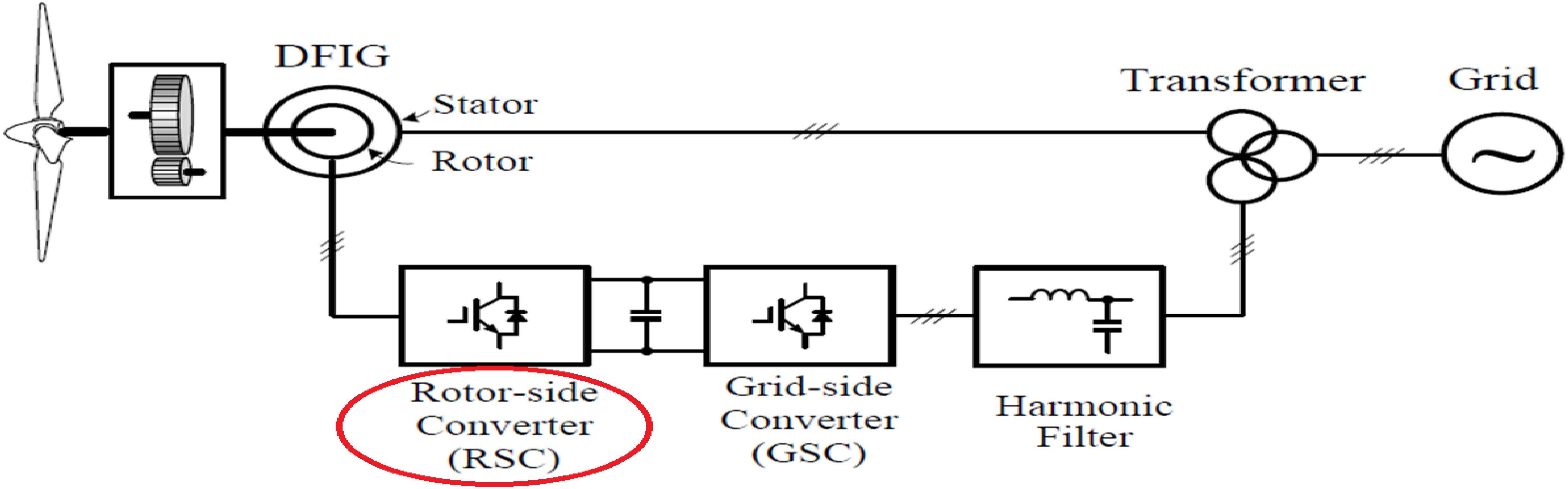
8.3 Unity Power Factor Operation of DFIG

- 1st we shall derive steady-state equivalent impedance for rotor-side converter(RSC).



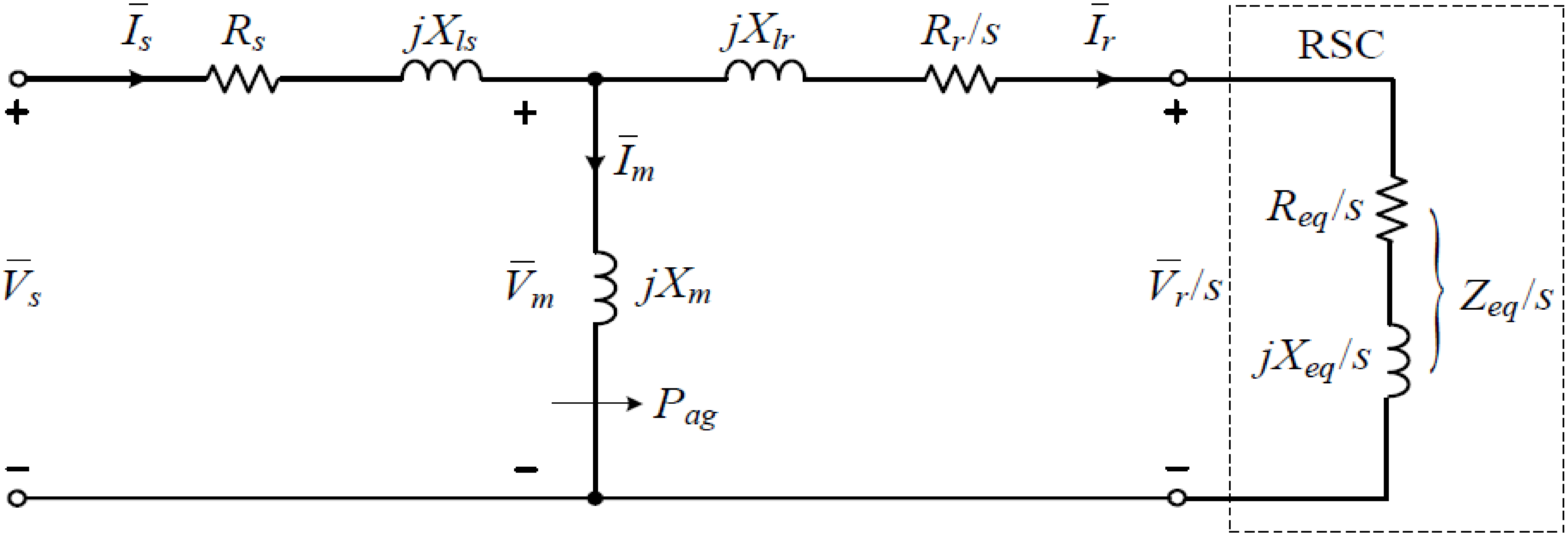
Based on steady-state equivalent impedance for rotor-side converter(RSC):

- Analysis of DFIG based WECS under unity power factor operation will be performed.

- Torque-slip characteristics of DFIG with rotor-side converter taken into account shall also be developed & analysed.

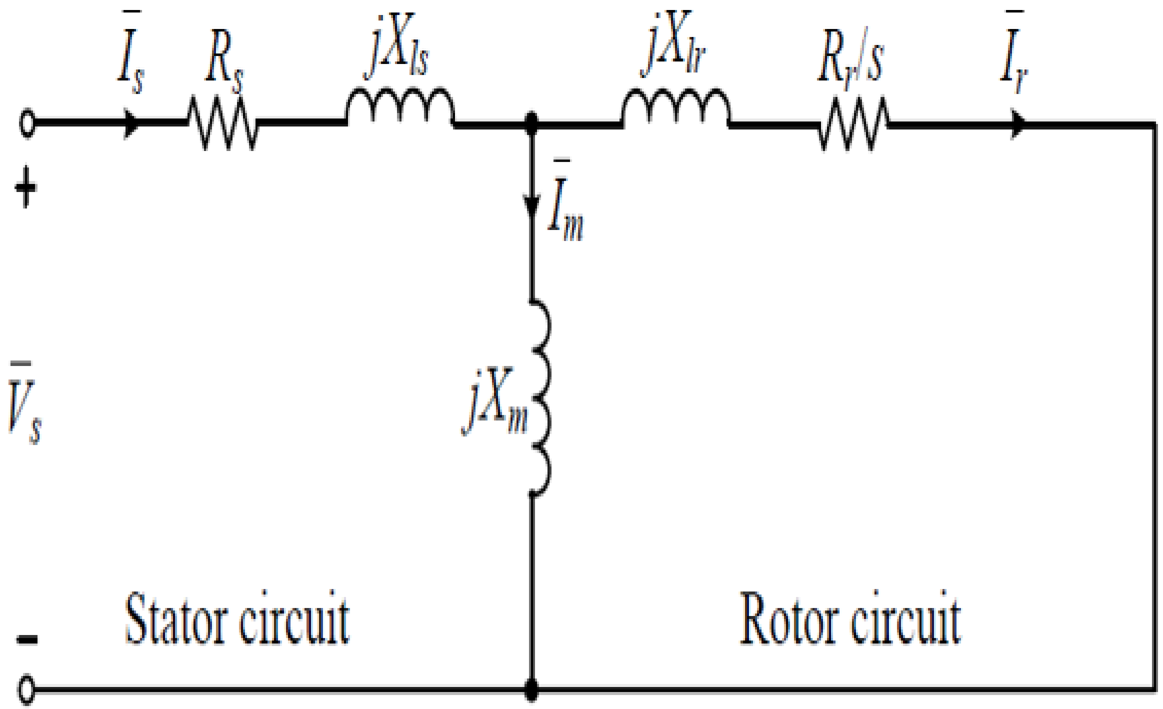
In order to investigate steady-state performance of DFIG based WECS rotor-side converter(RSC) can be modelled by an equivalent impedance(Zeq/s).

- Fig. shows a steady-state equivalent circuit of DFIG WECS.

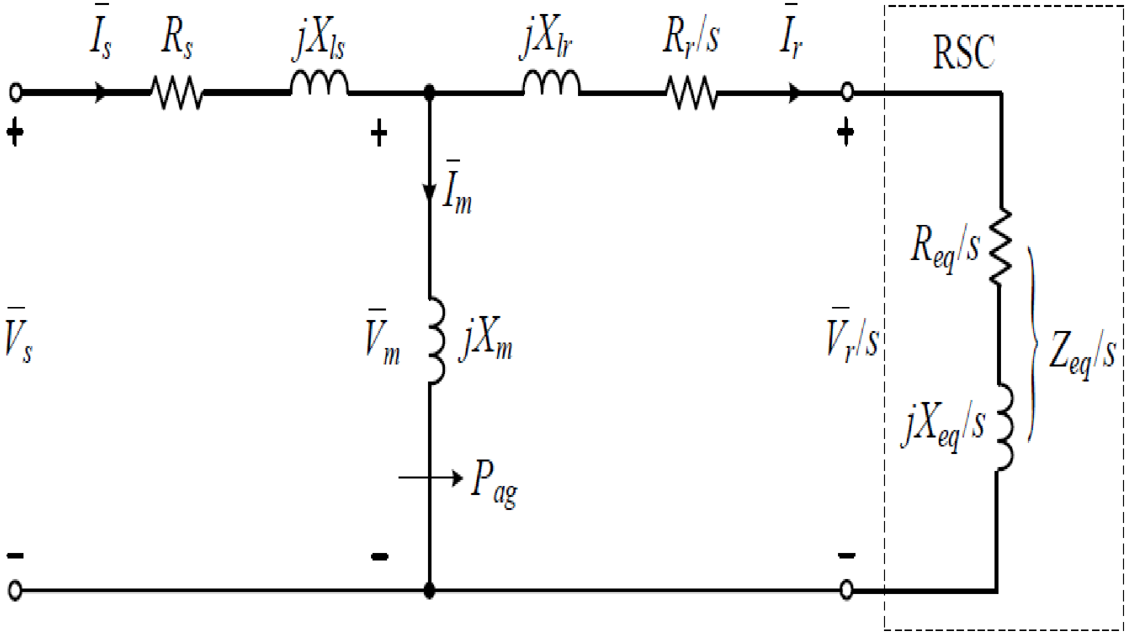


This equivalent circuit is developed by adding converter equivalent impedance Zeq/S to SCIG steady-state model

SCIG steady-state model



DFIG steady-state model



When Angular slip frequency=Stator frequency? i.e

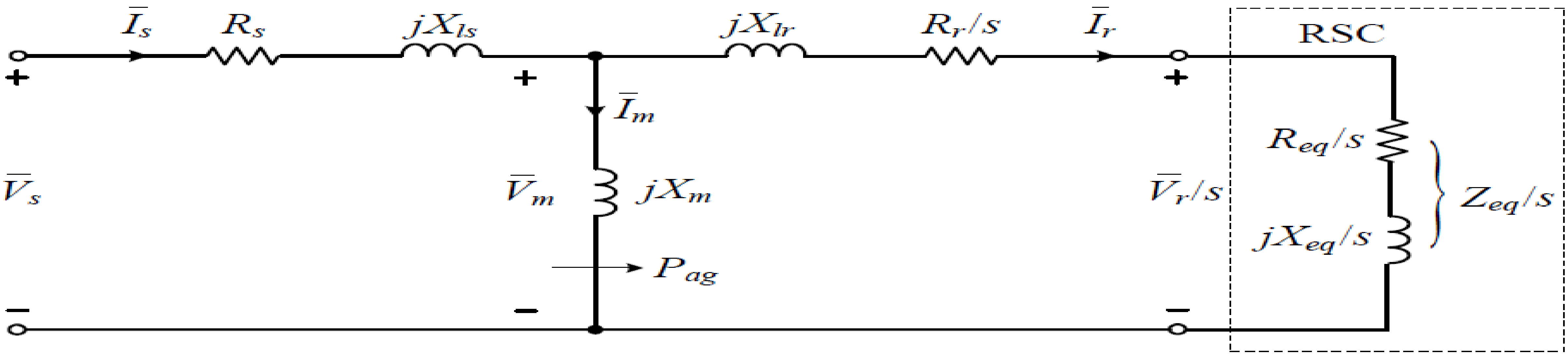
$$\omega_{sl} = \omega_s$$

Equivalent impedance of conv $\overline{Z}_{eq} = R_{eq} + jX_{eq} = R_{eq} + j\omega_{sl}L_{eq}$

where ωsl is angular slip frequency & Leq is equivalent inductance of RSC.

