EE595S : Class Lecture Notes

Parameter Identification

and

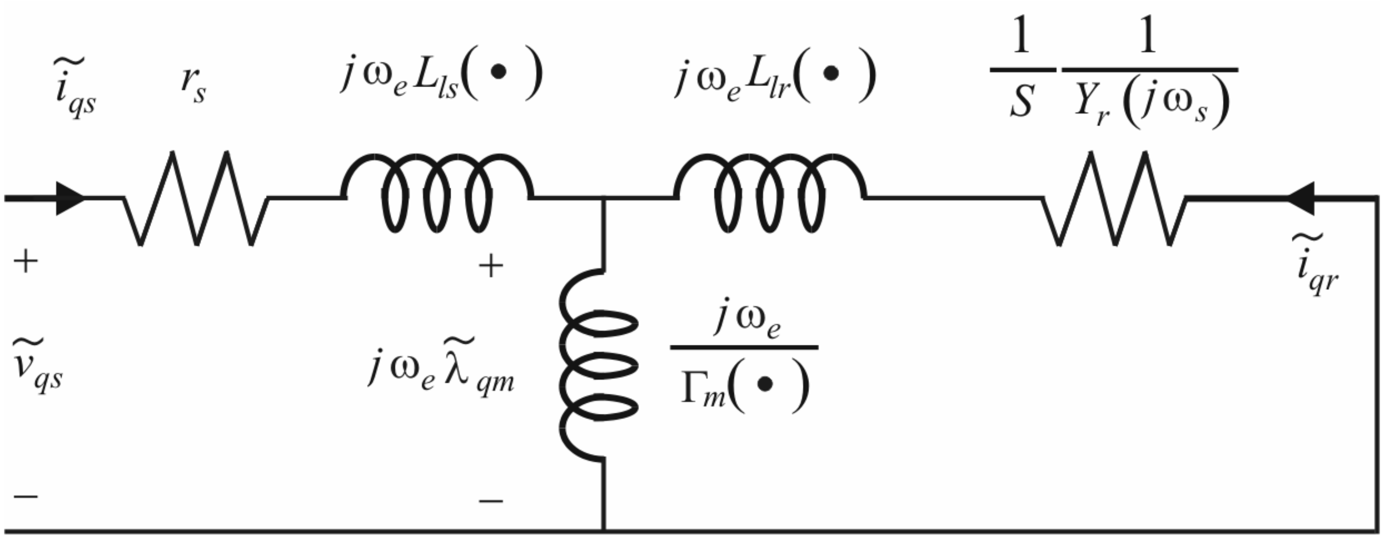
Maximum Torque Per Amp Control Algorithm

Fall 2005

Outline

- GA based AQDM Characterization Procedure
- MTPA Control strategy
- AMTPA Control Strategy

Alternate QD IM Model (AQDM)[1]



Steady-State T-Equivalent Circuit

$$S = \frac{\omega_e - \omega_r}{\omega_e}$$

[1] S. D. Sudhoff, D. C. Aliprantis, B. T. Kuhn , and P. L. Chapman, "An Induction Machine Model for Predicting Inverter –Machine Interaction," *IEEE Transactions on Energy Conversion*, Vol. 17, June 2002, pp. 203-210

Specific Forms of AQDM parameters

- For practical use of AQDM
  - $L_{ls}(\cdot) = l_{ls}\,(\text{const})$
  - $L_{lr}(\cdot) = l_{lr1} + \dfrac{l_{lr2}}{1 + \left(l_{lr3}\lambda_m\right)^{l_{lr4}}}$
  - $\Gamma_m(\cdot) = m_1 - m_2\lambda_m + e^{m_3(\lambda_m - m_4)} + e^{m_5(\lambda_m - m_6)}$
  - $Y_r(s) = \dfrac{y_{a1}}{y_{\tau 1}s+1} + \dfrac{y_{a2}}{y_{\tau 2}s+1} + \dfrac{y_{a3}}{y_{\tau 3}s+1}$

[2] S. D. Sudhoff, D. C. Aliprantis, B. T. Kuhn , and P. L. Chapman, "Experimental Characterization Procedure for Use With and Advanced Induction Machine Model," *IEEE Transactions on Energy Conversion*, Vol. 18, No. 1, March 2003, pp. 48-56

AQDM parameters

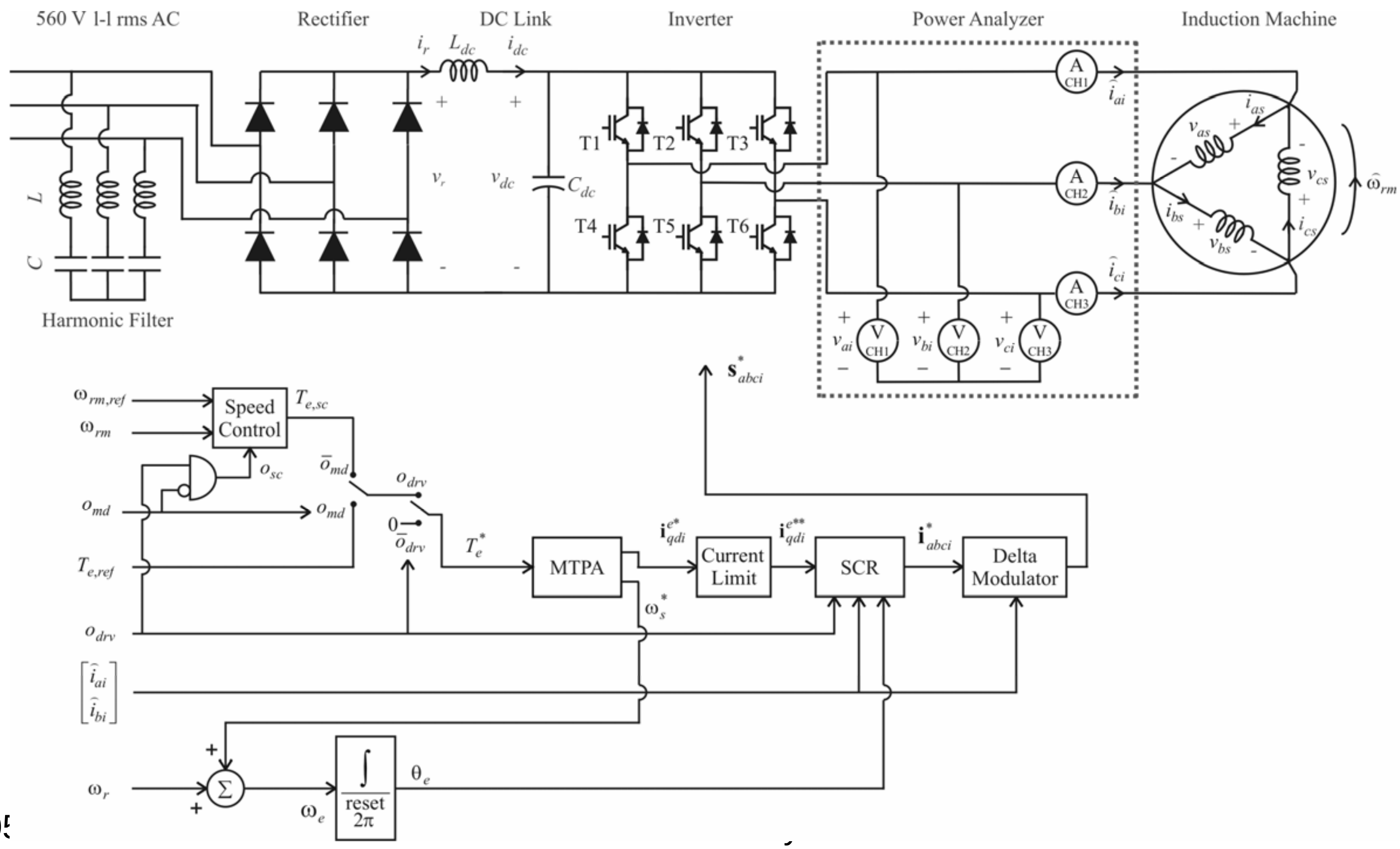
- Parameter vector to be identified is

Coefficients of $L_{ls}, \quad \Gamma_m, \quad L_{lr}, \quad Y_r$

$$\boldsymbol{\theta} = \Big[\overbrace{l_{s1}}^{L_{ls}} \; \overbrace{m_1 \; m_2 \; m_3 \; m_4 \; m_5 \; m_6}^{\Gamma_m} \; \overbrace{l_{r1} \; l_{r2} \; l_{r3} \; l_{r4}}^{L_{lr}} \; \underbrace{y_{a1} \; y_{\tau 1} \; y_{a2} \; y_{\tau 2} \; y_{a3} \; y_{\tau 3}}_{Y_r} \Big]$$

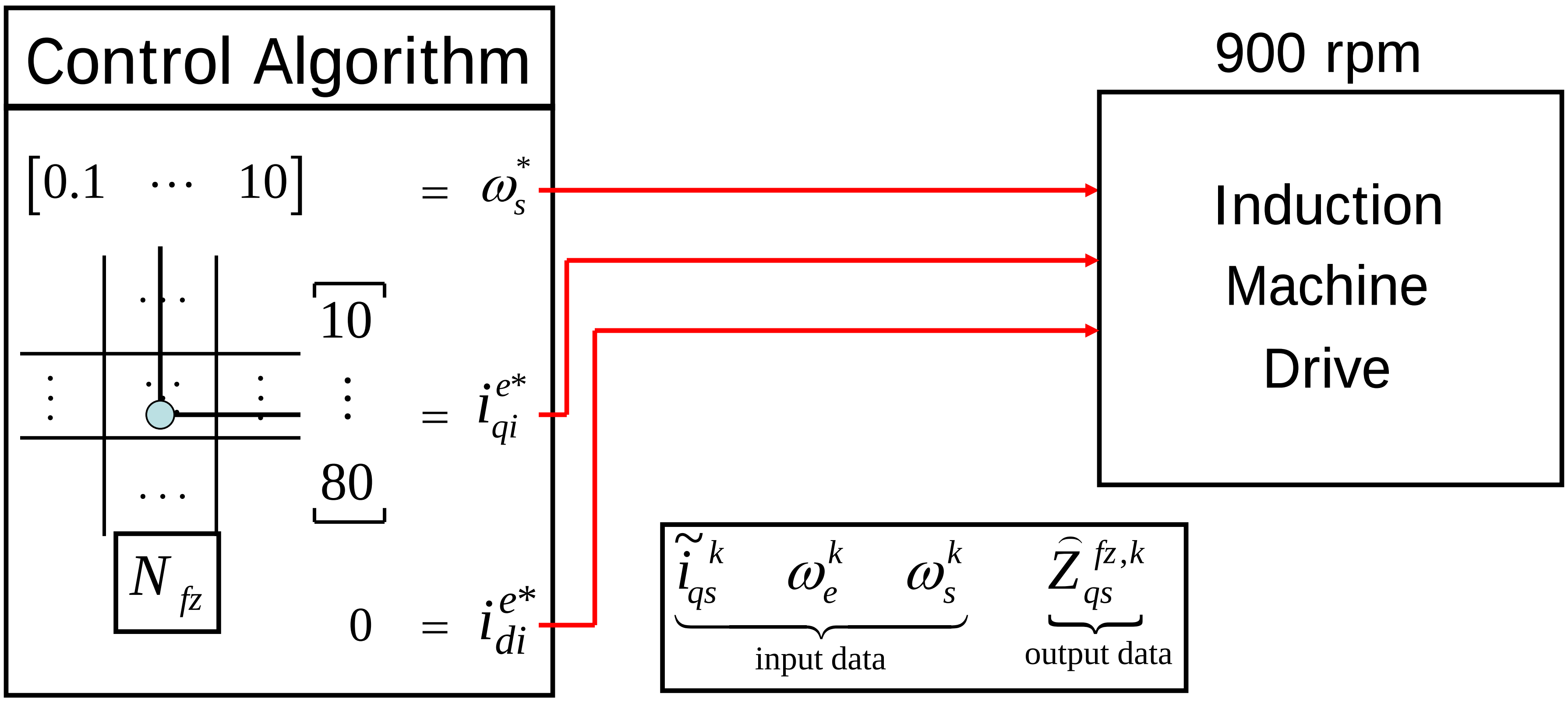
Experimental Measurements - I

- Fundamental frequency impedance test set-up



Experimental Measurements - I

- Fundamental frequency impedance $\hat{Z}_{qs}^{fz,k}$



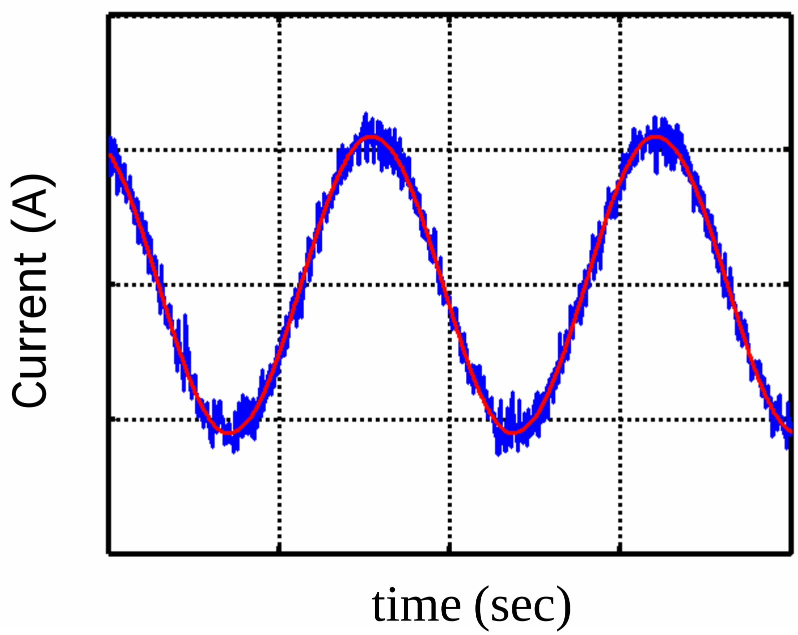
Experimental Measurements - I

- Analytical form of fundamental frequency impedance

$$\hat{Z}_{qs}^{fz,k} =$$

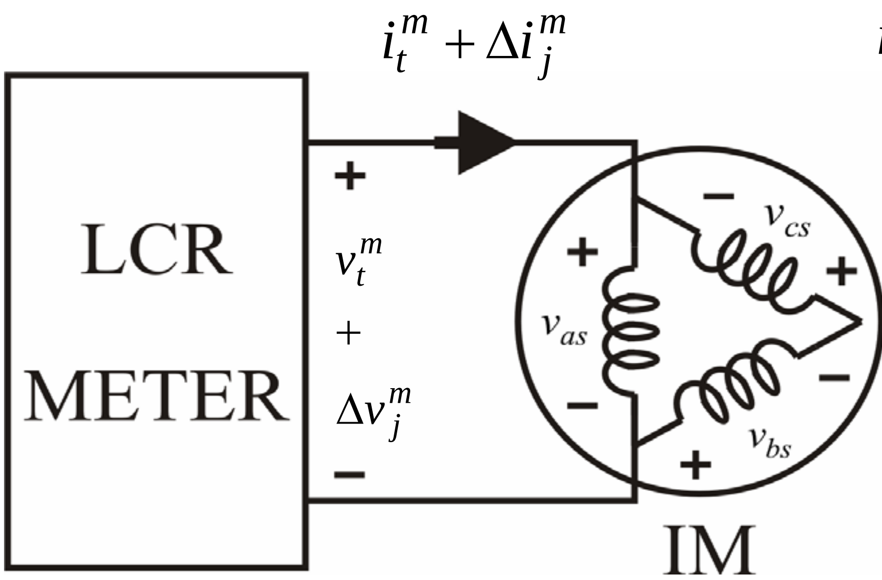
Experimental Measurements - II

- Stand Still Frequency Response impedances
  - To extract high frequency phenomenon in inverter-machine interaction



Experimental Measurements - II

- SSFR impedance test set-up $\hat{Z}_{qs,j}^{ssfr,m}$



$$m = \{05A \quad 10A \quad 15A \quad 22A\}$$

$$\underbrace{i_{qm0}^m = \frac{2}{3} i_t^m \qquad \omega_{e,j}^m}_{\text{input data}}$$

$$\underbrace{\hat{Z}_{qs,j}^{ssfr,m}}_{\text{output data}}$$

Experimental Measurements - II

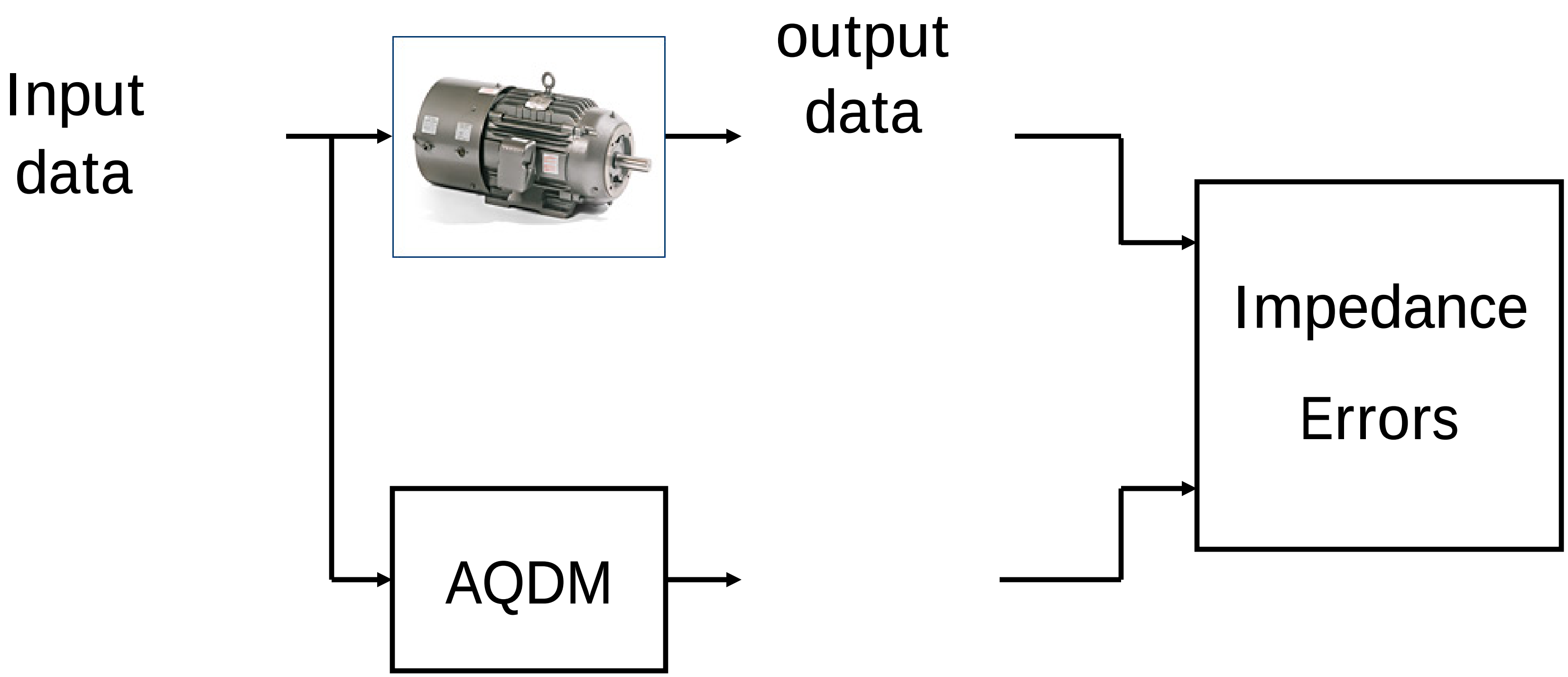
- Analytical form of SSFR impedance for given input data $\left\{ \tilde{i}_{qm0}^{m} \quad \omega_{e,i}^{m} \right\}$

$$\hat{Z}_{qs,j}^{ssfr,m} = \frac{\Delta v_j^m}{\Delta i_j^m} = r_s + sL_{ls}\left(\lambda_{qm0}^m\right)$$

$$+ \left(\frac{\partial L_{ls}\left(\lambda_{qm0}^m\right)}{\partial \lambda_m} i_{qs0}^m + 1 \right) \frac{sL_{M0}\left(Y_r^{-1}(s) + L_{lr}\left(\lambda_{qm0}^m\right)s\right)}{Y_r^{-1}(s) + \left(L_{lr}\left(\lambda_{qm0}^m\right) + L_{M0}\right)s}$$

where $s = j\omega_{e,i}^m$

Impedance Errors



Impedance Errors

- Fundamental frequency impedance error

- SSFR impedance error for each m=5,10,15,22 A

GA based Characterization Procedure

Parameter Identification for AQDM

⇩

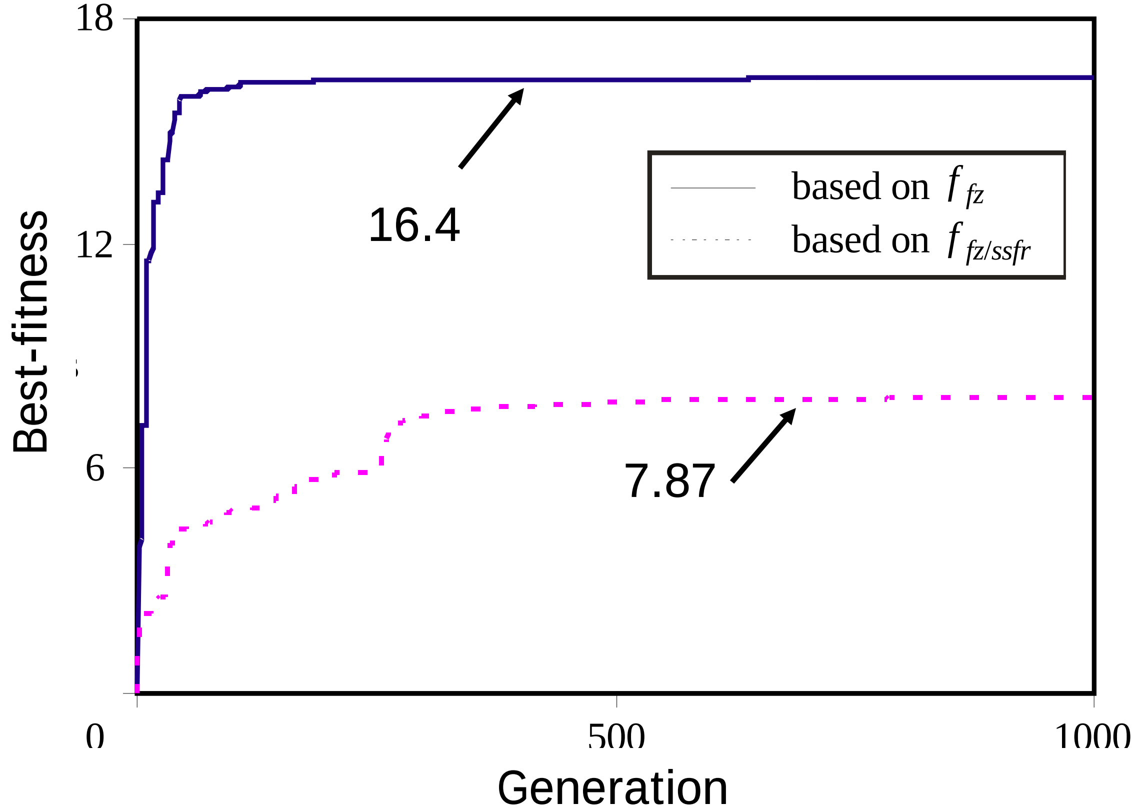
Nonlinear Optimization Problem

GA based Optimization problem (OP)

