FACULTY OF ELECTRICAL
ENGINEERING
UNIVERSITY OF WEST BOHEMIA

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Theory of Electric Machines 2

KEV/TS2

Karel Hruska / r20201109

FACULTY OF ELECTRICAL
ENGINEERING
UNIVERSITY OF WEST BOHEMIA

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Synchronous Reluctance Machines

Synchronous Reluctance Machines

- Synchronous reluctance machines are a specific type of synchronous machines

Synchronous Reluctance Machines

- Synchronous reluctance machines are a specific type of synchronous machines
- For the purpose of torque generation the difference of inductances in d and q axes is used

Synchronous Reluctance Machines

- Synchronous reluctance machines are a specific type of synchronous machines
- For the purpose of torque generation the difference of inductances in d and q axes is used
- In contrast to other synchronous machines there is no excitation

Synchronous Reluctance Machines

- Synchronous reluctance machines are a specific type of synchronous machines
- For the purpose of torque generation the difference of inductances in d and q axes is used
- In contrast to other synchronous machines there is no excitation
- The d–axis is commonly laid into the axis of highest inductance

Synchronous Reluctance Machines

- Synchronous reluctance machines are a specific type of synchronous machines
- For the purpose of torque generation the difference of inductances in d and q axes is used
- In contrast to other synchronous machines there is no excitation
- The d–axis is commonly laid into the axis of highest inductance
- In general, these machines have a relatively low power factor

Synchronous Reluctance Machines

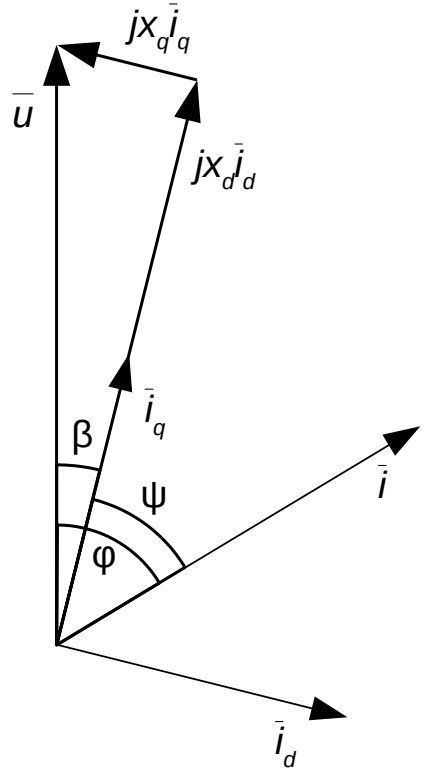
- Synchronous reluctance machines are a specific type of synchronous machines
- For the purpose of torque generation the difference of inductances in d and q axes is used
- In contrast to other synchronous machines there is no excitation
- The d–axis is commonly laid into the axis of highest inductance
- In general, these machines have a relatively low power factor
- Although that they are favoured for they constructional simplicity and minimal rotor losses

Synchronous Reluctance Machines

- The phasor diagram corresponds to a non-excited synchronous machine:

Synchronous Reluctance Machines

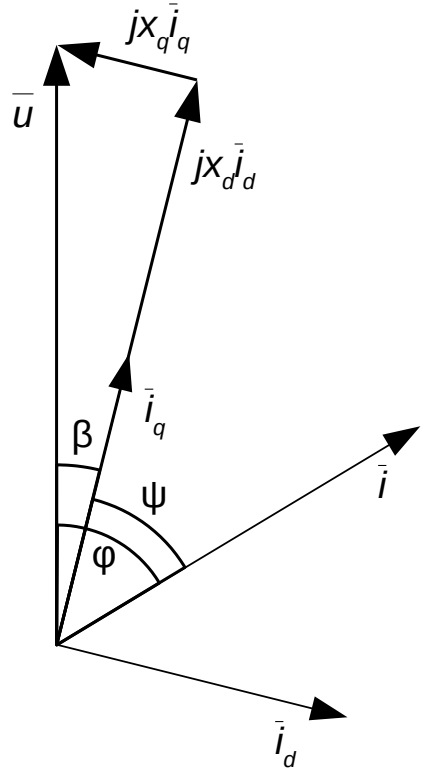
- The phasor diagram corresponds to a non-excited synchronous machine:



Synchronous Reluctance Machines

- The phasor diagram corresponds to a non-excited synchronous machine:
- The torque equations are also identical

$$M = \frac{p\,m}{\omega_1} U \left[\frac{U_{ib}}{X_d} \sin\beta + \frac{U}{2} \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\beta \right]$$



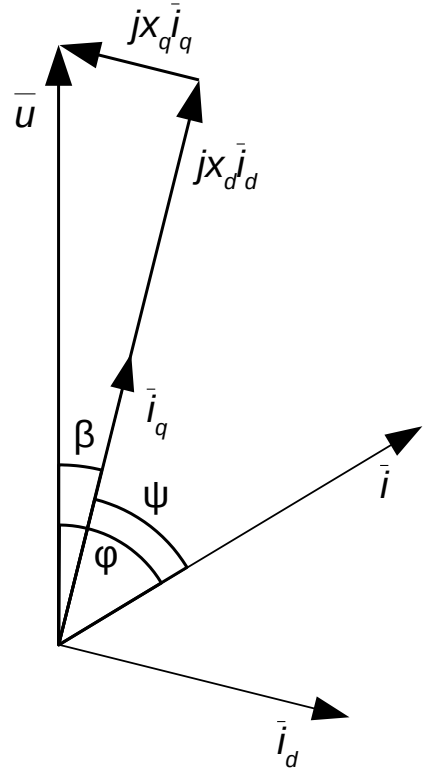
Synchronous Reluctance Machines

- The phasor diagram corresponds to a non-excited synchronous machine:
- The torque equations are also identical

$$M = \frac{p\,m}{\omega_1} U \left[\frac{U_{ib}}{X_d} \sin\beta + \frac{U}{2} \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\beta \right]$$

or

$$M = \frac{p\,m}{2} \left[\psi_{PM}\, i_q + \left(L_d - L_q \right) i_d\, i_q \right]$$



