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June 19-22, 2016 | du 19 au 22 juin 2016

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DRIVE ELECTRIC INNOVATION
PROPULSER L'INNOVATION EN MOBILITÉ ÉLECTRIQUE

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Driving-Scenario Oriented Optimal Design of an Axial-Flux Permanent-Magnet Motor for an Electric Vehicle

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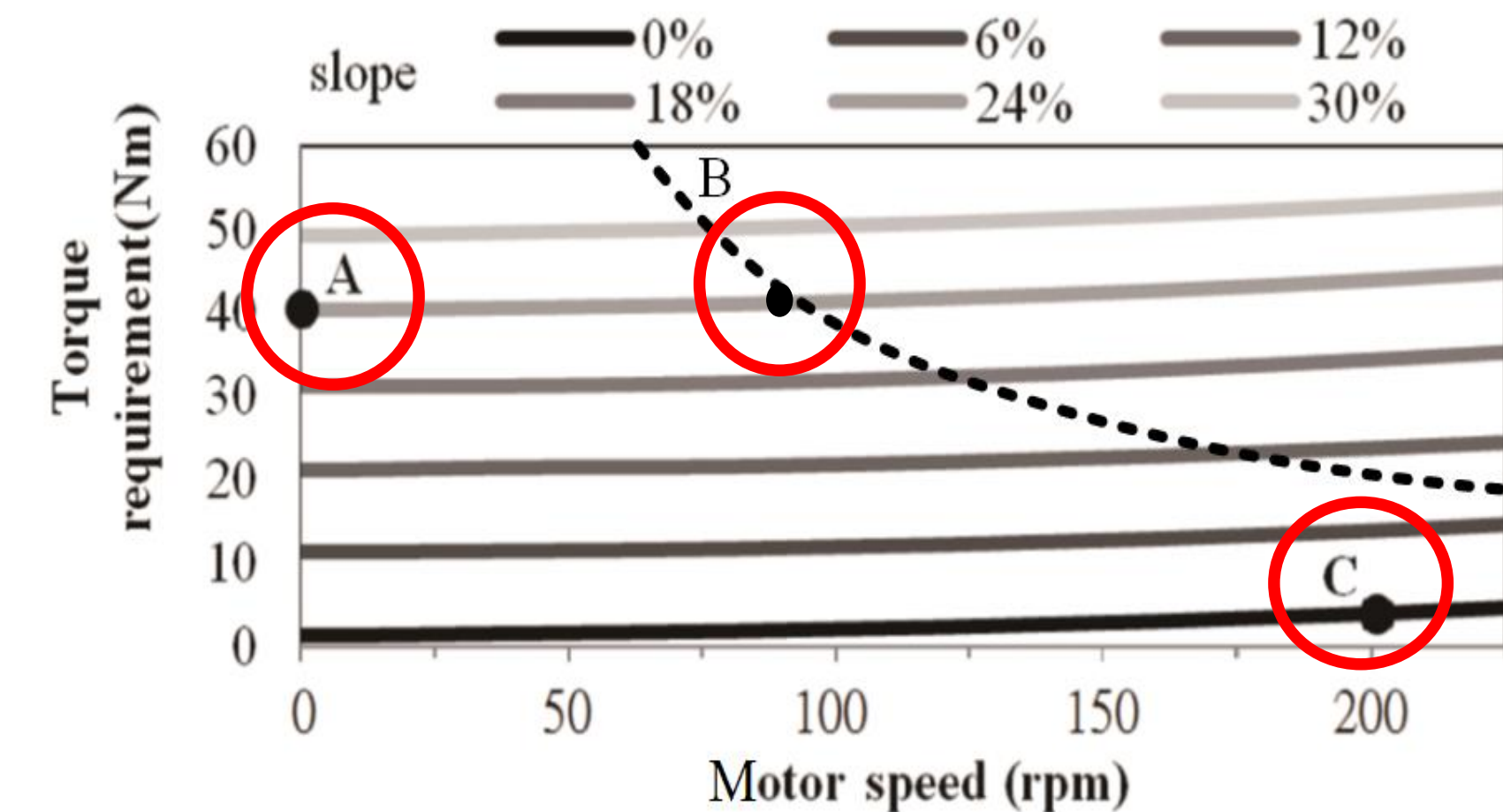
Traditional Design of a Traction Motor for an EV

Driving Requirements

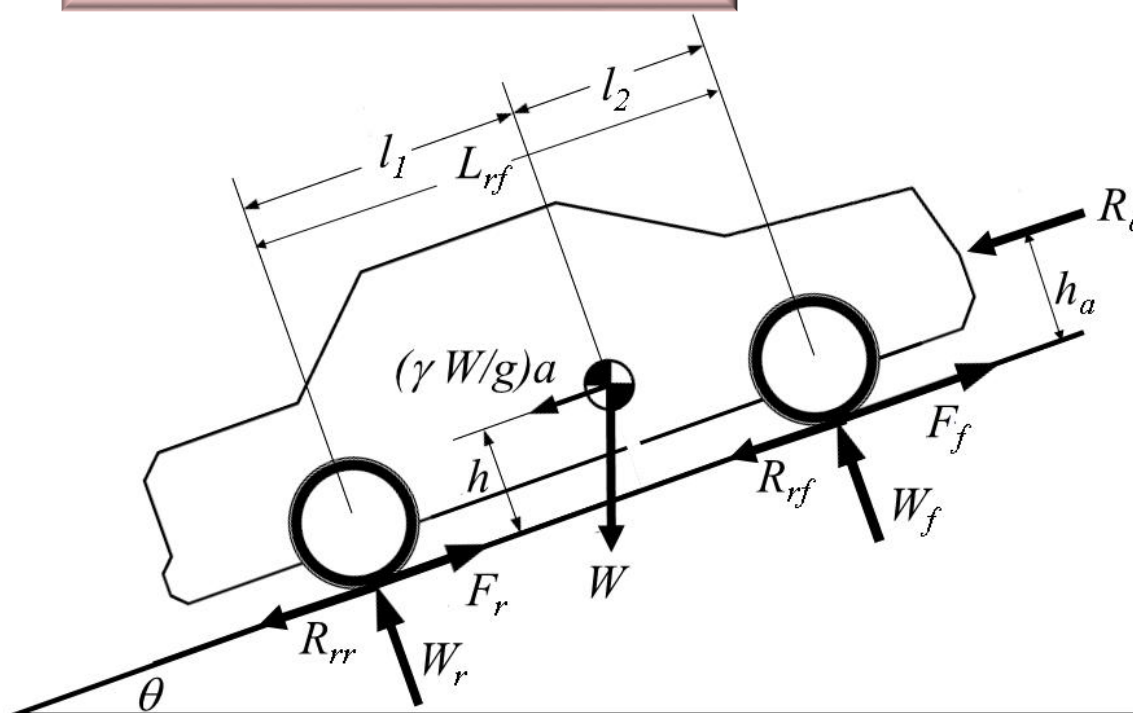
Battery: Voltage & Power
Vehicle: Acceleration
Max./Cont. Speed
Max. Slope

Operation points

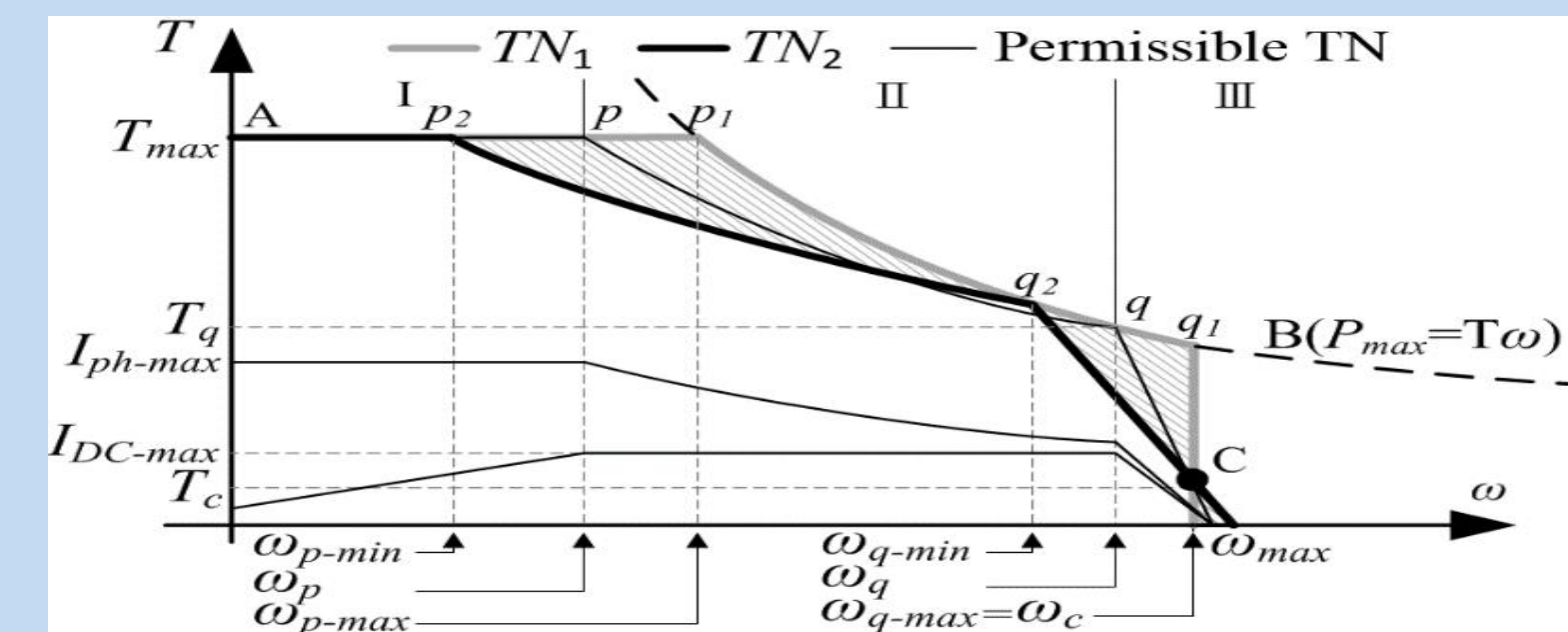
- Max. Torque **A**
- Rated operation **B**
- Max. Speed **C**



Drawback 1: Driving requirements define only 3 operation points to form a rough TN curve !



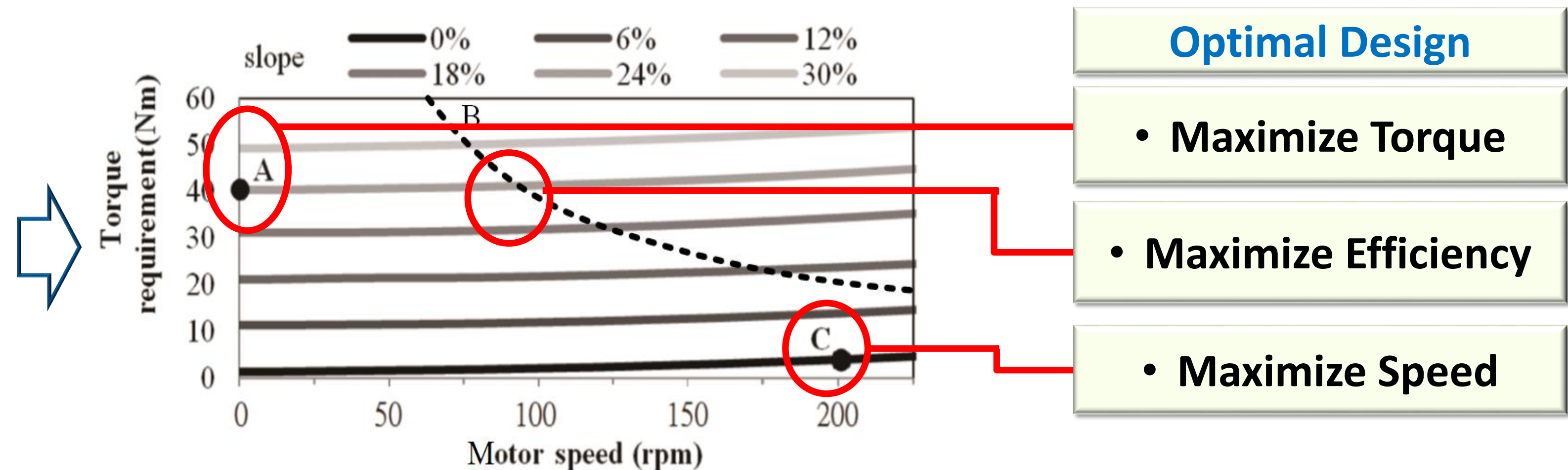
We want a complete target
TN curve that satisfies
all the driving scenarios!



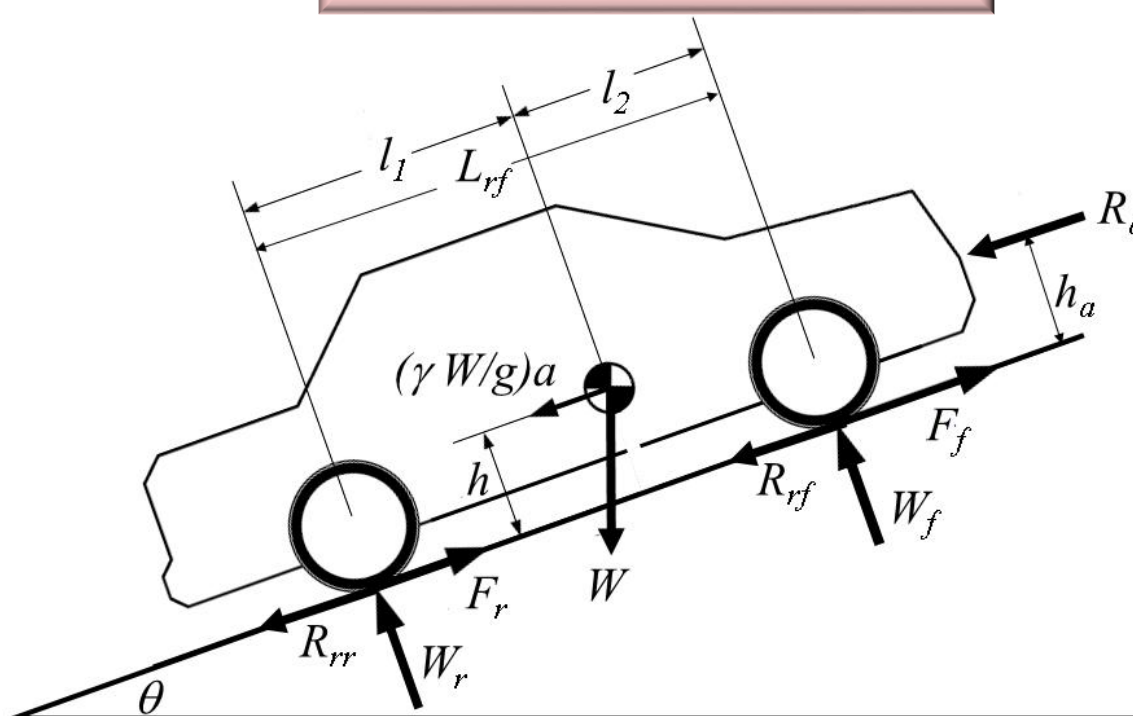
Traditional Design of a Traction Motor for an EV

Driving Requirements

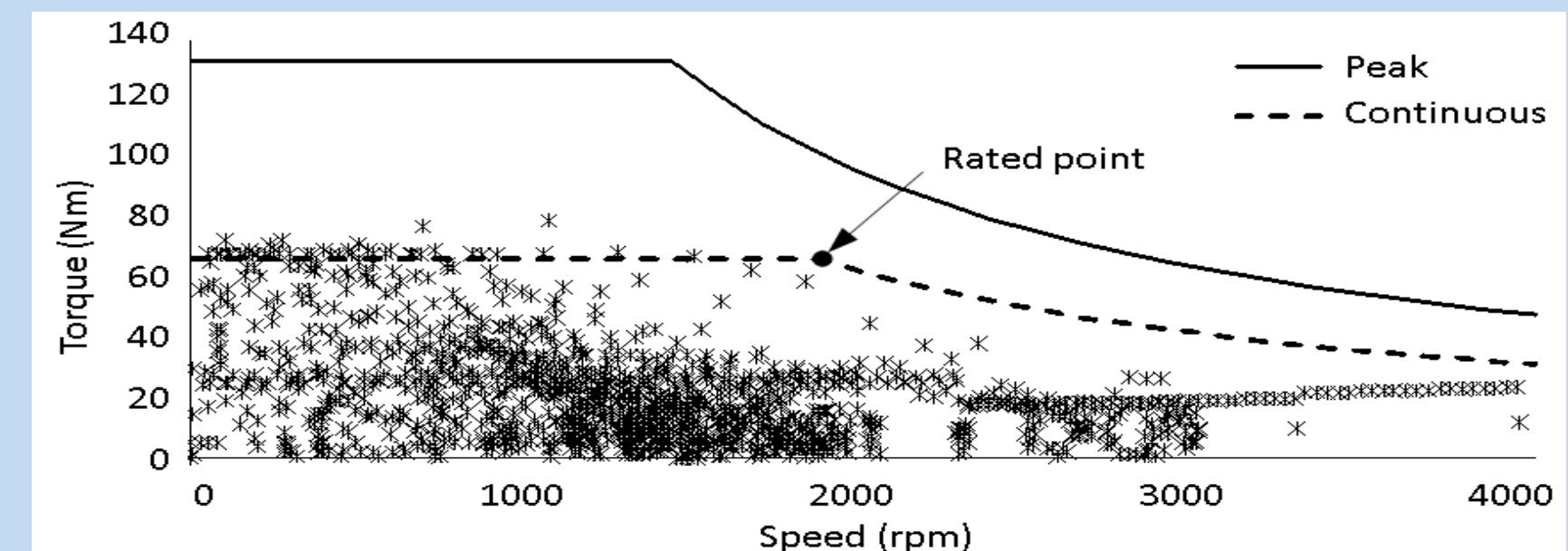
Battery: Voltage & Power
Vehicle: Acceleration
Max./Cont. Speed
Max. Slope



Drawback 2: Optimal design at only 2 or 3 operation points !



