Lecture#08

1. Case Study 3-2 Power &Efficiency Analysis

2. Solved & un-solved problems

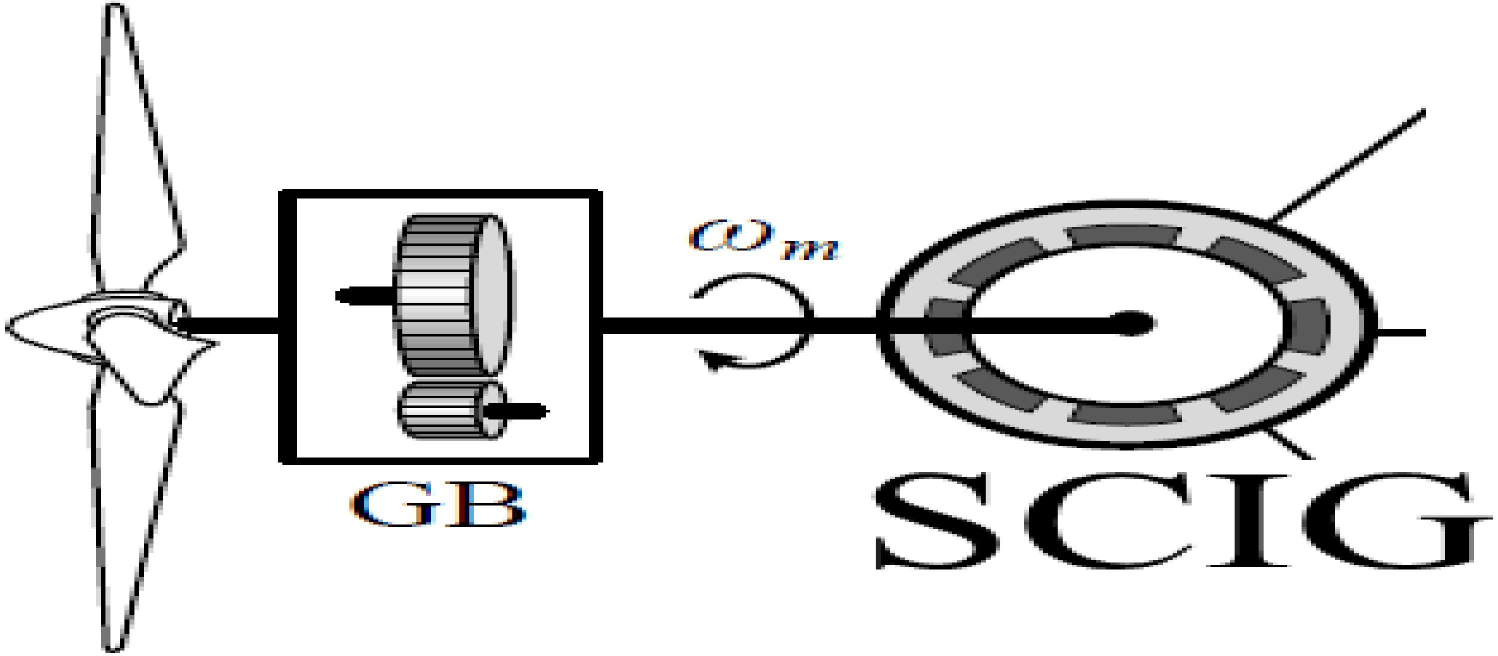
Case Study 3-2 Power &Efficiency Analysis

This case study is to:

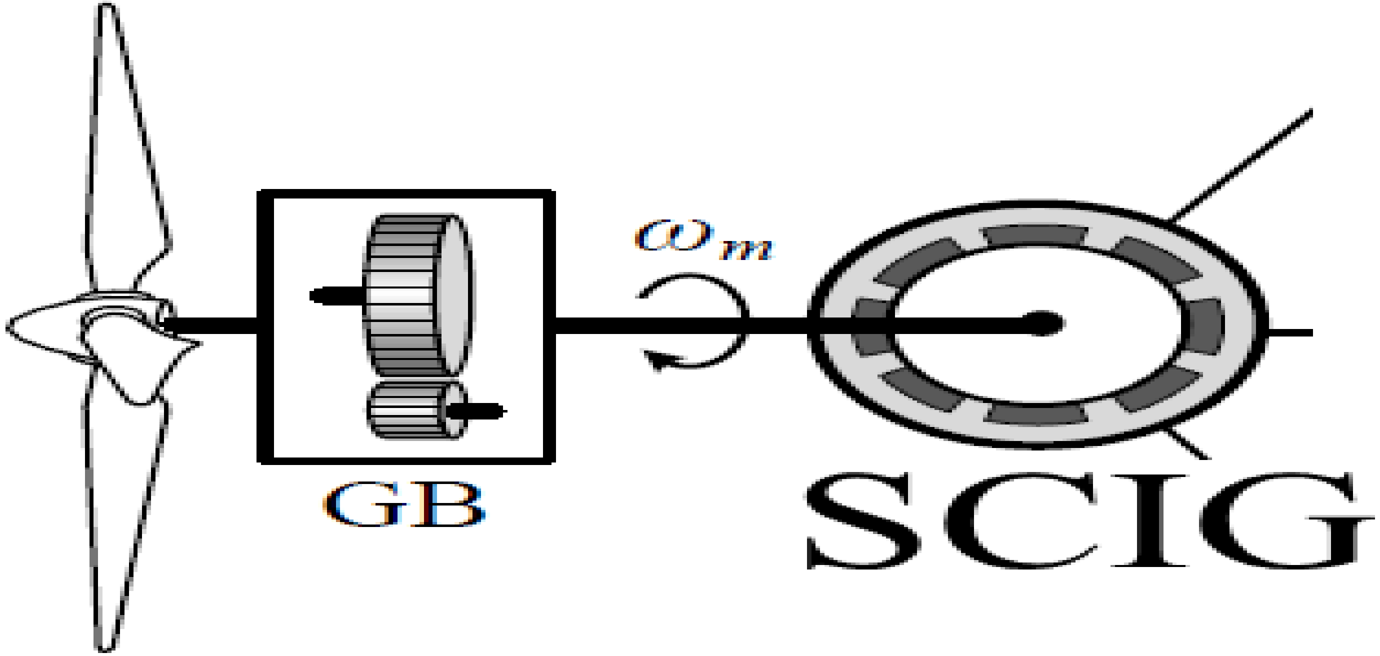
1) Investigate power losses & efficiency of SCIG based on its steady-state equivalent circuit

2) Examine differences between generating & motoring modes of operation.

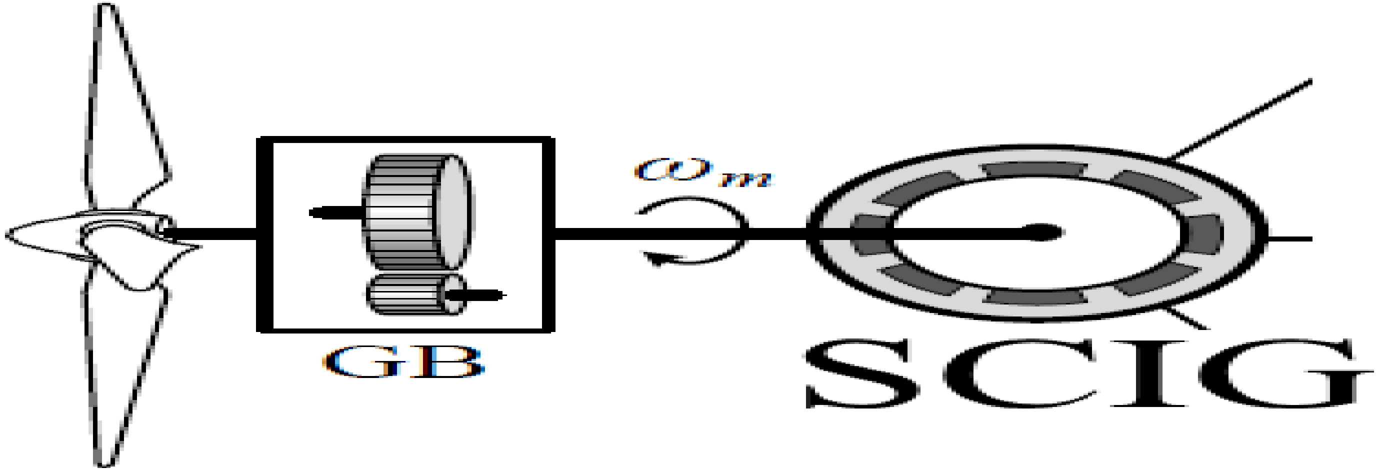
Consider 2.3MW/690V/50Hz/1512rpm SCIG in Case Study 3-1(pp.46)



Shaft of generator is coupled to wind turbine through a gearbox.



During systems start-up, **turbine & generator are brought by wind to a certain speed,** at which stator of generator is directly connected to grid of 690V/50Hz by circuit breaker.



For a given wind speed, generator operates **at a rotor speed of 1506 rpm**, at which the rotational losses of generator are 23kW.

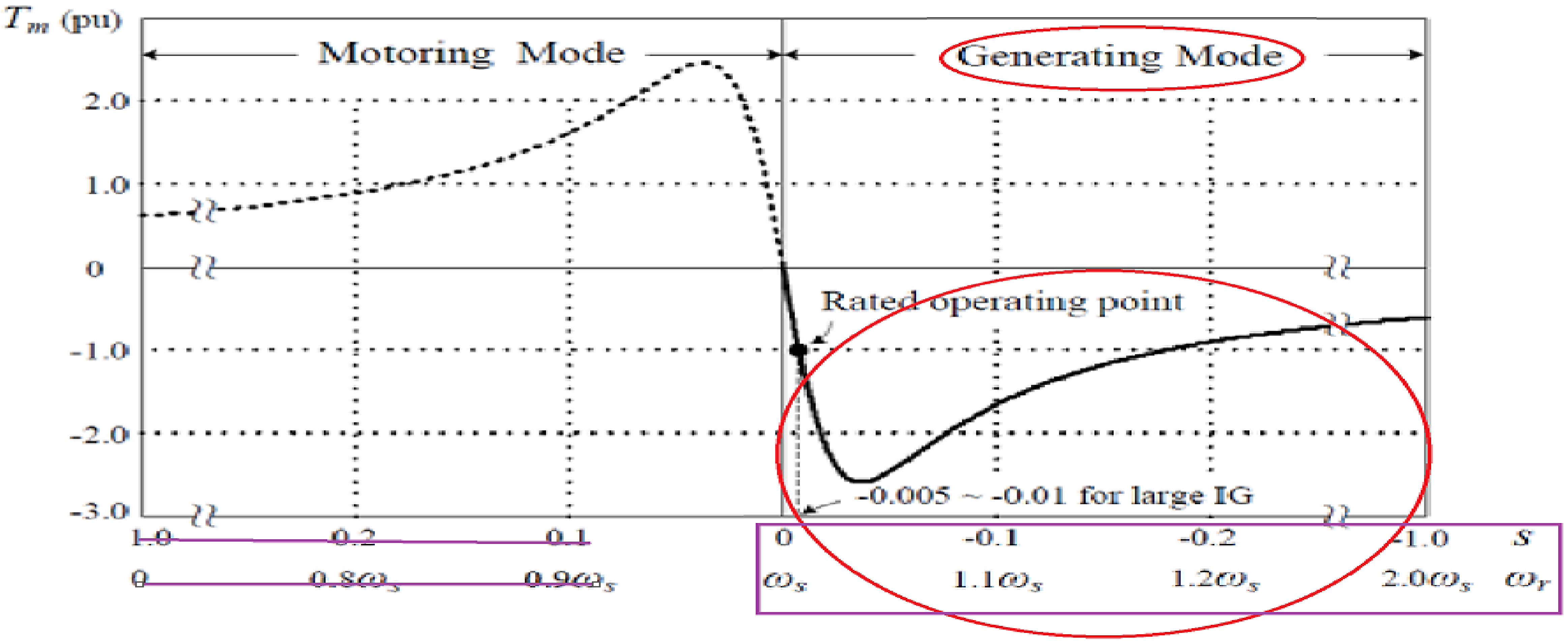
Table B-1 2.3MW/690V/50Hz Squirrel Cage Induction Generator (SCIG) nameplate and parameters

Generator Type	SCIG, 2.3MW/690V/50Hz	
Rated Output Power	2.30 MW	
Rated Mechanical Power	2.3339 MW	1.0 pu
Rated Apparent Power	2.59 MVA	1.0 pu
Rated Line-to-line Voltage	690 V (rms)	
Rated Phase Voltage	398.4 V (rms)	1.0 pu
Rated Stator Current	2168 A (rms)	1.0 pu
Rated Stator Frequency	50 Hz	1.0 pu
Rated Power Factor	0.888	
Rated Rotor Speed	1512 rpm	1.0pu
Rated Slip	-0.008	
Number of Pole Pairs	2	
Rated Mechanical Torque	14.74 kN.m	1.0 pu
Rated Stator Flux Linkage	1.2748 Wb (rms)	1.0053 pu
Rated Rotor Flux Linkage	1.2096 Wb (rms)	0.9539 pu
Stator Winding Resistance R_s	1.102 mΩ	0.006 pu
Rotor Winding Resistance R_r	1.497 mΩ	0.008 pu
Stator Leakage Inductance L_{ls}	0.06492 mH	0.111 pu
Rotor Leakage Inductance L_{lr}	0.06492 mH	0.111 pu
Magnetizing Inductance L_m	2.13461 mH	3.6481 pu
Moment of Inertia J	1200 kg.m^2	
Inertia Time Constant H	5.8078 sec	
Base Flux Linkage Λ_B	1.2681 Wb (rms)	1.0 pu
Base Impedance Z_B	0.1838 Ω	1.0 pu
Base Inductance L_B	0.58513 mH	1.0 pu
Base Capacitance C_B	17316.17 μF	1.0 pu
Note: $H = J(\omega_m)^2 / (2S_B)$		

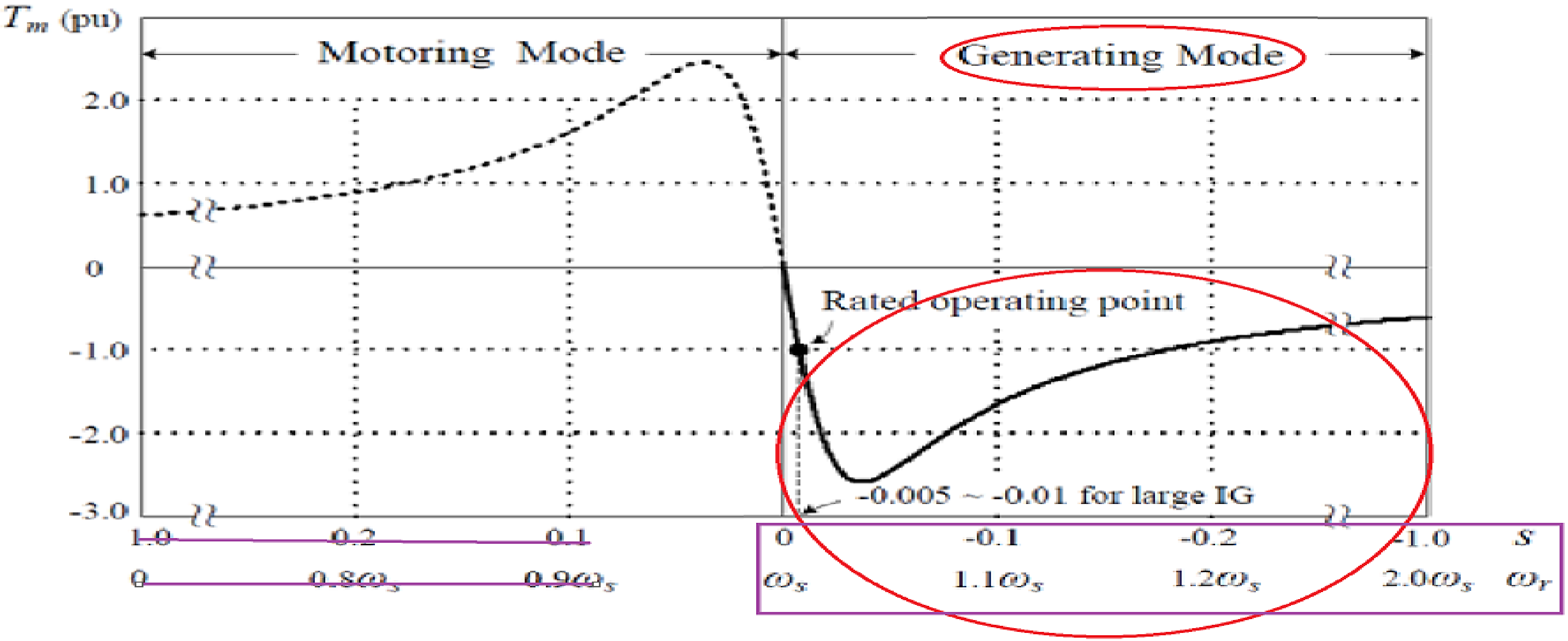
First of all we need to calculate the Slip s?

Why?

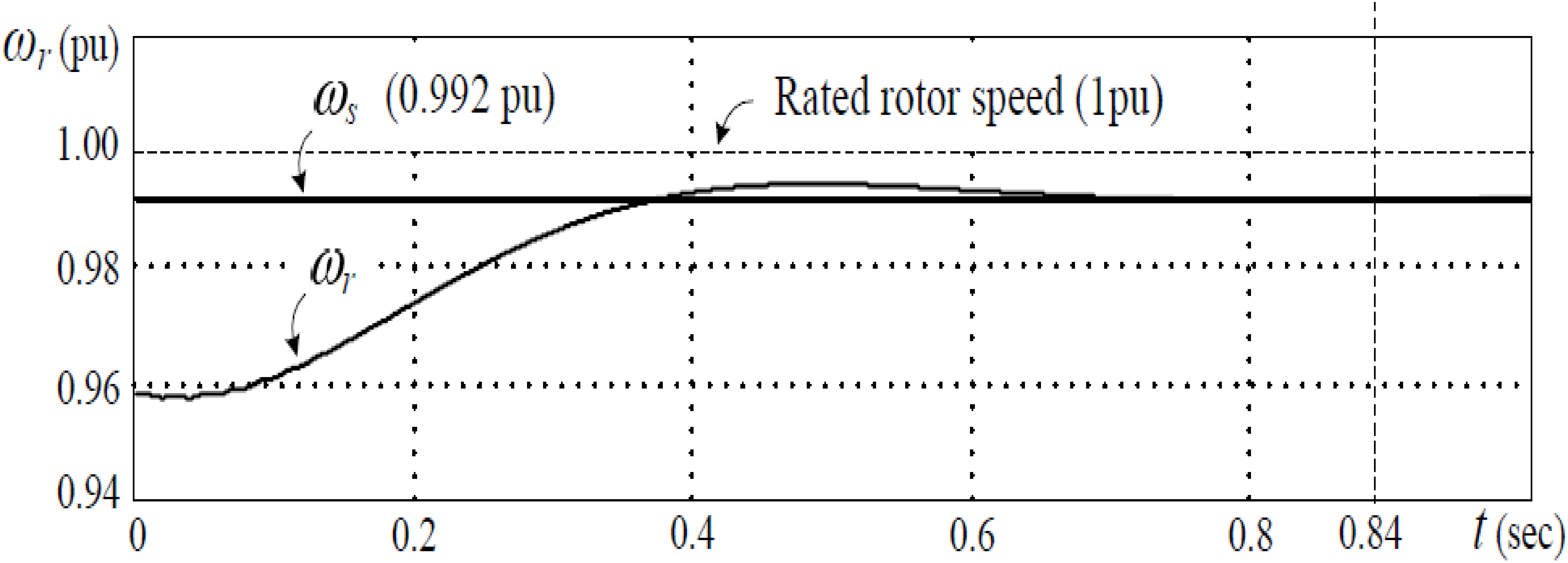
Slip s indicates:1. SCIG operates in Generating Mode(if s=-ve) or Motoring mode(if s=+ve).



Slip s indicates: 2. Mechanical torque Tm is +ve or -ve(if s=-ve,Tm=-ve i.e generating mode) or if s=+ve,Tm=+ve i.e motoring mode).



Slip s indicates: 3.Rotor speed is higher the synchronous speed i.e ωr > ωs



For slip we need 2 type of speeds?

(i)Synchronous and (ii)rotor speed

$$s = \frac{n_s - n_r}{n_s}$$

How we can find synchronous speed of Squirrel cage induction motor ns?

Synchronous speed of Squirrel cage induction motor ns?

- From previous knowledge of machines:

Synchronous speed of Squirrel cage induction motor ns? Right?

- ns=120p/f

Synchronous speed of Squirrel cage induction motor ns?

$$ns=120f/P$$

$$ns=120\times50/4$$

$$ns=1500rpm$$

Number of Pole Pairs	2

How many number of poles pairs P?

- **From appendix B**

Number of Pole Pairs	2

As number of **poles pairs** are 02

So total number of poles:P=?

So total number of poles:P=04

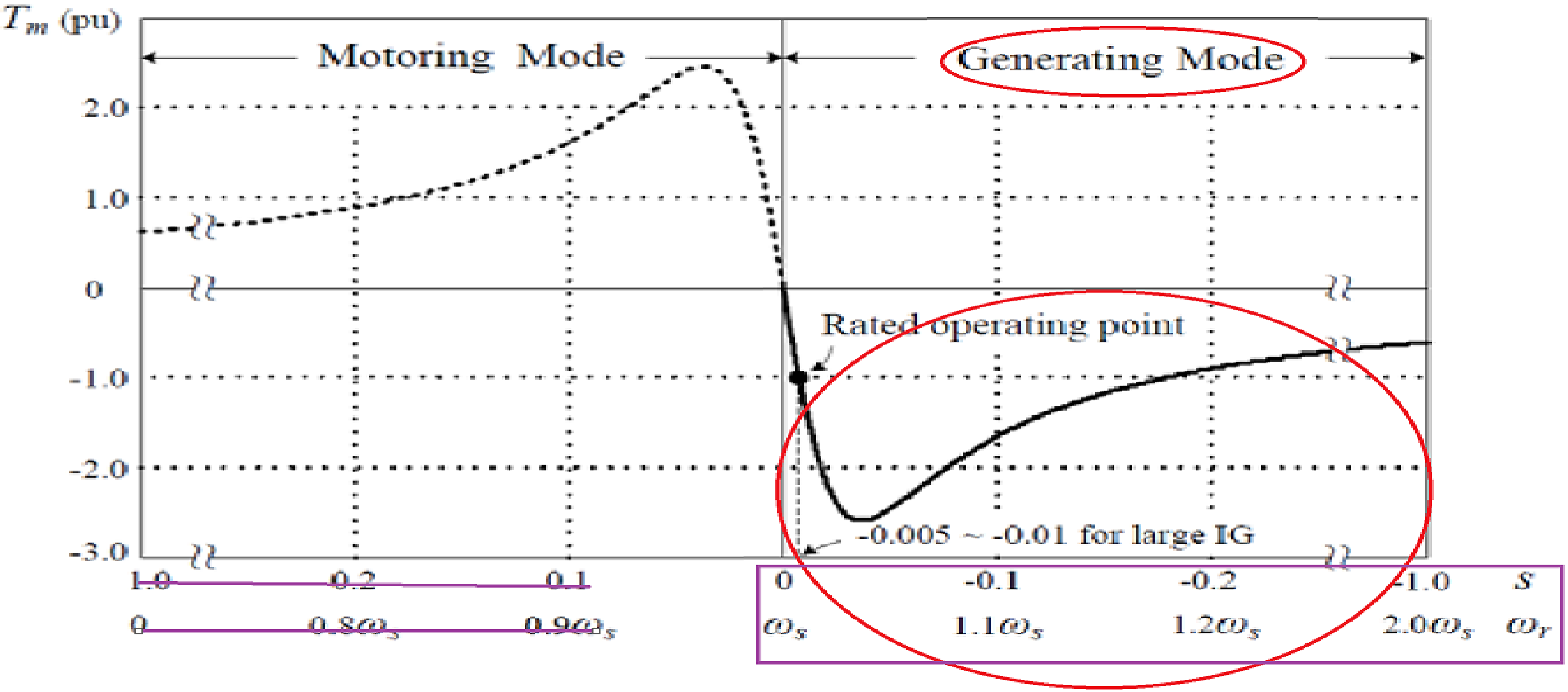
The slip $$s = \frac{n_s - n_r}{n_s}$$

ns=1500rpm

For a given wind speed, generator operates at a rotor speed of **1506 rpm=nr**

$$s = \frac{1500 - 1506}{1500} = -0.004$$

-ve slip indicates that **SCIG operates in generating mode.**



Lets calculate stator frequency?

Stator frequency in rad/sec

- $\varpi s = 2 \times \pi \times 50 = 314.16$ rad/sec

Calculation of X_{ls} and X_{lr} are stator& rotor leakage reactances & X_m is magnetizing reactance

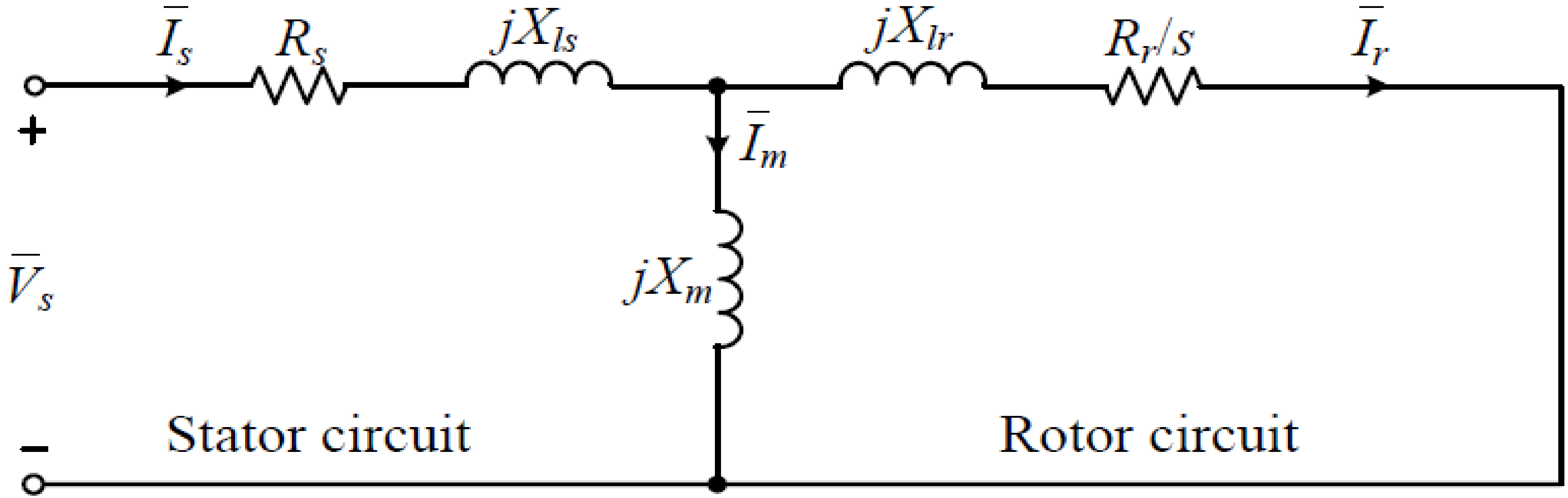
$$\begin{cases} X_{ls} = \omega_s L_{ls} \\ X_{lr} = \omega_s L_{lr} \\ X_m = \omega_s L_m \end{cases}$$

Stator Leakage Inductance L_{ls}	0.06492 mH
Rotor Leakage Inductance L_{lr}	0.06492 mH
Magnetizing Inductance L_m	2.13461 mH

ωs=2×π × 50=314.16rad/sec

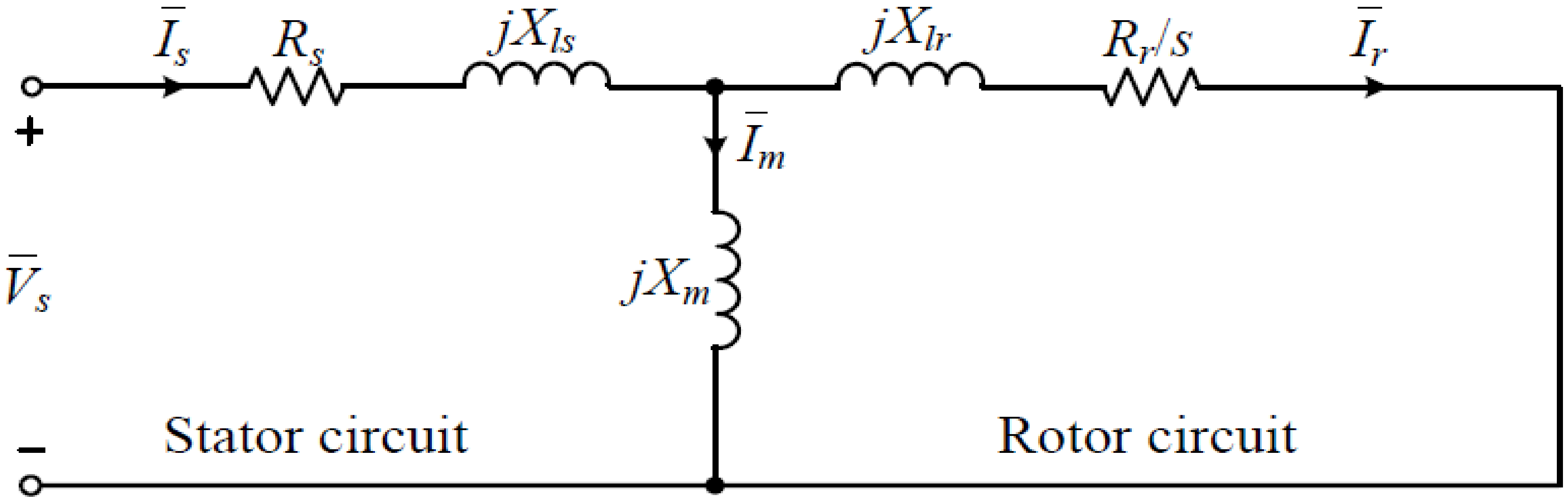
$$X_{ls} = \omega_s L_{ls} = 0.0204\,\Omega,\ X_{lr} = \omega_s L_{lr} = 0.0204\,\Omega \text{ and } X_m = \omega_s L_m = 0.6706\,\Omega$$

The equivalent impedance of SCIG?



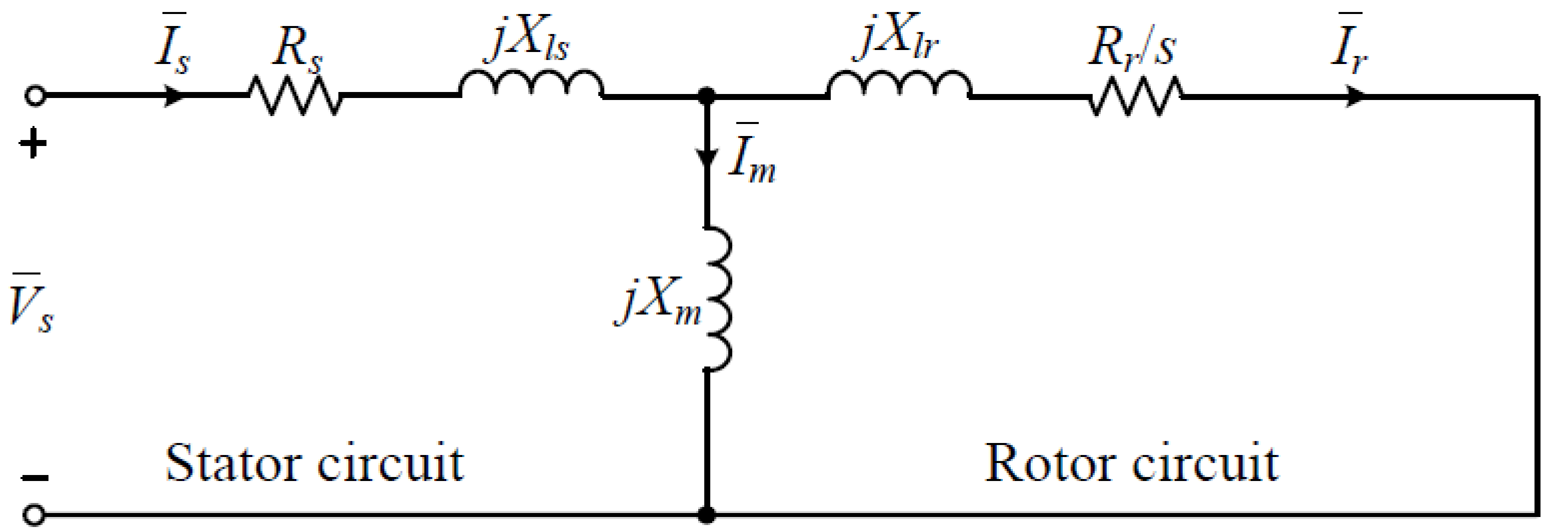
(b) SCIG

The equivalent impedance of SCIG



$$\overline{Z}_s = R_s + jX_{ls} + jX_m \,//\, (\frac{R_r}{s} + jX_{lr})$$

The total input impedance of the generator? $\overline{Z}_s$



Total input impedance $\bar{Z}_s$ of generator with these parameters

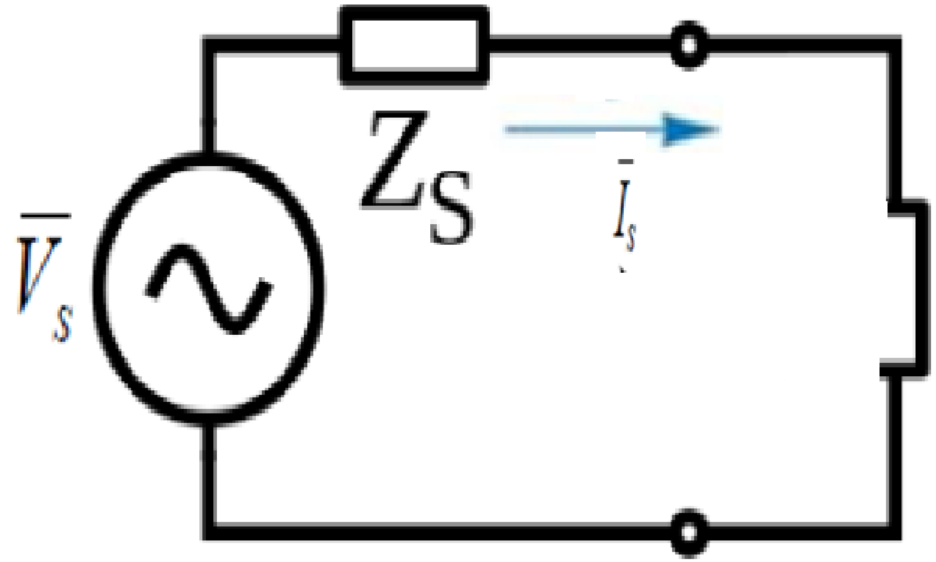
$$\bar{Z}_s = R_s + jX_{ls} + jX_m //(\frac{R_r}{s} + jX_{lr}) = 0.330\angle 145.3^\circ\ \Omega$$

Stator Winding Resistance R_s	1.102 mΩ
Rotor Winding Resistance R_r	1.497 mΩ

$X_{ls} = \omega_s L_{ls} = 0.0204\ \Omega$, $X_{lr} = \omega_s L_{lr} = 0.0204\ \Omega$ and $X_m = \omega_s L_m = 0.6706\ \Omega$ $\quad s = -0.004$

Stator current $\bar{I}_s$ can be obtained from

$$\bar{I}_s = \frac{\bar{V}_s}{\bar{Z}_s} = \frac{690/\sqrt{3}\angle 0^\circ}{0.330\angle 145.3^\circ} = 1206.9\angle -145.3^\circ \mathrm{A}$$



Q. Why stator Voltage Vs is divided by $\sqrt{3}$

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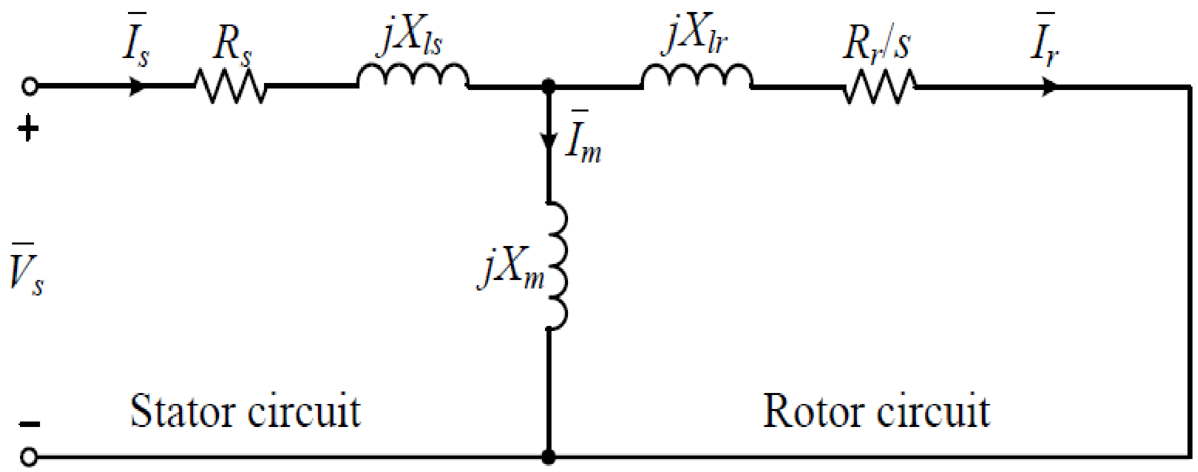
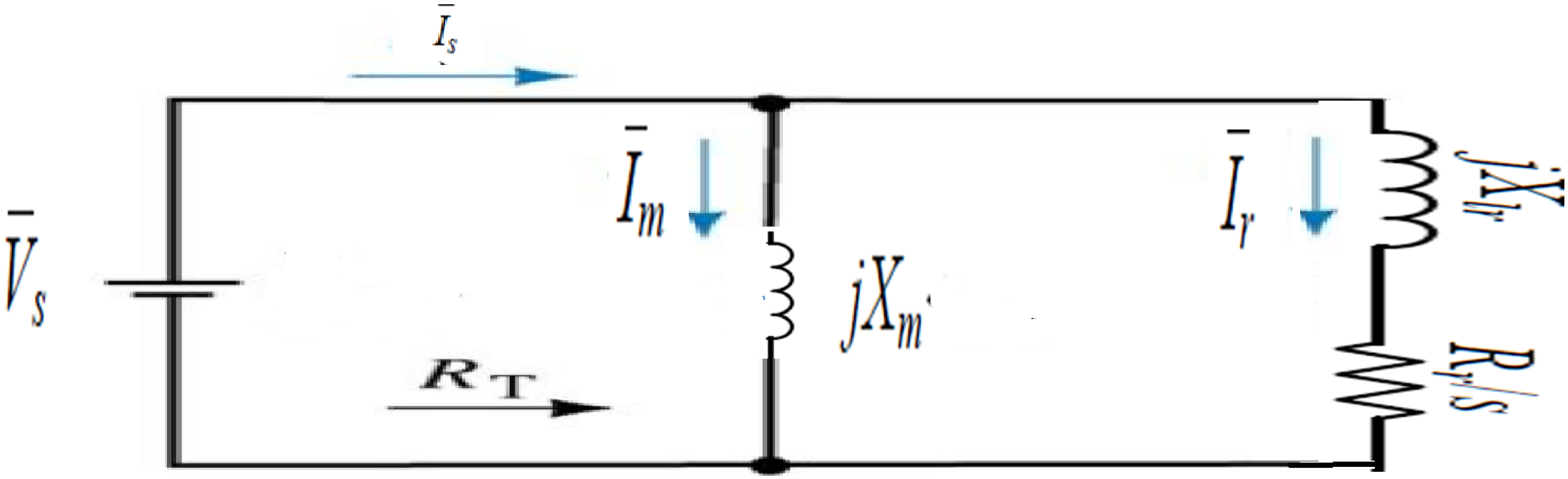
We know Rated Line-to-line Voltage=690 V (rms).
But for rated phase voltage it is mandatory to divide by $\sqrt{3}$

$$\frac{690}{\sqrt{3}} = 398.4V\,(\text{rms})$$

For rotor Current $\bar{I}_r$?