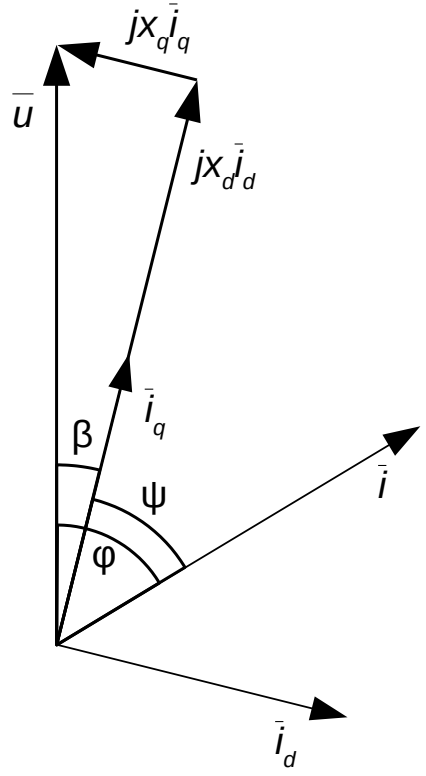
Synchronous Reluctance Machines

- The phasor diagram corresponds to a non-excited synchronous machine:
- The torque equations are also identical

$$M = \frac{p\,m}{\omega_1} U \left[\cancel{\frac{U_{ib}}{X_d} \sin\beta} + \frac{U}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\beta \right]$$

or

$$M = \frac{p\,m}{2}\left[\cancel{\psi_{PM} i_q} + \left(L_d - L_q\right) i_d i_q \right]$$



Synchronous Reluctance Machines

- The phasor diagram corresponds to a non-excited synchronous machine:
- The torque equations are also identical

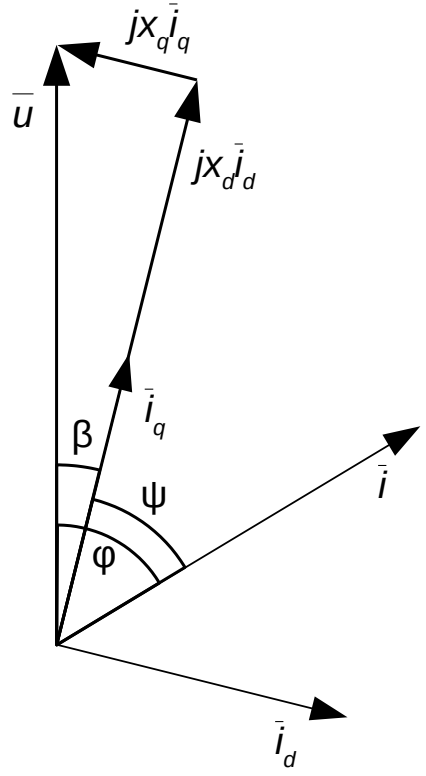
$$M = \frac{p\,m}{\omega_1} U \left[\cancel{\frac{U_{ib}}{X_d} \sin\beta} + \frac{U}{2} \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\beta \right]$$

or

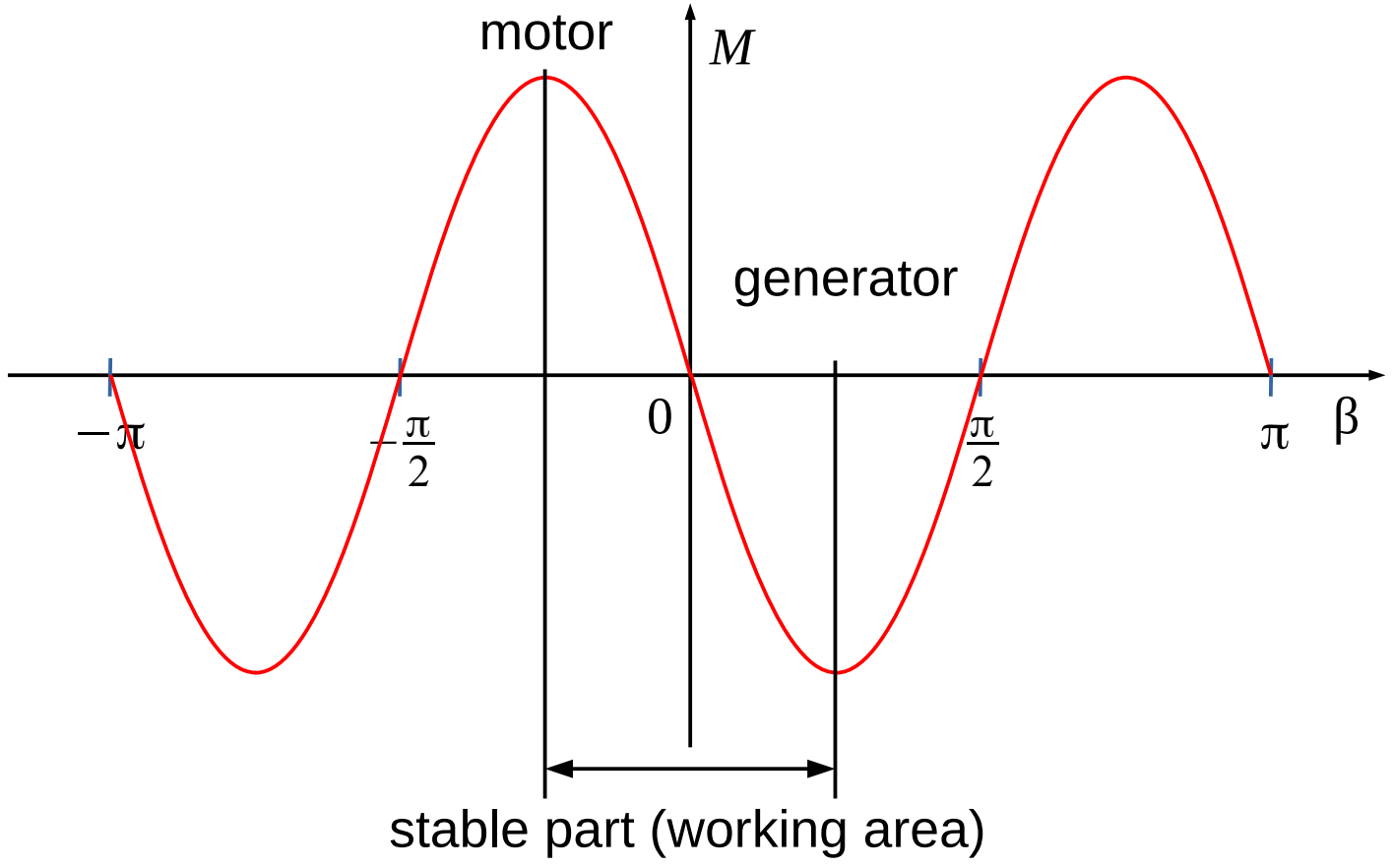
$$M = \frac{p\,m}{2} \left[\cancel{\psi_{PM} i_q} + \left(L_d - L_q \right) i_d i_q \right]$$