We want the vehicle/motor
to be **efficient for**
all the operation points!



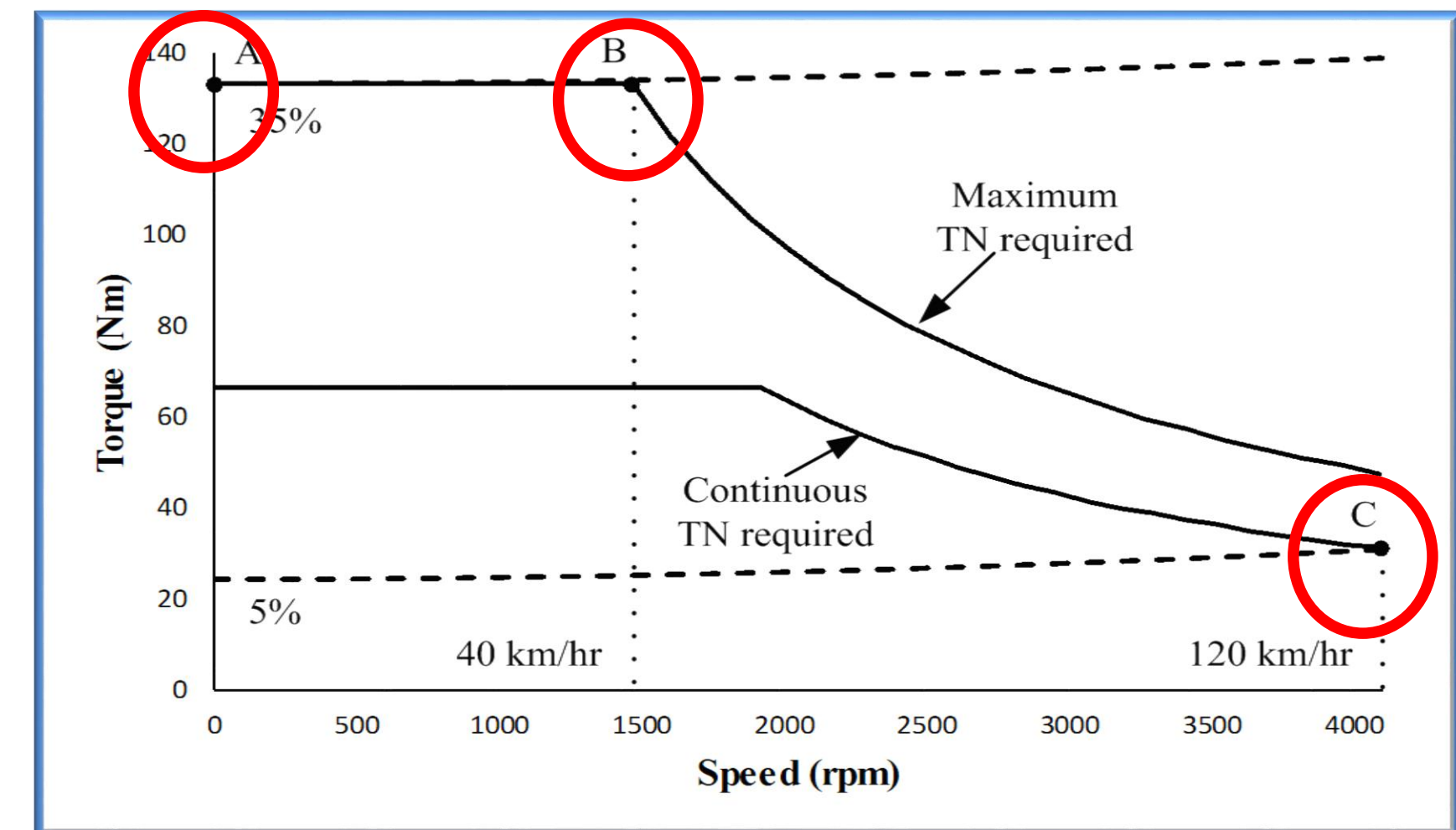
Traditional Design of a Traction Motor for an EV

Driving Scenarios

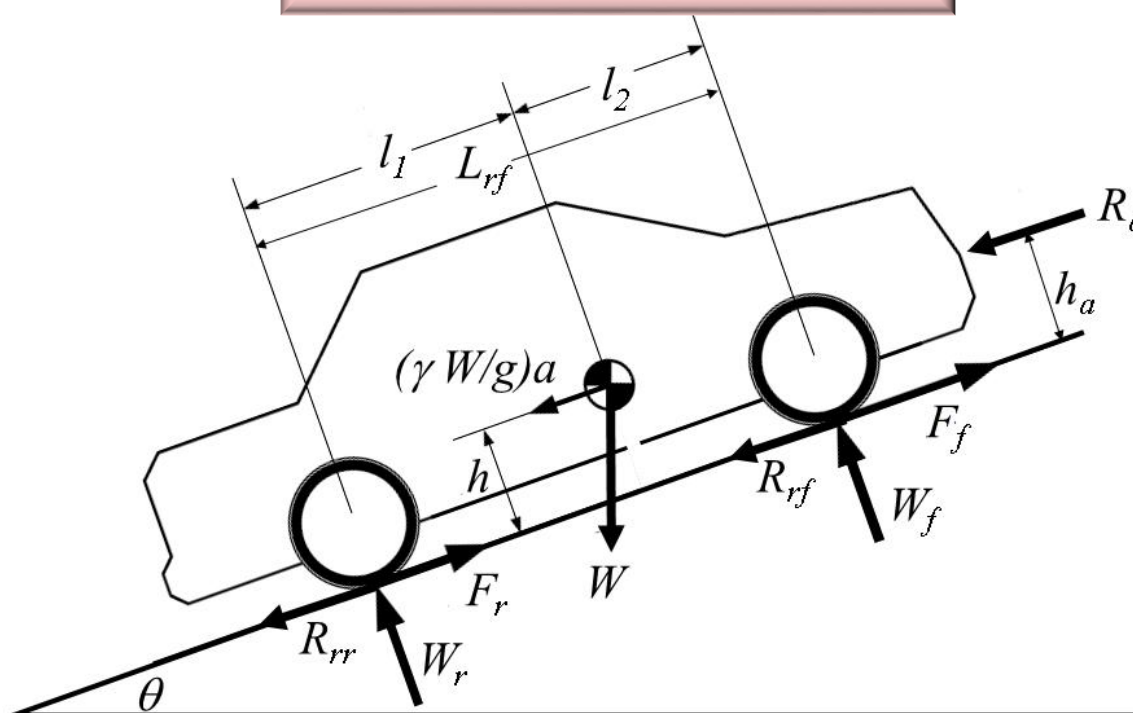
Battery: Voltage & Power
Vehicle: Acceleration
 Max./Cont. Speed
 Max. Slope

Optimal Design

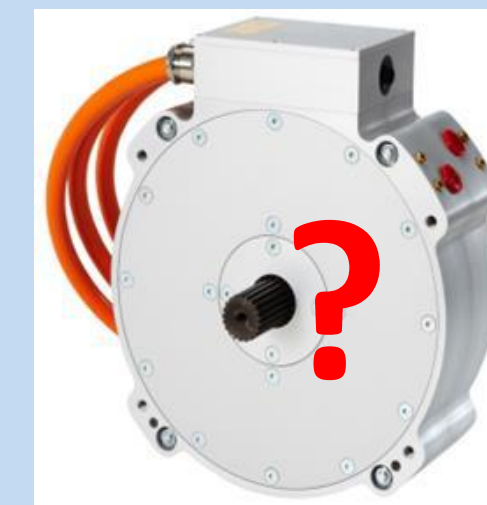
- Maximize Torque
- Maximize Speed
- Maximize Efficiency



Drawback 3: No close relationship between TN curve and motor parameters !



We want the driving scenario
 is explicitly related to key
 motor parameters !

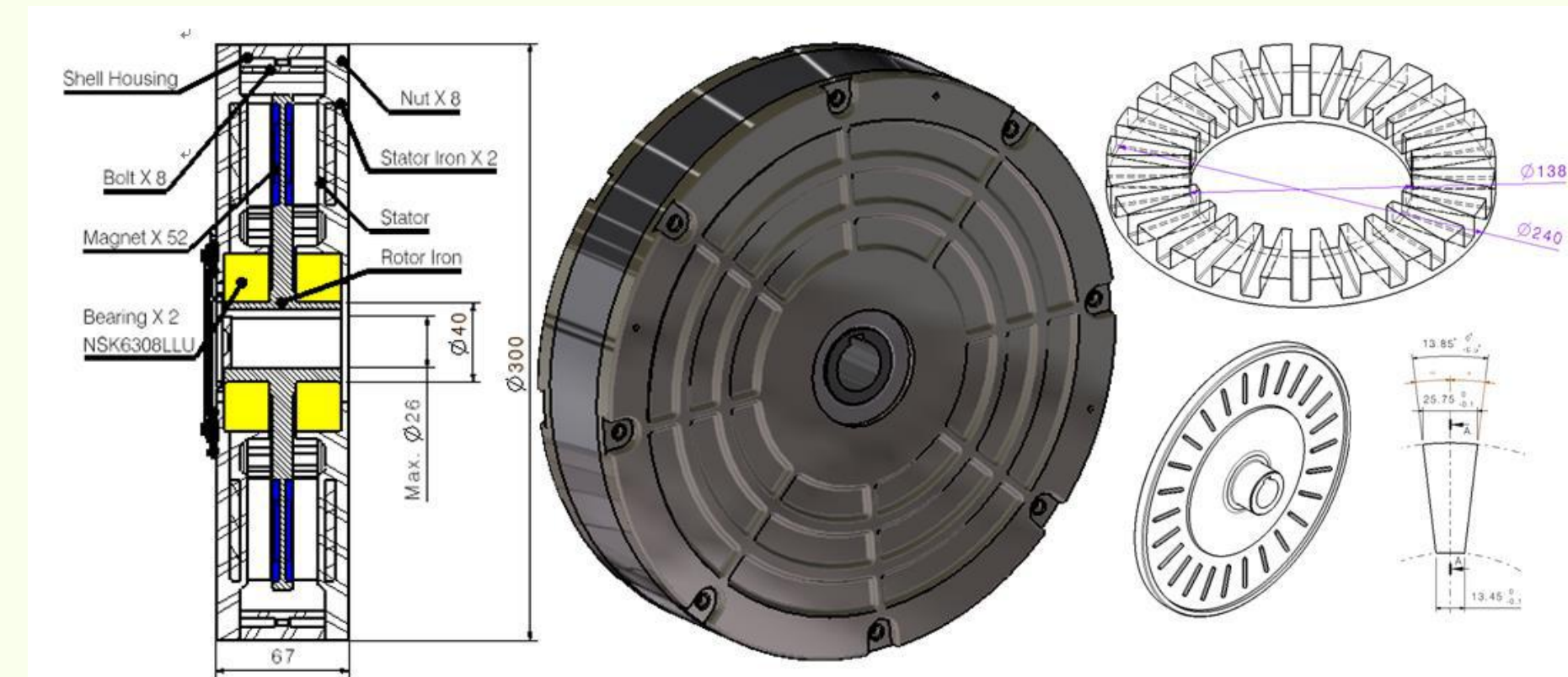
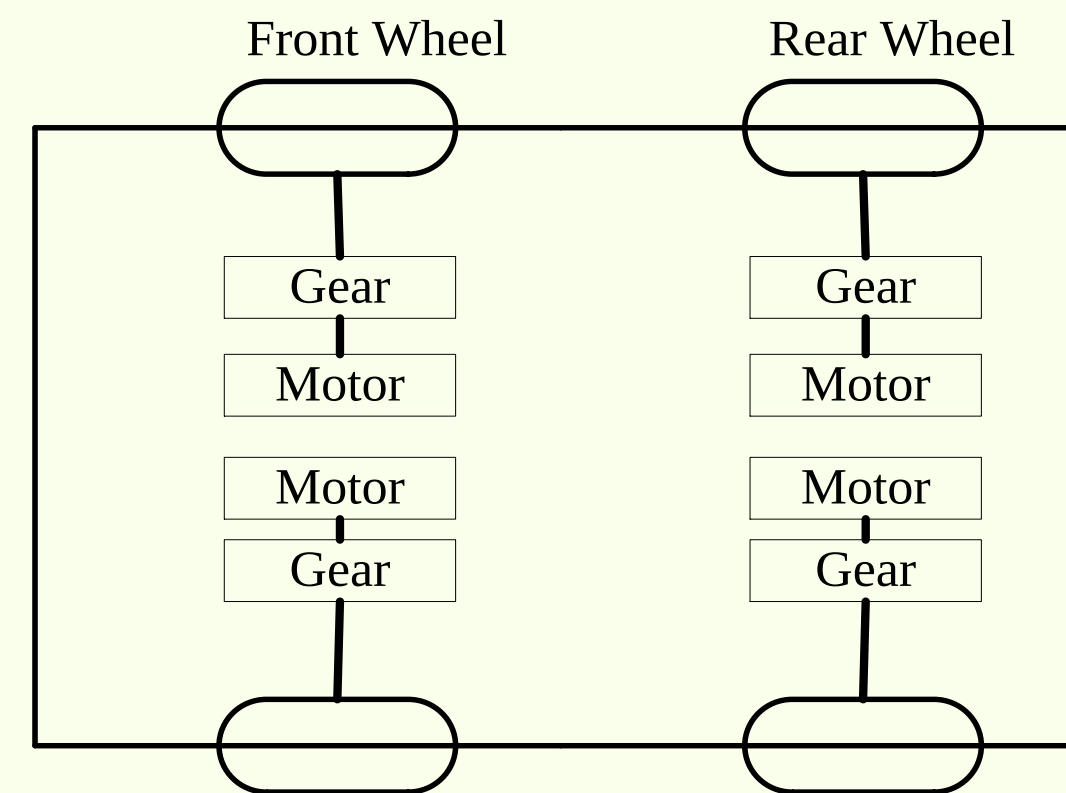


like back emf constant
 phase resistance

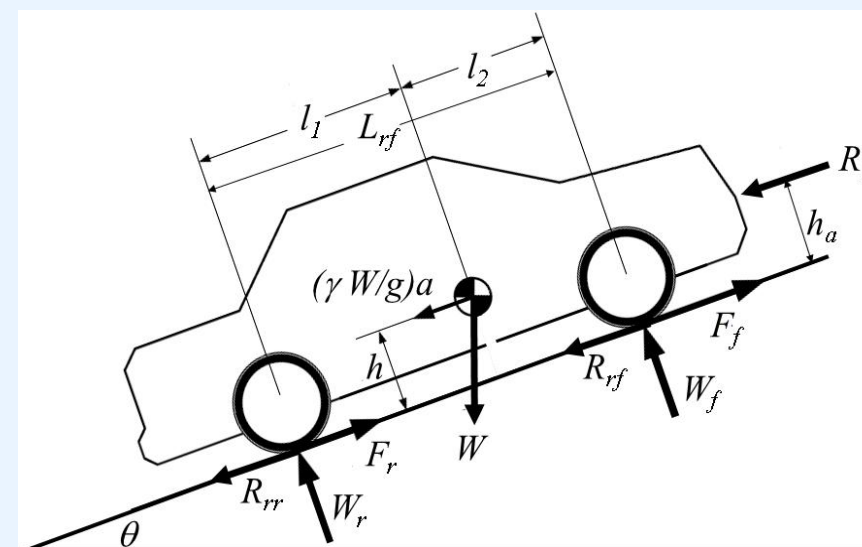
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Specifications

- **Vehicle type** : Four-wheel-drive electric passenger car
- **Motor type** : Axial-flux permanent-magnet (AFPM) motor