- GA is employed to solve the OP
  - Case I
  - Case II

Evolution Process

- Best fitness ($N_P = 1000$)



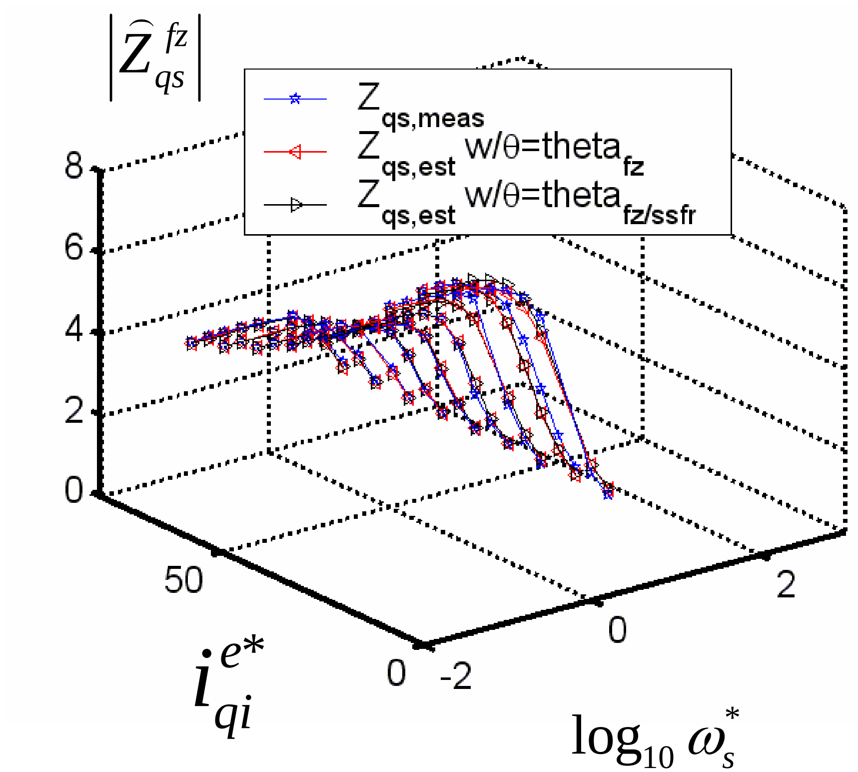
Quality of Fit

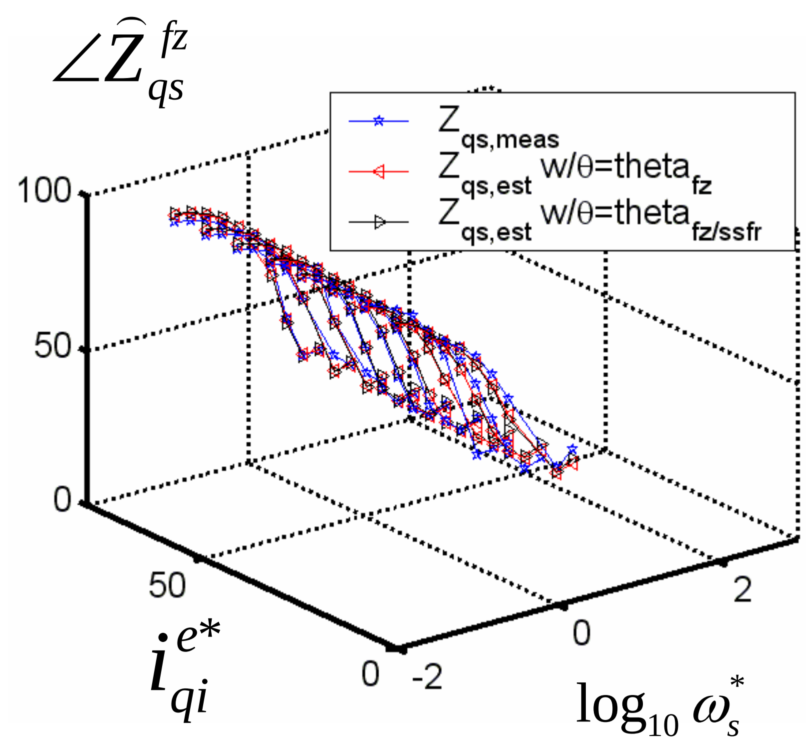
- In terms of impedance error

	AQDM $\theta = \theta_{fz}$	AQDM $\theta = \theta_{fz/ssfr}$
E_{fz}	0.0599	0.0625
E_{ssfr}^{5A}	0.3219	0.1026
E_{ssfr}^{10A}	0.3313	0.0389
E_{ssfr}^{15A}	0.3718	0.0325
E_{ssfr}^{22A}	0.4785	0.0803

