Servo Motor Design using MotorSolve

Introduction

A servo motor will be designed in this case study using the MotorSolve BLDC software. A typical design sequence is followed starting with design specifications and initialization using the sizing feature of MotorSolve. This is followed by a study of the initial design, winding design, design refinements and FEA based design verification.

Design Specifications

The task is to design a servo motor with the following specifications

Frame size	80 mm square (max.)
Frame length	No min.
Drive type	Sine wave
Voltage	dual 150/300
Rated speed	3500 RPM
Rated torque	2 Nm. (cont.)
Peak Torque	6 Nm. (5 secs.)
Rated current	2.23 A (RMS)
Peak Current	10 A
Efficiency	> 85%
Ambient Temp.	0-50 C
Insulation class	Class C
Duty cycle	10% at peak torque
Cooling	Natural convection

Rotor/Stator configuration, Number of Poles/slots

Detailed discussions of the factors that must be considered for selecting the motor type and configuration can be found in many motor design texts. Based on previous designs of servo motors, the following choices are made:

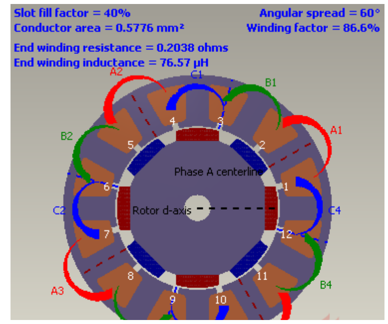
Rotor Template	Bread loaf with interior rotor
No of poles/slots	8 pole/ 12 slot

Material selection

For this motor, based on commonly used materials for such applications, the M19-29 G and NdFeB 32/16 are used as lamination and permanent magnet materials, respectively. MotorSolve's materials library contains these choices, in addition to nearly 200 other materials.

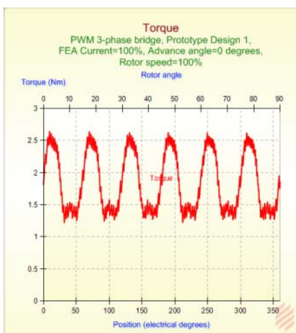
Model initialization, sizing and performance

After making the initial selections, an initial design including motor dimensions and winding details (winding layout, phase coil parameters and end winding resistance and inductance) is required. The *sizing* feature of MotorSolve can generate an initial model including model dimensions and winding details. This feature uses as input the target model performance specifications, design constraints and any other design selection prior to its application. Sizing has been applied to this example and the detailed model parameters are in APPENDIX A. The cross section of the sized model is shown in Fig. 1.

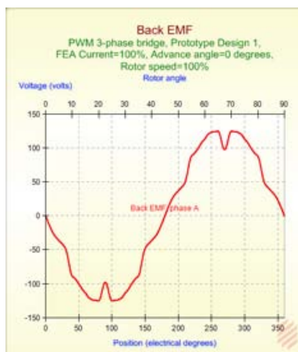


1 Cross section of motor model from sizing

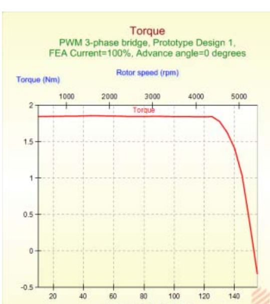
In order to proceed to the next step, the performance of this model is studied. Figs. 2-5 show the torque waveform, back emf, torque-speed characteristics and the cogging torque, respectively of the sizing output.



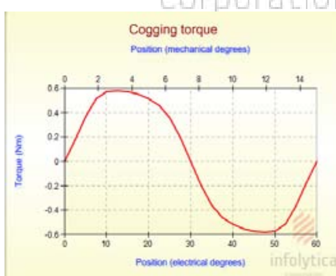
2 Torque waveform



3 Back EMF



4 Torque-Speed characteristics

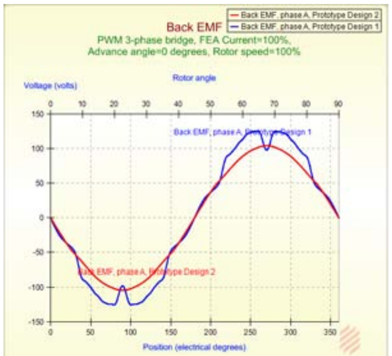


5 Cogging torque under rated conditions

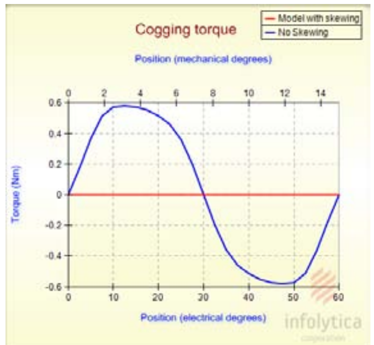
The efficiency of this motor, calculated using MotorSolve is 94.74%. It is clear from these results that this is a good initial model to continue the design sequence with.

