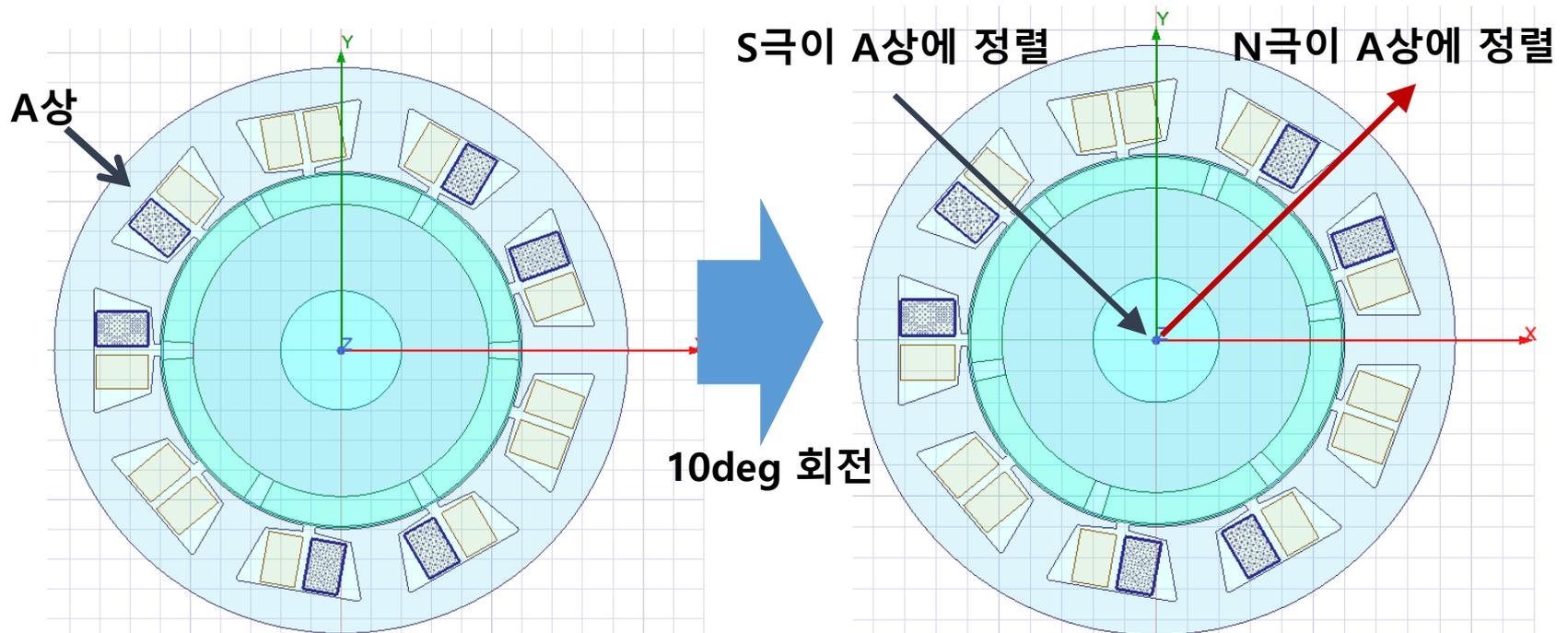
MotionSetup1 확인 (Maxwell)



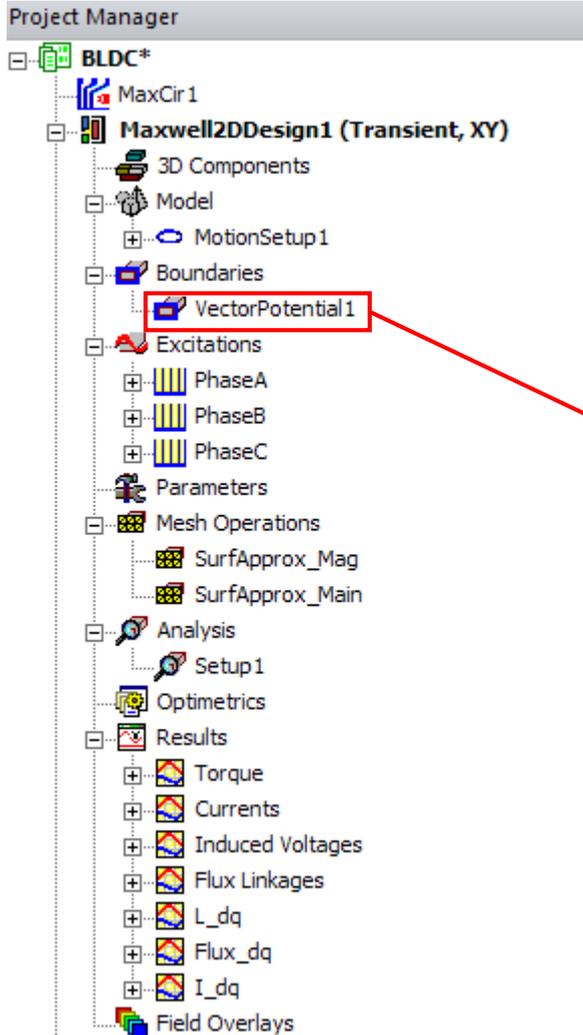
Initial Position 의미 (Maxwell)

Initial Position 설명

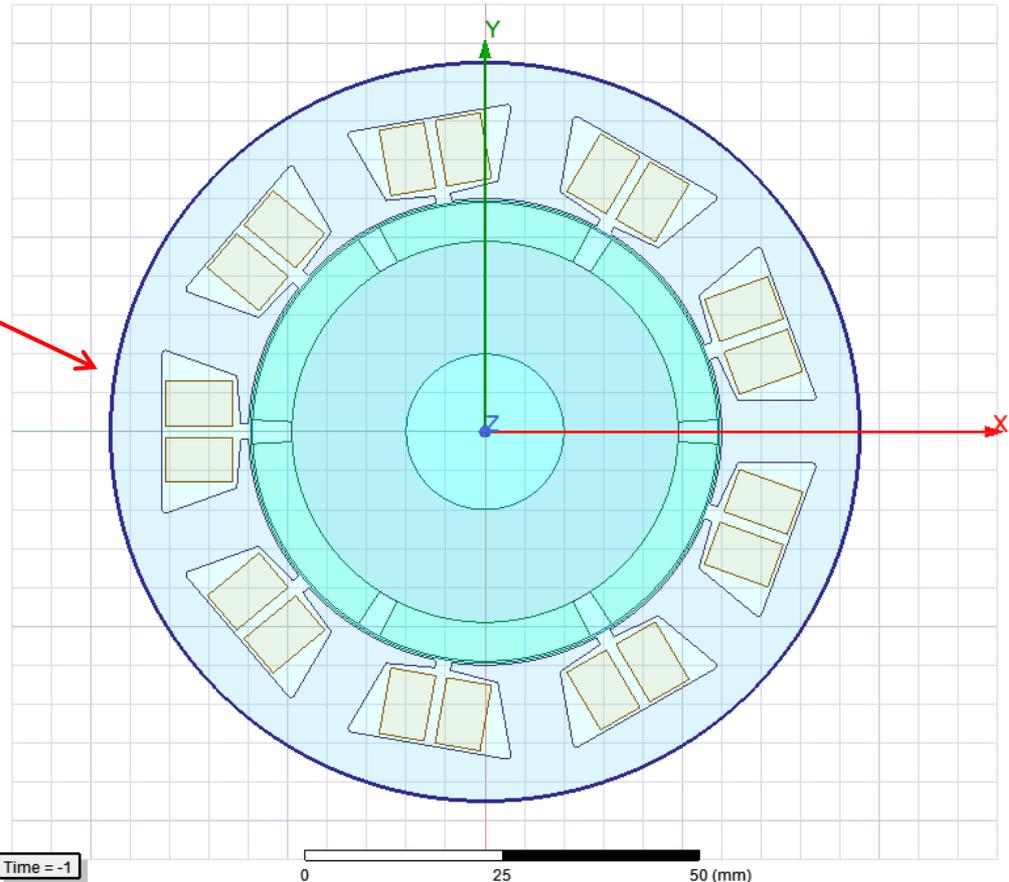
- Motor 구동시 A, B, C상에 3상 AC전류가 인가가 됨
- 해석 시 A상에 0deg, B,C상에서는 120deg, 240deg 위상차를 갖는 Sin파형 입력
- 따라서, A상 기준으로 자석이 정확하게 정렬이 되어있어야 구동토크가 발생
- A상은 초기 0초에 Sin파형으로 자기력이 없고, 주변의 B,C상으로 부터의 자기력으로 A상에 정렬된 자석이 회전함