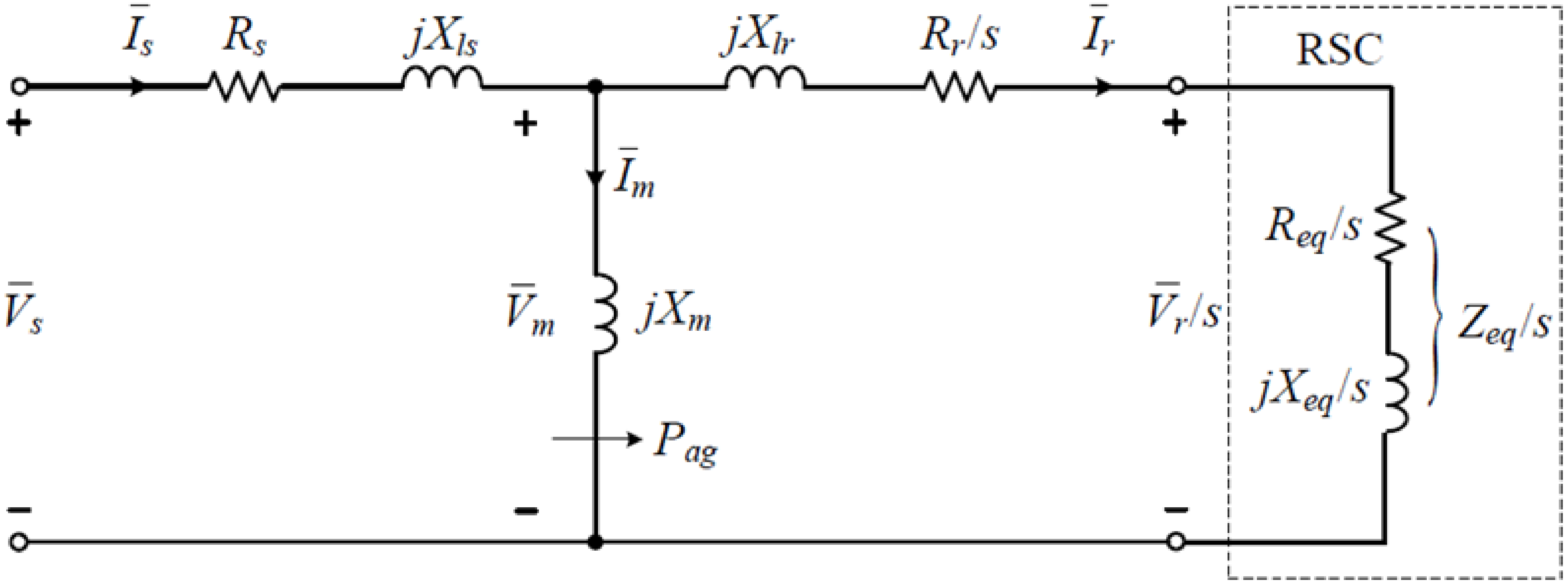
- Note: Frequency of rotor current in actual rotor winding flowing into converter is ωsl (angular slip frequency), not stator frequency ωs.

$$\omega_{sl} = s\omega_s$$



How to integrate converter equivalent impedance $\bar{Z}_{eq}$ into steady-state model with stator frequency ω_s?

Ans. Equivalent impedance $\bar{Z}_{eq}$ should be divided by slip *s*.



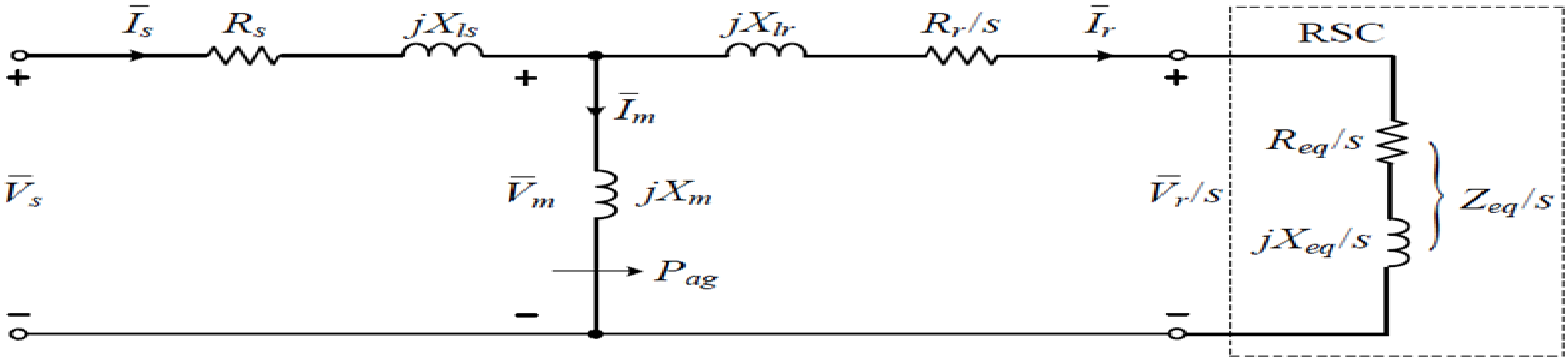
Equivalent impedance $\bar{Z}_{eq}$ referred to stator side is then given by:

$$\bar{Z}_{eq} = R_{eq} + jX_{eq} = R_{eq} + j\omega_{sl}L_{eq}$$

where ω_{sl} is angular slip frequency given by: $\omega_{sl} = s\omega_s$

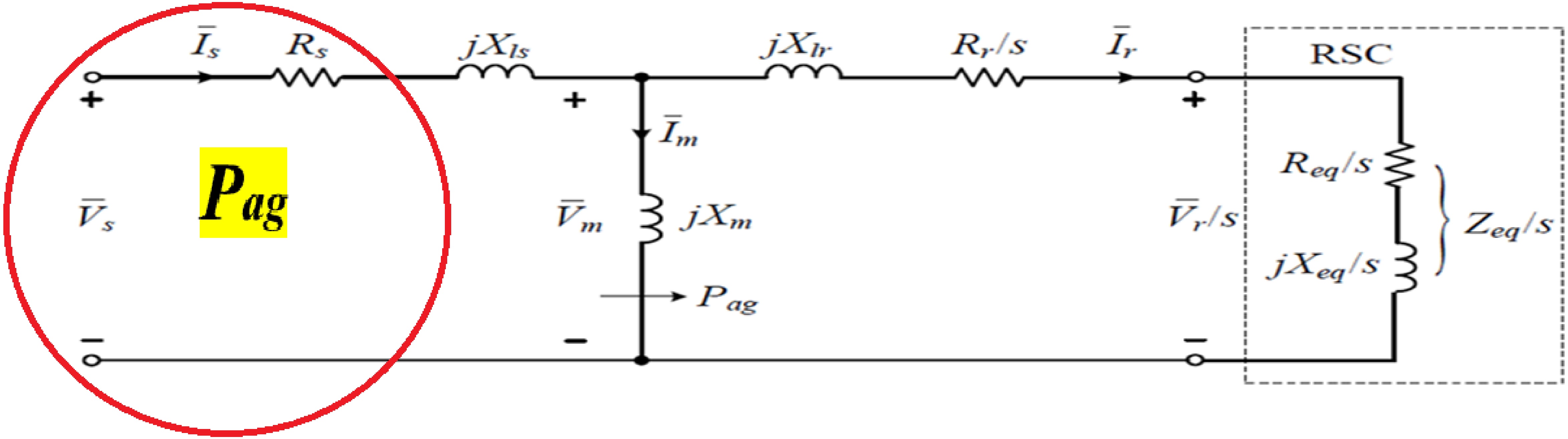
$$\bar{Z}_{eq}/s = R_{eq}/s + j\omega_{sl}L_{eq}/s = R_{eq}/s + j\omega_s L_{eq}$$

$$\omega_s = \frac{\omega_{sl}}{s}$$



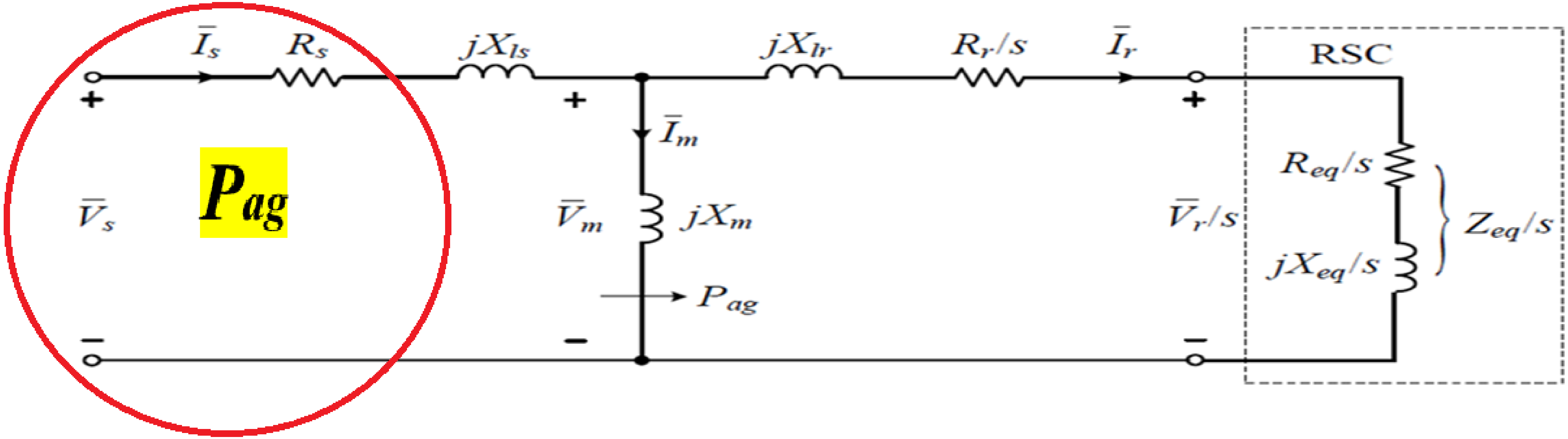
Air-gap power of generator

Assuming that stator operates at a unity power factor, air-gap power of generator?



Air-gap power of generator

Assuming that stator operates at a unity power factor, air-gap power of generator:



$$P_{ag} = 3(V_s - I_s R_s) I_s$$

From induction machine theory, air-gap power can also be calculated by

$$P_{ag} = \frac{\omega_s T_m}{P}$$

where T_m is mechanical torque &

P is the number of pole pairs of the generator.

By equating following equations:

$$P_{ag} = 3(V_s - I_s R_s) I_s$$

$$P_{ag} = \frac{\omega_s T_m}{P}$$

$$\frac{\omega_s T_m}{P} = 3(V_s - I_s R_s) I_s$$

from which

$$R_s I_s^2 - V_s I_s + \frac{\omega_s T_m}{3P} = 0$$

Obtain value of Is

$$R_s I_s^2 - V_s I_s + \frac{\omega_s T_m}{3P} = 0$$

Applying quadratic formula $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$.