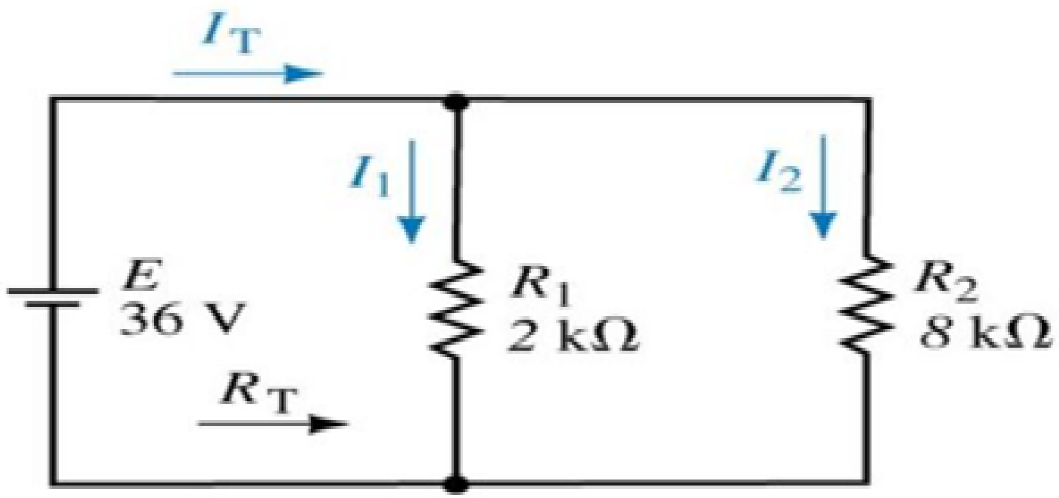
What is Current divider Rule?

Current divider Rule

- For only two resistors in parallel:

$$I_1 = \left(\frac{R_2}{R_1 + R_2}\right) I_T$$

$$I_2 = \left(\frac{R_1}{R_1 + R_2}\right) I_T$$



$$I_1 = \left(\frac{R_2}{R_1 + R_2} \right) I_T$$

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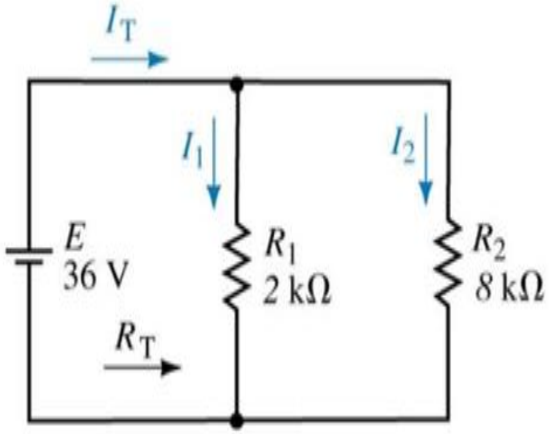
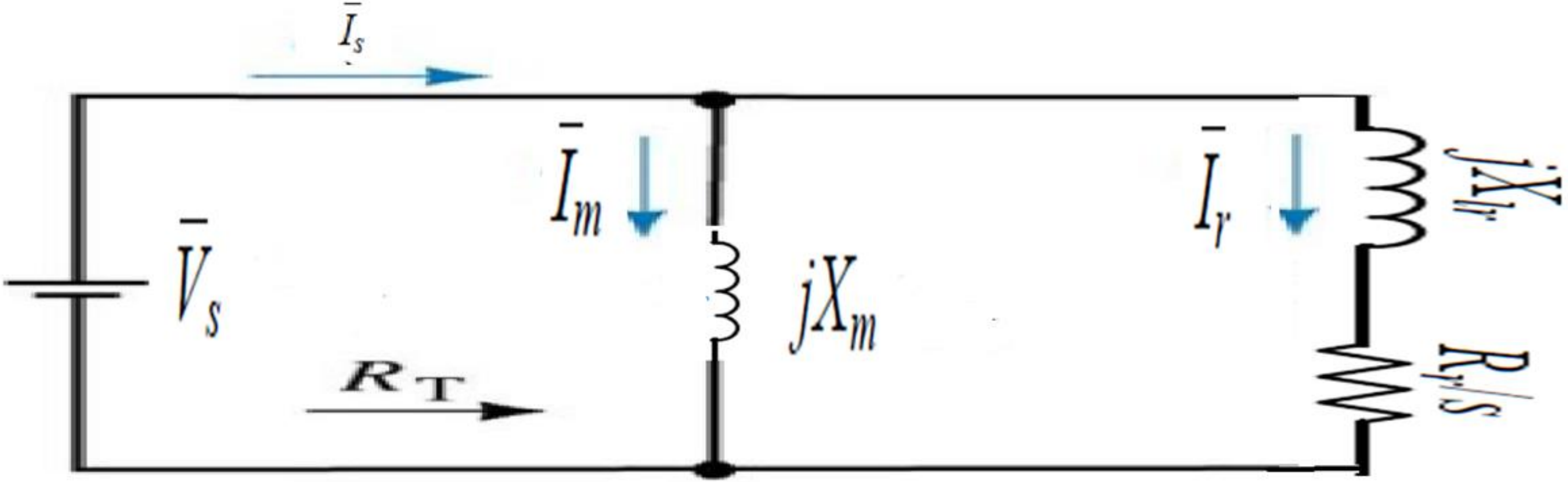


$$\bar{I}_r = \frac{jX_m \bar{I}_s}{jX_m + \left(R_r / s + jX_{lr} \right)} = 1030.0\angle -173.8°\text{A}$$



Q. How we can judge that generator **draws reactive power from grid?**

As stator current is -ve so it lags stator voltage, which implies that generator draws reactive power from grid.

$$\overline{I}_s = 1206.9\angle -145.3°A$$

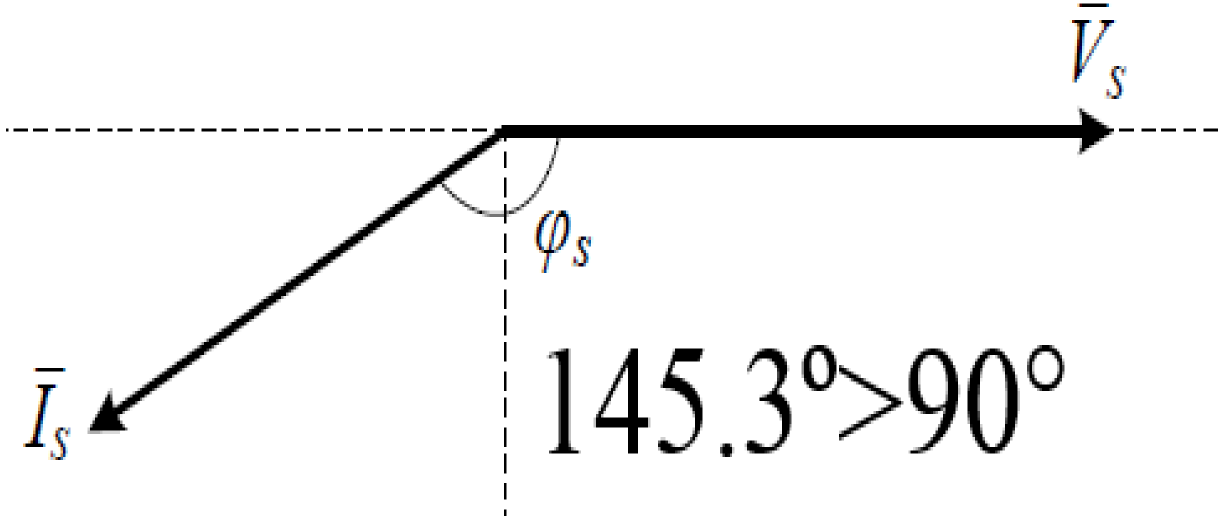
$$\overline{V}_s = 690/\sqrt{3}\angle 0°$$

Calculate stator power factor angle φ_s?

Stator power factor angle *φs* & power factor *PFs* can be calculated by

$$\overline{V}_s = 690/\sqrt{3}\angle 0^\circ \qquad \overline{I}_s = 1206.9\angle -145.3^\circ A$$

$$\begin{cases} \varphi_s = \angle\overline{V}_s - \angle\overline{I}_s = \angle 0^\circ - \angle -145.3^\circ = 145.3^\circ \\ PF_s = \cos\varphi_s = -0.822 \end{cases}$$



Machine operates in which mode?

Machine operates in generating mode because

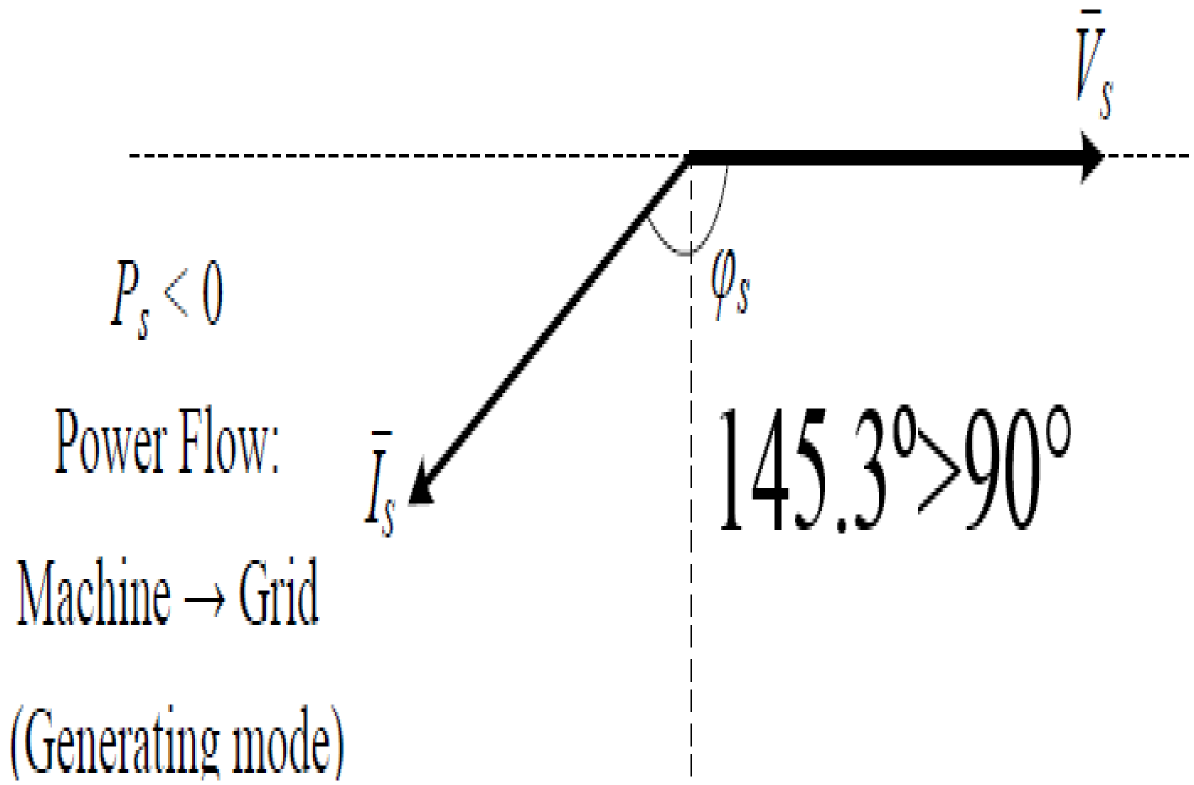
1. Stator power factor angle(145.3º>90°) &

2. Power factor is –ve.

3. Stator Power

Ps{*Vs*×*(-Is)<0*}

$$\begin{cases} \varphi_s = 145.3^\circ \\ PF_s = \cos\varphi_s = -0.822 \end{cases}$$



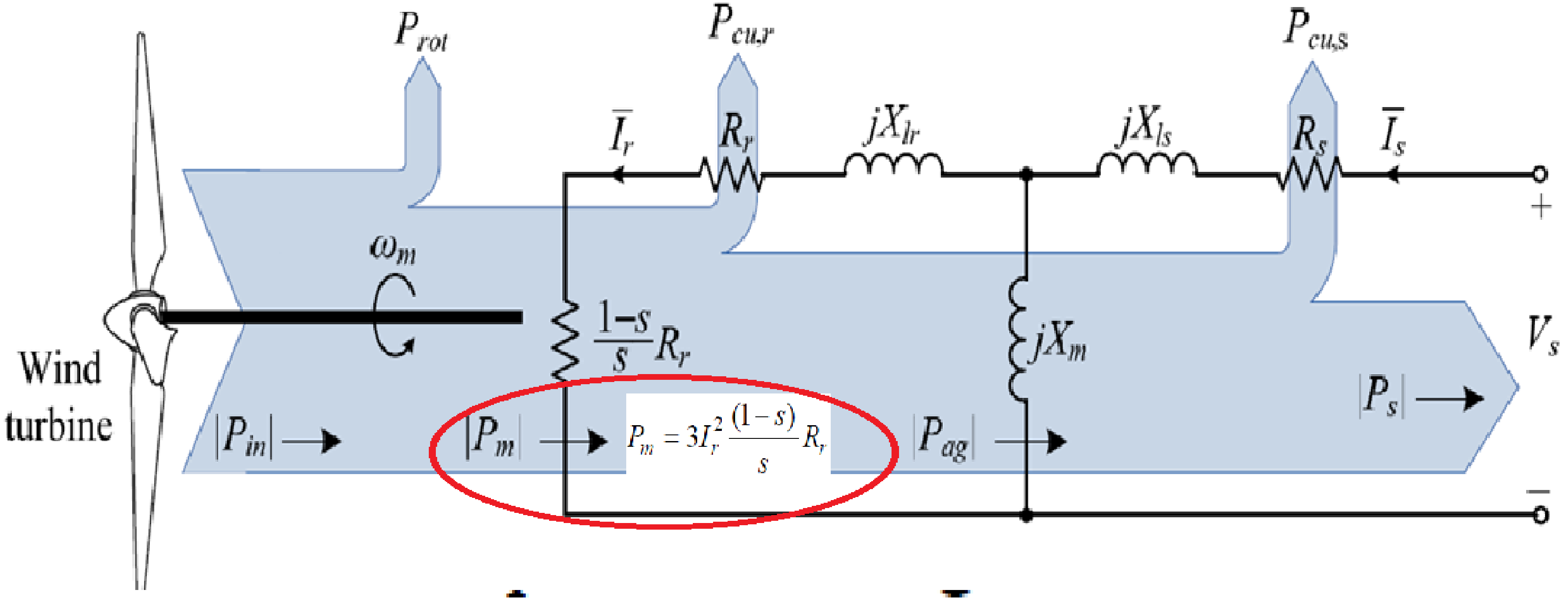
Stator power to grid can be calculated by:

$$P_s = 3V_s I_s \cos\varphi_s = 3\times 690/\sqrt{3}\times 1206.9\times(-0.822) = -1186.2\,\text{kW}$$

-ve power implies that generator delivers **active power to grid.**

Mechanical power *P*m from generator shaft can be calculated by:

$$P_m = 3I_r^2 \frac{(1-s)}{s} R_r$$



$$P_m = 3I_r^2 R_r (1-s)/s = -1195.78\,\text{kW}$$

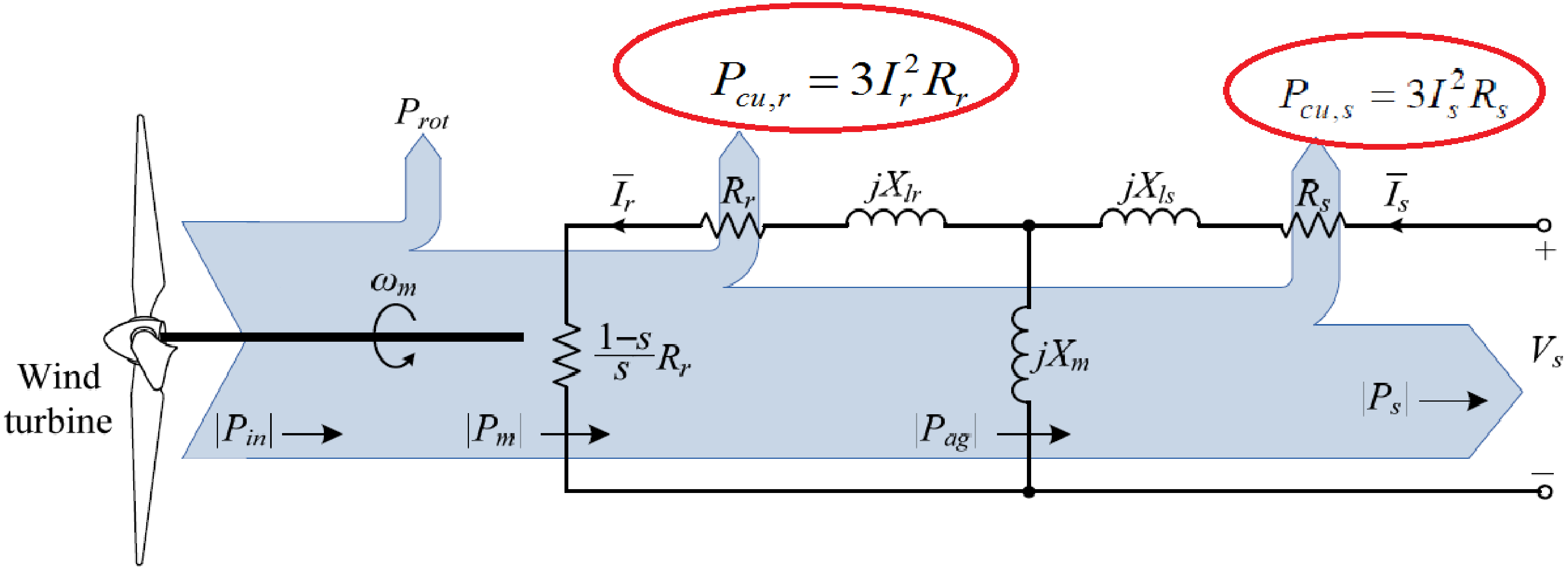
Rotor mechanical speed ω_m in rad/sec?

$$\omega_m = 1506 \times 2 \times \pi/60 = \mathit{157.707 rad/sec}$$

Mechanical torque Tm

$$T_m = \frac{P_m}{\omega_m} = \frac{-1195.8 \times 10^3}{157.707} = -7.58KN.m$$

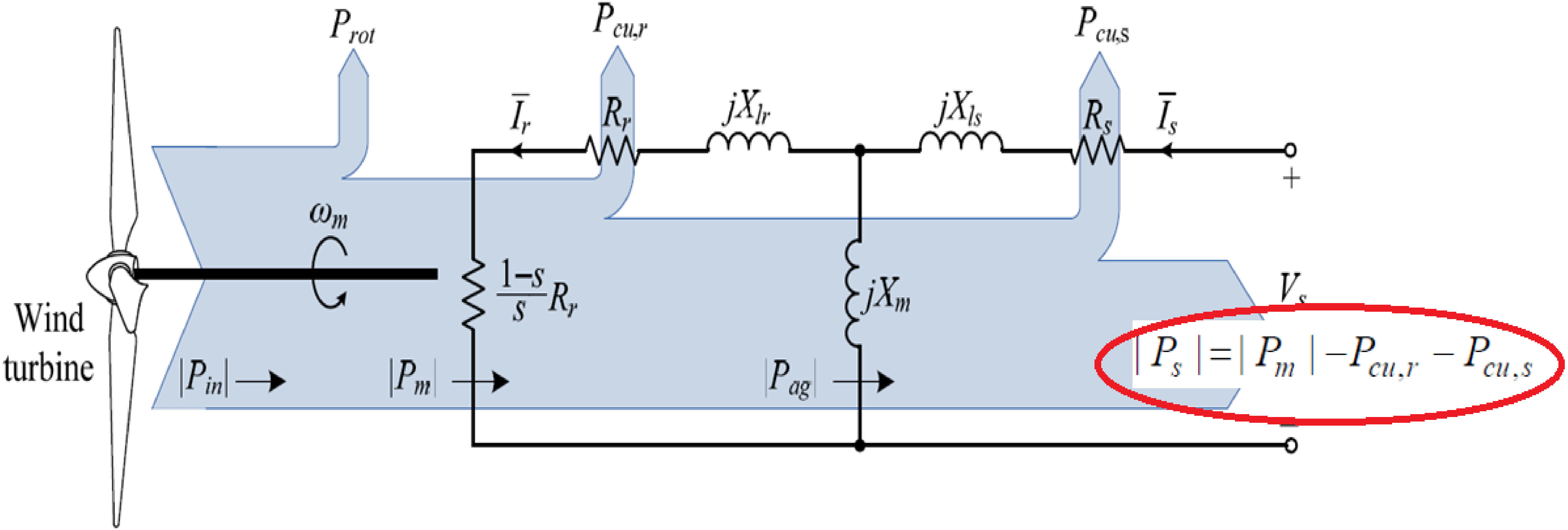
Copper losses of rotor $P_{cu,r}$ & stator windings are $P_{cu,s}$



$$
\begin{cases}
P_{cu,s} = 3I_s^2 R_s = 4.82\ \text{kW} \\
P_{cu,r} = 3I_r^2 R_r = 4.76\ \text{kW}
\end{cases}
$$

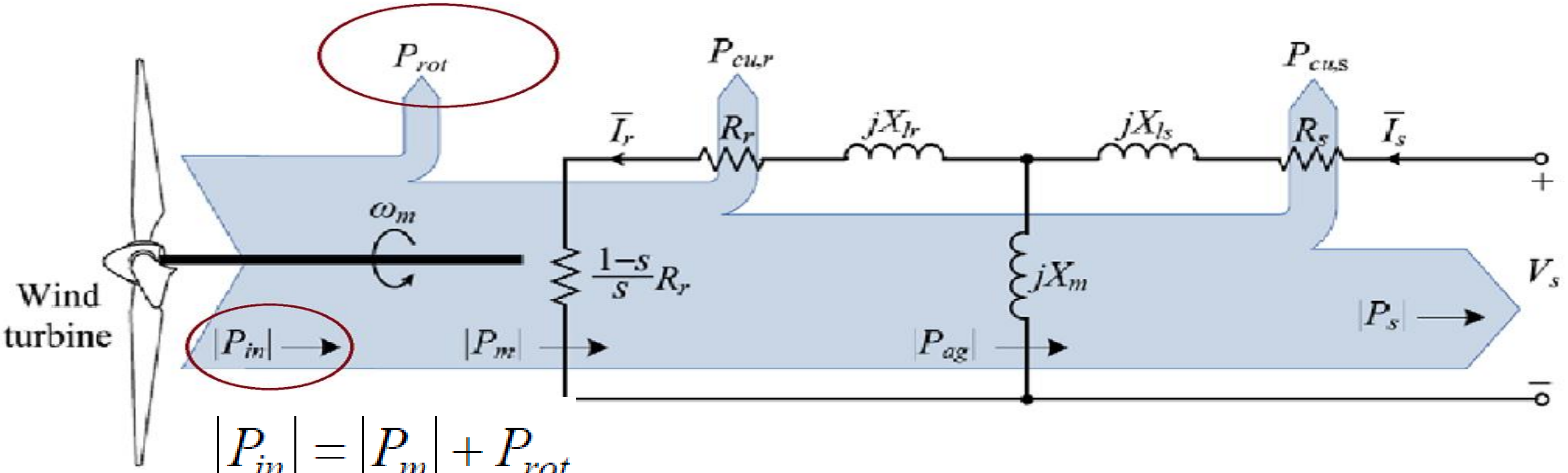
Stator power to grid is calculated by:

Ps=1195.78-4.82-4.76=1186.2kW



P_{in} is total input power produced by wind turbine

P_{rot} is total rotational losses of mechanical system (power losses of gearbox neglected for simplicity).



$$|P_{in}| = |P_m| + P_{rot}$$

Total input power from shaft of generator is

$$|P_{in}| = |P_m| + P_{rot}$$

Pin=1195.78+23=1218.8kW

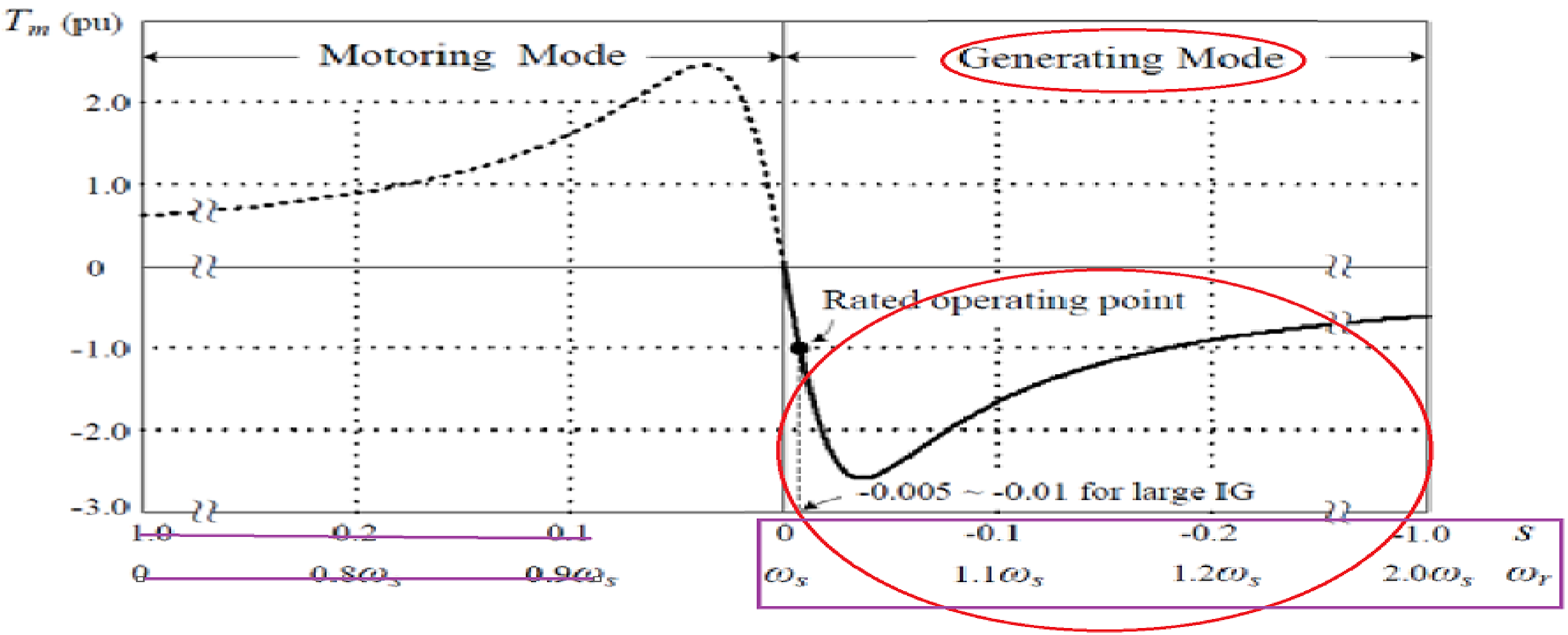
Generator efficiency is calculated by:

$$\eta = |P_s| / |P_{in}|$$

$$\eta = 1186.2/1218.8$$

$$\eta = 97.33\%$$

It can be observed from analysis that with IG operating in a generating mode,5 elements would be -ve?

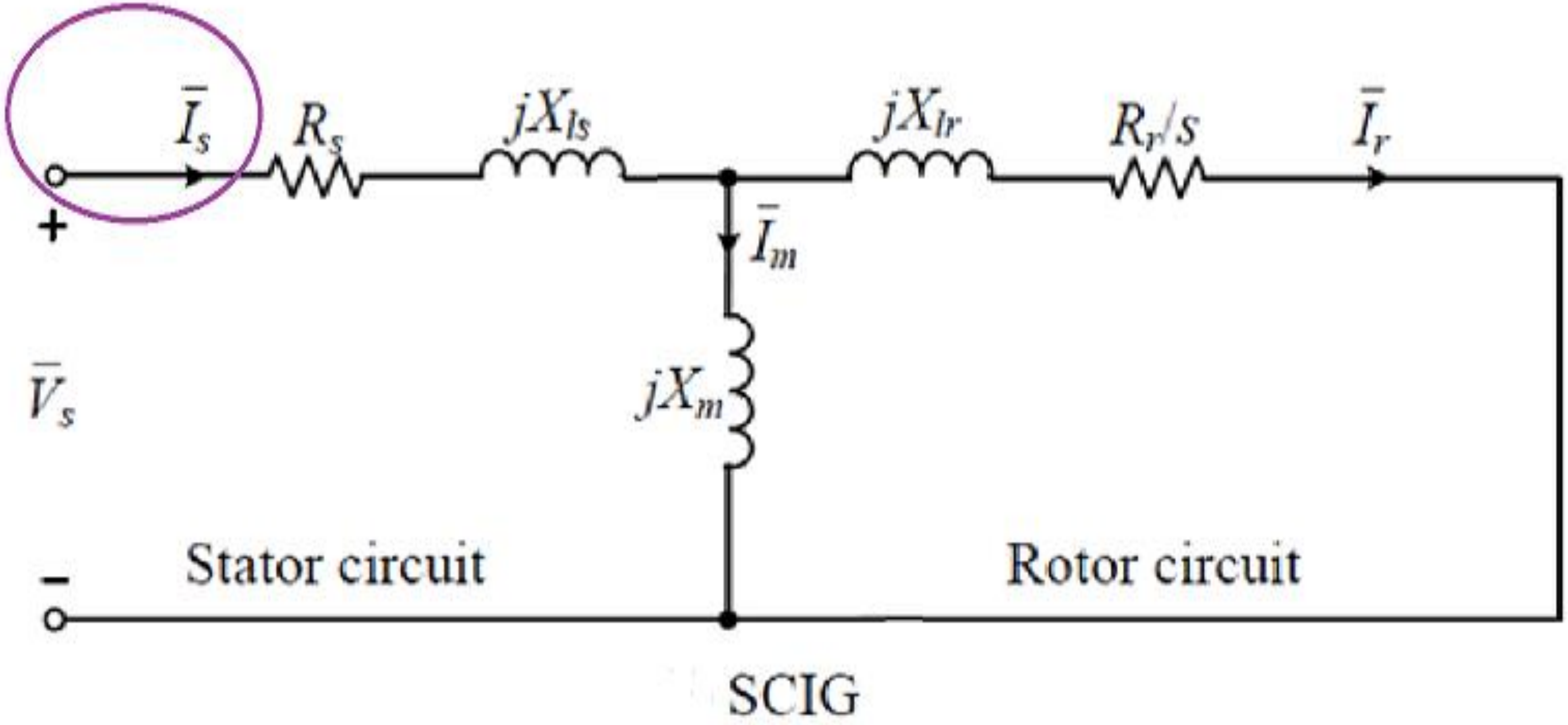


It can be observed from analysis that with IG operating in a generating mode:

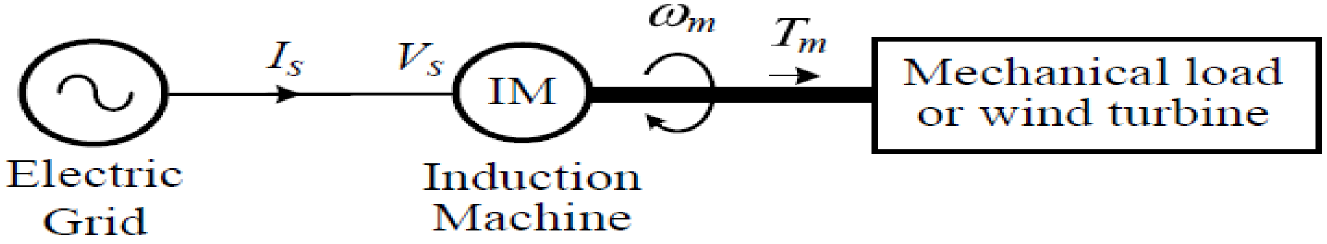
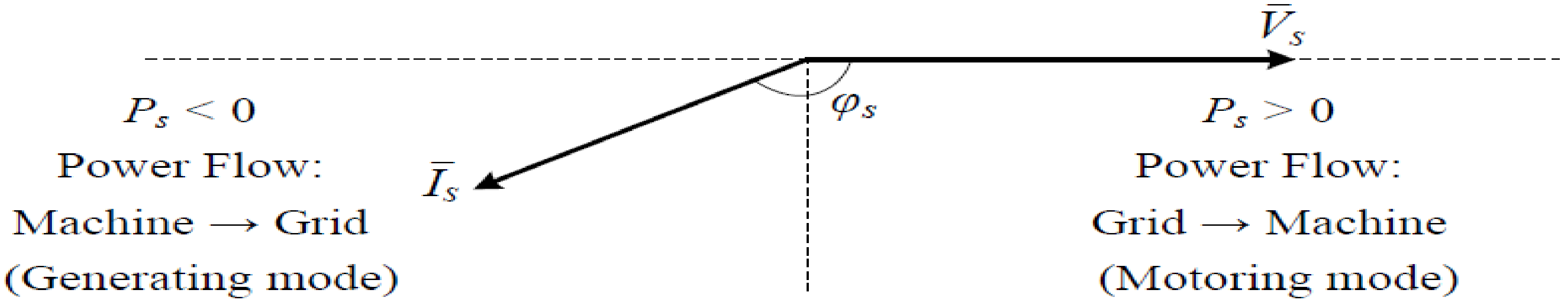
1. **Stator power p_s,**
2. **Mechanical power p_m,**
3. **Mechanical torque t_m,**
4. **Stator power factor p_{fs} &**
5. **Slip s**

are all -ve.

This is due to IG equivalent circuit with “motor convention”, where stator current $\bar{I}_s$ is assumed to flow into stator from grid.

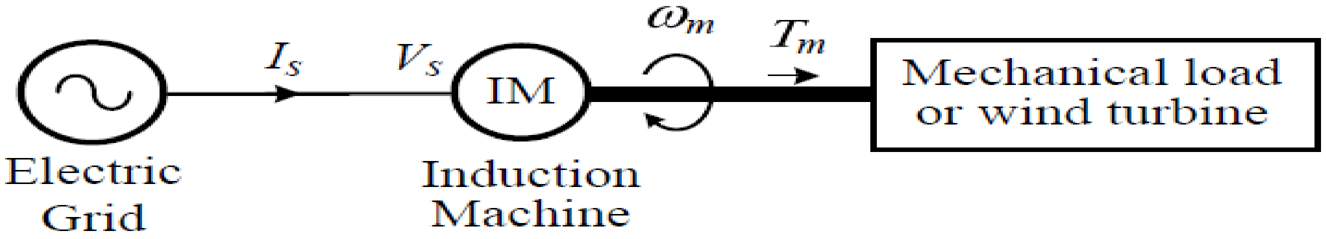


Summary of induction machine operating in motoring & generating modes, with connection diagram & its corresponding phasor diagram are also given.

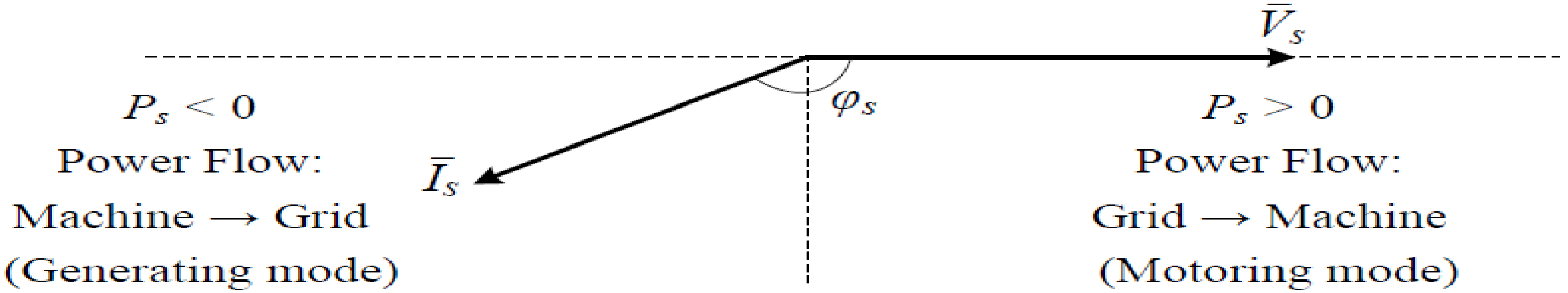
Connection				
Phasor diagram				
Operating mode	Generating mode		Motoring mode	
Stator power	$P_s = 3V_s I_s \cos\varphi_s < 0$		$P_s = 3V_s I_s \cos\varphi_s > 0$	
Slip and torque (Normal operation)	$s < 0$	$T_m < 0,\ T_e < 0$	$s > 0$	$T_m > 0,\ T_e > 0$
Power factor angle and power factor	$90° \le \varphi_s < 180°$	$-1 \le PF_s \le 0$	$0 \le \varphi_s < 90°$	$0 \le PF_s \le 1$

Stator power, power factor, electromagnetic & mechanical torque, & slip of induction machine are all +ve in motoring mode & -ve in generating mode.

