Motor Model

AMK DATA SHEET

General Information

How to read:

Orientation	Value	Min	Max	Step
A-U (right-left)	Current (A)	0	105 A	5.25A
1-201 (up-down)	Speed (RPM)	0	20,000	100 rpm

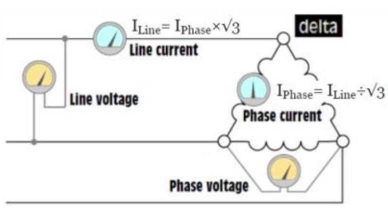
Variable DC Bus Voltage:

- Data is based on DC bus voltage of 600 VDC.
- At a lower DC bus voltage, not all calculated operating points can be approached.
- Which working points can still be reached, can be seen in the worksheets with the voltage that is set depending on the current and the speed. *See* Example in "*Information_Characteristic_Diagram" Sheet.*

Available Values

Worksheet	Description	Unit
<Speed>	Speed	rpm
<Shaft_Torque>	Torque on the shaft	Nm
<Stator_Current_Phase_Peak>	Amplitude phase current	Ampere
<Stator_Current_Phase_RMS>	RMS value phase current	Ampere
<Stator_Current_Line_Peak>	Amplitude line current	Ampere
<Stator_Current_Line_RMS>	RMS value line current	Ampere
<Voltage_Phase_Peak>	= Voltage_Line_Peak	Volt
<Voltage_Phase_RMS>	= Voltage_Line_RMS	Volt
<Voltage_Line_Peak>	= Voltage_Line_RMS	Volt
<Voltage_Line_RMS>	= Voltage_Line_Peak	Volt
<Id_Peak>	Amplitude field weakening current	Ampere
<Id_RMS>	RMS field weakening current	Ampere
<Iq_Peak>	Amplitude of torque generating current	Ampere
<Iq_RMS>	RMS value torque generating current	Ampere
<Vd_Peak>	Amplitude field weakening voltage	Volt
<Vd_RMS>	RMS field weakening voltage	Volt
<Vq_Peak>	Amplitude of torque generating voltage	Volt
<Vq_RMS>	RMS torque generating voltage	Volt
<Frequency>	Frequency	Hz

<Total_Loss>	Sum of: Stator_Copper_Loss, Iron_Loss, Magnet_Loss, Mechanical_Loss	Watt
<Stator_Copper_Loss>	Copper losses in the stator	Watt
<Iron_Loss>	Iron losses	Watt
<Magnet_Loss>	Magnetic losses	Watt
<Mechanical_Loss>	Mechanical losses	Watt
<Power_Factor>	Power factor	
<Electromagnetic_Torque>	Electromagnetic torque is the internal torque of the motor, which results from the simulation. From this the iron losses, magnet losses and mechanical losses are subtracted in order to obtain the mechanical torque on the shaft.	Nm



Term	Description
Line voltage / Phase voltage	In the case of a delta connection, the line voltage and the phase voltage are the voltages measured between any two conductors.
Line current	The line current, is the current flowing through any line between the inverter and the motor connection.
Phase current	The phase current, is the current that flows through the motor winding.
RMS	RMS value Root Mean Square The effective value for sine waves is: RMS value = amplitude / $\sqrt{2}$
Peak	Peak value or amplitude (not peak / peak)

Model Planning

"Flow Chart" for basic modelling (no temp blending, no interpolation between operating points)

1. **Input**
   - **V_DCb (DC bus voltage)**
   - **T_dmd (Torque demand)**
   - **Temp (Temperature of motor)**

2. **Find and choose nearest operating temperature point. (between 80C, 100C, and 120C)**

3. **Scan matrices "Electromagnetic_Torque" and "V_Phase_Peak" with the objective of finding an operating point that satisfies:**
   - **V(I, S) <= V_dcb + deltaV**
   - **T(I, S) >= T_dmd + deltaT**

   And optimizes:
   - **High RPM first** (scan bottom to top in the outer loop, high RPM -> low)
   - **Low Current Second** (scan left to right in inner loop, low Current -> high)

   Throughout the loop, if iterations exist where V(I, S) <= V_dcb + deltaV is satisfied and T(I, S) >= T_dmd + deltaS is NOT satisfied, keep a record of the MAX T(I, S) encountered under these conditions, T_emg_max.