- In final form:

$$M = \frac{p\,m}{\omega_1} \frac{U^2}{2} \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\beta \qquad M = \frac{m}{2} p \left(L_d - L_q \right) i_d i_q$$



Synchronous Reluctance Machines



FACULTY OF ELECTRICAL
ENGINEERING
UNIVERSITY OF WEST BOHEMIA

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Mechanical Design of Synchronous Reluctance Machines

Mechanical Design of Synchronous Reluctance Machines

- The stator of synchronous reluctance motors corresponds to a stator of common synchronous or asynchronous machines

Mechanical Design of Synchronous Reluctance Machines

- The stator of synchronous reluctance motors corresponds to a stator of common synchronous or asynchronous machines
- With respect to harmonic composition of the torque, almost in all cases a distributed winding with integral amount of slots per pole and phase is chosen

Mechanical Design of Synchronous Reluctance Machines

- The stator of synchronous reluctance motors corresponds to a stator of common synchronous or asynchronous machines
- With respect to harmonic composition of the torque, almost in all cases a distributed winding with integral amount of slots per pole and phase is chosen
- The magnetic circuit of the machine must be designed for magnetic flux corresponding to terminal voltage of the machine

Mechanical Design of Synchronous Reluctance Machines

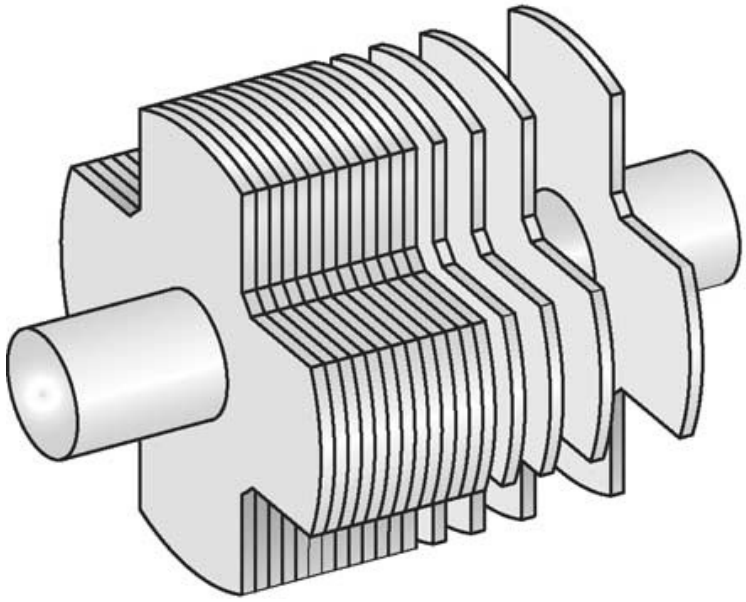
- The stator of synchronous reluctance motors corresponds to a stator of common synchronous or asynchronous machines
- With respect to harmonic composition of the torque, almost in all cases a distributed winding with integral amount of slots per pole and phase is chosen
- The magnetic circuit of the machine must be designed for magnetic flux corresponding to terminal voltage of the machine
  … to achieve possibly highest saliency of the machine is should be unsaturated

Mechanical Design of Synchronous Reluctance Machines

- There is a variety of rotor topologies:

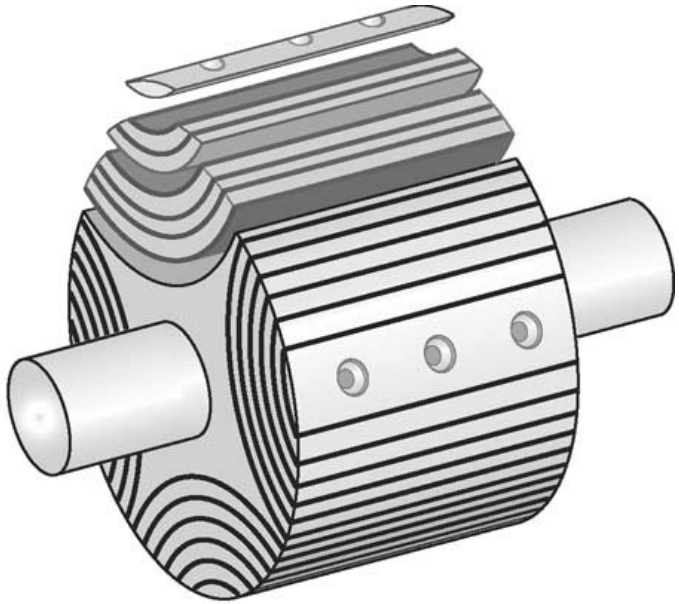
Mechanical Design of Synchronous Reluctance Machines

- There is a variety of rotor topologies:
  - Rotor based on salient pole synchronous machine
    - Almost unused
    - Low saliency
    - Mechanically very robust
    - Made of common electrical steel sheets



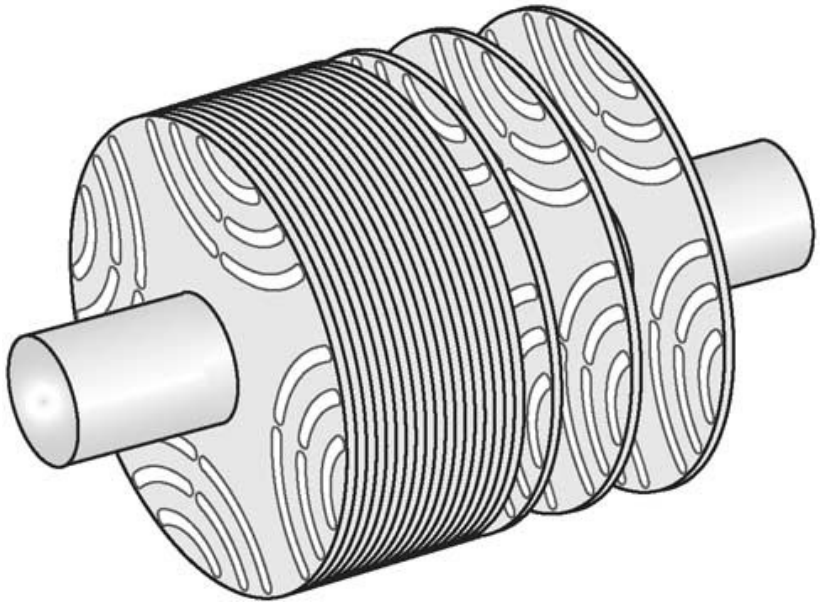
Mechanical Design of Synchronous Reluctance Machines

- There is a variety of rotor topologies:
  - Radially layered rotor
    - The steel sheets are interleaved by thick insulation
    - Complicated manufacture
    - Limited mechanical strength



Mechanical Design of Synchronous Reluctance Machines

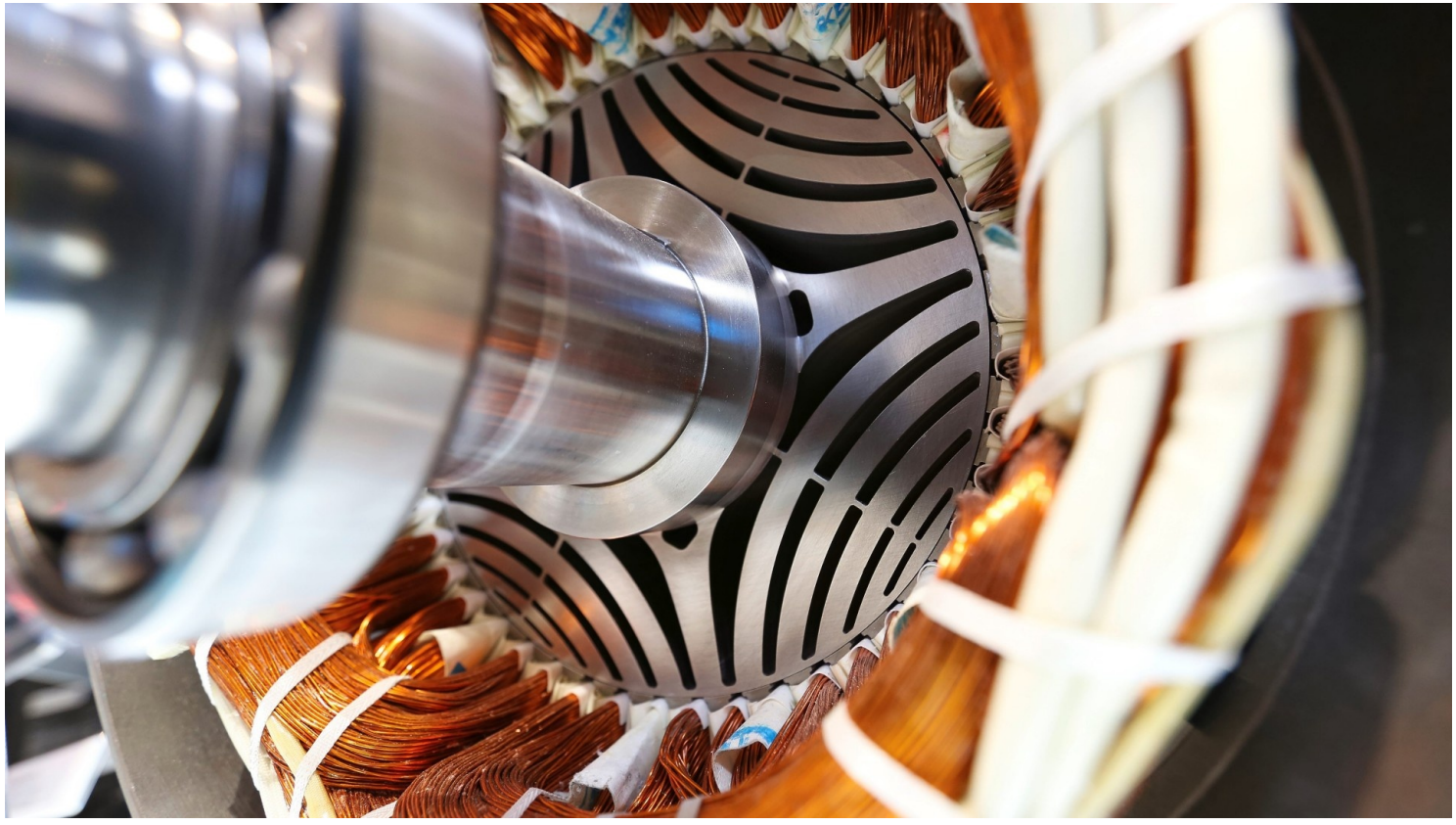
- There is a variety of rotor topologies:
  - Rotor with magnetic barriers
    - Uses common electrical steel sheets
    - The shape of the sheet include air barriers
    - Limited mechanical strength
    - ABB/SIEMENS