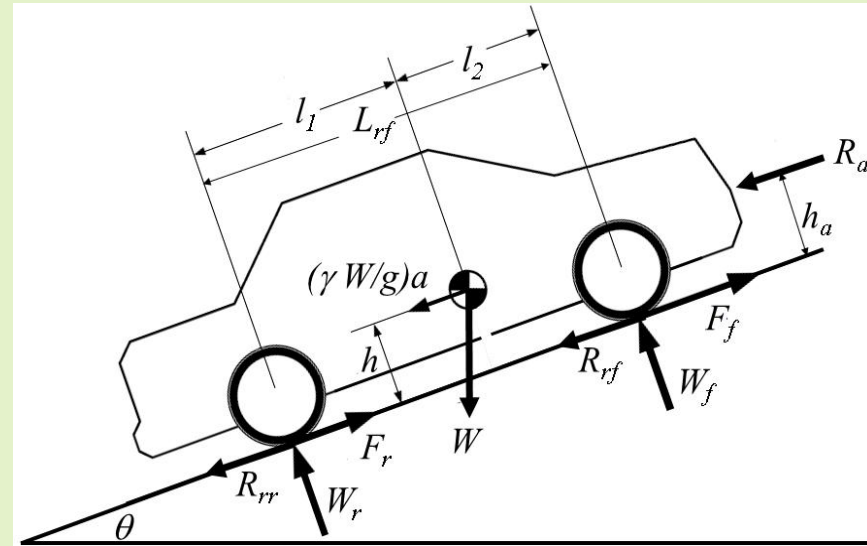
● Driving Scenario



- (1) Maximum slope 35%
- (2) Maximum acceleration under 40 km/hr
- (3) Maximum cruise speed 120 km/hr on a 5% slope

Summary of Design Goals

● Driving Scenario

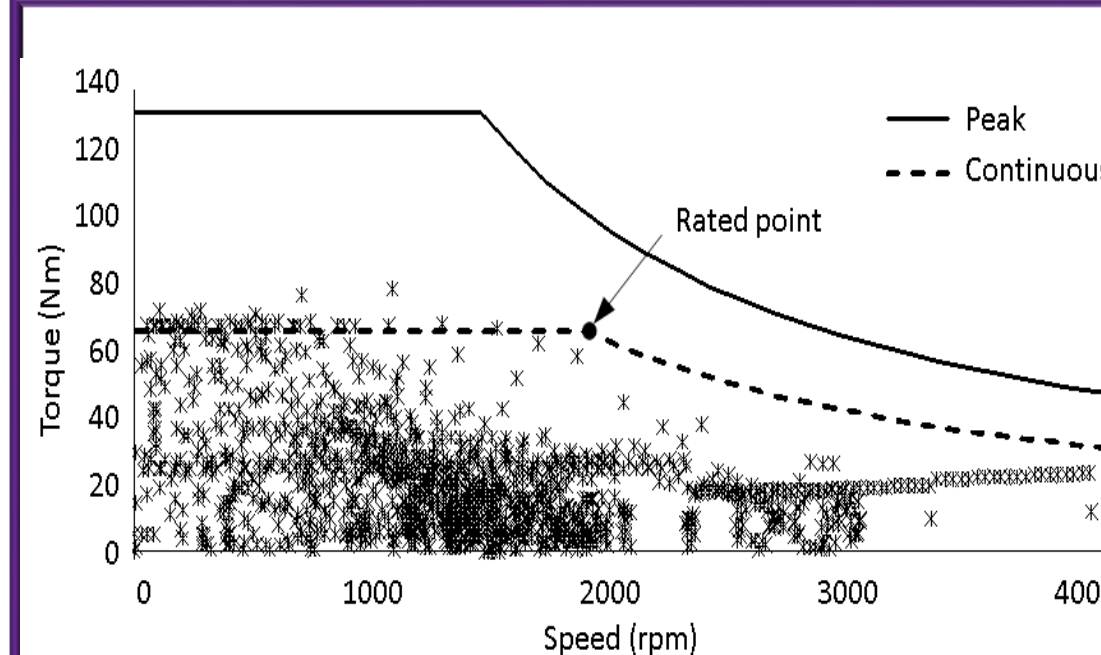
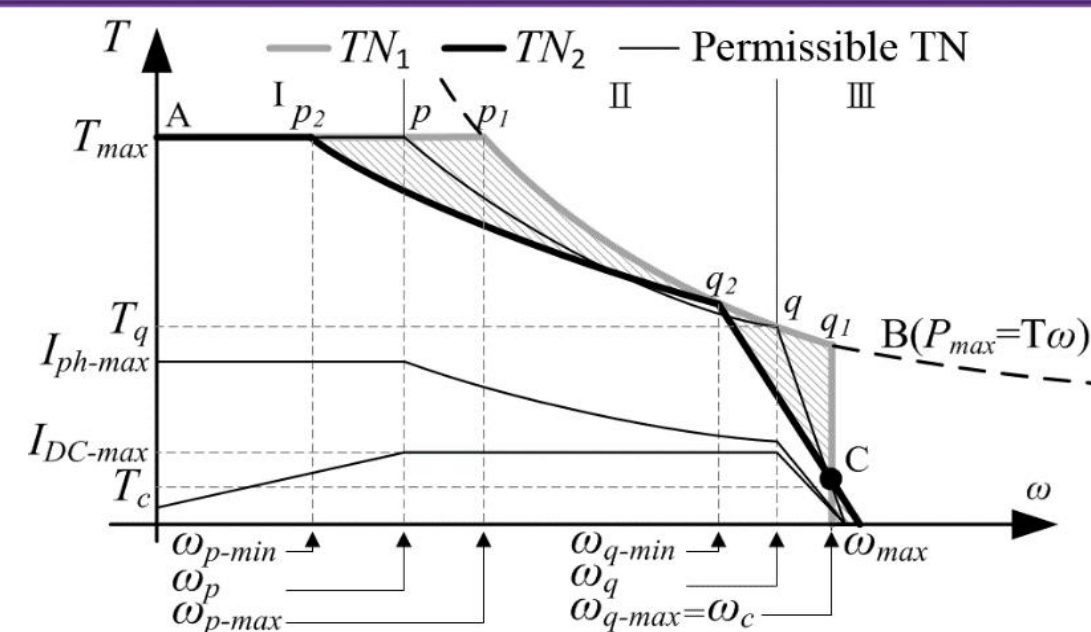


- (1) Maximum slope 35%
- (2) Maximum acceleration under 40 km/hr
- (3) Maximum cruise speed 120 km/hr on a 5% slope
- (4) Battery power (20.4 kW) and voltage (380 V)

We want a complete target TN curve that satisfies all the driving scenarios!

We want the vehicle to be efficient for all the operation points!

We want the driving scenario is explicitly related to the key motor parameters like back emf constant & phase resistance !

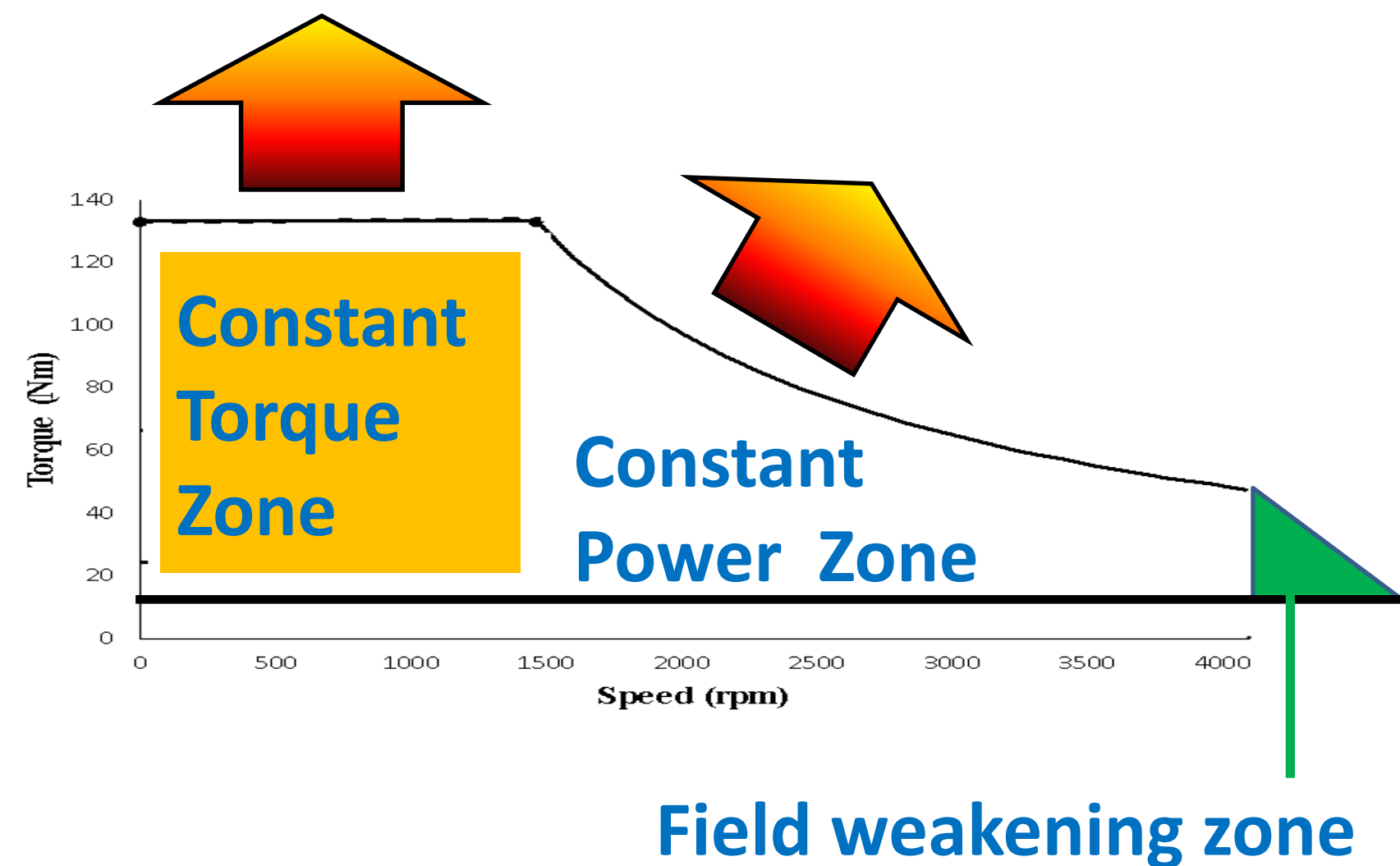


$$V_d = R_{ph} i_d - L_q i_q N_p \omega$$

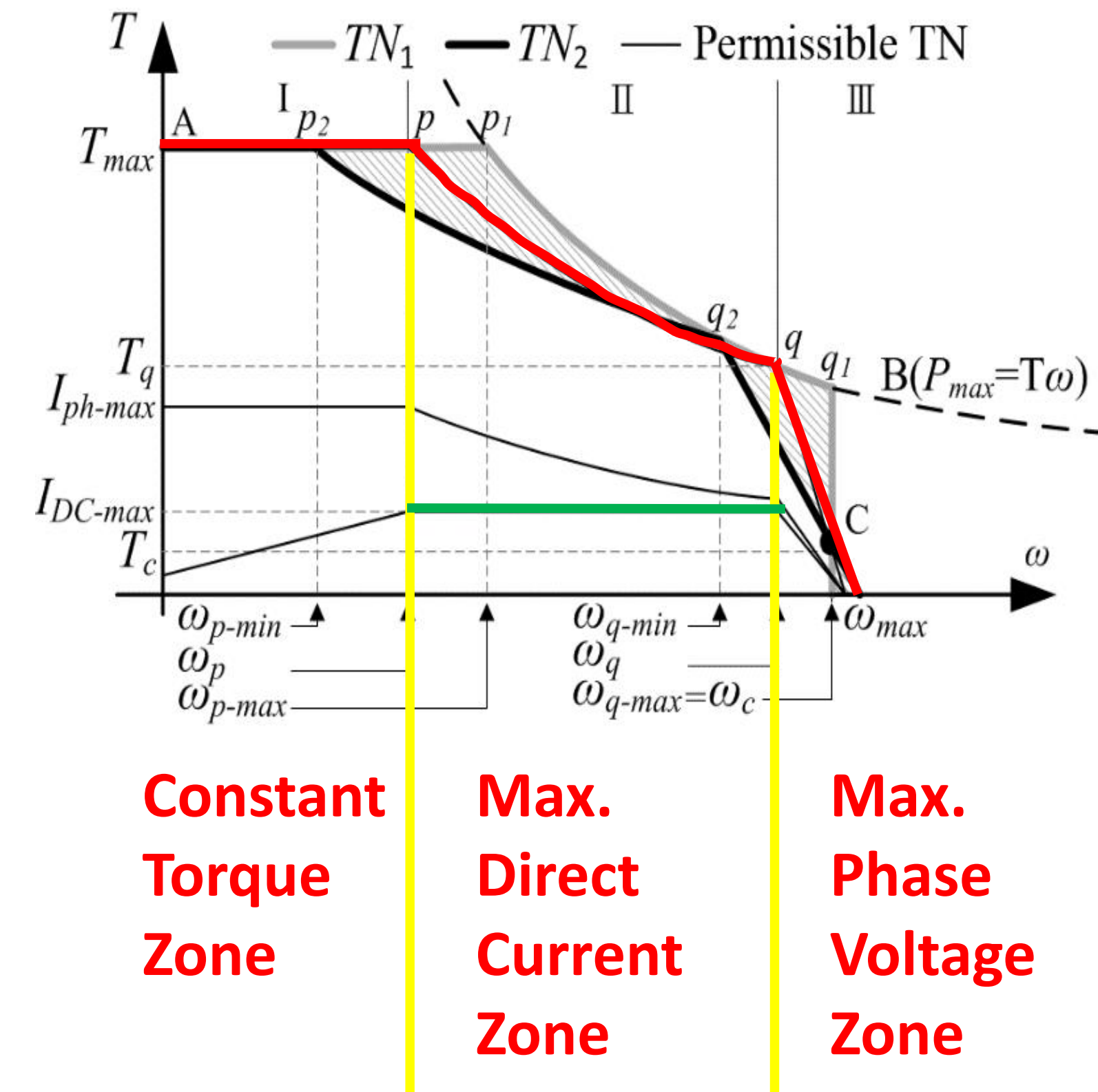
$$V_q = R_{ph} i_q + L_d i_d N_p \omega + K_e \omega$$

Traditional TN Curve vs. Target TN Curve

- Traditional TN curve



- Proposed Target TN curve



Target TN Curve – Zone I

- Zone I : constant torque zone

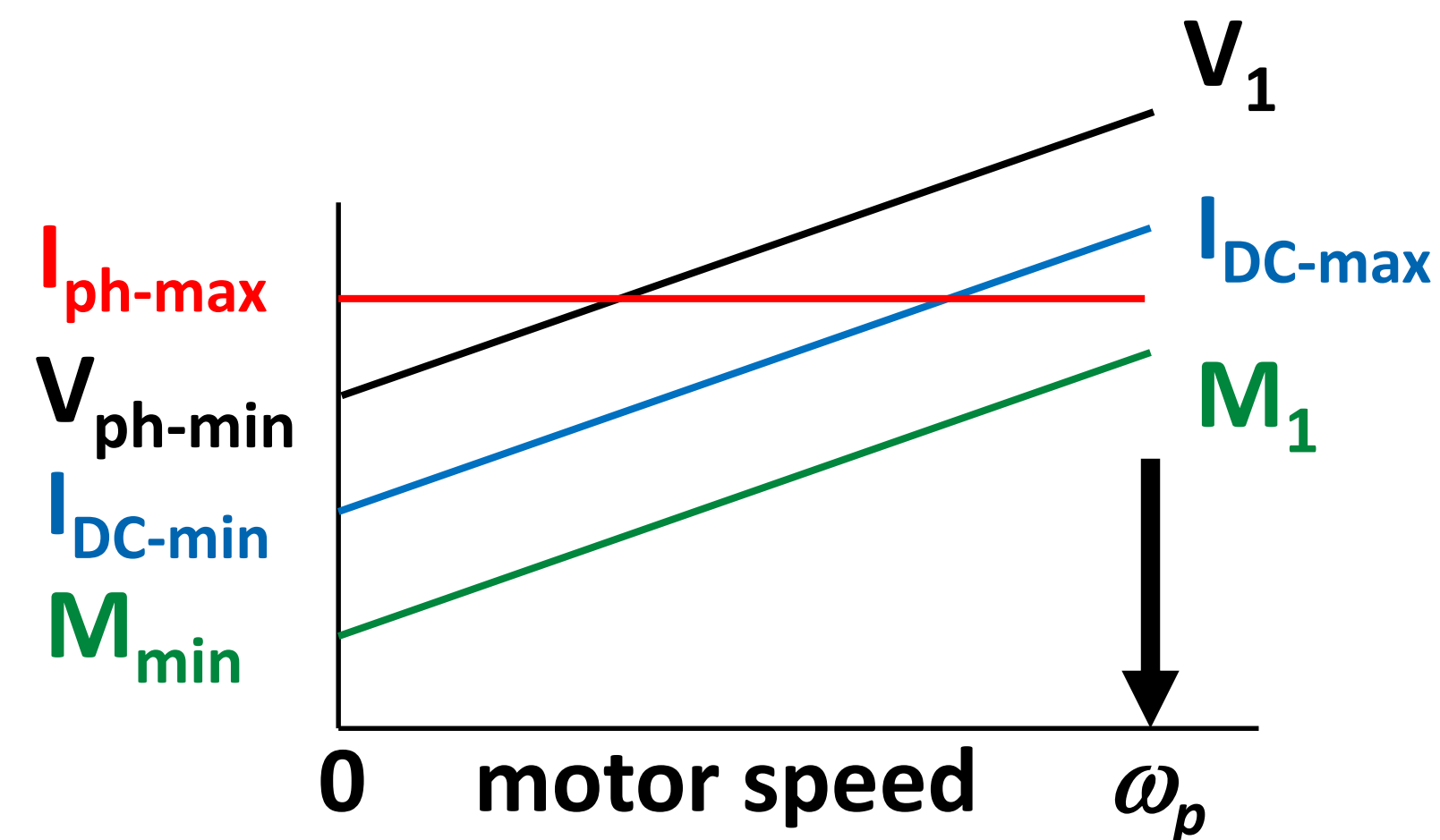
$$T_{\max} = (3/2)K_e I_{\text{ph-max}}$$