$$R_s I_s^2 - V_s I_s + \frac{\omega_s T_m}{3P} = 0$$

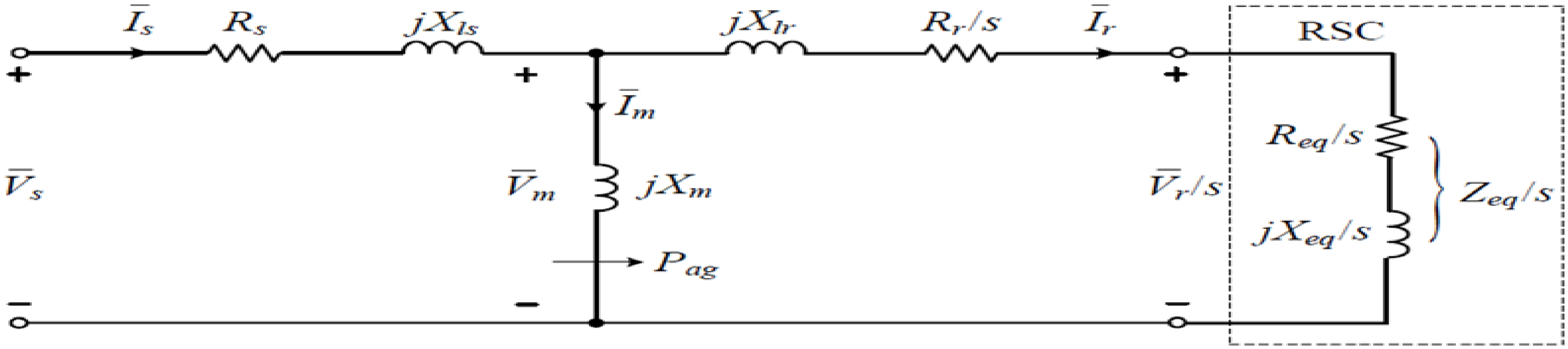
$$ax^2 + bx + c = 0$$

$$I_s = \frac{V_s \pm \sqrt{V_s^2 - \frac{4R_s \omega_s T_m}{3P}}}{2R_s}$$

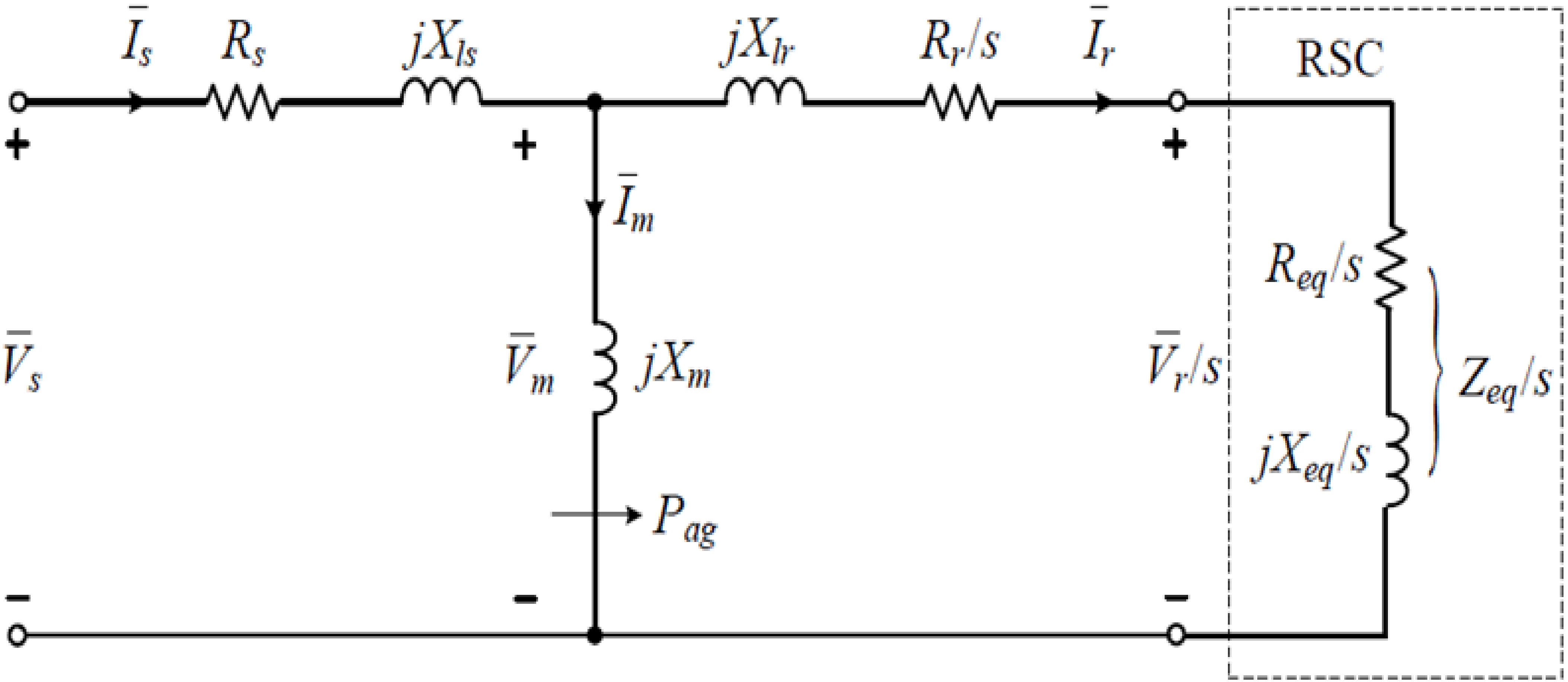
How to find rotor voltage $\bar{V}_r$ & rotor $\bar{I}_r$ current

$$I_s = \frac{V_s \pm \sqrt{V_s^2 - \dfrac{4R_s\omega_s T_m}{3P}}}{2R_s}$$

With magnitude of stator current I_s calculated, we can use equivalent circuit of Fig. to find rotor voltage $\bar{V}_r$ & rotor current $\bar{I}_r$.

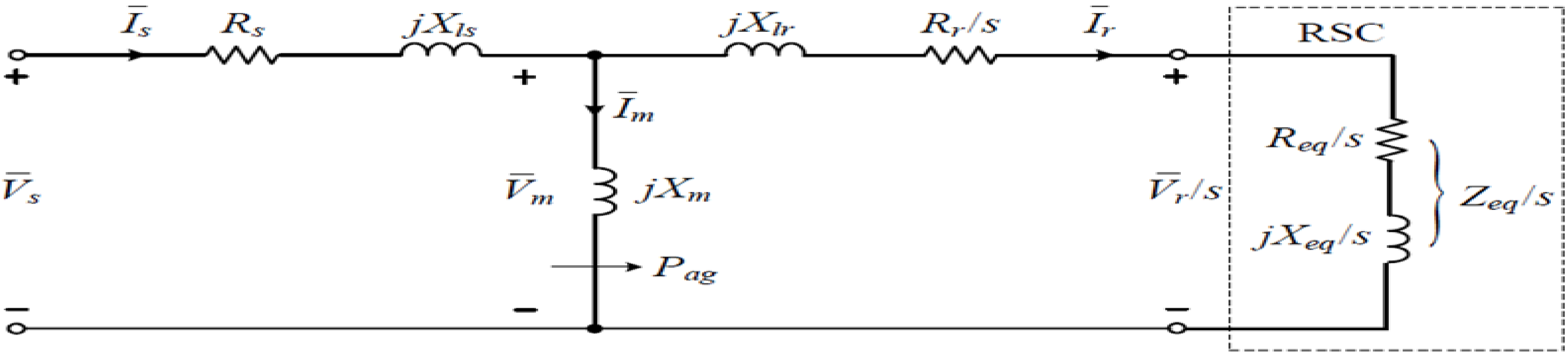


Voltage across magnetizing branch $\bar{V}_m$?



Voltage across magnetizing branch $\overline{V}_m$

$$\overline{V}_m = \overline{V}_s - \overline{I}_s\left(R_s + j\omega_s L_{ls}\right)$$



where stator voltage & current are given by

$$\overline{V}_s = V_s\angle 0^\circ \quad \text{and} \quad \overline{I}_s = I_s\angle 180^\circ$$

Q. What information we can get if stator voltage & current are 180° out of phase?

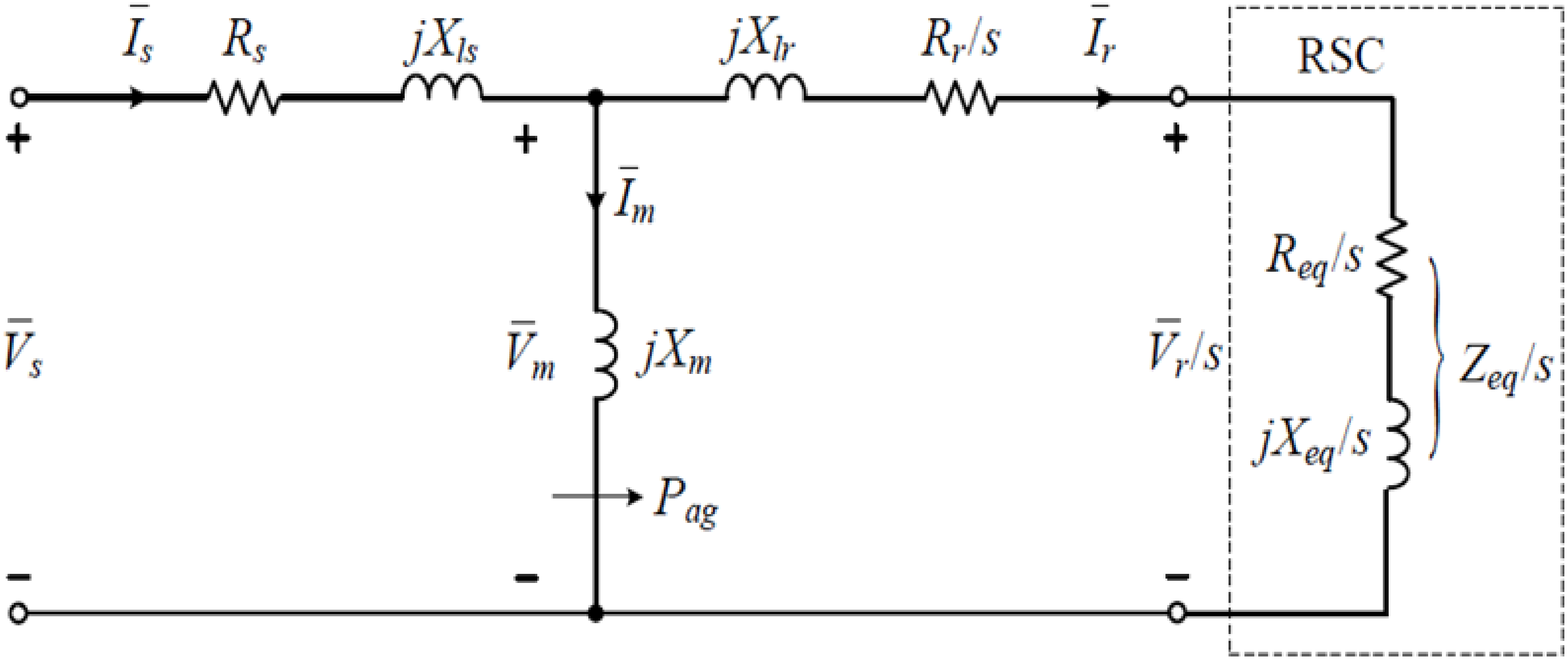
$$\bar{V}_s = V_s \angle 0° \quad \text{and} \quad \bar{I}_s = I_s \angle 180°$$

Answer. If stator voltage & current are 180° out of phase then:

1. DFIG is in generating mode &

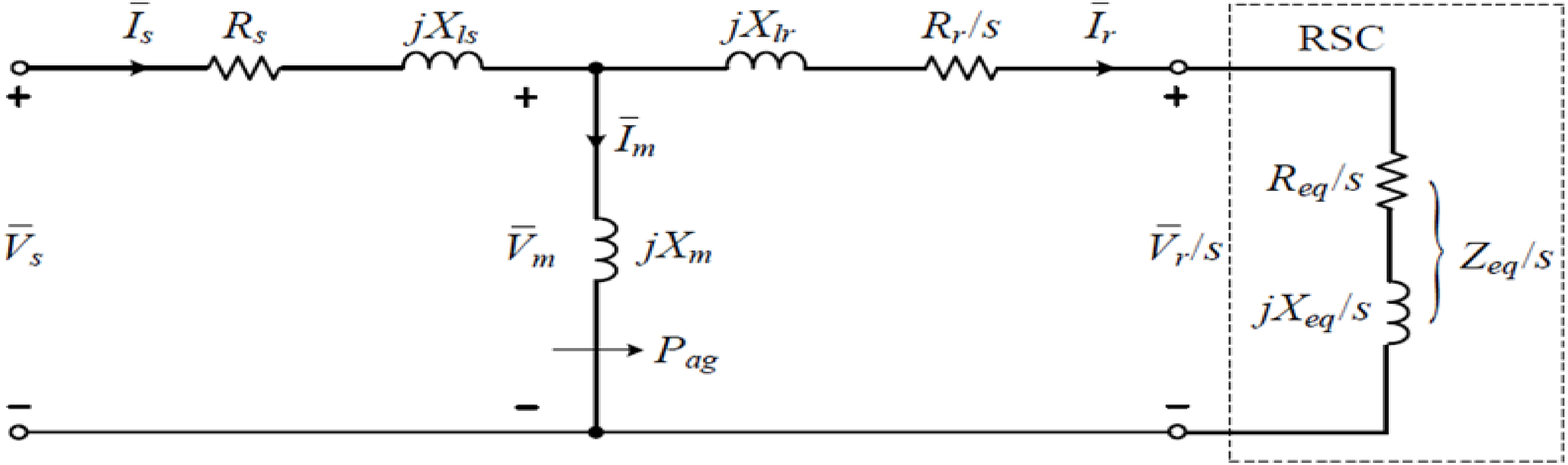
2. Stator power factor (*PFs*) is unity[Cos(180°)=-1].

Write equation for Magnetizing current *Im*?