Mechanical Design of Synchronous Reluctance Machines



Mechanical Design of Synchronous Reluctance Machines



Mechanical Design of Synchronous Reluctance Machines

- The design of the rotor is focused on achivement of possibly highest saliency, i.e. maximal difference between inductances L_d and L_q

Mechanical Design of Synchronous Reluctance Machines

- The design of the rotor is focused on achivement of possibly highest saliency, i.e. maximal difference between inductances L_d and L_q

  => possibly widest flux barriers
- The remaining parts of the magnetic circuit must not be saturated ($B_m < 1{,}4\ T$)

Mechanical Design of Synchronous Reluctance Machines

- The design of the rotor is focused on achivement of possibly highest saliency, i.e. maximal difference between inductances L_d and L_q

  => possibly widest flux barriers
- The remaining parts of the magnetic circuit must not be saturated ($B_m < 1{,}4\ T$)
- The amount of barriers is chosen based in similar way as the amount of rotor slots in case of induction machines

Mechanical Design of Synchronous Reluctance Machines

- If for an induction machine we have a relation

$$Q_1 \pm p \neq Q_2 \pm p$$

where Q_2 is the amount of rotor slots (= amount of barrier ends)

Mechanical Design of Synchronous Reluctance Machines

- If for an induction machine we have a relation

$$Q_1 \pm p \neq Q_2 \pm p$$

  where Q_2 is the amount of rotor slots (= amount of barrier ends)

- Then the total amount of barriers must be one half in comparison to the amount of slots:

$$N_{bc} = \frac{Q_2}{2}$$

Mechanical Design of Synchronous Reluctance Machines

- If for an induction machine we have a relation

$$Q_1 \pm p \neq Q_2 \pm p$$

  where Q_2 is the amount of rotor slots (= amount of barrier ends)

- Then the total amount of barriers must be one half in comparison to the amount of slots:

$$N_{bc} = \frac{Q_2}{2}$$

- And there are

$$N_b = \frac{N_{bc}}{2\,p}$$

  barriers per pole

Mechanical Design of Synchronous Reluctance Machines

- If for an induction machine we have a relation

$$Q_1 \pm p \neq Q_2 \pm p$$

  where Q_2 is the amount of rotor slots (= amount of barrier ends)

- Then the total amount of barriers must be one half in comparison to the amount of slots:

$$N_{bc} = \frac{Q_2}{2}$$

- And there are

$$N_b = \frac{N_{bc}}{2\,p}$$

  barriers per pole, thus

$$N_b = \frac{Q_2}{4\,p}$$

Mechanical Design of Synchronous Reluctance Machines

- The we obtain

$$Q_1 \pm p \neq 2\,pN_b \pm p$$

Mechanical Design of Synchronous Reluctance Machines

- The we obtain

$$Q_1 \pm p \neq 2\,pN_b \pm p$$

- And after modification

$$N_b \neq \frac{Q_1}{2\,p} \pm 1$$

Mechanical Design of Synchronous Reluctance Machines

- The we obtain

$$Q_1 \pm p \neq 2\,pN_b \pm p$$

- And after modification

$$N_b \neq \frac{Q_1}{2\,p} \pm 1$$

- In case of inappropriate barrier choice, the machine may not start, or it will be noisy

Mechanical Design of Synchronous Reluctance Machines

- The we obtain

$$Q_1 \pm p \neq 2\,pN_b \pm p$$

- And after modification

$$N_b \neq \frac{Q_1}{2\,p} \pm 1$$

- In case of inappropriate barrier choice, the machine may not start, or it will be noisy
- For the purpose of lowering of the noise level the skewing of stator slots is often applied

FACULTY OF ELECTRICAL
ENGINEERING
UNIVERSITY OF WEST BOHEMIA

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Optimal Control of Synchronous Reluctance Machines