$$V_{\text{ph}} = R_{\text{ph}} I_{\text{ph-max}} + K_e \omega$$

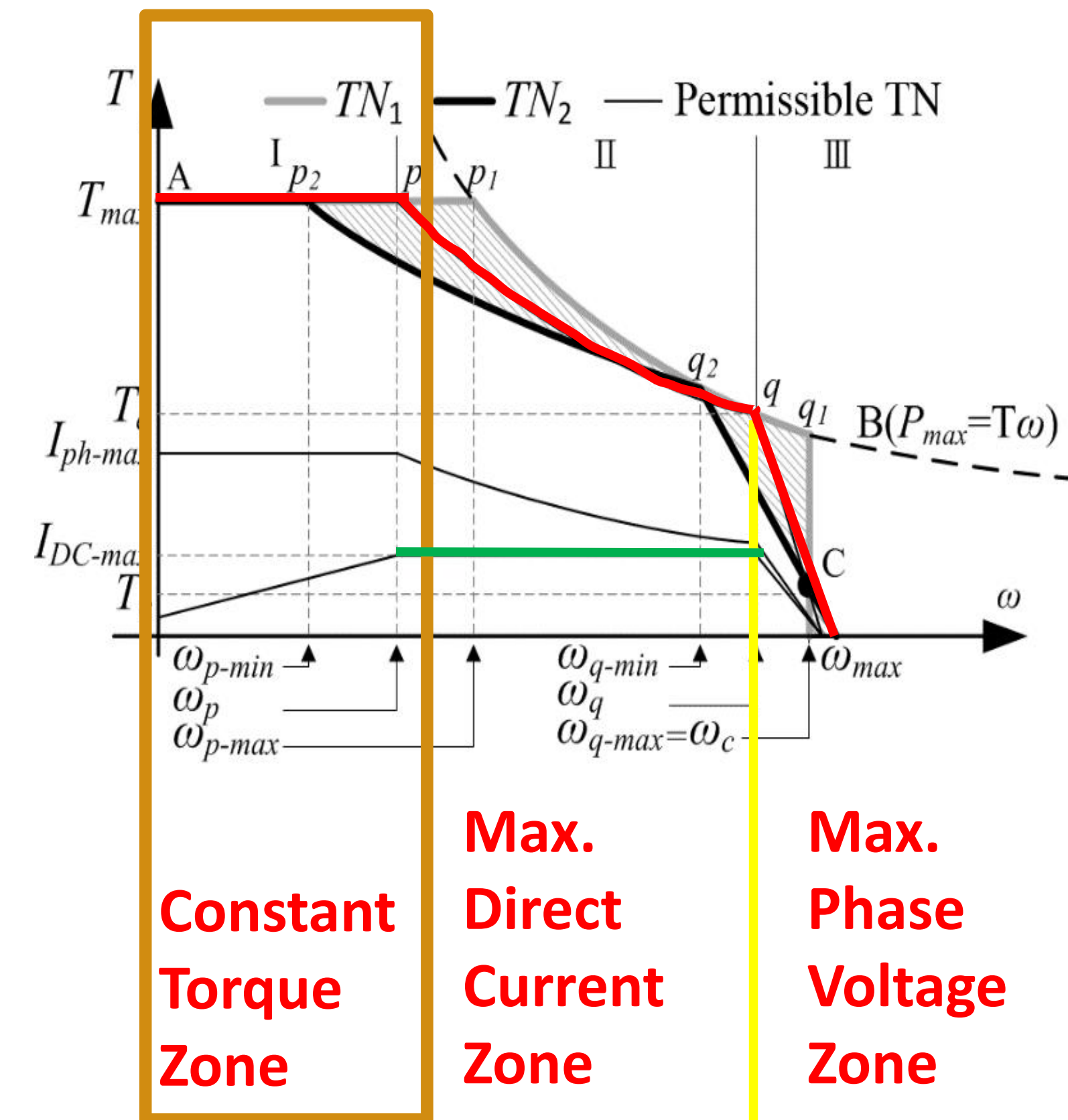
$$V_{\text{ph}} = \frac{1}{\sqrt{3}} M_i V_{\text{DC}}$$

$$I_{\text{DC}} = \frac{\sqrt{3}}{2} M_i I_{\text{ph}}$$

$$T = \frac{3}{2} K_e I_{\text{ph}}$$

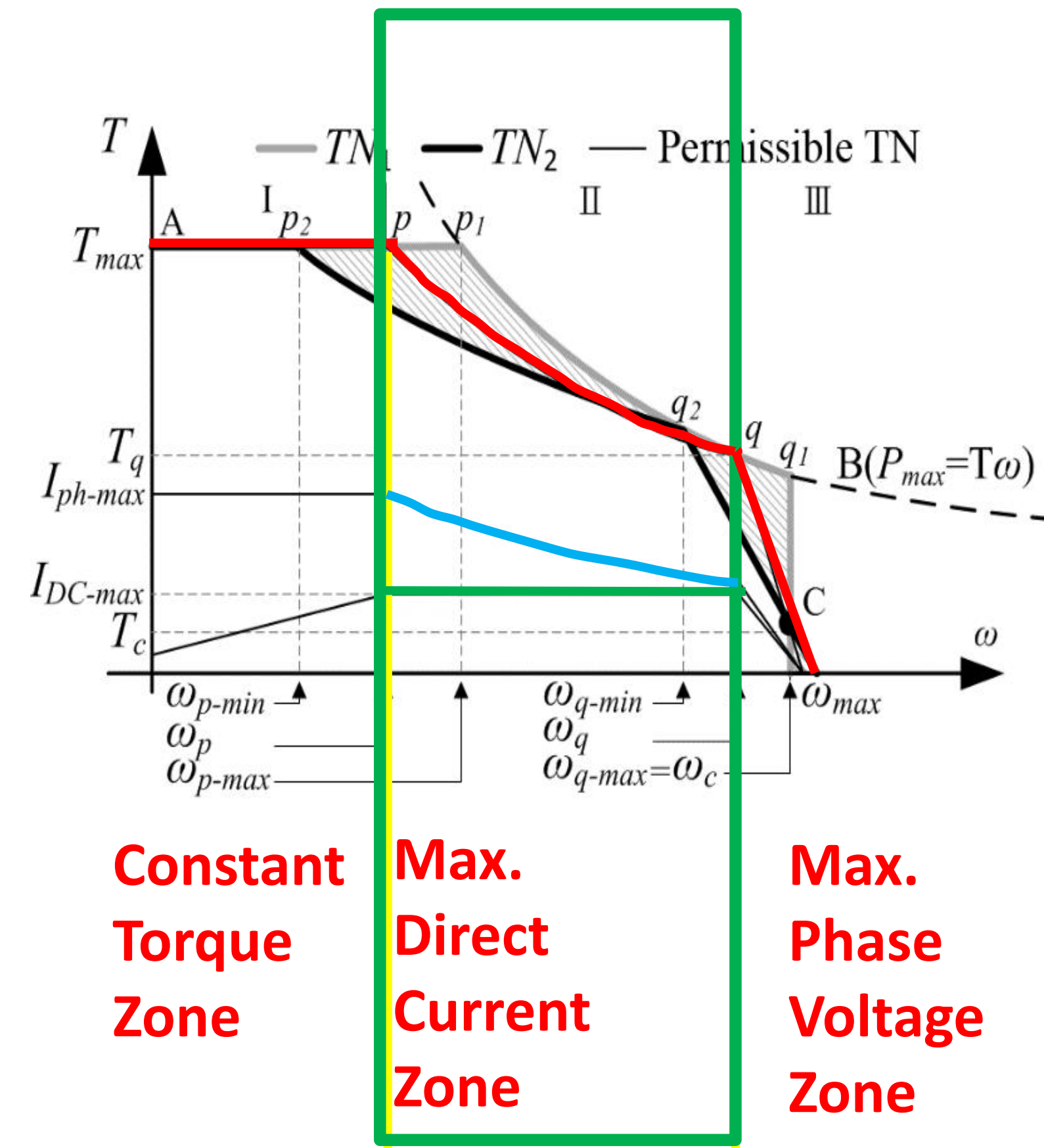
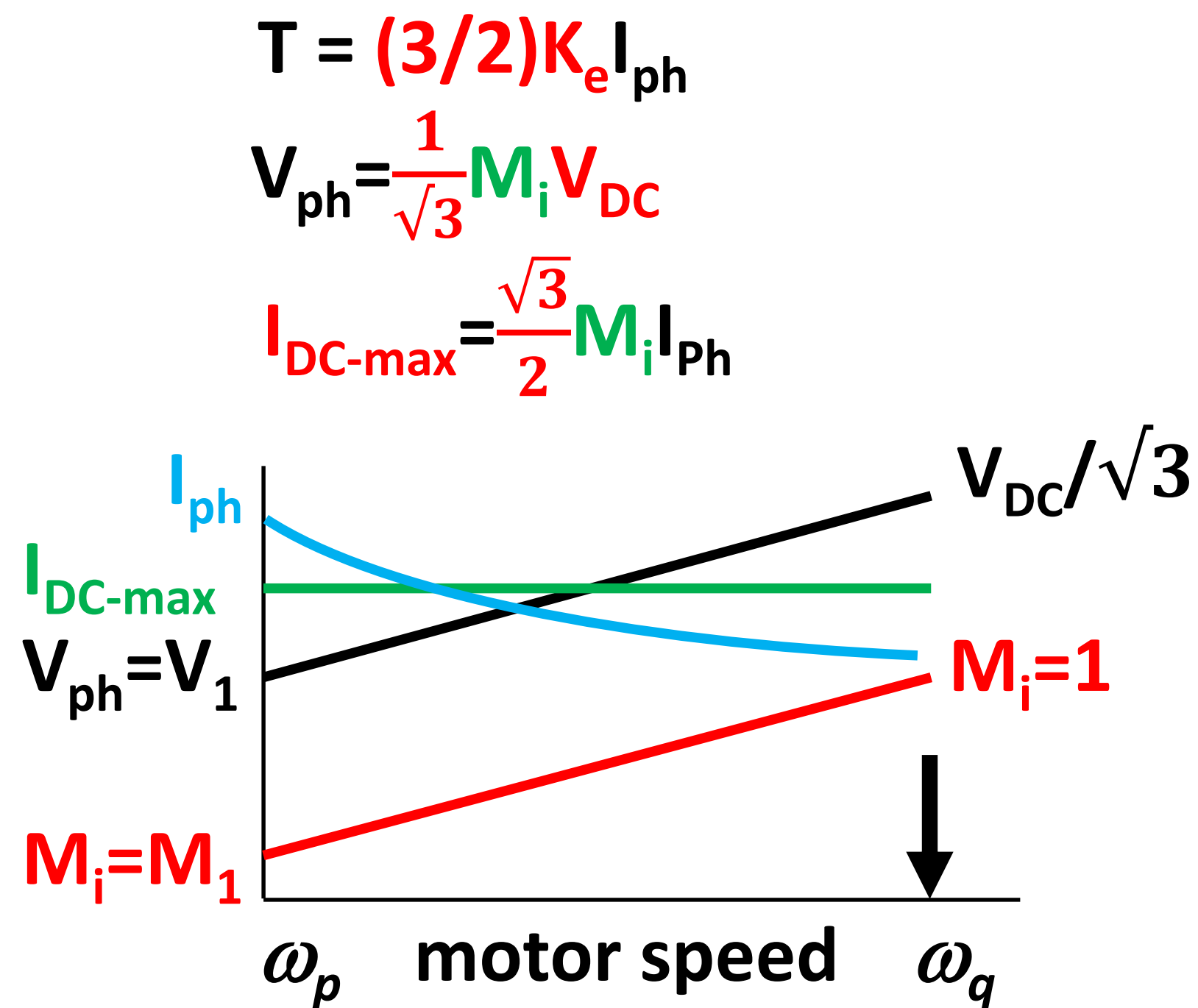


- Proposed Target TN curve



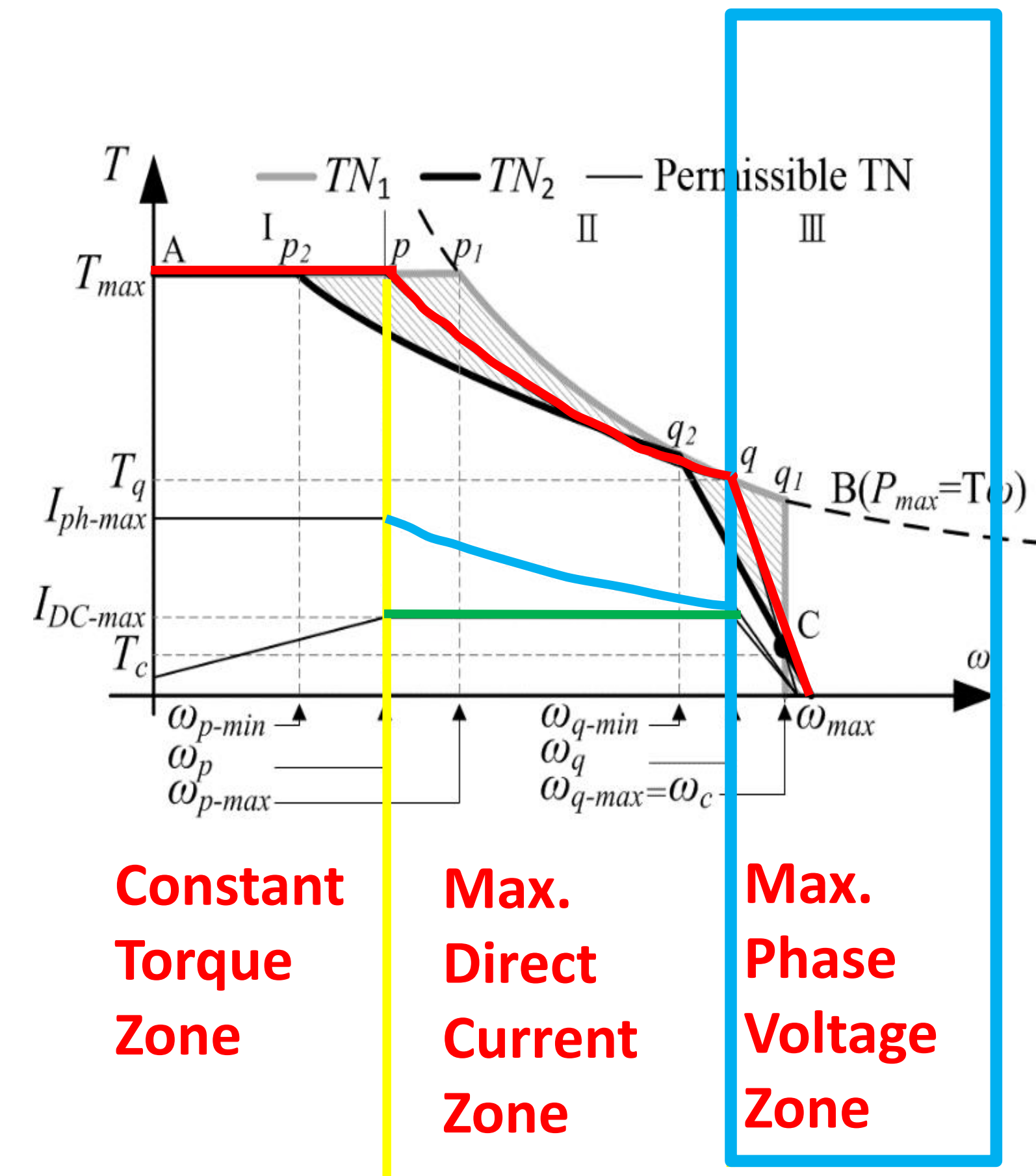
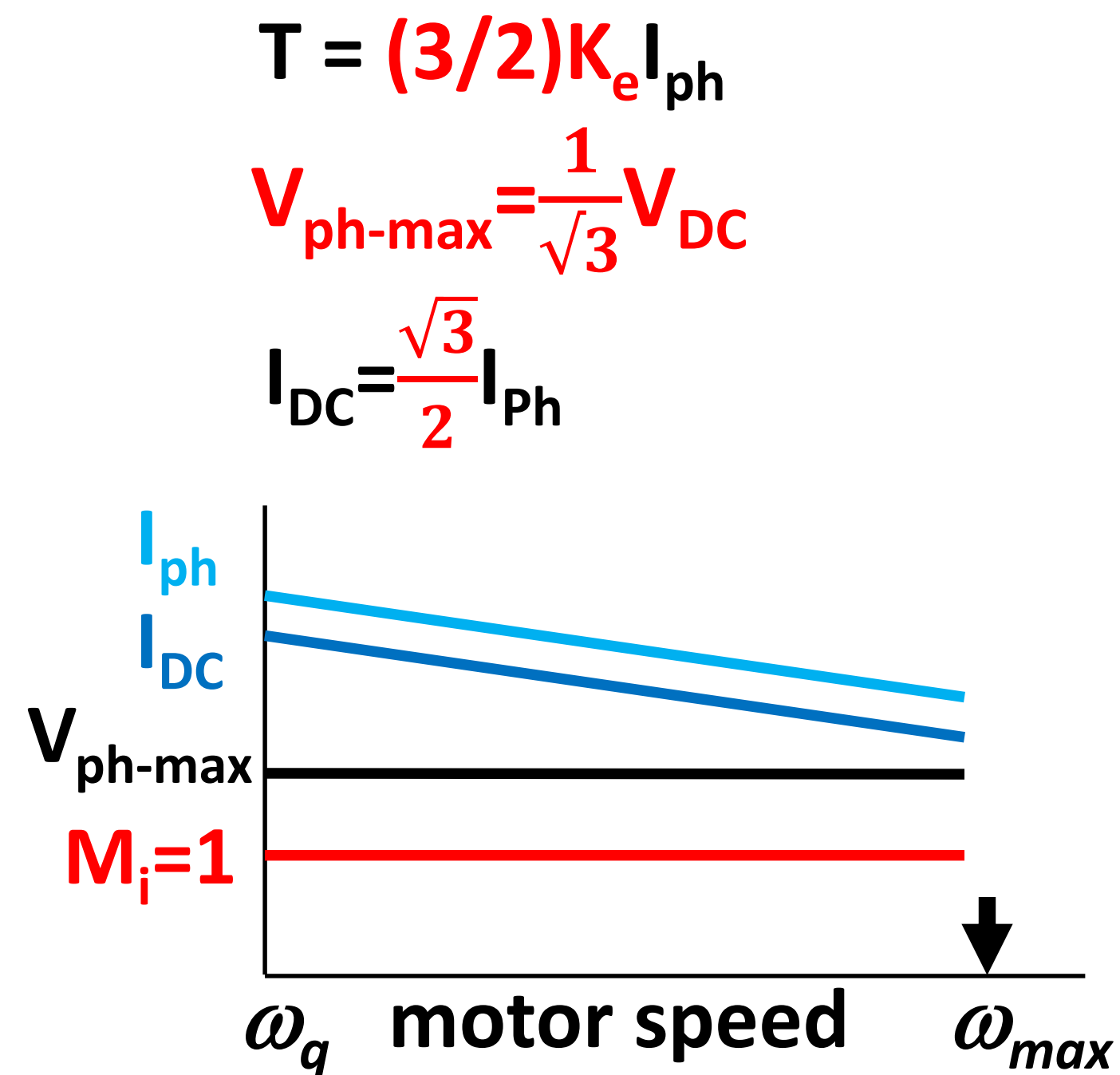
Target TN Curve – Zone 2