Back emf, Cogging torque and Skewing

Consider Fig. 3, which shows that the back emf profile is not an ideal sinusoid (as per model drive type specification). Typically a more sinusoidal profile can be obtained by skewing the motor. A 30 degree skew (corresponding to one slot pitch) has been applied to the rotor and the resulting back emf and cogging torque of the modified model are shown in Figs 6,7 which shows a sinusoidal back emf profile of the model as well as negligible cogging torque.



6 Back emf



7 cogging torque

Winding design

Winding Layout

By winding layout we mean how the phase coils are distributed over the stator slots. Depending on the number of poles and slots, there are usually multiple possibilities for balanced winding layouts and the quality of each of these is quantified by the so called *winding factor*. In MotorSolve, for any pole/slot combination, all possible balanced winding configurations and the corresponding winding factors are computed automatically. For the 8 pole/12slot case, there is only one balanced configuration with a winding factor of 86.6% (shown in Fig. 1). As such, the winding layout is kept fixed during the design process for this example.

Phase coil design

The second aspect of winding design is phase coil design. By phase coil design, we mean the following aspects (as applied to each phase);

- Connection type (Wye/Delta, series, parallel): In this model, the phases are Wye connected and in series.
- Drive type (six step/sinusoidal): as per specifications, sinusoidal drive type is used for this model.
- Number of turns per coil: can be calculated using the back emf (K_e) and torque constants (K_t) in MotorSolve. The sizing output includes this value and it is set at 36 turns/coil. Further changes of this parameter may be necessary later during the design process.
- Wire gauge selection: The sizing output also computes this and it is given as .5776 mm^2.

End effects

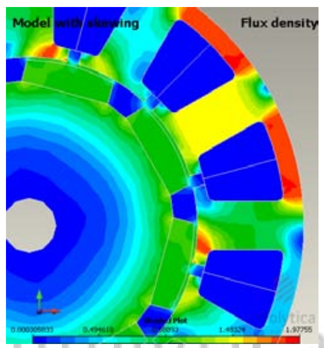
MotorSolve automatically computes the end winding inductance and resistances and takes end affects into account when machine performance is computed. These values are given by 76.57 µH and .2038 Ohms.

Flux Density, Rotor and Stator Dimensions

Refinements of the rotor and stator dimensions are considered next. Fine tuning of the rotor and stator dimensions are usually based on desired flux density levels in various parts of the motor. Typical values of these could be:

Air gap	0.65 -0 .85 T
Stator Yoke	1.0 - 1.5 (peak) T
Stator Teeth	1.3 - 1.7 T
Rotor Yoke	1.0 - 1.3 T

Fig. 8 shows a shaded plot of the flux density distribution of the motor designed up to now:

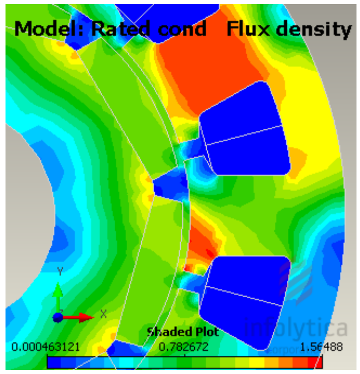


8 Flux density before refinement

The maximum flux density in various model parts are given by,

Air gap	1.23 T
Stator Yoke	1.87 T
Stator Teeth	1.85 T
Rotor Yoke	1.12 T

Comparing these values to the desired values, the following changes are applied to the motor; increase the back iron depth, tooth tang depth and the tooth tang angle in the stator. Change also the magnet thickness, magnet gap angle, the air gap thickness and the shaft diameter. The resulting flux density and distribution are shown in Fig. 9.