Connection

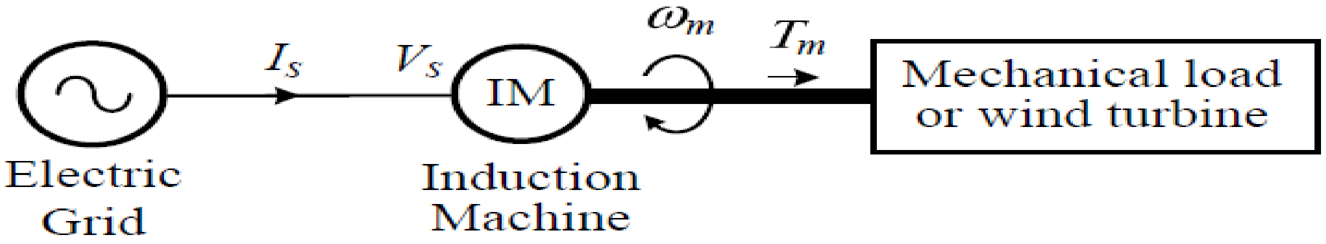
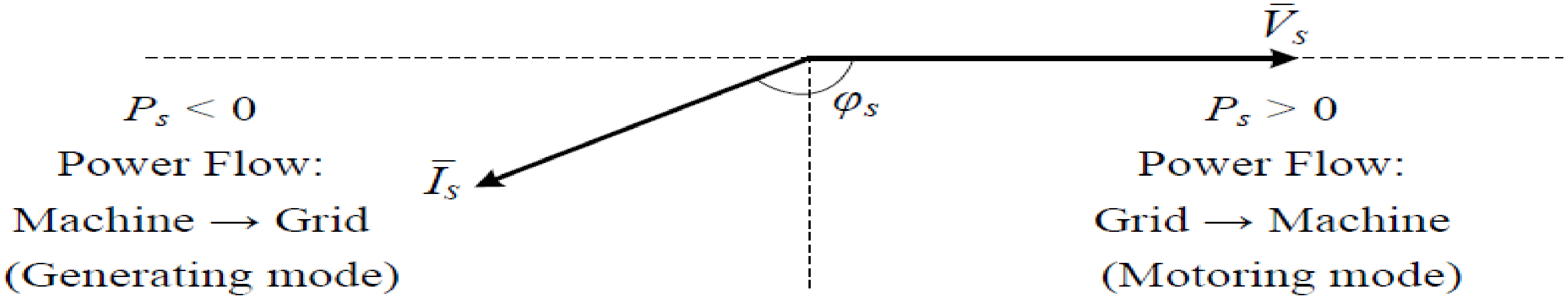


Phasor diagram



Operating mode	Generating mode		Motoring mode	
Stator power	$P_s = 3V_sI_s \cos \varphi_s < 0$		$P_s = 3V_sI_s \cos \varphi_s > 0$	
Slip and torque (Normal operation)	$s < 0$	$T_m < 0$, $T_e < 0$	$s > 0$	$T_m > 0$, $T_e > 0$
Power factor angle and power factor	$90° \le \varphi_s < 180°$	$-1 \le PF_s \le 0$	$0 \le \varphi_s < 90°$	$0 \le PF_s \le 1$

Stator power factor angle is in range of $0 \le \varphi s < 90°$ for motoring mode.

Connection				
Phasor diagram				
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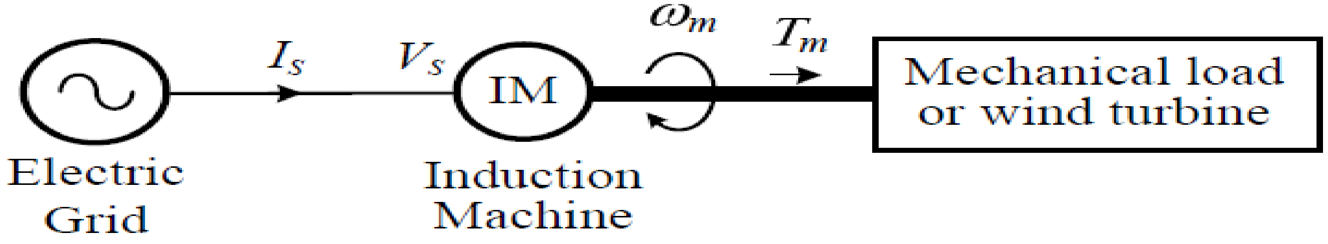
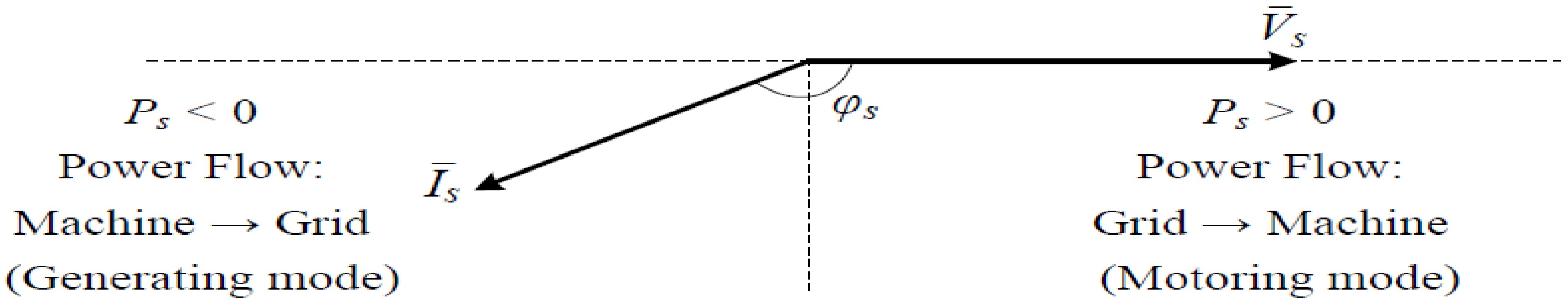
Stator power factor angle is in range of $90° \leq \varphi s < 180°$ for generating mode.

Connection				
Phasor diagram				
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Numericals

Topic: Steady-state & Power Flow Analysis of Induction Generators using Conventional Equivalent Circuit pp.249

3-1 (Solved Problem)

A 2.3MW/690V/50Hz squirrel-cage induction generator (SCIG) is used in a fixed-speed wind energy conversion system (WECS). The SCIG is directly connected to the grid of 690V/50Hz. Generator parameters are given in Table B-1 of Appendix B. At a given wind speed, **SCIG operates at rated speed of 1512 rpm**. Using induction generator equivalent circuit of Fig. 3.3-9b, determine following:

a) slip, & rotor mechanical and electrical speeds,

b) stator and rotor currents,

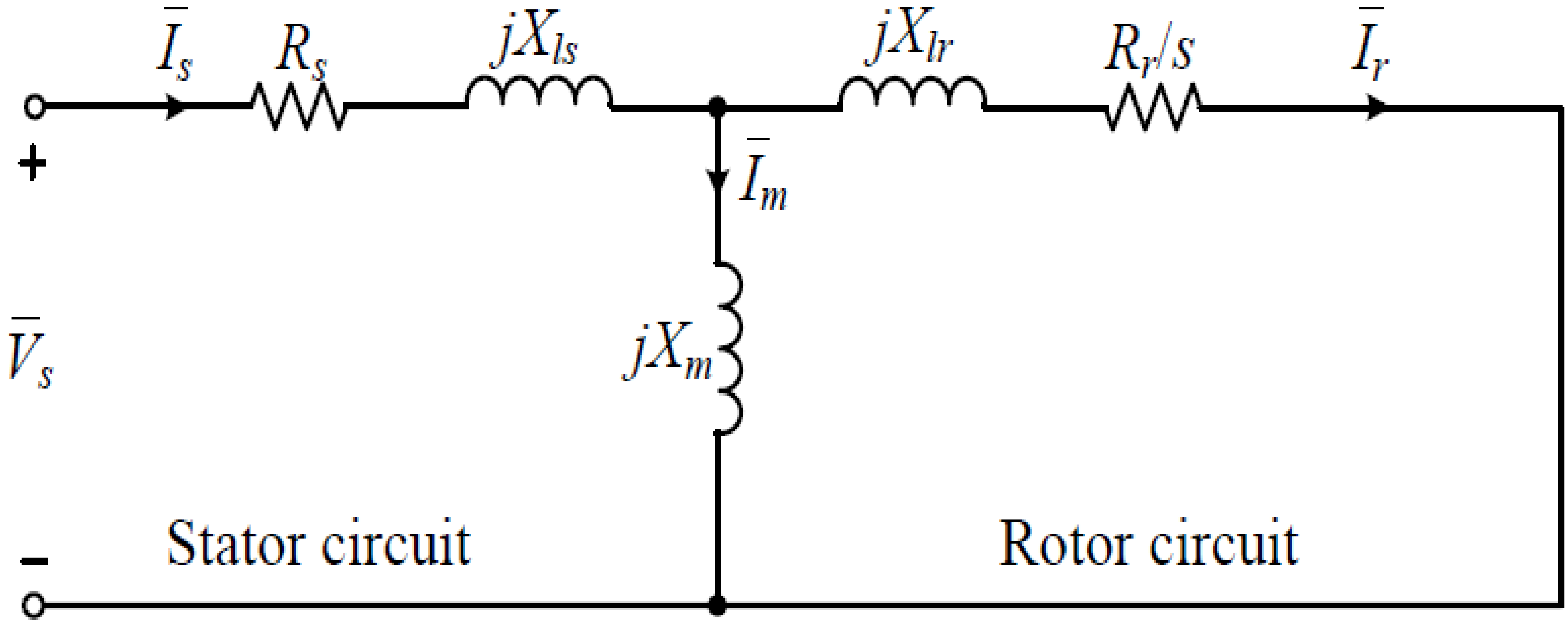
c) mechanical power & torque,

d) stator and rotor winding losses,

e) generator efficiency and power factor, &

f) stator and rotor flux linkages.

Induction generator equivalent circuit of Fig. 3.3-9b



(b) SCIG

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Inertia Time Constant H	5.8078 sec	
Base Flux Linkage Λ_B	1.2681 Wb (rms)	1.0 pu
Base Impedance Z_B	0.1838 Ω	1.0 pu
Base Inductance L_B	0.58513 mH	1.0 pu
Base Capacitance C_B	17316.17 μF	1.0 pu

Note: $H = J(\omega_m)^2 / (2S_B)$

Solution: a) The slip:

SCIG operates at rated speed of 1512 rpm

$$s = \frac{n_s - n_r}{n_s} = \frac{1500 - 1512}{1500} = -0.008 \ \text{(negative slip)}$$

SCIG operates at rated speed n_s=1512 rpm

- The rotor mechanical speed in rad/s?

The rotor mechanical speed:

$$\omega_m = 1512 \times (2\pi / 60) = 158.336 \text{ rad/sec}$$

The rotor electrical speed:

ω_m – rotor mechanical speed ($\omega_m = \omega_r / P$) [rad/sec]

P – number of pole pairs:

$$\omega_r = \omega_m \times P = 158.336 \times 2 = 316.67 \text{ rad/sec}$$

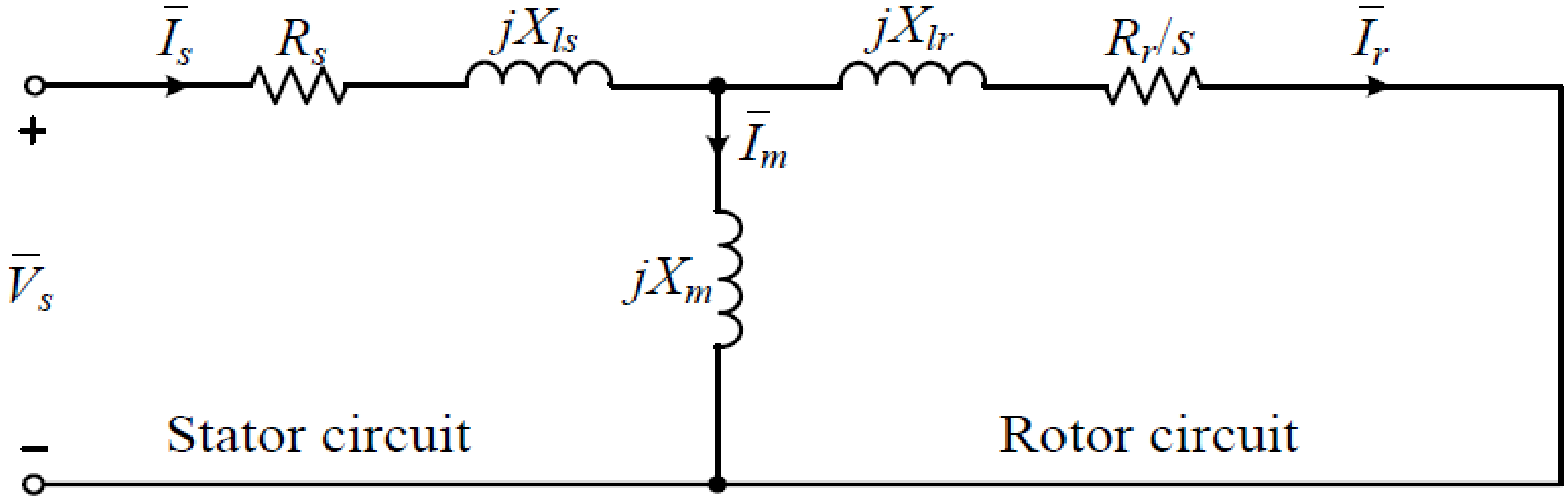
The stator frequency in rad/sec:

$$\omega_s = 2\pi \times 50 = 314.16 \text{ rad/sec}$$

b) The stator voltage:

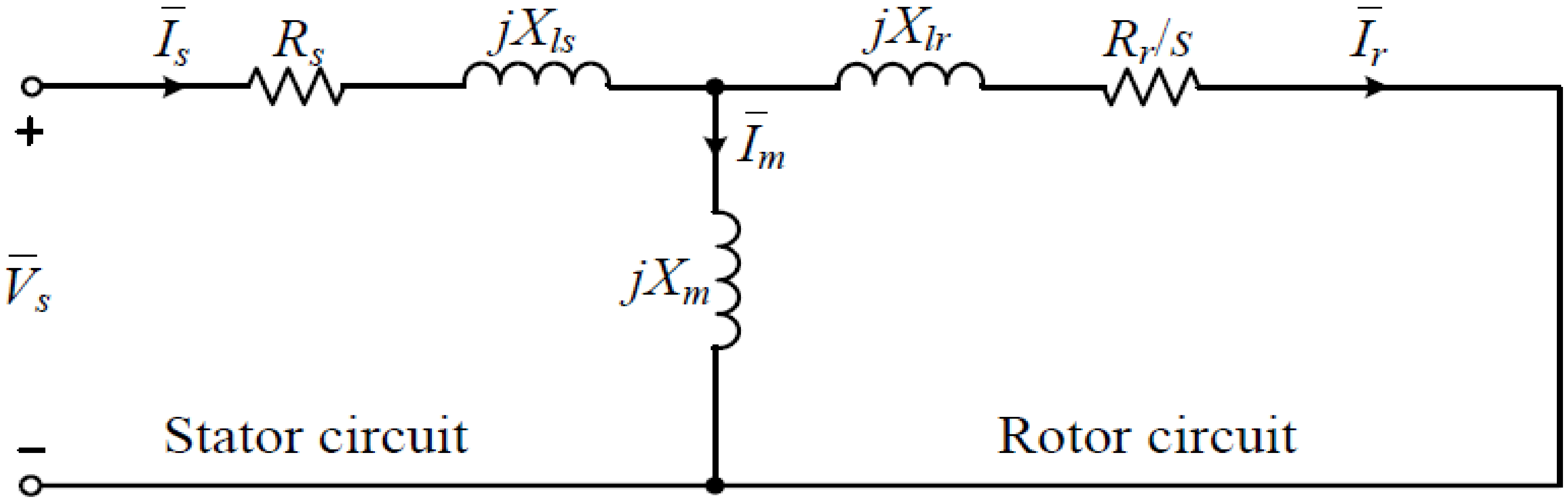
$$\overline{V}_s = 690/\sqrt{3}\angle 0° = 398.37\angle 0° \text{ V (rms)}$$

The equivalent impedance of SCIG?



(b) SCIG

The equivalent impedance of SCIG



$$\overline{Z}_s = R_s + jX_{ls} + jX_m // (\frac{R_r}{s} + jX_{lr})$$

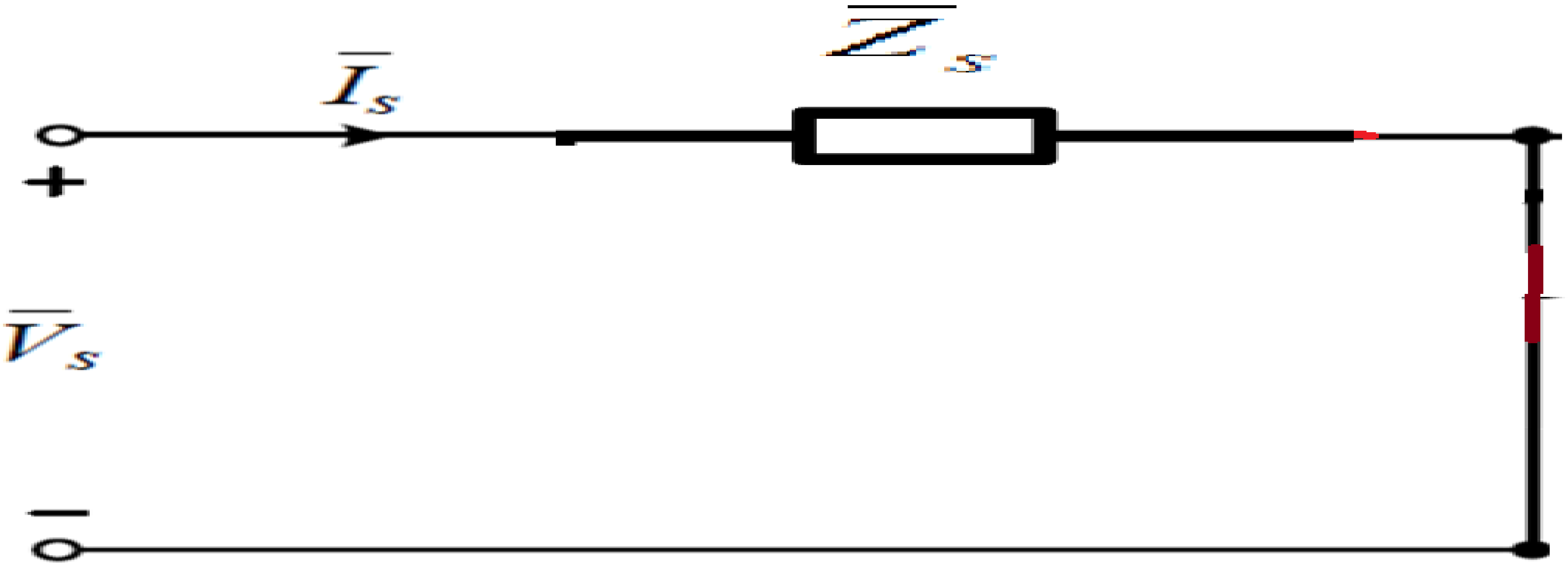
The equivalent impedance of SCIG

$$\bar{Z}_s = R_s + jX_{ls} + jX_m // (\frac{R_r}{s} + jX_{lr}) = 0.1838\angle 152.6^\circ\,\Omega$$

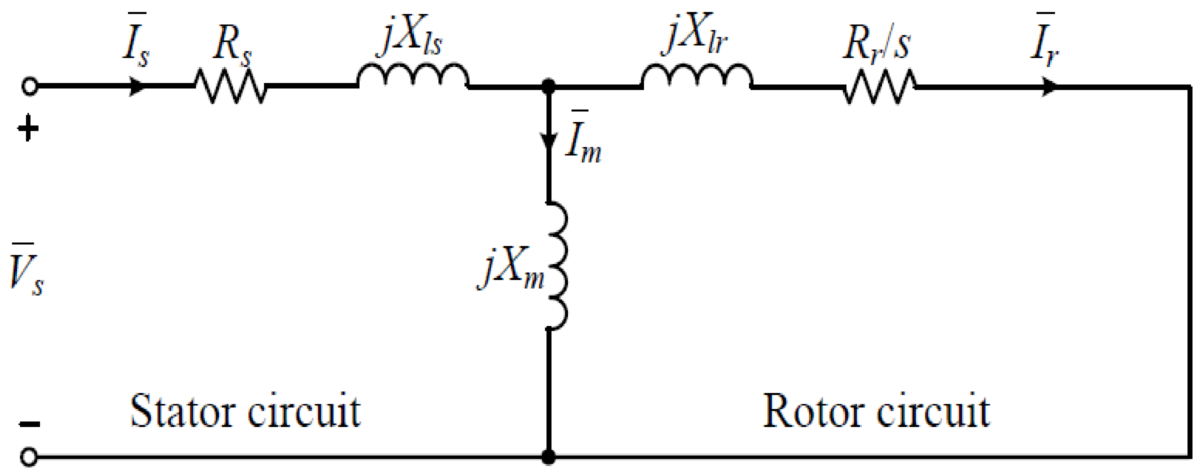
where $X_{ls} = \omega_s L_{ls} = 0.0204\,\Omega$, $X_{lr} = \omega_s L_{lr} = 0.0204\,\Omega$ and $X_m = \omega_s L_m = 0.6706\,\Omega$

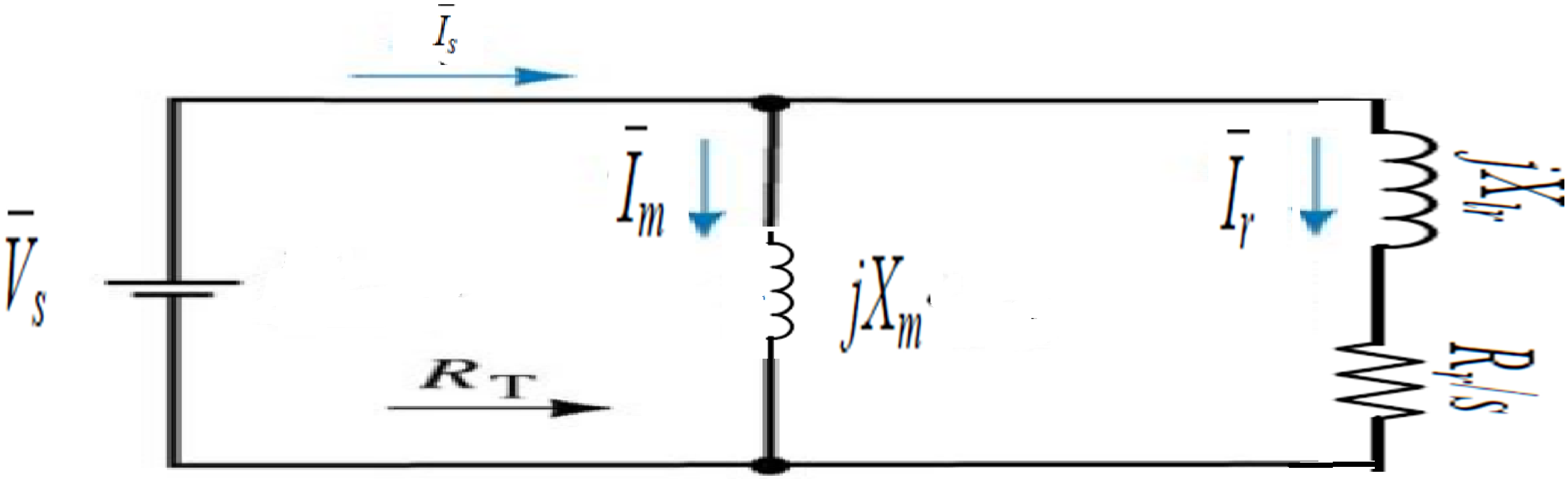
Stator Winding Resistance R_s	1.102 mΩ	0.006 pu
Rotor Winding Resistance R_r	1.497 mΩ	0.008 pu
Stator Leakage Inductance L_{ls}	0.06492 mH	0.111 pu
Rotor Leakage Inductance L_{lr}	0.06492 mH	0.111 pu
Magnetizing Inductance L_m	2.13461 mH	3.6481 pu

Stator current: $\bar{I}_s = \dfrac{\bar{V}_s}{\bar{Z}_s} = \dfrac{690/\sqrt{3}\angle 0^\circ}{0.1838\angle 152.6^\circ} = 2168\angle -152.6^\circ \text{ A (rms)}$



For rotor Current $\bar{I}_r$?





Rotor Current $\bar{I}_r$

$$\bar{I}_r = \frac{jX_m \bar{I}_s}{jX_m + (\frac{R_r}{s} + jX_{lr})} = 2030.8\angle -167.7^\circ \text{ A (rms)}$$

c) The mechanical power:

$$P_m = \left| 3I_r^2 \frac{R_r}{s}(1-s) \right| = \left| 3 \times 2030.8^2 \times \frac{1.497 \times 10^{-3}}{-0.008}(1+0.008) \right| = 2.3339 \times 10^6 \text{ W}$$

The mechanical torque:

$$T_m = P_m \times P / \omega_r = 14740 \text{ N.m}$$

d) The stator winding loss:

$$P_{cu,s} = 3 \times I_s^2 R_s = 15.538 \times 10^3 \text{ W}$$

The rotor winding loss:

$$P_{cu,r} = 3 \times I_r^2 R_r = 18.521 \times 10^3 \text{ W}$$

e) The stator output power of SCIG:

$$P_s = \left|P_m\right| - \left|P_{cu,s}\right| - \left|P_{cu,r}\right| = 2.3339\times10^6 - 18.521\times10^3 - 15.538\times10^3 = 2300\times10^3 \text{ W}$$

The SCIG efficiency:

$$\eta = \frac{P_s}{P_m} = 98.54\%$$

The stator power factor angle:

$$\varphi_s = \angle V_s - \angle I_s = 0° - (-152.6°) = 152.6°$$

The stator power factor:

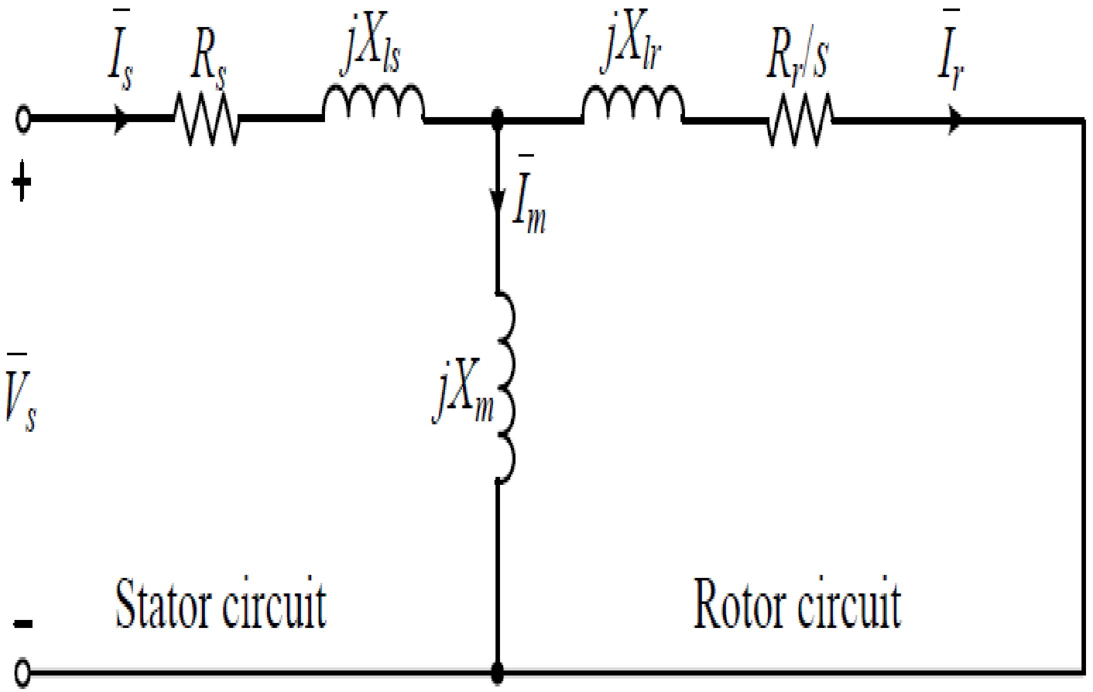
$$PF_s = \cos\varphi_s = -0.888$$

The stator power factor:

$$PF_s = \cos\varphi_s = -0.888$$

f) The magnetizing flux linkage can be expressed as

$$\bar{\Lambda}_m = \bar{I}_m \quad L_m$$



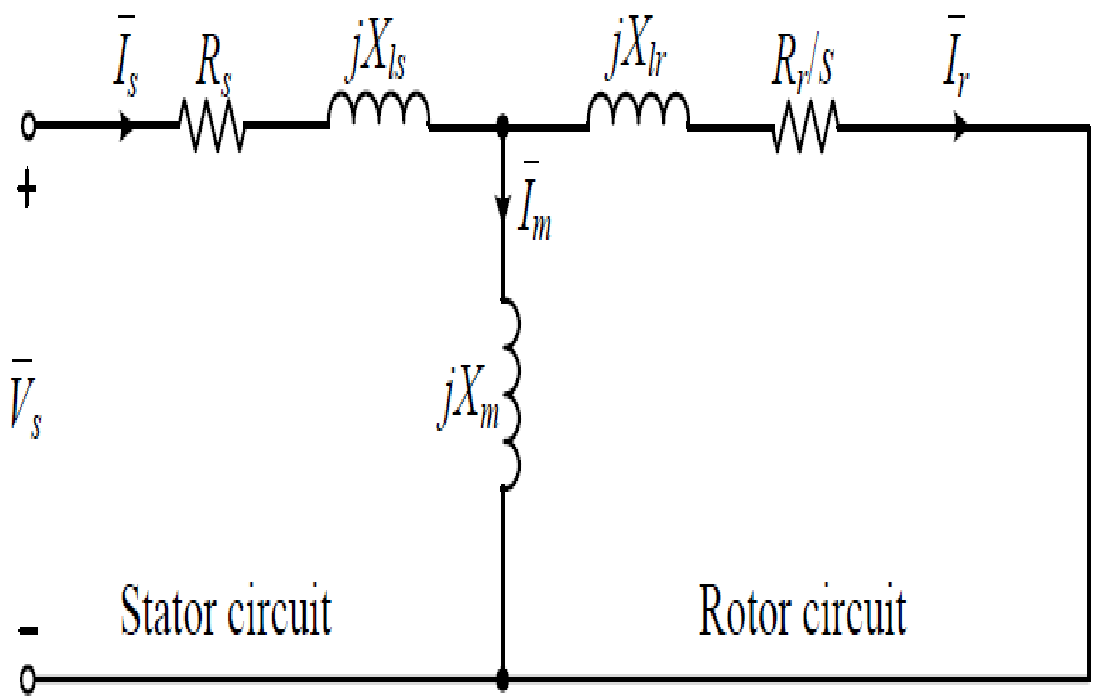
(b) SCIG

$$\bar{\Lambda}_m = (\bar{I}_s - \bar{I}_r)L_m = 1.2168\angle -83.9^\circ \text{ Wb (rms)}$$

Stator flux linkage

$$\overline{\Lambda}_s = L_{ls}\overline{I}_s + L_m\overline{I}_m$$

$$\overline{\Lambda}_s = L_{ls}\overline{I}_s + \overline{\Lambda}_m$$



(b) SCIG

$$\overline{\Lambda}_s = \overline{\Lambda}_m + L_{ls}\overline{I}_s = 1.2748\angle -89.8^\circ \text{ Wb (rms)}$$

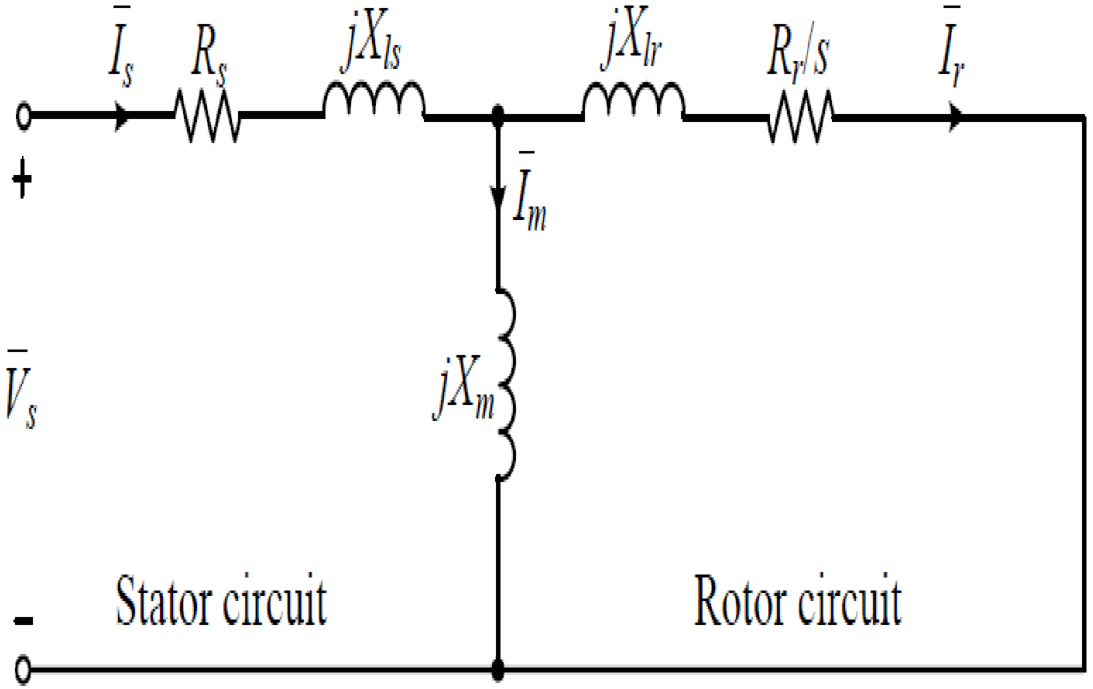
The peak value of stator flux:

$$\lambda_s = \sqrt{2}\Lambda_s = 1.8028 \text{ Wb}$$

Rotor flux linkage

$$\overline{\Lambda_r} = -L_{lr}\overline{I_r} + L_m\overline{I_m}$$

$$\overline{\Lambda_r} = \overline{\Lambda_m} - L_{lr}\overline{I_r}$$



(b) SCIG

$$\bar{\Lambda}_r = \bar{\Lambda}_m - L_{lr}\bar{I}_r = 1.2096\angle -77.7° \text{ Wb (rms)}$$

The peak value of rotor flux:

$$\lambda_r = \sqrt{2}\Lambda_r = 1.7106 \text{ Wb}$$

Unsolved problem

3-2 Repeat Problem 3-1 when the SCIG operates at a speed of 1508 rpm:

A 2.3MW/690V/50Hz squirrel-cage induction generator (SCIG) is used in a fixed-speed wind energy conversion system (WECS). The SCIG is directly connected to the grid of 690V/50Hz. Generator parameters are given in Table B-1 of Appendix B. At a given wind speed, **SCIG operates at rated speed of 1508 rpm**. Using induction generator equivalent circuit of Fig. 3.3-9b, determine following:

a) slip, & rotor mechanical and electrical speeds,

b) stator and rotor currents,

c) mechanical power & torque,

d) stator and rotor winding losses,

e) generator efficiency and power factor, &

f) stator and rotor flux linkages.

Answers:

a) $s = -0.00533$, $\omega_m = 157.92$ rad/sec, $\omega_r = 315.83$ rad/sec

b) $\bar{Z}_s = 0.2617\angle 149.62^\circ\ \Omega$, $\bar{I}_s = 1521.9\angle -149.62^\circ$ A, $\bar{I}_r = 1368.4\angle -171.73^\circ$ A

c) $P_m = 1.585\times 10^6$ W, $T_m = 10038$ N.m d) $P_{cu,s} = 7.6577\times 10^3$ W, $P_{cu,r} = 8.41\times 10^3$ W

e) $P_s = 1.5692\times 10^6$ W, $\eta = 98.97\%$, $PF_s = -0.8627$

f) $\bar{\Lambda}_m = 1.2259\angle -85.89^\circ$ Wb, $\bar{\Lambda}_s = 1.2727\angle -89.88^\circ$ Wb, $\bar{\Lambda}_r = 1.2226\angle -81.73^\circ$ Wb

Topic: Steady-state & Power Flow Analysis of Induction Generators using Approximate Equivalent Circuit

Consider 2.3MW/690V/50Hz SCIG in a wind energy conversion system. Generator is directly connected to grid of 690V/50Hz. Generator parameters are given in Table B-1 of Appendix B. At a given wind speed, SCIG operates at a speed of 1510 rpm. Using approximate induction generator equivalent circuit of Fig. P3-3, calculate following:

a) slip, and rotor mechanical and electrical speeds,

b) rotor and stator currents,

c) mechanical power and torque,

d) stator and rotor winding losses, &

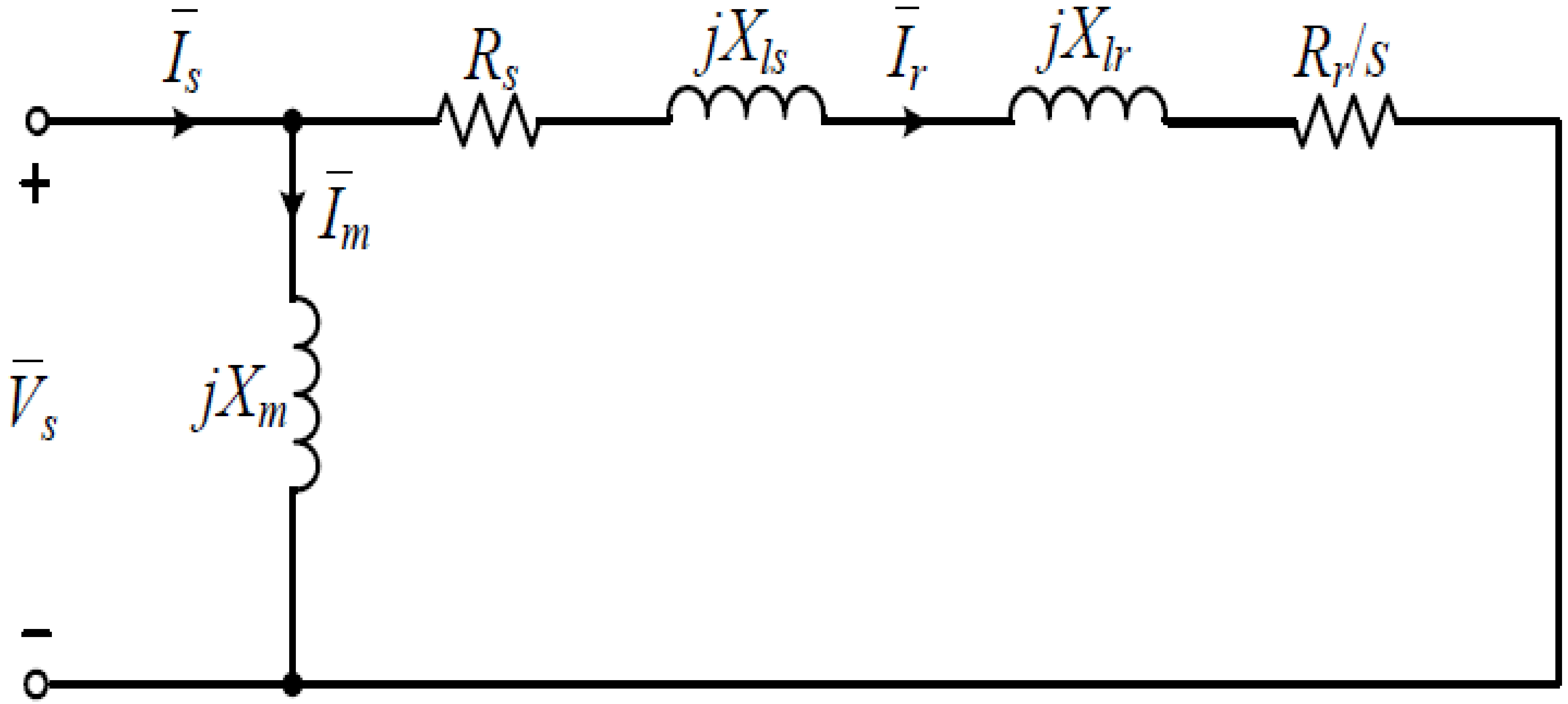
e) generator efficiency and power factor.