- Zone 2 : max. direct current zone
- Proposed Target TN curve



Target TN Curve – Zone 3

- Zone 3 : max. phase voltage zone
- Proposed Target TN curve



Target TN Curve Boundaries

Determined by motor equations and modulation index

- Motor equations

$$V_d = R_{ph} i_d - L_q i_q N_p \omega$$

$$V_q = R_{ph} i_q - L_d i_d N_p \omega$$

$$T = \frac{3K_e V_{ph}}{2R_{ph}} \frac{-\frac{K_e \omega}{V_{ph}} + \sqrt{1 + \left(\xi \frac{K_e \omega}{V_{ph}} \right)^2} - \xi^2 \left(\frac{K_e \omega}{V_{ph}} \right)^4}{\left(\xi \frac{K_e \omega}{V_{ph}} \right)^2 + 1}$$

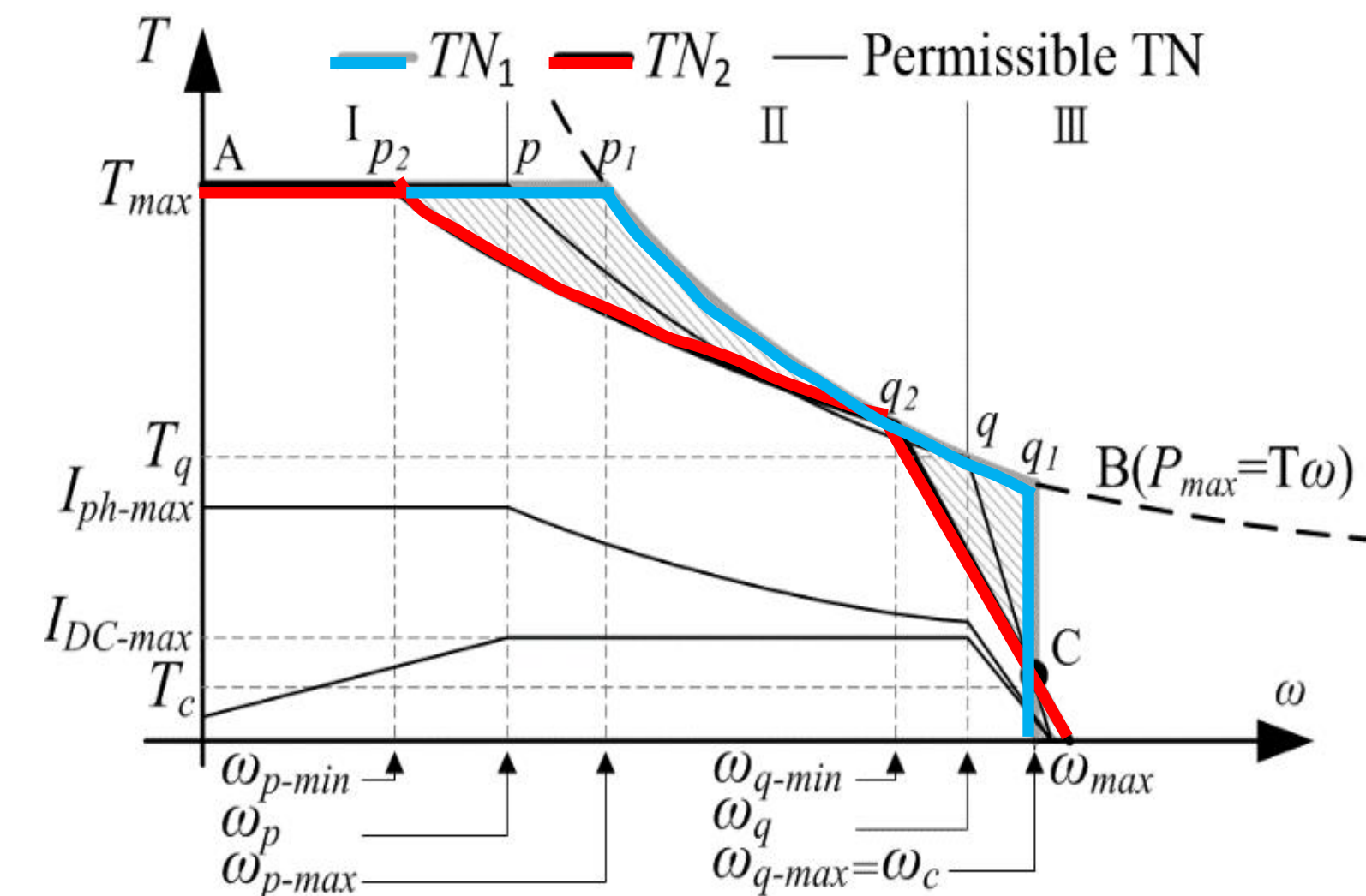
$$T_{max} = (3/2)K_e I_{ph-max}$$

- Modulation index equations

$$V_{ph} = \frac{1}{\sqrt{3}} M_i V_{DC}$$

$$I_{DC} = \frac{\sqrt{3}}{2} M_i I_{Ph}$$

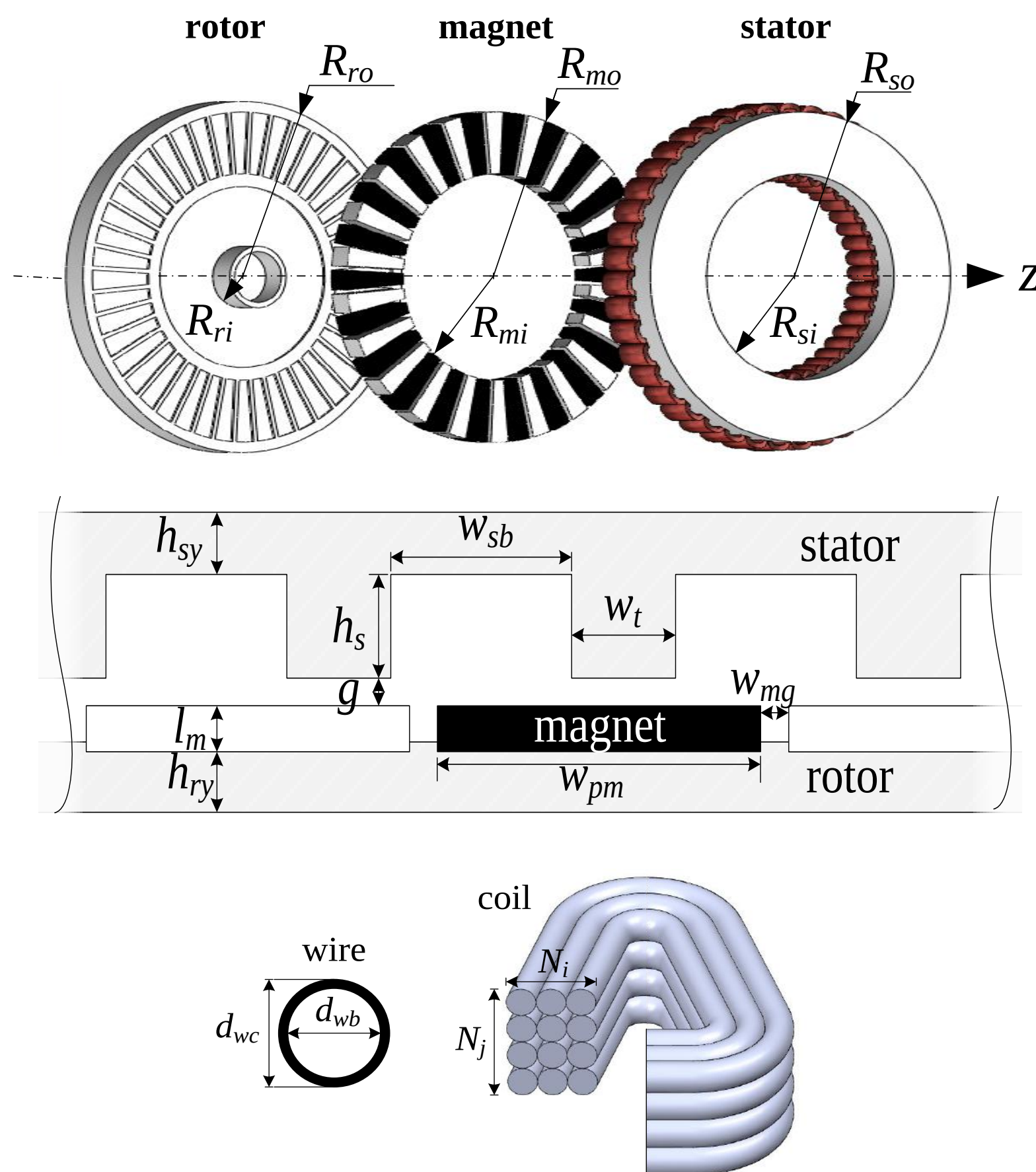
- Proposed Target TN curve



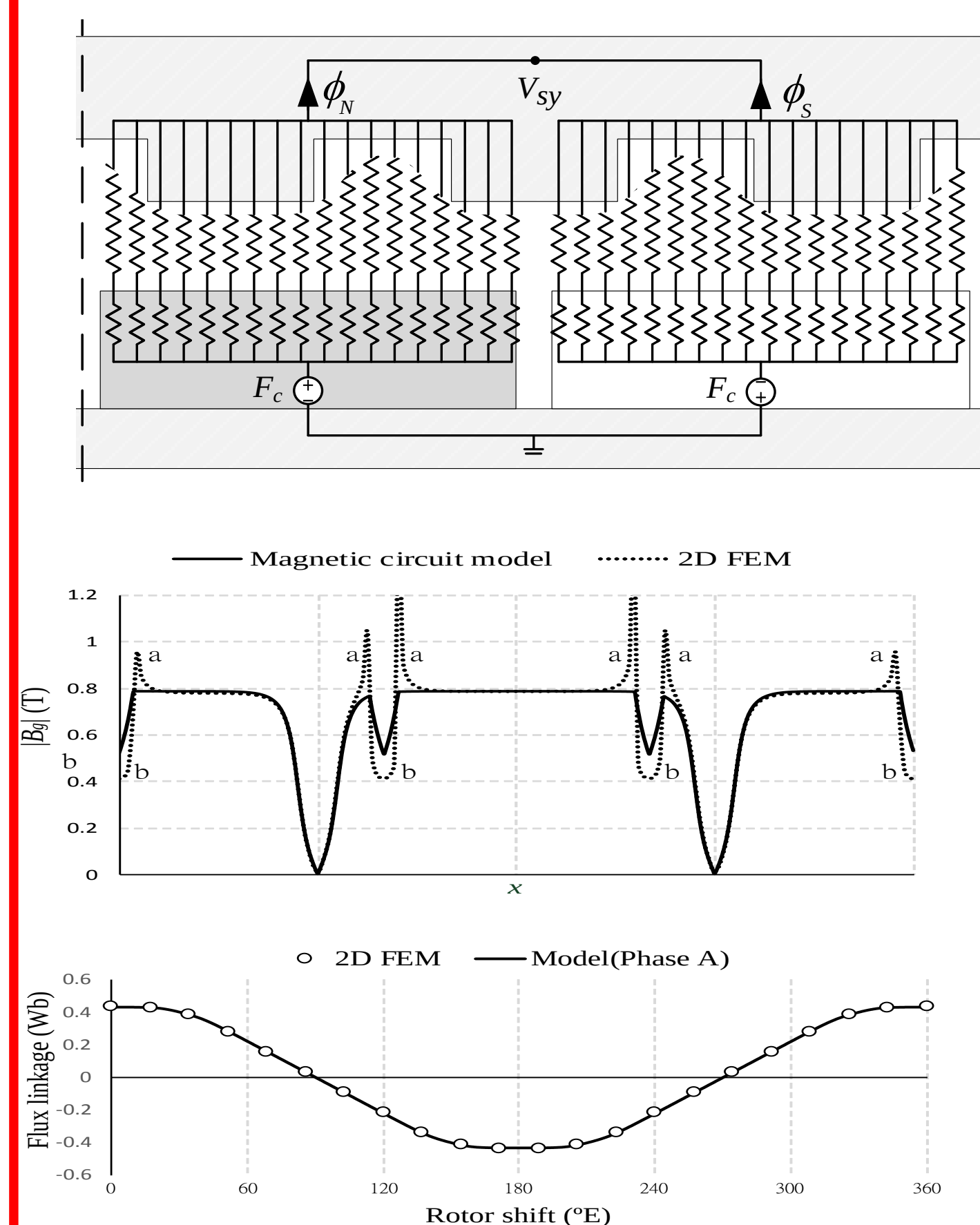
Boundary	TN ₁		TN ₂	
K _e (V/rad/s)	K _{e-max}	0.512	K _{e-min}	0.441
R _{ph} (Ω)	R _{ph-min}	ε (0<ε<<1)	R _{ph-max}	0.641
ω _{max} (rpm)	4094 (=ω _c)		4884	
I _{DC-max} (A)	70.4		81.8	
I _{ph-max} (A)	173.5		201.4	
ω _p (rpm)	ω _{p-max}	1918	ω _{p-min}	631
ω _q (rpm)	ω _{q-max}	4094	ω _{q-min}	3225
T _q (Nm)	T _{q1}	47.58	T _{q2}	60.40