Magnetizing current can be determined by

$$\bar{I}_m = \frac{\bar{V}_m}{j\omega_s L_m}$$

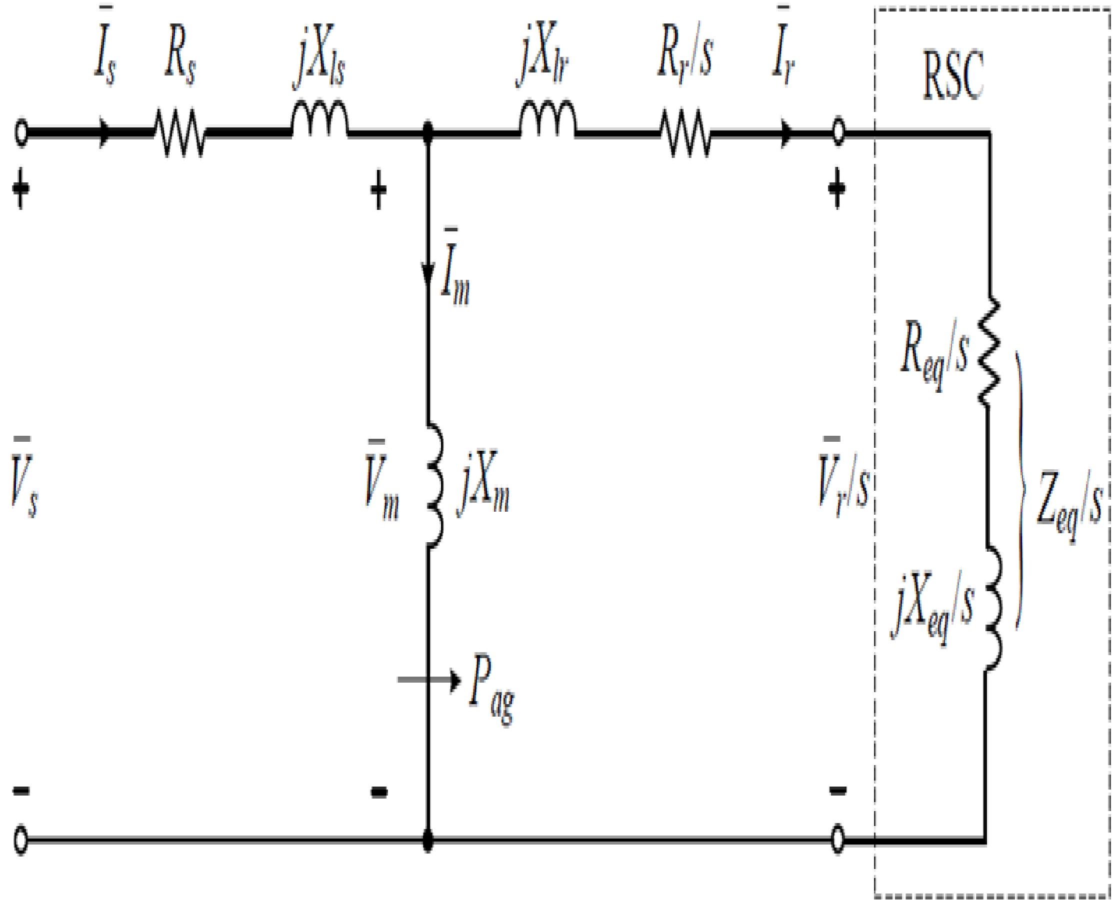


Rotor current $\bar{I}_r$

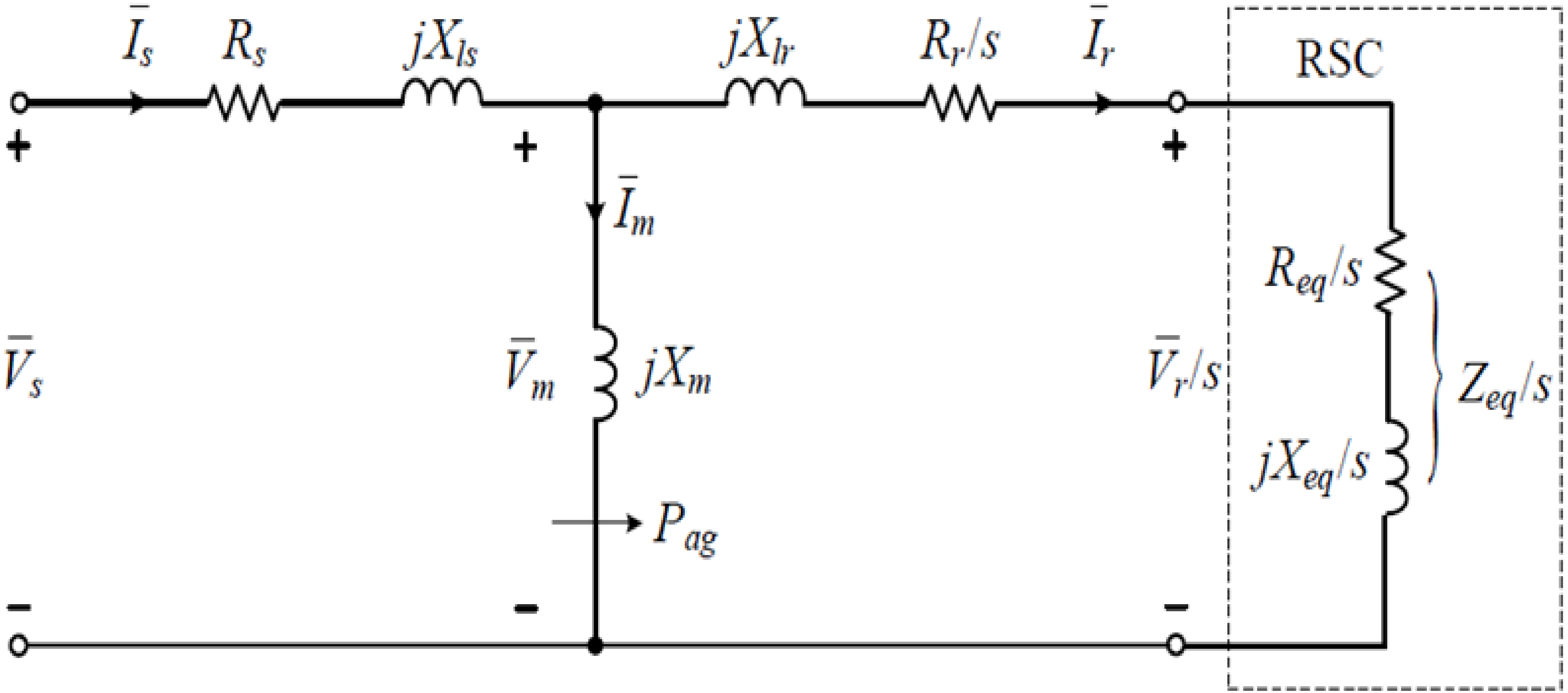
$$\bar{I}_r = \bar{I}_s - \bar{I}_m$$

$$I_s = \frac{V_s \pm \sqrt{V_s^2 - \frac{4R_s\omega_s T_m}{3P}}}{2R_s}$$

$$\bar{I}_m = \frac{\bar{V}_m}{j\omega_s L_m}$$

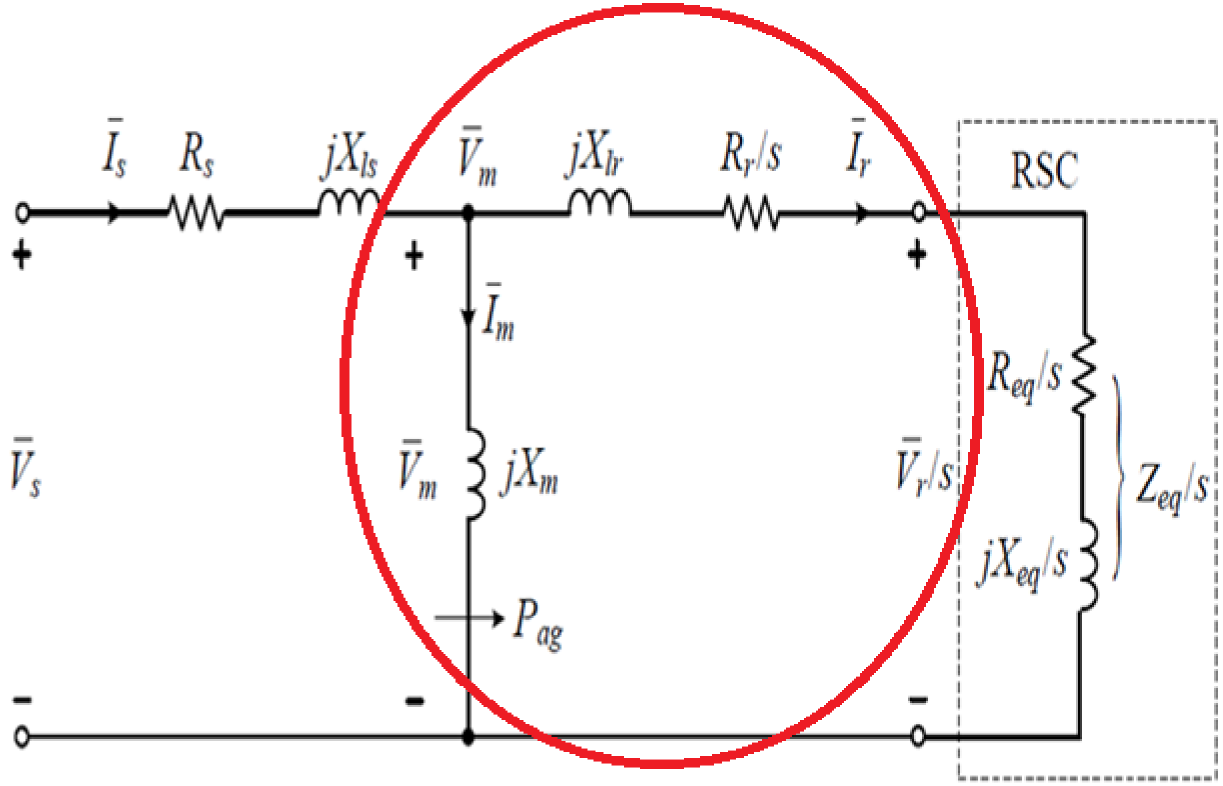


Rotor voltage Vr can be calculated by?



Rotor voltage Vr can be calculated by:

$$\overline{V}_r / s = \overline{V}_m - \overline{I}_r\left(\frac{R_r}{s} + j\omega_s L_{lr}\right)$$



from which

$$\overline{V}_r = s\overline{V}_m - \overline{I}_r\left(R_r + js\omega_s L_{lr}\right)$$

Rotor voltage & current relate to equivalent resistance R_{eq} & reactance X_{eq} by