Table B-1 2.3MW/690V/50Hz Squirrel Cage Induction Generator (SCIG) Parameters

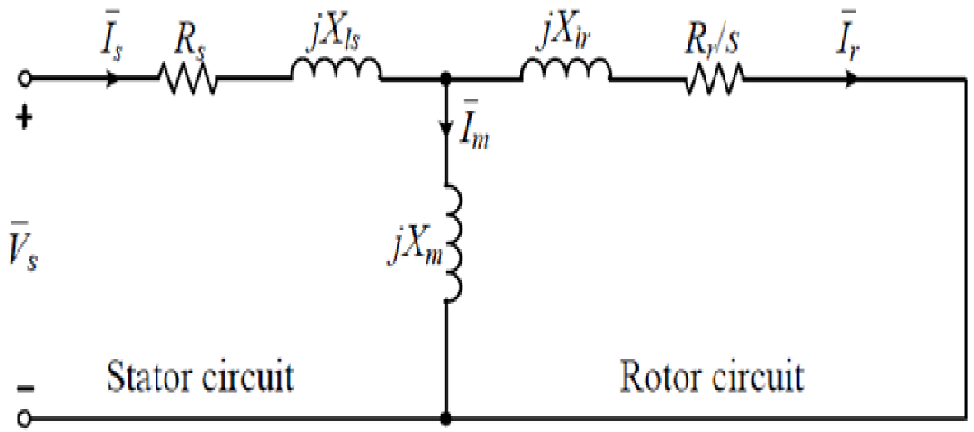
Generator Type	**SCIG, 2.3MW/690V/50Hz**	
Rated Output Power	2.30 MW	
Rated Mechanical Power	2.3339 MW	1.0 pu
Rated Apparent Power	2.59 MVA	1.0 pu
Rated Line-to-line Voltage	690 V (rms)	
Rated Phase Voltage	398.4 V (rms)	1.0 pu
Rated Stator Current	2168 A (rms)	1.0 pu
Rated Stator Frequency	50 Hz	1.0 pu
Rated Power Factor	0.888	
Rated Rotor Speed	1512 rpm	1.0pu
Rated Slip	-0.008	
Number of Pole Pairs	2	
Rated Mechanical Torque	14.74 kN.m	1.0 pu
Rated Stator Flux Linkage	1.2748 Wb (rms)	1.0053 pu
Rated Rotor Flux Linkage	1.2096 Wb (rms)	0.9539 pu
Stator Winding Resistance R_s	1.102 mΩ	0.006 pu
Rotor Winding Resistance R_r	1.497 mΩ	0.008 pu
Stator Leakage Inductance L_{ls}	0.06492 mH	0.111 pu
Rotor Leakage Inductance L_{lr}	0.06492 mH	0.111 pu
Magnetizing Inductance L_m	2.13461 mH	3.6481 pu
Moment of Inertia J	1200 kg.m^2	
Inertia Time Constant H	5.8078 sec	
Base Flux Linkage Λ_B	1.2681 Wb (rms)	1.0 pu
Base Impedance Z_B	0.1838 Ω	1.0 pu
Base Inductance L_B	0.58513 mH	1.0 pu
Base Capacitance C_B	17316.17 μF	1.0 pu

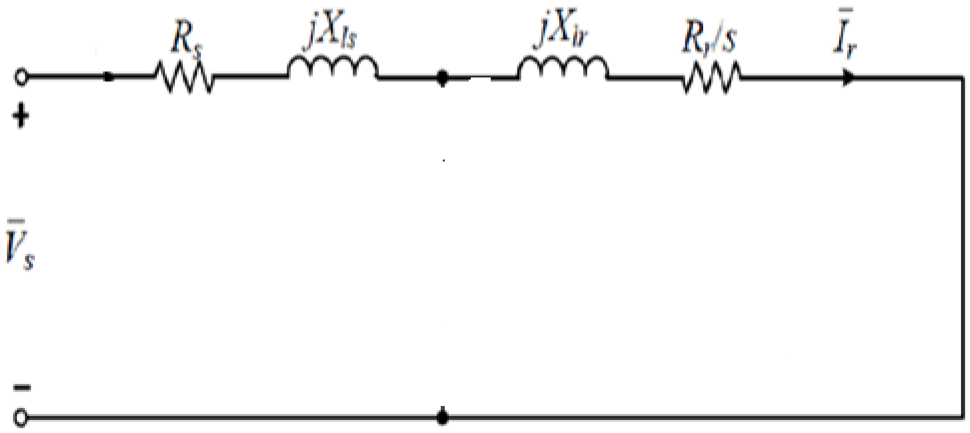
Note: $H = J(\omega_m)^2/(2S_B)$

Fig. P3-3 Approximate induction generator equivalent circuit



Neglecting magnetizing branch in Fig. for simplicity and calculating equivalent impedance





Solution:

a) The slip:

$$s = \frac{n_s - n_r}{n_s} = \frac{1500 - 1510}{1500} = -0.00667 \text{ (negative slip)}$$

The rotor mechanical speed:

$$\omega_m = 1510 \times (2\pi / 60) = 158.127 \text{ rad/sec}$$

The rotor electrical speed:

$$\omega_r = \omega_m \times P = 158.127 \times 2 = 316.254 \text{ rad/sec}$$

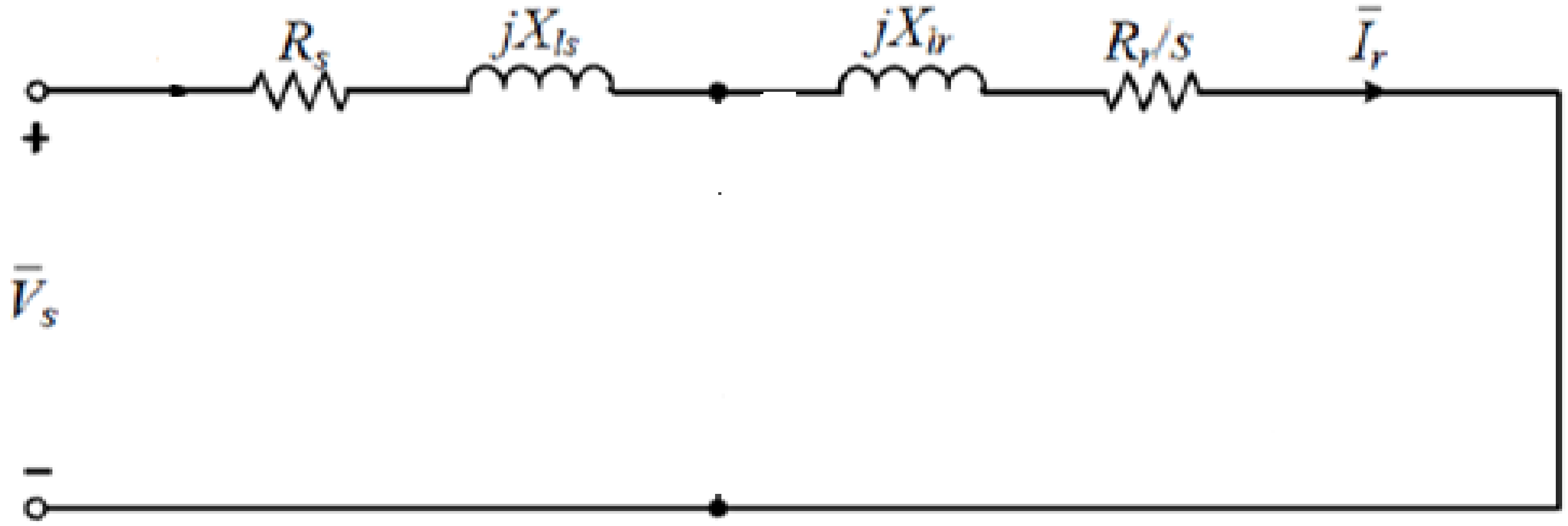
The stator frequency:

$$\omega_s = 2\pi \times 50 = 314.16 \text{ rad/sec}$$

b) The stator voltage:

$$\overline{V}_s = 690/\sqrt{3}\angle 0° = 398.37\angle 0° \text{ V (rms)}$$

The equivalent impedance of SCIG:



$$\bar{Z}_{sr} = R_s + jX_{ls} + \frac{R_r}{s} + jX_{lr} = 0.22714\angle 169.65°\,\Omega$$

where $X_{ls} = \omega_s L_{ls} = 0.0204\,\Omega$, $X_{lr} = \omega_s L_{lr} = 0.0204\,\Omega$ and $X_m = \omega_s L_m = 0.6706\,\Omega$

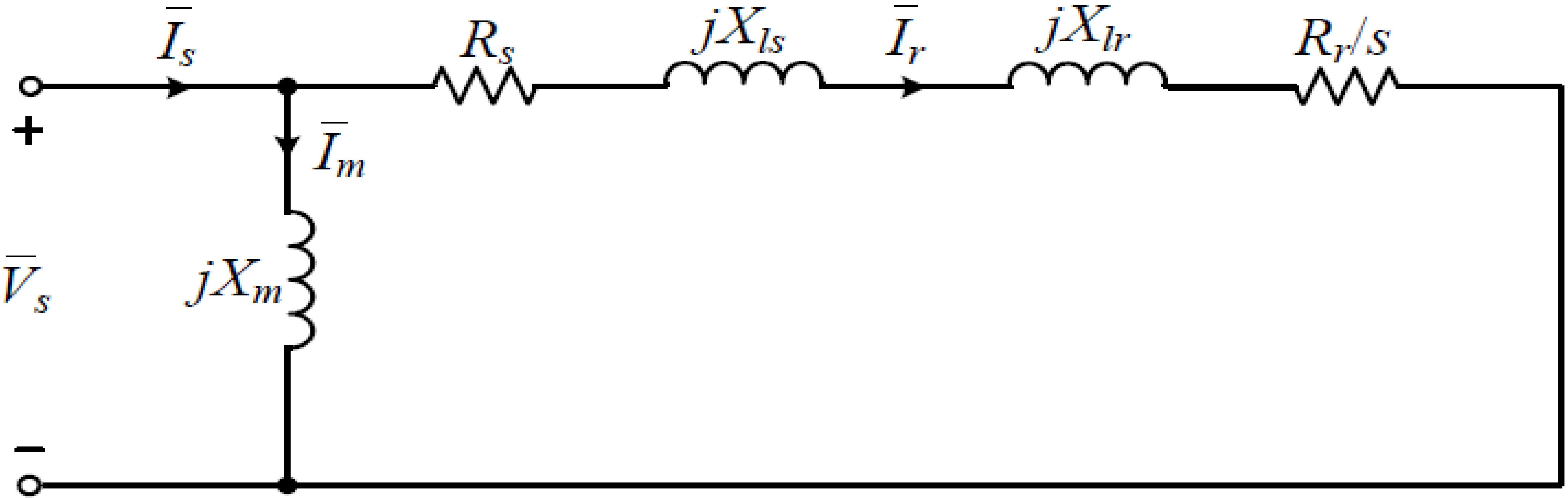
The rotor current:

$$\bar{I}_r = \frac{\bar{V}_s}{\bar{Z}_{sr}} = 1753.855\angle -169.65°\ \text{A (rms)}$$

The magnetizing current:

$$\bar{I}_m = \frac{\overline{V}_s}{jX_m} = 594.05\angle -90^\circ \text{ A (rms)}$$

The stator current:



$$\bar{I}_s = \bar{I}_r + \bar{I}_m = 1950.1\angle -152.22° \text{ A (rms)}$$

c) The mechanical power:

$$P_m = \left| 3I_r^2 \frac{R_r}{s}(1-s) \right| = 2.086 \times 10^6 \text{ W}$$

Generator mechanical torque:

$$T_m = P_m \times P / \omega_r = 13191.7\ \mathrm{N.m}$$

d) The stator winding loss:

$$P_{cu,s} = 3 \times I_s^2 R_s = 12.573 \times 10^3 \text{ W}$$

The rotor winding loss:

$$P_{cu,r} = 3 \times I_r^2 R_r = 13.814 \times 10^3 \text{ W}$$

e) The stator output power of SCIG:

$$P_s = \left|P_m\right| - \left|P_{cu,s}\right| - \left|P_{cu,r}\right| = 2.0596 \times 10^6 \text{ W}$$

The SCIG efficiency:

$$\eta = \frac{P_s}{P_m} = 98.74\%$$

The stator power factor angle:

$$\varphi_S = \angle V_S - \angle I_S = 0° - (-152.22°) = 152.22°$$

The stator power factor:

$$PF_s = \cos\varphi_s = -0.8847$$

3-4 Repeat Problem 3-3 when the SCIG operates at a speed of 1504 rpm:

Consider 2.3MW/690V/50Hz SCIG in a wind energy conversion system. Generator is directly connected to grid of 690V/50Hz. Generator parameters are given in Table B-1 of Appendix B. At a given wind speed, SCIG operates at a speed of 1504 rpm. Using approximate induction generator equivalent circuit of Fig. P3-3, calculate following:

a) slip, and rotor mechanical and electrical speeds,

b) rotor and stator currents,

c) mechanical power and torque,

d) stator and rotor winding losses, &

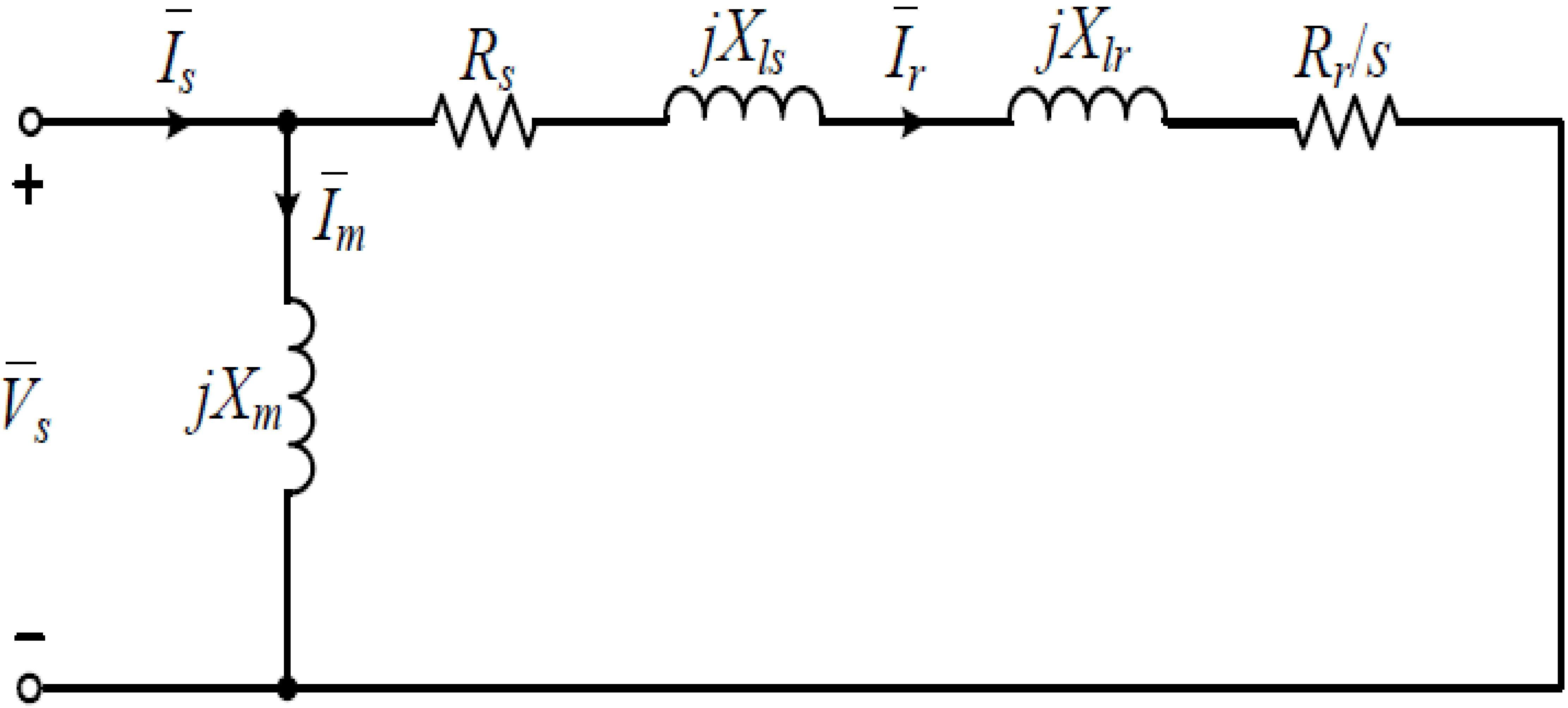
e) generator efficiency and power factor.

Table B-1 2.3MW/690V/50Hz Squirrel Cage Induction Generator (SCIG) Parameters

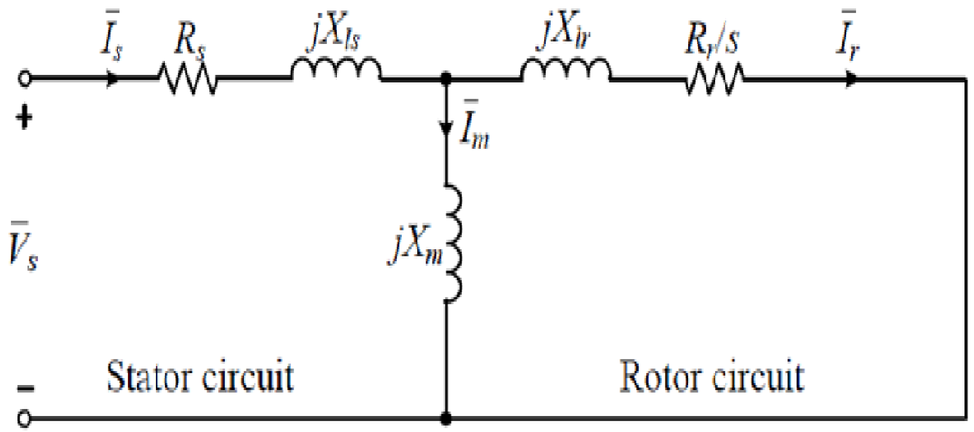
Generator Type	**SCIG, 2.3MW/690V/50Hz**	
Rated Output Power	2.30 MW	
Rated Mechanical Power	2.3339 MW	1.0 pu
Rated Apparent Power	2.59 MVA	1.0 pu
Rated Line-to-line Voltage	690 V (rms)	
Rated Phase Voltage	398.4 V (rms)	1.0 pu
Rated Stator Current	2168 A (rms)	1.0 pu
Rated Stator Frequency	50 Hz	1.0 pu
Rated Power Factor	0.888	
Rated Rotor Speed	1512 rpm	1.0pu
Rated Slip	-0.008	
Number of Pole Pairs	2	
Rated Mechanical Torque	14.74 kN.m	1.0 pu
Rated Stator Flux Linkage	1.2748 Wb (rms)	1.0053 pu
Rated Rotor Flux Linkage	1.2096 Wb (rms)	0.9539 pu
Stator Winding Resistance R_s	1.102 mΩ	0.006 pu
Rotor Winding Resistance R_r	1.497 mΩ	0.008 pu
Stator Leakage Inductance L_{ls}	0.06492 mH	0.111 pu
Rotor Leakage Inductance L_{lr}	0.06492 mH	0.111 pu
Magnetizing Inductance L_m	2.13461 mH	3.6481 pu
Moment of Inertia J	1200 kg.m^2	
Inertia Time Constant H	5.8078 sec	
Base Flux Linkage Λ_B	1.2681 Wb (rms)	1.0 pu
Base Impedance Z_B	0.1838 Ω	1.0 pu
Base Inductance L_B	0.58513 mH	1.0 pu
Base Capacitance C_B	17316.17 μF	1.0 pu

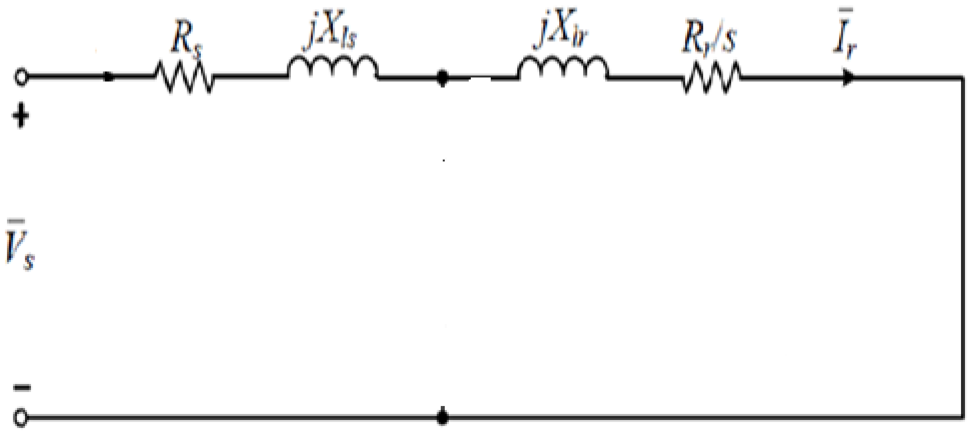
Note: $H = J(\omega_m)^2/(2S_B)$

Fig. P3-3 Approximate induction generator equivalent circuit



Neglecting magnetizing branch in Fig. for simplicity and calculating equivalent impedance





Answers:

a) $s = -0.00267$, $\omega_m = 157.5\ \text{rad/sec}$, $\omega_r = 314.997\ \text{rad/sec}$

b) $\bar{Z}_{sr} = 0.5618\angle 175.84°\ \Omega$, $\bar{I}_r = 709.15\angle -175.84°\ \text{A}$, $\bar{I}_s = 957.59\angle -137.61°\ \text{A}$

c) $P_m = 849.205 \times 10^3\ \text{W}$, $T_m = 5391.83\ \text{N.m}$

d) $P_{cu,s} = 3.0315 \times 10^3\ \text{W}$, $P_{cu,r} = 2.2585 \times 10^3\ \text{W}$

e) $P_s = 843.915 \times 10^3\ \text{W}$, $\eta = 99.38\%$, $PF_s = -0.7386$

Lecture#09

3.4 Synchronous Generators

3.4.1 Construction

3.4.2 Dynamic Model of SG

3.4.3 Steady-State Equivalent Circuits

What stuff we shall share in this section?

1. Construction of:

i. Wound Rotor Synchronous Generator(WRSG)

ii. Permanent Magnet Synchronous Generator(PMSG)

2. Dynamic & steady-state models for both types of synchronous generators.

3. Block diagrams for simulation of synchronous generator

4. Case studies for dynamic & steady-state analysis of generators.

3.4 Synchronous Generators

- Synchronous Generators (SG) are widely used in wind energy conversion systems of a few KW to a few MW.

Synchronous Generators (SG) can be classified into?

Classification of Synchronous Generators (SG)

1. Wound Rotor Synchronous Generator (WRSG)

   &

2. Permanent Magnet Synchronous Generator (PMSG).

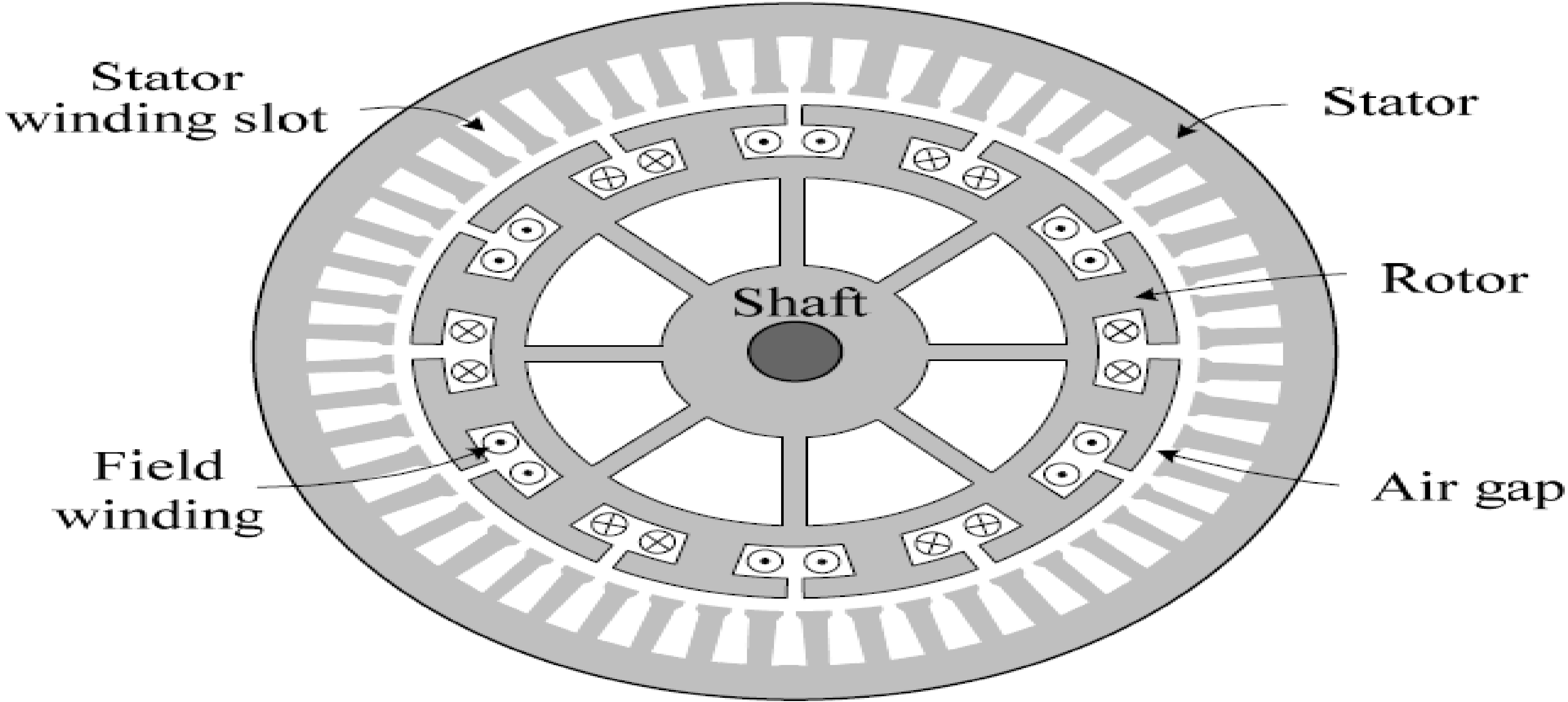
Wound Rotor Synchronous Generator (WRSG) versus PMSG

- In WRSG **rotor flux** is generated by rotor field winding while PMSG uses permanent magnets to produce rotor flux.
- Depending on shape of rotor & distribution of air gap along perimeter of rotor, synchronous generator can be categorized into **salient-pole & non-salient-pole types.**

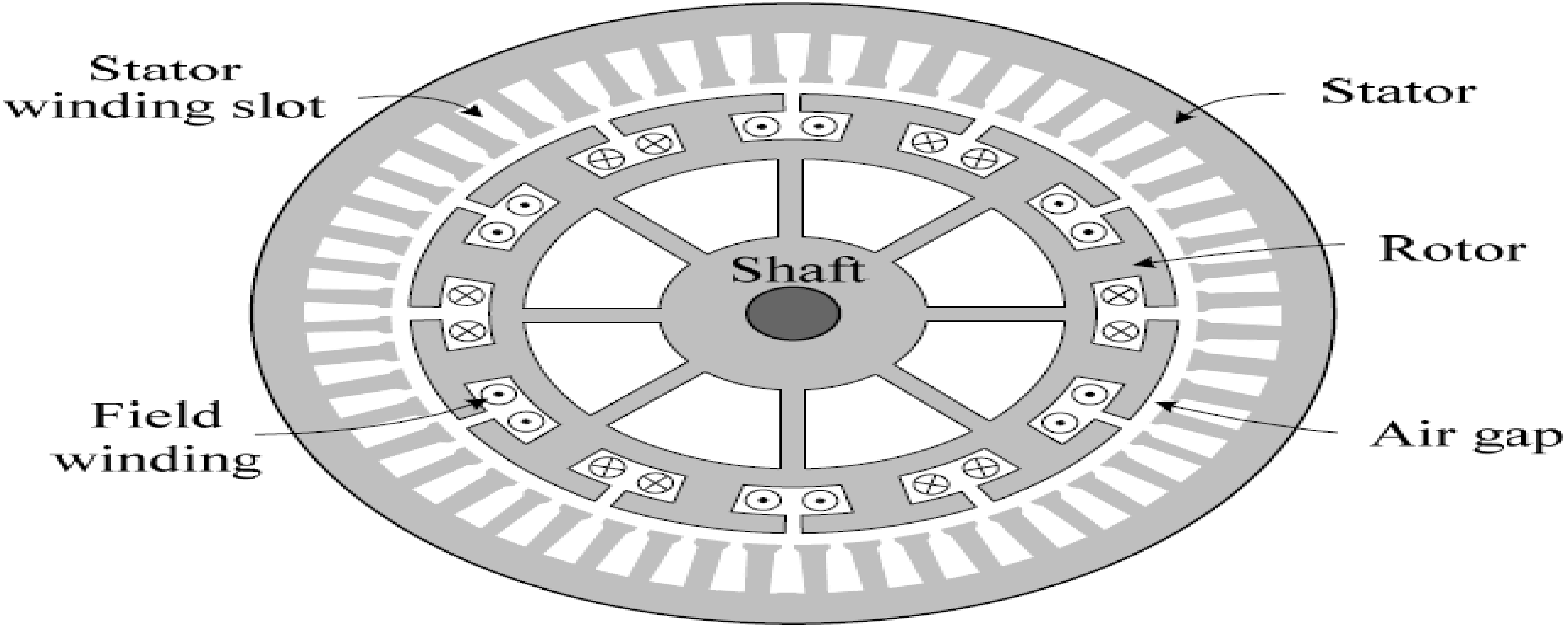
3.4.1 Construction

- Similar to induction generator, synchronous generator is mainly composed of (i)stator & (ii) rotor.
- Construction of stator of both wound-rotor & permanent-magnet synchronous generators is essentially same as that of induction generator.

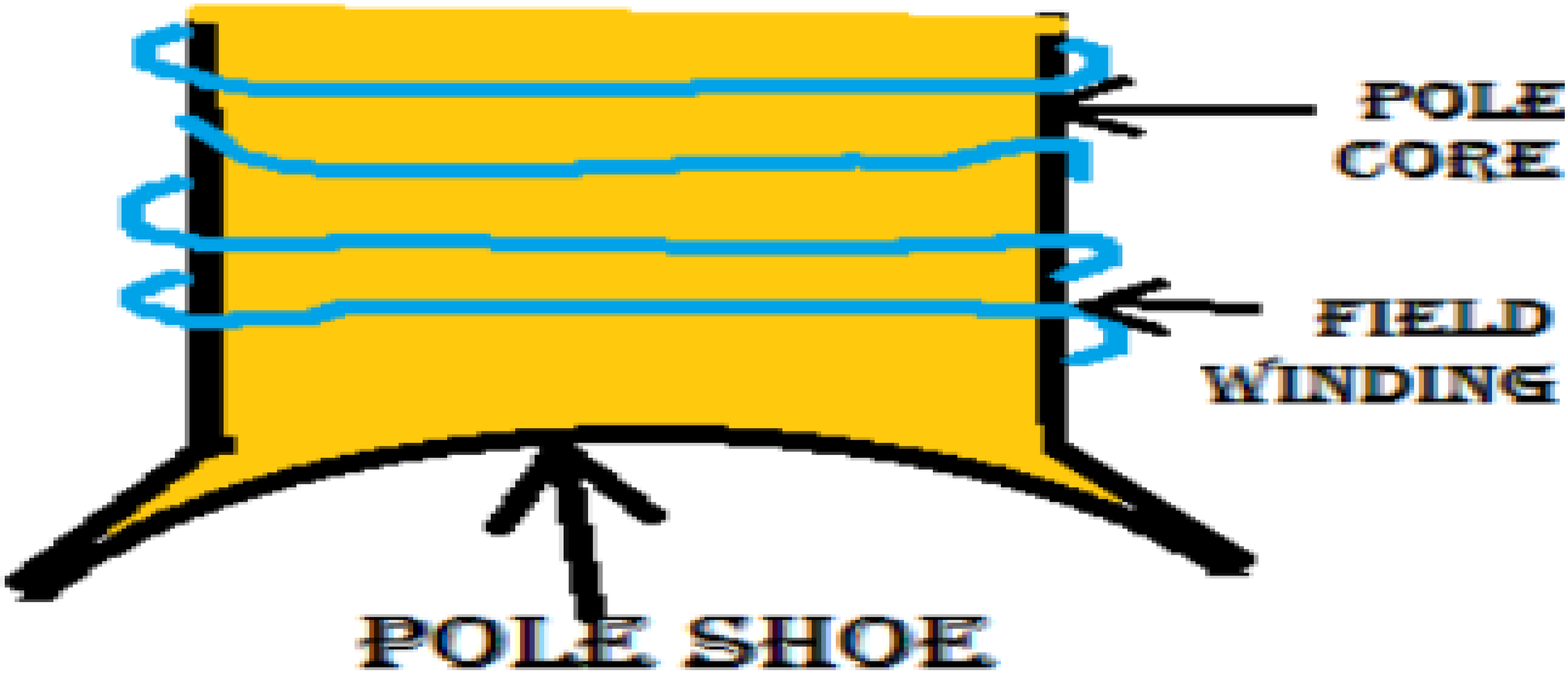
a) Wound-Rotor Synchronous Generators



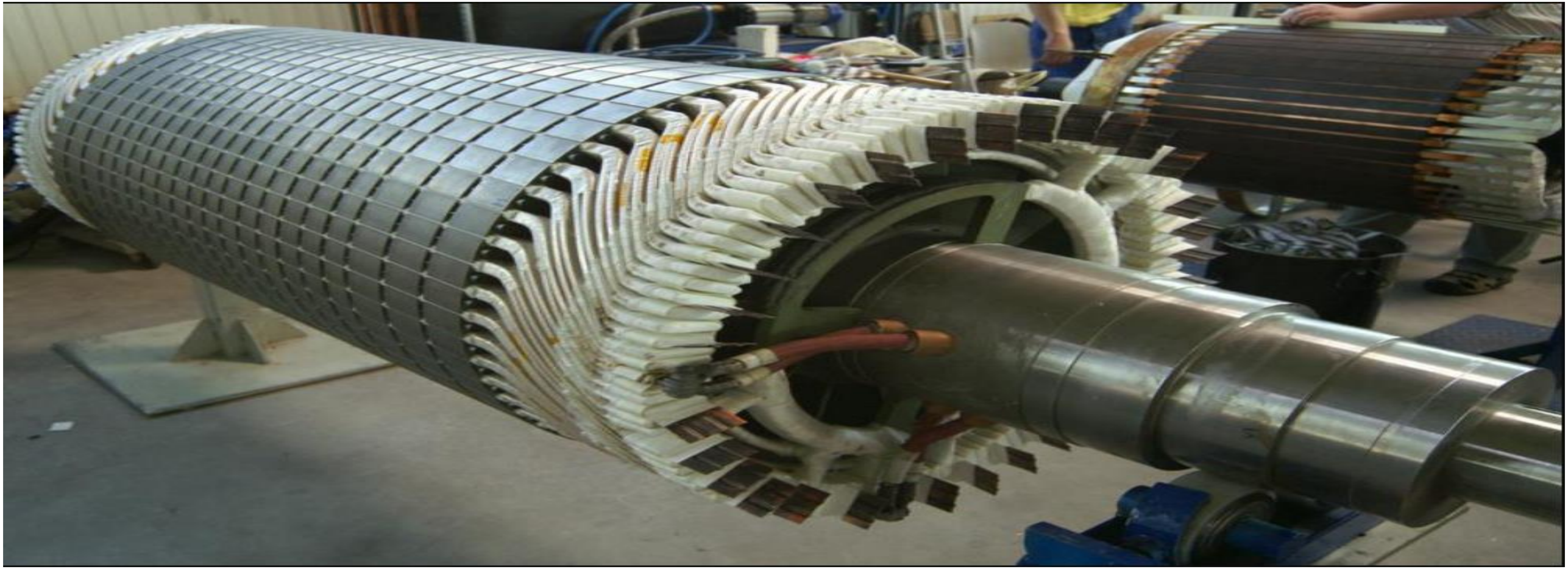
As name indicates, wound-rotor synchronous generator has **a wound rotor configuration** to generate rotor magnetic flux.



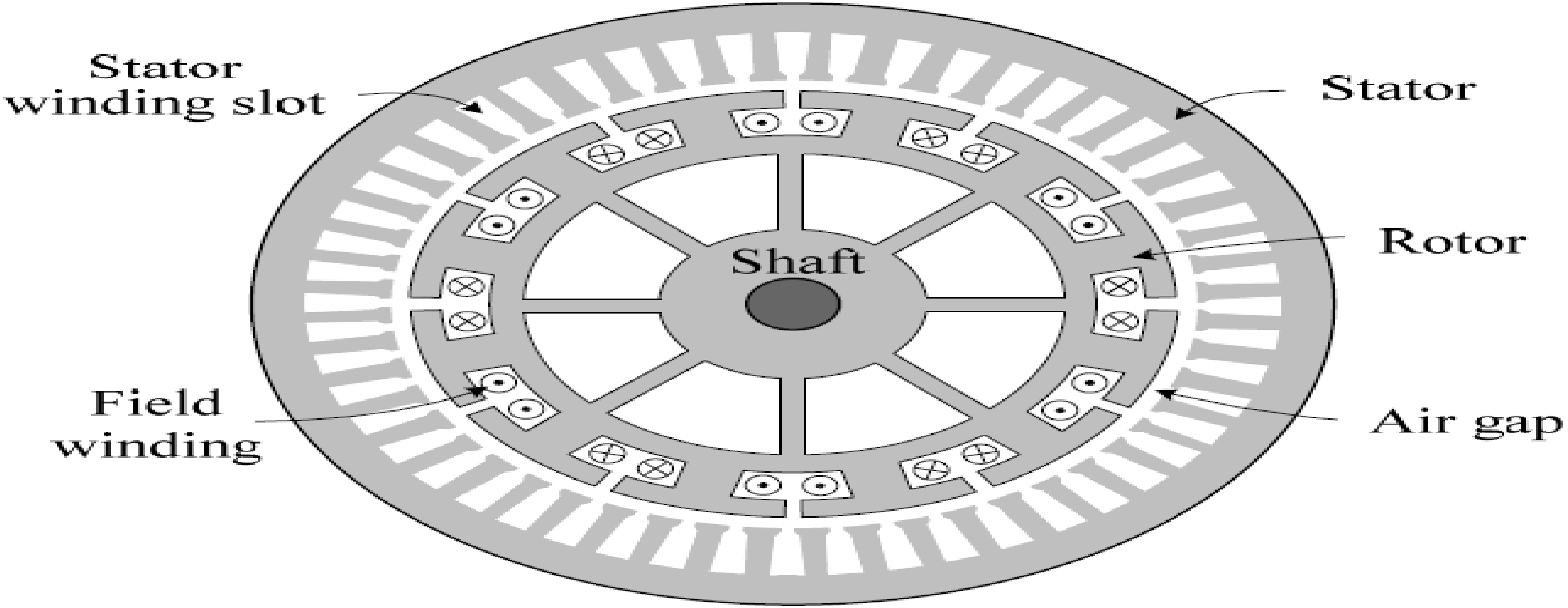
Field winding in wound around pole shoes.