Optimal Control of Synchronous Reluctance Machines

- The criterion of optimal control of a synchronous reluctance machine results, like in case of a PMSM, from its torque equation in d/q coordinate system

$$M = \frac{p\,m}{2}\left(L_d - L_q\right) i_d\, i_q$$

Optimal Control of Synchronous Reluctance Machines

- The criterion of optimal control of a synchronous reluctance machine results, like in case of a PMSM, from its torque equation in *d/q* coordinate system

$$M = \frac{p\,m}{2}\left(L_d - L_q\right) i_d\, i_q$$

- There both current components may be introduced

$$i_d = -i \sin \psi$$

$$i_q = i \cos \psi$$

Optimal Control of Synchronous Reluctance Machines

- The criterion of optimal control of a synchronous reluctance machine results, like in case of a PMSM, from its torque equation in *d/q* coordinate system

$$M = \frac{p\,m}{2}\left(L_d - L_q\right) i_d\, i_q$$

- There both current components may be introduced

$$i_d = -i \sin \psi$$

$$i_q = i \cos \psi$$

then we obtain

$$M = -\frac{p\,m}{2}\left[\left(L_d - L_q\right) i^2 \sin \psi \cos \psi\right]$$

Optimal Control of Synchronous Reluctance Machines

- For the multiplication of the sinus and cosinus of the inner power factor we may substitute from $$\sin\psi\cos\psi=\frac{1}{2}\cos 2\psi$$

Optimal Control of Synchronous Reluctance Machines

- For the multiplication of the sinus and cosinus of the inner power factor we may substitute from

$$\sin\psi\cos\psi=\frac{1}{2}\cos 2\psi$$

and then to perform the derivation

$$\frac{\partial M}{\partial \psi}=0$$

Optimal Control of Synchronous Reluctance Machines

- For the multiplication of the sinus and cosinus of the inner power factor we may substitute from

$$\sin\psi\cos\psi=\frac{1}{2}\cos 2\psi$$

  and then to perform the derivation

$$\frac{\partial M}{\partial \psi}=0$$

- Which results in the MTPA condition for synchronous reluctance machines:

$$\frac{\partial M}{\partial \psi}=\frac{p\,m}{2}\left[\left(L_d-L_q\right)i^2\sin 2\psi\right]=0$$

Optimal Control of Synchronous Reluctance Machines

- For the multiplication of the sinus and cosinus of the inner power factor we may substitute from

$$\sin\psi\cos\psi=\frac{1}{2}\cos 2\psi$$

  and then to perform the derivation

$$\frac{\partial M}{\partial \psi}=0$$

- Which results in the MTPA condition for synchronous reluctance machines:

$$\frac{\partial M}{\partial \psi}=p\,m\left[\left(L_d-L_q\right)i^2\sin 2\psi\right]=0$$

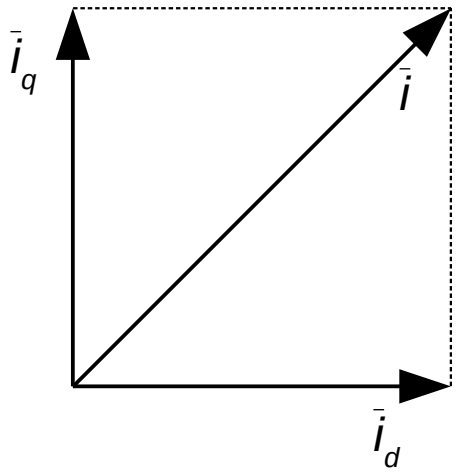
- This condition is valid in case of $\psi = 45°$, thus for equality of i_d and i_q

Optimal Control of Synchronous Reluctance Machines

- The after-effect of the synchronous reluctance machine MTPA criterion ($\psi = 45°$) is then

$$i_d = i_q = \frac{1}{\sqrt{2}} i$$

thus the current i and the q – axis form angle of 45°



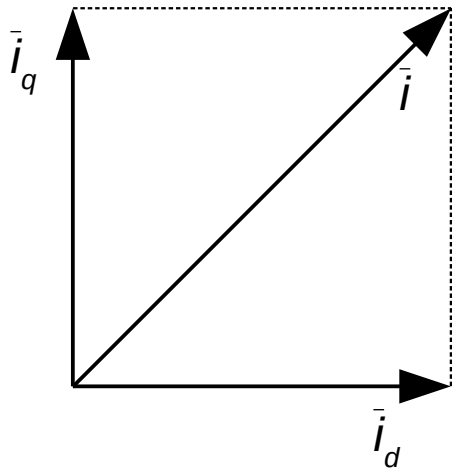
Optimal Control of Synchronous Reluctance Machines

- The after-effect of the synchronous reluctance machine MTPA criterion ($\psi = 45°$) is then

$$i_d = i_q = \frac{1}{\sqrt{2}} i$$

  thus the current i and the q – axis form angle of 45°
- The value of both current components is then

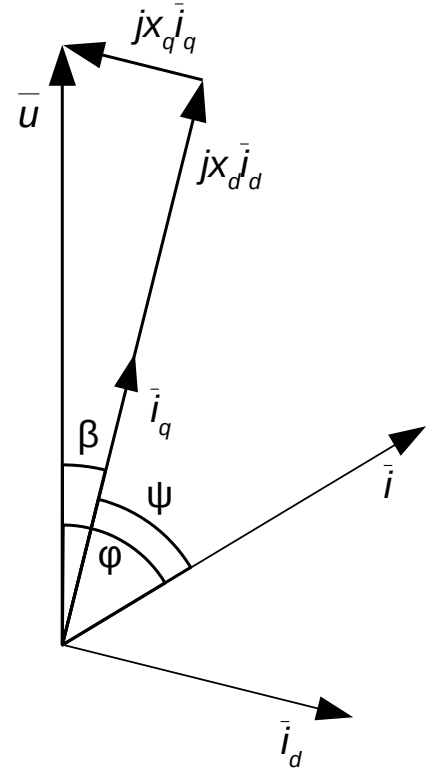
$$i_d = i_q = \frac{1}{\sqrt{2}} i = 0.707\ p.u.$$