Magnetic Circuit Model and Motor Sizing Equations

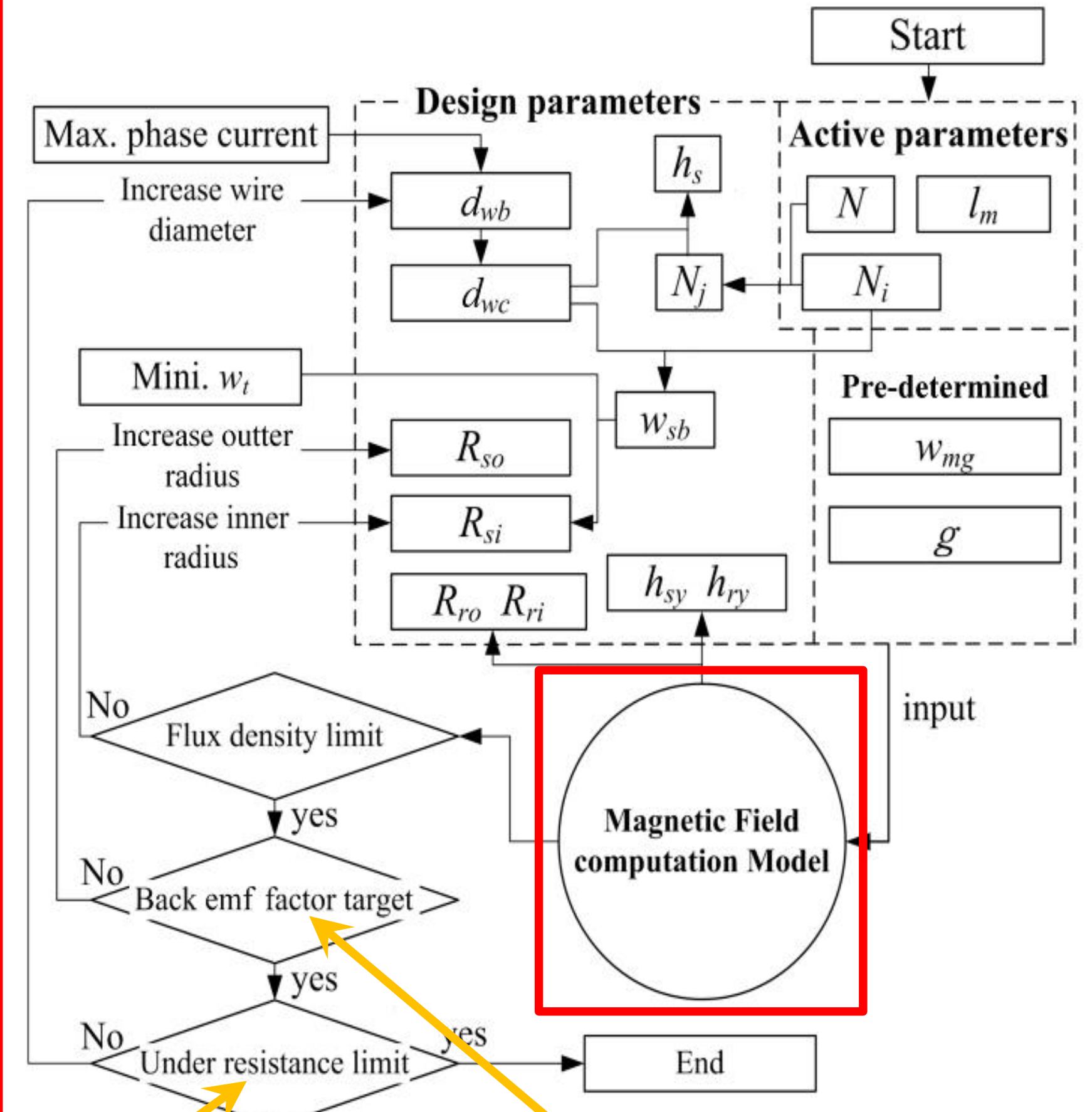
Design Parameters



2D Magnetic Circuit Model



Motor Sizing



$$0 \sim R_{ph-min} < R_{ph} < R_{ph-max}$$

$$K_{e-min} < K_e < K_{e-max}$$

Multi-Objective Optimization

• Objectives

– Minimize motor weight

$$\text{Min. } W = W_s + W_r + W_w$$

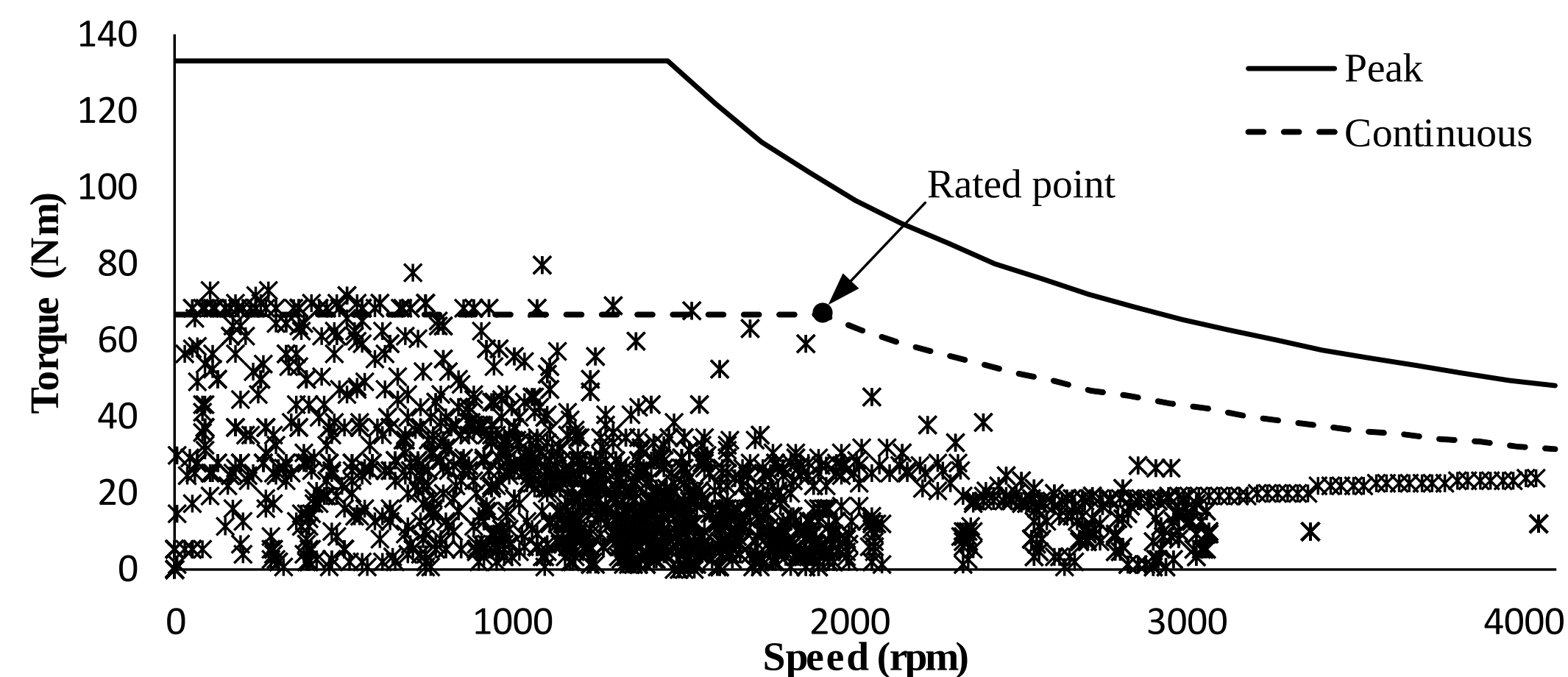
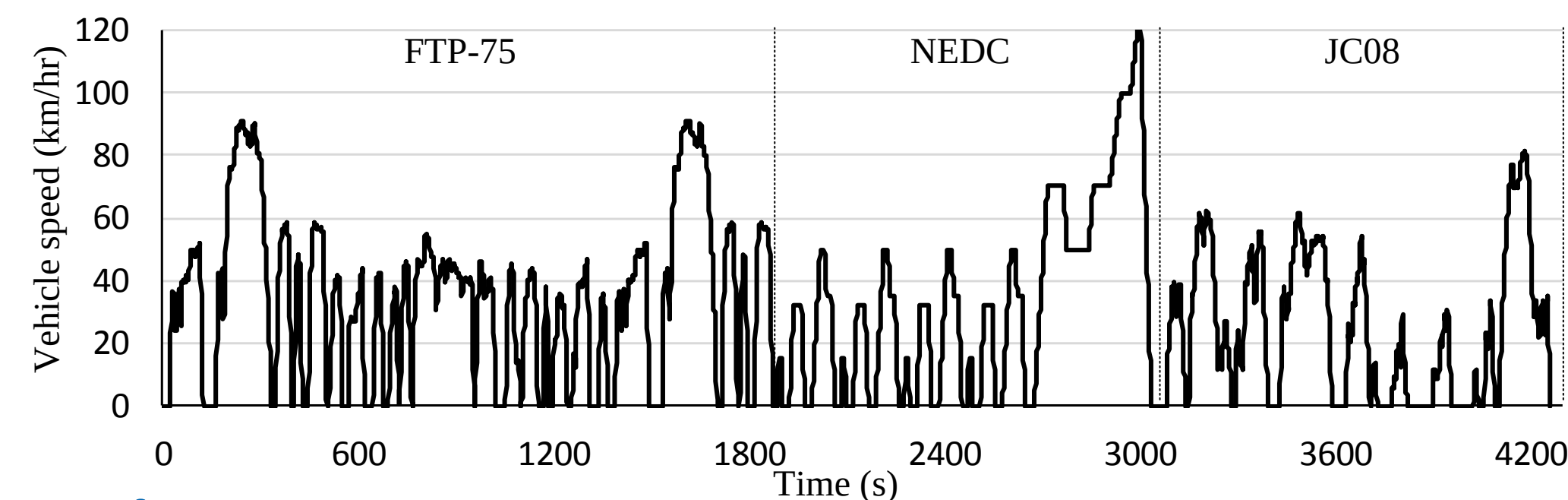
– (Proposed) Minimize energy loss during driving cycles

$$\text{Min. } EL = \sum_{i=1}^n [k_F P_{l,F}(\omega_i, T_i) + k_N P_{l,N}(\omega_i, T_i) + k_J P_{l,J}(\omega_i, T_i)] \Delta t$$

– (Traditional) Maximize efficiency at the rated operation point

$$\text{Max. } \eta_r = \frac{T_r \omega_r}{T_r \omega_r + P_r + P_c + P_s}$$

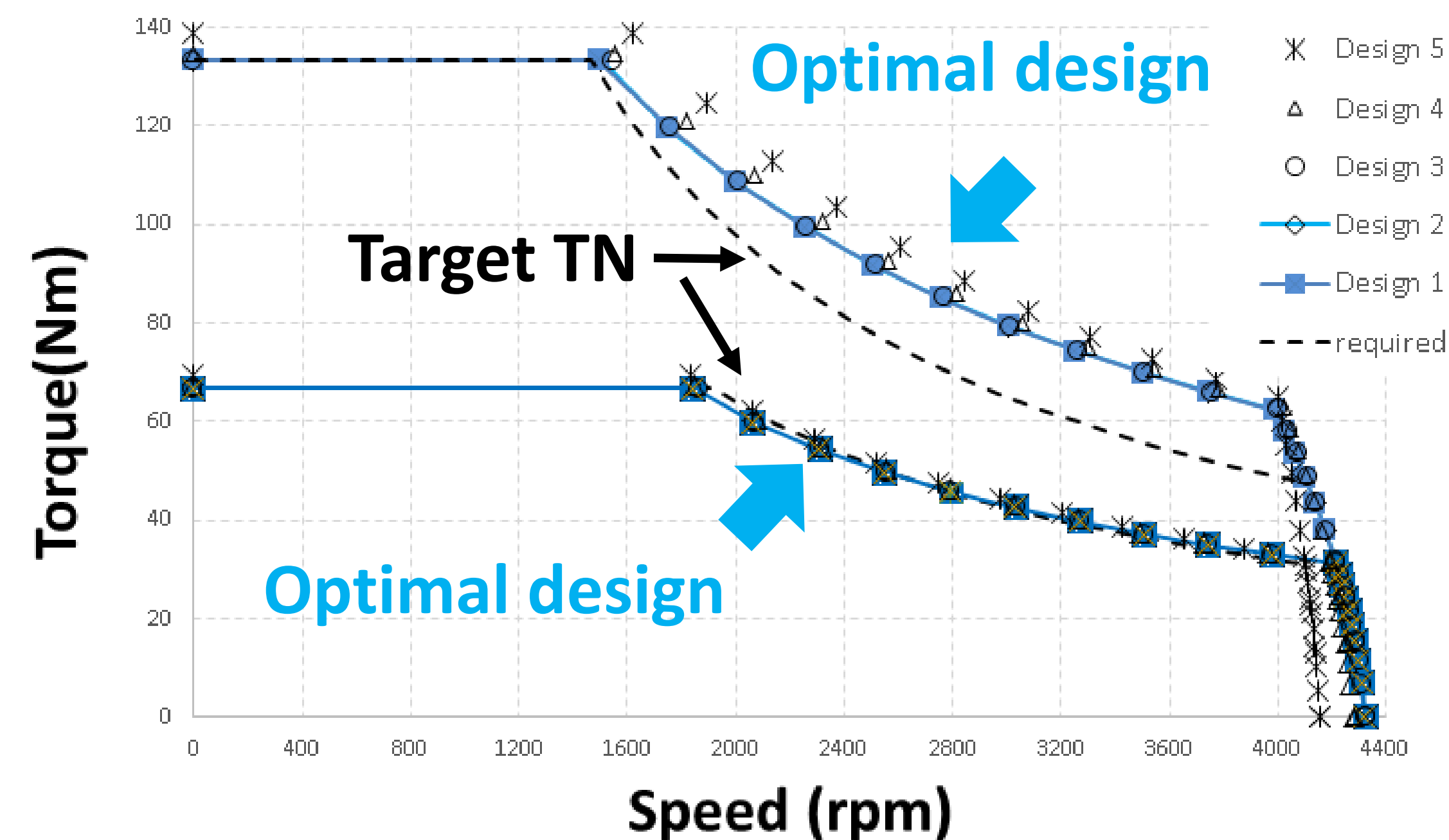
• Optimizer – Multifunctional Optimization System Tool (MOST)



FTP-75, which is the Federal Test Procedure defined by the US Environmental Protection Agency; NEDC, which is known as New European Driving Cycle; and JC08, which is a new Japanese test cycle.

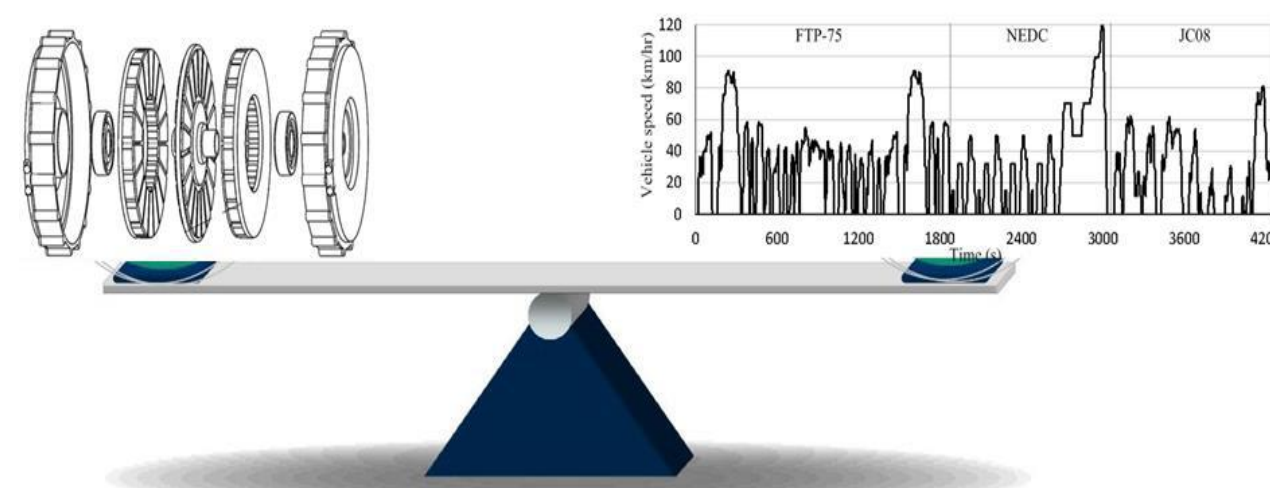
Multi-Objective Optimization Results

Case			1	2	3	4	5
Weighing factor	Motor weight (W)		0.7	0.85	0	0.8	0
	Energy loss	FTP-75	0.1	0.05	1/3	0	0
		NEDC	0.1	0.05	1/3	0	0
		JC08	0.1	0.05	1/3	0	0
	Rated efficiency (η_r)		0	0	0	0.2	1
Weight (kg)			11.60	10.92	13.92	11.82	13.82
Energy loss (kJ)			796.72	818.98	763.08	808.02	898.83
Efficiency (%) @ rated speed			93.28	93.14	93.19	93.40	93.45
K_e (V/rad/s)			0.485	0.485	0.485	0.490	0.504
L_{ph} (μ H)			208.71	207.44	288.33	176.79	127.57
R_{ph} (ohm)			0.0438	0.0444	0.0471	0.0430	0.0406
Zone I	T_{max} (Nm)		133.34	133.23	133.20	134.63	138.59
	ω_p (rpm)		1491	1503	1547	1555	1620
Zone II	P_{max} (kW)		26.10	26.11	26.17	26.57	27.21
	Rated torque @ 4094 rpm		32.18	32.18	32.19	32.34	32.54
Zone III	ω_{max} (rpm)		4320	4323	4324	4278	4156

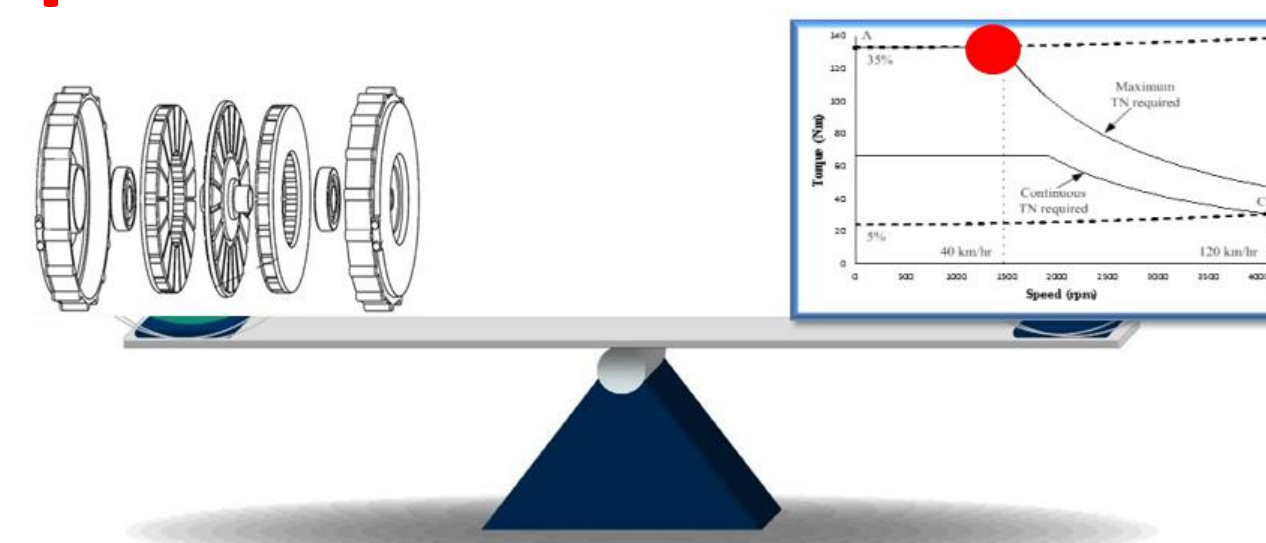


Which is more important ?