9 Flux distribution after refinement

The resulting max flux density values are now,

Air gap	.91 T
Stator Yoke	1.15 T
Stator Teeth	1.42 T
Rotor Yoke	1.27 T

Motor performance and fine tuning

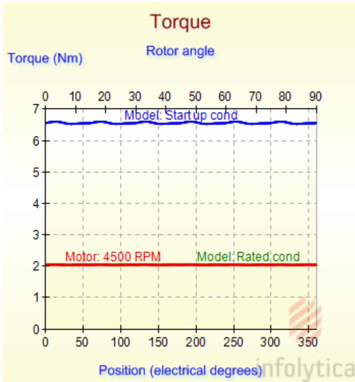
Detailed performance of the machine designed is presented next. It is important to consider the performance of the motor under various conditions;

- rated condition
- At start up
- At or close to no-load

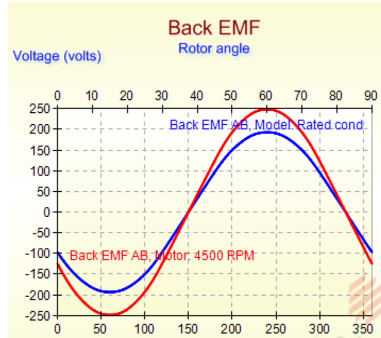
At each load point, the dynamic performance (torque, back emf, air gap flux, torque-speed characteristics and the flux linkage waveforms) of the machine under ideal and 3-phase H-bridge PWM simulations are computed. Also, static and time averaged analysis of flux density distribution, machine losses (ohmic, hysteresis and eddy current losses), demagnetization characteristics, back emf constant (K_e), torque constant (K_t), efficiency, d and q-axis inductances of the machine are also computed. Where appropriate, the harmonic components of various waveforms are reported as well.

Dynamic Performance

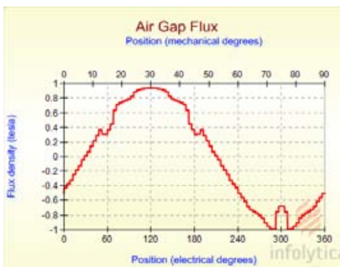
Torque, back emf, air gap flux and flux linkage waveforms under various load points when appropriate, are reported in Figs. 10-15,



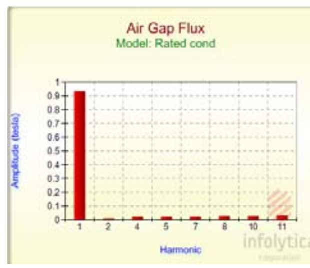
10 Torque waveform at load points



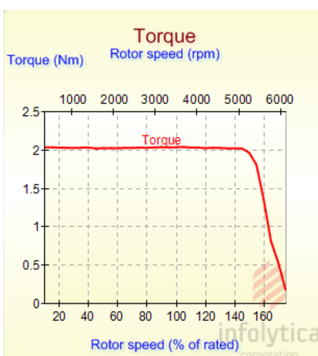
11 Back EMF waveform



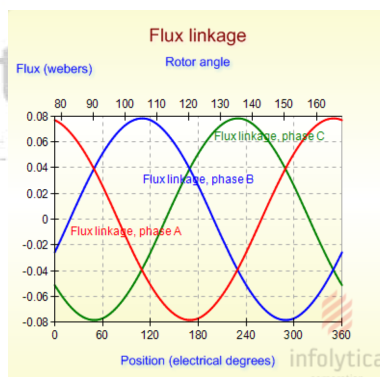
12 Air gap flux



13 Harmonic component of air gap flux



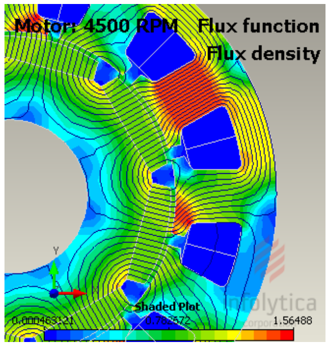
14 Torque-speed characteristics



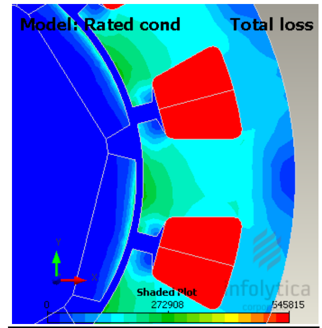
15 Phase flux linkage vs. postion

Static and Time averaged Analysis

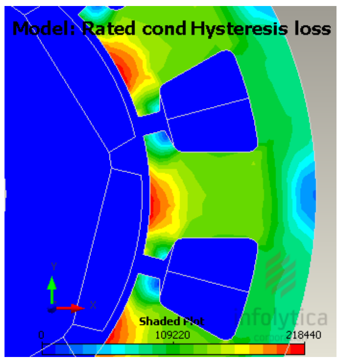
These results are presented in Figs. 16-21.