4. **We end up with 4 possible end cases during the sweep.**

   4i. V(I, S) <= V_dcb + deltaV and T(I, S) >= T_dmd + deltaS are both satisfied.

   - Store corresponding values for I_op, T_emg_op, S_op, V_op.
   - Break loop and then go to step 5.

   4ii. T(I, S) >= T_dmd + deltaT is satisfied, V(I, S) <= V_dcb + deltaV is NOT satisfied.

   - Continue loop.
   - If is final sweep possible, go to step 6.

   4iii. T(I, S) >= T_dmd + deltaT and V(I, S) <= V_dcb + deltaV are both NOT satisfied.

Commented [m1]: See P1

Commented [m2]: See P2 for tolerance explanation

Commented [m3]: See P3 for other ways to structure the sweep, and how this would affect the results.

Commented [m4]: See P4 on explanation for case 4iv

- Continue loop.
- If is final loop possible, go to step 6.

4iv. V(I, S) <= V_dcb + deltaV is satisfied at some point but T(I, S) >= T_dmd + deltaS is NOT satisfied.

- Continue loop.
- If is final loop possible, use , T_emg_max point and corresponding values for I_op, T_emg_op, S_op, V_op, and then go to step 5**.**

5. **Use corresponding, I_op and S_op values to find corresponding T_shaft_op, I_phase, Mech_loss, and Pf values from matrices Shaft_Torque' 'Stator_Current_Phase_RMS', 'Mechanical_Loss', and 'Power_Factor" respectively.**

6. **For case 4ii and 4iii, write error messages that there is no Valid Operating point at any given voltage.** Maybe add a note that requested torque is also not available in case ii....

7. **End!**

Justifications + Room for Improvement

P1. This is a considerable oversimplification of the model. In this mode, the operating point just defaults to the data sheet with the closet temperature. What should really happen is a linear approximation if the operating temperature falls between these data sheets. Extrapolating would be much more difficult and inaccurate. More explanations are in the following flow chart.

P2. Some of these values have voltage values that are like 599.99999999923 and 600.00000000234, making it "fail" some of the cases despite being in a good range. Adding a tolerance ensures that there is some room for "error" in the data sheets.

P3. This code maximizes rpm first and then minimizing current draw second by sweeping bottom to top, left to right. I chose this because there is already a requested torque, so I assume we would not more that that. If you want to maximize torque/current draw first, and then rpm, we could scan right to left, bottom to top… I think… but like it doesn't really make munch sense to do that tbh. Unless I'm missing something.

P4. Just to make it more clear, this case occurs when there is enough voltage for the motor to operate but can't achieve the requested torque. This may be because of 1 of 2 reasons. 1. The requested torque cannot be achieved by the motor. 2. The voltage supply is less than 600 VDC, so its operations are limited. In this case, instead of just erroring out, it makes sense to output the best torque output possible with the current voltage. The code also gives an error message so that the motor's operations are being limited though.

Room for improvement

- Temperature Blending
- Interpolation between discrete values. Right now, the code chooses the most "limiting" options, kind of giving it a bit of a safety factor… Like the conditions: V(I, S) <= V_dcb + deltaV, T(I, S) >= T_dmd + deltaT, uses a lower voltage than what I know I can deliver and higher Torque than I am requesting. Good news here, is that in most of these matrices, the values from one cell to another is very small, so the numbers I'm pulling are not widely different than what I am requesting. This also makes me feel more comfortable linearly approximating it in a future model to capture intermediate points. Bad news is it's a bit more simplified than what is really going on. The logic here seems a bit harder than the temperature blending… so I'll figure this one out later.

Manually Verifying Test Cases

Case i:

```
% input parameters
V_dc = 600;        % DC bus / peak-phase voltage limit (V)
T_dmd = 18.5;      % Requested electromagnetic torque (Nm)
Temp = 80;         % Temperature (Celsius)
```

	Q	R	S
191	9.0593352	19.5106835	19.695845
192	9.0088455	19.4372547	19.595964
193	8.9559385	19.3617929	19.495411
194	8.9008126	19.2844511	19.395538
195	8.8436317	19.2053695	19.296353
196	8.7845462	19.124677	19.1978
197	18.723695	19.0424922	19.100060
198	18.661206	18.9589244	19.002957
199	8.5971975	18.8740746	18.906554
200	8.5317793	18.7880361	18.810803
201	8.4650527	18.7008954	18.71585

Magnet_Loss | Mechanical_Loss | Power_Factor | Electromagnetic_Torque

From manually scanning, I expect this to be my T_emg, which corresponds to...