Case 1, 2, 3

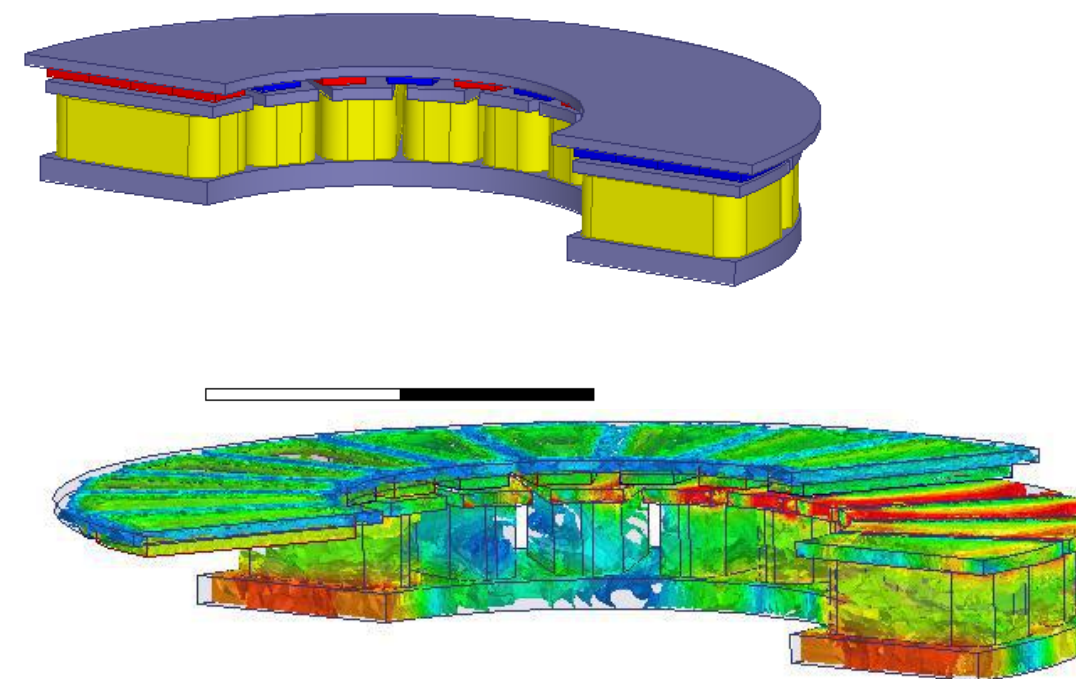
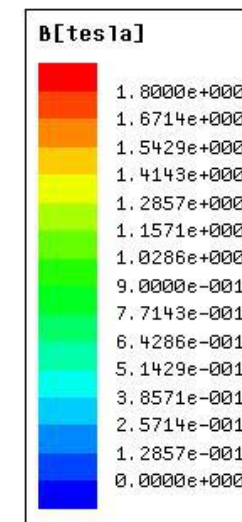
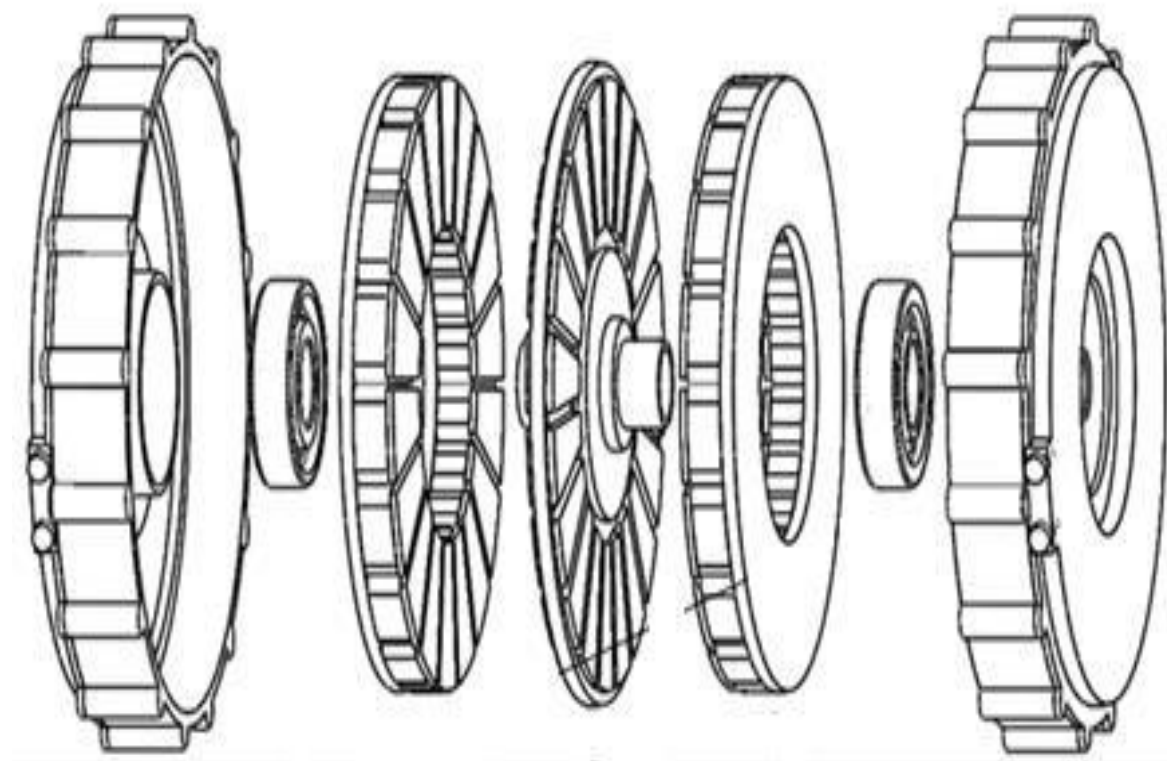


Case 4, 5

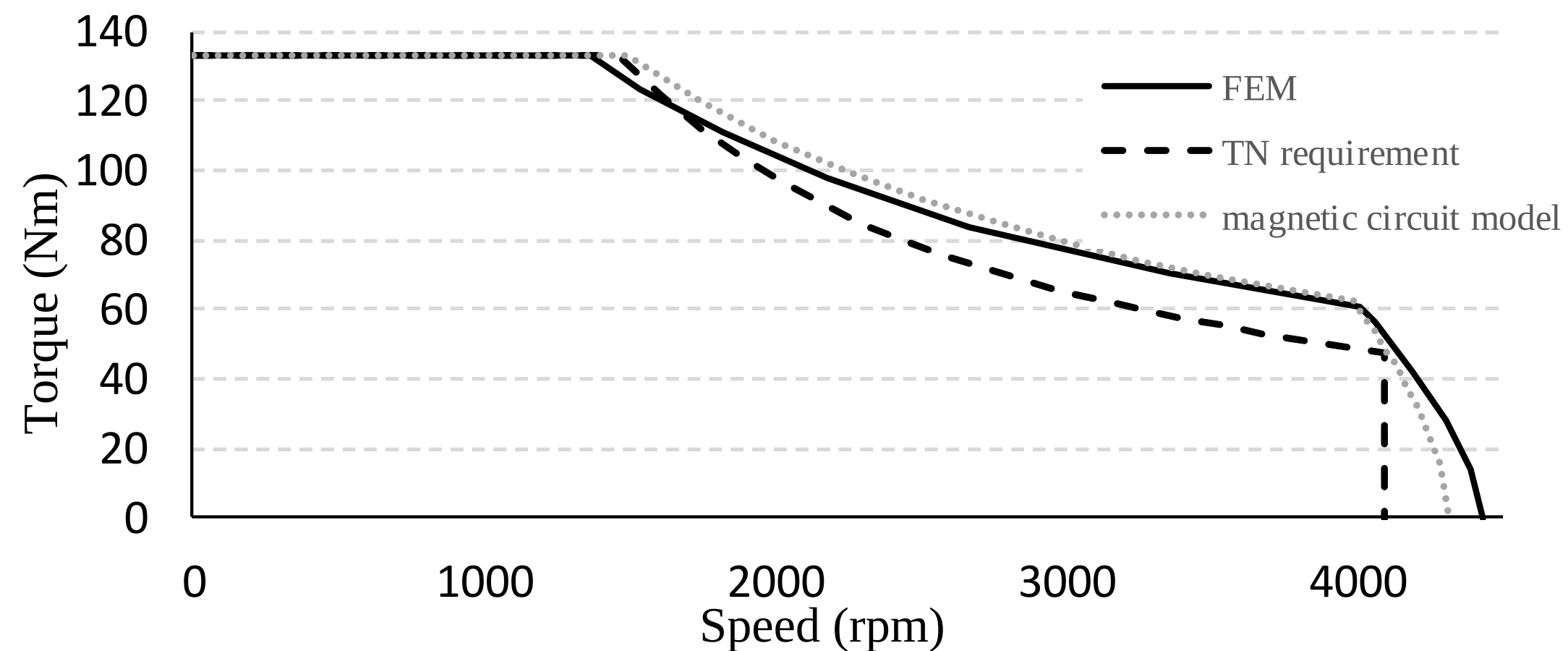
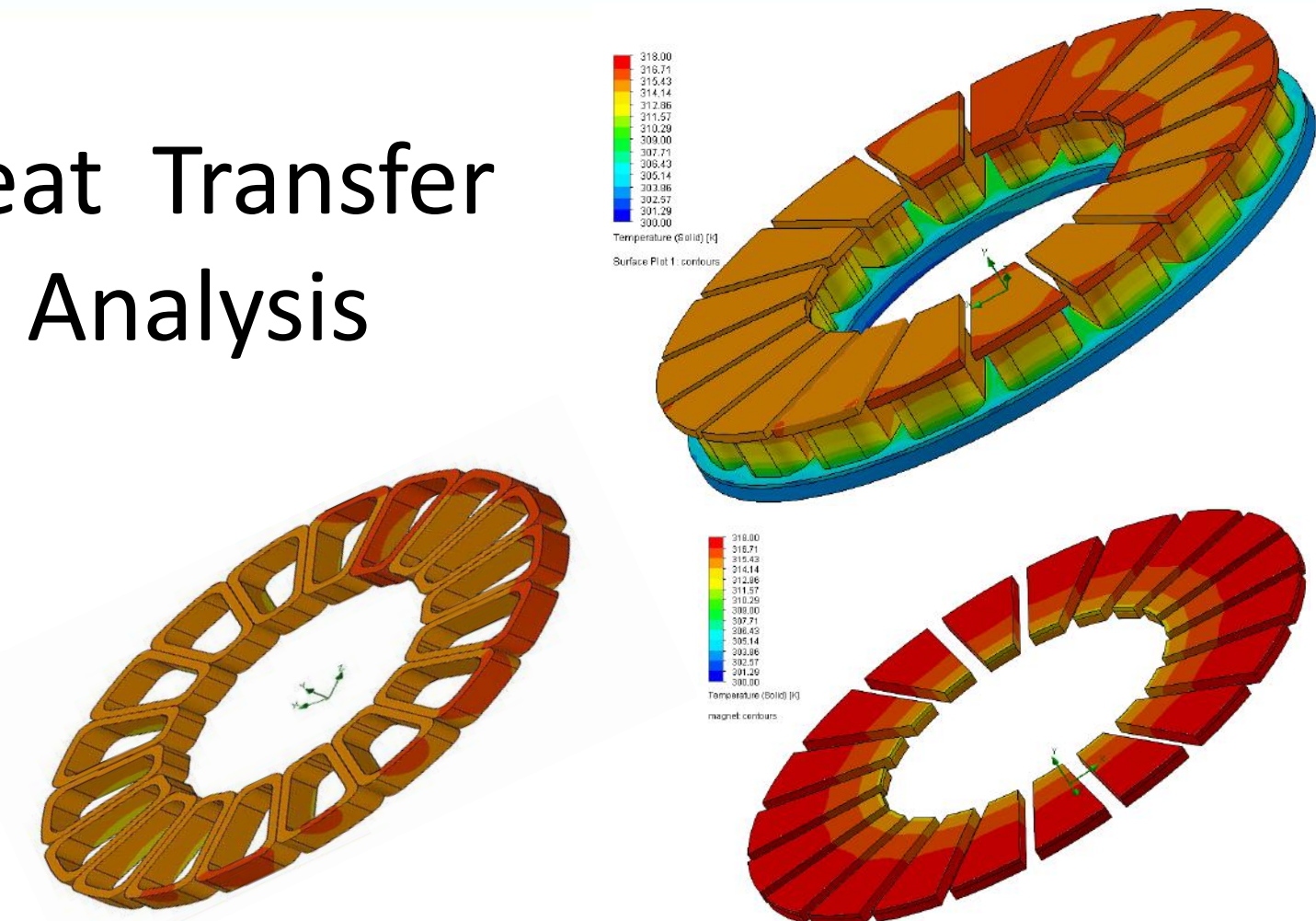