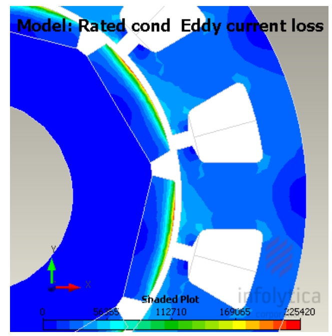
16 Flux function and density



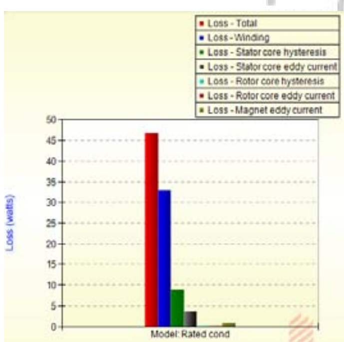
17 Total loss distribution



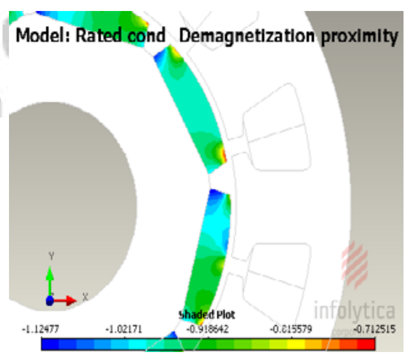
18 Hysteresis loss distribution



19 Eddy current loss distribution



20 Loss comparison bar chart



21 Demagnetization susceptibility

Kt (torque constant)	RMS current (% of rated)	100
	RMS current (A)	3.12
	Kt (Nm/A)	0.66236168512435
Ke (Back-EMF constant)	RMS current (% of rated)	100
	RMS current (A)	3.12
	Ke (V/rad/s)	0.382414697207438
Ld (d-axis inductance)	RMS current (% of rated)	100
	RMS current (A)	3.12
	Inductance (henries)	0.0035314094203598
Lq (q-axis inductance)	RMS current (% of rated)	100
	RMS current (A)	3.12
	Inductance (henries)	0.00358354311837085
Rs (stator resistance)	RMS current (% of rated)	100
	RMS current (A)	3.12
	Resistance (ohms)	1.12878648645379

	Efficiency	
		Efficiency (%)
1	Model: Rated cond	95.6473700062199

22 d-q inductances, stator resistance, torque and back emf constants, efficiency

Design validation and summary

Analyzing the results from the previous section and comparing them to the design specifications shows that the motor designed up to now satisfies the desired criterion. Further refinements and fine tuning may yet be carried out. For this case study, however, no further refinements are done as we have demonstrated how MotorSolve can be used to implement it.

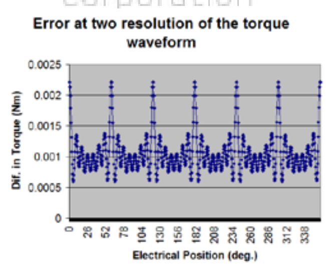
The final step of the design process is design validation. Once a design has been completed, it is very important that the results are validated. Model validation is usually carried out in two steps;

i) FEA based numerical verification of convergence of model results.

ii) By building a prototype and carrying out experiments using a dynamometer and comparing the results to those obtained from FEA based calculations.

The second step of model verification is of course, an experimental process. This is not covered here. The first step is a numerical calculation and is carried out using MotorSolve.

In MotorSolve, convergence can be checked by solving the model at different resolutions and checking to make sure that the model results are approximately the same (i.e., the difference in results is negligible). An example of this, for the steady state torque waveform, is shown in Fig. 23. The maximum difference, of the order of 10^{-3}, is a reasonable indication of convergent results. The final design parameters are given in APPENDIX B.