Selected column index: 18

Phase current (Arms): 51.52851153

Shaft Torque achieved (Nm): 17.1674403

Phase-peak voltage (V): 600.000

Speed (rpm): 20000.

Output:

```
Motor Operating Point Results:
------------------------------------
Selected column index: 18
Phase current (Arms): 51.529
Shaft Torque achieved (Nm): 17.167
Phase-peak voltage (V): 600.000
Speed (rpm): 20000.0

Notes:
 - Using data file for 80 C (closest to requested 80 C).
 - Exact operating point found at row 201 (20000.0 rpm), col 18 (I=89.2 A): T=18.7, V=600.
 - Final outputs extracted from maps at row 201, col 18.
>>
```

Case ii: V=0

```
% input parameters
V_dc = 0;        % DC bus / peak-phase voltage limit (V)
T_dmd = 18.5;      % Requested electromagnetic torque (Nm)
Temp = 80;         % Temperature (Celsius)
```

Output:

```
Motor Operating Point Results:
------------------------------------
Selected column index: NaN
Phase current (Arms): NaN
Shaft Torque achieved (Nm): NaN
Phase-peak voltage (V): NaN
Speed (rpm): NaN

Notes:
 - Using data file for 80 C (closest to requested 80 C).
 - No operating point found. Voltage constraint prevents operation at the demanded torque and available currents.
>>
```

Case iii: V=0, T=23

```
% input parameters
V_dc = 0;       % DC bus / peak-phase voltage limit (V)
T_dmd = 23;     % Requested electromagnetic torque (Nm)
Temp = 80;        % Temperature (Celsius)
```

Output:

```
Motor Operating Point Results:
------------------------------------
Selected column index: NaN
Phase current (Arms): NaN
Shaft Torque achieved (Nm): NaN
Phase-peak voltage (V): NaN
Speed (rpm): NaN

Notes:
 - Using data file for 80 C (closest to requested 80 C).
 - No operating point found. Voltage constraint prevents operation at the demanded torque and available currents.
>>
```

Case iiii.

Ok, in P4 I stated “This may be because of 1 of 2 reasons. 1. The requested torque cannot be achieved by the motor. 2. The voltage supply is less than 600 VDC, so its operations are limited.”

I searched a bit, and now that I think about it, if I need a minimum torque that is achievable, I don’t think scenario 2 is even possible. Because the model will continuously trade off torque for speed, if that torque is achievable. This would result in a super low rpm. I’ll keep the reasoning in this doc, just in case there’s an odd value for where it exists. So, I’ll be testing for scenario 1.

		T	U	V
156	756	21.6550276	22.3056525	
157	756	21.6550276	22.3056525	
158	756	21.6550276	22.3056525	
159	756	21.6550276	22.3056525	
160	756	21.6550276	22.3056525	
161	756	21.6550276	22.3056525	
162	756	21.6550276	22.3056525	
163	756	21.6550276	22.3056525	
164	756	21.6550276	22.3028522	
165	756	21.6550276	22.2813244	

```
% input parameters
V_dc = 600;       % DC bus / peak-phase voltage limit (V)
T_dmd = 25;     % Requested electromagnetic torque (Nm)
Temp = 80;        % Temperature (Celsius)
```

```
Motor Operating Point Results:
------------------------------------
Selected column index: 21
Phase current (Arms): 60.622
Shaft Torque achieved (Nm): 20.354
Phase-peak voltage (V): 598.136
Speed (rpm): 16200.0

Notes:
 - Using data file for 80 C (closest to requested 80 C).
 - Torque was either unachievable or limited by supplied voltage. Using next best operating point where voltage requirement was satisfied.
 Chosen fallback at row 163 (16200.0 rpm), col 21 (I=105 A) with T=22.3 and V=598.
 - Final outputs extracted from maps at row 163, col 21.
>>
```

The sweep works! Catches the torque possible first, and then highest rpm after that.

At intermediate Temps?

```
>> testmodel
Motor Operating Point Results:
------------------------------------
Selected column index: 21
Phase current (Arms): 60.622
Shaft Torque achieved (Nm): 19.884
Phase-peak voltage (V): 596.427
Speed (rpm): 16200.0

Notes:
 - Using data file for 100 C (closest to requested 91 C).
 - Torque was either unachievable or limited by supplied voltage. Using next best operating point where voltage requirement was satisfied.
 Chosen fallback at row 163 (16200.0 rpm), col 21 (I=105 A) with T=21.8 and V=596.
 - Final outputs extracted from maps at row 163, col 21.
>>
```

Nice!