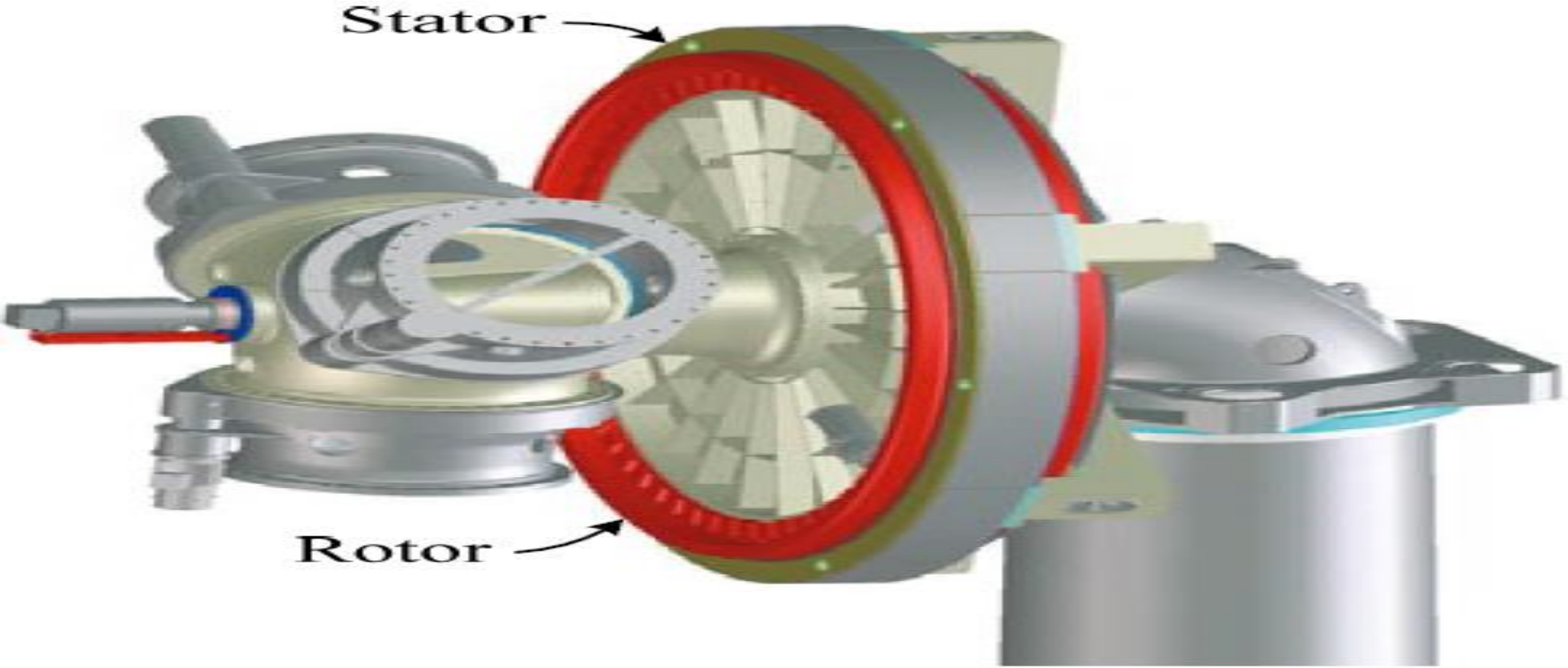
Field winding is placed symmetrically on perimeter of rotor in a radial configuration around shaft to accommodate large number of poles.



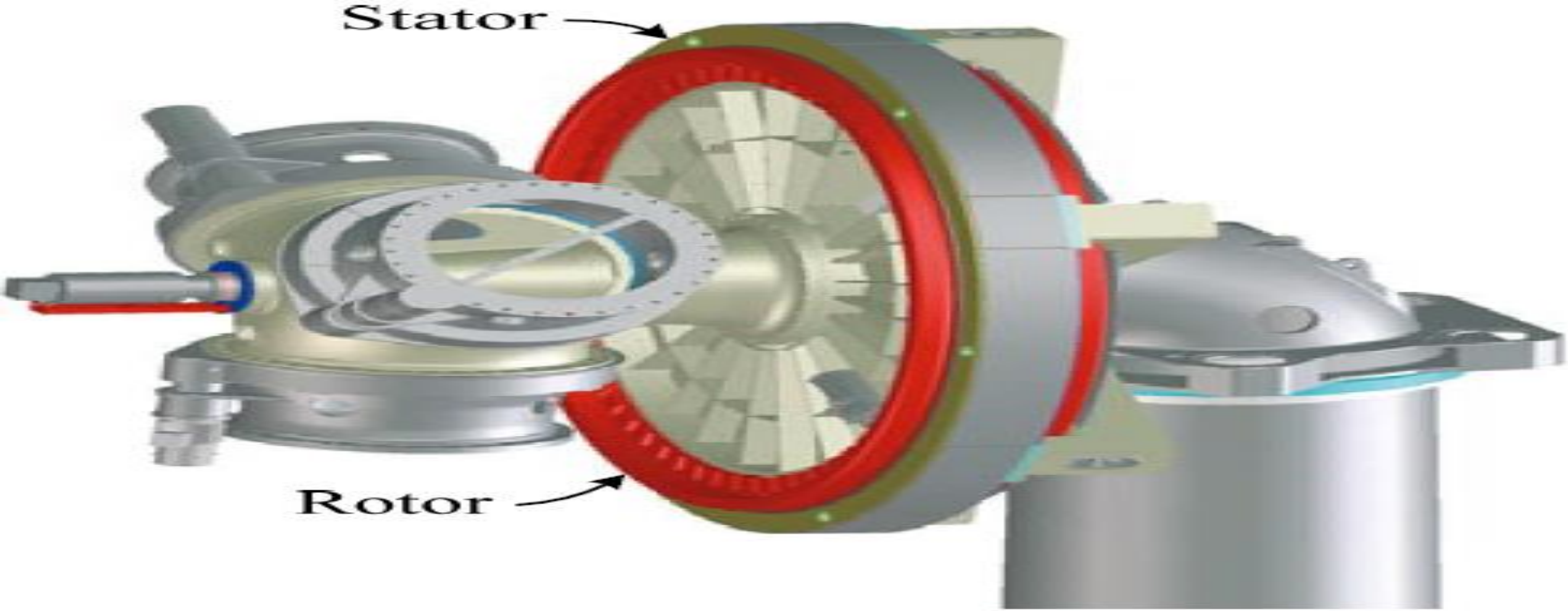
Generator has an uneven air gap flux distribution due to salient structure of rotor.



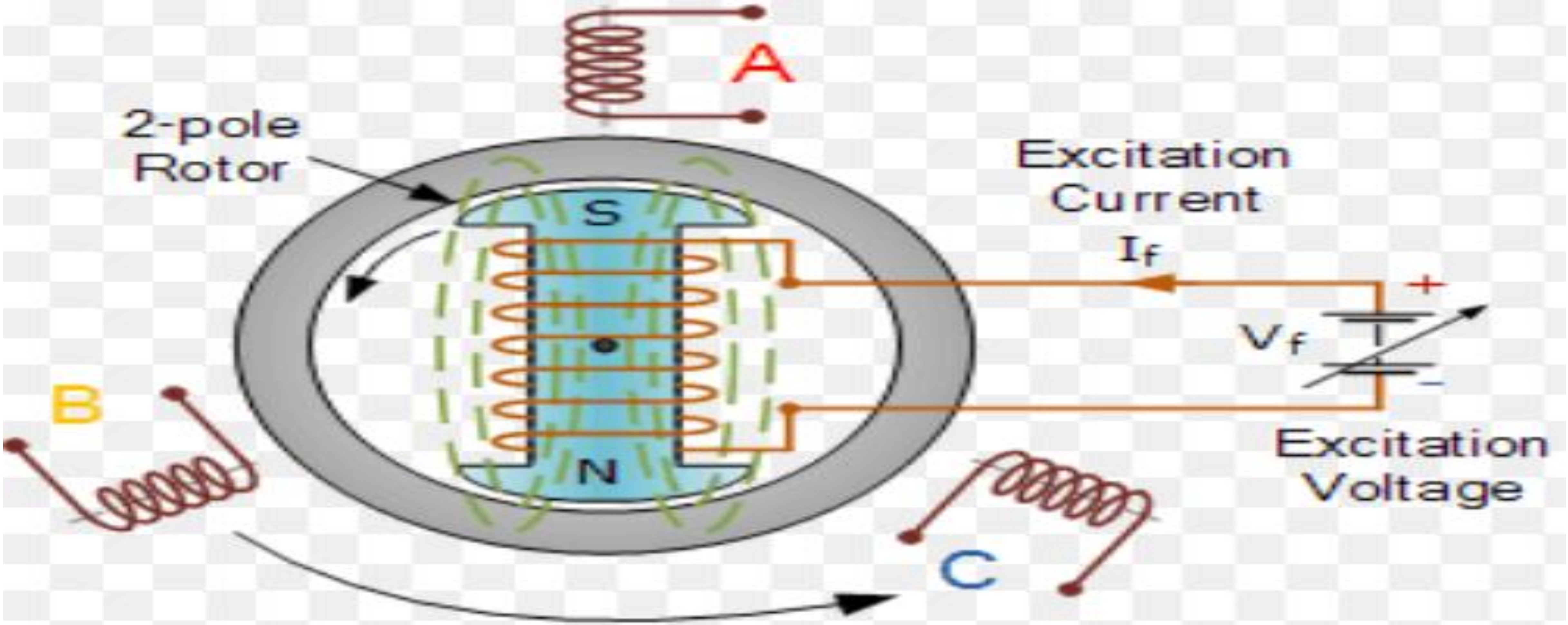
a) A practical example of Wound-Rotor Synchronous Generators



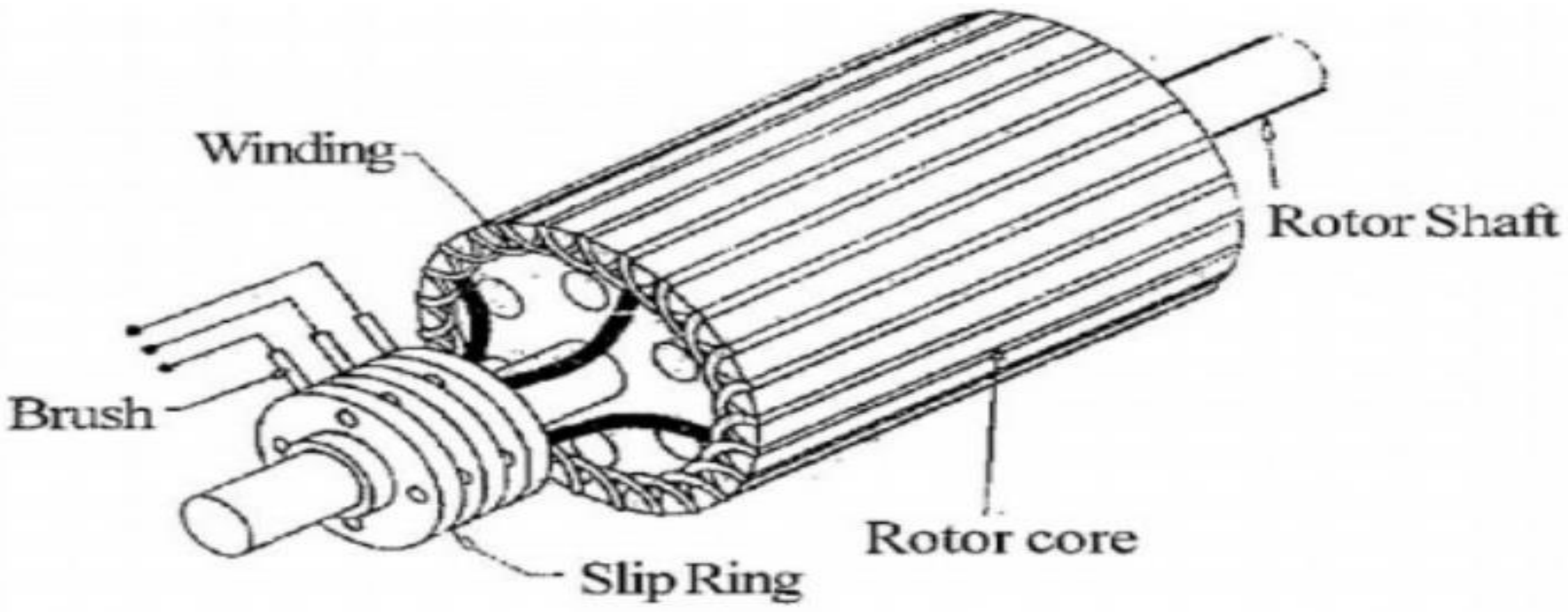
Synchronous generators with high number of poles **(e.g. 72 poles)** operating low rotational speeds can be used in direct-driven MW wind energy systems, where there is no need for a gearbox.



Rotor field winding of synchronous generator requires a dc excitation.



Rotor current can be supplied directly by brushes in contact with slip rings attached to shaft & electrically connected to rotor winding.



Alternatively, a **brushless exciter** physically attached to shaft can be used.

- Exciter generates ac currents that are rectified into dc using a diode bridge for rotor winding.
- 1st option is simple but requires regular maintenance of brushes & slip rings,
- 2nd option is more expensive & complex but needs little maintenance.

b) Permanent Magnet Synchronous Generators

- In PMSG, rotor magnetic flux is generated by permanent magnets, & these generators are therefore **brushless.**
- Because of absence of rotor windings, a high power density can be achieved, reducing size & weight of generator.
- In addition, there are no rotor winding losses, reducing thermal stress on rotor.

b) Permanent Magnet Synchronous Generators

- Drawbacks of these generators lie in the fact that permanent magnets are:

(i) more expensive &

(ii) prone to demagnetization.

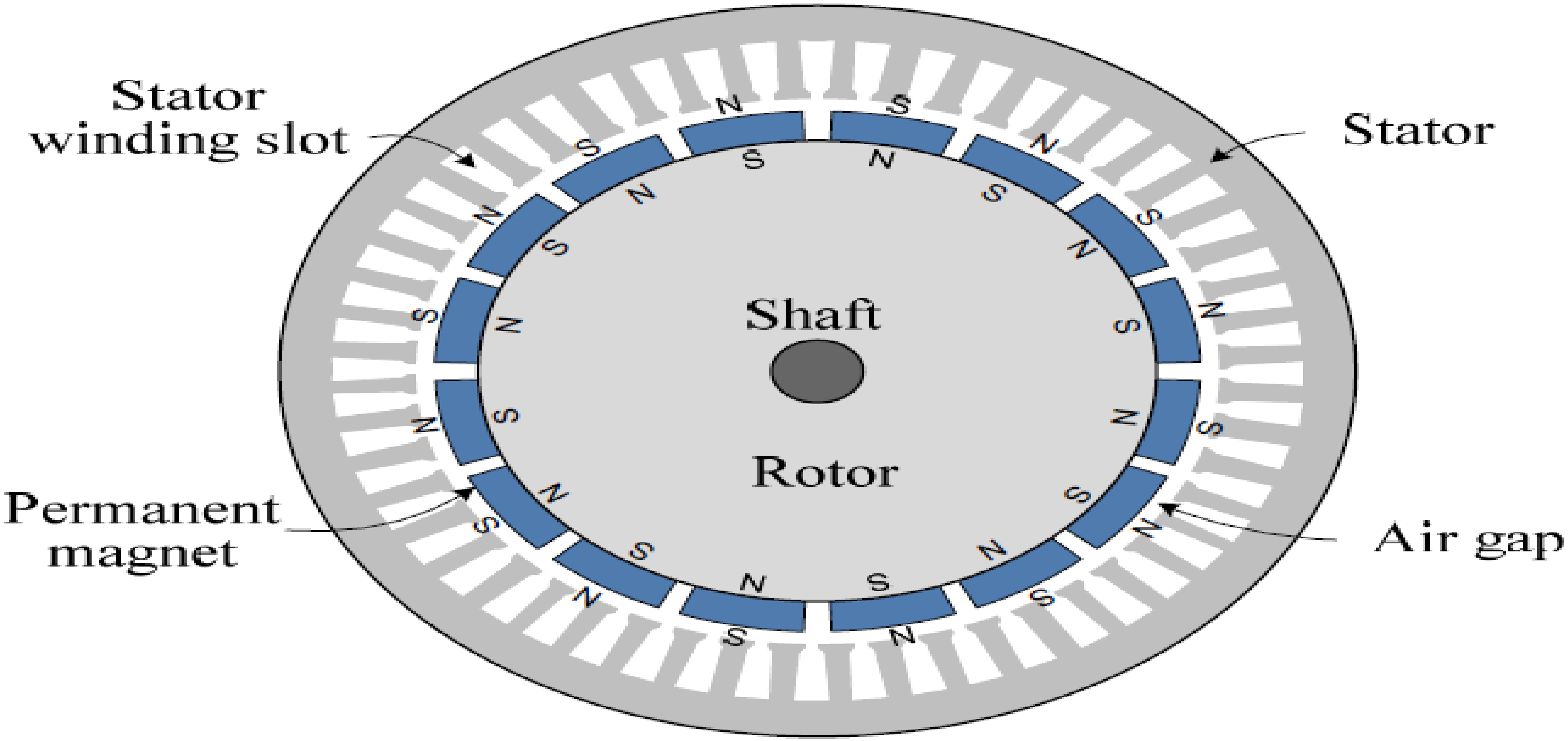
Classification of PMSG

- Depending on how permanent magnets are mounted on rotor, PMSG can be classified into

(i)Surface mounted &

(ii)Inset PM generators.

b.1) Surface-Mounted PMSG



In surface-mounted PMSG, permanent magnets are placed on rotor surface.

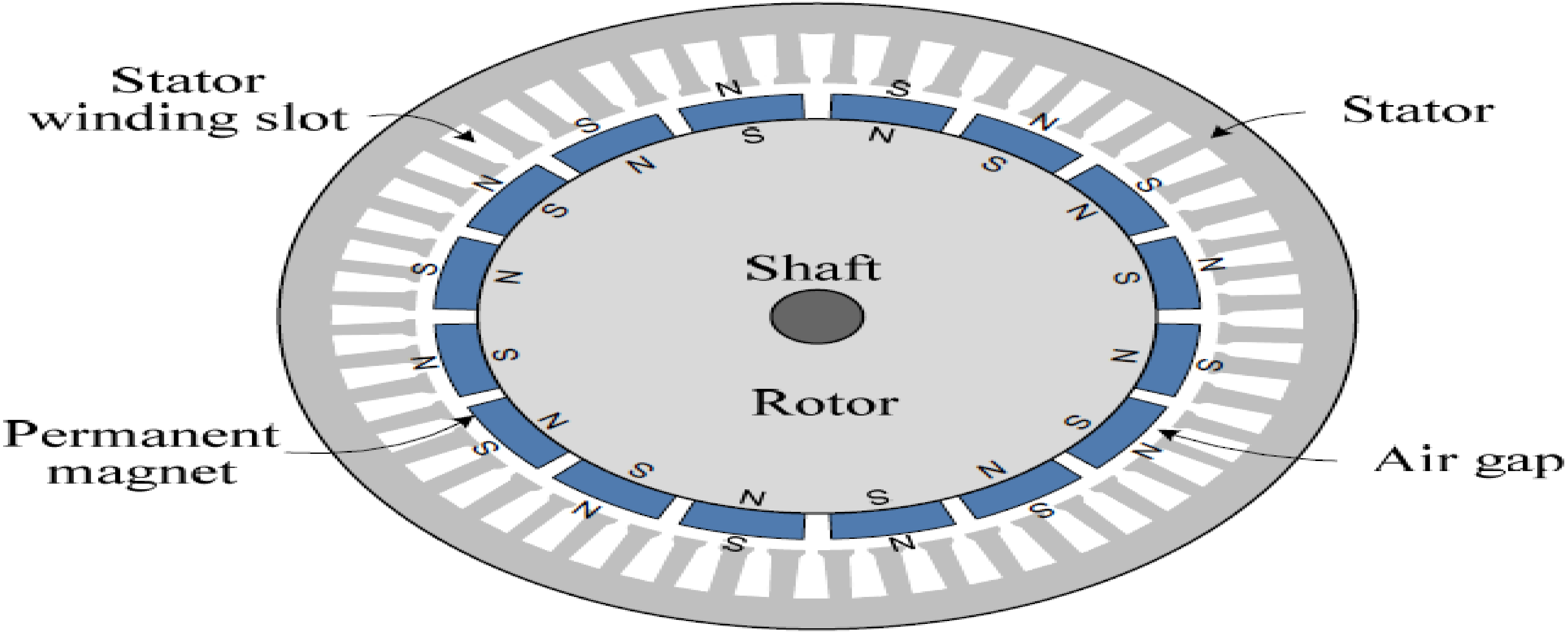
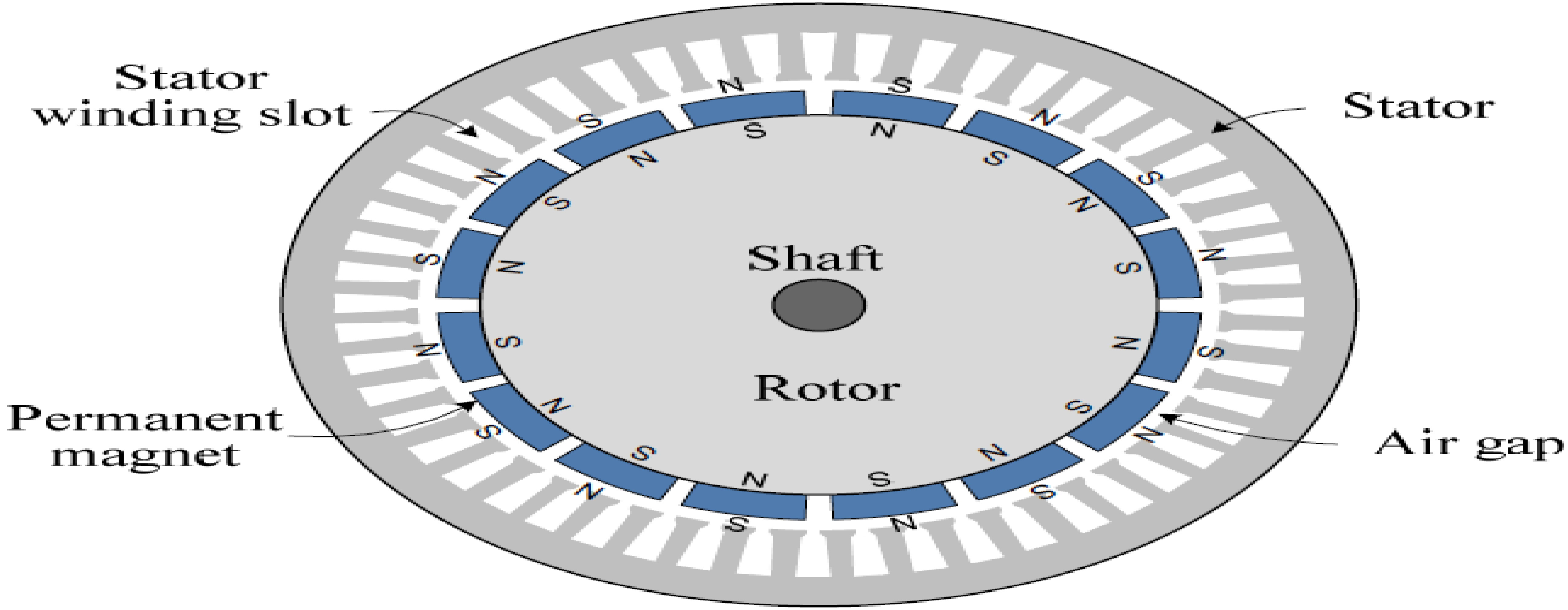
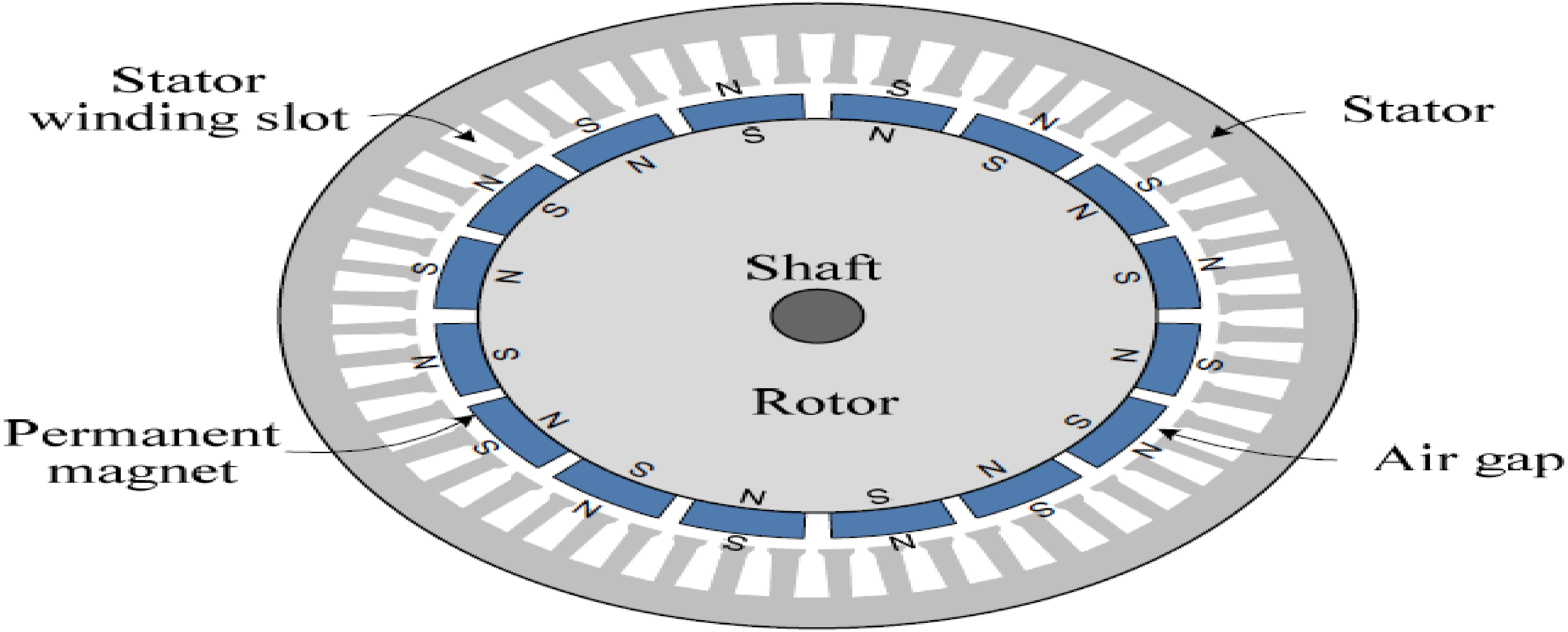


Fig. shows such a generator, where 16 magnets are evenly mounted on surface of rotor core, separated by non-ferrite materials between 2 adjacent magnets.



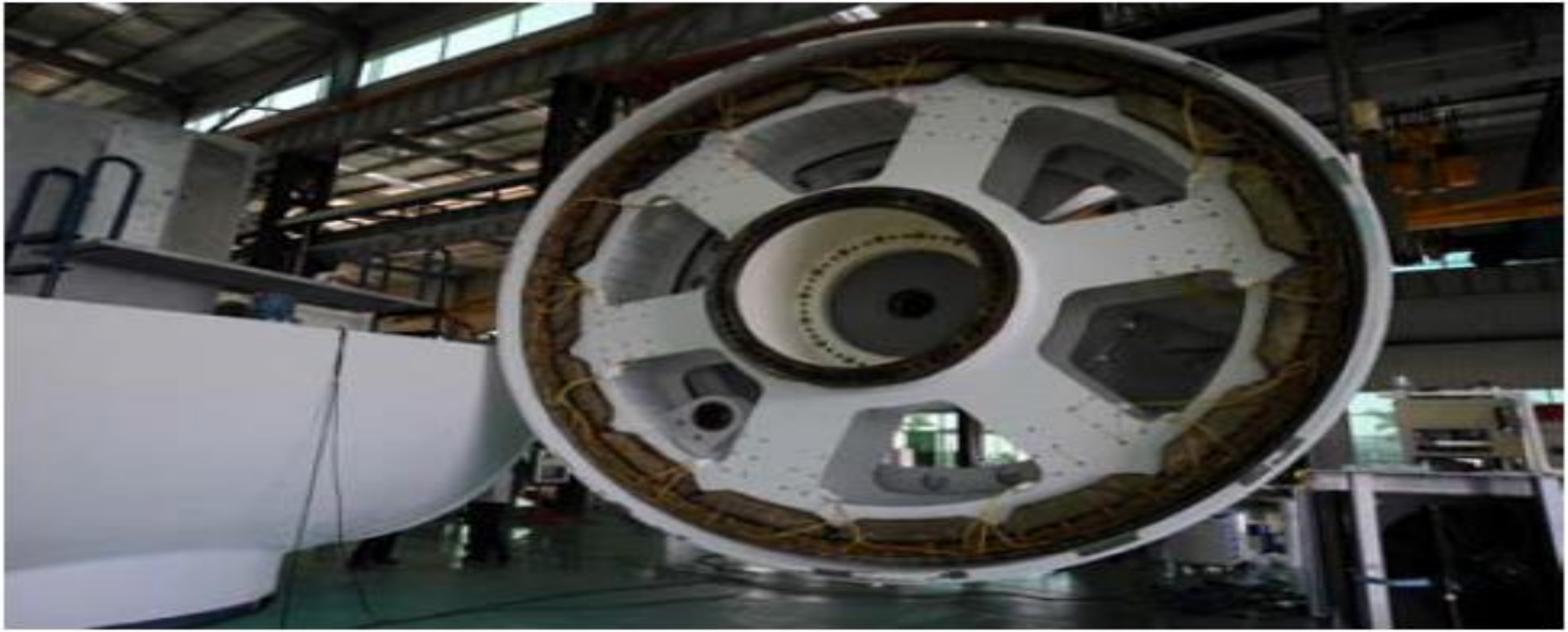
Since permeability of magnets is very close to that of non-ferrite materials, effective air gap between rotor core & stator is uniformly distributed around surface of rotor.



Pros & cons of Surface-Mounted PMSG

- Main advantage of surface-mounted SG is its simplicity & low construction cost in comparison to inset PMSG.
- Magnets are subject to centrifugal forces that can cause their detachment from rotor,
- So surface mounted PMSG are mainly used in low-speed applications.

In direct-driven WECS, synchronous generator with high number of poles is used, like one shown in Fig.



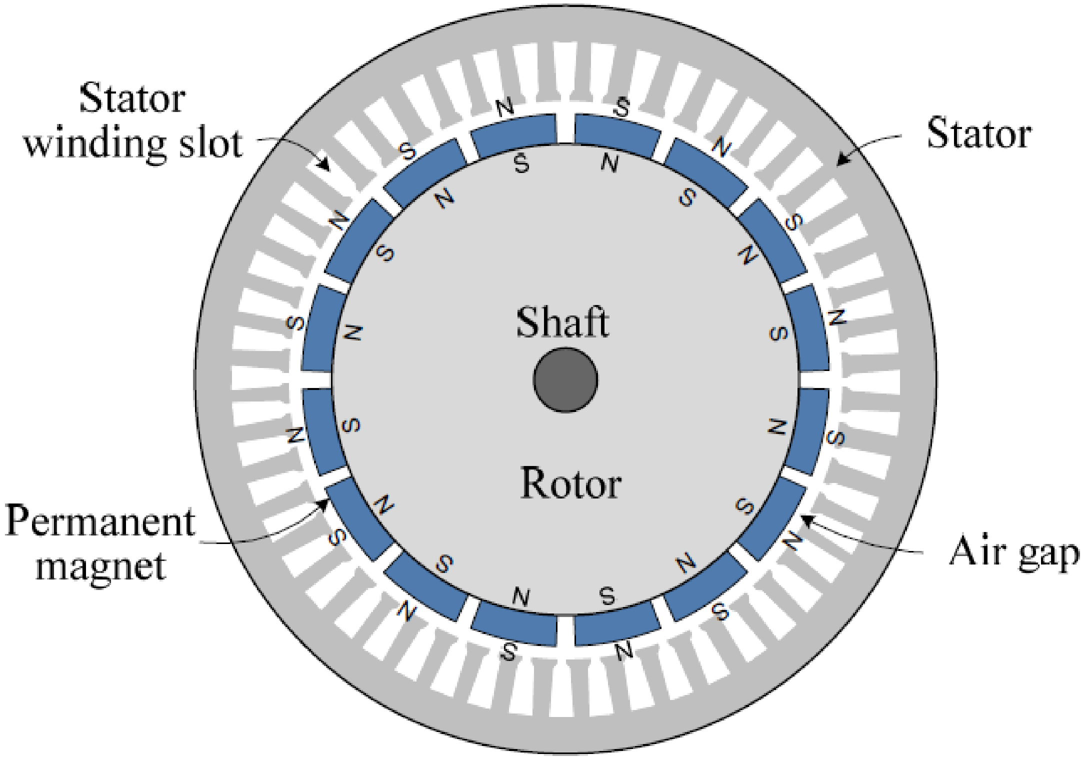
Surface-mounted PMSG can have an external rotor, where permanent magnets are attached to inner surface of rotor .

b.2) Inset PMSG

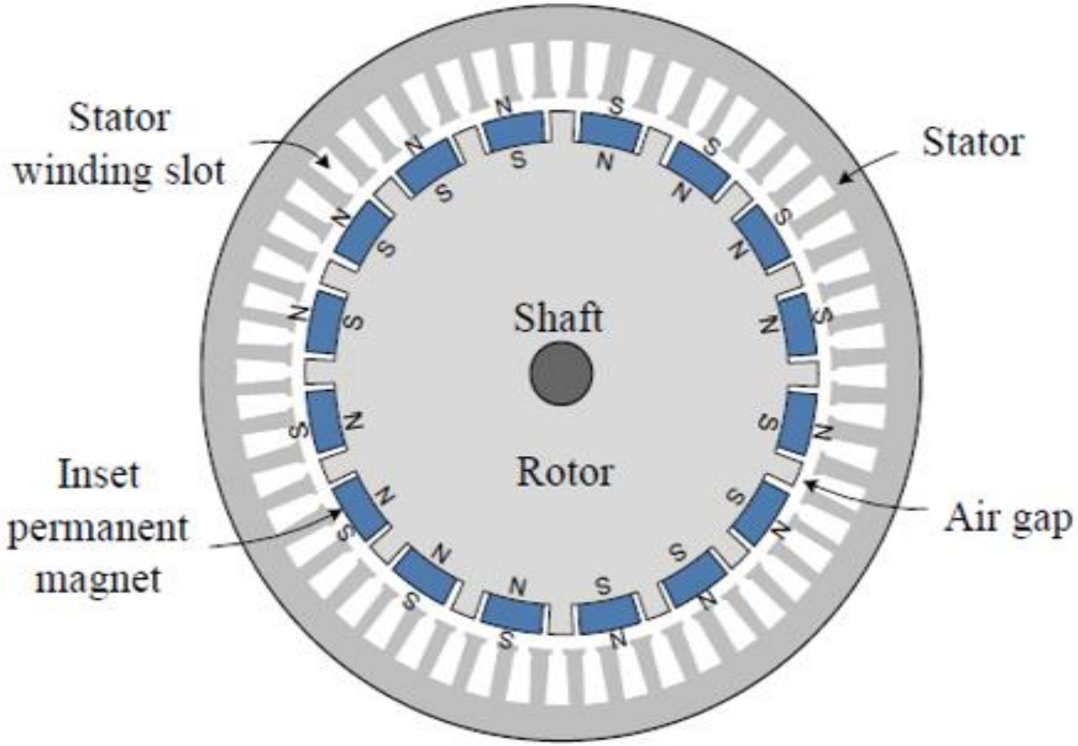
In surface-mounted PMSG, permanent magnets are placed on rotor surface

In inset PMSG, permanent magnets are inset into rotor surface

Surface-Mounted PMSG

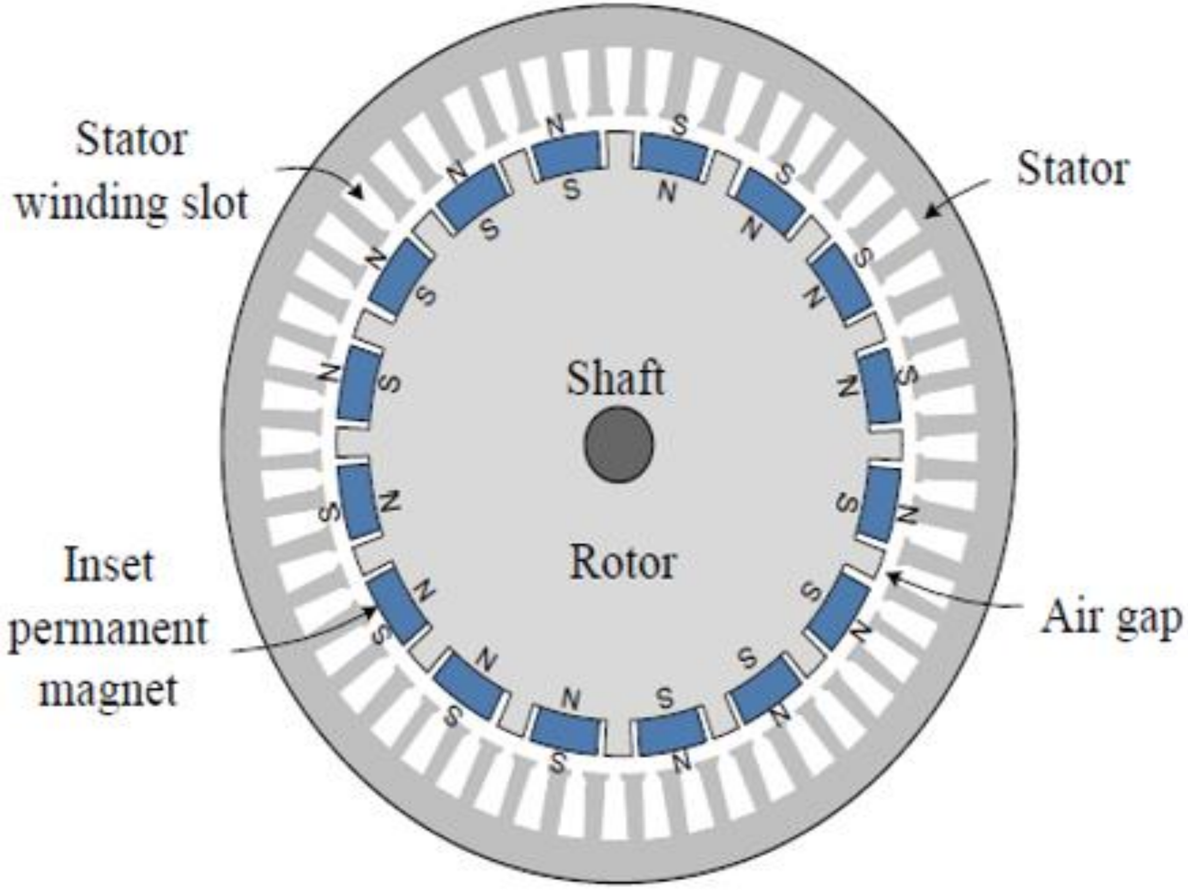


Inset PMSG



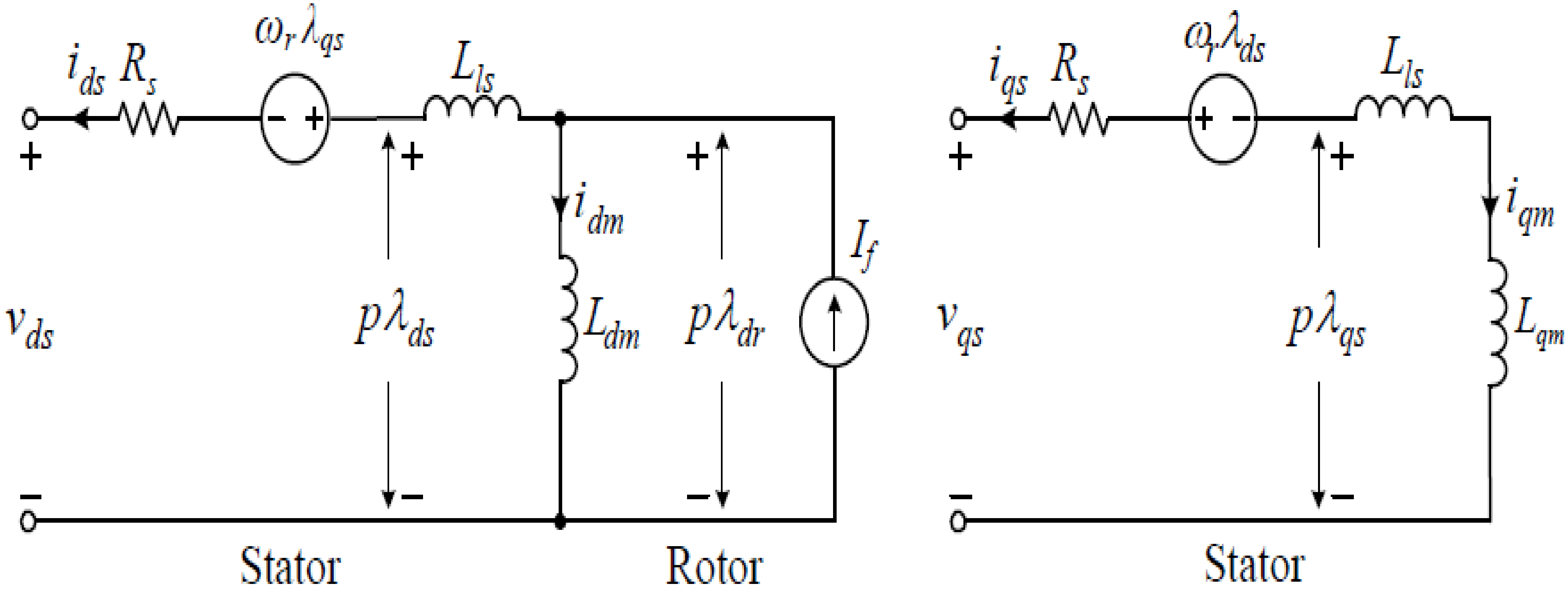
Saliency is created by different permeability of rotor core material & magnets.