23 Pointwise torque waveform difference at two model resolutions

APPENDIX A: MotorSolve Sizing Report

MotorSolve Data and Results

	Prototype Design 1
General Settings	
Specifications	
Supply voltage	300
Rated current	2.59
Rated speed	3500
Global	
Number of phases	3
Number of poles	8
Number of slots	12
Motor outer diameter	80
Air gap thickness	0.5
Stack length	55.3
Description	
Parts	
Rotor location	Interior
Rotor type	Bread-loaf with non-embedded magnets
Stator type	Square
Protected dimension method	Automatic
Units	
Length	millimeter
Temperature	degree Celsius
Frequency	hertz
Time	millisecond
Mass	gram

Current	ampere
Force	newton
Viewing Options	
Discretization angle	5
Rotor (Bread-loaf with non-embedded magnets)	
General	
Skew	0
Skew angle	0
Number of magnets per pole	1
Temperature	20
Rotor material	M-19 29 Ga
Magnet material	Neodymium Iron Boron: 32/16
Sleeve material	304 Stainless steel
Override with radial magnetization	False
Protected dimensions	
Core	
Mid-gap core thickness	17.0522
Mid-magnet core thickness	16.0816
Diameters	
Inner diameter	7.83673
Outer diameter	48
Sleeve thickness	0
Magnets	
Magnet angle	31.5
Magnet exposure	3.09893
Magnet gap angle	8.91618
Magnet inset	0

Magnet thickness	4
Magnet width	13.0291
Fillets	
Magnet tip radius	0
Viewing Options	
Rotor core transparency	255
Rotor sleeve transparency	255
Rotor magnet transparency	255
Stator (Square)	
General	
Skew	0
Skew angle	0
Temperature	20
Stator material	M-19 29 Ga
Coil material	Copper: 5.77e7 Siemens/meter
Protected dimensions	
Diameters	
Back iron depth	2.72
Inner diameter	49
Outer diameter	80
Teeth	
Bifurcation radius	-3.114E-22
Shank length	10.8816
Slot area	103.969
Slot depth	12.78
Tooth gap angle	4.23384
Tooth gap width	1.81

Tooth tang angle	0
Tooth tang depth	1.77
Tooth width	7.09
Fillets	
Bottom shaft radius	0.888889
Tooth tang radius	2.72853E-14
Top shaft radius	0.888889
Viewing Options	
Stator core transparency	255
Stator winding transparency	255
Coil Windings	
Drive	
Connection type	Wye (Star)
Drive type	Sinewave
Number of parallel paths	1
Diode voltage drop	0.6
Switch voltage drop	0.2
Current hysteresis	15
End Effects	
End winding input method	Automatic
Overhang input method	% of the coil span
Overhang percentage	50
General	
Wire size method	Fill factor
Fill factor	40
Layout method	Automatic
Automatic Layout	

Winding type	Lap
Coil span	1
Number of layers	2
Number of coils per set	1
Phase offsets	1
Layout	1 4 7 10
Number of turns	36
Manual Layout	
Phase B offset	1
Phase C offset	1
Number of phase A coils	4
Number of phase B coils	4
Number of phase C coils	4
Layout of phase A	Coil #=1, Go=1, Return=2, # of Turns=36 Coil #=2, Go=4, Return=5, # of Turns=36 Coil #=3, Go=7, Return=8, # of Turns=36 Coil #=4, Go=10, Return=11, # of Turns=36
Layout of phase B	Coil #=1, Go=2, Return=3, # of Turns=36 Coil #=2, Go=5, Return=6, # of Turns=36 Coil #=3, Go=8, Return=9, # of Turns=36 Coil #=4, Go=11, Return=12, # of Turns=36
Layout of phase C	Coil #=1, Go=3, Return=4, # of Turns=36 Coil #=2, Go=6, Return=7, # of Turns=36 Coil #=3, Go=9, Return=10, # of Turns=36 Coil #=4, Go=12, Return=1, # of Turns=36
Chart Viewing Options	
Chart to display	Back EMF
Effective pole angle	120
Model Viewing Options	
Phases to display	A
Animation	Off
Sizing	
Specifications	

Supply voltage	300
Rated speed	3500
Rated torque	2
Global Design Parameters	
Number of phases	3
Number of poles	8
Number of slots	12
Air gap thickness	0.5
Motor aspect ratio	0.6
Maximum outer diameter	80
Maximum length	(Unlimited)
Rotor Parameters	
Rotor location	Interior
Rotor type	Bread-loaf with non-embedded magnets
Rotor temperature	20
Rotor magnet material	Neodymium Iron Boron: 32/16
Stator Parameters	
Stator type	Square
Stator temperature	20
Stator coil material	Copper: 5.77e7 Siemens/meter
Sizing Parameters	
Sizing method	Torque per unit volume
Torque per unit volume	20
Fill factor	40
Rotor-stator ratio	0.6
Stator flux density	1.2
Back-EMF limit	0.9