경계조건 확인 (Maxwell)

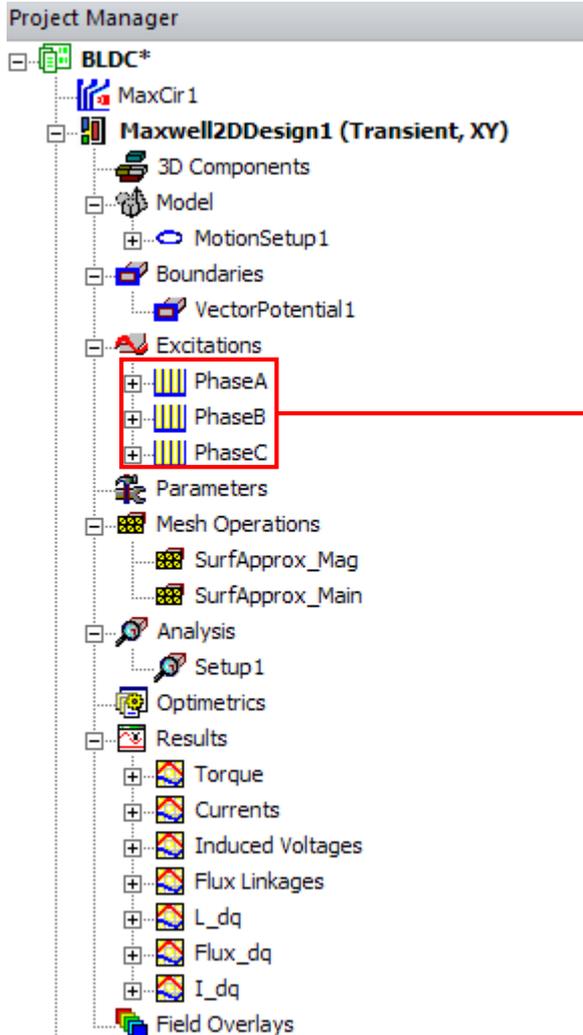


- Full model 이기 때문에 가장 바깥쪽에 VectorPotential 설정



입력 확인 (Maxwell)

- 3상 모두 외부회로(External Circuit)와 연결



Name	Value	Unit
Name	PhaseA	
Type	Winding Group	
Winding Type	External	
IsSolid	Stranded	
Initial Current	0	A
Number of Parallel Branches	1	

Name	Value	Unit
Name	PhaseB	
Type	Winding Group	
Winding Type	External	
IsSolid	Stranded	
Initial Current	0	A
Number of Parallel Branches	1	

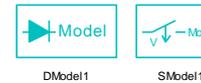
Name	Value	Unit
Name	PhaseC	
Type	Winding Group	
Winding Type	External	
IsSolid	Stranded	
Initial Current	0	A
Number of Parallel Branches	1	

외부회로 확인 (Maxwell)