Quality of Fit

- In terms of fundamental frequency impedance

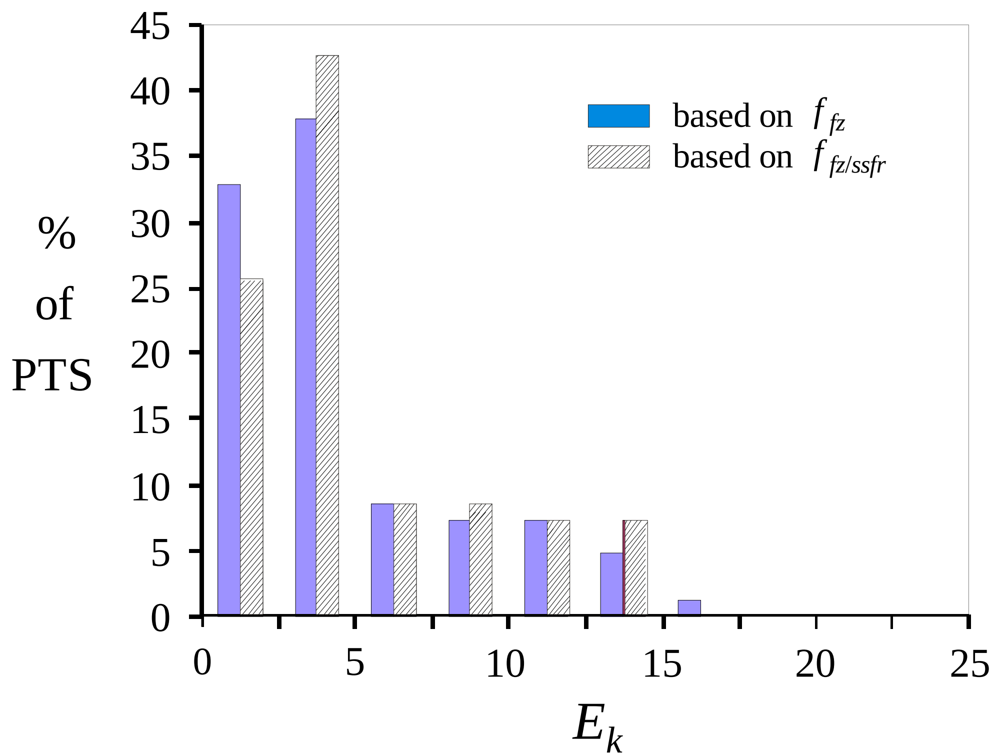




Quality of Fit

- In terms of fundamental frequency impedance

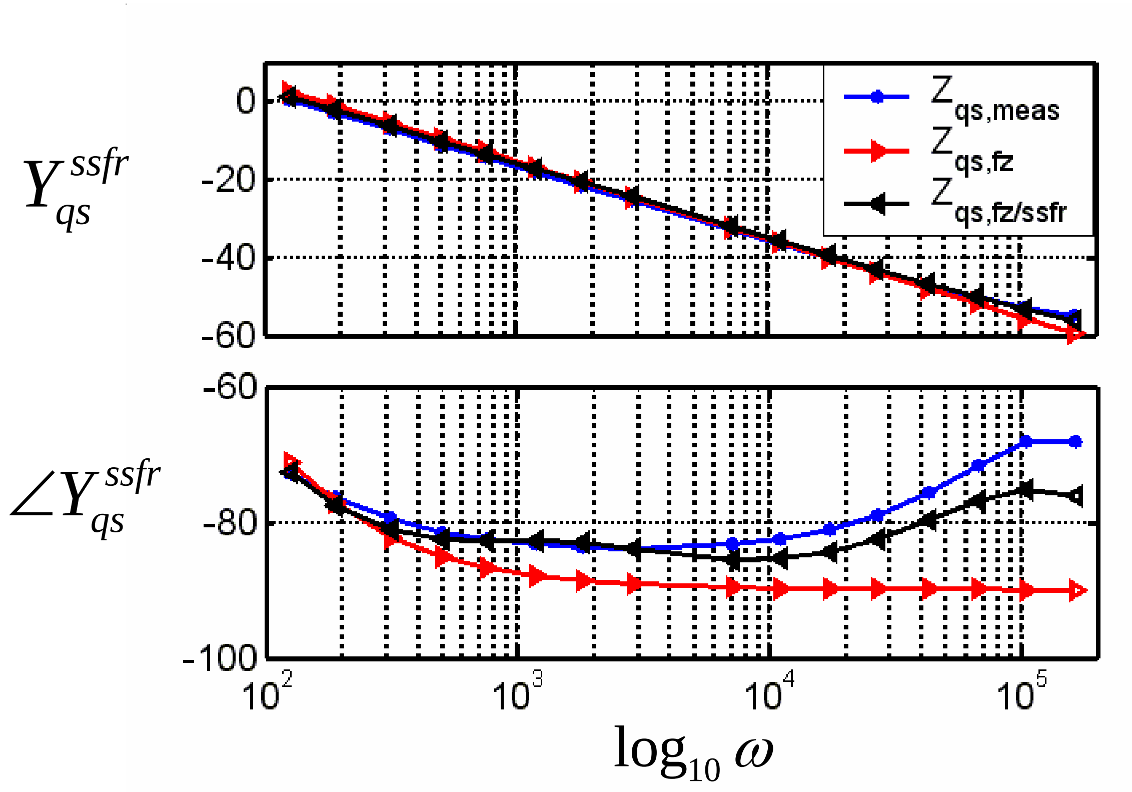
$E_k =$



Quality of Fit

- In terms of SSFR impedance

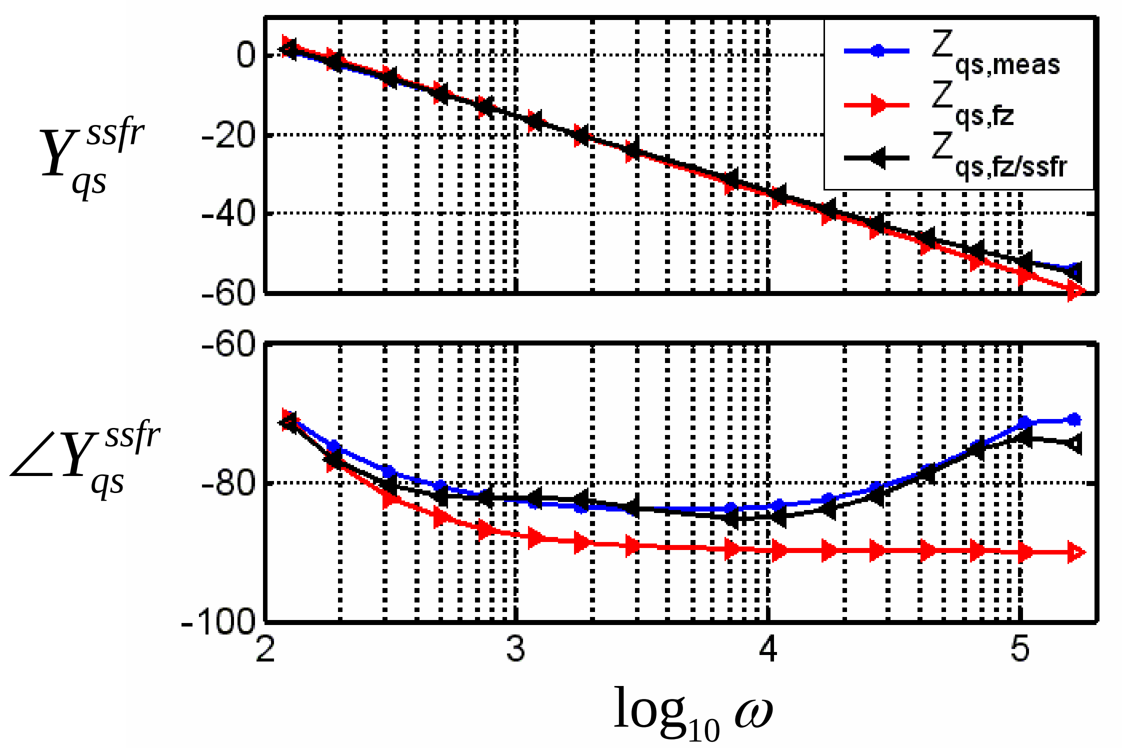
$$i_t = 05A$$



Quality of Fit

- In terms of SSFR impedance

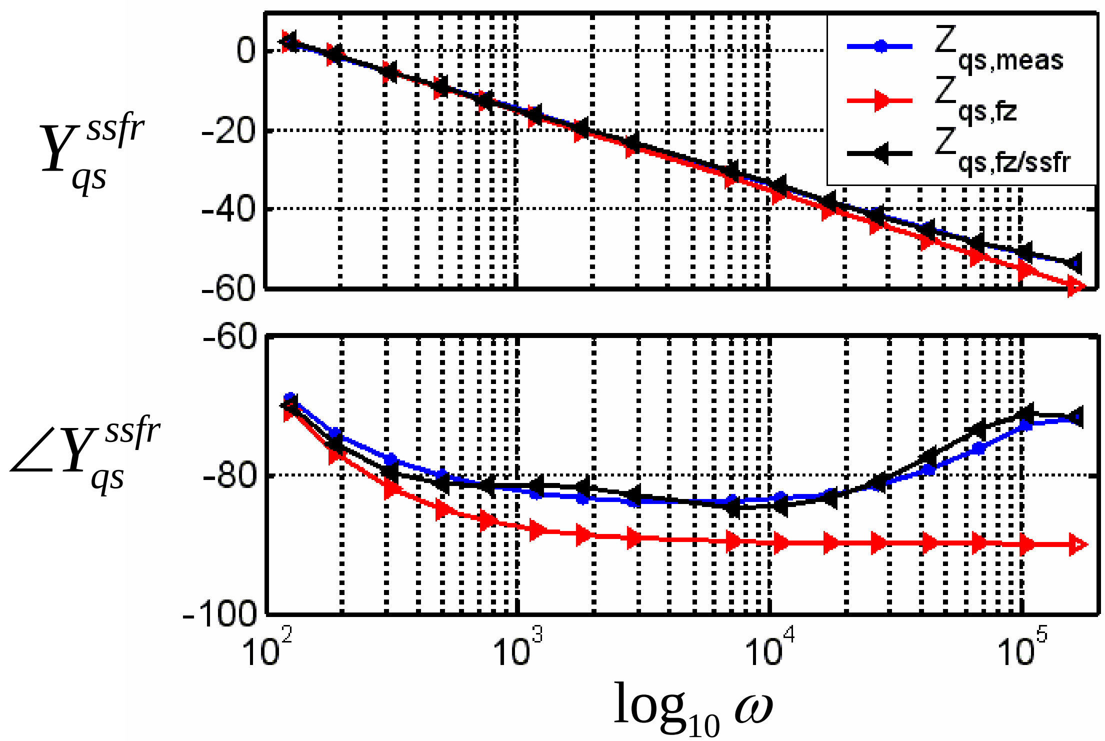
$i_t = 10\,\text{A}$



Quality of Fit

- In terms of SSFR impedance

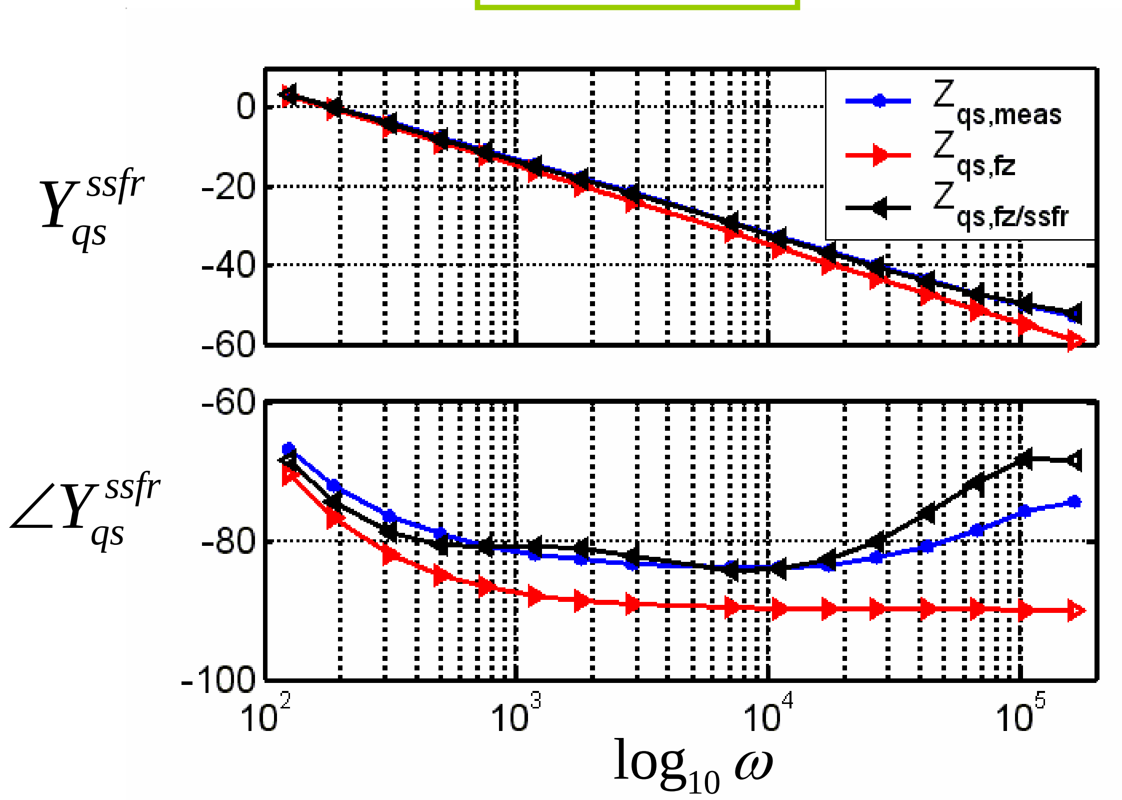
$$i_t = 15\text{A}$$



Quality of Fit

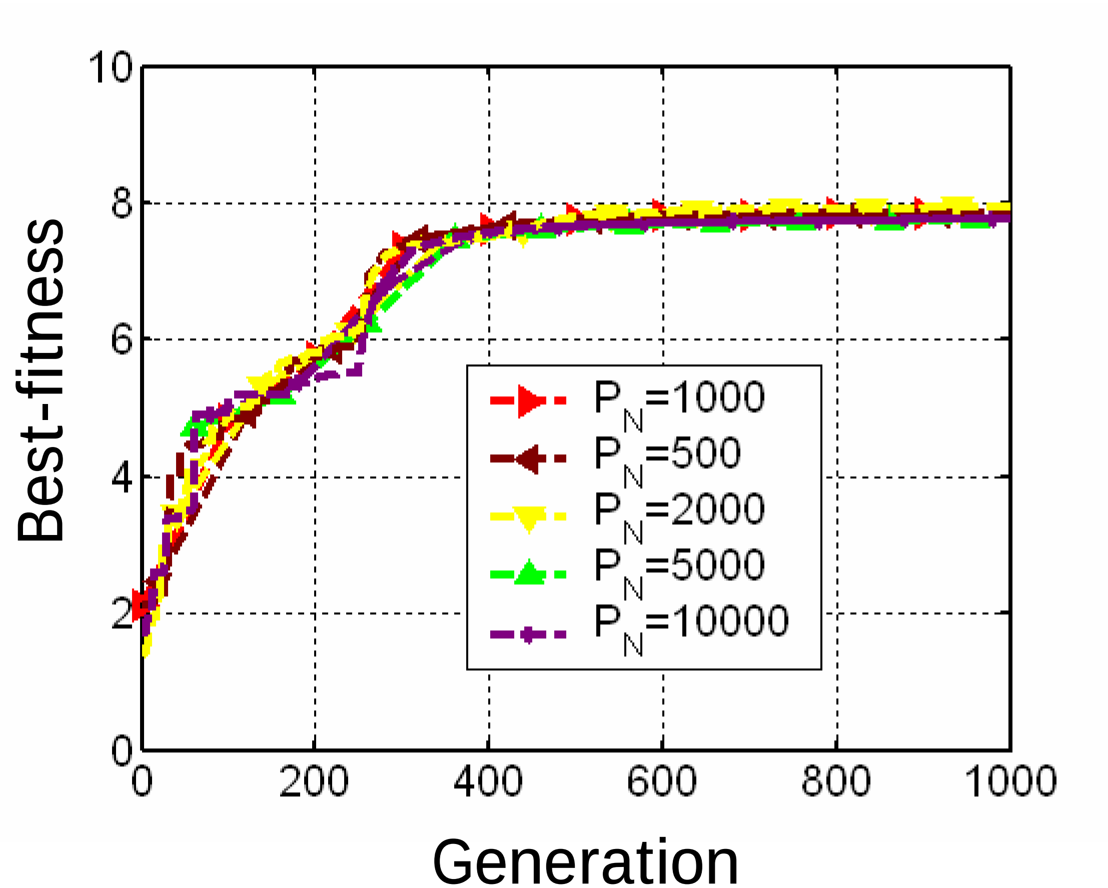
- In terms of SSFR impedance

$$i_t = 22\text{A}$$



Dependency on population size

- N_P = 1000,500,2000,5000, and 10000



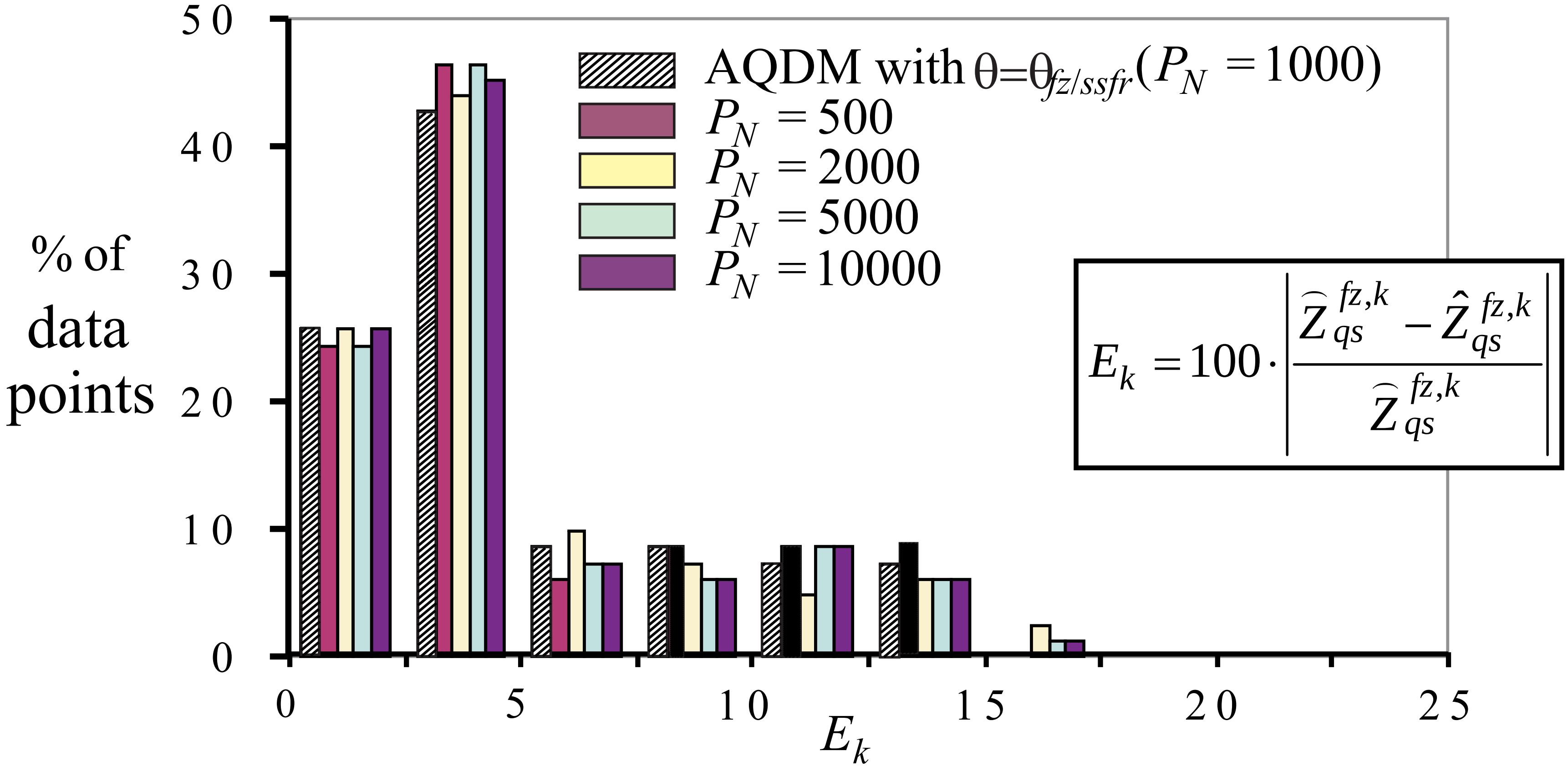
Dependency on population size

- In terms of impedance errors

N_P	f	E_{fz}	E_{ssfr}^{5A}	E_{ssfr}^{10A}	E_{ssfr}^{15A}	E_{ssfr}^{22A}
$\boldsymbol{\theta}_{fz/ssfr}$	7.86	0.063	0.103	0.039	0.033	0.080
500	7.95	0.063	0.101	0.037	0.034	0.077
2000	7.77	0.063	0.100	0.035	0.035	0.088
5000	7.96	0.063	0.103	0.037	0.033	0.076
10000	7.98	0.063	0.102	0.037	0.033	0.075

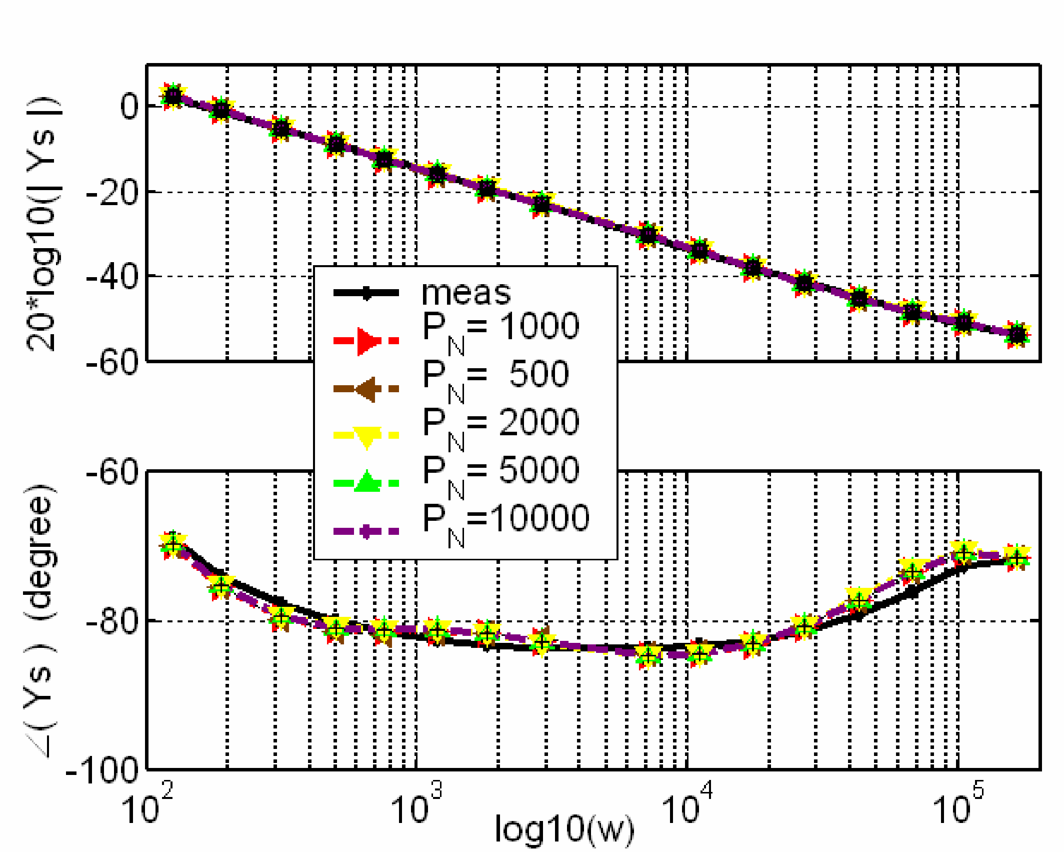
Dependency on population size

- In terms of Fundamental frequency



Dependency on population size

- In terms of SSFR impedance at 15 A DC bias



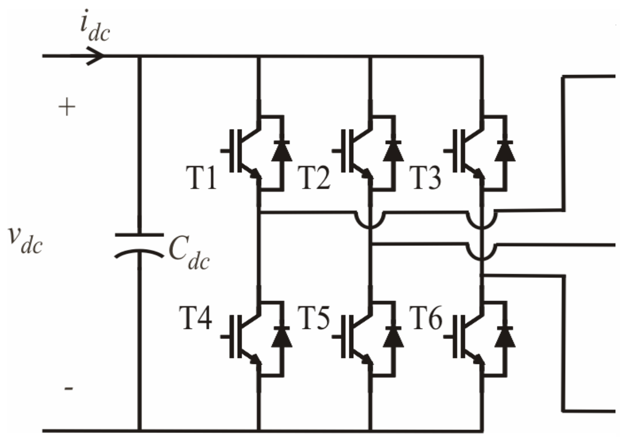
Consistency in repeated applications

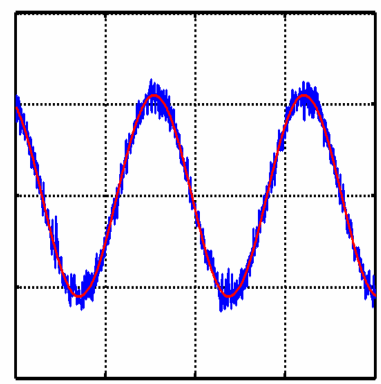
- 100 repeated applications with N_P =500

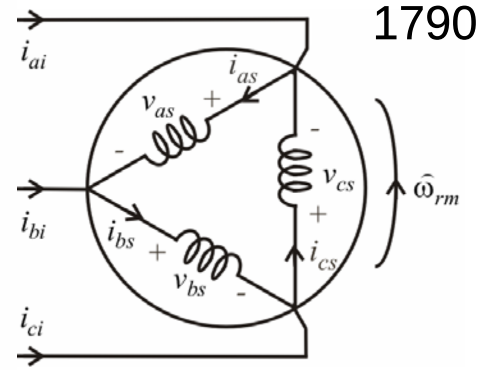
	f	E_{fz}	$E_k \leq 5\%$
μ	7.834	0.0628	69.70
σ	0.0955	0.00045	1.253

	E_{ssfr}^{5A}	E_{ssfr}^{10A}	E_{ssfr}^{15A}	E_{ssfr}^{22A}
μ	0.1003	0.0358	0.0355	0.0841
σ	0.00178	0.00173	0.00146	0.00642

Validation I–Time domain simulation







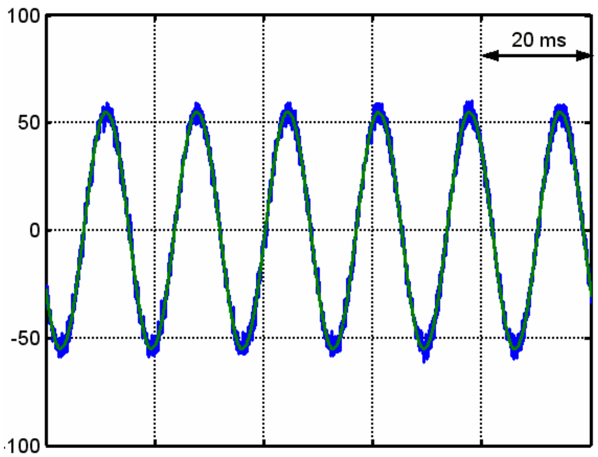
1790 rpm

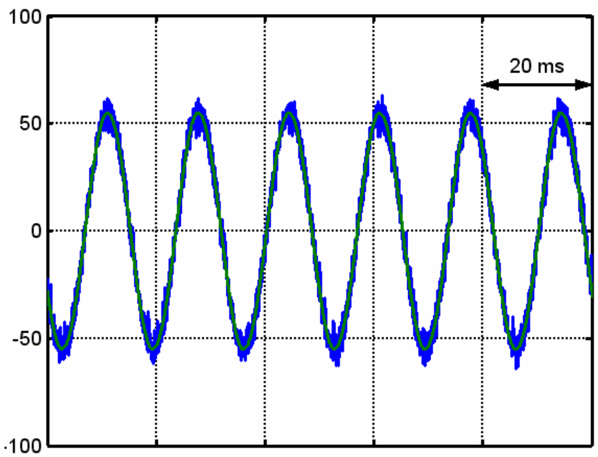
- Comparison of c-phase current ripple
- Measurement of c-phase current
  - ✓ IM was driven at a speed of 1790 rpm
  - ✓ $i_{qi}^{e*} = 55A$ and $\omega_s^* = 2.09$ rad/sec
- Use of Oscilloscope with 20*u* sec data acquisition sampling time

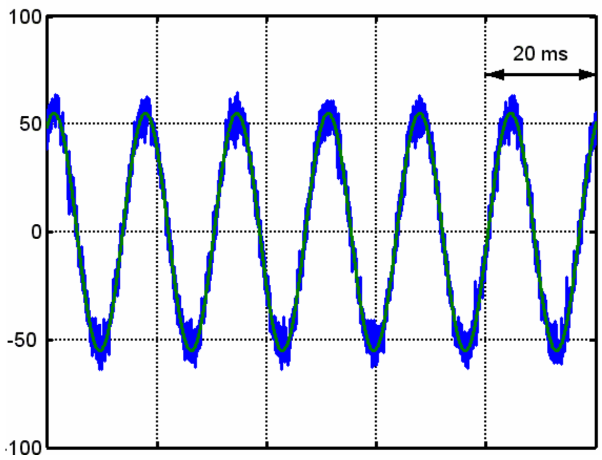
Validation I–Time domain simulation

- C-phase current waveform and its ripple

➢ AQDM with $\theta = \theta_{fz}$ ➢ AQDM with $\theta = \theta_{fz/ssfr}$ ➢ Measured







Validation I–Time domain simulation

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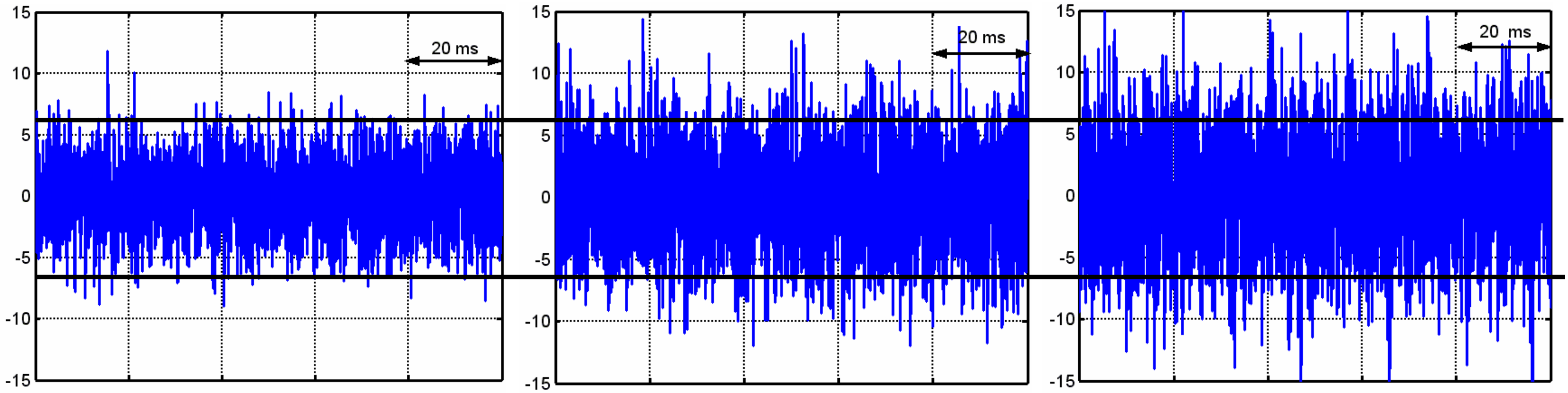
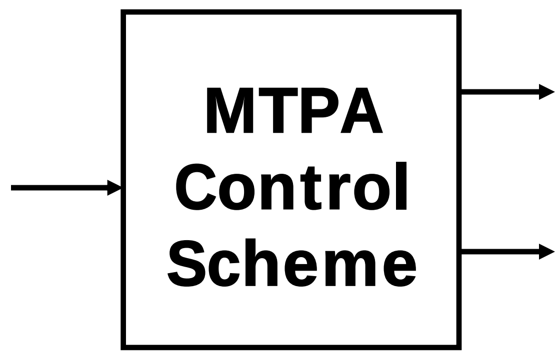


Validation II – Application to MTPA

- Structure



- Goal
  - (Tracking)
  - (MTPA condition)

MTPA Control based AQDM

- Derivation

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{dm}^{e} i_{qs}^{e} - \lambda_{qm}^{e} i_{ds}^{e}\right)$$