Magnet air gap ratio	8
Magnet coverage	0.7
Outputs	
Rated current	2.59
Motor aspect ratio	0.691
Motor outer diameter	80
Stack length	55.3
Airgap diameter	48
Stator diameter ratio	0.6
Rated current density	4.32
Back-EMF ratio	0.9
Power factor	99.8

APPENDIX B: Final Model MotorSolve Report

MotorSolve Data and Results

	Model: Rated cond
General Settings	
Specifications	
Supply voltage	300
Rated current	3.12
Rated speed	3500
Global	
Number of phases	3
Number of poles	8
Number of slots	12
Motor outer diameter	80
Air gap thickness	0.75
Stack length	55.3
Description	
Parts	
Rotor location	Interior
Rotor type	Bread-loaf with non-embedded magnets
Stator type	Square
Protected dimension method	Automatic
Units	
Length	millimeter
Temperature	degree Celsius
Frequency	hertz
Time	millisecond

Mass	gram
Current	ampere
Force	newton
Viewing Options	
Discretization angle	5
Rotor (Bread-loaf with non-embedded magnets)	
General	
Skew	1
Skew angle	30
Number of magnets per pole	1
Temperature	20
Rotor material	M-19 29 Ga
Magnet material	Neodymium Iron Boron: 32/16
Sleeve material	304 Stainless steel
Override with radial magnetization	False
Protected dimensions	Inner diameter, Magnet gap angle, Magnet thickness
Core	
Mid-gap core thickness	9.83918
Mid-magnet core thickness	8.5
Diameters	
Inner diameter	23
Outer diameter	48
Sleeve thickness	0
Magnets	
Magnet angle	36.3078
Magnet exposure	2.80535
Magnet gap angle	4

Magnet inset	0
Magnet thickness	4
Magnet width	14.9554
Fillets	
Magnet tip radius	0
Viewing Options	
Rotor core transparency	255
Rotor sleeve transparency	255
Rotor magnet transparency	255
Stator (Square)	
General	
Skew	0
Skew angle	0
Temperature	20
Stator material	M-19 29 Ga
Coil material	Copper: 5.77e7 Siemens/meter
Protected dimensions	Back iron depth, Tooth gap width, Tooth tang depth, Tooth width
Diameters	
Back iron depth	5
Inner diameter	49.5
Outer diameter	80
Teeth	
Bifurcation radius	-3.114E-22
Shank length	7.53326
Slot area	63.3836
Slot depth	10.25
Tooth gap angle	4.19105

Tooth gap width	1.81
Tooth tang angle	15
Tooth tang depth	2
Tooth width	8
Fillets	
Bottom shaft radius	0.888889
Tooth tang radius	2.72853E-14
Top shaft radius	0.888889
Viewing Options	
Stator core transparency	255
Stator winding transparency	255
Coil Windings	
Drive	
Connection type	Wye (Star)
Drive type	Sinewave
Number of parallel paths	1
Diode voltage drop	0.6
Switch voltage drop	0.2
Current hysteresis	15
End Effects	
End winding input method	Automatic
Overhang input method	% of the coil span
Overhang percentage	50
General	
Wire size method	Fill factor
Fill factor	40
Layout method	Automatic

Automatic Layout	
Winding type	Lap
Coil span	1
Number of layers	2
Number of coils per set	1
Phase offsets	1
Layout	1 4 7 10
Number of turns	36
Manual Layout	
Phase B offset	1
Phase C offset	1
Number of phase A coils	4
Number of phase B coils	4
Number of phase C coils	4
Layout of phase A	Coil #=1, Go=1, Return=2, # of Turns=36 Coil #=2, Go=4, Return=5, # of Turns=36 Coil #=3, Go=7, Return=8, # of Turns=36 Coil #=4, Go=10, Return=11, # of Turns=36
Layout of phase B	Coil #=1, Go=2, Return=3, # of Turns=36 Coil #=2, Go=5, Return=6, # of Turns=36 Coil #=3, Go=8, Return=9, # of Turns=36 Coil #=4, Go=11, Return=12, # of Turns=36
Layout of phase C	Coil #=1, Go=3, Return=4, # of Turns=36 Coil #=2, Go=6, Return=7, # of Turns=36 Coil #=3, Go=9, Return=10, # of Turns=36 Coil #=4, Go=12, Return=1, # of Turns=36
Chart Viewing Options	
Chart to display	Back EMF
Effective pole angle	120
Model Viewing Options	
Phases to display	A
Animation	Off