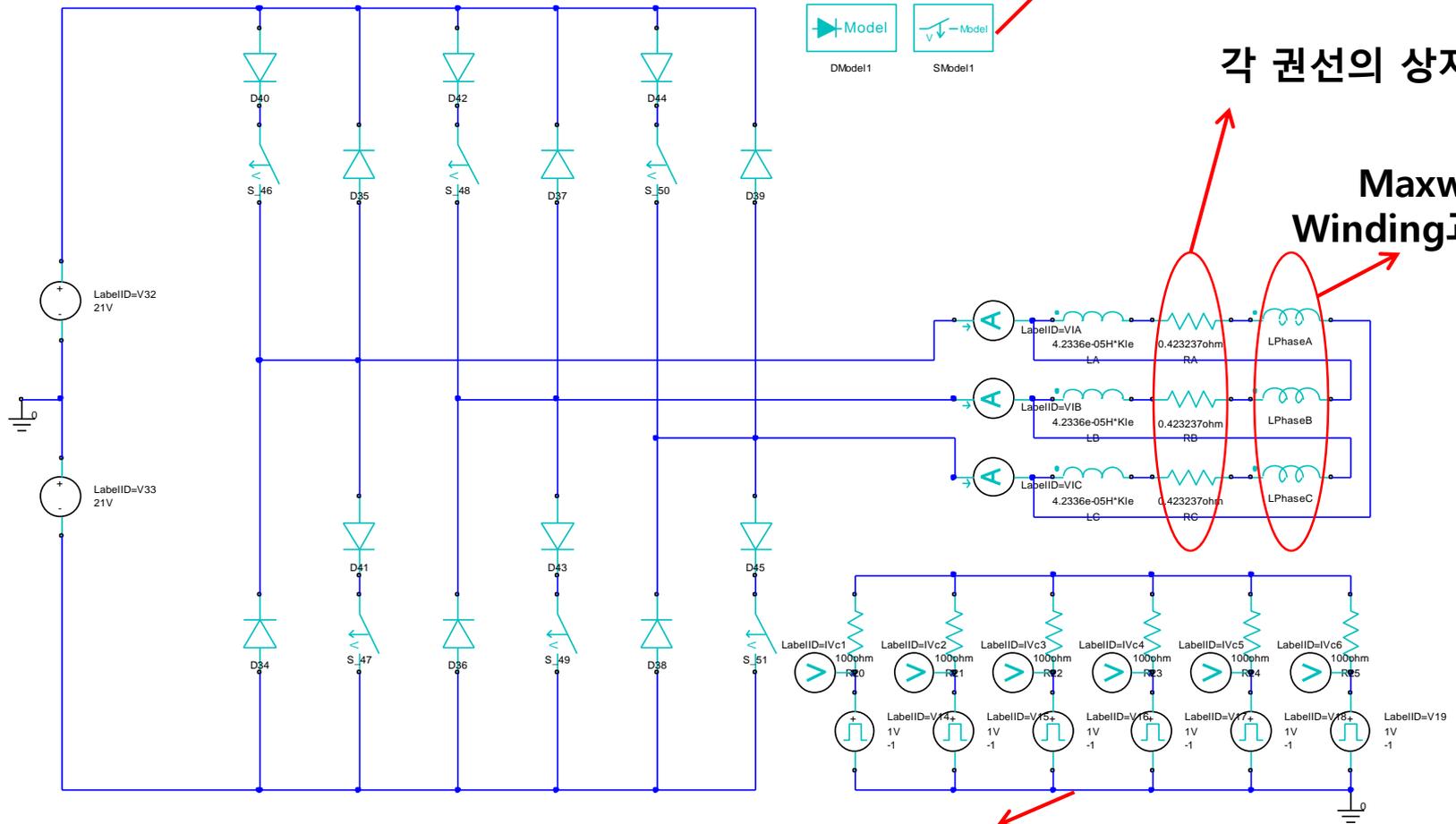
전체 Diode 정보

전체 switch 정보



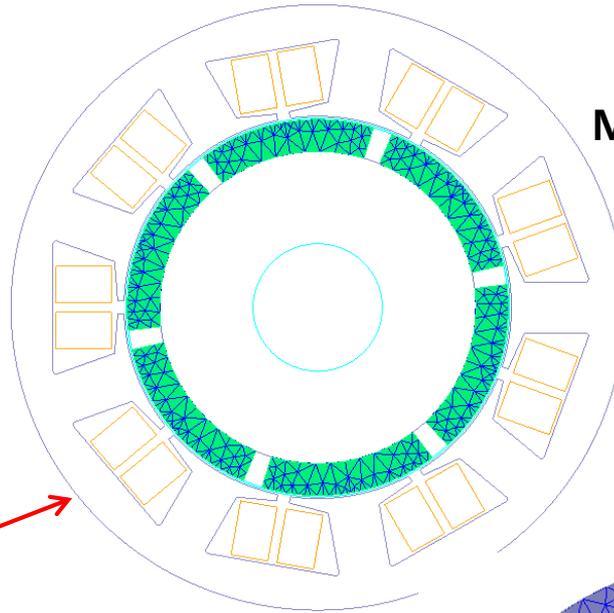
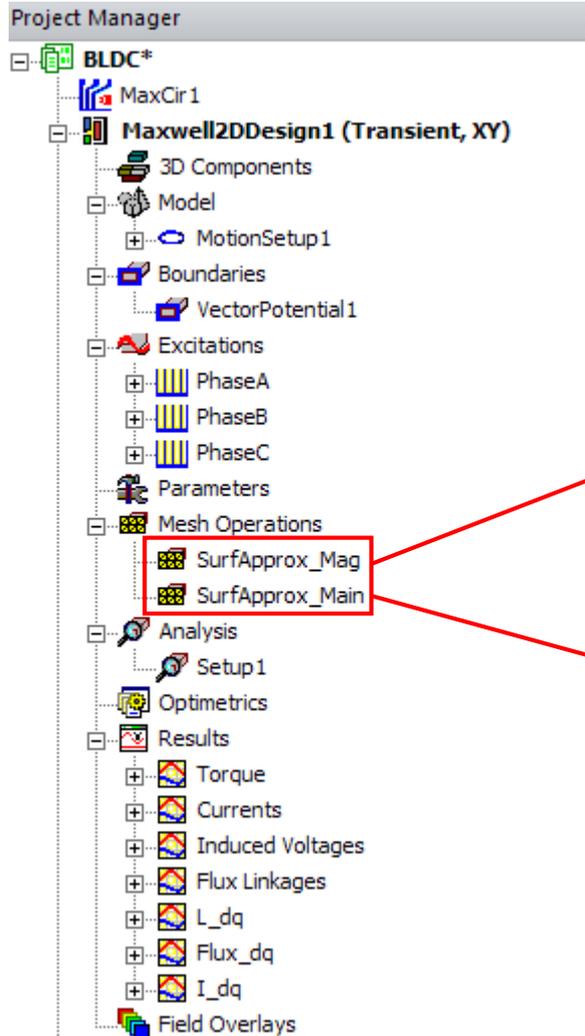
각 권선의 상저항

Maxwell Winding과 연결

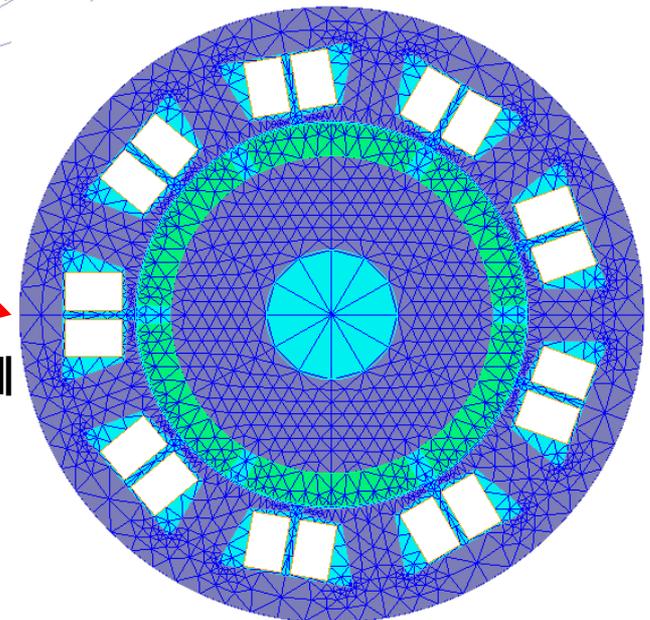


6개의 스위치 제어 회로

Mesh 확인 (Maxwell)



Magnet에 mesh 적용



Core와 해석 가상 범위에
mesh 적용

Setup1 확인 (Maxwell)

- 기계적인 속도

$$Rpm = 1000rpm$$

$$Rps = 1000/60=16.667Hz$$

$$T_{mech} = 1/16.667=0.06s$$

- 전기적인 속도

$$T_{ele} = T_{mech}/3 = 0.02s$$

$$Frequency = 1/T_{ele}=50Hz$$

$$Stop\ time = 0.04s$$

(전기적으로 2주기)

(기계적으로 1/3바퀴)

$$Time\ step = 0.0002s$$

(전기적으로 100step

= 3.6deg씩 해석)

The image shows a screenshot of the ANSYS Maxwell software interface. On the left is the Project Manager tree, and on the right are two 'Solve Setup' dialog boxes.

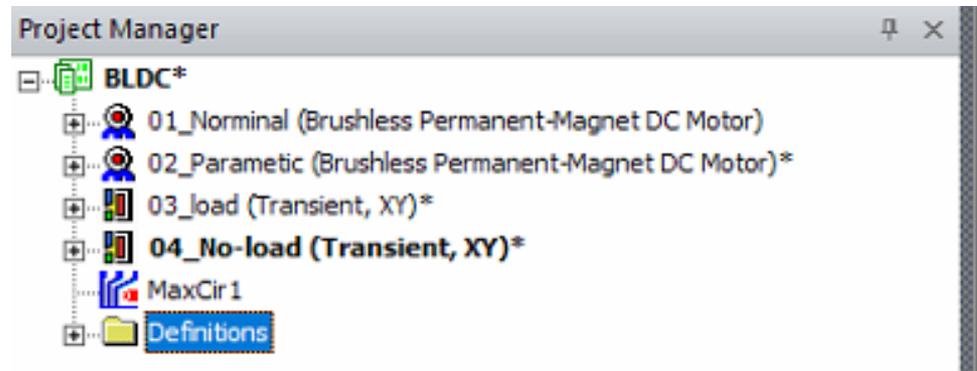
Project Manager: The tree shows a project named 'ipmsm_rmxp1'. Under 'Maxwell3DDesign1 (Transient)*', the 'Analysis' folder is expanded, and 'Setup1' is highlighted with a red box. An arrow points from this box to the 'Save Fields' tab of the 'Solve Setup' dialog.

Solve Setup (General Tab): This dialog shows the 'General' tab selected. The 'Name' is 'Setup1' and it is 'Enabled'. Under 'Transient Setup', 'Adaptive Time Step' is unchecked. 'Stop time' is set to 0.04 s, and 'Time step' is set to 0.0002 s.

Solve Setup (Save Fields Tab): This dialog shows the 'Save Fields' tab selected. A message states: 'The stop time defined in the General Page will be included automatically.' Under 'Additional field save times ...', the 'None' radio button is selected. The 'Every' option is also visible with a value of 1, and the 'to' value is 0.04 s.