- This configuration also reduces rotational stress associated to centrifugal forces in comparison to surface mounted PMSG, &
- Therefore this type of generator can operate at higher rotor speeds.



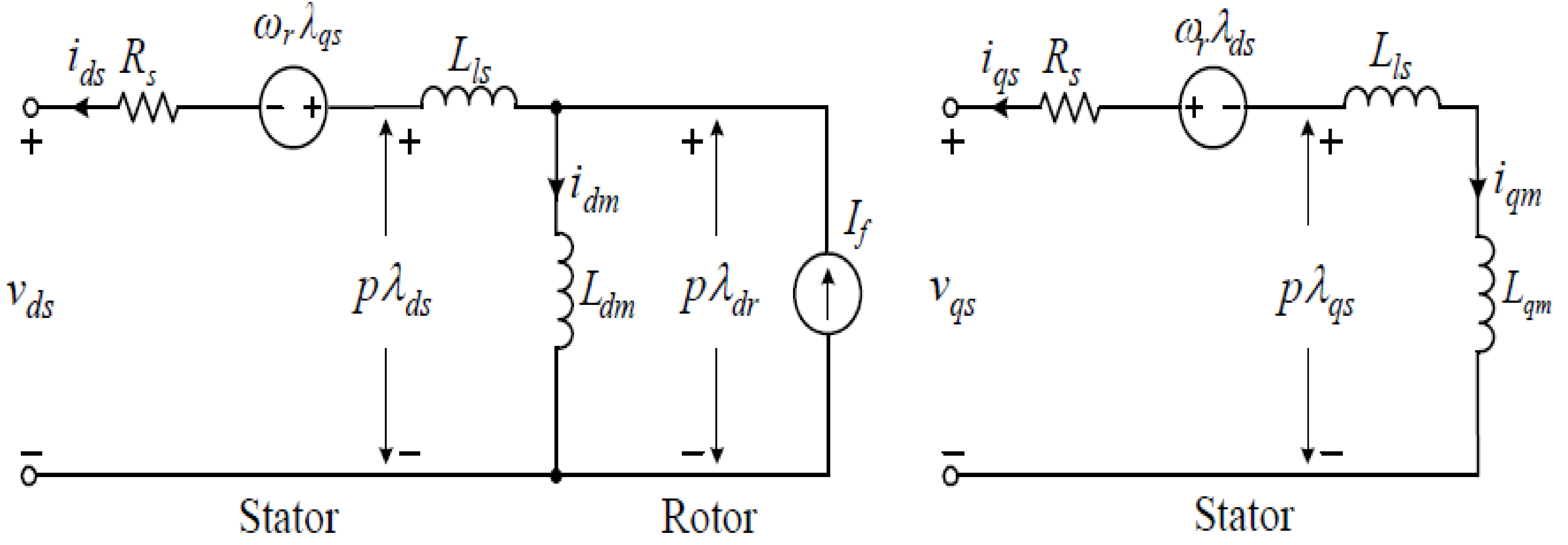
A practical low pole number PMSG used in WECS

3.4.2 Dynamic Model of synchronous generator in dq-axes



(a) *d*-axis circuit (b) *q*-axis circuit

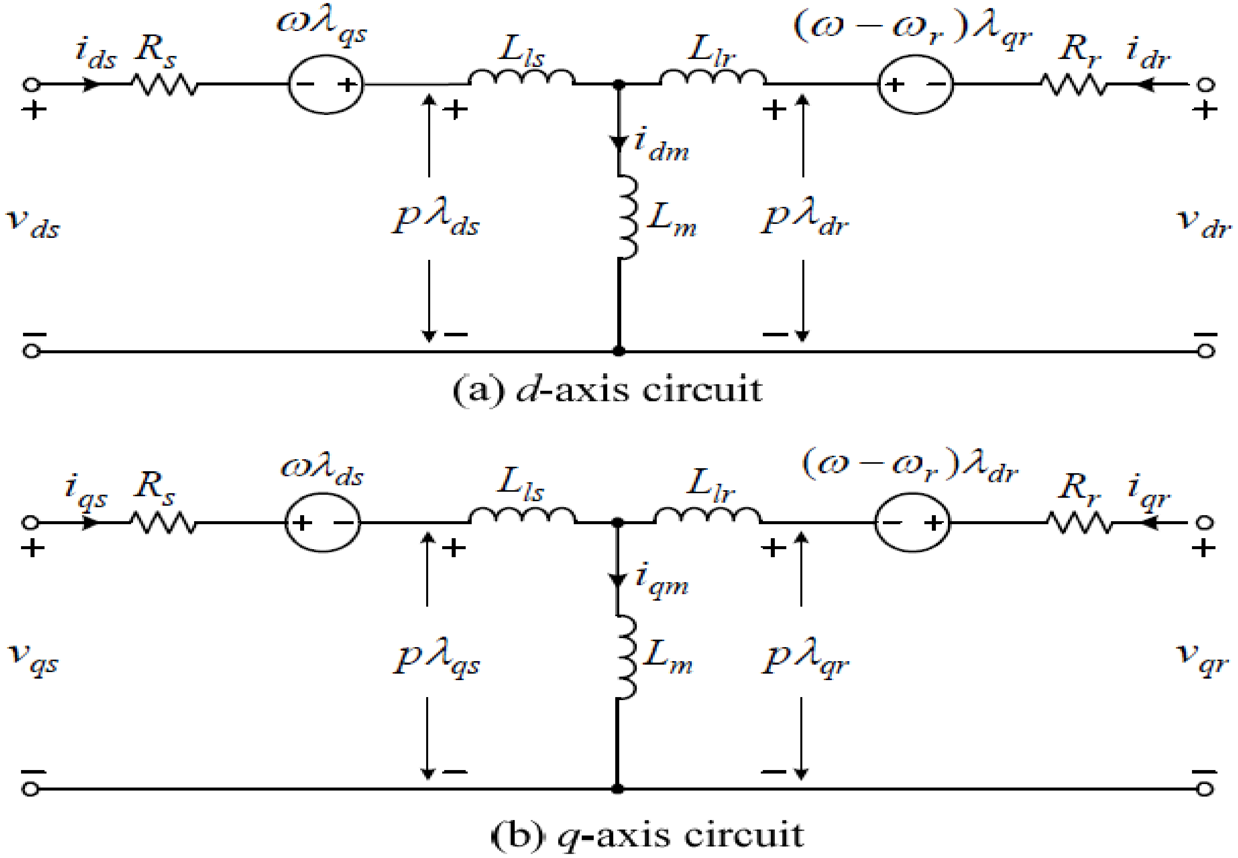
To simplify analysis, SG is normally modelled in **rotor field synchronous reference frame ωr.**



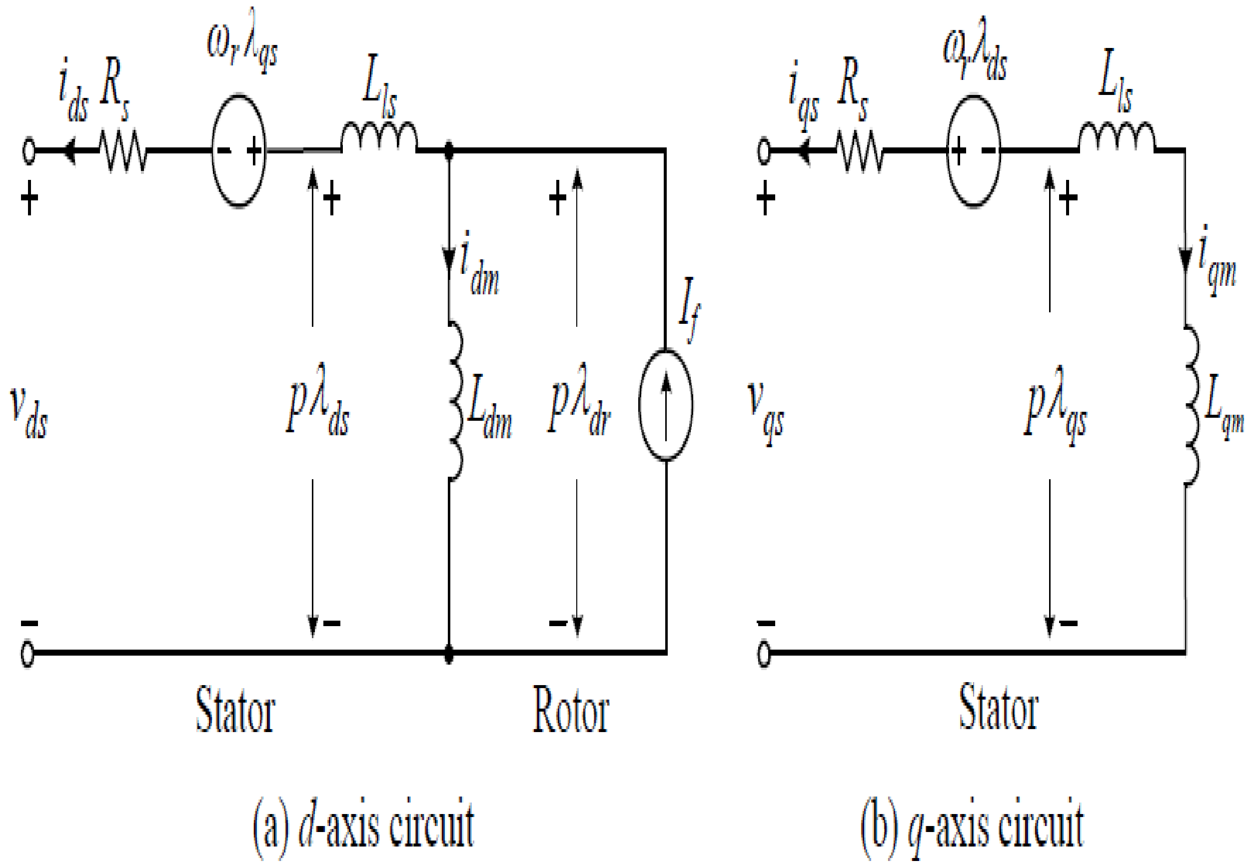
(a) *d*-axis circuit (b) *q*-axis circuit

3 simple steps for transformation of IG dq-axis model into SG dq-axis model

***dq*-axis model of induction generator**

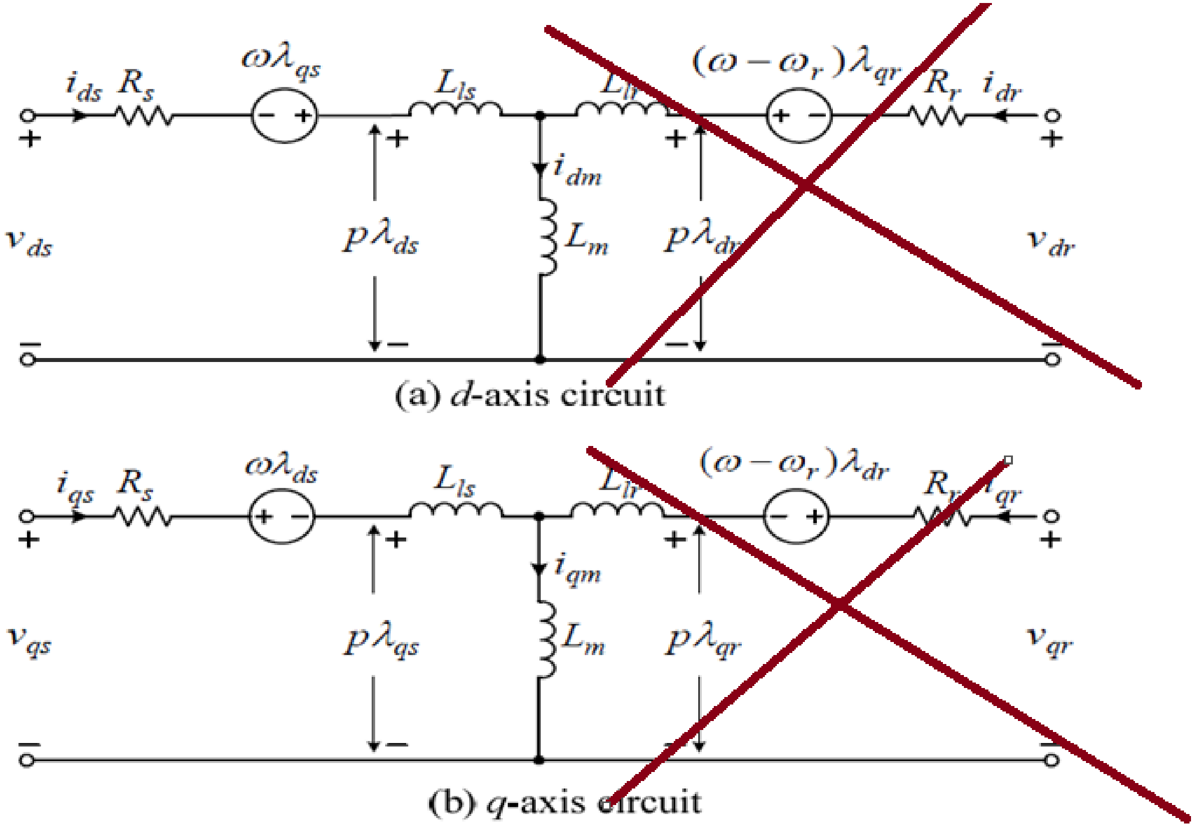


***dq*-axis model of synchronous generator**

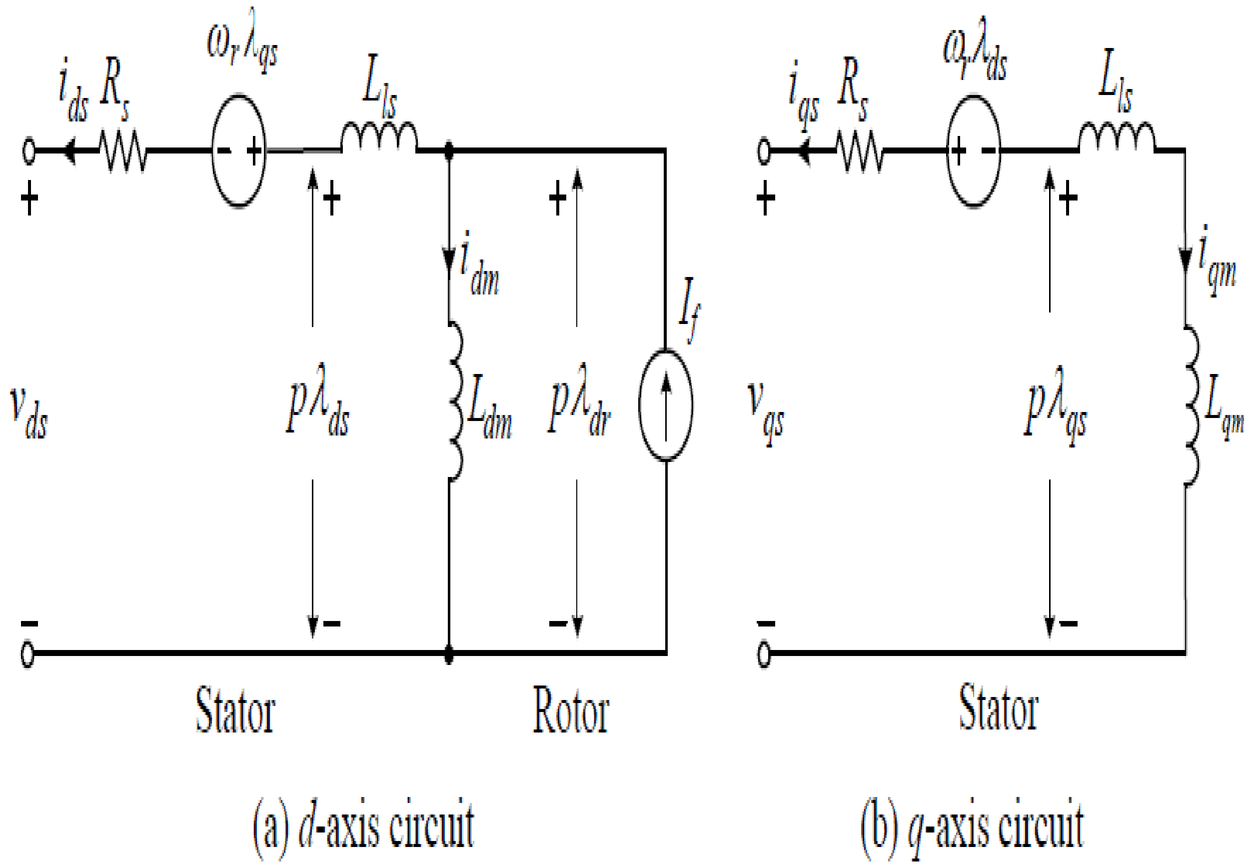


(i) Replace $\omega = \omega r$ *in dq*-axis model of induction generator

dq-axis model of induction generator

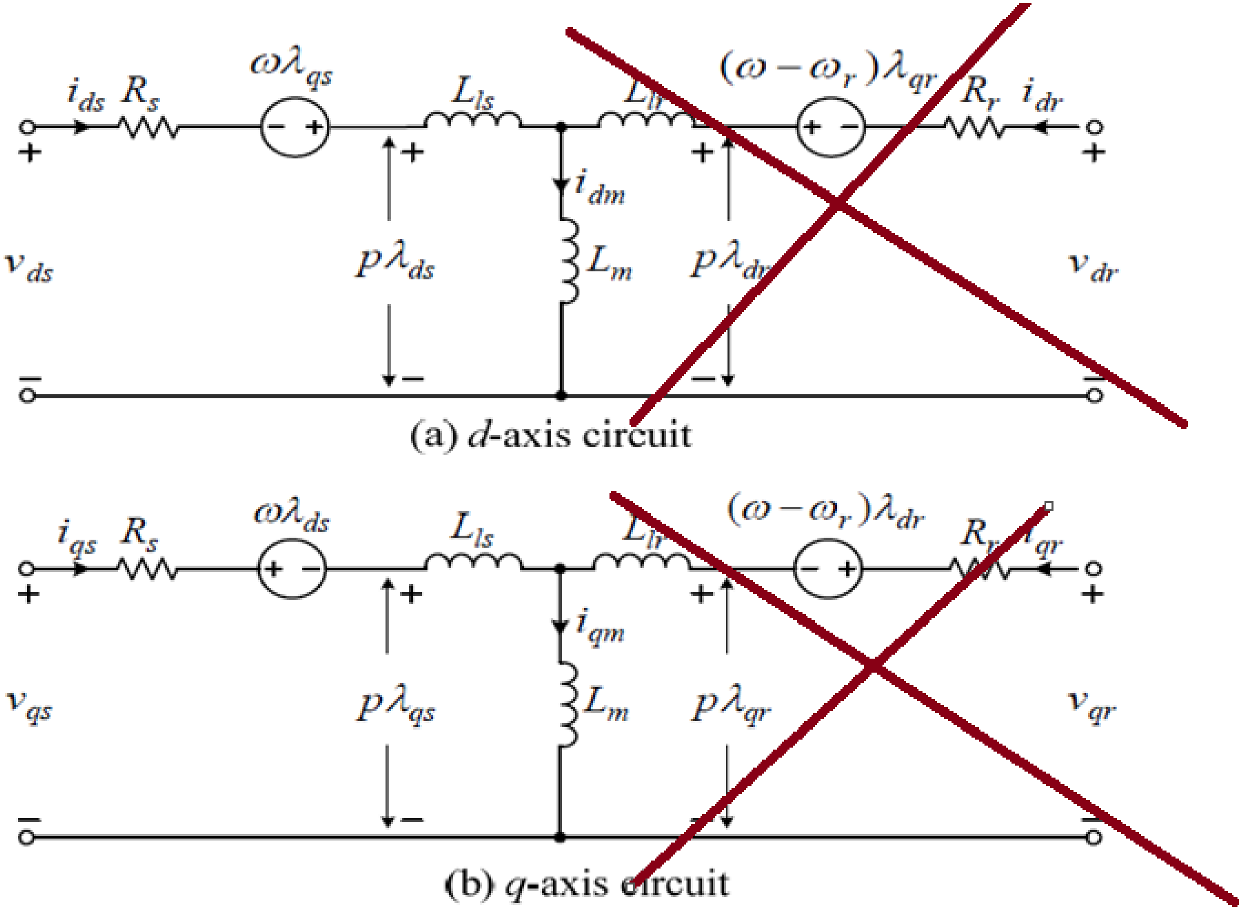


dq-axis model of synchronous generator



(ii)Magnetizing inductance *Lm* is replaced by *dq*-axis magnetizing inductances *Ldm* & *Lqm* of synchronous generator.

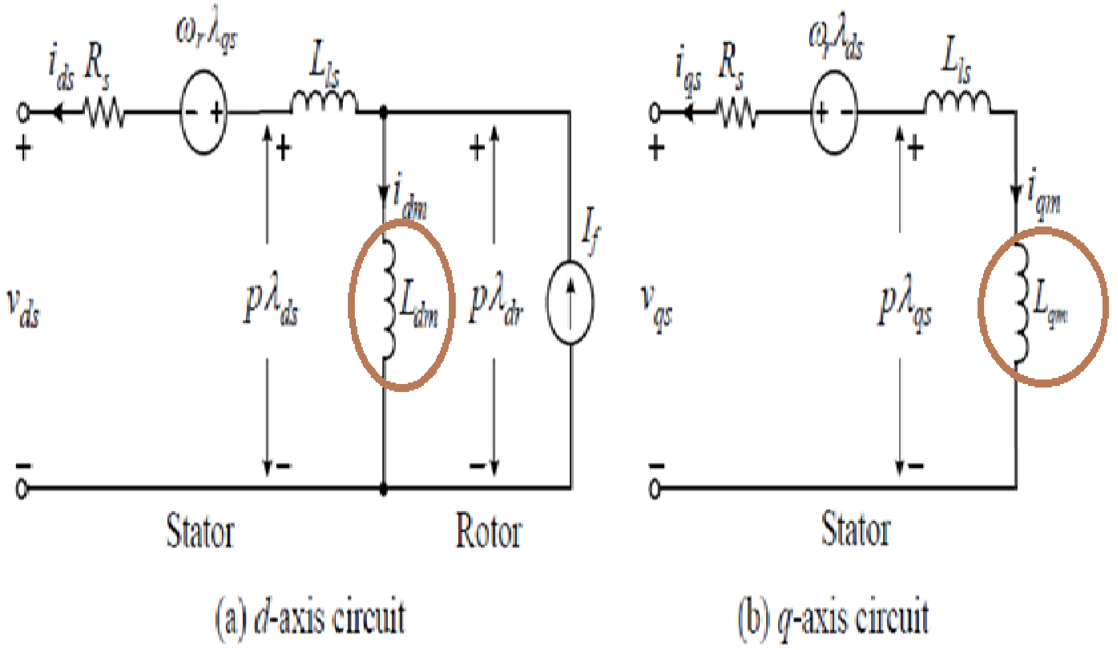
_dq_-axis model of induction generator



(a) *d*-axis circuit

(b) *q*-axis circuit

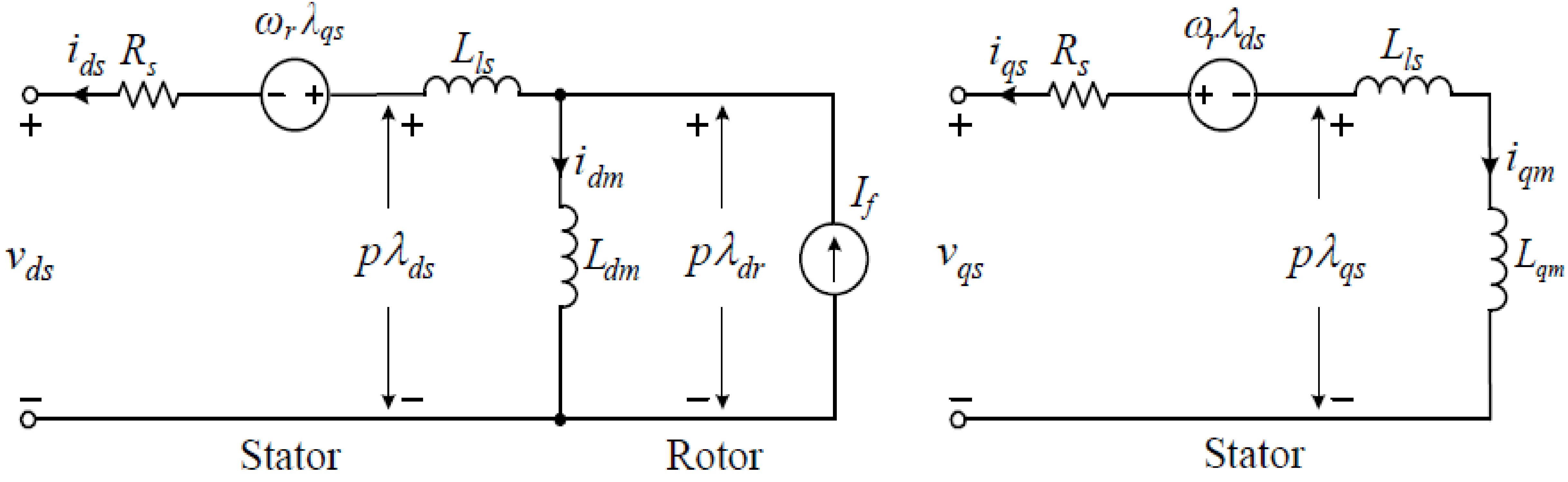
_dq_-axis model of synchronous generator



(a) *d*-axis circuit

(b) *q*-axis circuit

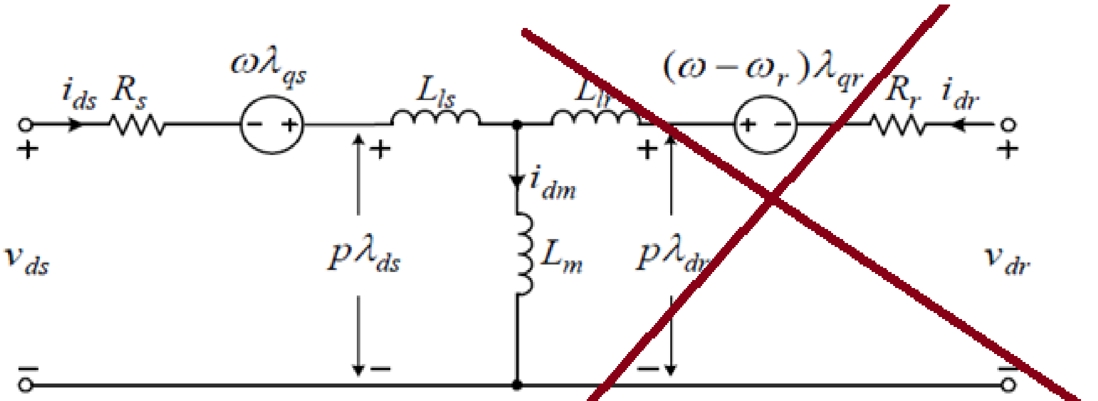
In a non-salient SG, *d*- & *q*-axis magnetizing inductances are equal ($L_{dm} = L_{qm}$), whereas in salient-pole generators, $L_{dm} < L_{qm}$



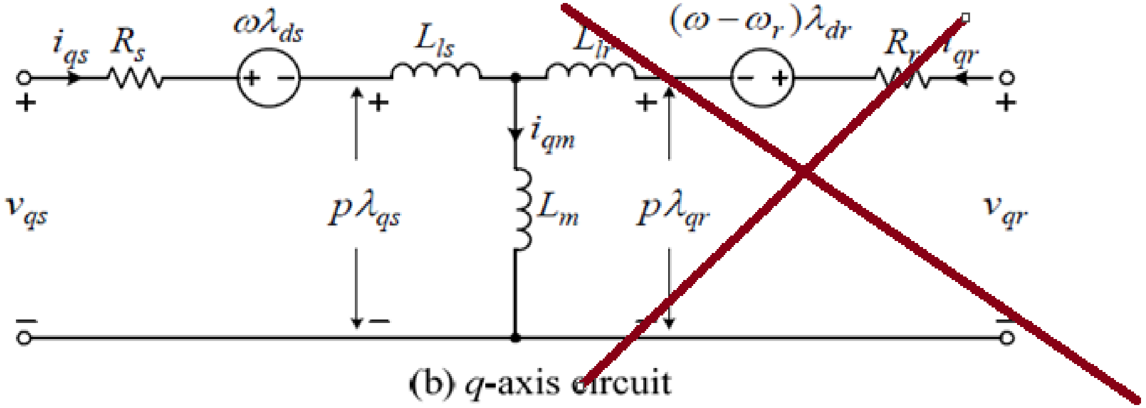
(a) *d*-axis circuit (b) *q*-axis circuit

(iii) *dq*-axis stator currents, *ids* & *iqs*, flow out of stator.

_dq_-axis model of induction generator

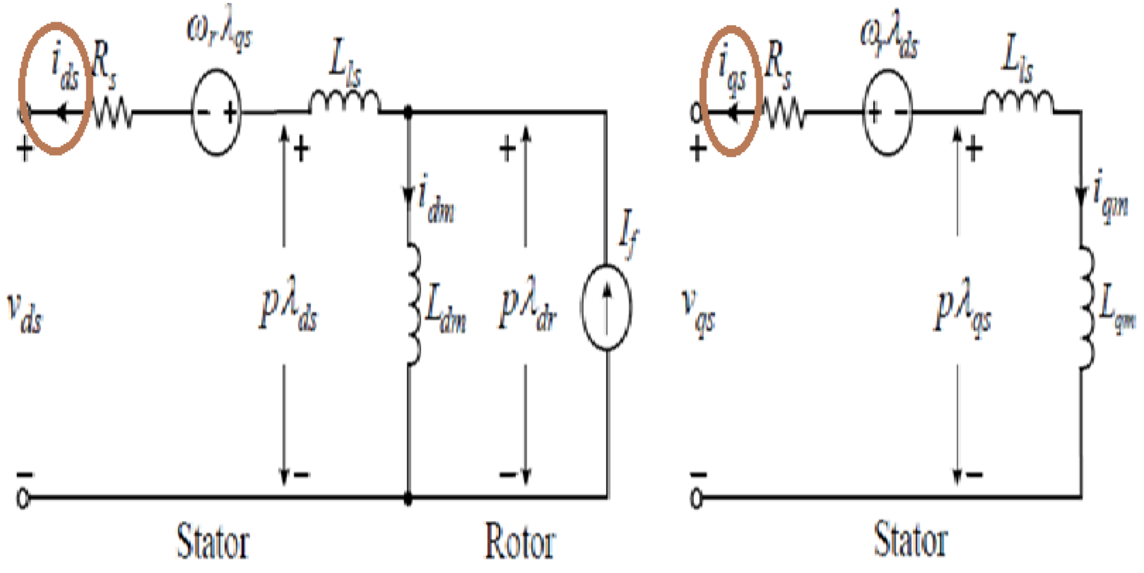


(a) *d*-axis circuit

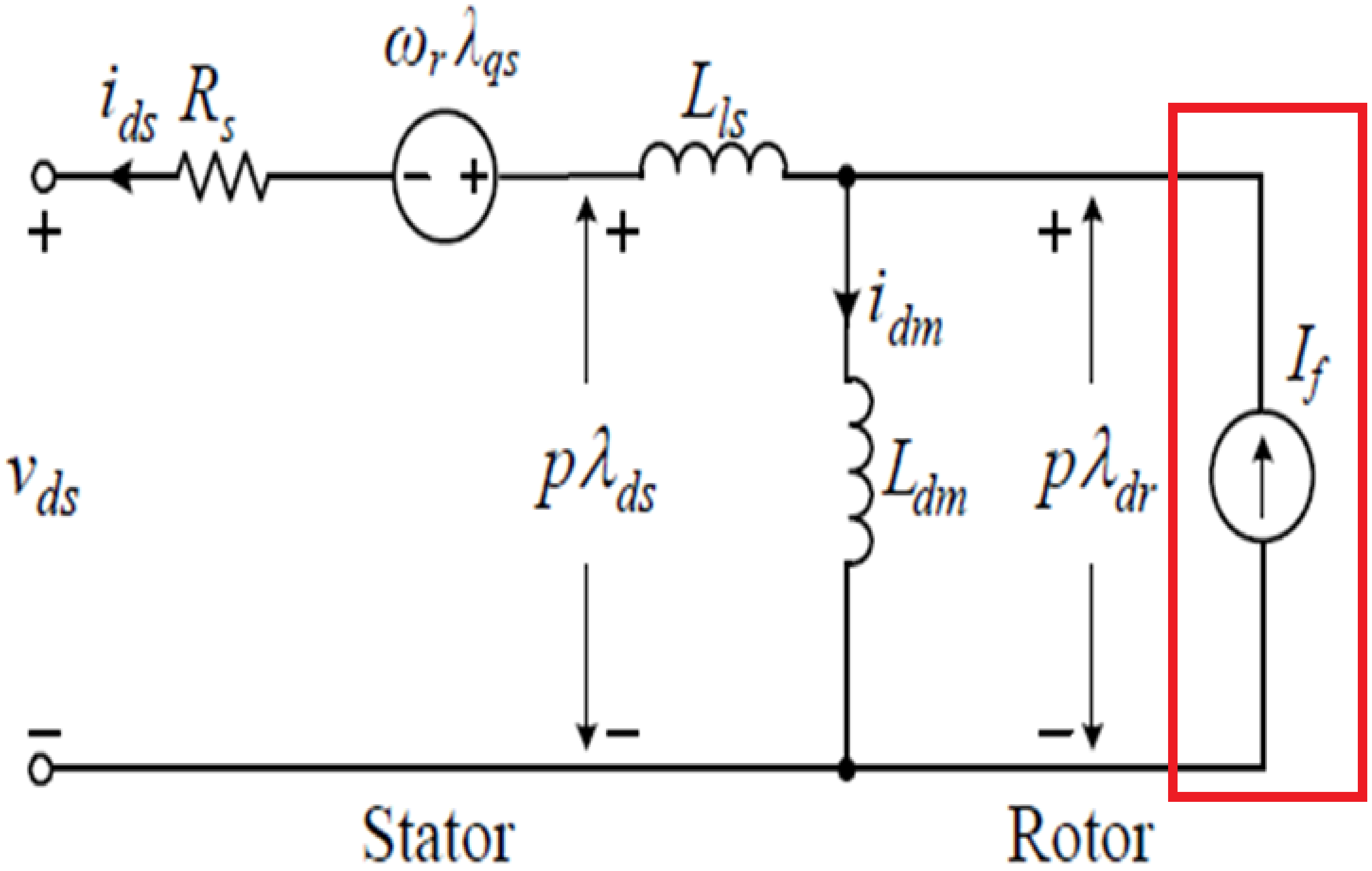


(b) *q*-axis circuit

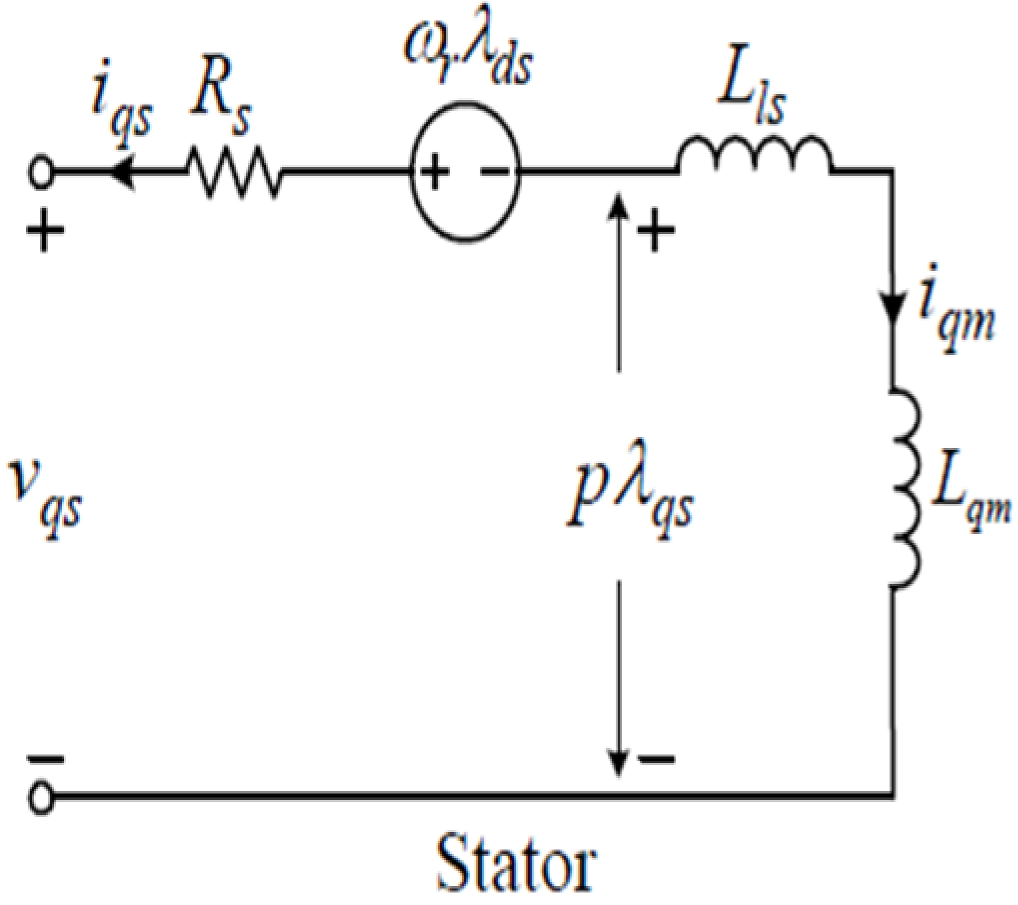
_dq_-axis model of synchronous generator