“Flow Chart” for basic modelling (w temp blending, no interpolation between operating points)

Coming 2025-11-26

Synchronous Motors Background Basics (for me, not necessarily all relevant)

d-q Equivalent Circuits

The stator carries sinusoidal currents in 3 phases. As a result, the rotor with permanent (in our case) poles, spins.

The d-q frame is located on the rotor. POV: you are in in the centre of the rotor and spinning with it. With respect to this frame, you perceive the sum of all phase currents at some *stationary* point, and at a direction defined by the phase advance angle (θ).

d-axis: along the magnet

- *Direct axis: Flux Producing current*

q-axis: perpendicular to d-axis (or pole)

- *Quadrature Axis: Torque Producing Current*

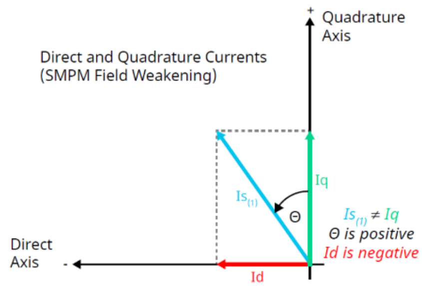


Figure 2. Negative Id under field weakening of a SMPM.

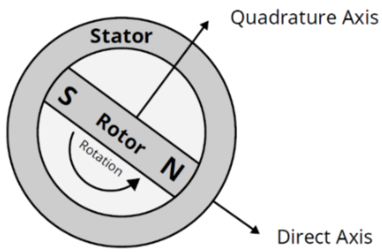
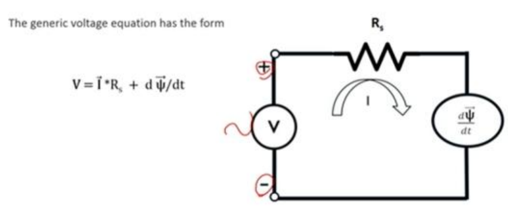


Figure 3. Visual representation of direct and quadrature axis with two-pole motor.

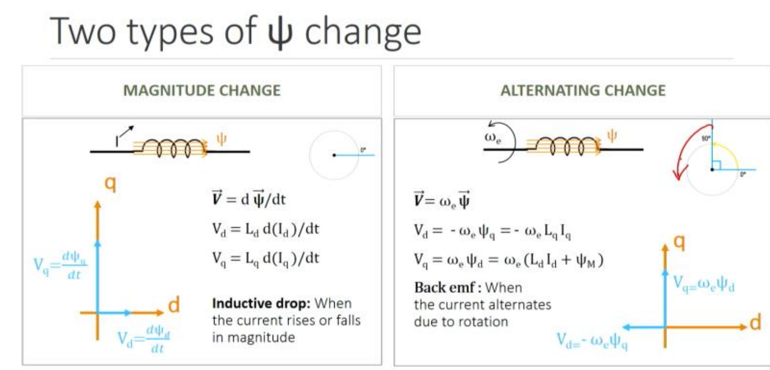
This rotating reference frame that is synchronised with the AC current, enables the three-phase system to be quantified in a two-phase one.

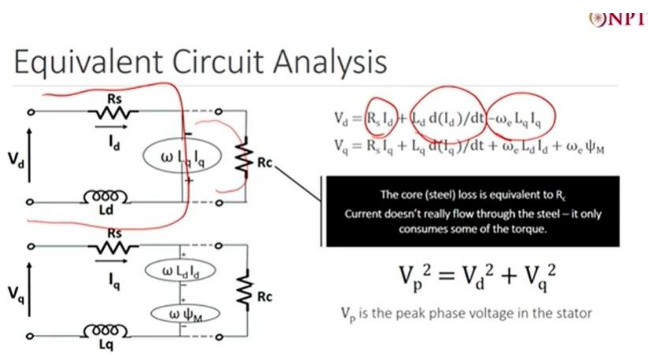
Voltage Equations



Rs is the stator phase resistance. A pair of Voltage Equation for Vd and Vq can be developed.