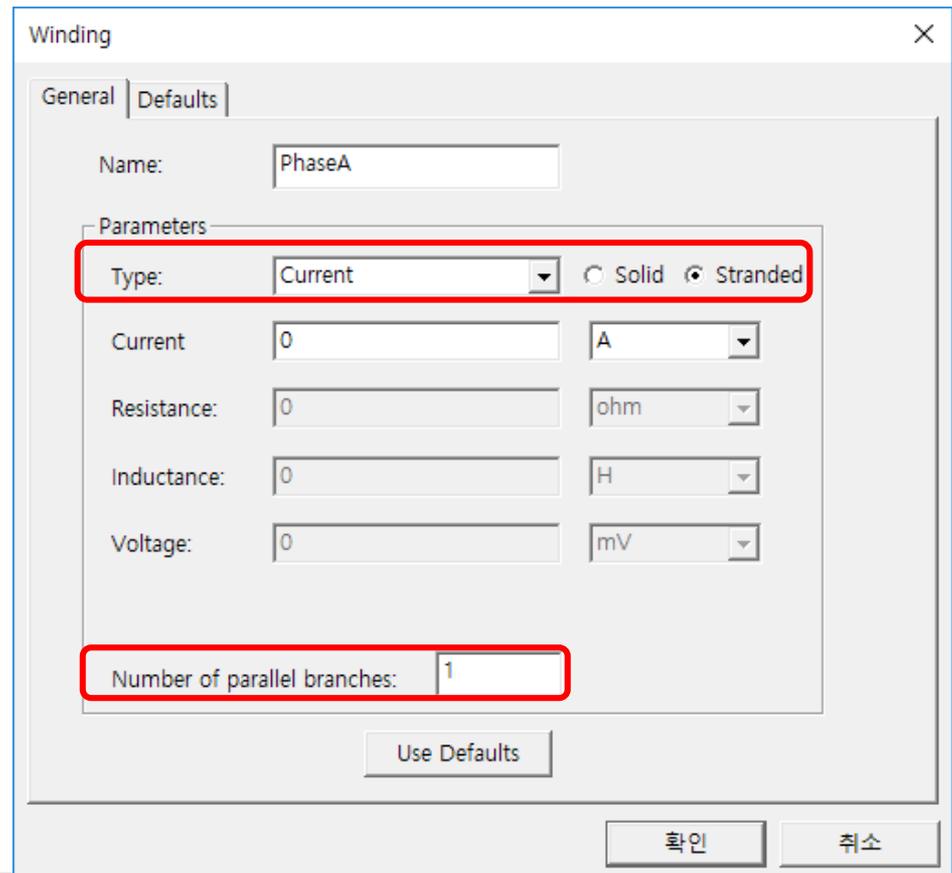
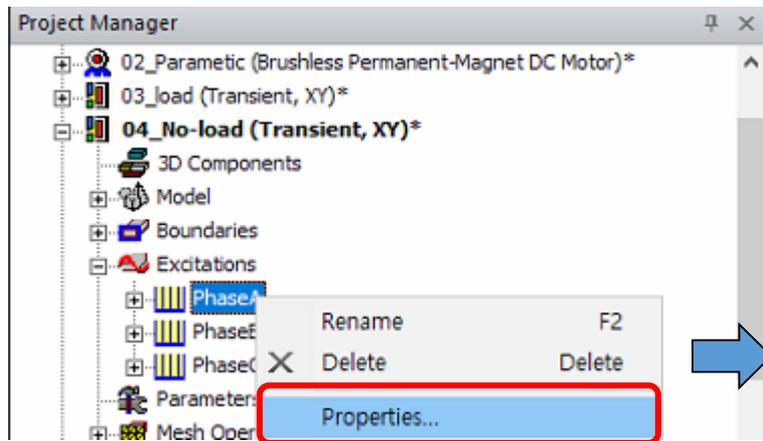
No-load 해석

- MaxwellDesign1 선택해서 RMB () – Copy
- BLDC 프로젝트에서 RMB () – Paste
- 이름 변경
 - MaxwellDesign1 → 03_load
 - MaxwellDesign2 → 04_No-load



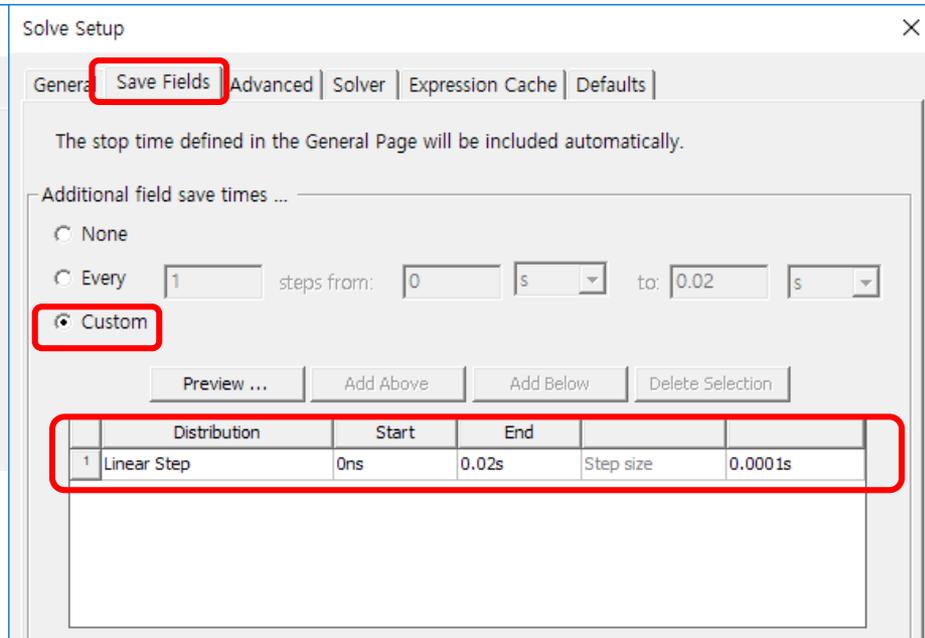
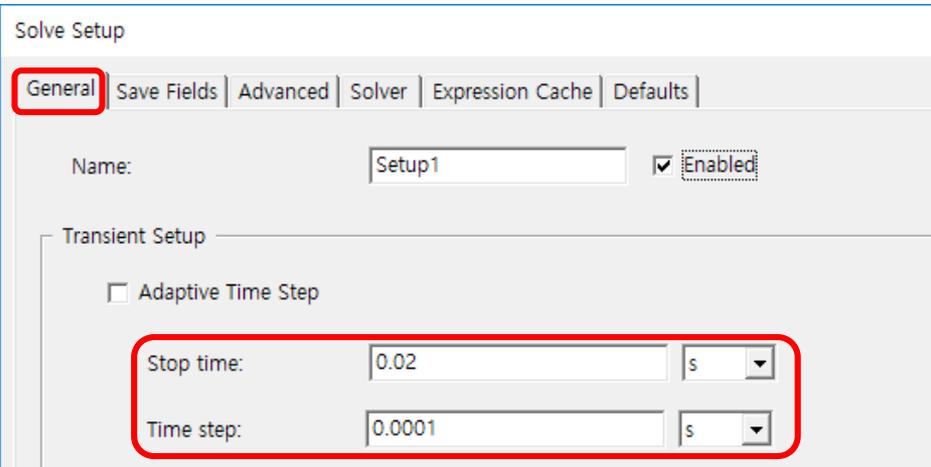
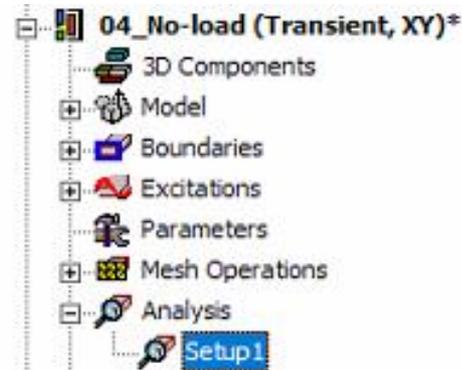
No-load : Excitation 설정

- PhaseA 선택하여 RMB () 클릭하고 Properties 선택
 - Type 을 Current 로 변경하고, 값을 "0" 으로 입력
 - Number of parallel branches 는 "1" 를 유지 (RMxprt 에서 설정한 값임)
 - PhaseB 와 PhaseC 도 같은 값으로 변경