To model rotor circuit, **field current in rotor winding is represented by a constant current source I_f in d-axis circuit**

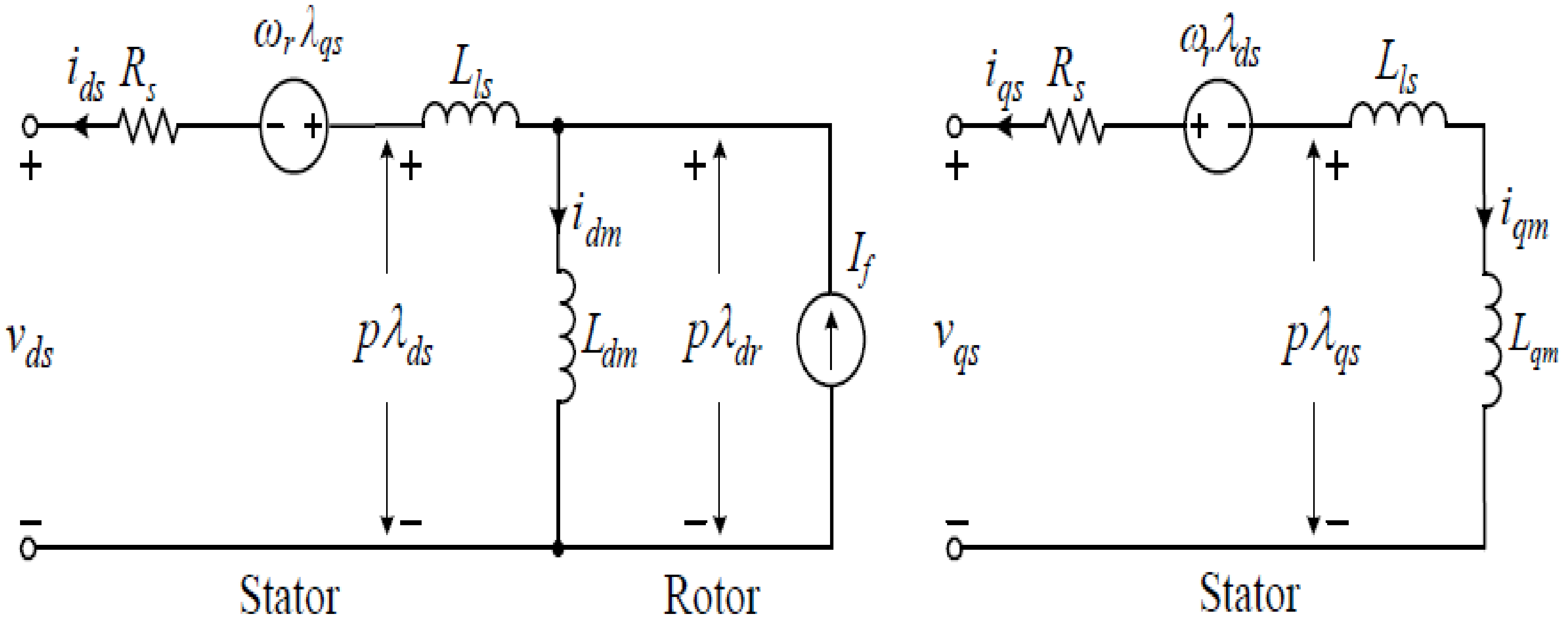


(a) d-axis circuit



(b) q-axis circuit

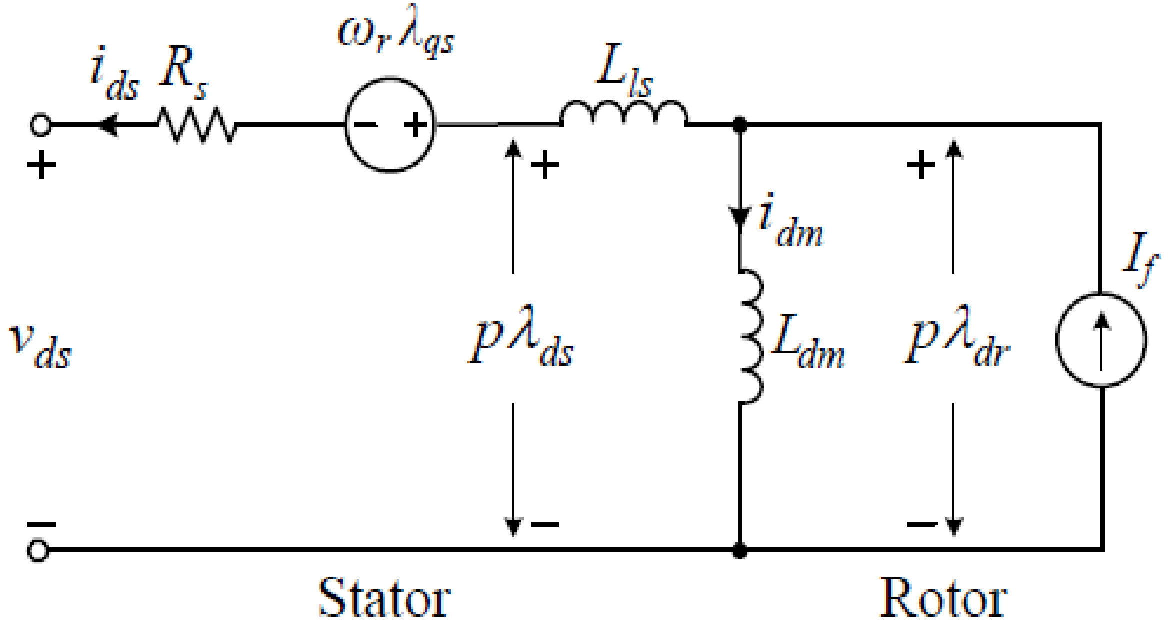
Write voltage equations for SG(v_{ds} & v_{qs})?



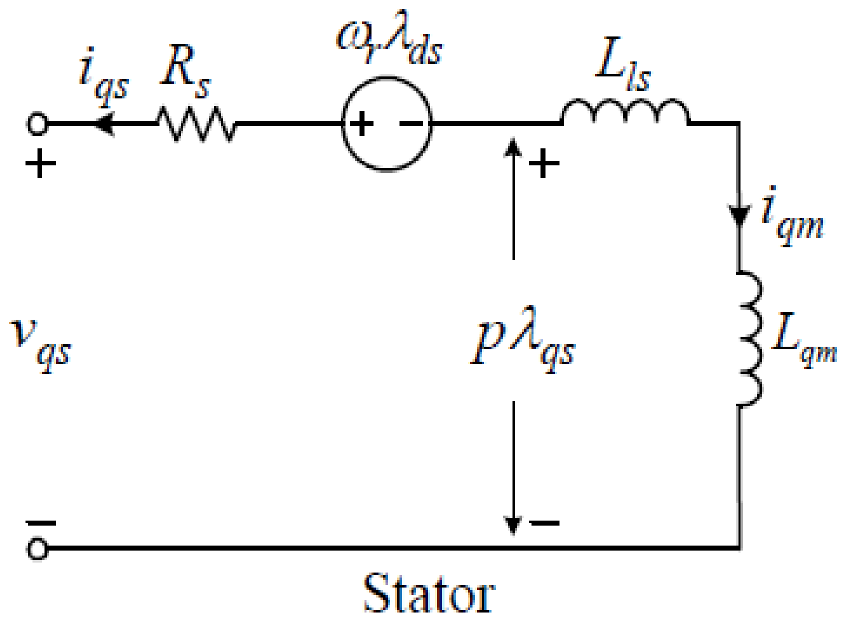
(a) *d*-axis circuit (b) *q*-axis circuit

Voltage equations for SG

$$\begin{cases} v_{ds} = -R_s i_{ds} - \omega_r \lambda_{qs} + p\lambda_{ds} \\ v_{qs} = -R_s i_{qs} + \omega_r \lambda_{ds} + p\lambda_{qs} \end{cases}$$



(a) *d*-axis circuit



(b) *q*-axis circuit

d-axis stator flux linkages λ_{ds}

$$\lambda_{ds} = -L_{ls} i_{ds} + L_{dm} i_{dm}$$

$$\lambda_{ds} = -L_{ls} i_{ds} + L_{dm}(\mathrm{I}_f - i_{ds})$$

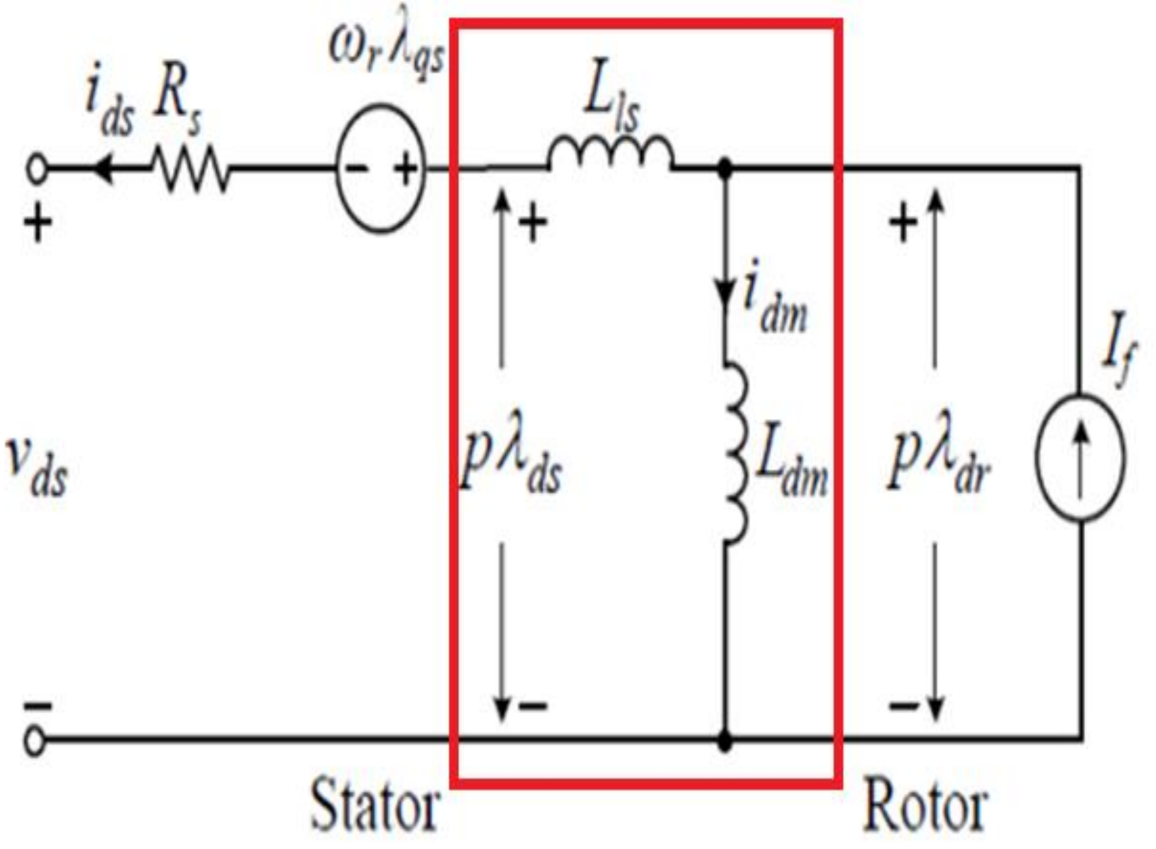
$$\lambda_{ds} = -(L_{ls} + L_{dm}) i_{ds} + L_{dm}\,\mathrm{I}_f$$

$$\lambda_{ds} = -L_d i_{ds} + \lambda_r$$

where, λr is rotor flux & Ld is self inductance of stator d-axis

$$\lambda_r = L_{dm} I_f$$

$$L_d = L_{ls} + L_{dm}$$



(a) d-axis circuit

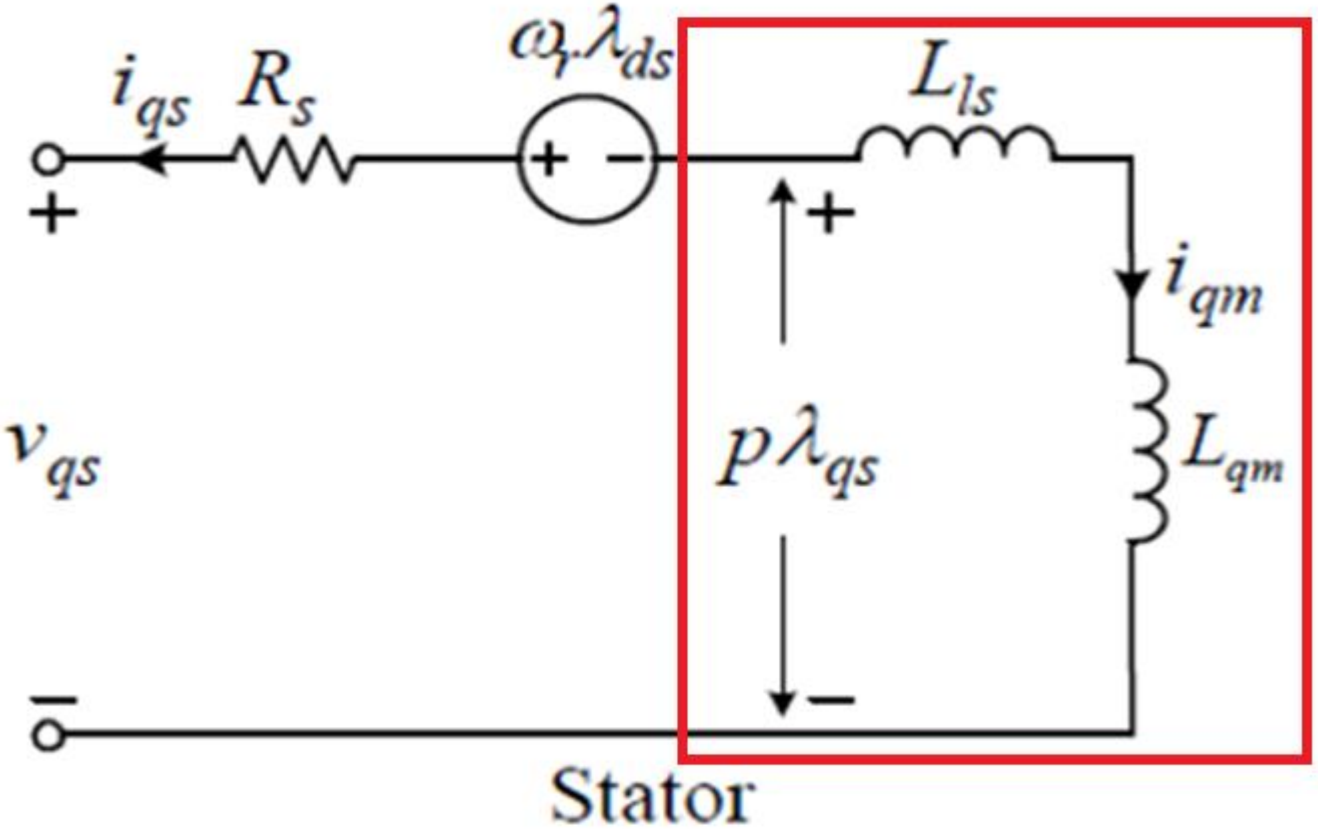
q-axis stator flux linkages λqs

$$\lambda_{qs} = -(L_{ls} + L_{qm})i_{qs}$$

$$\lambda_{qs} = -L_q i_{qs}$$

where L_q is self-inductance of stator q-axis

$$L_q = L_{ls} + L_{qm}$$



(b) q-axis circuit

Substituting $$\begin{aligned}\lambda_{ds} &= -L_d \boldsymbol{i}_{ds} + \lambda_r \\ \lambda_{qs} &= -L_q \boldsymbol{i}_{qs}\end{aligned}$$ into voltage equations

$$v_{ds} = -R_s i_{ds} - \omega_r \lambda_{qs} + p\lambda_{ds}$$

$$v_{ds} = -R_s i_{ds} - \omega_r(-\mathrm{L}_q \mathrm{i}_{qs}) + \mathrm{p}(-\mathrm{L}_d \mathrm{i}_{ds} + \lambda_r)$$

$$v_{ds} = -R_s i_{ds} + \omega_r \mathrm{L}_q \mathrm{i}_{qs} - L_d p \mathrm{i}_{ds} + p\lambda_r$$

dλr/dt =pλr= 0 for constant field current ***If*** in WRSG, we have

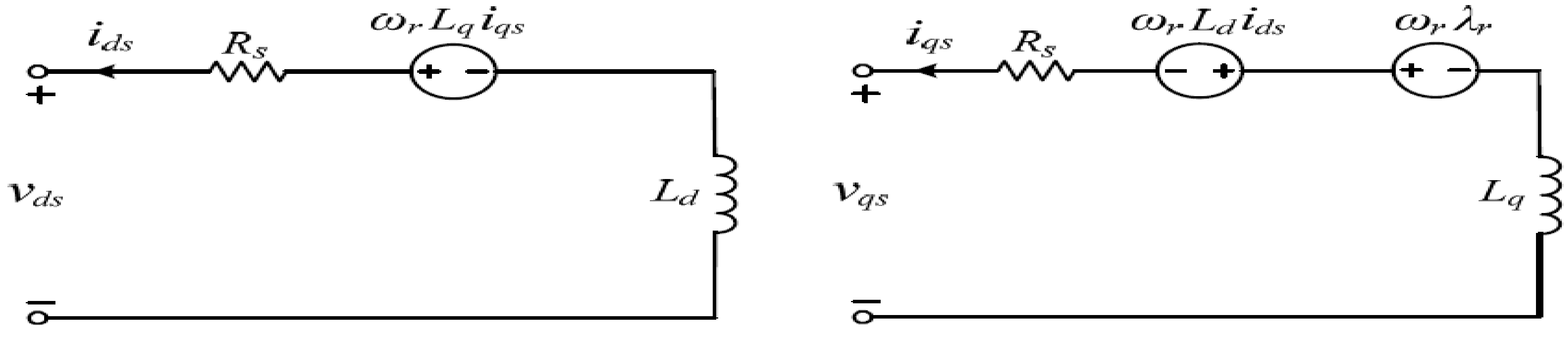
$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q p i_{qs} \end{cases}$$

Based on the derived equations design simplified model for synchronous generators?

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q p i_{qs} \end{cases}$$

Based on the derived equations simplified model for synchronous generators

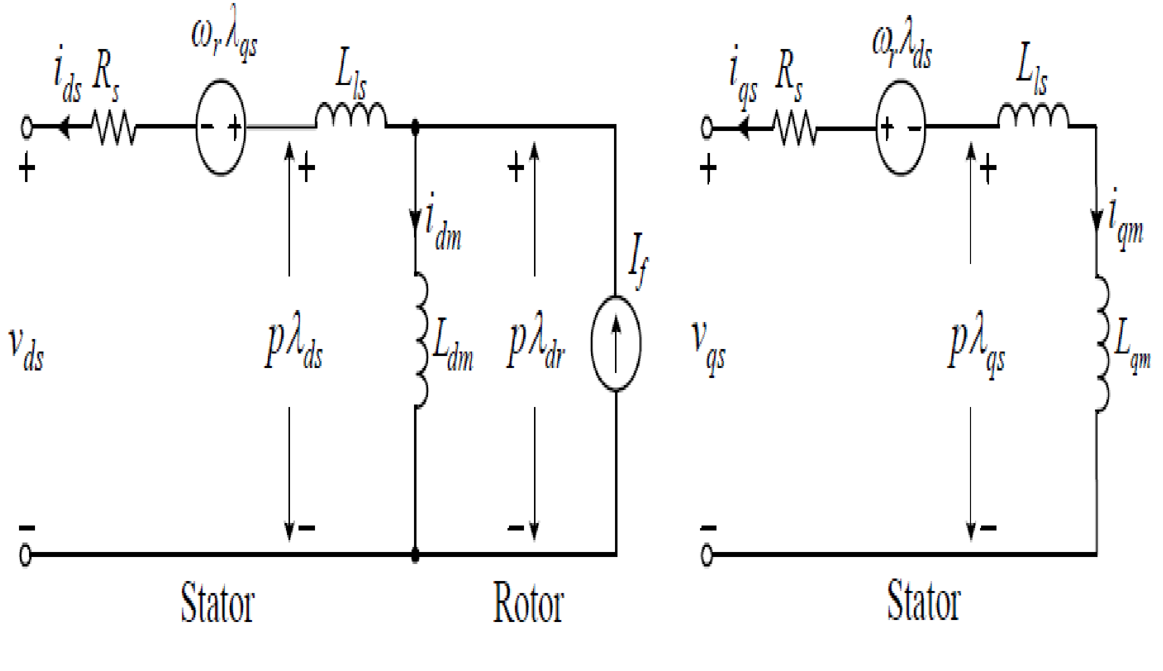
$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q p i_{qs} \end{cases}$$



(a) d-axis circuit (b) q-axis circuit

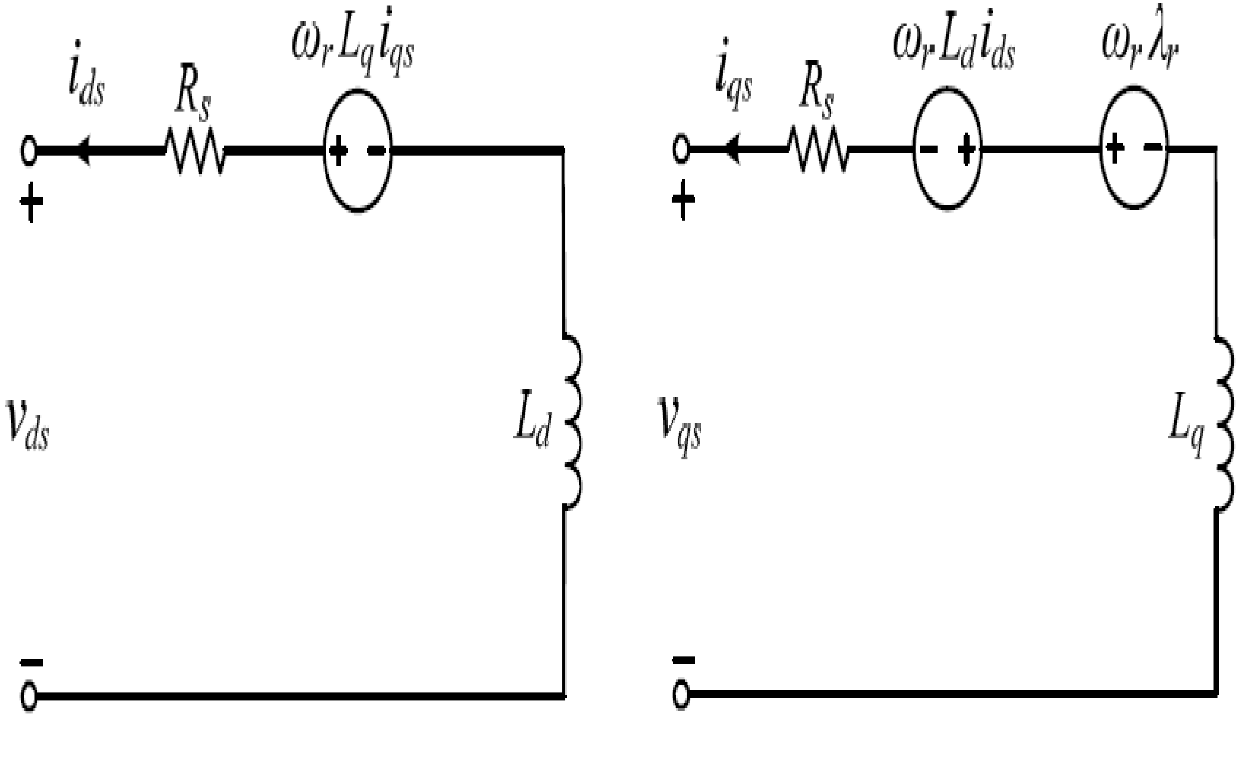
Simplified mode is as accurate as general model since no assumption was made during derivation of simplified model.

General *dq*-axis model of SG in rotor field synchronous reference frame



(a) d-axis circuit (b) q-axis circuit

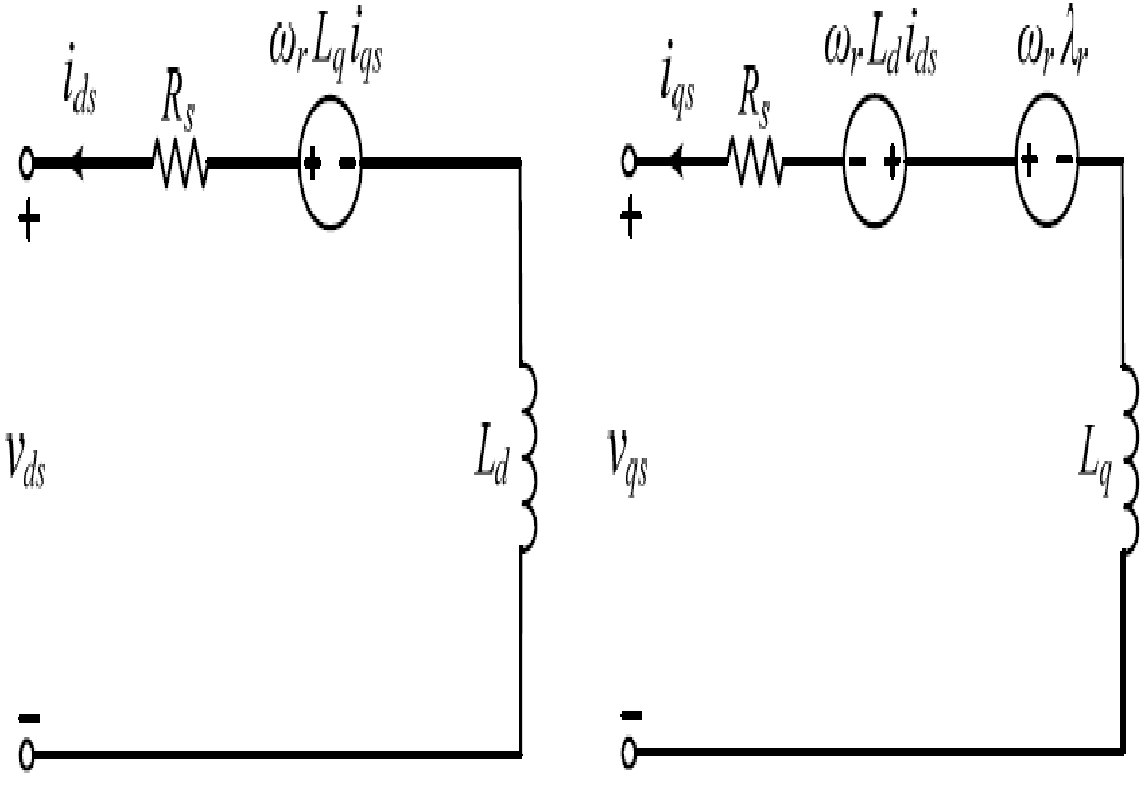
Simplified *dq*-axis model of SG in rotor field synchronous reference frame.



(a) d-axis circuit (b) q-axis circuit

SG model is valid for both wound-rotor & PMSG.

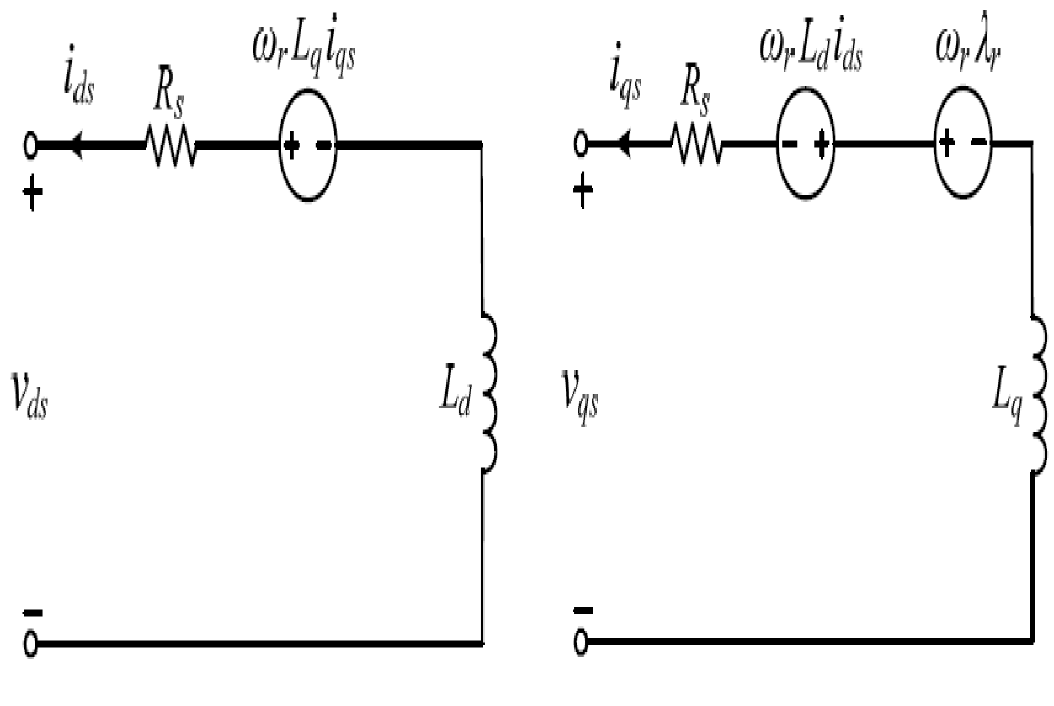
- For a given field current I_f in WRSG, rotor flux can be calculated by: $\lambda_r = L_{dm} I_f$
- For PMSG rotor flux λ_r is produced by permanent magnets &
- Its rated value can be obtained from nameplate data & generator parameters



(a) *d*-axis circuit (b) *q*-axis circuit

Model is also valid for both salient & non-salient pole synchronous generators.

- For a non-salient generator, *dq*-axis synchronous inductances, *Ld*=*Lq*, whereas they are different for a salient-pole generator.
- *d*-axis synchronous inductance of PMSG is usually lower than that of *q*-axis (*Ld* < *Lq*).



(a) *d*-axis circuit (b) *q*-axis circuit

Electromagnetic torque *Te* produced by SG can be calculated by same equation for IG, by substituting

$$\lambda_{ds} = -L_d \boldsymbol{i}_{ds} + \lambda_r$$

$$\lambda_{qs} = -L_q \boldsymbol{i}_{qs}$$

$$T_e = \frac{3P}{2}\left[\boldsymbol{i}_{qs}\lambda_{ds} - \boldsymbol{i}_{ds}\lambda_{qs}\right]$$

$$T_e = \frac{3P}{2}\left[\boldsymbol{i}_{qs}(-\mathrm{L}_d\, \boldsymbol{i}_{ds} + \lambda_r) - \boldsymbol{i}_{ds}(-\mathrm{L}_q\, \boldsymbol{i}_{qs})\right]$$

$$T_e = \frac{3P}{2}\left[\lambda_r \boldsymbol{i}_{qs} - \mathrm{L}_d\, \boldsymbol{i}_{ds}\boldsymbol{i}_{qs} + \mathrm{L}_q\, \boldsymbol{i}_{ds}\boldsymbol{i}_{qs})\right]$$

$$T_e = \frac{3P}{2}\left[\lambda_r \boldsymbol{i}_{qs} - (\mathrm{L}_d - \mathrm{L}_q)\boldsymbol{i}_{qs}\boldsymbol{i}_{ds})\right]$$

Write Motion equation?

Rotor speed *ωr can be obtained from* **Motion equation**

$$J\frac{d\omega_m}{dt} = T_e - T_m$$

where

J	– moment of inertia of the rotor [kgm^2];
P	– number of pole pairs;
T_m	– mechanical torque from the generator shaft [N.m];
T_e	– electromagnetic torque [N.m]; and
ω_m	– rotor mechanical speed ($\omega_m = \omega_r / P$) [rad/sec].

Rotor speed ω_r is governed by motion equation

$$J\frac{d\omega_m}{dt} = T_e - T_m$$

J.S. $\omega r/P = Te\text{-}Tm$

$$\omega_r = \frac{P}{JS}\left(T_e - T_m\right)$$

where S is Laplace operator

Dynamic simulation of synchronous generators

To derive SG model for dynamic simulation of synchronous generators, which equation should be re-arranged?