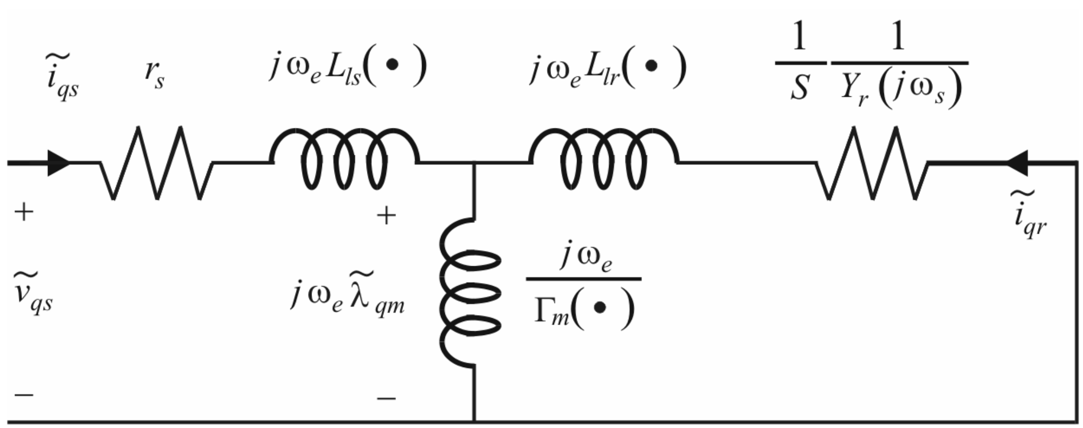
MTPA Control based AQDM

- Derivation (cont)

$$T_e\left(I_s,\omega_s\right)=\frac{3}{2}P\cdot\mathrm{Im}\left(\overline{\left(\frac{Z_{ag}\left(\lambda_m,\omega_s\right)}{j\omega_e}\cdot I_s\right)}\cdot I_s\right)$$

MTPA Control based AQDM

- How to calculate λ_m
  - ➢ Newton-Raphson method



MTPA Control based AQDM

- Find optimal ω_s^* for a given I_s and λ_m
  - Optimal technique - Newton method

MTPA Control based AQDM

- Newton Method (cont)

$$T_e\left(I_s,\omega_s\right)=\frac{3}{2}P\cdot\mathrm{Im}\left(\overline{\left(\frac{Z_{ag}\left(\lambda_m,\omega_s\right)}{j\omega_e}\cdot I_s\right)}\cdot I_s\right)$$

MTPA Control based AQDM

- Maximum Torque for given I_s

$$T_{e,\max} = \max_{\omega_s} T_e\left(\omega_s, I_s\right)$$

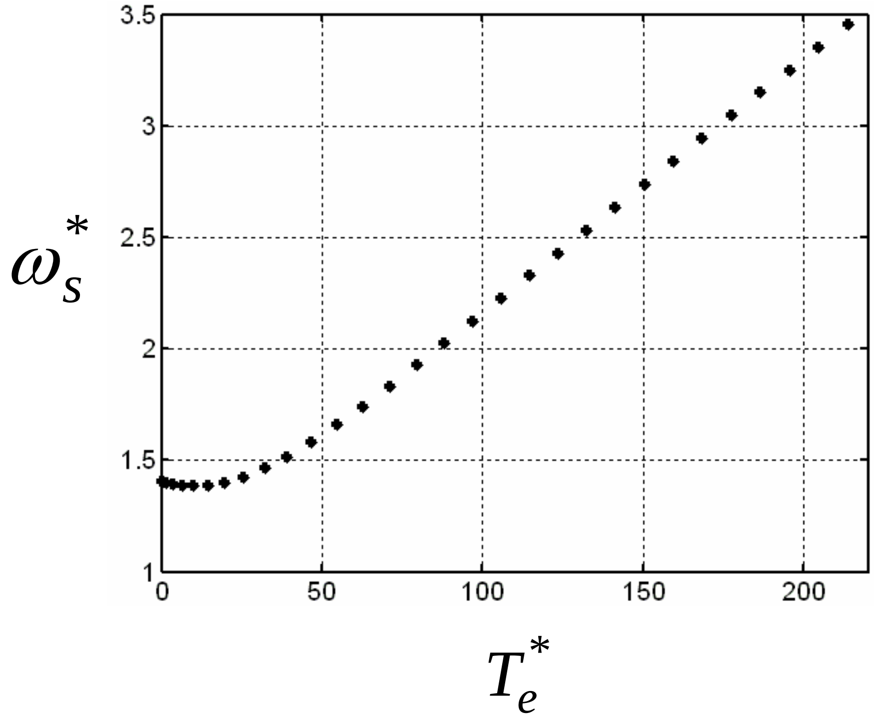
fixed

$T_{e,1}$	$\omega_{s,1}$	$I_{s,1}$	0A
$\vdots$	$\vdots$	$\vdots$	
$T_{e,j}$	$\omega_{s,j}$	$I_{s,j}$	
$\vdots$	$\vdots$	$\vdots$	
T_{e,N_J}	ω_{s,N_J}	I_{s,N_J}	$I_{s,rat}$

MTPA Control based AQDM

- Curve Fitting

$I_s^* \text{ vs } T_e^*$



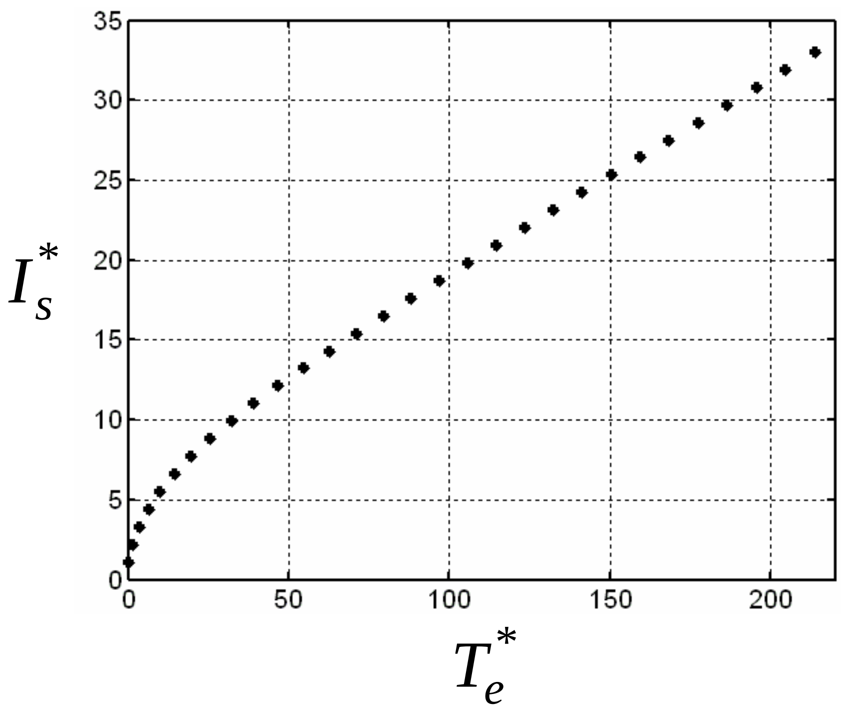
$$I_s^* = a_1 \cdot T_e^* + a_2 \cdot T_e^{*b_1} + a_3 \cdot T_e^{*b_2}$$

$$\theta = \{a_1 \quad a_2 \quad a_3 \quad b_1 \quad b_2\}$$

MTPA Control based AQDM

- Curve Fitting

ω_s^* vs T_e^*



$$\omega_s^* = c_0 + c_1 \cdot T_e^* + c_2 \cdot T_e^{*2} + c_3 \cdot T_e^{*3} + c_4 \cdot T_e^{*4}$$

$$\theta = \left\{ c_1 \quad c_2 \quad c_3 \quad c_4 \quad c_5 \right\}$$

Validation II–MTPA design

- AQDM with $\theta = \theta_{fz}$

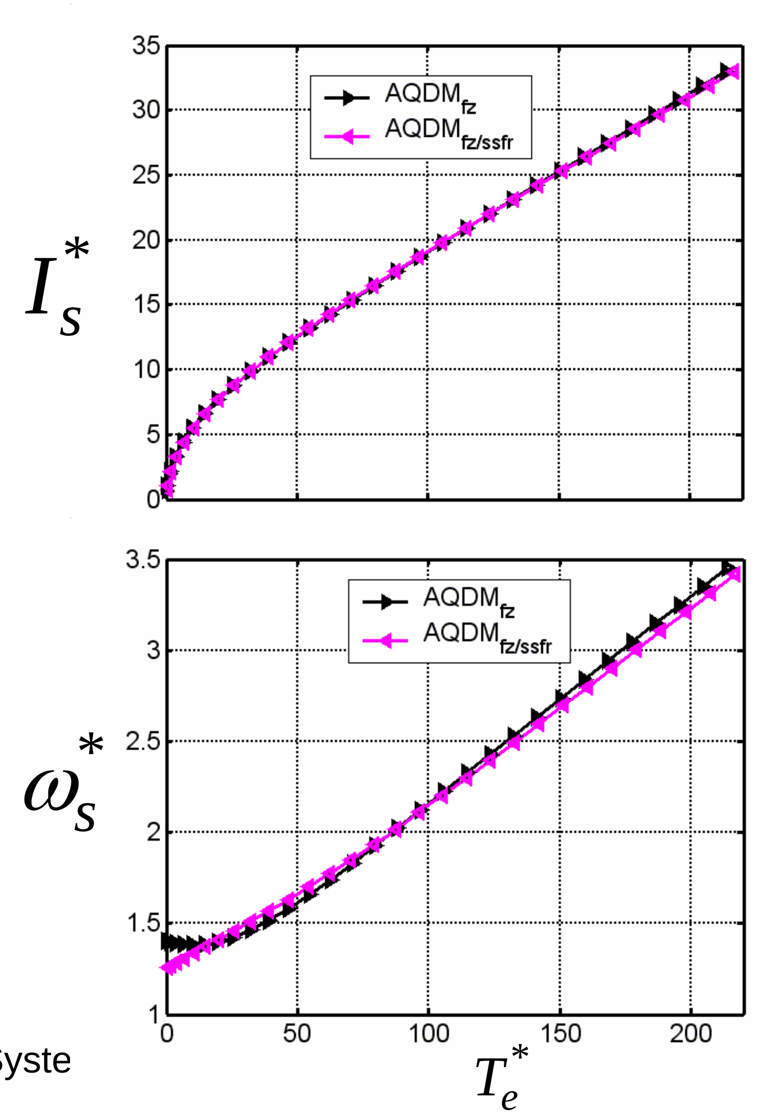
$$I_s^*\left(T_e^*\right) = 0.109 \cdot T_e^* - 17.0 \cdot T_e^{*0.0177} + 18.5 \cdot T_e^{*0.0799}$$

$$\omega_s^*\left(T_e^*\right) = 1.4 - 2.4 \cdot 10^{-3} T_e^* + 176 \cdot 10^{-6} T_e^{*2} - 933 \cdot 10^{-9} T_e^{*3} + 1.74 \cdot 10^{-9} T_e^{*4}$$

- AQDM with $\theta = \theta_{fz/ssfr}$

$$I_s^*\left(T_e^*\right) = 0.102 \cdot T_e^* - 6.41 \cdot T_e^{*0.0110} + 7.79 \cdot T_e^{*0.152}$$

$$\omega_s^*\left(T_e^*\right) = 1.3 + 7 \cdot 10^{-3} T_e^* + 25.7 \cdot 10^{-6} T_e^{*2} - 63.1 \cdot 10^{-9} T_e^{*3} + 42.1 \cdot 10^{-12} T_e^{*4}$$

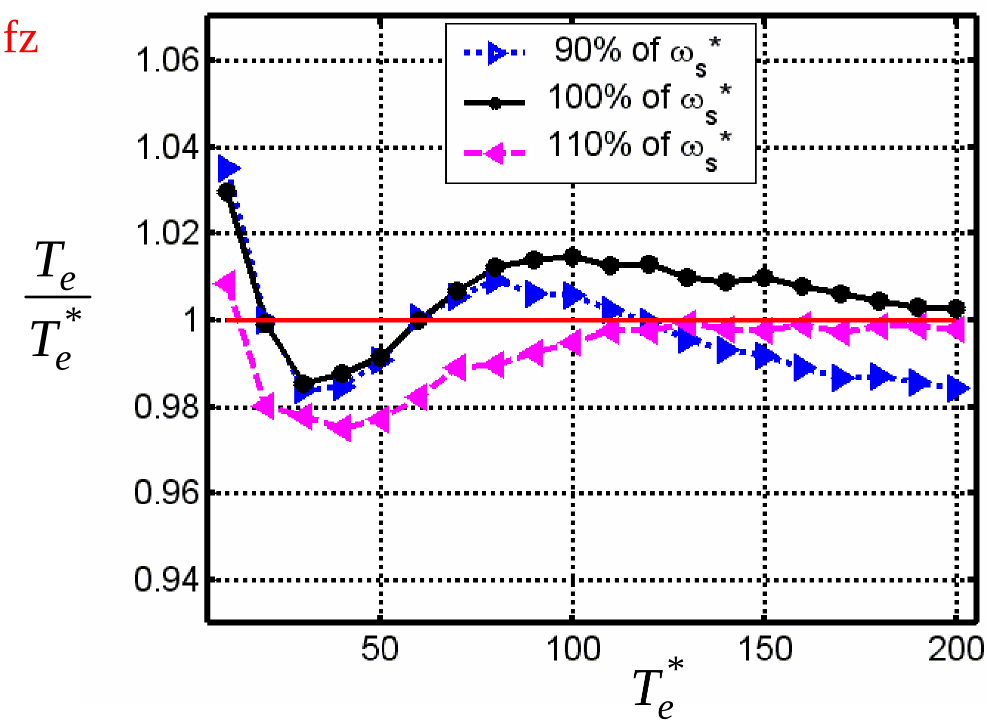


Validation II–MTPA design

- Question?
  - How to show that MTPA condition is met at ω_s^*

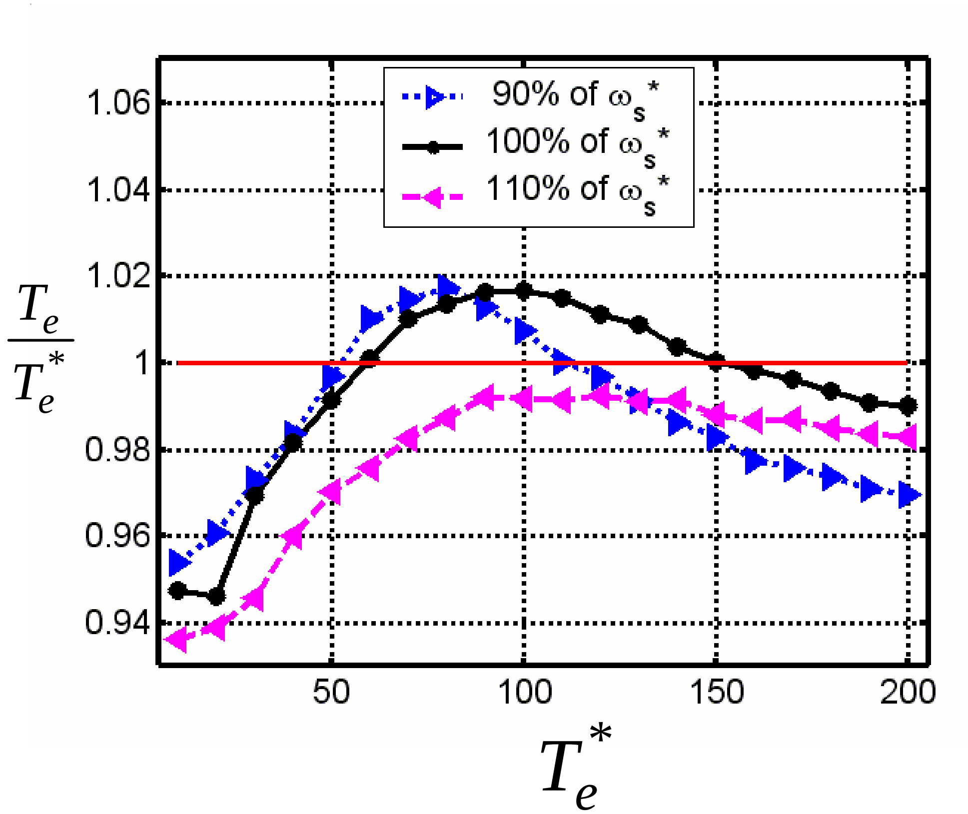
Validation II–MTPA design

- Measured torque achieved in open loop torque mode using AQDM based MTPA control strategy
  - AQDM with $\boldsymbol{\theta = \theta_{fz}}$



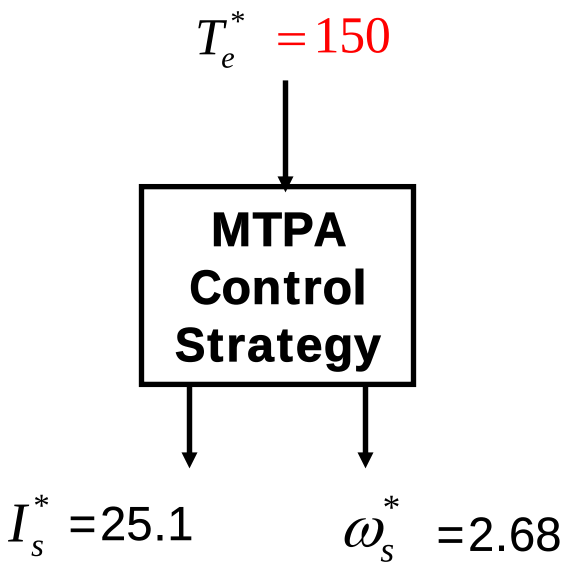
Validation II–MTPA design

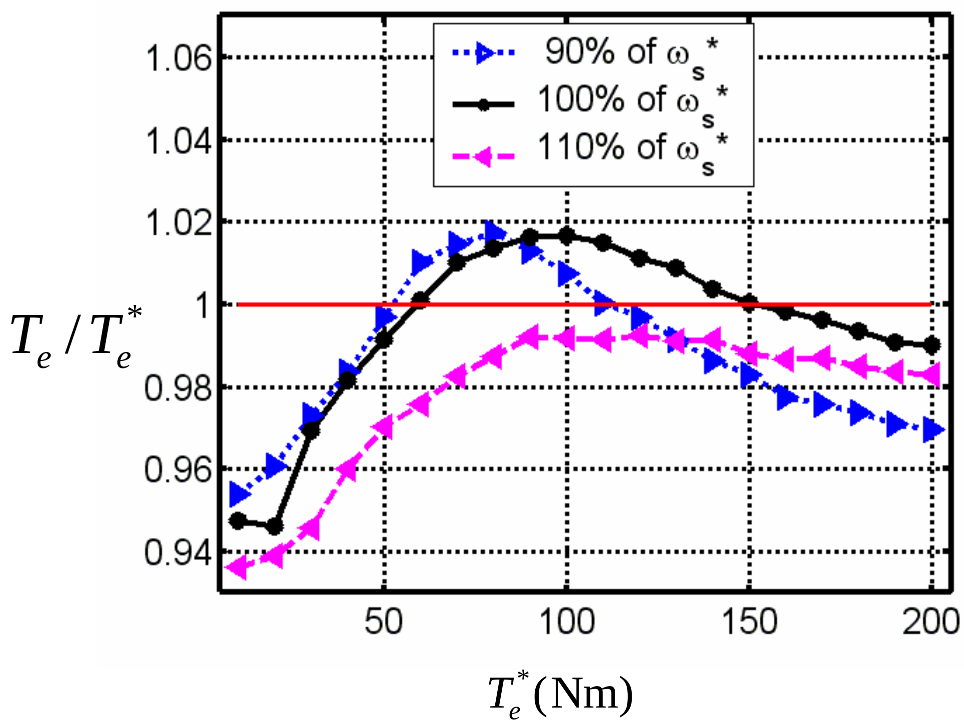
➢ AQDM with $\boldsymbol{\theta} = \boldsymbol{\theta}_{fz/ssfr}$



MTPA performance at a temperature

- Torque achieved by MTPA in open loop torque mode at the temperature $T_s(^\circ C)$ when IM was characterized