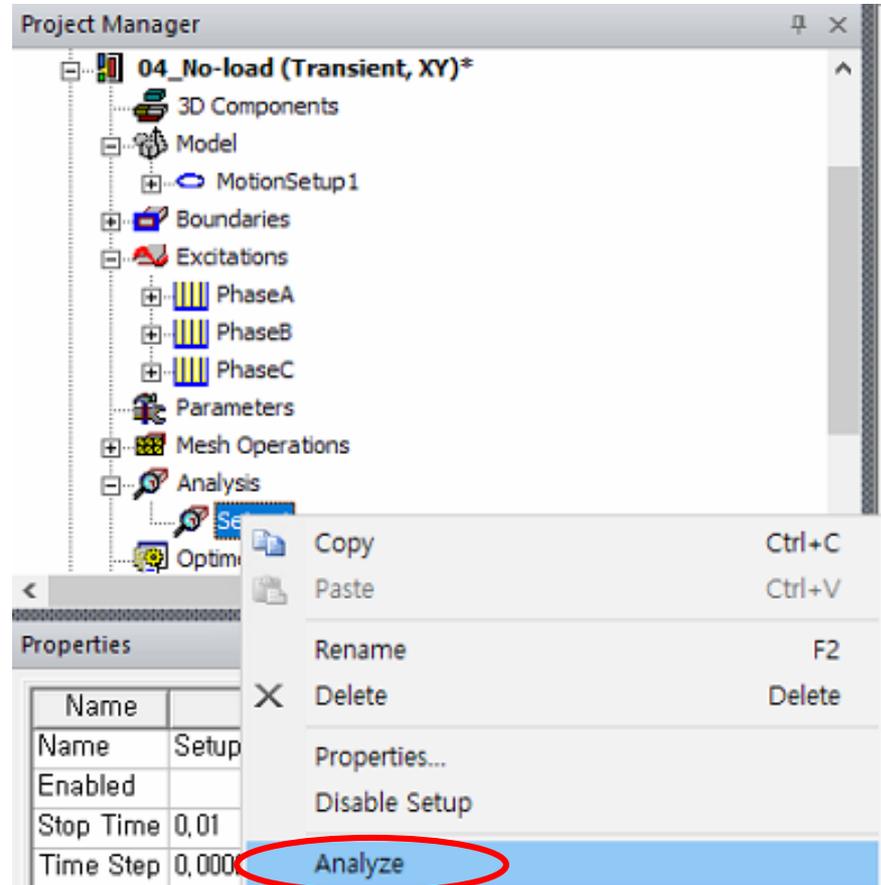
No-load : Setup1 설정

- Setup1 더블 클릭
 - General tab
 - Stop time : 0.02s
 - Time step : 0.0001s
 - Save Fields tab
 - Custom 체크
 - Distribution : Linear Step
 - Start : 0 , End : 0.02s , Step size : 0.0001s



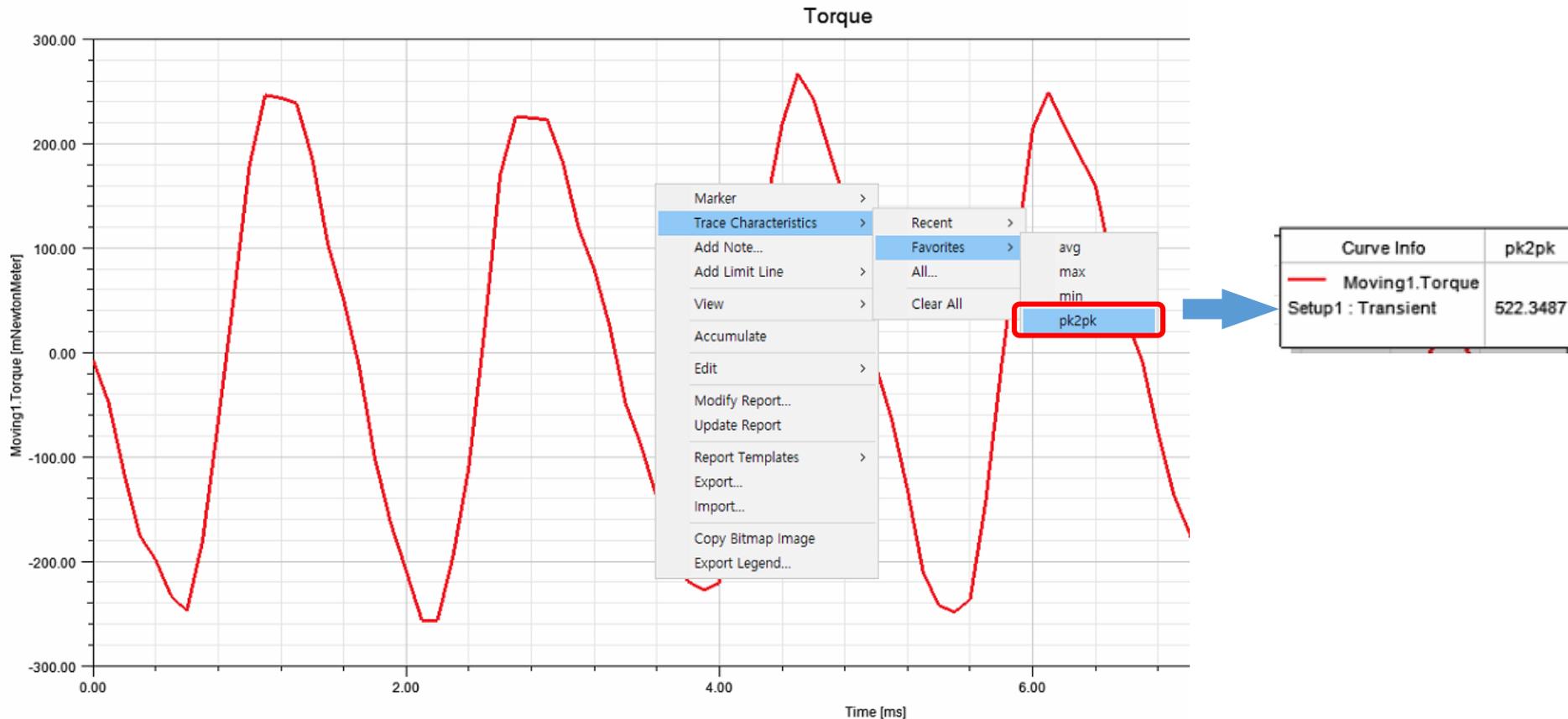
No-load : Analyze & Results

- Analysis 아래에 있는 Setup1 선택한 후, RMB () 하여 Analyze 선택 :



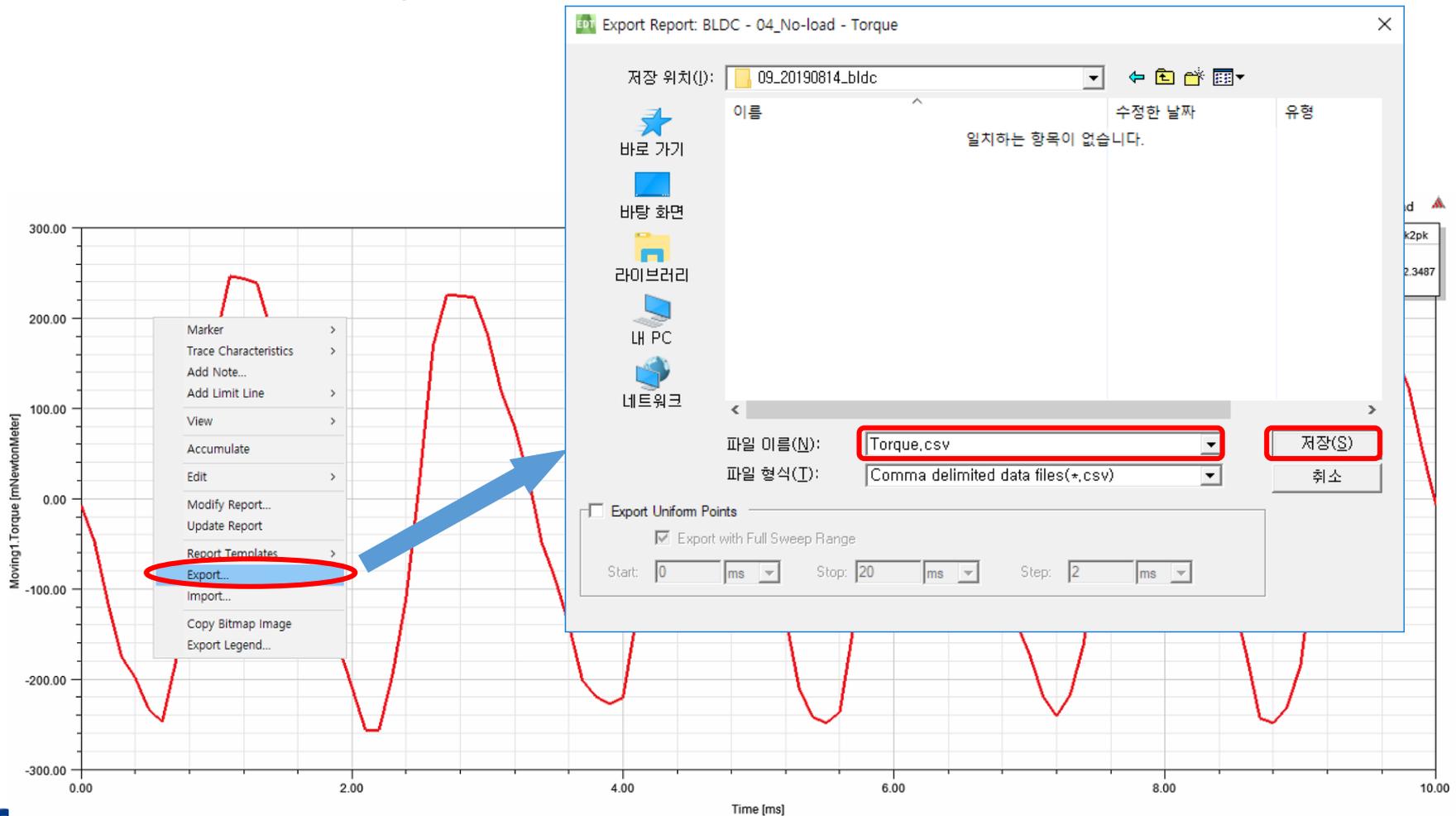
No-load : Analyze & Results

- Results > Torque 를 Double Click
- Plot에서 마우스 우클릭 > Trace Characteristics > Favorites > pk2pk
- 522.3487 mNm 확인