$$\frac{\overline{V}_r / s}{\bar{I}_r} = R_{eq}/s + jX_{eq}/s$$

$$R_{eq} + jX_{eq} = \frac{\overline{V}_r}{\bar{I}_r}$$

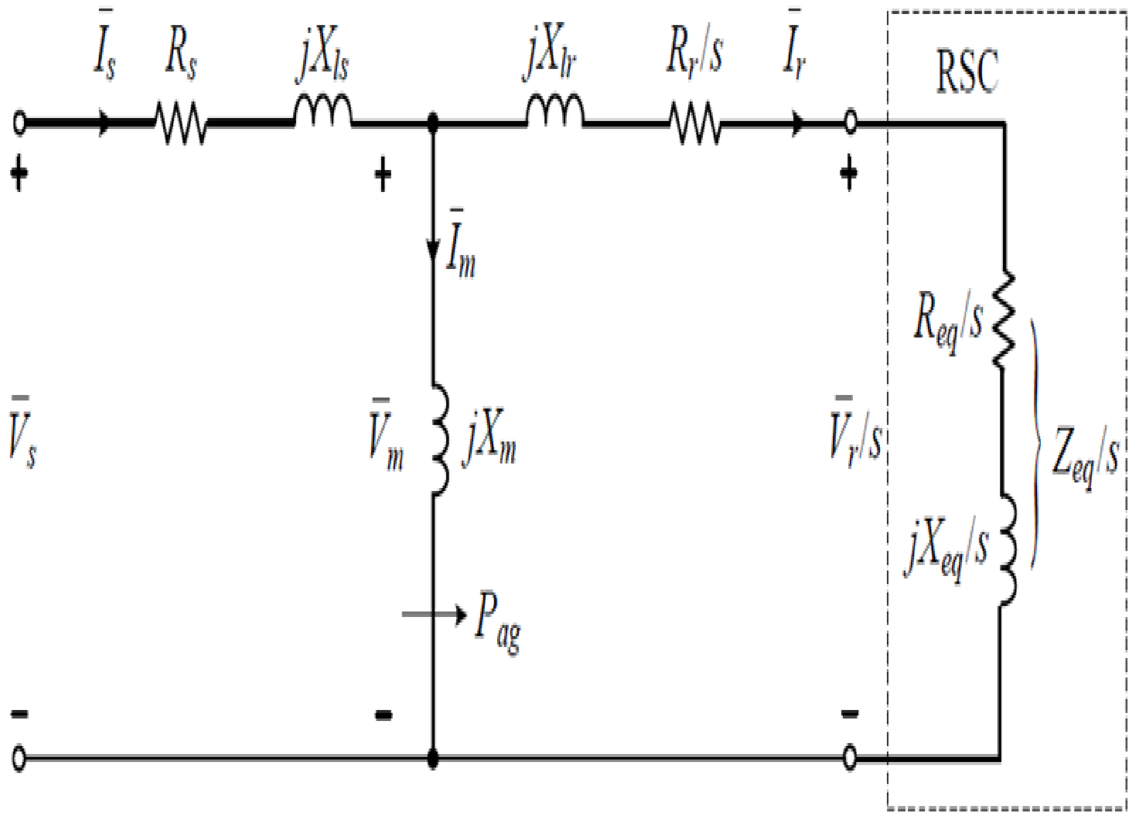
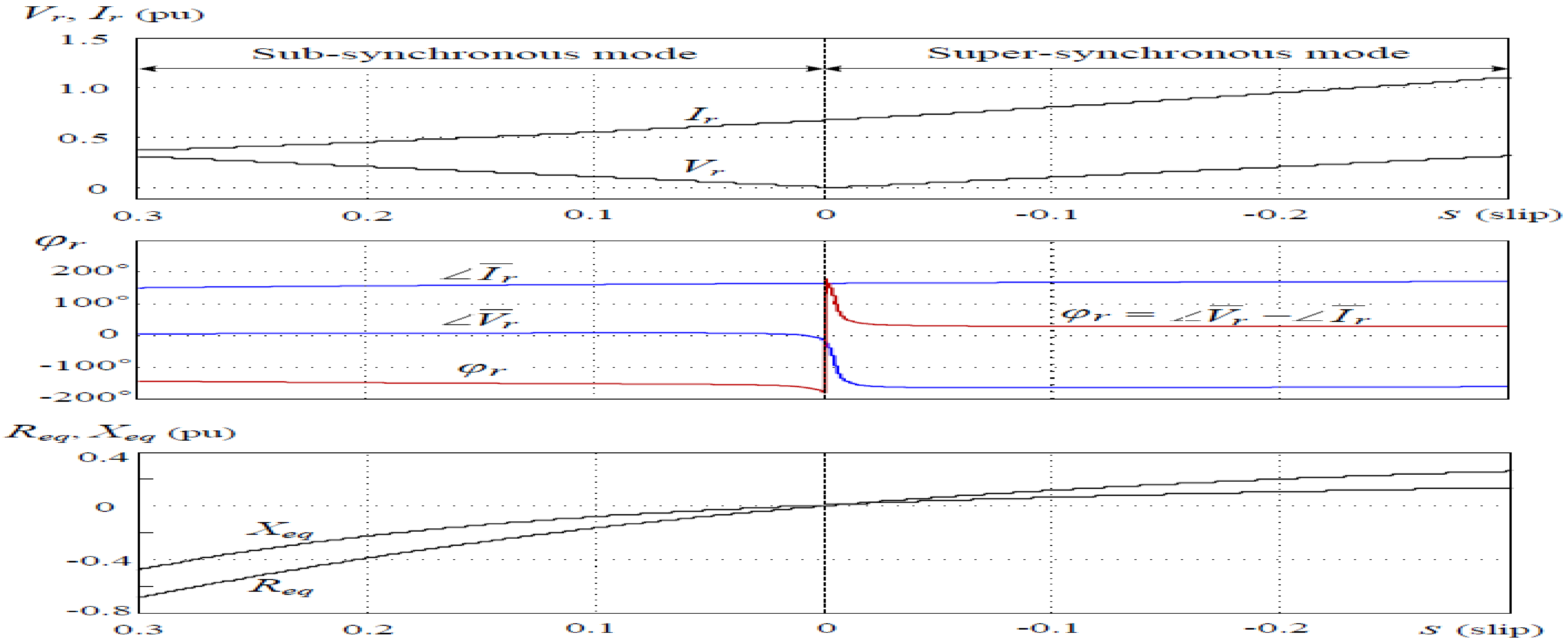
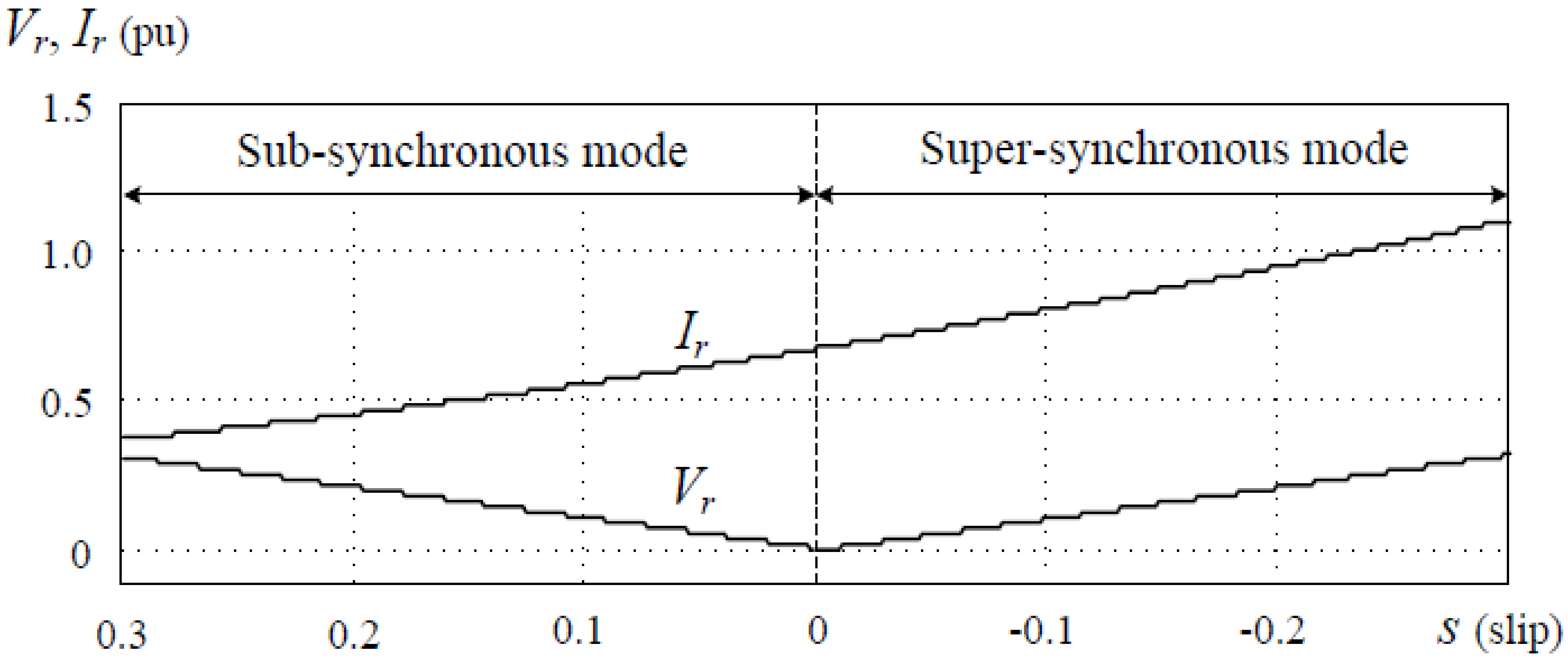


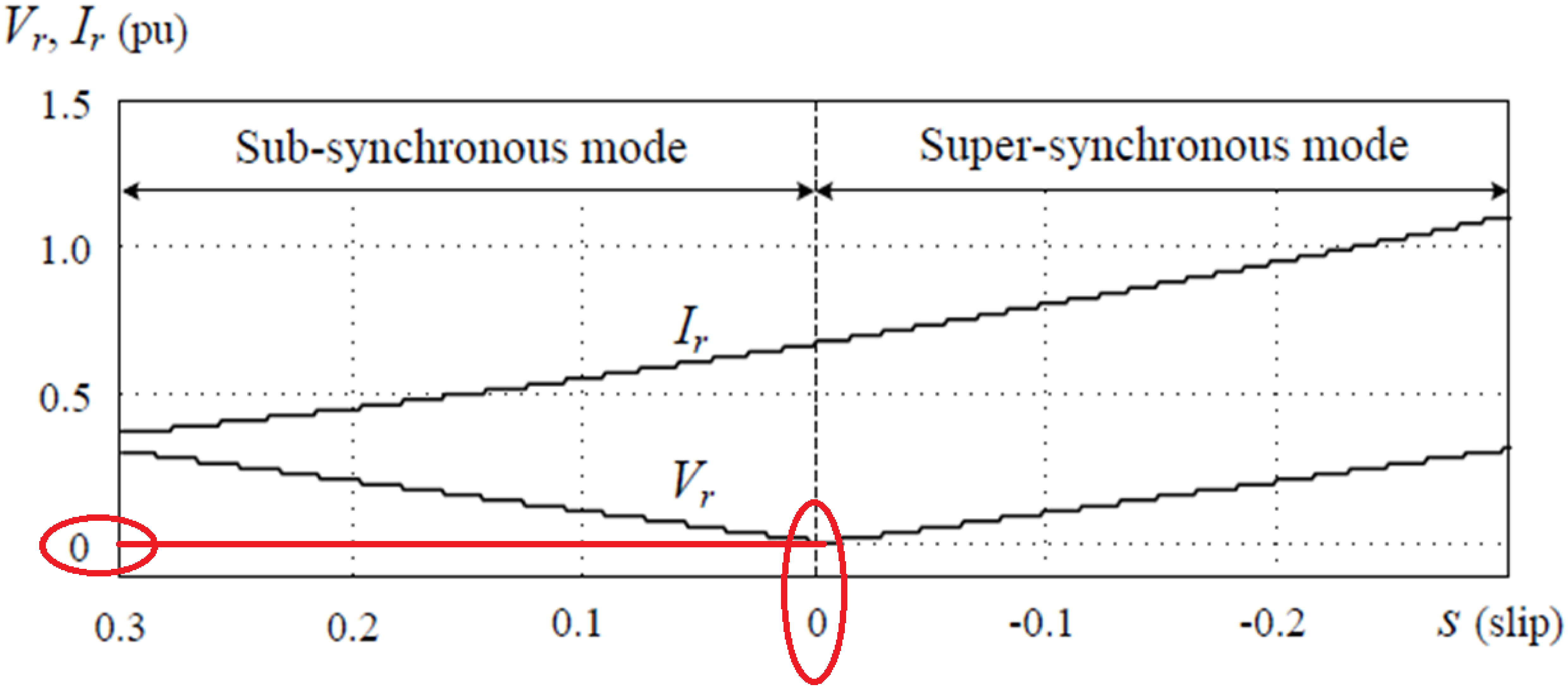
Fig. shows rotor current(Ir), rotor voltage(Vr) & equivalent impedance(Zeq) of rotor-side converter when slip of DFIG varies from +0.3 to -0.3.