Optimal Control of Synchronous Reluctance Machines

- From the phasor diagram of the machine we may derive

$$u^2 = (x_d i_d)^2 + (x_q i_q)^2$$



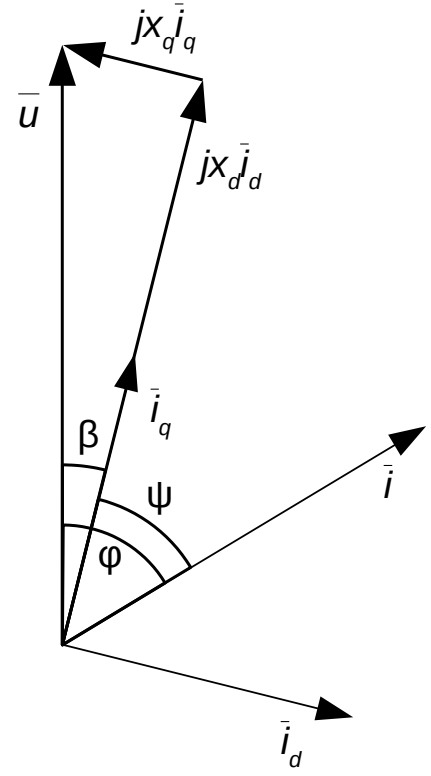
Optimal Control of Synchronous Reluctance Machines

- From the phasor diagram of the machine we may derive

$$u^2 = (x_d i_d)^2 + (x_q i_q)^2$$

which, after substitution by currents, gives

$$u^2 = \frac{1}{2}(x_d i)^2 + \frac{1}{2}(x_q i)^2$$



Optimal Control of Synchronous Reluctance Machines

- From the phasor diagram of the machine we may derive

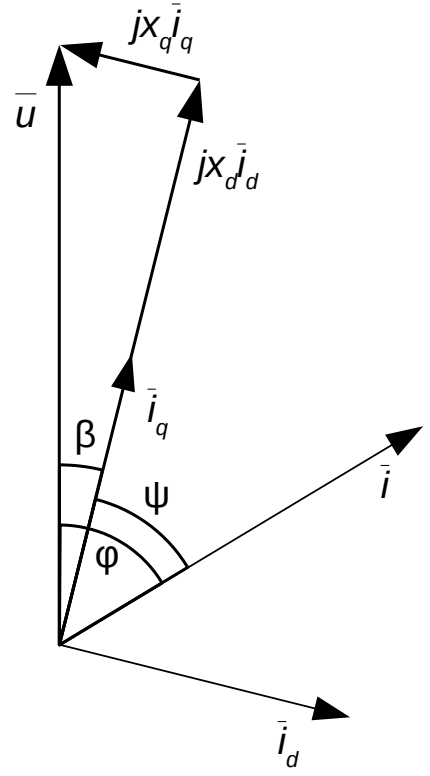
$$u^2 = (x_d i_d)^2 + (x_q i_q)^2$$

which, after substitution by currents, gives

$$u^2 = \frac{1}{2}(x_d i)^2 + \frac{1}{2}(x_q i)^2$$

- And while considering rated voltage ($u = 1\ p.u.$) and current ($i = 1\ p.u.$) it results in

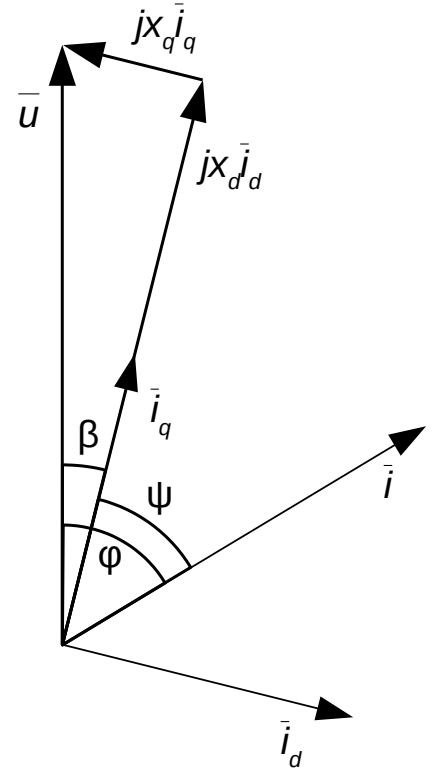
$$x_d^2 + x_q^2 = 2$$



Optimal Control of Synchronous Reluctance Machines

- The phase shift between the voltage and current is

$$\varphi = \psi + \beta$$



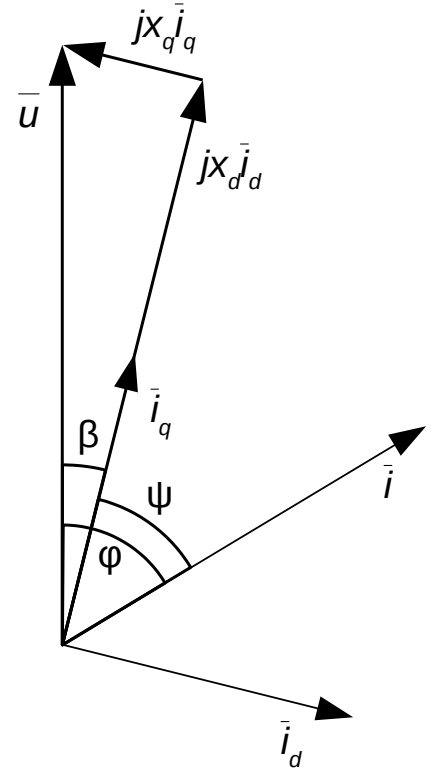
Optimal Control of Synchronous Reluctance Machines