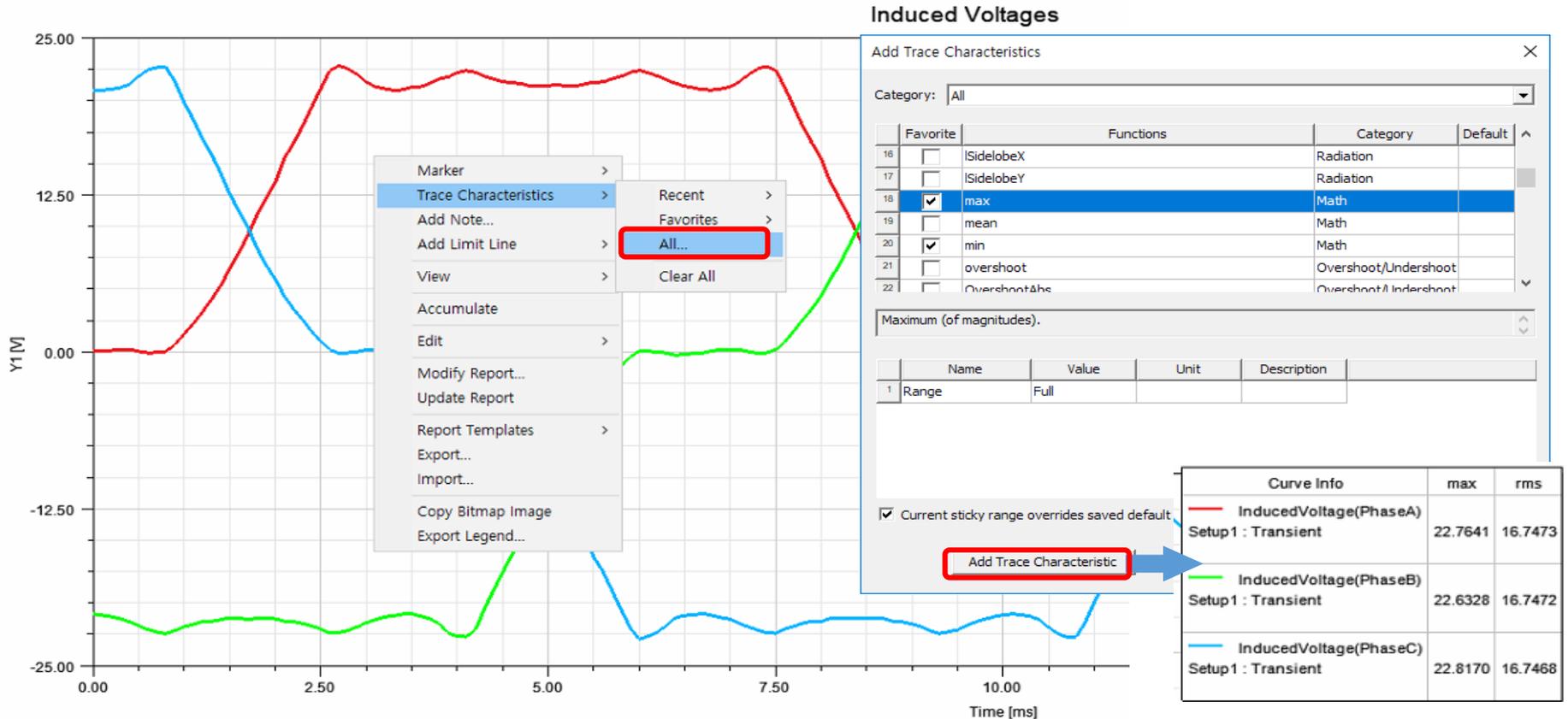
No-load : Analyze & Results

- Plot에서 마우스 우클릭 > Export...
- 개인폴더에 "Torque.csv"로 저장



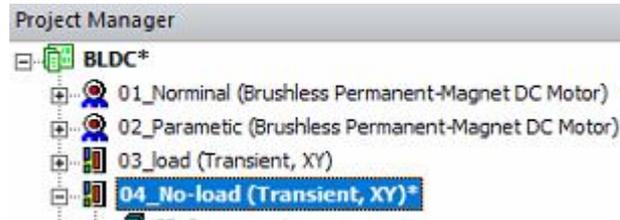
No-load : Analyze & Results

- Results > Induced Voltages 를 Double Click
- Plot에서 마우스 우클릭 > Trace Characteristics > All...
- Max 선택 > Add Trace Characteristic
- rms 선택 > Add Trace Characteristic