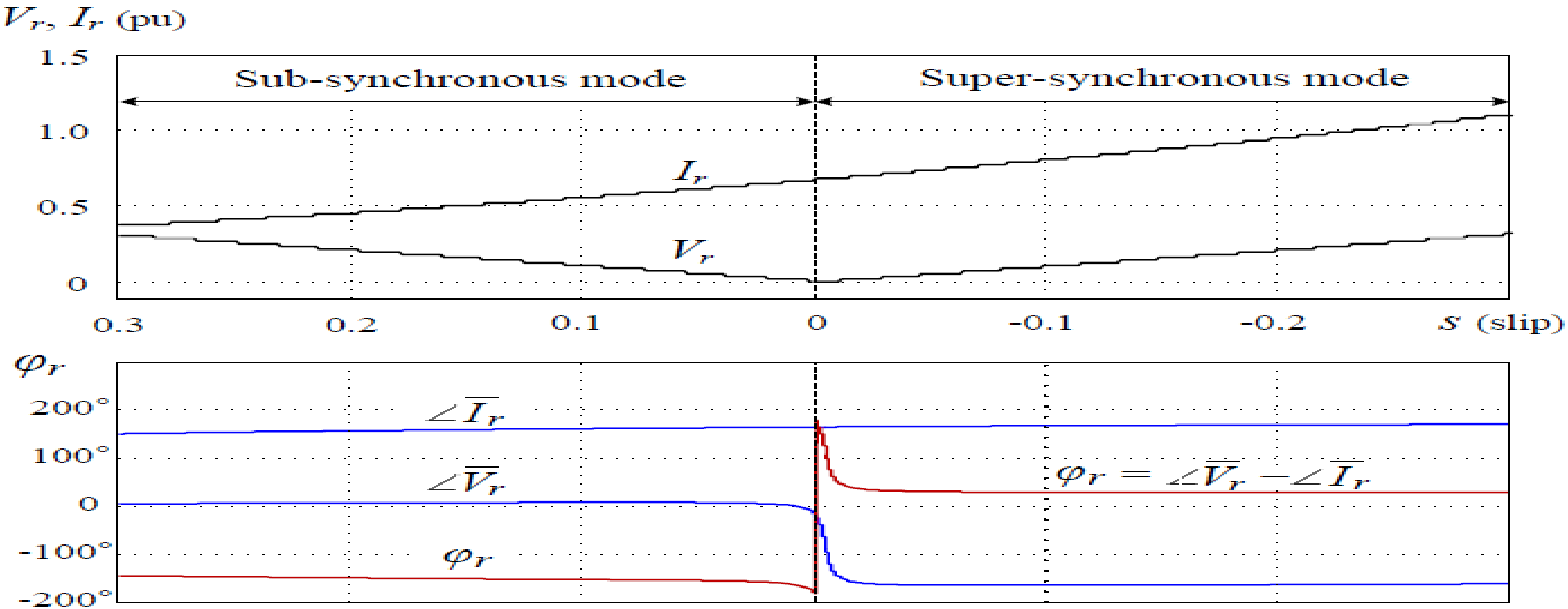
Rotor current *Ir* increases whether slip is +ve or -ve



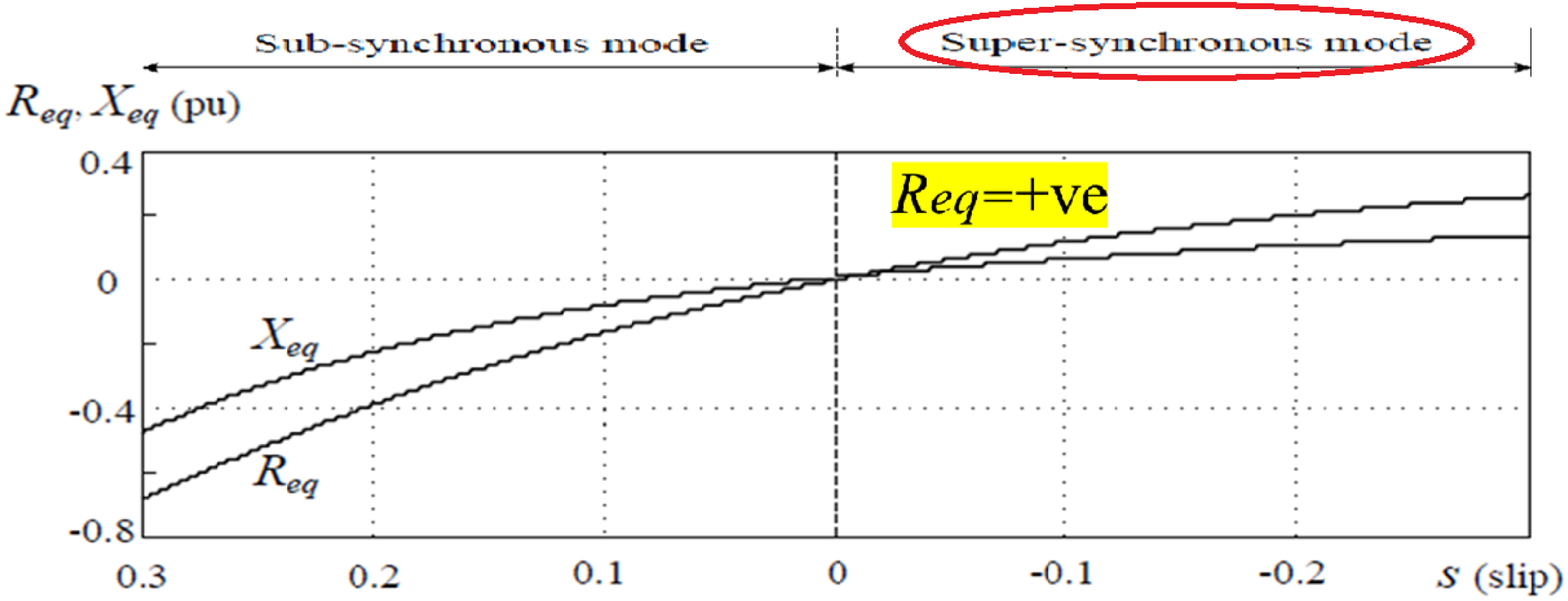
Rotor voltage *Vr* decreases when slip varies from 0.3 to 0, (at *s* = 0,*Vr=0*) .*Vr* increases with a -ve slip.



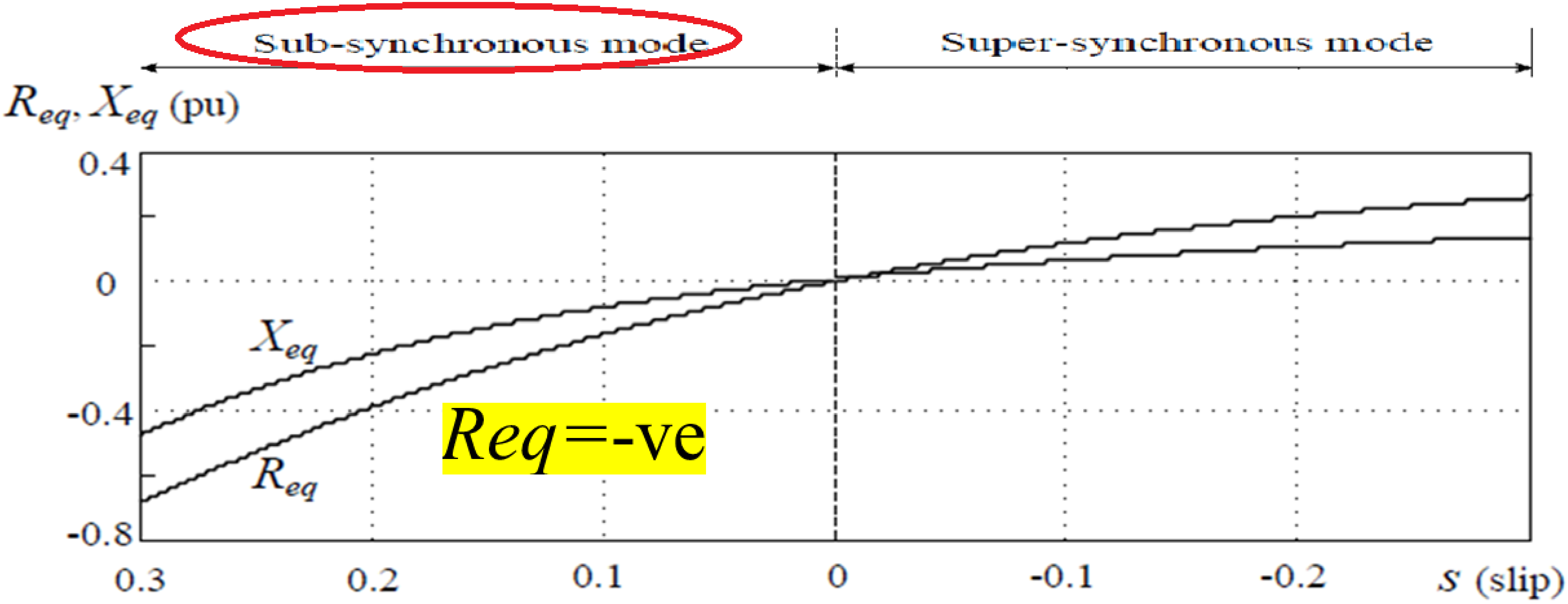
Phase angle of rotor voltage, rotor current, & rotor power factor angle ϕ_r ($\phi r = \angle V\, r - \angle I\, r$) are also shown.



When DFIG operates in super-synchronous mode, equivalent resistance *Req* of RSC is +ve, indicating that an active power is delivered from rotor to converter.



When generator is in sub-synchronous mode, *Req* is -ve, signifying that converter transfers an active power to rotor.



Case Study 8-1 Equivalent Impedance of Rotor-Side Converter

- Consider a 1.5MW/690V/50Hz/1750rpm DFIG wind energy system.
- Parameters of generator are given in Table B-5 of Appendix B.

Generator Type	DFIG, 1.5MW/690V/50Hz	
Rated Mechanical Power	1.5 MW	1.0 pu
Rated Stator Line-to-line Voltage	690 V (rms)	
Rated Stator Phase Voltage	398.4 V (rms)	1.0 pu
Rated Rotor Phase Voltage	67.97 V (rms)	0.1706 pu
Rated Stator Current	1068.2 A (rms)	0.8511 pu
Rated Rotor Current	1125.6 A (rms)	0.8968 pu
Rated Stator Frequency	50 Hz	1.0 pu
Rated Rotor Speed	1750 rpm	1.0pu
Nominal Rotor Speed Range	1200–1750 rpm	0.686–1.0pu
Rated Slip	-0.1667	
Number of Pole Pairs	2	
Rated Mechanical Torque	8.185 kN.m	1.0 pu
Stator Winding Resistance R_s	2.65 mΩ	0.0084 pu
Rotor Winding Resistance R_r	2.63 mΩ	0.0083 pu
Stator Leakage Inductance L_{ls}	0.1687 mH	0.167 pu
Rotor Leakage Inductance L_{lr}	0.1337 mH	0.1323 pu
Magnetizing Inductance L_m	5.4749 mH	5.419 pu
Base Current $I_B = 1.5\text{MW}/(\sqrt{3}\times 690\text{V})$	1255.1 A (rms)	1.0 pu
Base Flux Linkage Λ_B	1.2681 Wb (rms)	1.0 pu
Base Impedance Z_B	0.3174 Ω	1.0 pu
Base Inductance L_B	1.0103 mH	1.0 pu
Base Capacitance C_B	10028.7 μF	1.0 pu

Generator operates with an MPPT scheme, & its mechanical torque *Tm* is proportional to square of rotor speed.

- Stator power factor is unity.
- This case study is to investigate relationship between:
- rotor voltage,
- rotor current, &
- equivalent impedance of rotor-side converter when DFIG operates at

1.Super-synchronous 2.Synchronous, & 3. sub-synchronous speeds.

i) Converter Equivalent Impedance at 1750rpm (Super-synchronous mode)

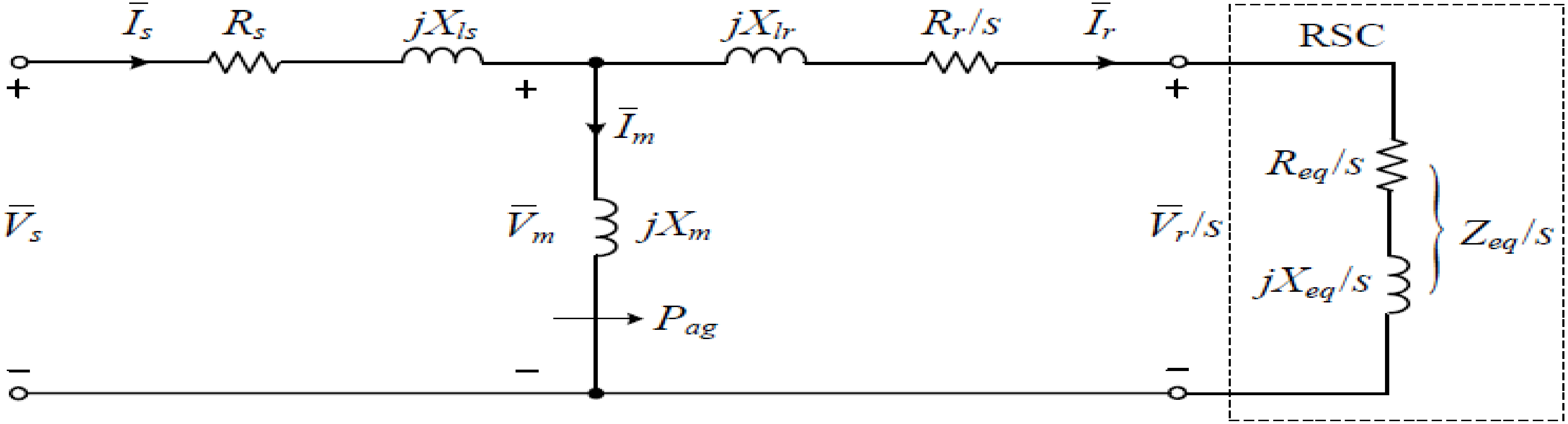
Stator current *Is* is calculated by:

$$I_s = \frac{V_s \pm \sqrt{V_s^2 - \frac{4R_s T_m \omega_s}{3P}}}{2R_s} = -1068.2\text{ A} \quad (\text{the other solution } I_s = 1.514\times 10^5\text{ A omitted})$$

where $V_s = 690/\sqrt{3}$ V, $T_m = -8185.1$ N.m, $\omega_s = 2\pi \times 50$ rad/sec, $R_s = 6.25$ mΩ and $P = 2$