Finite Element Verification

Electromagnetic Analysis

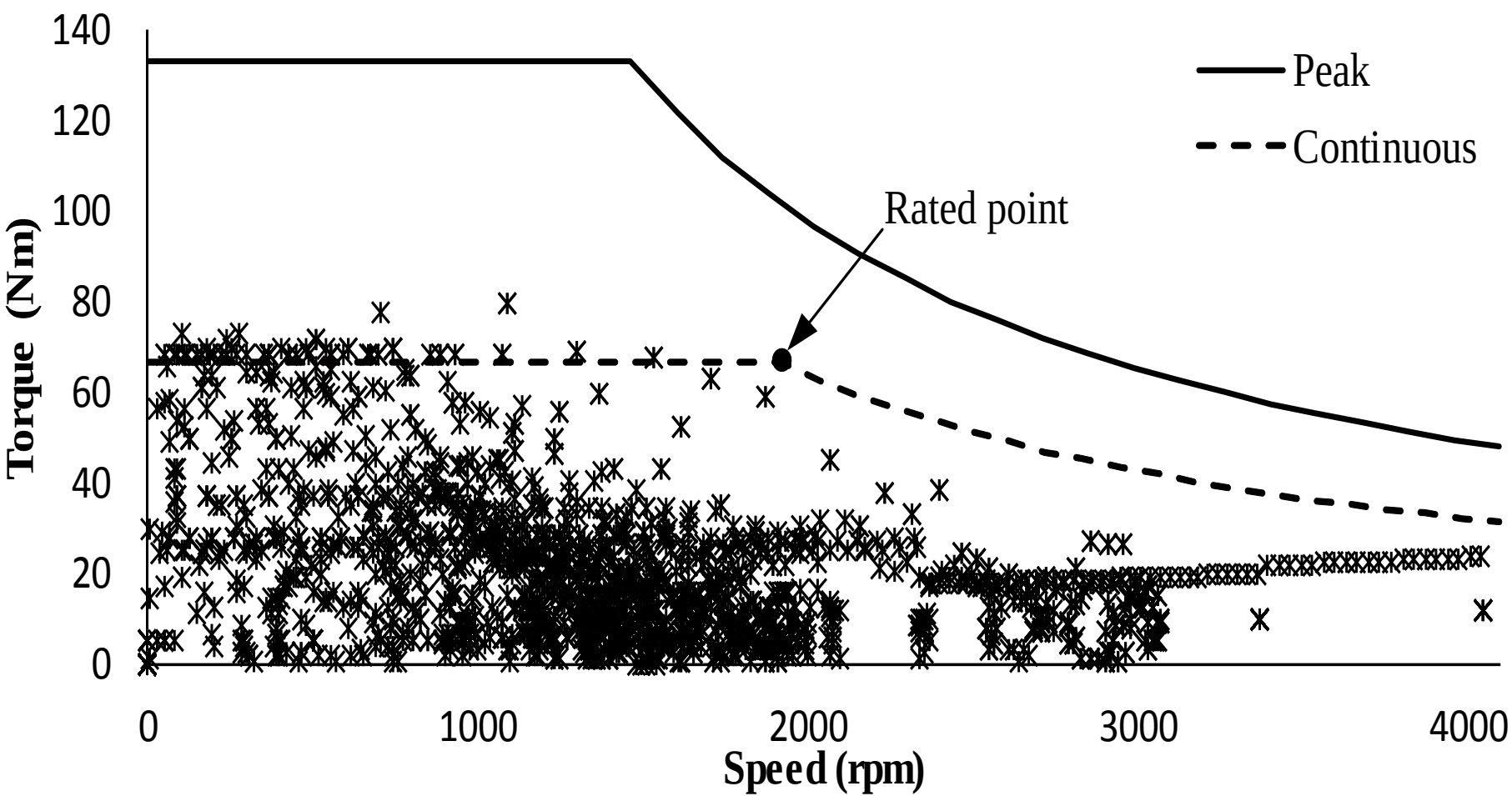
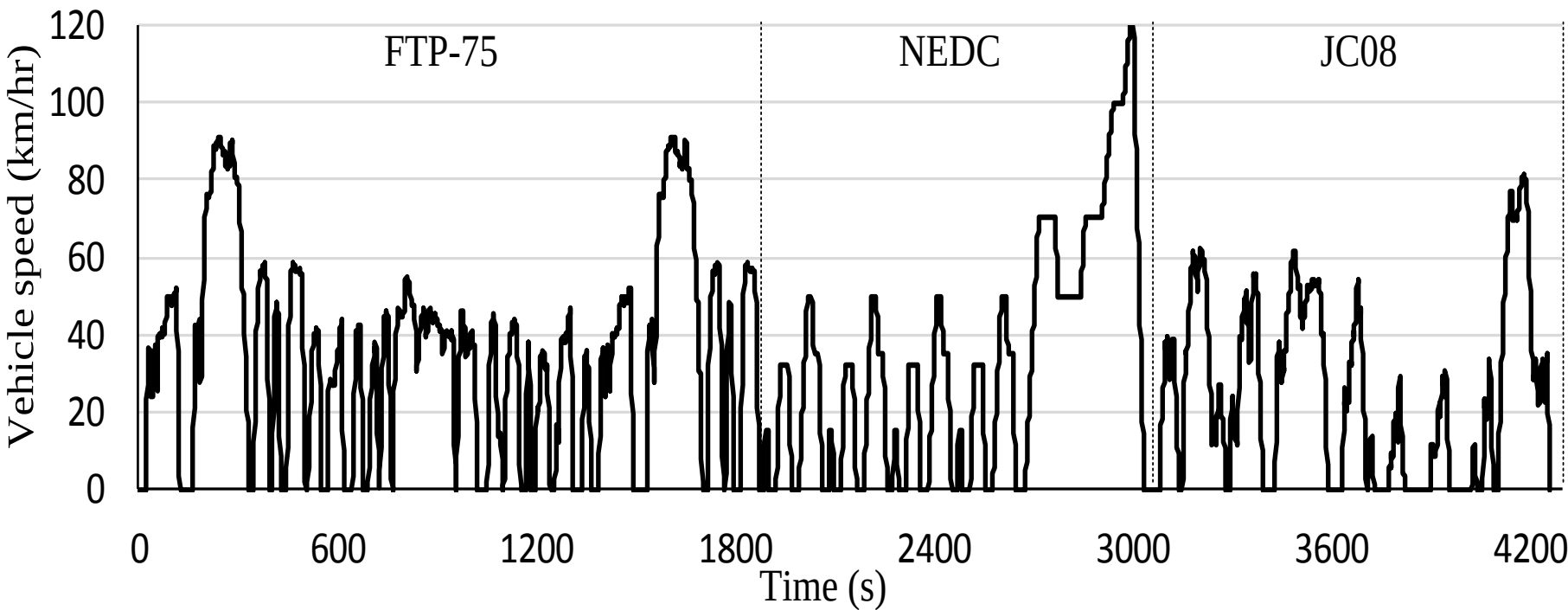
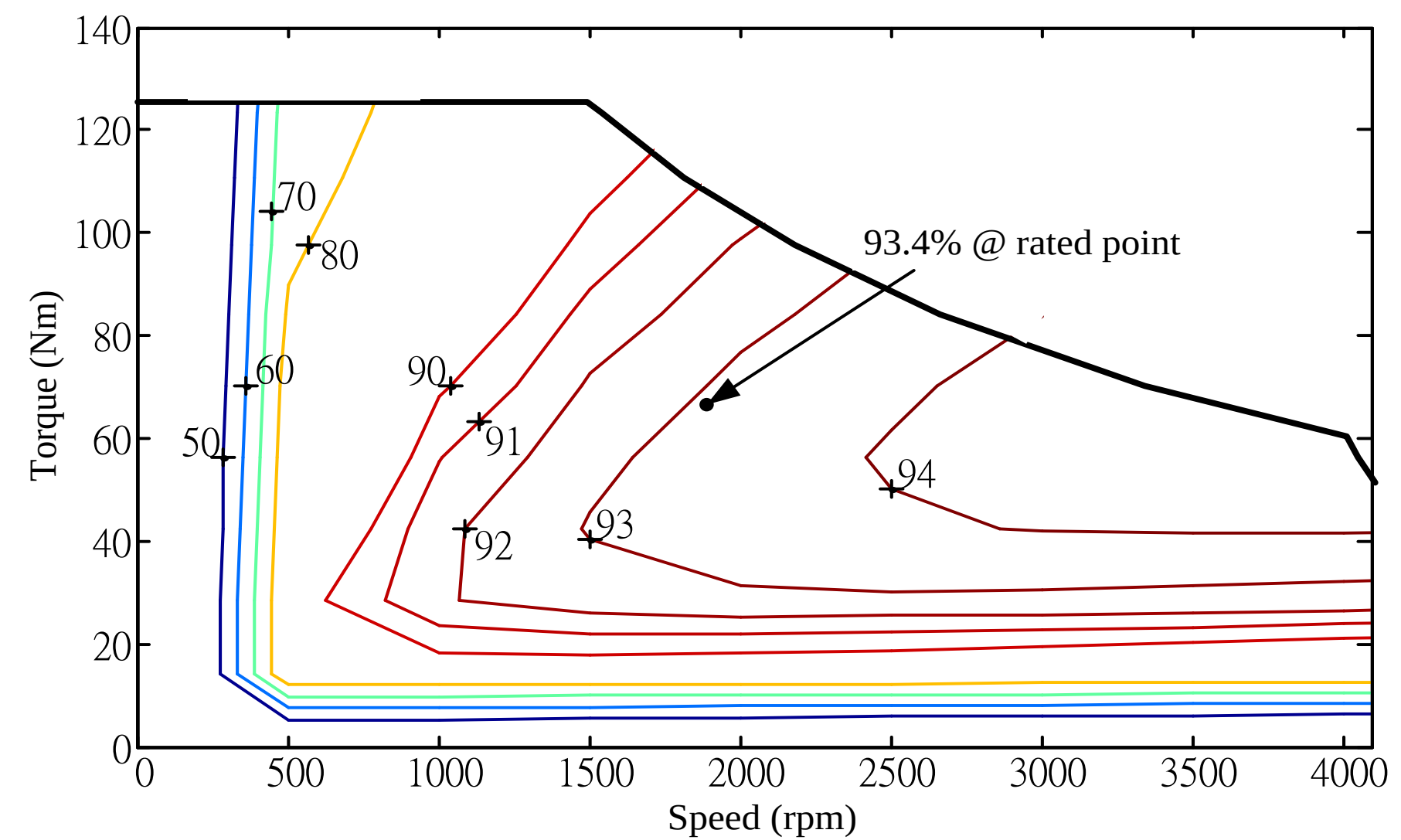


Heat Transfer Analysis



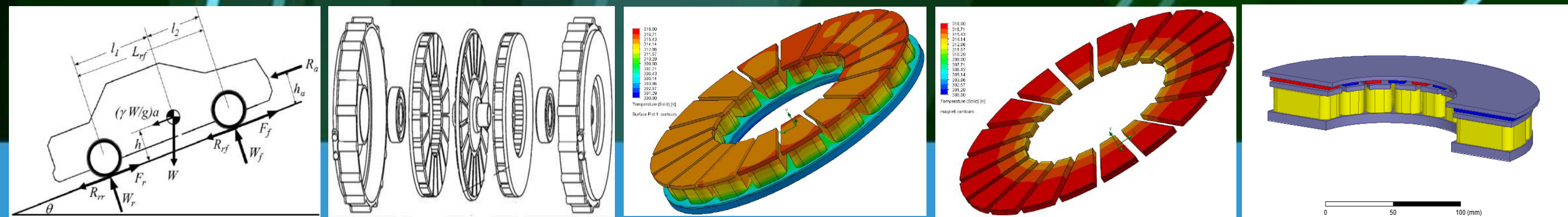
Model	I_{ph-max} (A)	ω_p (rpm)	ω_q (rpm)	ω_{max} (rpm)	K_e (V/rad/s)	L_{ph} (μH)
Magnetic circuit	183.3	1491	4023	4320	0.485	208.71
Finite element	195.5	1363	4010	4428	0.473	237.18
error	+6.7%	-8.6%	-0.3%	+2.5%	-2.5%	+13.6%

Energy Loss Analysis

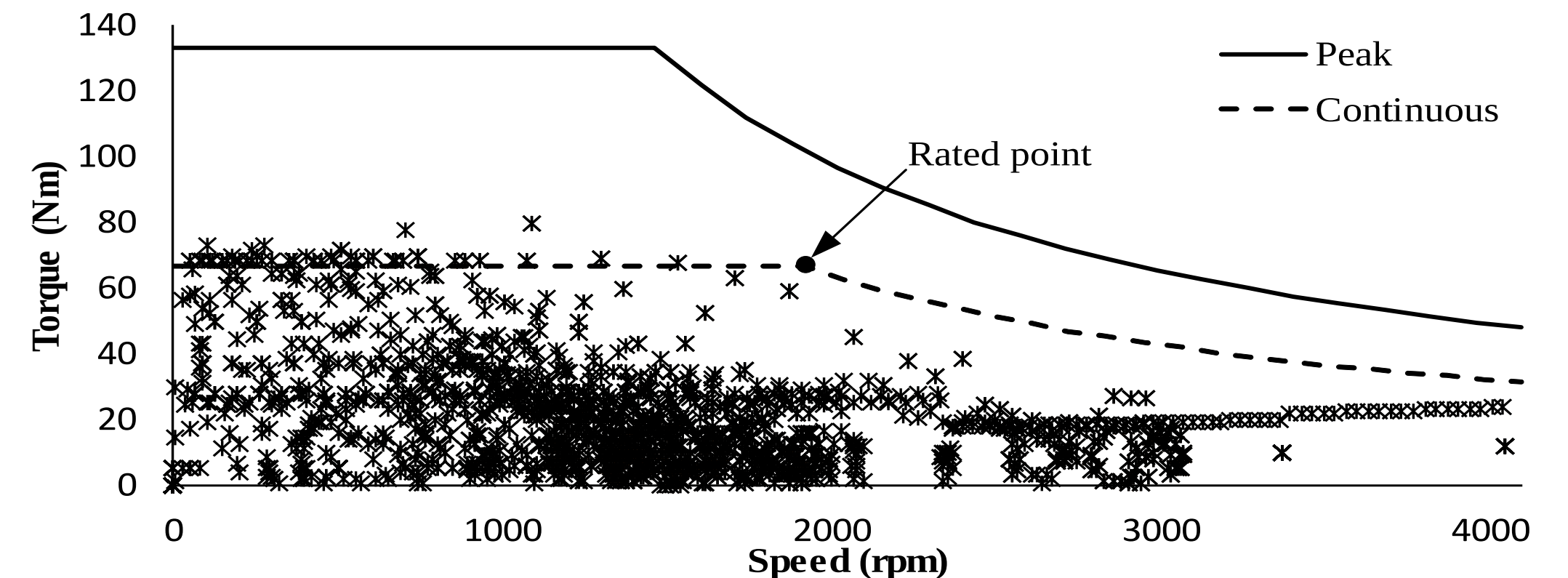
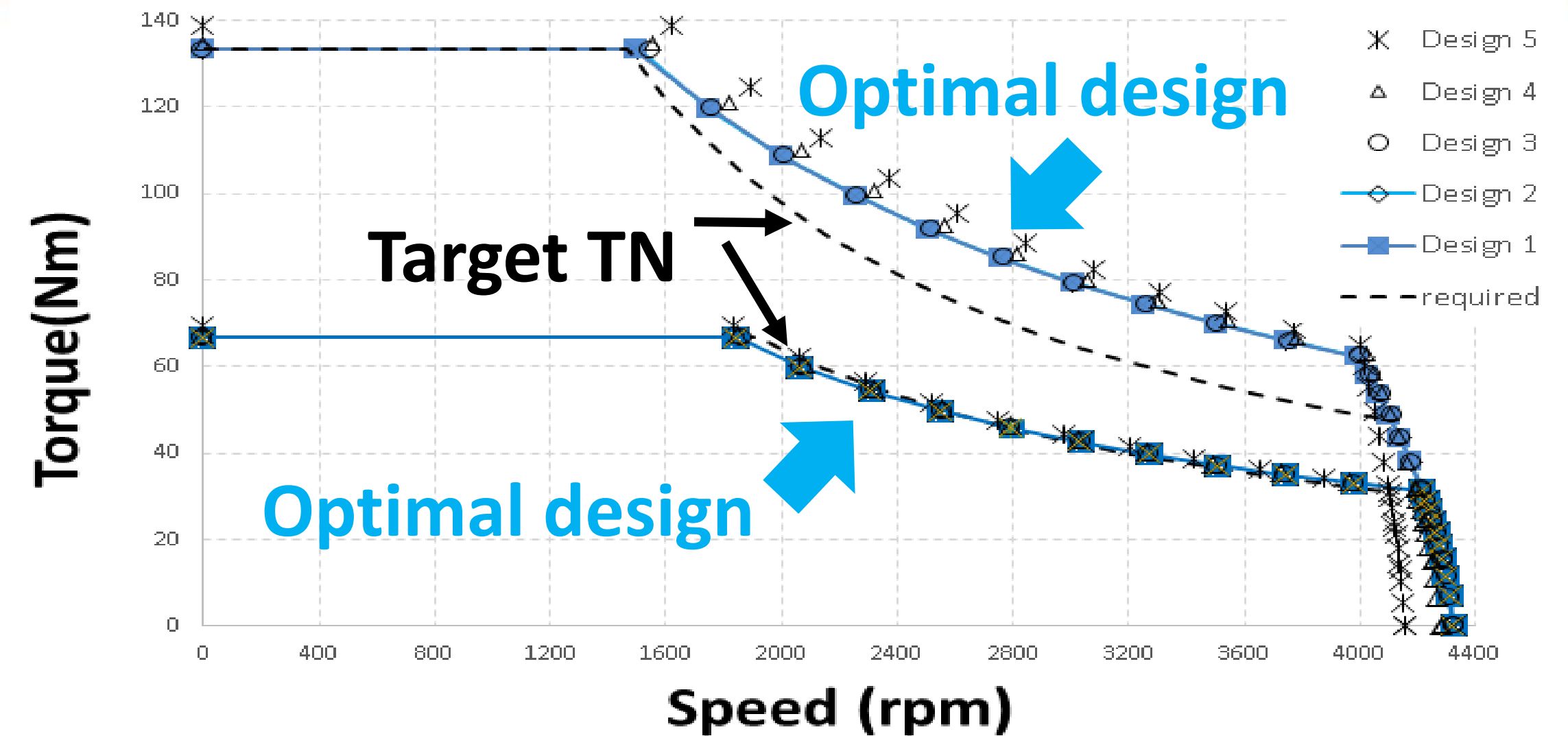


Energy Loss (kJ/cycle)		Copper loss	Iron loss	Magnet loss	Total
FTP-75	FEM	106.98	255.52	11.19	373.69
	MCM	100.45	294.00	-	394.45
NEDC	FEM	32.50	184.44	8.66	225.60
	MCM	30.63	212.14	-	242.77
JC08	FEM	42.15	103.91	4.10	150.16
	MCM	39.66	119.84	-	159.50

Conclusions



- We proposed a **driving-scenario oriented** optimal design of an AFPM motor for electric vehicles.
- The driving scenario determines a boundary of **target TN curves**.
- The target TN curves are related to **the ranges of the phase resistance and the back emf constant** of the motor.
- We optimize the motor **by minimizing the energy loss of all the operation points of driving cycles**, instead of one rated operation point.
- This is a novel and systematic design process of a traction motor for electric vehicle.



Thank you for your attention!