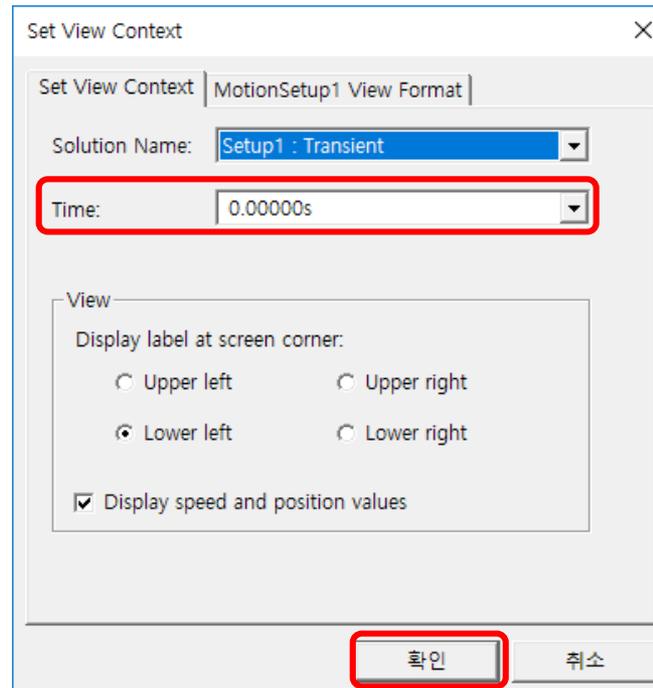


No-load : Results

- "04_No-load" 더블 클릭

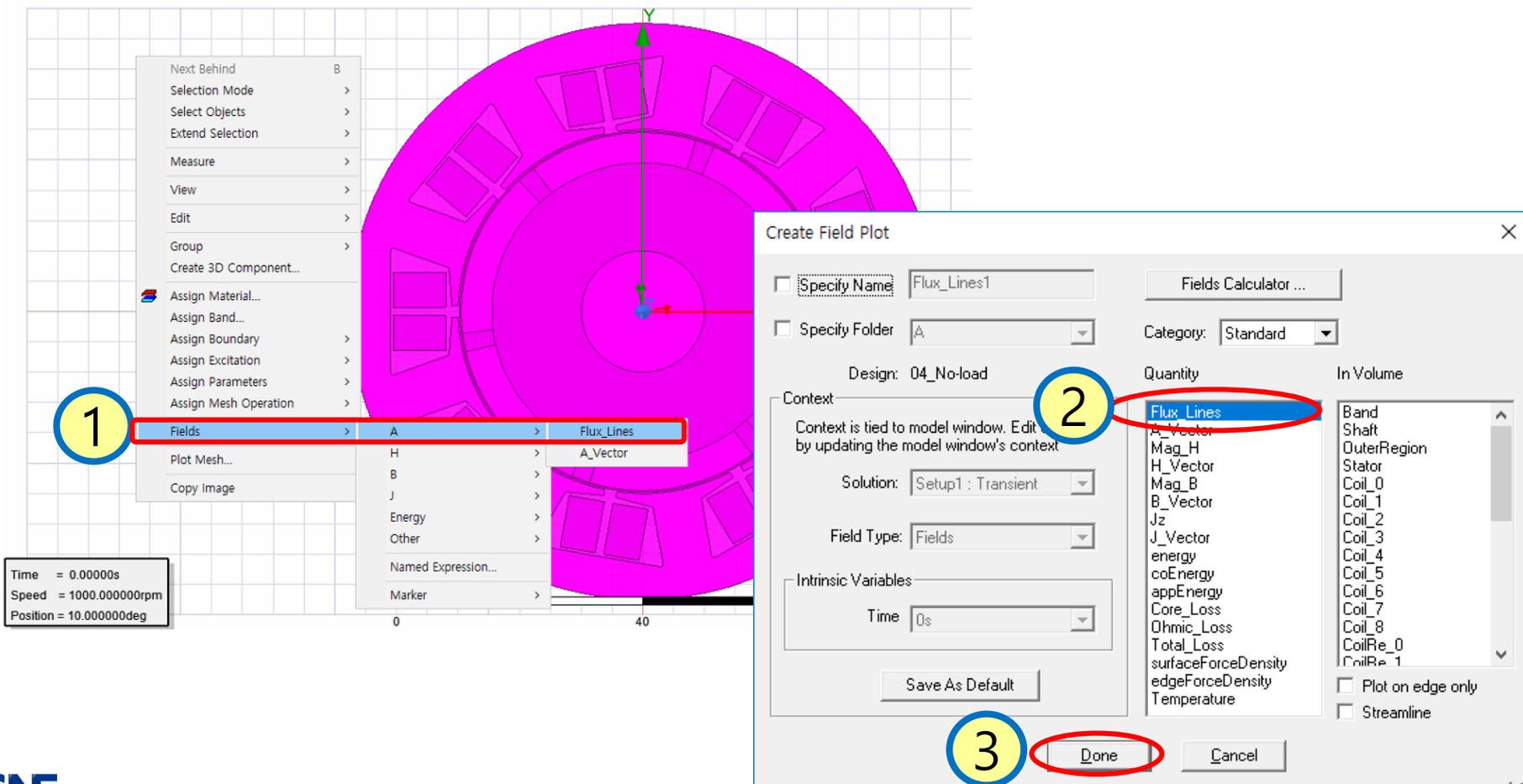


- Menu 에서 View > Set Solution Context → "0s" 선택 → "확인"



No-load : Flux Lines

- Modeler Window 에서 CTRL+A 를 입력하여 모든 objects 선택
 - RMB () > Fields > A > Flux_Lines 선택



1

2

3

Time = 0.00000s
Speed = 1000.000000rpm
Position = 10.000000deg

0 40

Create Field Plot

Specify Name: Flux_Lines1 Fields Calculator ...

Specify Folder: A Category: Standard

Design: 04_No-load

Context: Context is tied to model window. Edit by updating the model window's context

Solution: Setup1 : Transient

Field Type: Fields

Intrinsic Variables: Time 0s

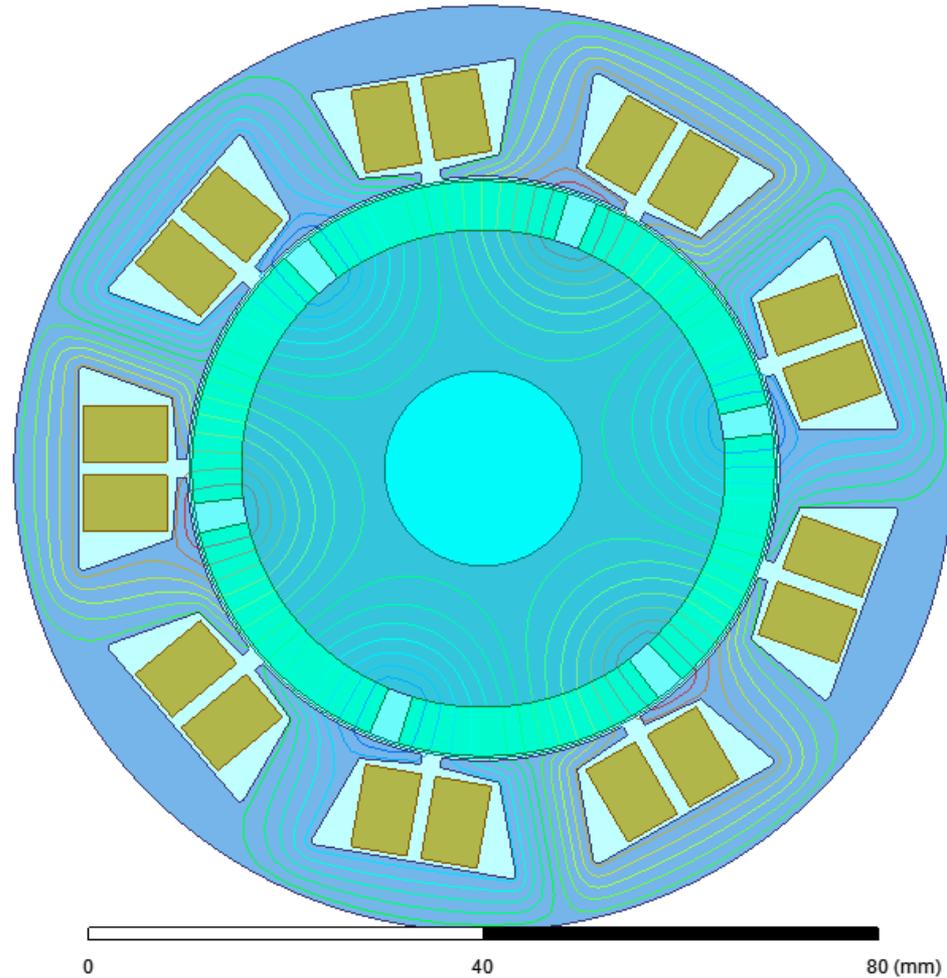
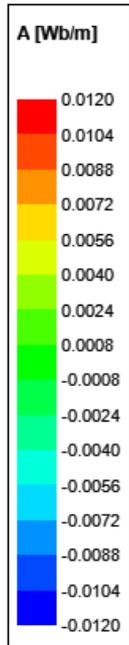
Quantity: Flux_Lines

In Volume: Band, Shaft, OuterRegion, Stator, Coil_0, Coil_1, Coil_2, Coil_3, Coil_4, Coil_5, Coil_6, Coil_7, Coil_8, CoilRe_0, CoilRe_1