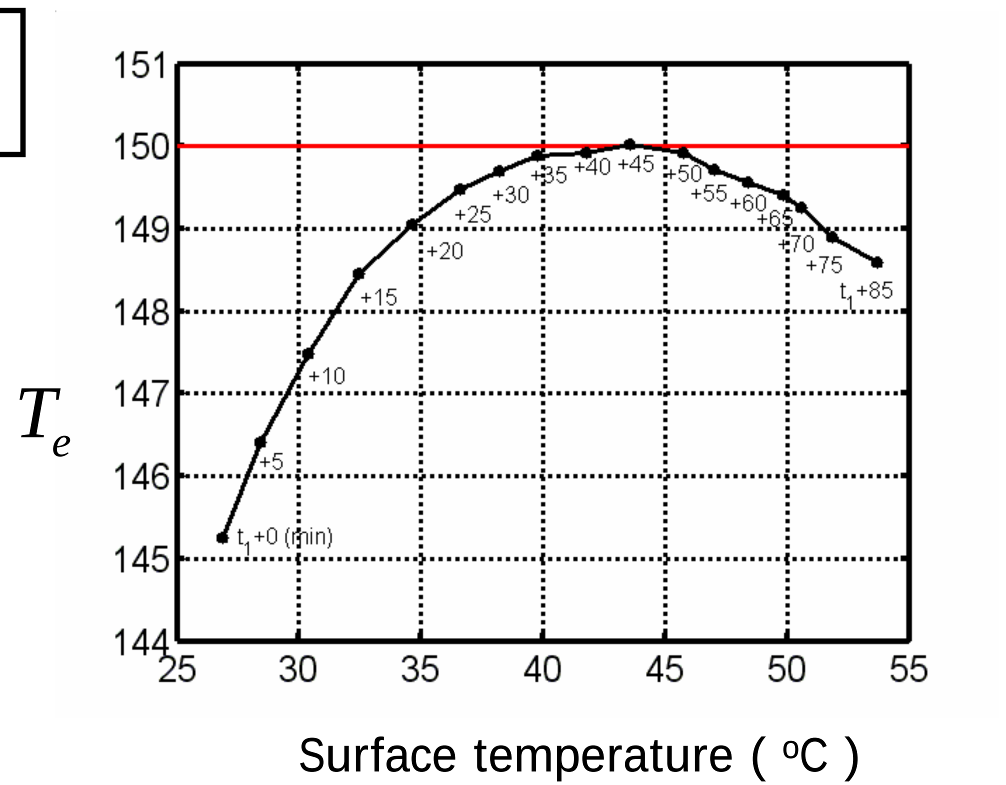


Thermal Effect on MTPA performance

- Torque achieved by MTPA in open loop torque mode

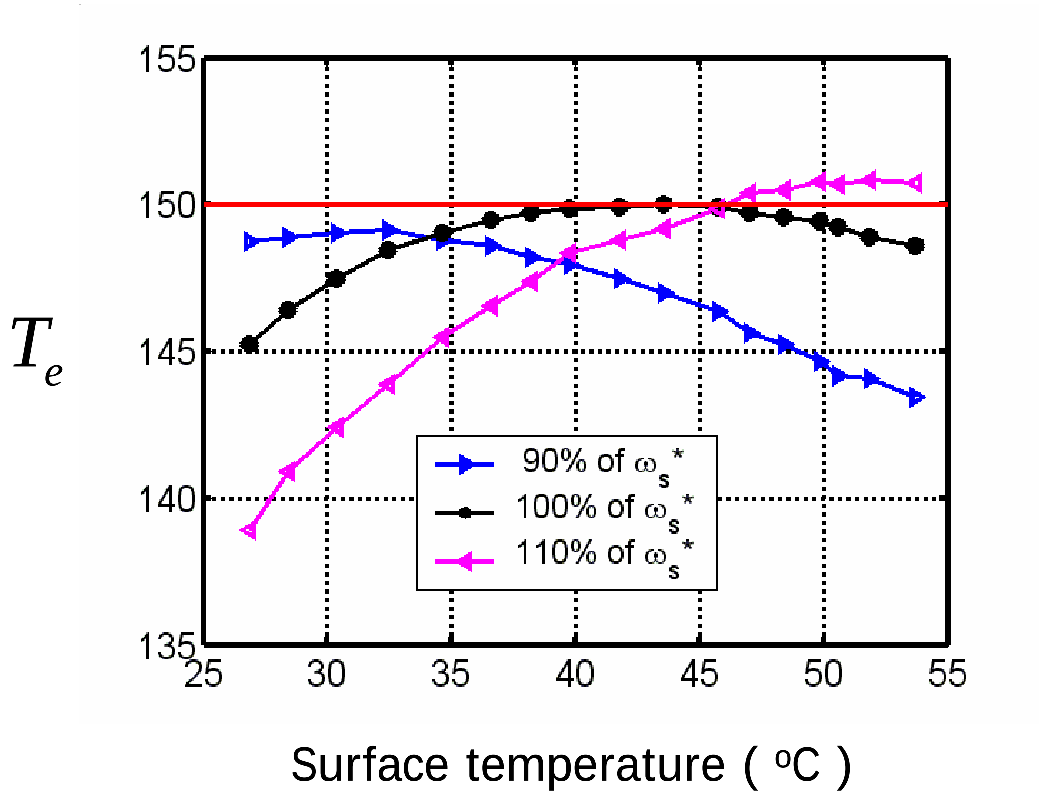
$I_s^* = 25.1$ $\omega_s^* = 2.68$

- Torque at w_s^*



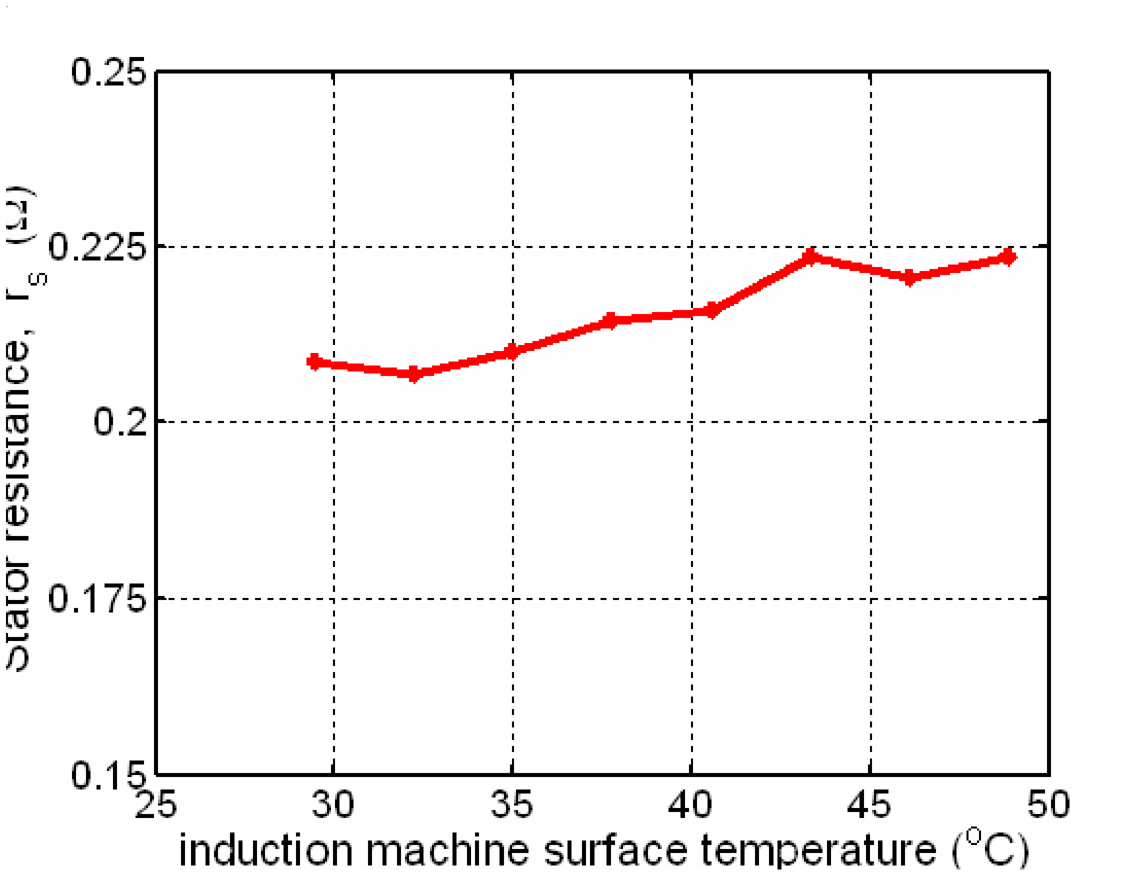
Thermal Effect on MTPA performance

- Torque at 3 different ω_s^*



Variation of stator resistance

- Off-line Multi meter measurement



Variation of stator resistance

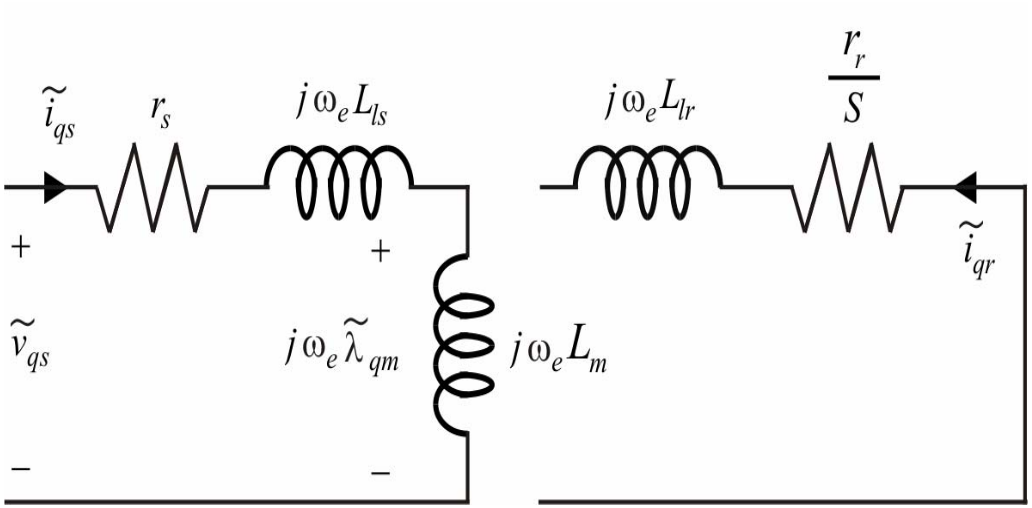
- No dependence of MTPA control on stator resistance

$$T_e\left(I_s,\omega_s\right)=\frac{3}{2}P\cdot\mathrm{Im}\left(\overline{\left(\frac{Z_{ag}\left(\lambda_m,\omega_s\right)}{j\omega_e}\cdot I_s\right)}\cdot I_s\right)$$

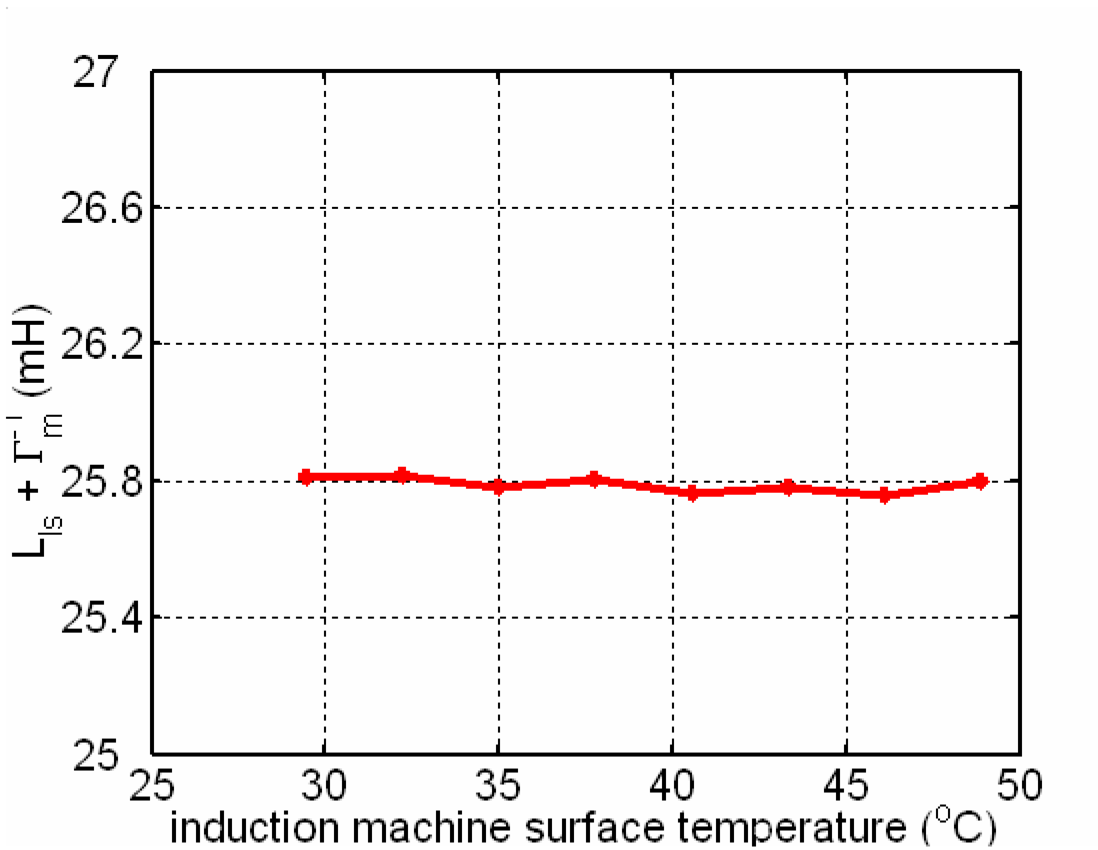
$$\begin{cases} Z_{ag}=\dfrac{\omega_e}{-j\Gamma_m\left(\lambda_m\right)+\dfrac{\omega_s}{j\omega_s L_{lr}\left(\lambda_m\right)+\dfrac{1}{Y_r\left(j\omega_s\right)}}} \\ \text{Newton-Raphson methond} \\ \left|\omega_e\lambda_m\right|=\sqrt{2}\cdot\left|I_s\cdot Z_{ag}\left(\lambda_m,\omega_s\right)\right| \end{cases}$$

Variation of inductance

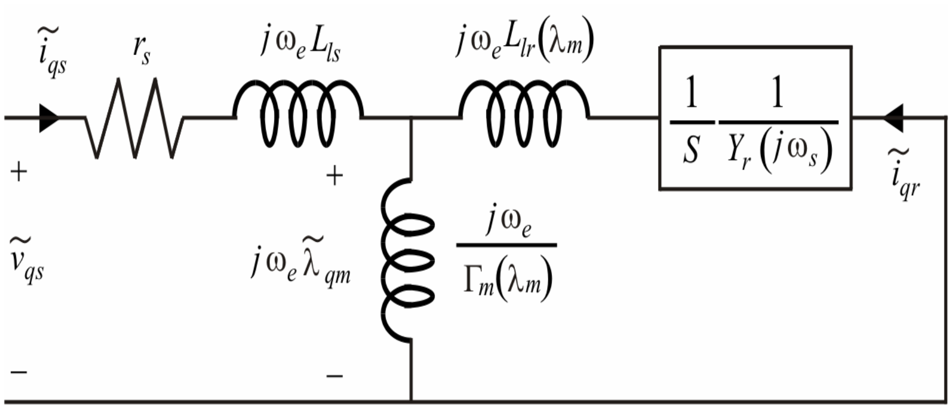
- No load test ：



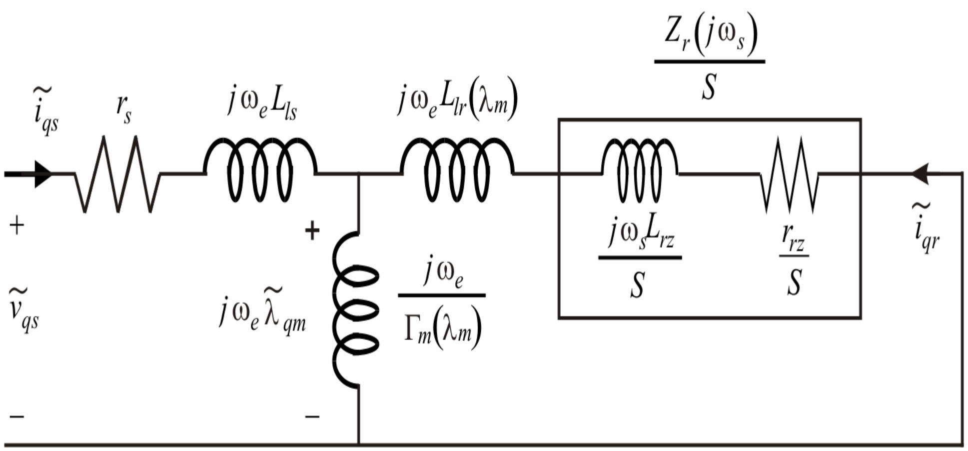
Variation of inductance



AQDM with $r_r(j\omega_s)$ in explicit form



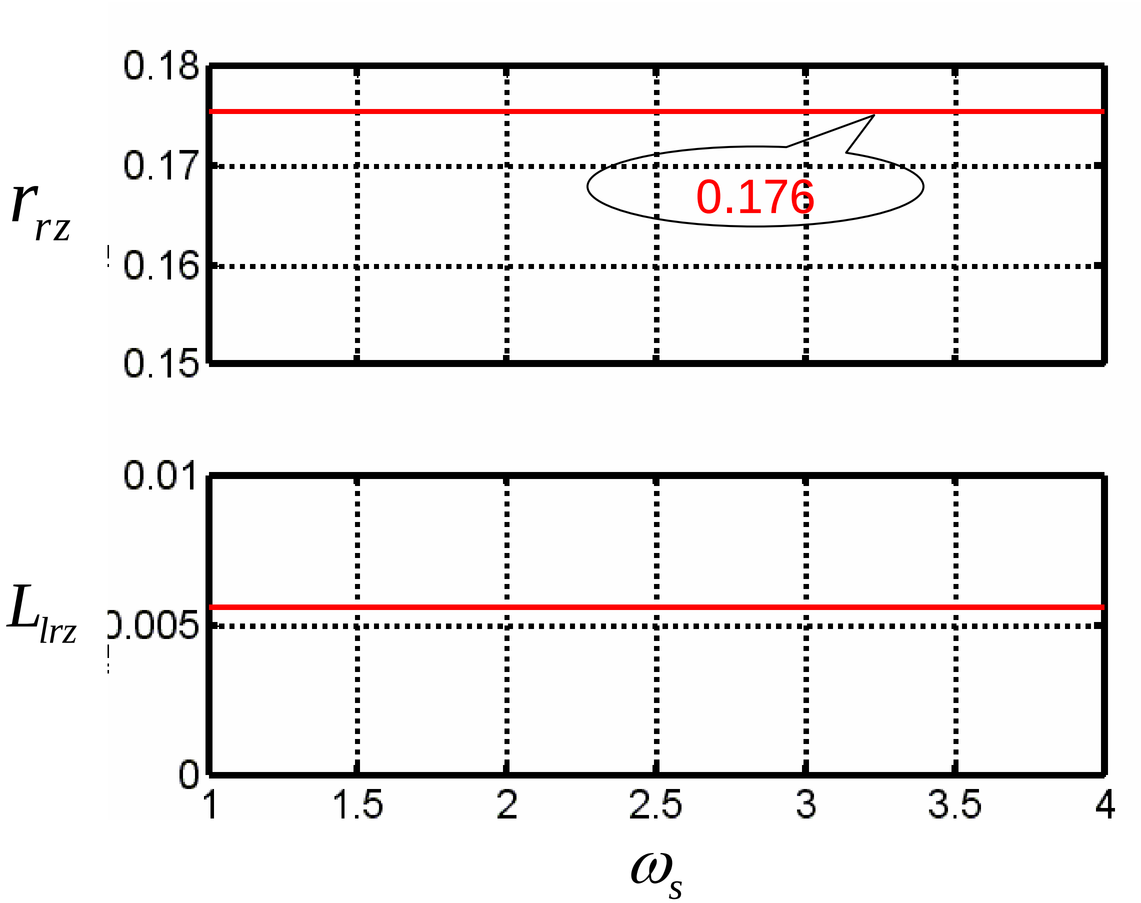
Steady-state equivalent circuit



$$
\begin{cases}
Z_r(j\omega_s) = r_{rz}(j\omega_s) + j\omega_s L_{lrz}(j\omega_s) \\
r_{rz}(j\omega_s) = \mathrm{Re}(Z_r(j\omega_s)) \\
L_{lrz}(j\omega_s) = \dfrac{1}{\omega_s}\mathrm{Im}(Z_r(j\omega_s))
\end{cases}
$$