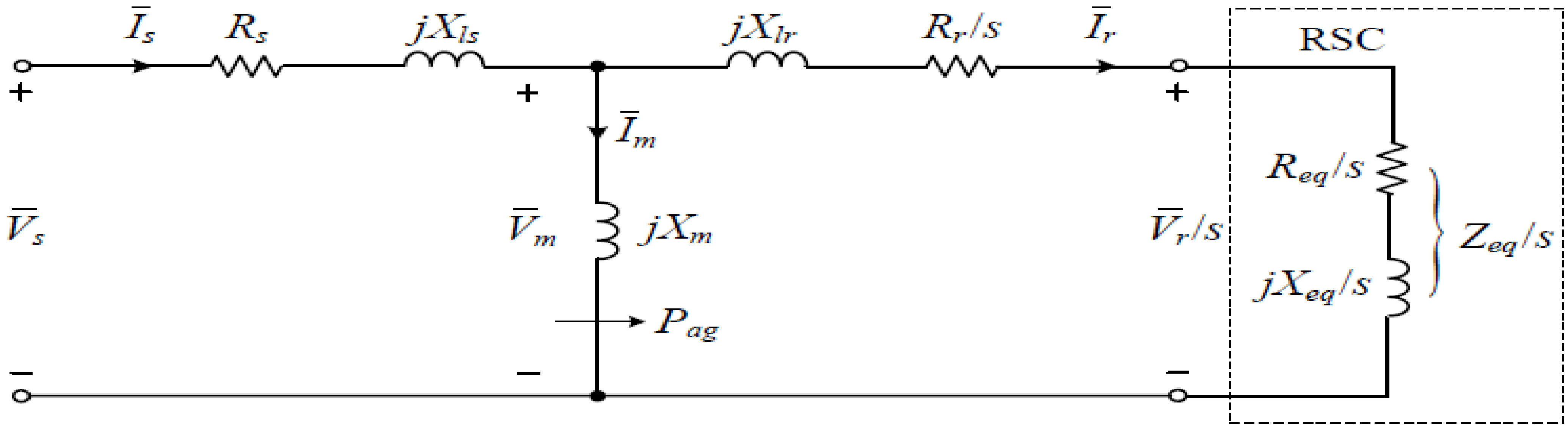
In super synchronous, or synchronous or sub-synchronous modes I_s would be -ve

Using equivalent circuit voltage across magnetizing branch *Vm* is



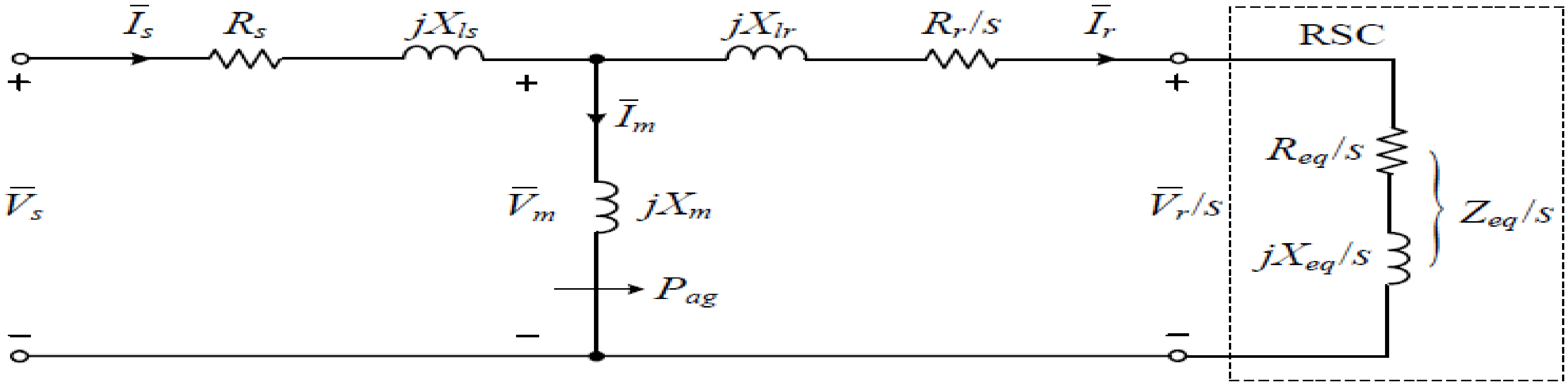
$$\overline{V}_m = \overline{V}_s - \overline{I}_s\left(R_s + j\omega_s L_{ls}\right)$$
$$= 690/\sqrt{3}\angle 0° - 1068.2\angle 180° \times (0.00625 + j100\pi \times 0.1687 \times 10^{-3})$$
$$= 401.2 + j56.6 = 405.2\angle 8° \ \text{ V}$$

Magnetizing current is calculated by



$$\bar{I}_m = \frac{\bar{V}_m}{j\omega_s L_m} = 32.92 - j233.26 = 235.6\angle -82.0^\circ \ \text{A}$$

The rotor current is



$$\overline{I}_r = \overline{I}_s - \overline{I}_m = -1101.1 + j233.26 = 1125.6\angle 168.0° \text{ A}$$

The rotor voltage is $\overline{V}_r = s\overline{V}_m - \overline{I}_r\left(R_r + js\omega_s L_{lr}\right) = 67.97\angle -164.9° \text{ V}$

where $s = (\omega_s - \omega_r)/\omega_s = -0.1667$

Equivalent impedance for rotor-side converter is given by

$$\overline{Z}_{eq} = \overline{V}_r / \overline{I}_r = 0.05375\ \Omega + j0.2751\ \Omega$$

From which

$$\begin{cases} R_{eq} = 0.05375\ \Omega \\ X_{eq} = 0.02751\ \Omega \end{cases}$$

ii) Converter Equivalent Impedance at 1500rpm (Synchronous Speed)

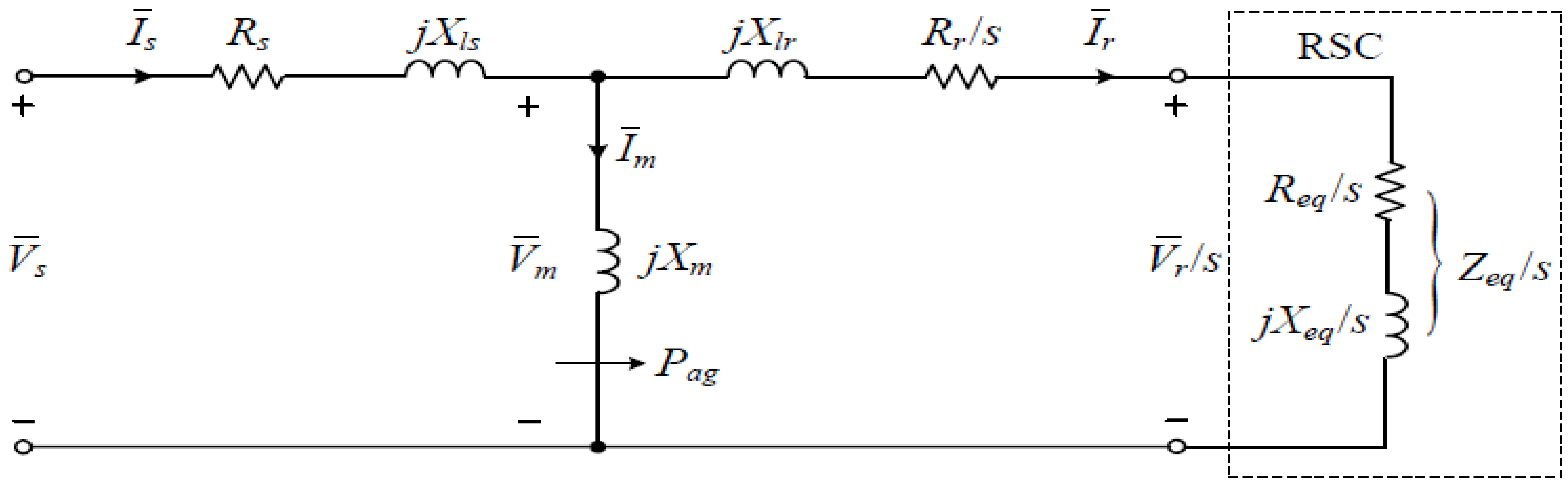
- When generator operates at 1500 rpm, stator current is

$$I_s = \frac{V_s \pm \sqrt{V_s^2 - \dfrac{4R_sT_m\omega_s}{3P}}}{2R_s} = -786.3\ \text{A} \quad (\text{the other solution } I_s = 1.511\times 10^5\ \text{A omitted})$$

$$\text{where} \quad T_m = -(1500/1750)^2 \times 8.1851 = -6.0135\ \text{kN.m}$$

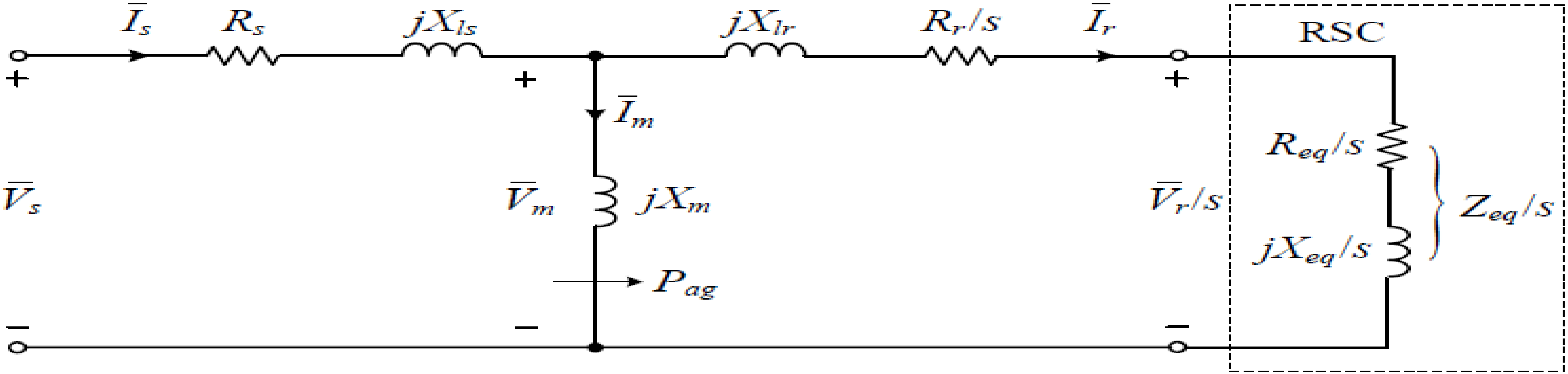
Voltage across magnetizing branch(Vm) is:

$$\overline{V}_m = \overline{V}_s - \overline{I}_s\left(R_s + j\omega_s L_{ls}\right) = 400.5 + j41.7 = 402.6\angle 5.9^\circ \ \text{V}$$



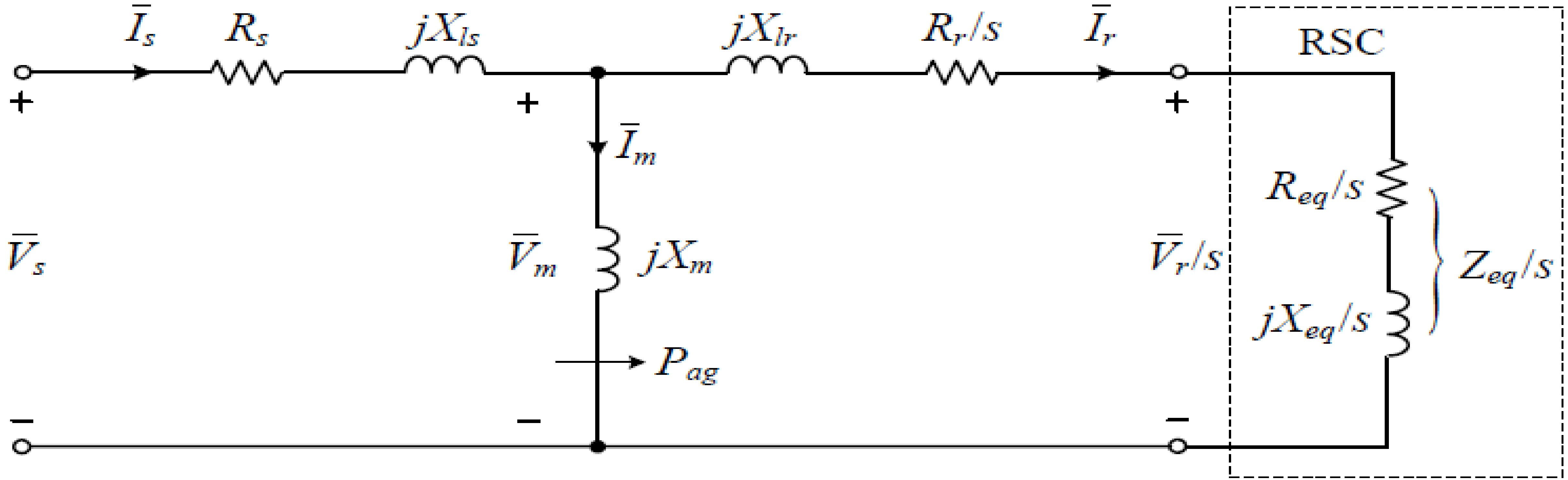
Magnetizing current(*Im*) can be determined by

$$\bar{I}_m = \frac{\bar{V}_m}{j\omega_s L_m} = 24.23 - j232.82 = 234.1\angle -84.1^\circ \ \text{A}$$