Plot on edge only
 Streamline

Save As Default Done Cancel

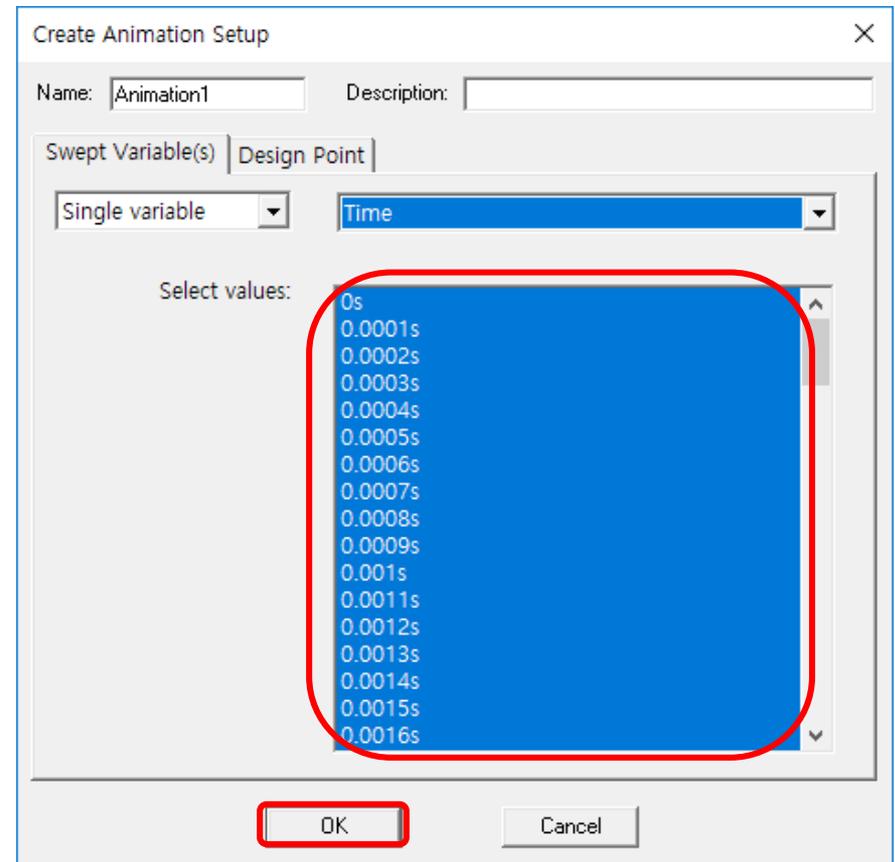
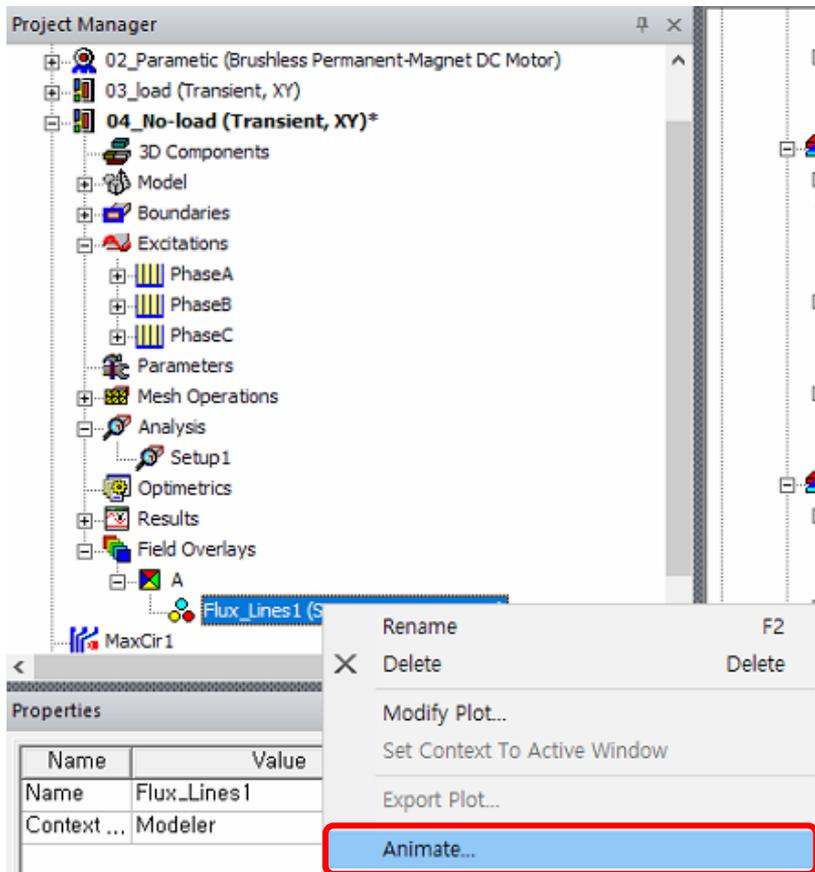
No-load : Flux Lines



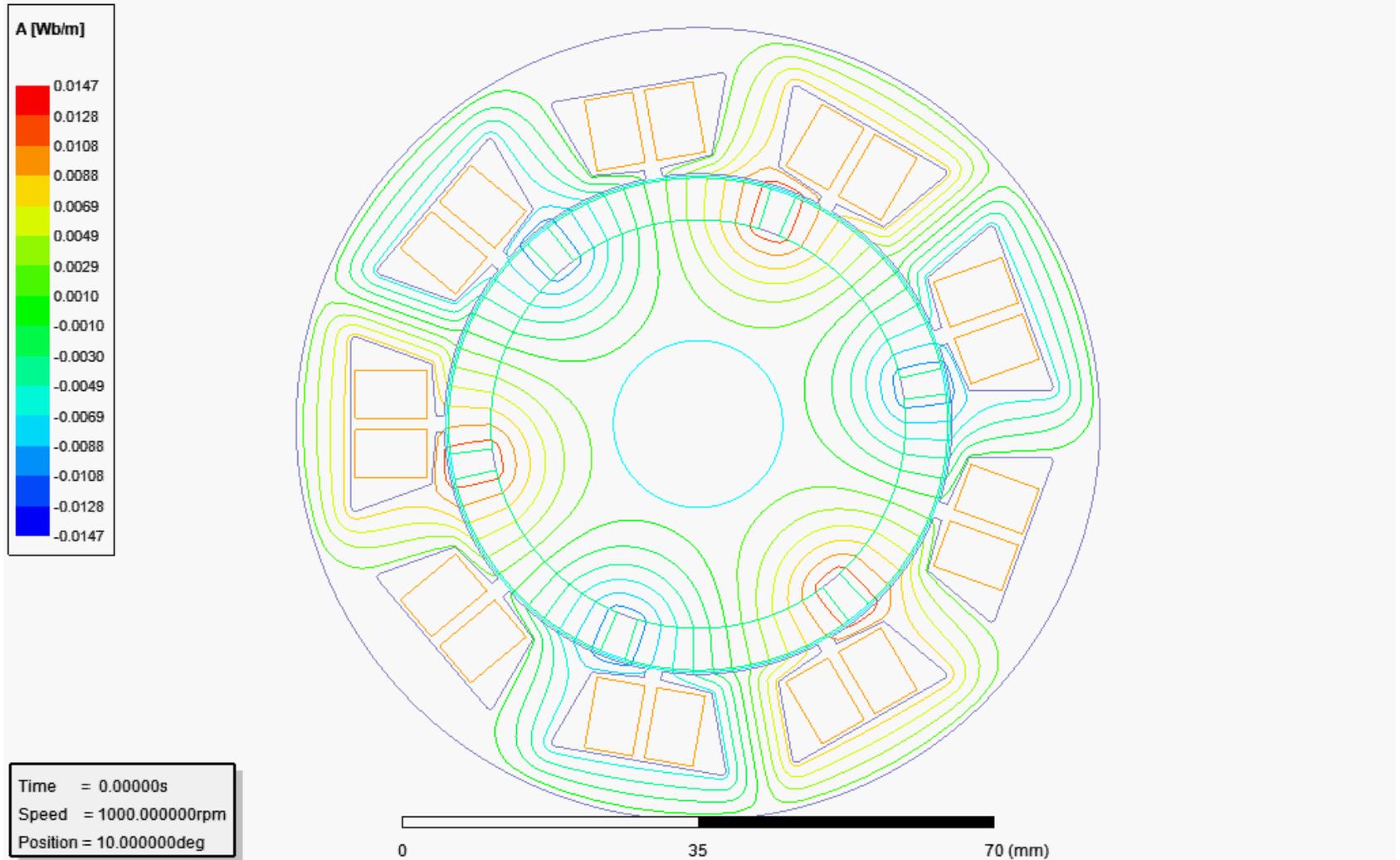
Time = 0.00000s
Speed = 1000.000000rpm
Position = 10.000000deg

No-load : Animation

- Field Overlays > A > Flux_Lines1 마우스 우클릭 > Animate 선택
- Time 전체 선택 후 OK



No-load : Animation



감사합니다.

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※ 본 자료의 모든 콘텐츠의 저작권은 소프트웨어 개발사와 (주)태성에스엔이에 있으므로 무단 전재 및 변형, 배포할 수 없습니다.