Justification of r_r in AQDM for MTPA design

r_{rz} from 1 to 4 rad/sec of ω_s at $T_s(^\circ C)$



$$Z_r(j\omega_s) = r_{rz}(j\omega_s) + j\omega_s L_{lrz}(j\omega_s)$$

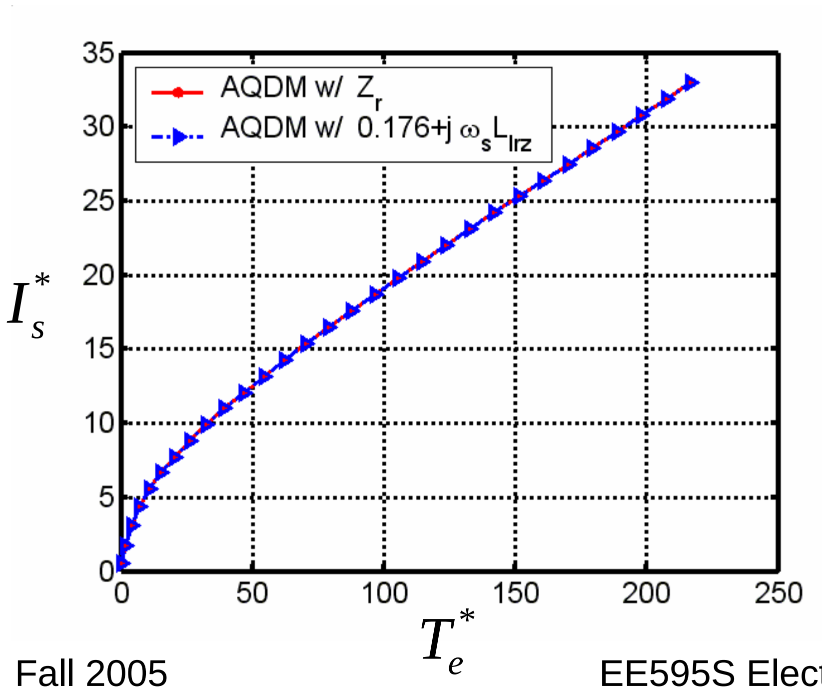
$$Z_r(j\omega_s) = r_{rz} + j\omega_s L_{lrz}(j\omega_s)$$

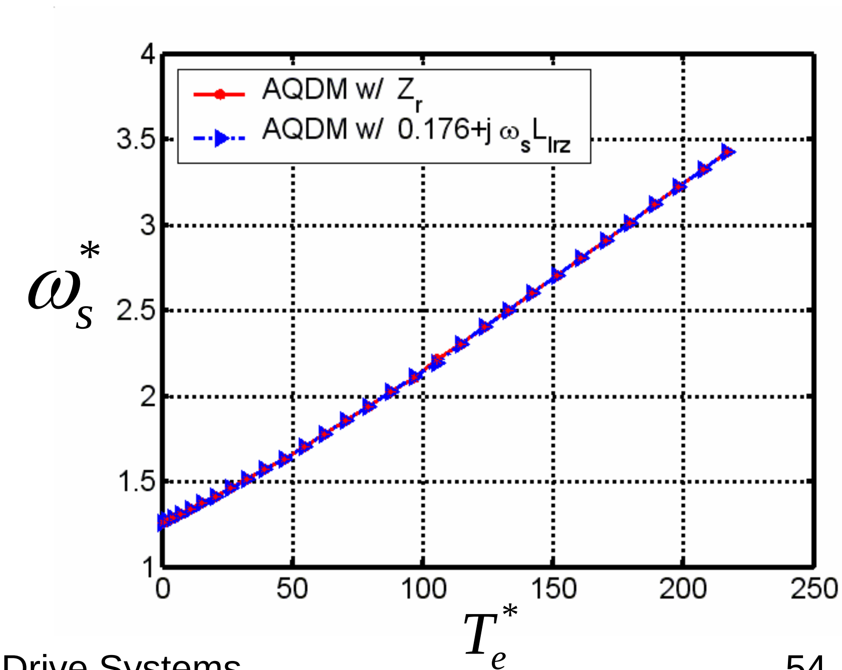
Comparison between MTPA laws

- MTPA law based on AQDM with

$$Z_r \begin{cases} \triangleright\ r_{rz}(j\omega_s) + j\omega_s L_{lrz} \\ \triangleright\ r_{rz} \qquad + j\omega_s L_{lrz} \end{cases}$$

$$r_{rz} = 0.176 \text{ at } T_s(^\circ C)$$



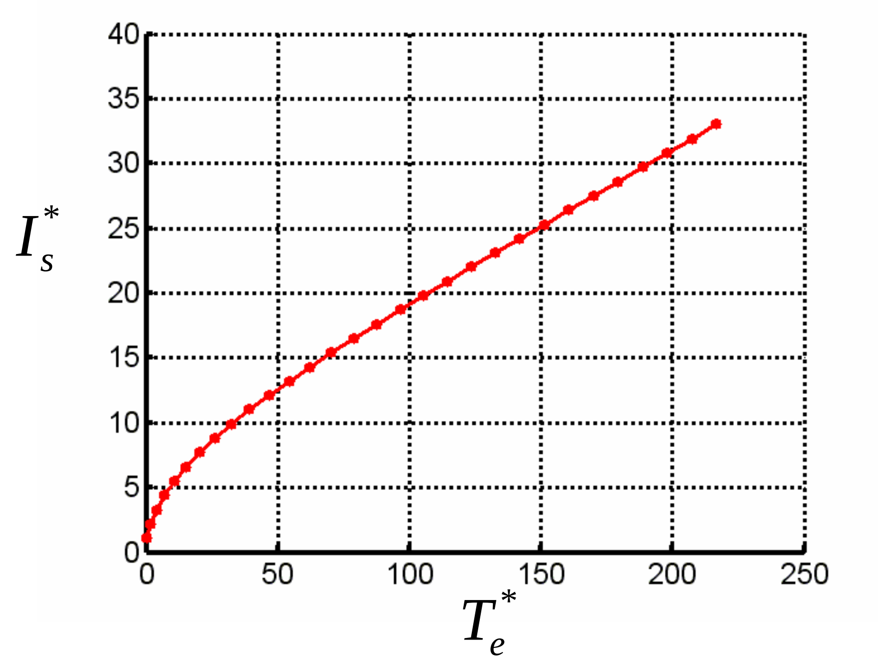


Influence of r_r on MTPA control law

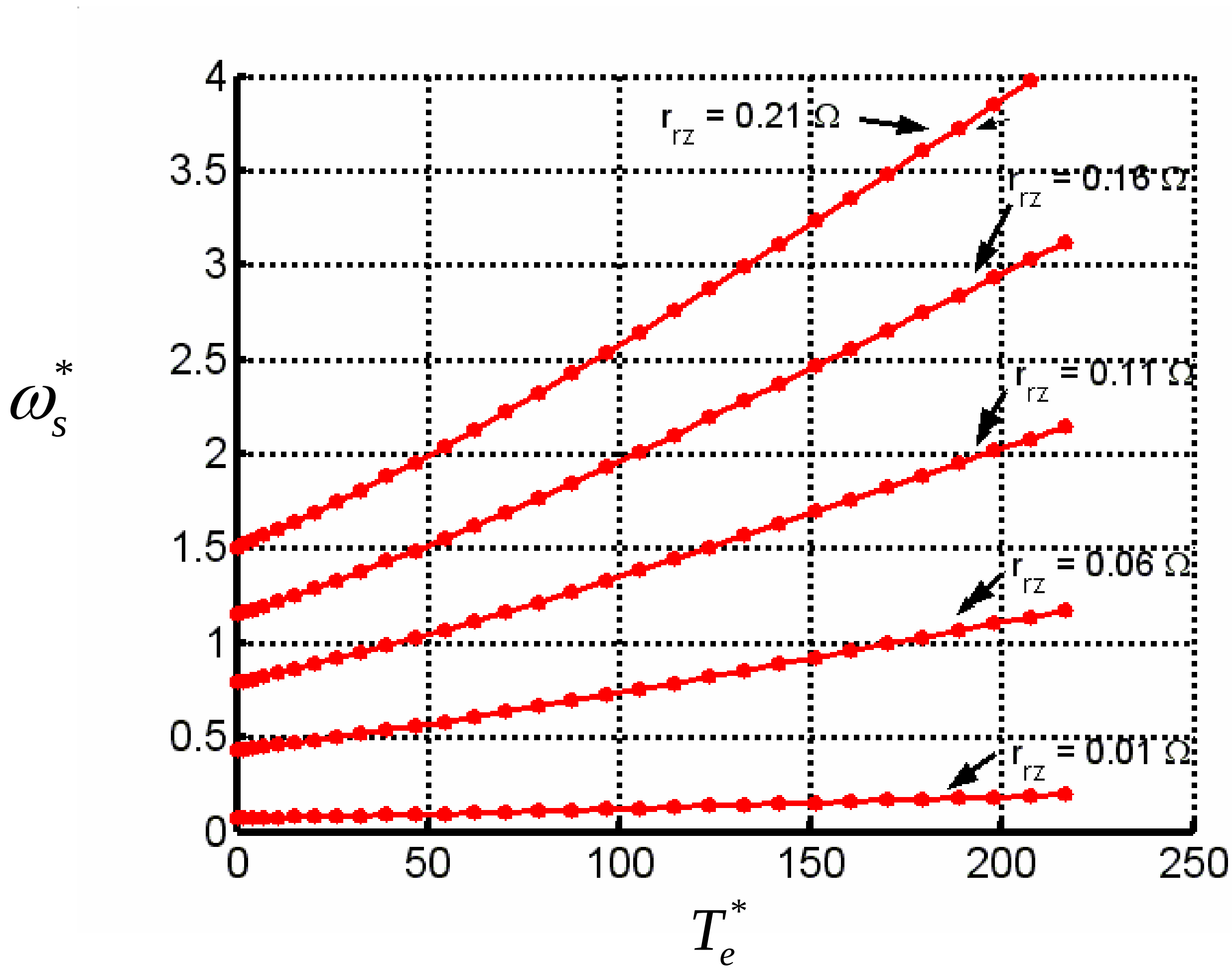
- MTPA control laws based on AQDM with

$$Z_r(j\omega_s) = r_{rz} + j\omega_s L_{lrz}(j\omega_s)$$

where r_{rz} vary from 0.01Ω to 0.21Ω in 5 steps

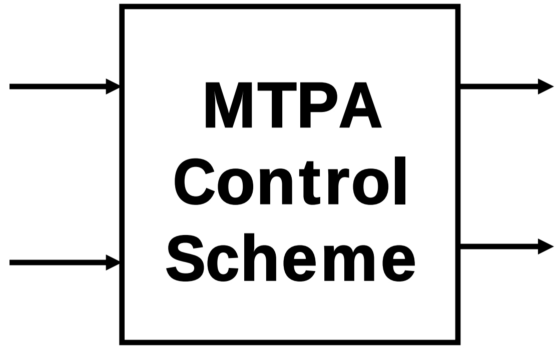


Influence of r_r on MTPA control law



AMTPA control strategy

- Structure



- Goal
  - (Tracking)
  - (MTPA condition)

AMTPA control strategy

$$T_e\left(I_s,\omega_s,\hat{r}_r\right)=\frac{3}{2}P\cdot\mathrm{Imag}\left(\overline{\left(\frac{Z_{ag}\left(\lambda_m,\omega_s,\hat{r}_r\right)}{j\omega_e}I_s\right)}I_s\right)$$

- Maximum Torque for a given $I_s,\ r_r$

$$T_{e,\max}=\max_{\omega_s}\left\{T_e\left(\omega_s,\left(I_s,\hat{r}_r\right)\right)\right\}$$

T_e ω_s I_s r_r (fixed)

AMTPA control strategy

- Maximum Torque for a given $I_{s,}$ r_{rz}

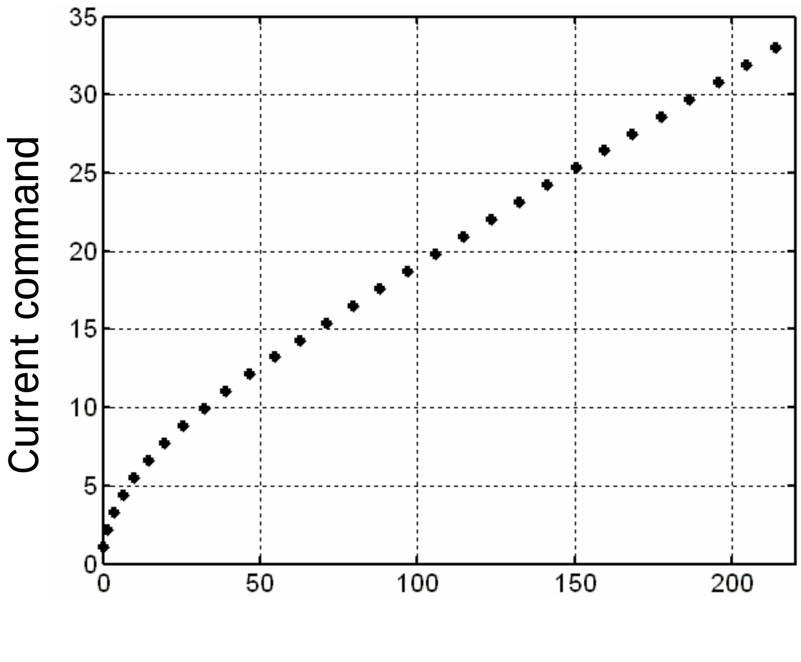
$$T_{e,\max} = \max_{\omega_s} T_e\left(\omega_s, I_s, r_{rz}\right)$$

fixed

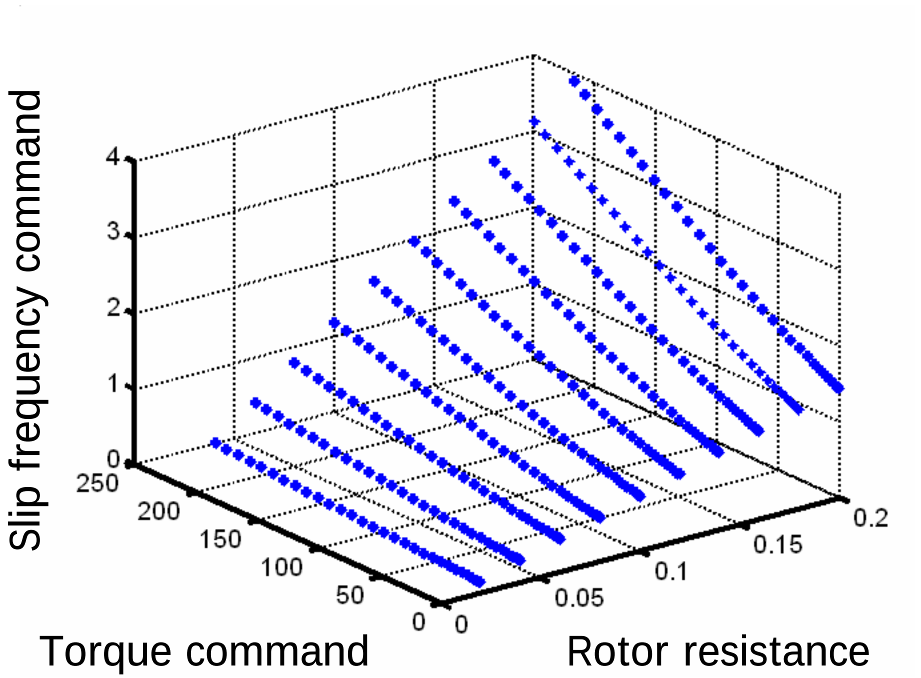
$T_{e,1,1}$	$\omega_{e,1,1}$	0A	$I_{s,1}$	$r_{rz,1}$	0.01Ω
$\vdots$	$\vdots$		$\vdots$	$\vdots$	
$T_{e,j,k}$	$\omega_{e,j,k}$		$I_{s,j}$	$r_{rz,k}$	
$\vdots$	$\vdots$		$\vdots$	$\vdots$	
T_{e,N_J,N_K}	ω_{e,N_J,N_K}	$I_{s,rat}$	I_{s,N_J}	r_{rz,N_K}	0.21Ω

AMTPA control strategy

I_s^* vs T_e^*

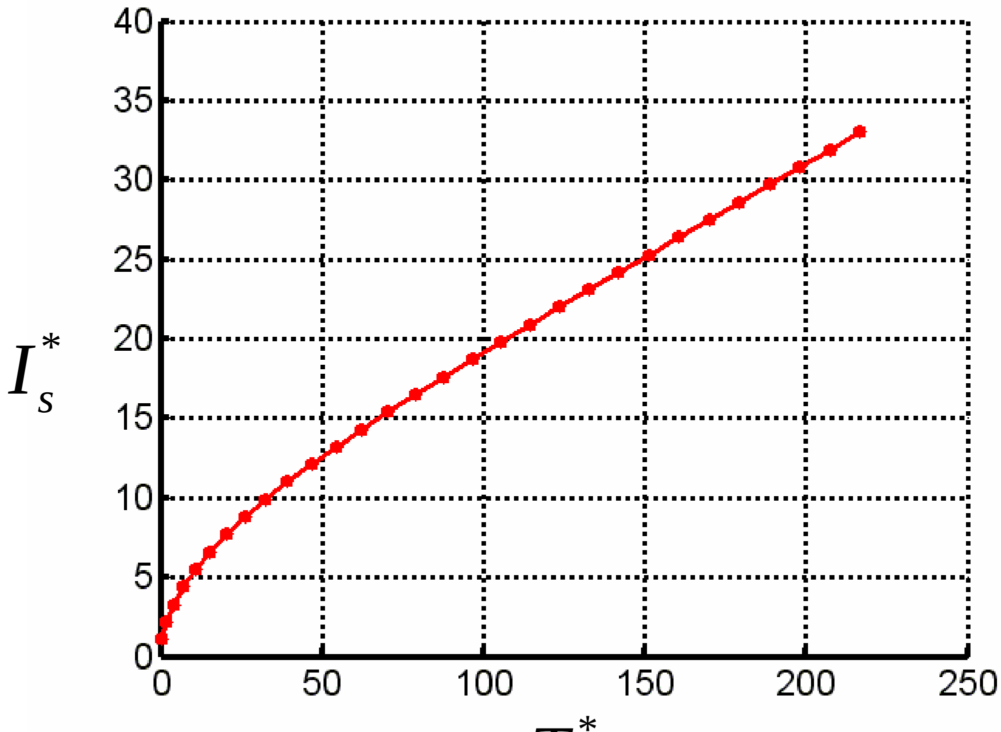


ω_s^* vs T_e^* and r_r



AMTPA control strategy

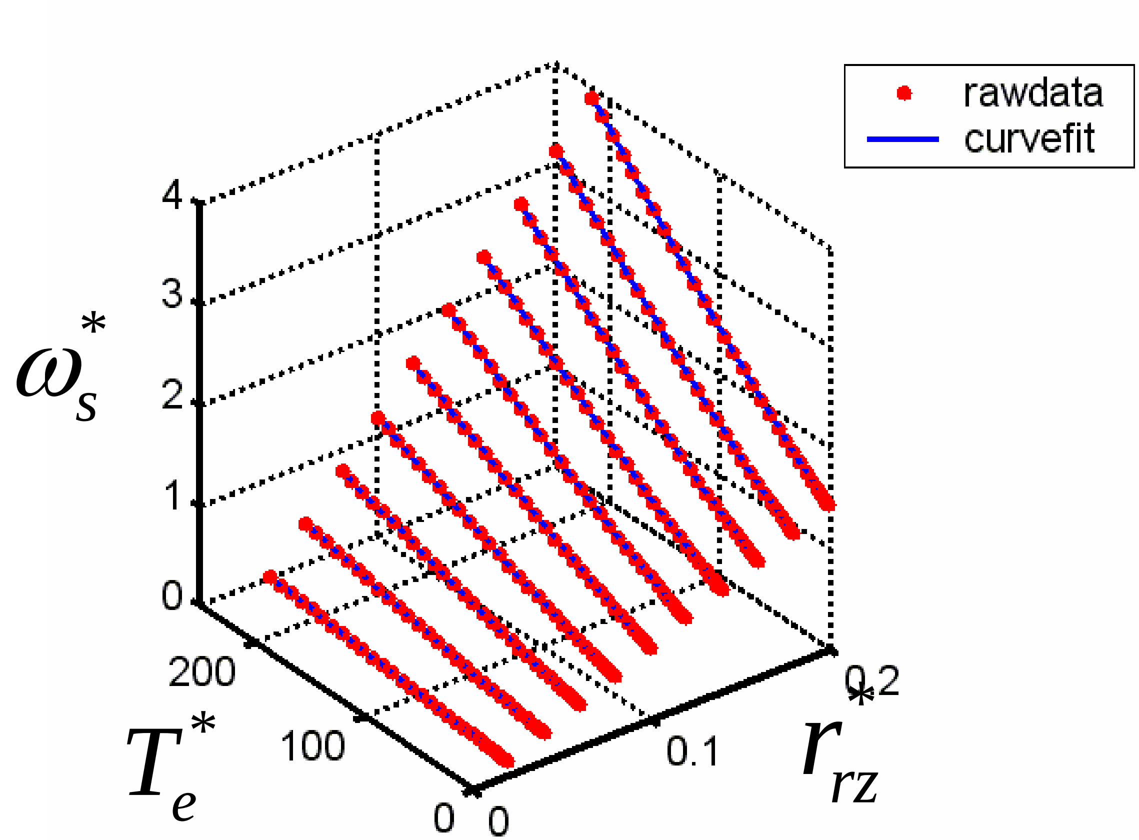
$$I_s^*\left(T_e^*\right) = 0.102 \cdot T_e^* - 6.41 \cdot T_e^{*\,0.0110} + 7.79 \cdot T_e^{*\,0.152}$$