- The phase shift between the voltage and current is

$$\varphi = \psi + \beta$$

whereas the torque angle of the machine is given by

$$\beta = \operatorname{atan} \frac{x_q}{x_d}$$



Optimal Control of Synchronous Reluctance Machines

- The phase shift between the voltage and current is

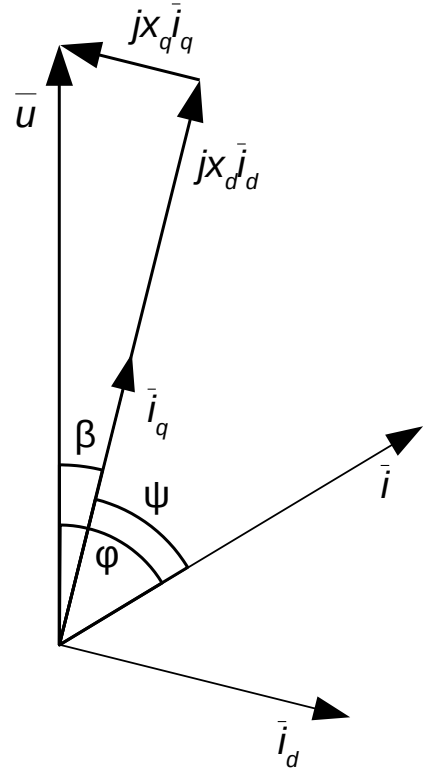
$$\varphi = \psi + \beta$$

whereas the torque angle of the machine is given by

$$\beta = \operatorname{atan} \frac{x_q}{x_d}$$

and from the MTPA condition is $\psi = 45°$

$$\varphi = 45° + \operatorname{atan} \frac{x_q}{x_d}$$



Optimal Control of Synchronous Reluctance Machines

- Conclusions:
  - Theoretically the maximal achievable valute of the power factor of the SynRM is according to the MTPA

$$\cos\varphi = \cos 45\,° = 0{,}707$$

Optimal Control of Synchronous Reluctance Machines

- Conclusions:
  - Theoretically the maximal achievable valute of the power factor of the SynRM is according to the MTPA

$$\cos\varphi = \cos 45° = 0{,}707$$

  - To achieve this power factor, it would be necessary to have $x_q = 0\ p.u.$ and $x_d = 1.41\ p.u.$

Optimal Control of Synchronous Reluctance Machines

- Conclusions:
  - Theoretically the maximal achievable valute of the power factor of the SynRM is according to the MTPA

$$\cos\varphi = \cos 45° = 0{,}707$$

  - To achieve this power factor, it would be necessary to have $x_q = 0\ p.u.$ and $x_d = 1.41\ p.u.$
  - For any real saliency the power factor worsens

Optimal Control of Synchronous Reluctance Machines

- Example:
  - We seek for a suitable value of reactances of a machine with expected

$$L_d = 4\,L_q$$

Optimal Control of Synchronous Reluctance Machines

- Example:
  - We seek for a suitable value of reactances of a machine with expected

$$L_d = 4\,L_q$$

  - From the condition of per unit reactances we have

$$16\,x_q^2 + x_q^2 = 2$$

Optimal Control of Synchronous Reluctance Machines

- Example:
  - We seek for a suitable value of reactances of a machine with expected

$$L_d = 4\,L_q$$

  - From the condition of per unit reactances we have

$$16\,x_q^2 + x_q^2 = 2$$

  - Thus

$$x_q = \sqrt{\frac{2}{17}} = 0{,}343\;p.u.$$

Optimal Control of Synchronous Reluctance Machines

- Example:
  - We seek for a suitable value of reactances of a machine with expected

$$L_d = 4\,L_q$$

  - From the condition of per unit reactances we have

$$16\,x_q^2 + x_q^2 = 2$$

  - Thus

$$x_q = \sqrt{\frac{2}{17}} = 0{,}343\;p.u.$$

$$x_d = 4\,x_q = 4 \cdot \sqrt{\frac{2}{17}} = 1{,}372\;p.u.$$

Optimal Control of Synchronous Reluctance Machines

- Example:
  - The theoretical phase shift between voltage and current of this machine is

$$\varphi = 45\,° + \operatorname{atan}\frac{0{,}3434}{1{,}372} = 59{,}03\,°$$

Optimal Control of Synchronous Reluctance Machines

- Example:
  - The theoretical phase shift between voltage and current of this machine is

$$\varphi = 45\,° + \operatorname{atan}\frac{0{,}3434}{1{,}372} = 59{,}03\,°$$

  - And its power factor will be

$$\cos\varphi = \cos 59{,}03\,° = 0{,}514$$

Optimal Control of Synchronous Reluctance Machines

- Similarly to the PMSM, the synchronous machine will be designed for optimal duty on the border of the flux-weakening area at rated speed and power

Optimal Control of Synchronous Reluctance Machines

- Similarly to the PMSM, the synchronous machine will be designed for optimal duty on the border of the flux-weakening area at rated speed and power
- A machine designed according to the MTPA will act according to it even if supplied from the power network

  => may be used also for design of industrial machines

Optimal Control of Synchronous Reluctance Machines

- Similarly to the PMSM, the synchronous machine will be designed for optimal duty on the border of the flux-weakening area at rated speed and power
- A machine designed according to the MTPA will act according to it even if supplied from the power network

  => may be used also for design of industrial machines
- Although there is an effort to have possibly thinnest air gap in case of synchronous reluctance machines, it is more suitable to design it according to the MTPA criterion

FACULTY OF ELECTRICAL
ENGINEERING
UNIVERSITY OF WEST BOHEMIA

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Thank You for Your Attention!

Karel Hruska / +420 377 63 4429 / khruska@fel.zcu.cz