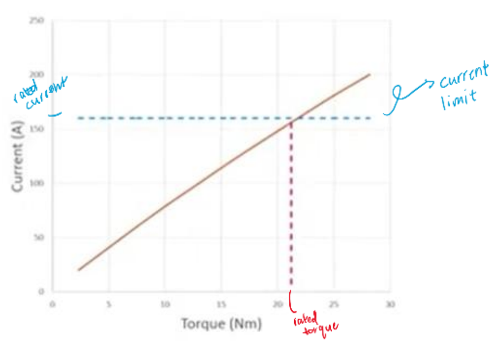
The flux can change in magnitude. As current increases, flux increases with no phase difference. As it is an AC current, the flux can also change direction, but with a 90-degree phase change. (change in direction of current in positive d-axis would cause change in direction of voltage in positive q-axis). Voltage in q-axis





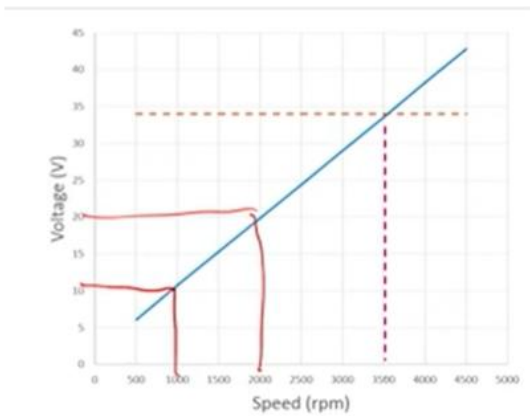
The Current Limit

Motor and electronic controllers are rated to perform under a certain current limit to limit unacceptable temps for the devices. This current would also limit torque.

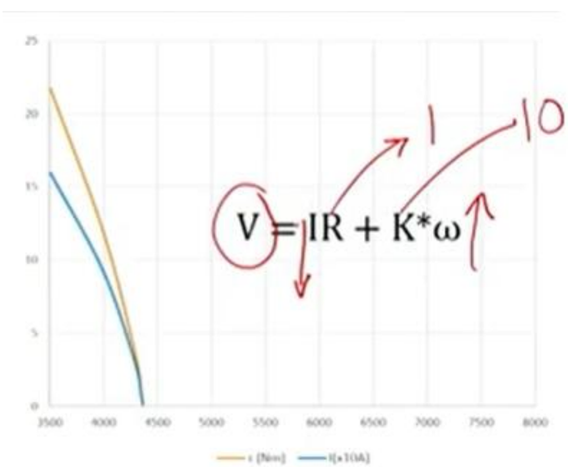


The Voltage Limit

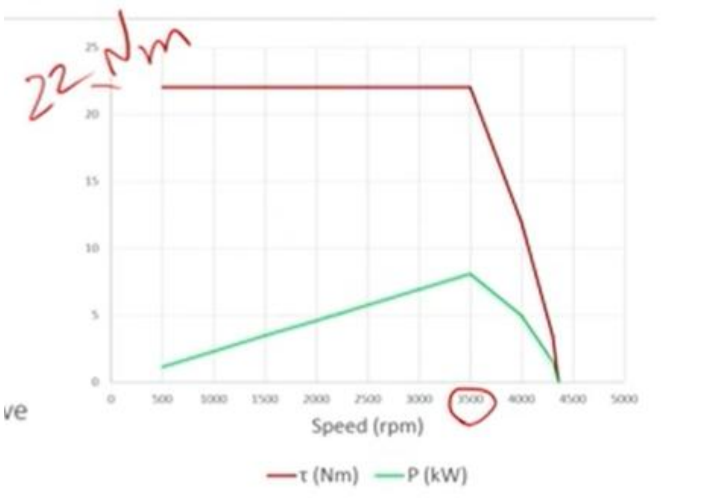
As speed increases, back EMF increases which is proportional to voltage. More Fast -> More Voltage to compensate for the Back EMF.



Based on the earlier equations, we can achieve a speed beyond the *rated speed* by reducing current. However, resistance in designed to be small compared to back emf (which enables torque), so you don't get the same magnitude out. So you lose a lot of torque to gain a bit of speed. This is reflected in the following curves.



Speed Torque Curves



That peak point on the green curve is the **knee point**.

I don't think any of this really matters. Basically, all this to lead into Flux Weakening.

Flux Weakening

The data sheets gives me operable and real output and losses so this should be accounted for.