Rotor current(Ir) is

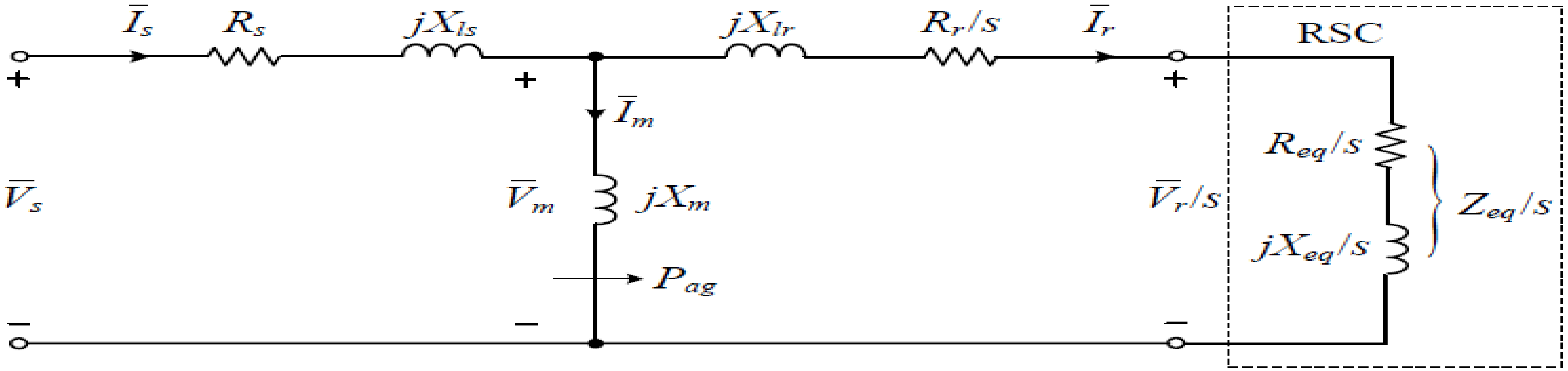
$$\overline{I}_r = \overline{I}_s - \overline{I}_m = -810.50 + j232.82 = 843.28\angle 164.0^\circ \text{ A}$$



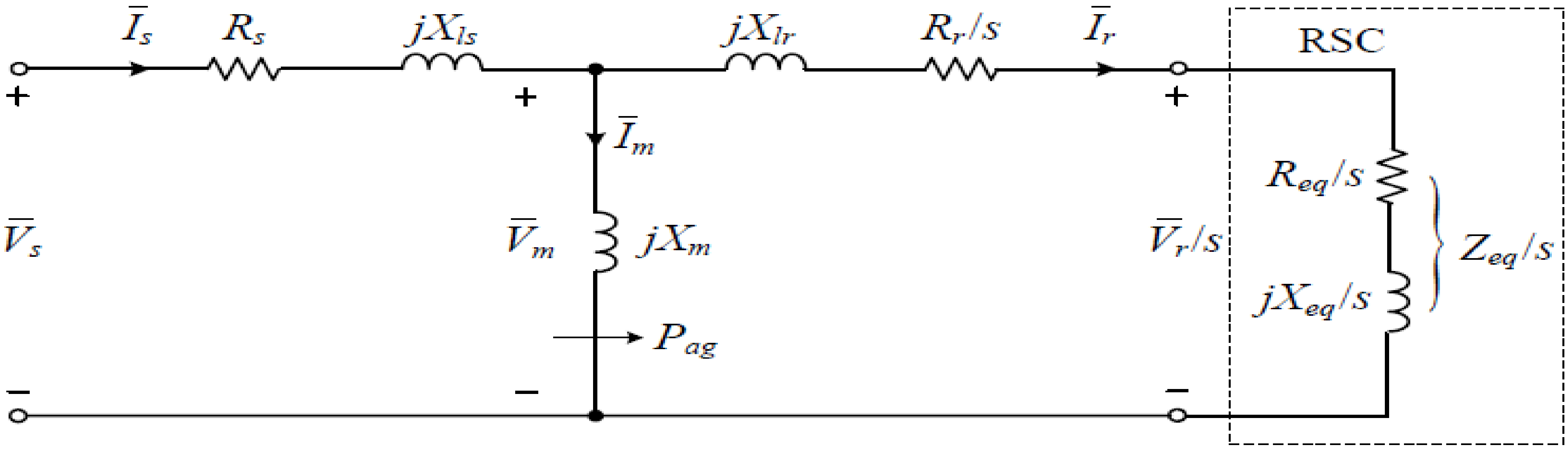
Rotor voltage $\overline{V}_r = s\overline{V}_m - \overline{I}_r(R_r + js\omega_s L_{lr}) = -\overline{I}_r R_r = 2.2178\angle -16°\ \text{V}$

Equivalent resistance & reactance for rotor-side converter are

$$\overline{Z}_{eq} = \overline{V}_r \,/\, \overline{I}_r = 0.00263\angle -180° = -0.00263 + j\,0.0\,\Omega$$



Alternatively, following equation can be established based on Fig.



$$\overline{V}_m - \overline{I}_r(R_r / s + j\omega_s L_{lr}) = \overline{I}_r(R_{eq} / s + jX_{eq} / s)$$

From which

$$s\overline{V}_m - \overline{I}_r(R_r + j s \omega_s L_{lr}) = \overline{I}_r(R_{eq} + j\omega_{sl} L_{eq})$$

$$s\overline{V}_m - \overline{I}_r\left(R_r + j\,s\,\omega_s L_{lr}\right) = \overline{I}_r\left(R_{eq} + j\,\omega_{sl} L_{eq}\right)$$

- At synchronous speed slip *s=0* & slip frequency ω_{sl}*=0*, the above equation is simplified to

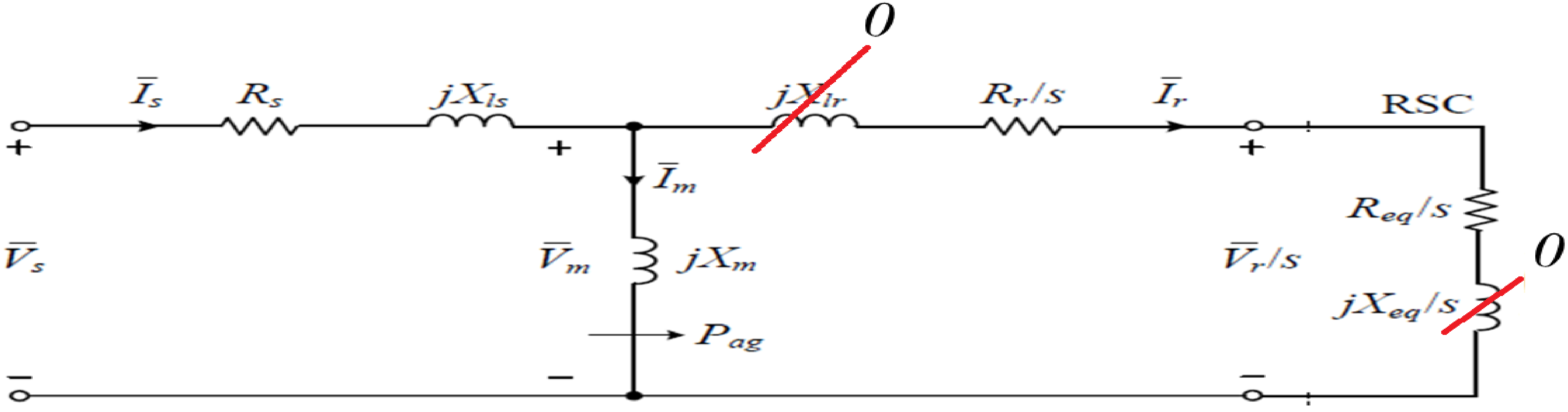
$$-\bar{I}_r R_r = \bar{I}_r R_{eq}$$

Thus equivalent resistance and reactance for rotor-side converter are

$$\begin{cases} R_{eq} = -R_r = -0.00263\ \Omega \\ X_{eq} = \omega_{sl} L_{eq} = 0 \end{cases}$$

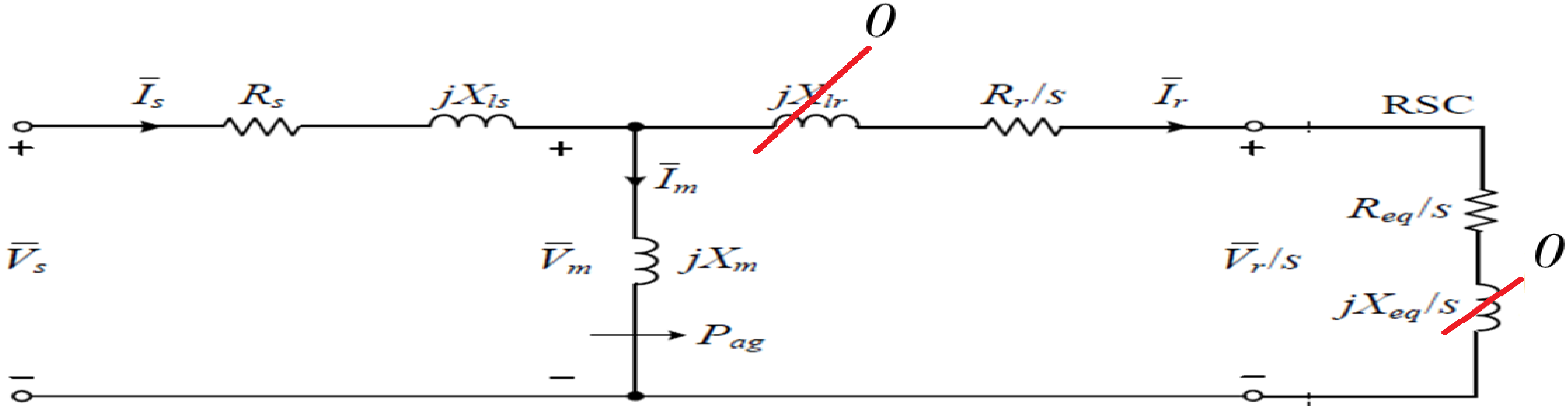
When DFIG operates at synchronous speed, both slip $s=0$ & slip frequency $\omega_{sl}=0$.

- This implies that a dc current flows through rotor circuit, & rotor leakage reactance X_{lr} & equivalent reactance X_{eq} are both 0.



In this case, induction generator operates just like a wound rotor synchronous generator, where rotor flux is produced by a dc current through a dc exciter.

- In DFIG wind energy system, dc excitation is provided by rotor-side converter



iii) Converter Equivalent Impedance at Sub-synchronous Speed

- Following same procedure, calculated rotor voltage, rotor current, & equivalent impedance of rotor-side converter in sub-synchronous mode (1200 & 1350 rpm) are summarized in Table .
- For convenience of comparison, calculated results for DFIG operating in synchronous (1500 rpm) & super-synchronous (1650 &1750 rpm) modes are also given in table.

Equivalent impedance of RSC in 1.5MW/690V DFIG WECS (*PFs* = 1)

	Sub-synchronous		(Synchronous Speed)	**(Super-synchronous mode)**	
Rotor Speed (rpm)	1200	1350	1500	1650	1750 (rated)
Slip	0.2	0.1	0	-0.1	-0.1667 (rated)
T_m [kN.m]	3.849	4.871	6.014	7.276	8.185
$\bar{V}_r$ [V]	$83.756\angle 6.2°$	$43.068\angle 7.4°$	$2.218\angle -16.0°$	$39.711\angle -165.8°$	$67.965\angle -164.9°$
$\bar{I}_r$ [A]	$569.285\angle 155.9°$	$697.103\angle 160.5°$	$843.281\angle 164.0°$	$1006.991\angle 166.6°$	$1125.566\angle 168.0°$
R_{eq} [Ω]	-0.126989	-0.055113	-0.00263	0.034942	0.053751
X_{eq} [Ω]	-0.074293	-0.027918	0	0.018281	0.027513