T_e^*

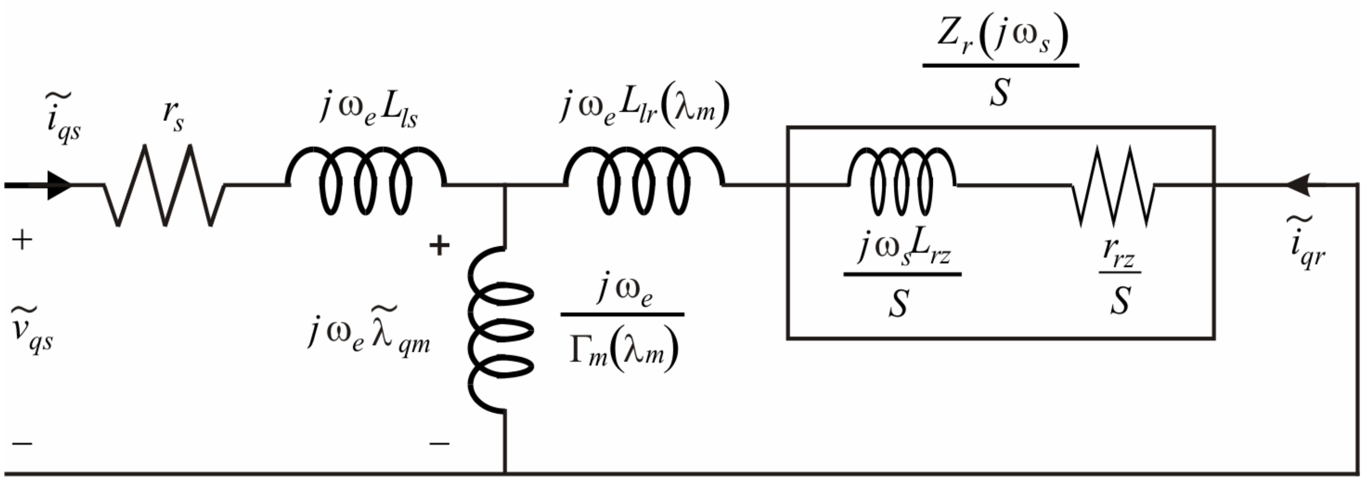
AMTPA control strategy

$$\omega_s^*\left(T_e^*, r_{rz}\right) = 7.22 \cdot r_{rz}^{\ 0.9998} + 0.025 \cdot r_{rz}^{\ 1.00} \cdot T_e^{*\,1.15}$$



AQDM based rr estimator

- Derivation

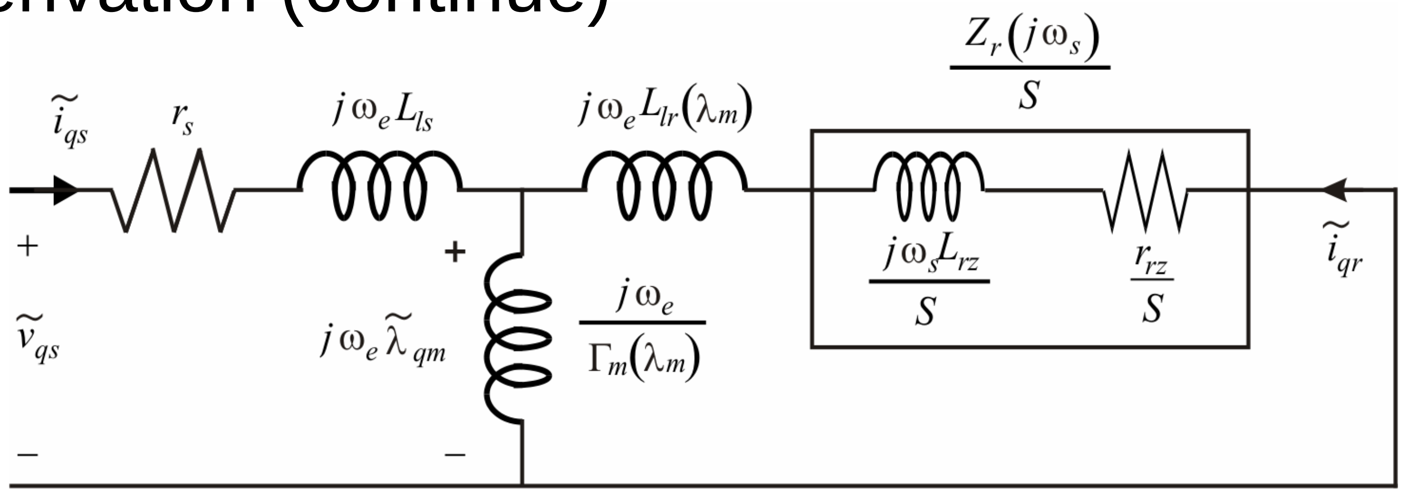


- Estimate of rotor resistance

AQDM based rr estimator

- Derivation (continue)

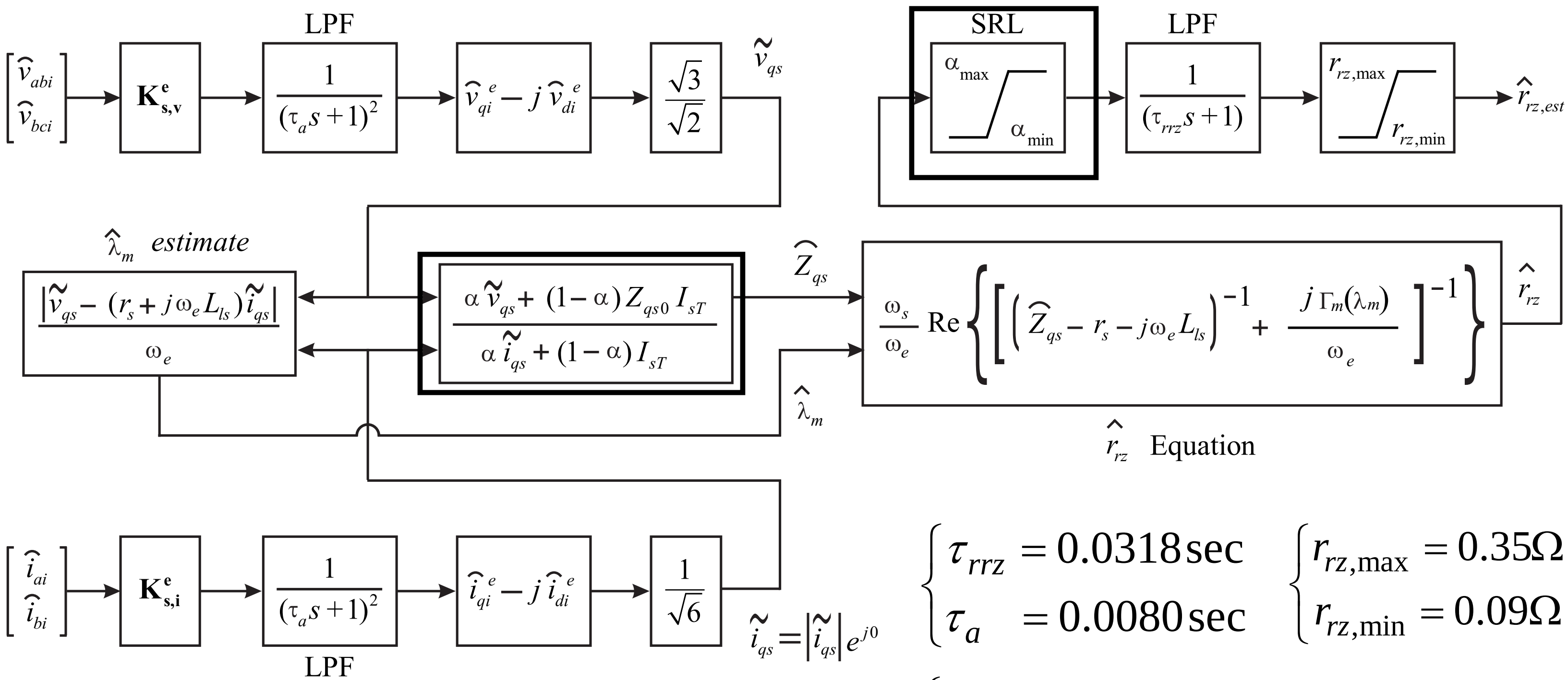
$\hat{Z}_{qs}$ ⇨



  - Estimate of rotor resistance

$$\hat{r}_{rz} = S \cdot \text{Re}\left\{ \qquad \right\}$$

AQDM based rr estimator



$$\begin{cases} \tau_{rrz} = 0.0318\,\text{sec} \\ \tau_a = 0.0080\,\text{sec} \end{cases} \qquad \begin{cases} r_{rz,\max} = 0.35\Omega \\ r_{rz,\min} = 0.09\Omega \end{cases}$$

$$\begin{cases} \alpha_{\max} = 0.005\Omega/\text{s} \\ \alpha_{\min} = -0.005\Omega/\text{s} \end{cases}$$

AQDM based rr estimator

- α

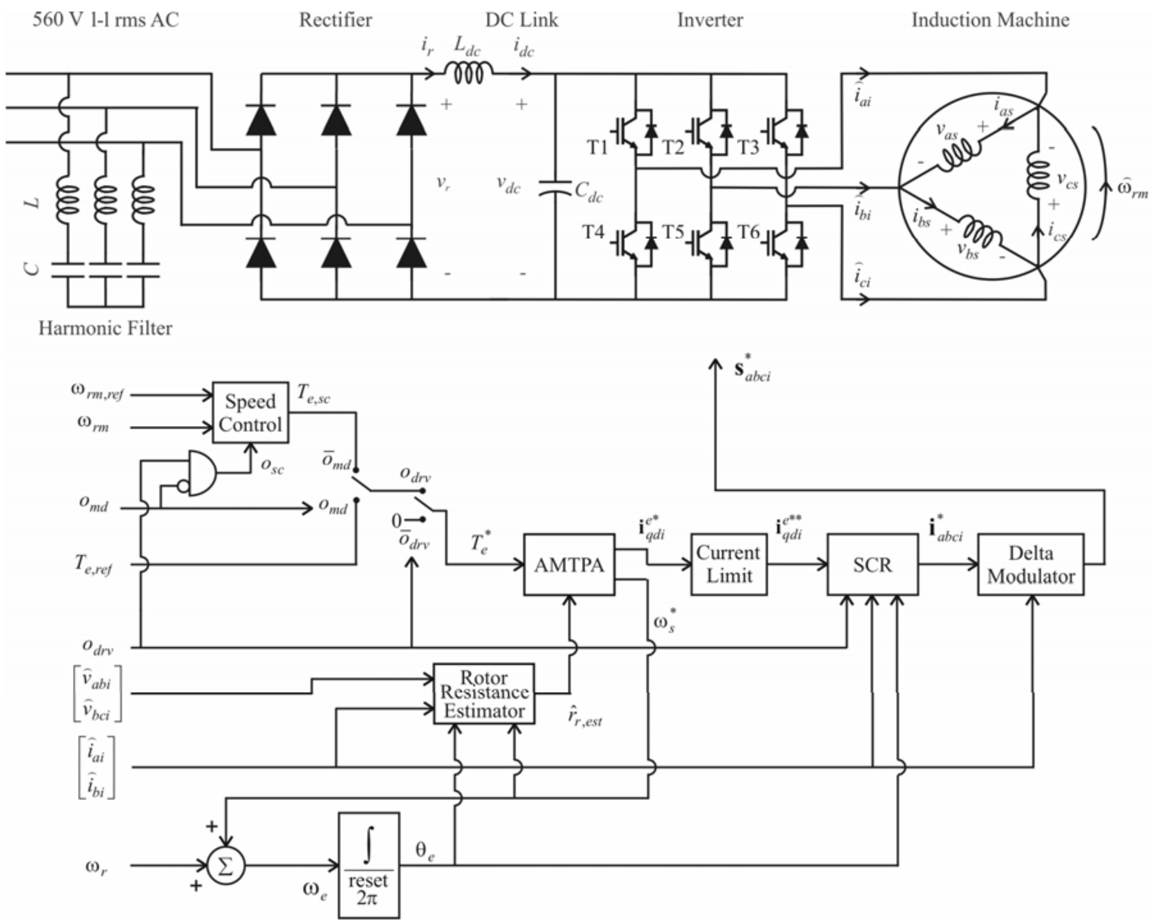
$$\alpha = \min(\alpha_v, \alpha_i)$$

where

$$\alpha_v = \begin{cases} 1 & if \quad |\tilde{v}_{qs}| = 0 \\ |\tilde{v}_{qs}| / V_{sT} & else \quad |\tilde{v}_{qs}| > V_{sT} \end{cases}$$

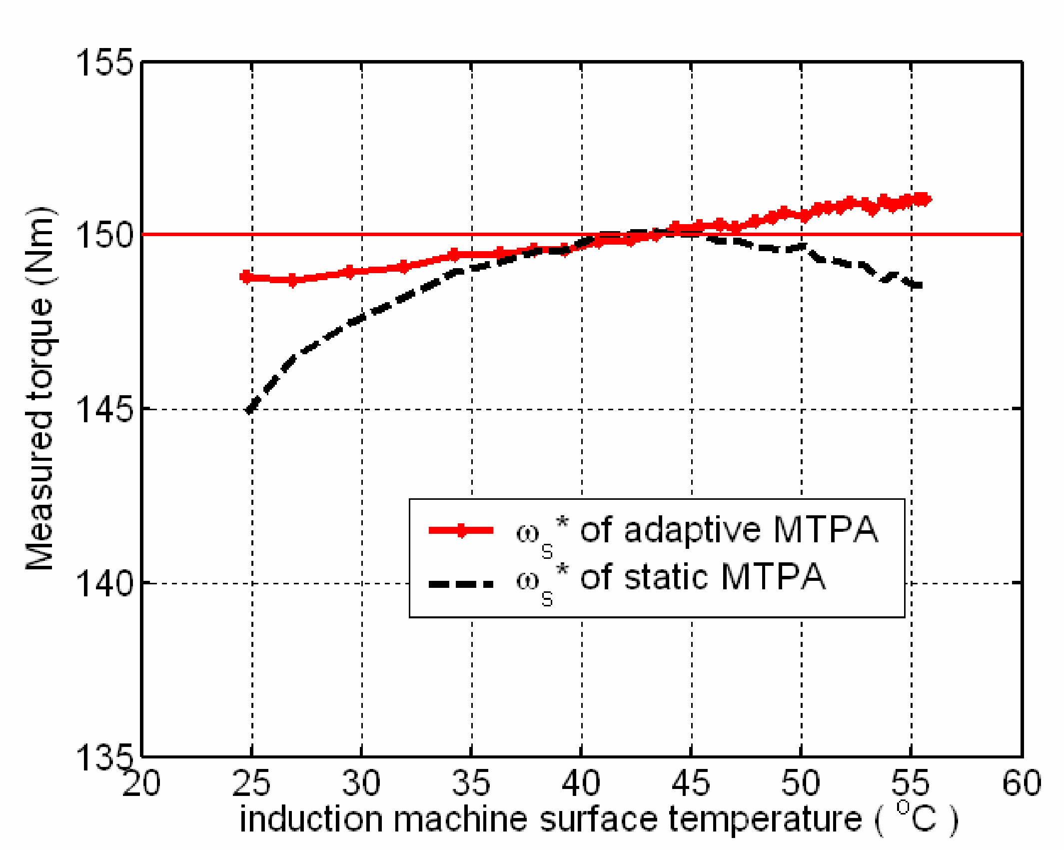
$$\alpha_i = \begin{cases} 1 & if \quad |\tilde{i}_{qs}| = 0 \\ |\tilde{i}_{qs}| / I_{sT} & else \quad |\tilde{i}_{qs}| > I_{sT} \end{cases}$$

Validation - AMTPA

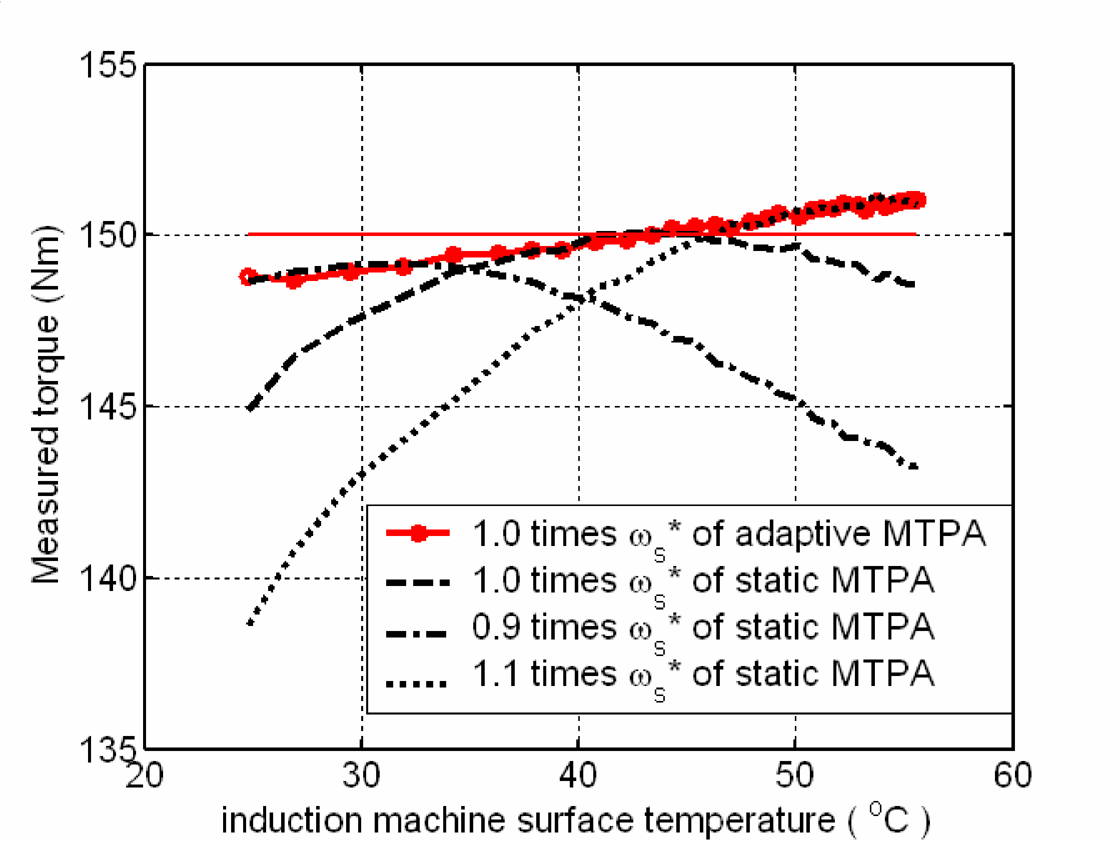


Validation - AMTPA

- One operating condition

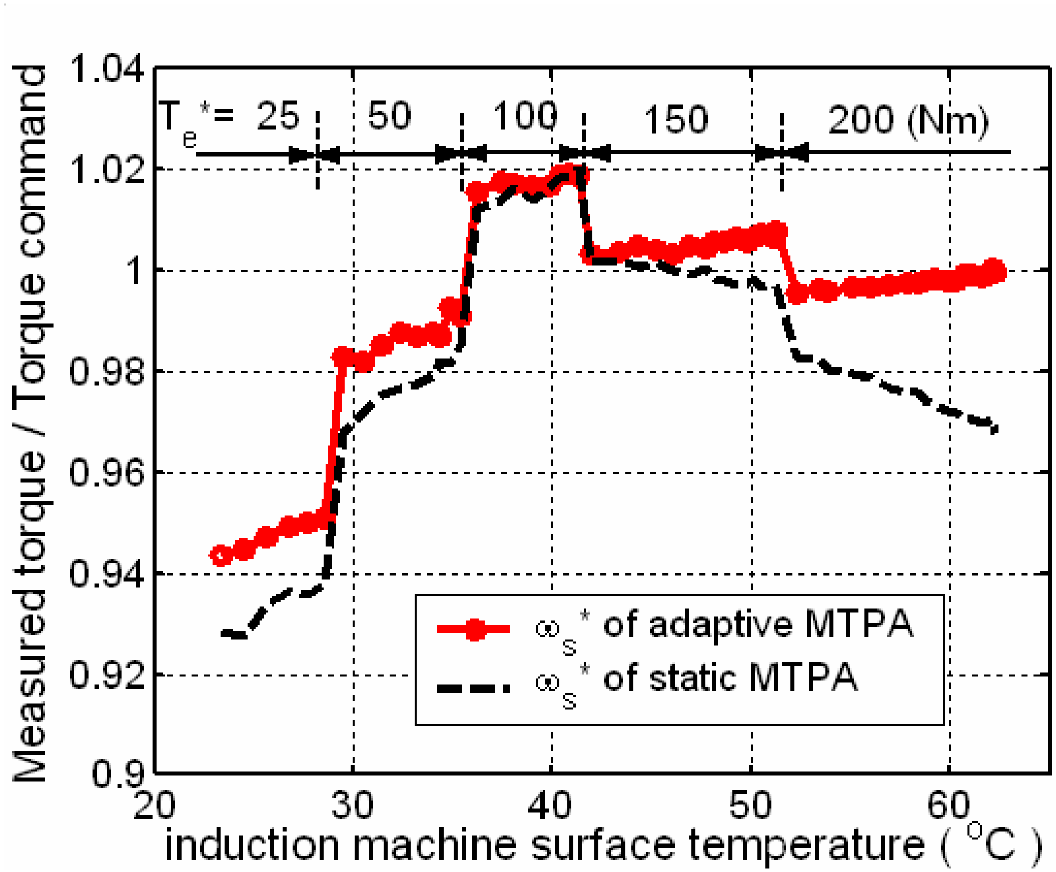


Validation - AMTPA

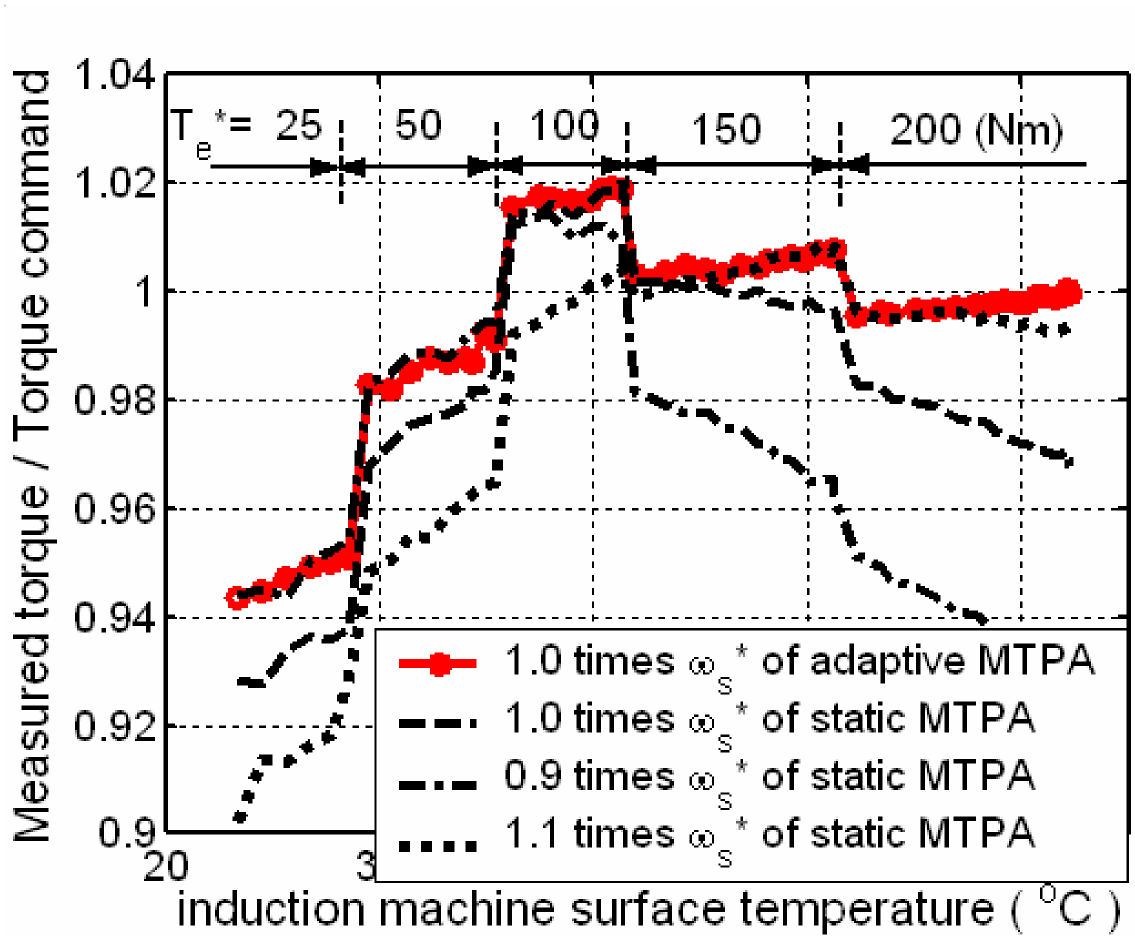


Validation - AMTPA

- Changing operating conditions

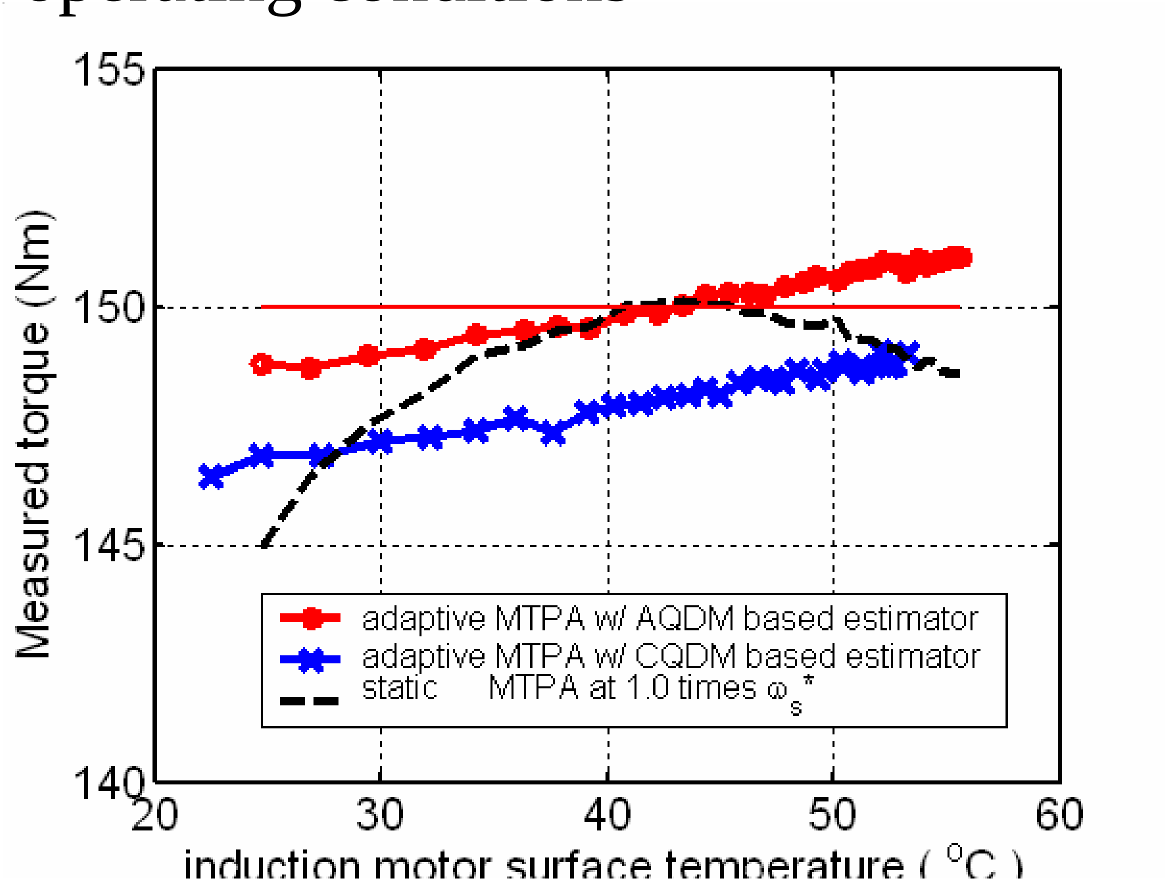


Validation - AMTPA

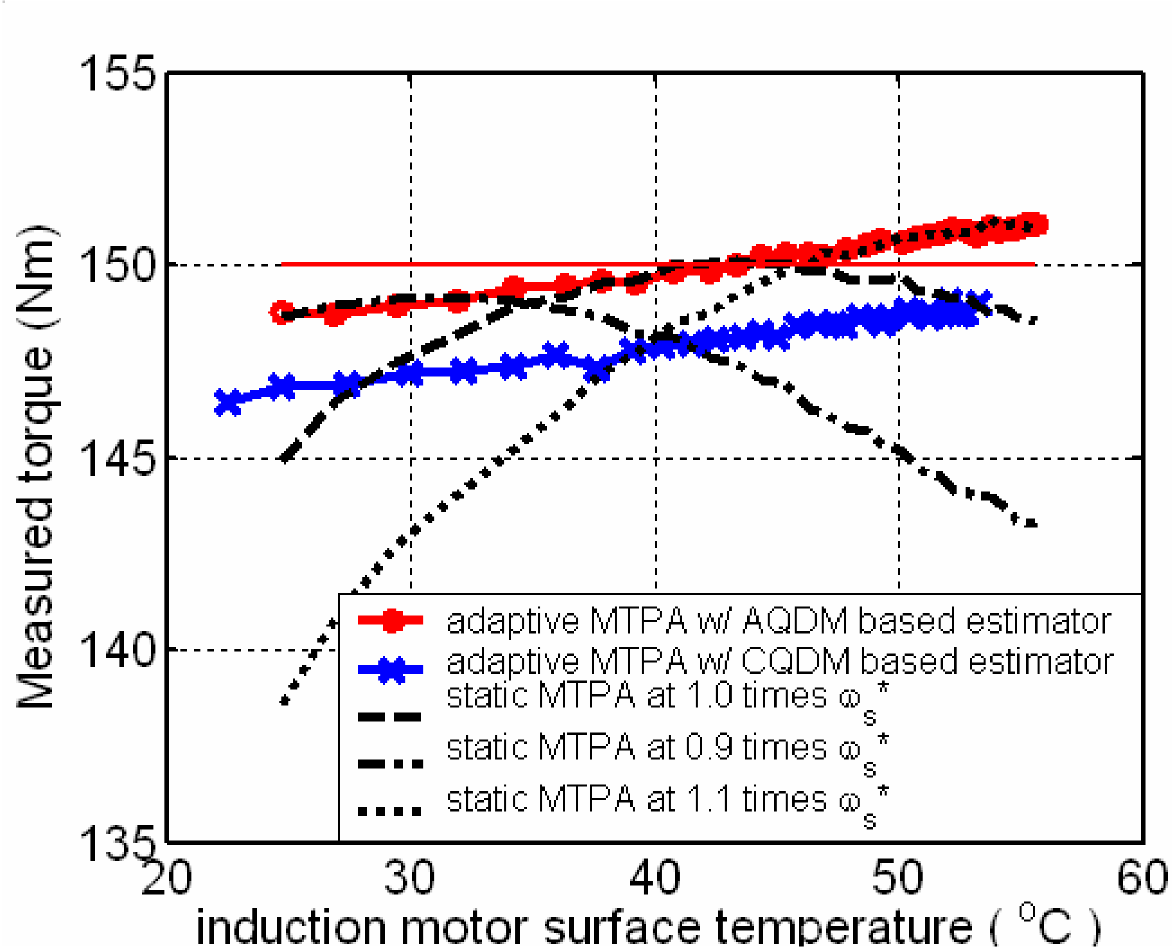


Validation – AQDM based rr estimator

- One operating conditions

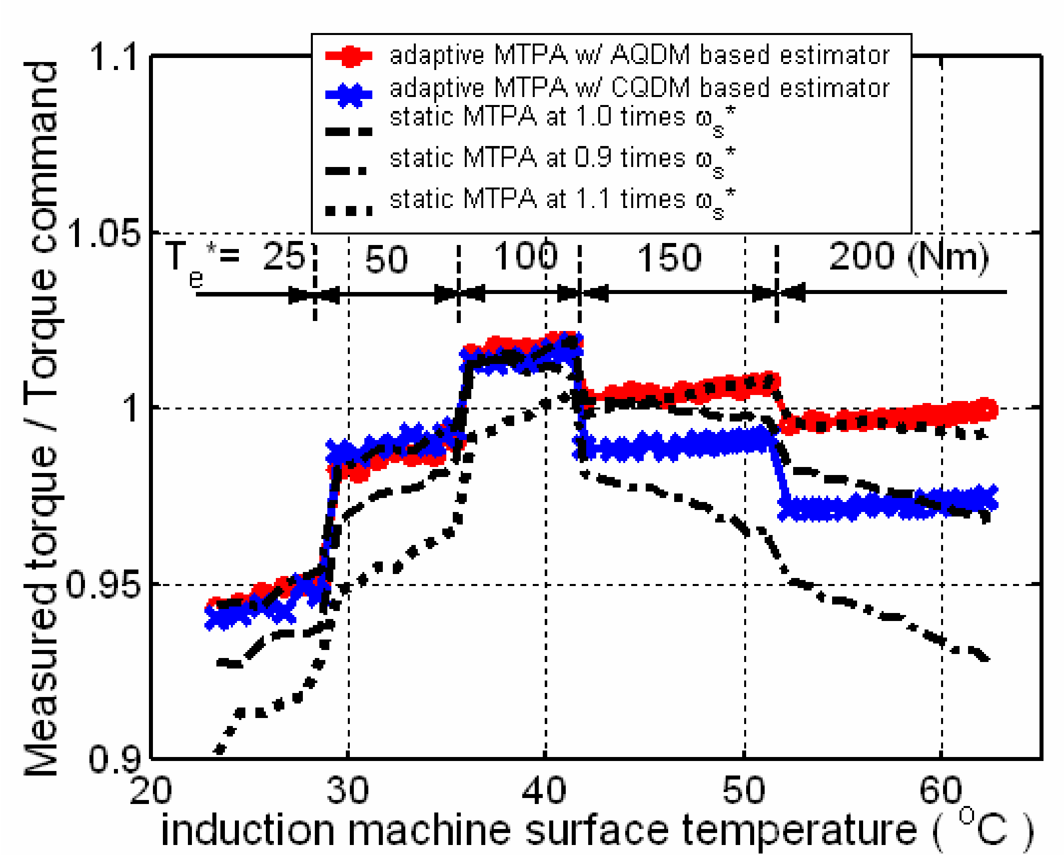


Validation – AQDM based rr estimator



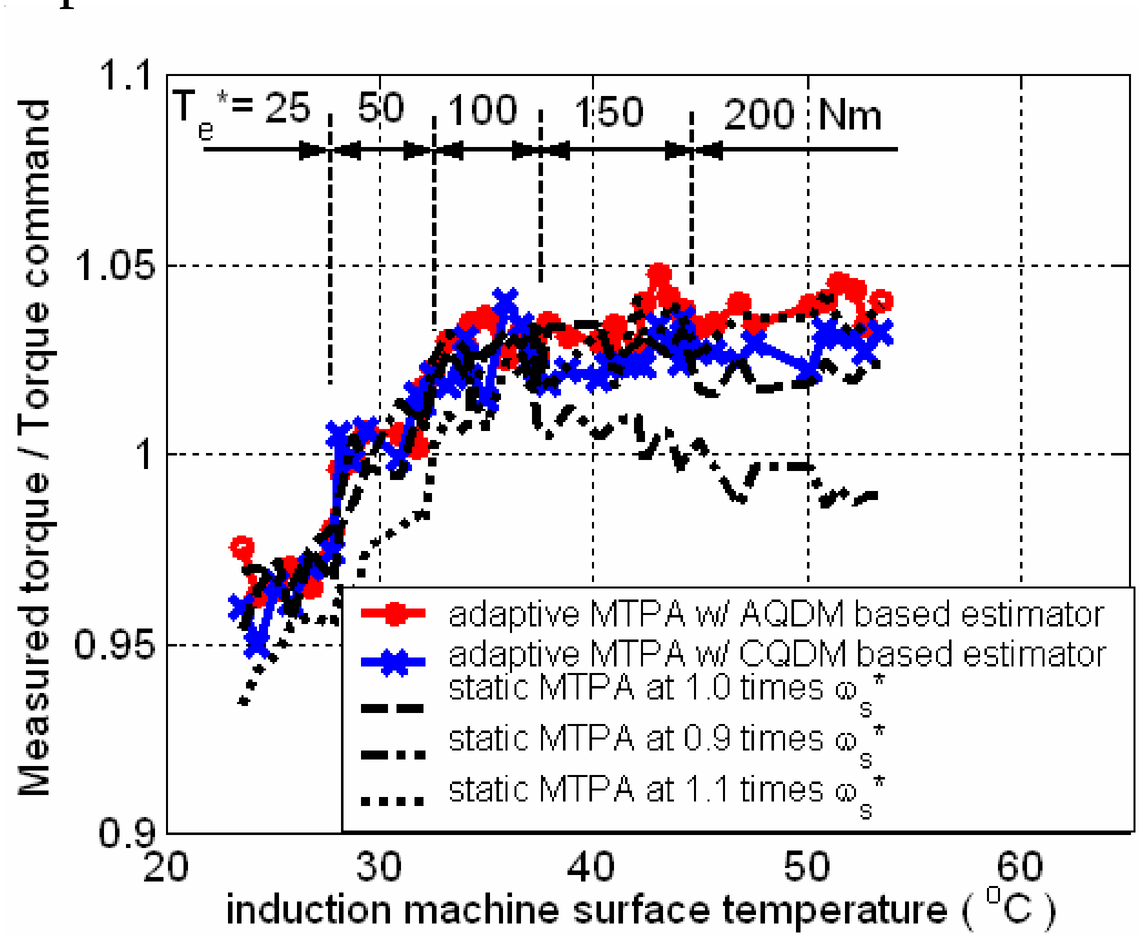
Validation – AQDM based rr estimator

- Changing operating conditions
  - at 900 rpm



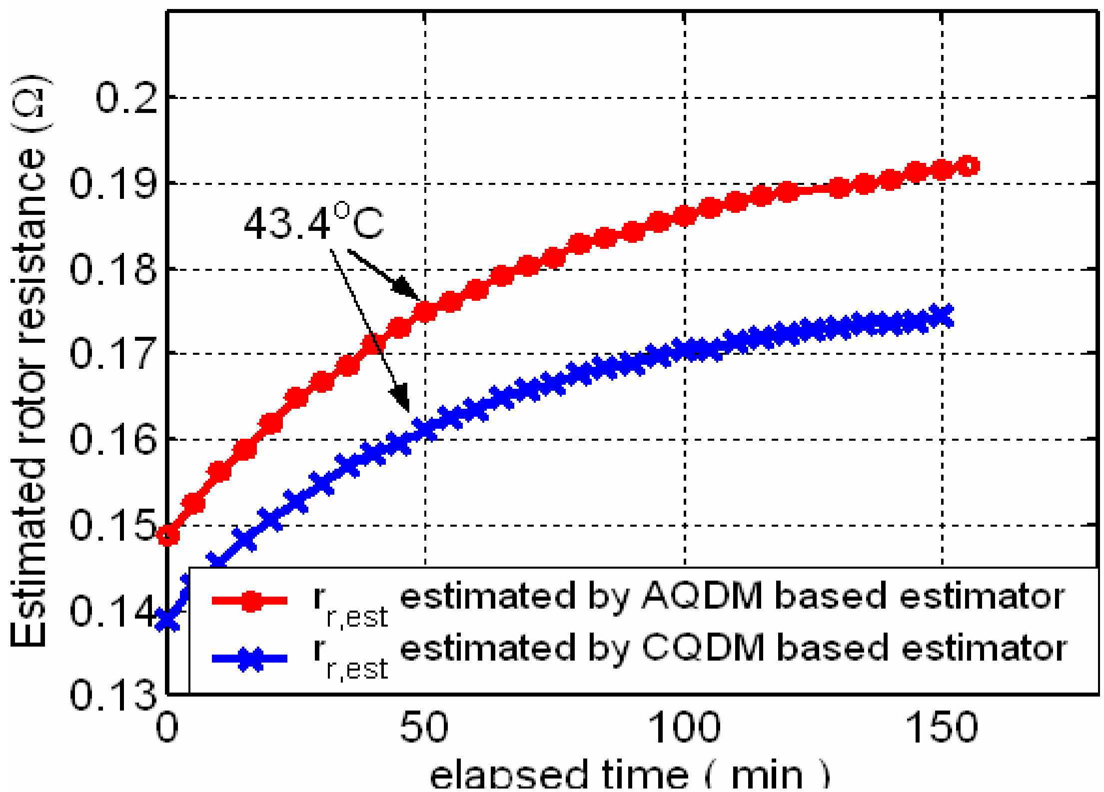
Validation – AQDM based rr estimator

- at 180 rpm



Validation – AQDM based rr estimator

- Comparison of the estimated rotor resistances
  - One operating conditions



Validation – AQDM based rr estimator

- Changing operating conditions