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q p i_{qs} \end{cases}$$

$$T_e = \frac{3P}{2}\left[\lambda_r i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right]$$

$$\omega_r = \frac{P}{JS}\left(T_e - T_m\right)$$

Get free i_{ds} & iqs from operator d/dt=p

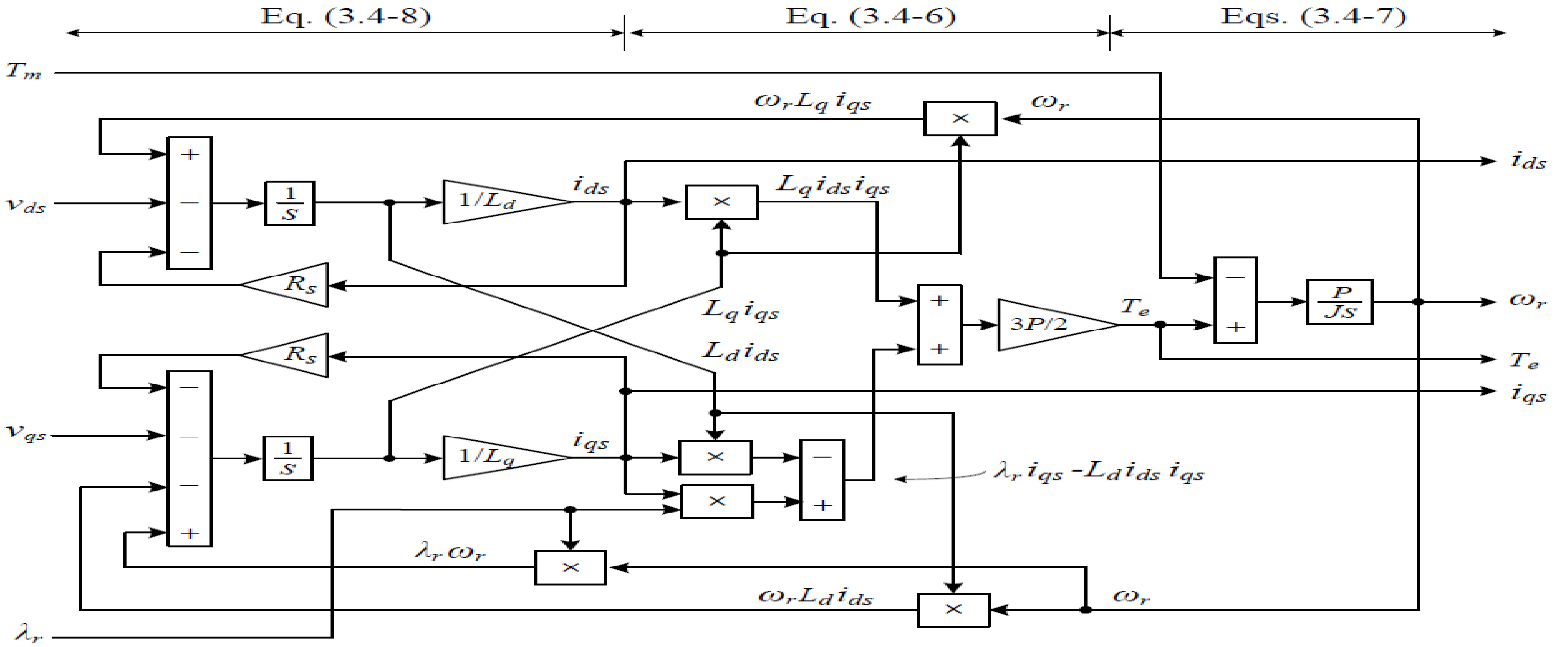
$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p \boxed{i_{ds}} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q p \boxed{i_{qs}} \end{cases}$$

$$\begin{cases} i_{ds} = \dfrac{1}{S}\left(-v_{ds} - R_s i_{ds} + \omega_r L_q i_{qs}\right) / L_d \\ i_{qs} = \dfrac{1}{S}\left(-v_{qs} - R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r\right) / L_q \end{cases}$$

$$\begin{cases} i_{ds} = \dfrac{1}{S}\left(-v_{ds} - R_s i_{ds} + \omega_r L_q i_{qs}\right)/\,L_d \\ i_{qs} = \dfrac{1}{S}\left(-v_{qs} - R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r\right)/\,L_q \end{cases}$$

$$T_e = \frac{3P}{2}\left[\lambda_r\, i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right]$$

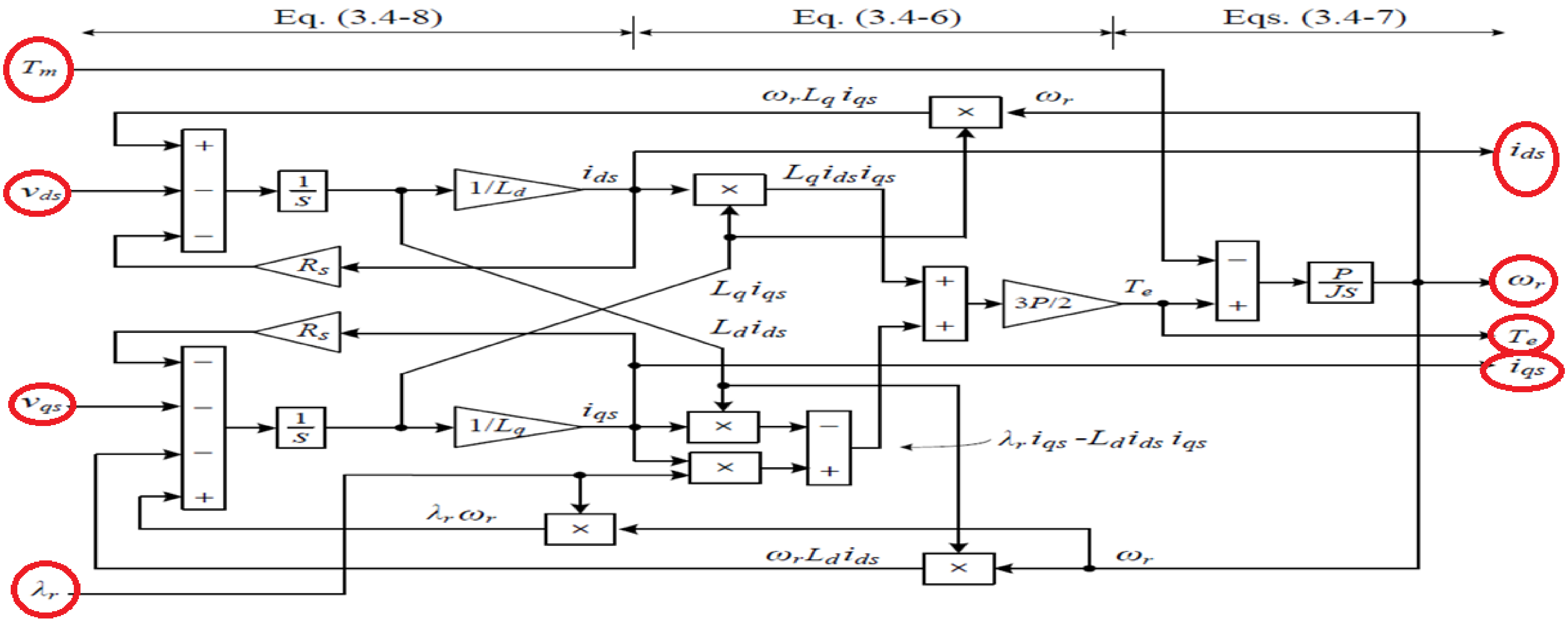
$$\omega_r = \frac{P}{JS}\left(T_e - T_m\right)$$



$$\begin{cases} i_{ds} = \dfrac{1}{S}\left(-v_{ds} - R_s i_{ds} + \omega_r L_q i_{qs}\right) / L_d \\ i_{qs} = \dfrac{1}{S}\left(-v_{qs} - R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r\right) / L_q \end{cases}$$

$$T_e = \frac{3P}{2}\left[\lambda_r i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right]$$

$$\omega_r = \frac{P}{JS}\left(T_e - T_m\right)$$



Case Study 3-3

- Analysis of Synchronous Generator in Standalone Operation

Main purpose of this case study is to:

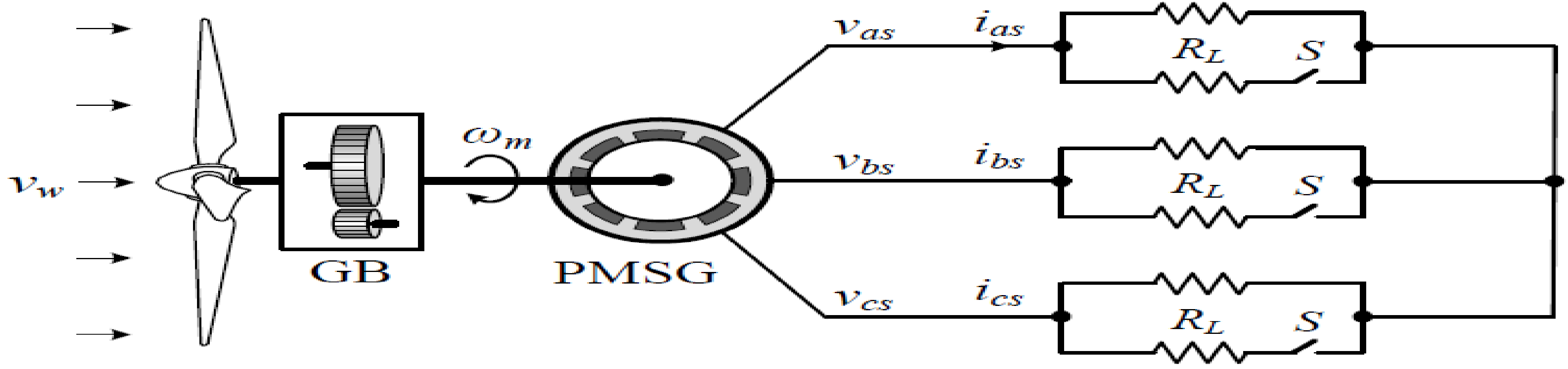
1. Investigate operation of a standalone SG wind energy system feeding a 3-phase resistive load
2. Illustrate how to effectively use simulation model of Fig. for simulation of synchronous generators
3. Reveal relationship between 3-phase *abc* variables in stationary frame & *dq* variables in synchronous frame.

Generator used in study is a 2.45MW/4000V/53.33Hz/400rpm non-salient pole PMSG, whose parameters are given in Table B-10 in Appendix B.pp.247

Generator Type	PMSG, 2.45MW/4000V/53.33Hz, Non-Salient Pole	
Rated Mechanical Power	2.4487 MW	1.0 pu
Rated Apparent Power	3.419 MVA	1.0 pu
Rated Line-to-line Voltage	4000 V (rms)	
Rated Phase Voltage	2309.4 V (rms)	1.0 pu
Rated Stator Current	490 A (rms)	1.0 pu
Rated Stator Frequency	53.33 Hz	1.0 pu
Rated Power Factor	0.7162	
Rated Rotor Speed	400 rpm	1.0pu
Number of Pole Pairs	8	
Rated Mechanical Torque	58.4585 kN.m	1.0 pu
Rated Rotor Flux Linkage	4.971 Wb (rms)	0.7213 pu
Stator Winding Resistance R_s	24.21 mΩ	0.00517 pu
d-axis Synchronous Inductance L_d	9.816 mH	0.7029 pu
q-axis Synchronous Inductance L_q	9.816 mH	0.7029 pu
Base Flux Linkage Λ_B	6.892 Wb (rms)	1.0 pu
Base Impedance Z_B	4.6797 Ω	1.0 pu
Base Inductance L_B	13.966 mH	1.0 pu
Base Capacitance C_B	637.72 μF	1.0 pu

Table B-10 2.45MW/4000V/53.33Hz Non-Salient Pole PMSG Parameters

- Generator is loaded with a 3-phase balanced resistive load R_L & operates at 320 rpm (0.8 pu)[400*0.8=320rpm] at a given wind speed.
- **Loading of generator can be changed by switch *S*. When *S* is closed, load resistance is reduced to $R_L/2$ per phase?[As resistances are in parallel]**



(a) SG with a three-phase resistive load

Combined moment of inertia J

$$\omega_r = \frac{P}{JS}\left(T_e - T_m\right)$$

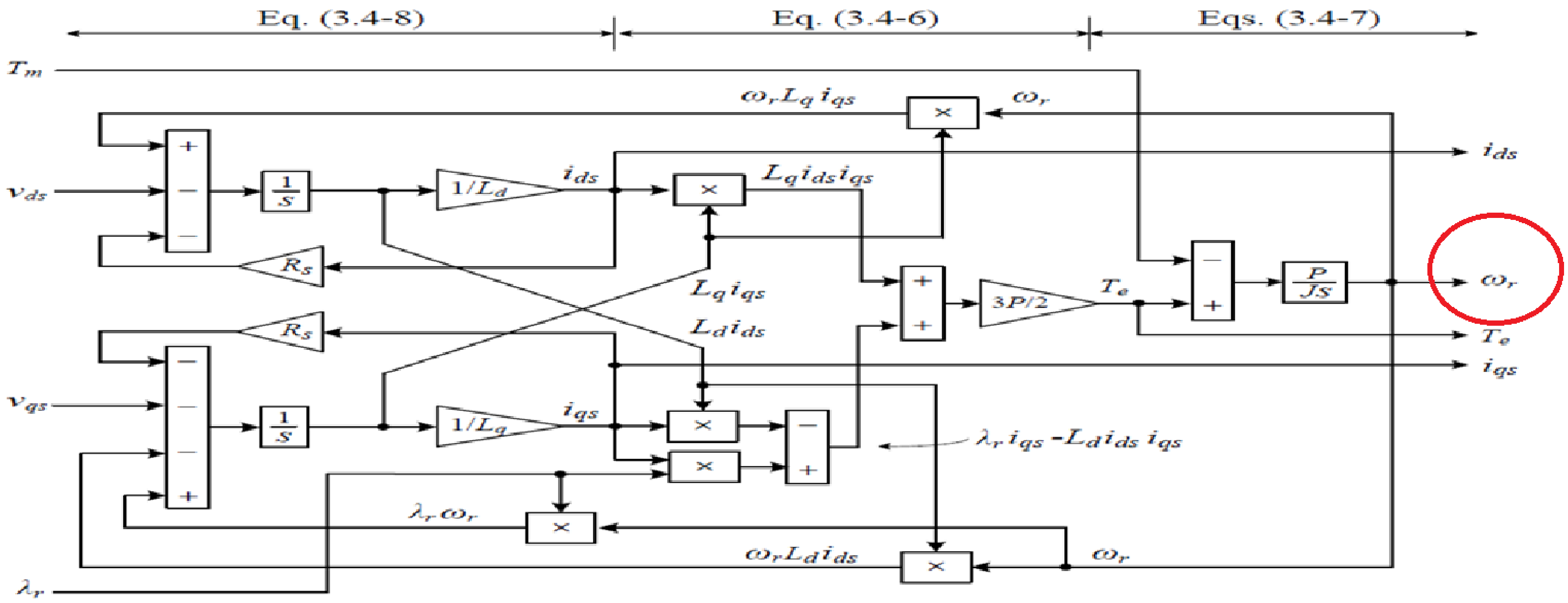
- It is assumed that combined moment of inertia of blades, rotor hub & generator are very large such that
- rotor speed ω_r is kept constant at 320 rpm during **transients caused by changes in load resistance.**

Motion equation is then not needed

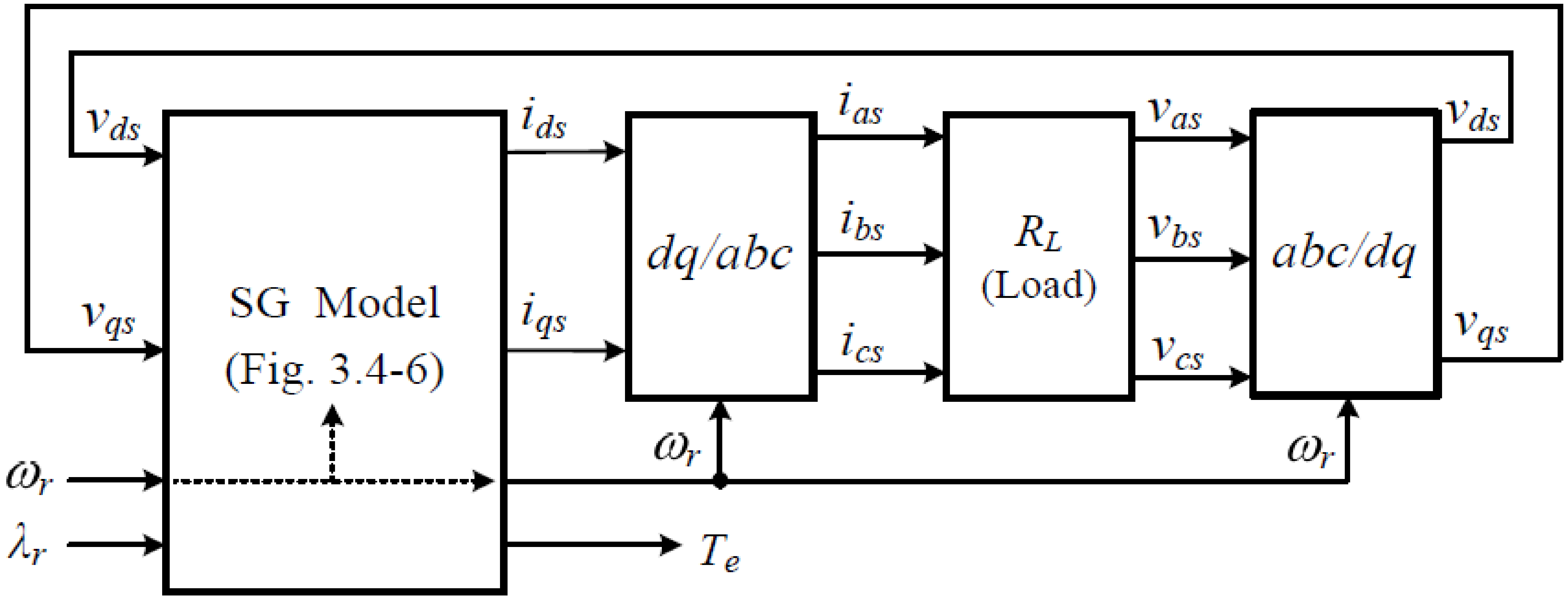
Since rotor speed ***ω_r*= 320 rpm** is known, it becomes system input variable.

$$\omega_r = \frac{P}{JS}\left(T_e - T_m\right)$$

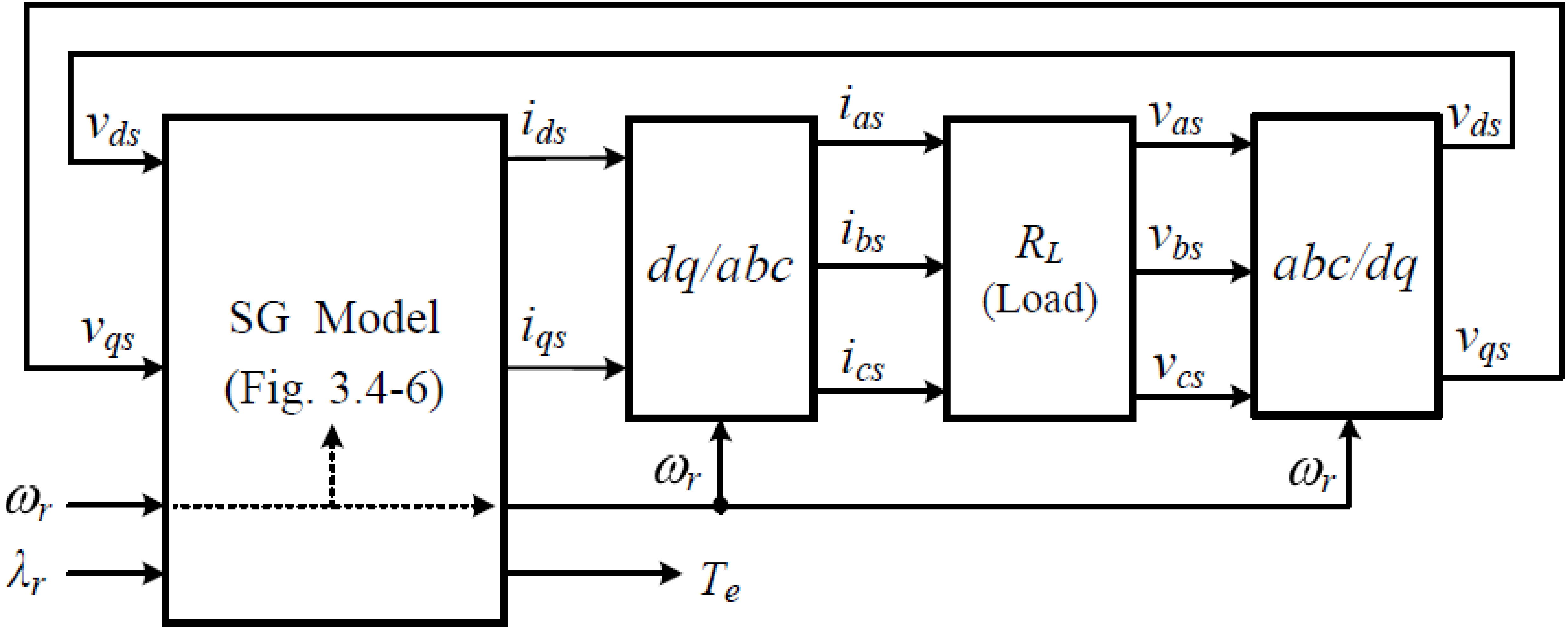
SG simulation algorithm given in Fig. should be slightly modified accordingly.



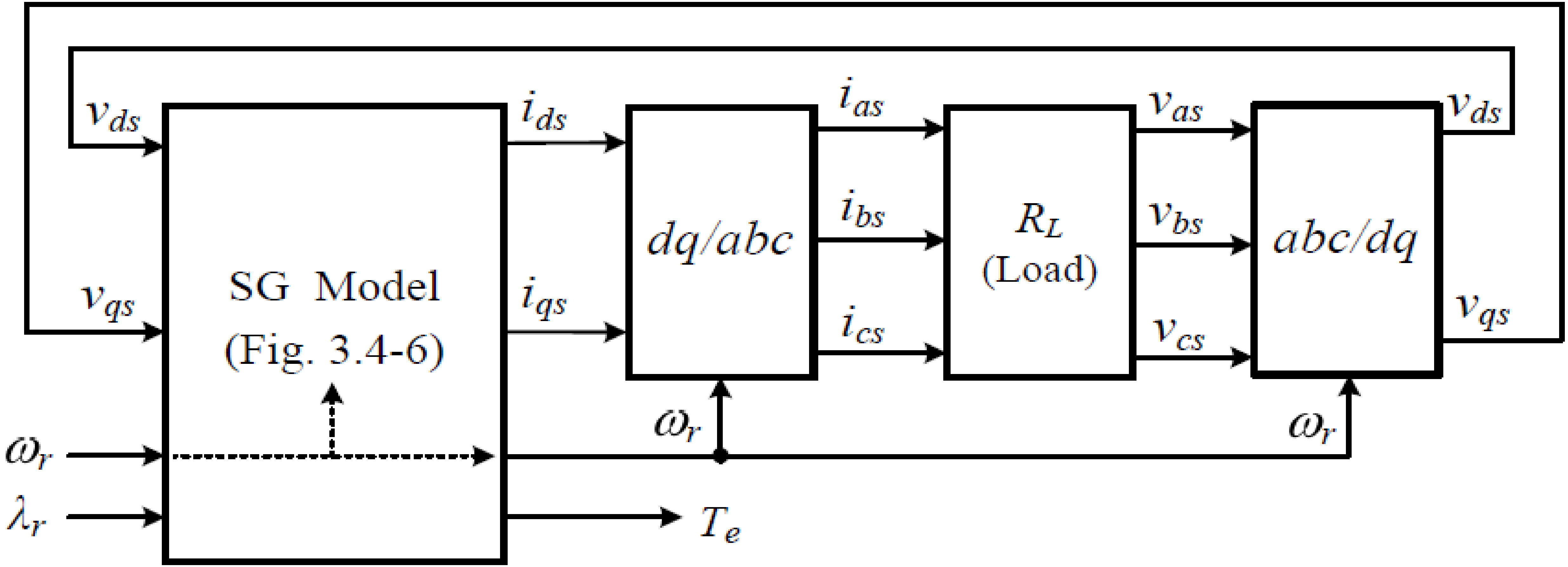
Block diagram for simulation of SG standalone operation is shown in Fig.



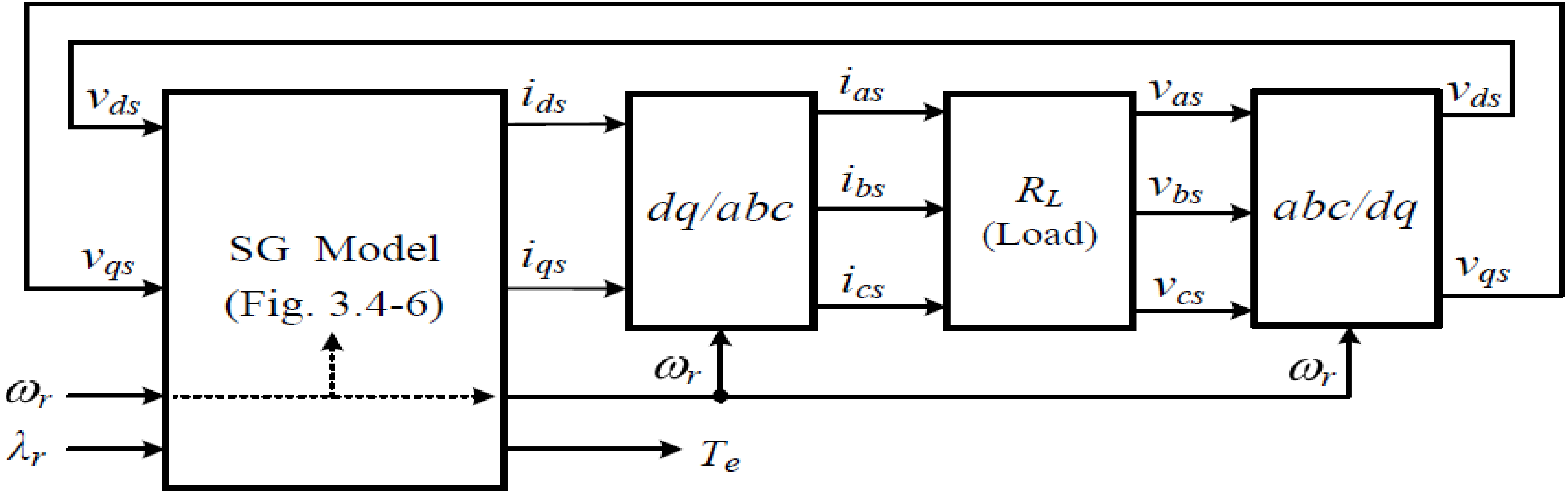
dq-axis stator currents, i_{ds} & i_{qs}, in synchronous frame rotating at synchronous speed of ω_r are calculated by SG model.



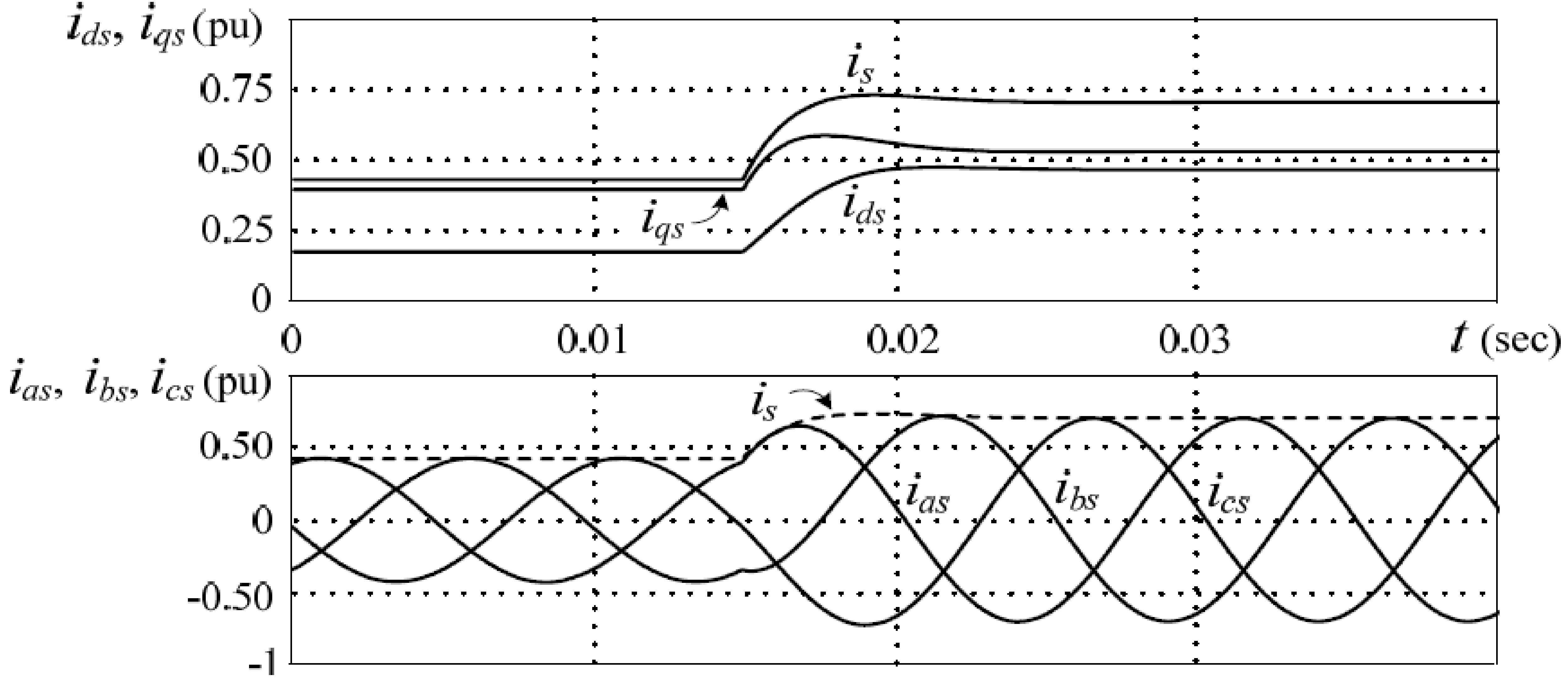
i_{ds} & i_{qs} are transformed into *abc*-axis stator currents, i_{as}, i_{bs} & i_{cs}, in stationary frame through *dq*/*abc* transformation.



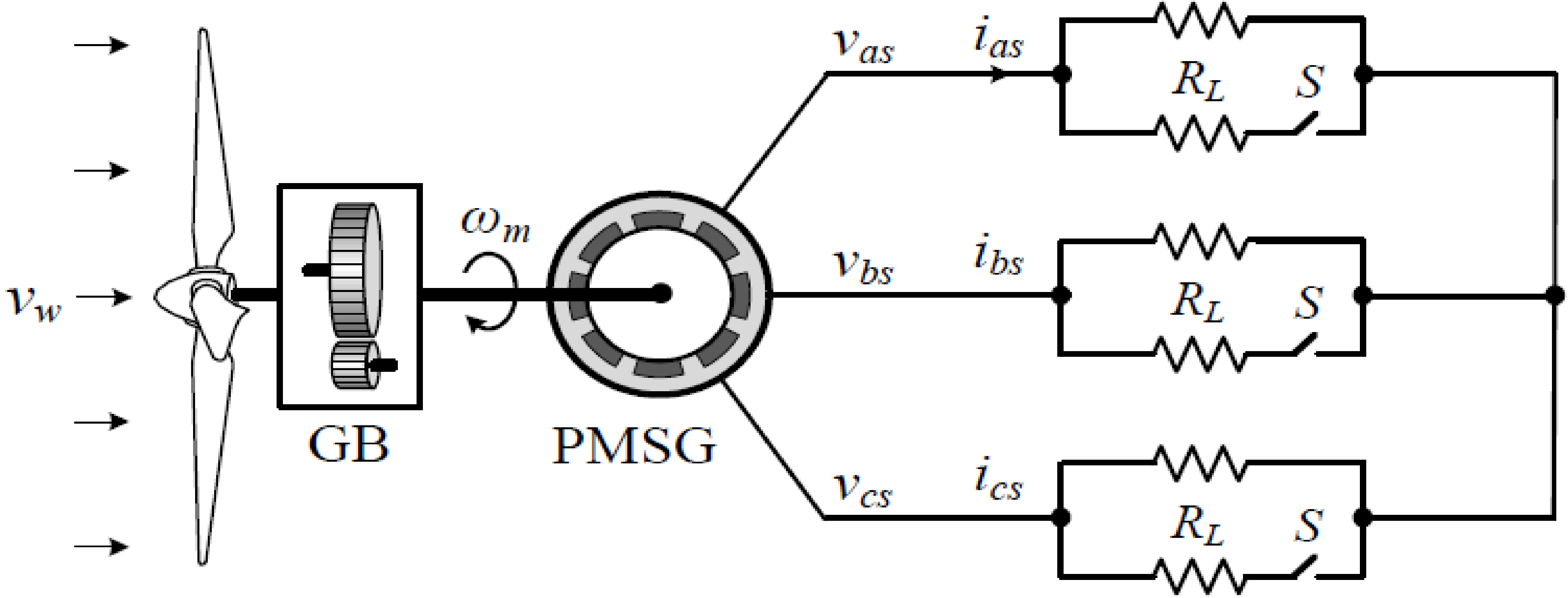
Calculated load voltages, v_{as}, v_{bs} & v_{cs}, which are also stator voltages, are transformed to *dq*-axis voltages v_{ds} & v_{qs} in synchronous frame, which are then fed back to SG model.



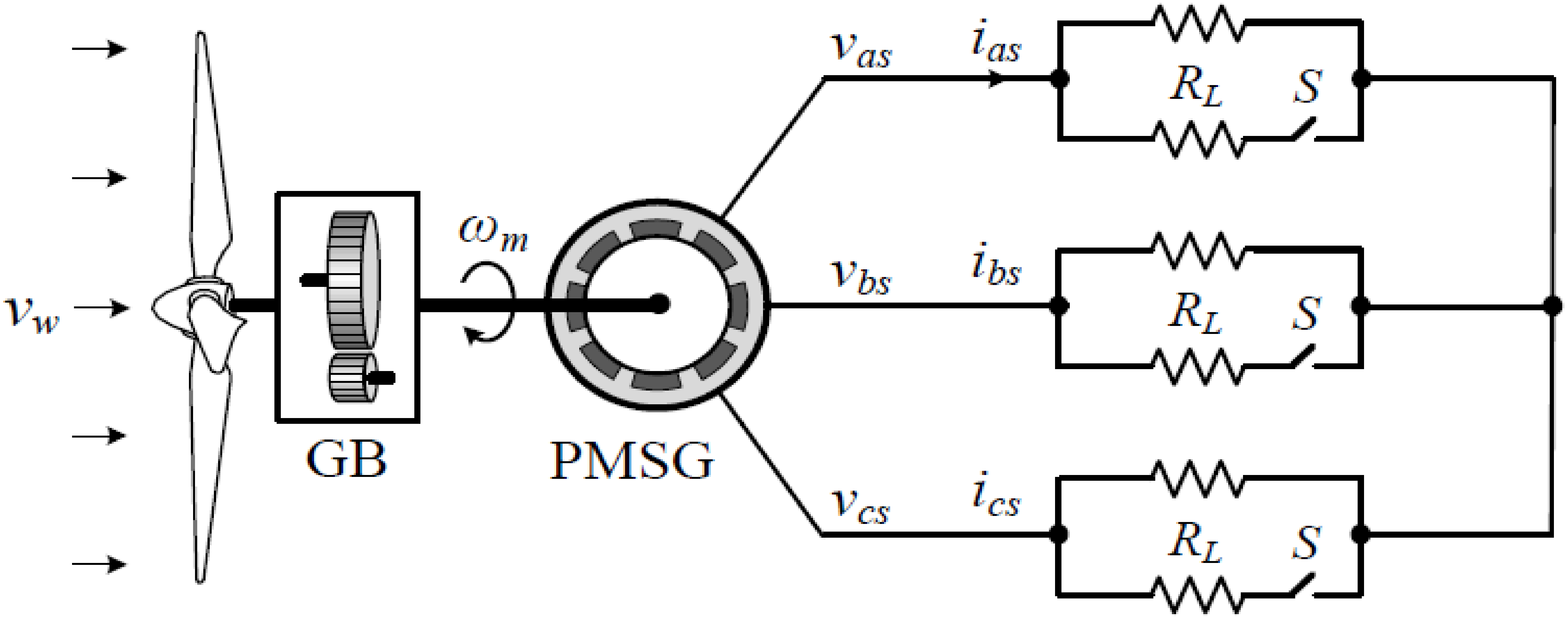
Simple test for synchronous generator in standalone operation is carried out, and results are given in Fig.



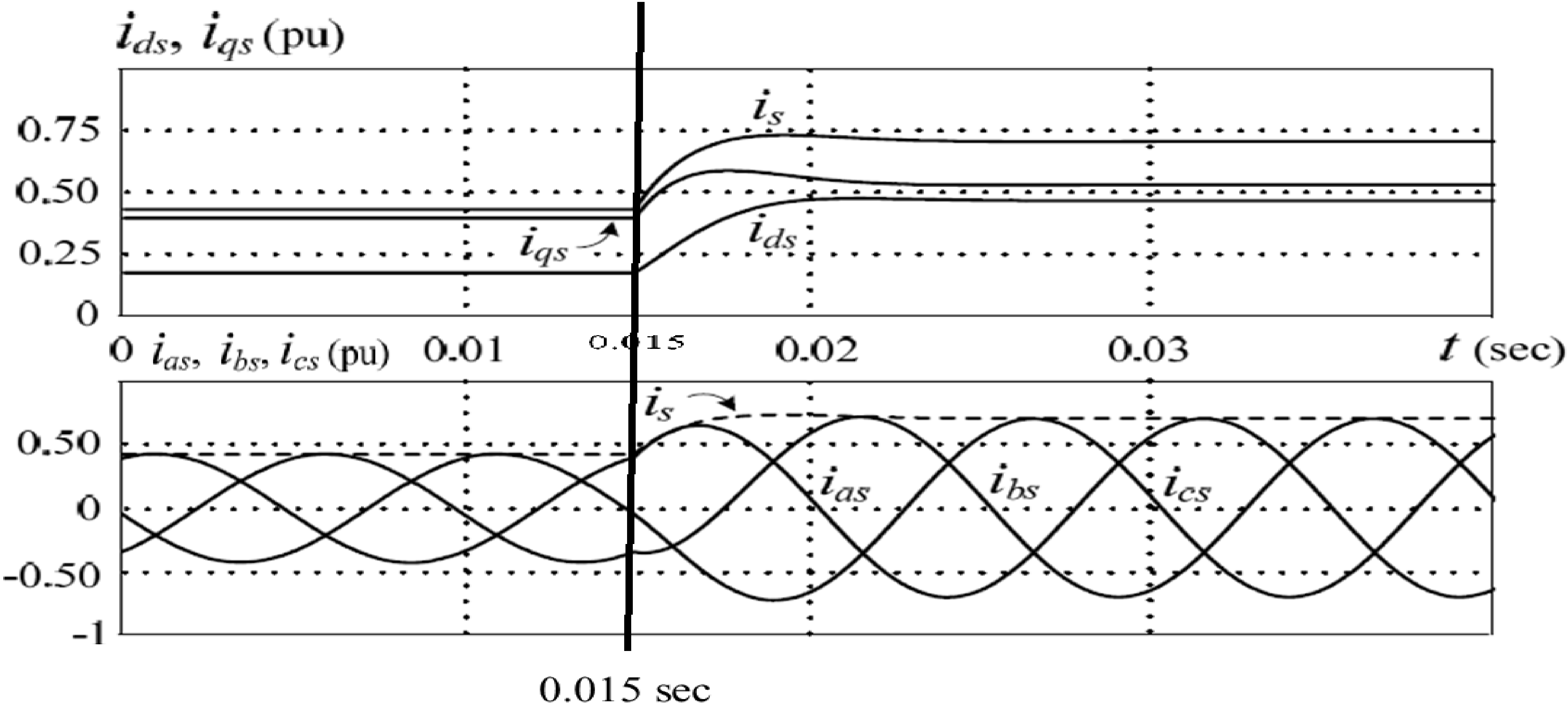
Generator initially operates in steady state with a resistive load of *RL*.



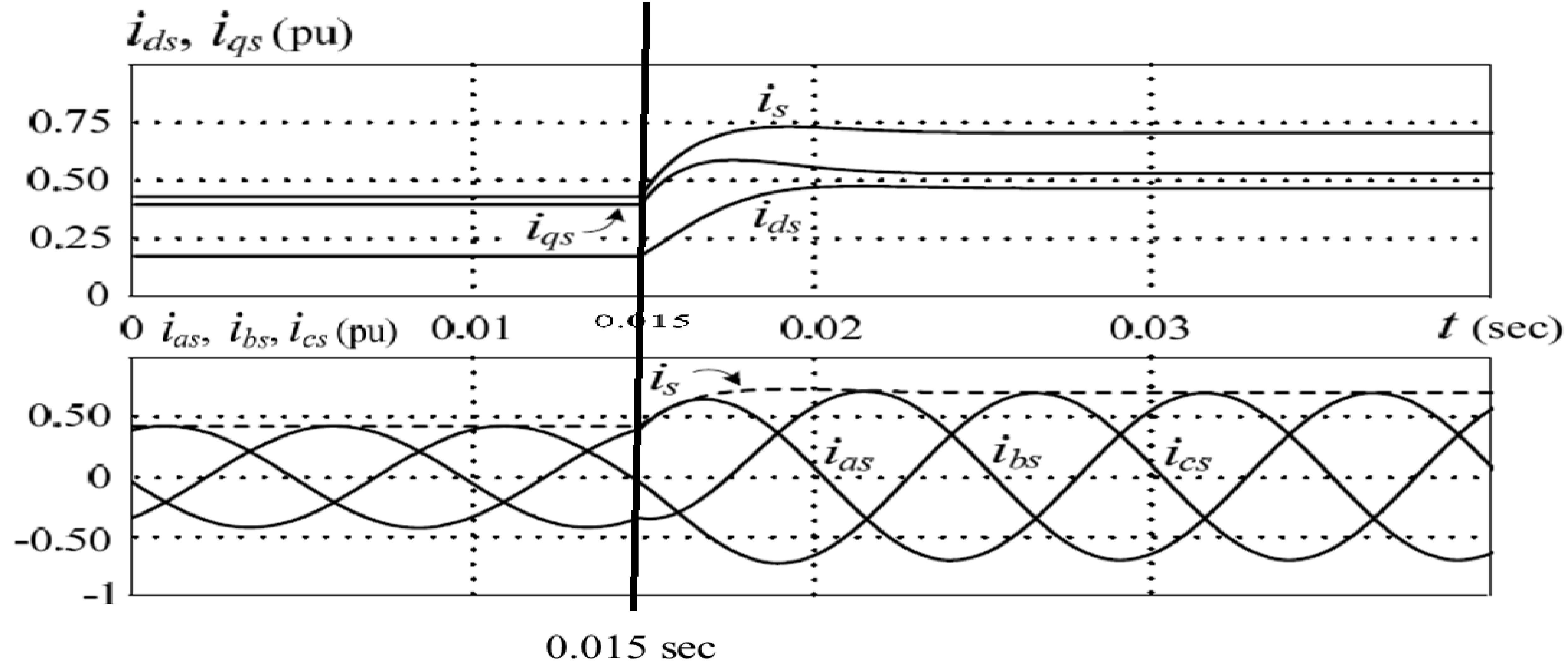
Load resistance is reduced to $R_L/2$ by closing switch S at t = 0.015 sec.



After a short transient period, system reaches a new steady-state operating point.

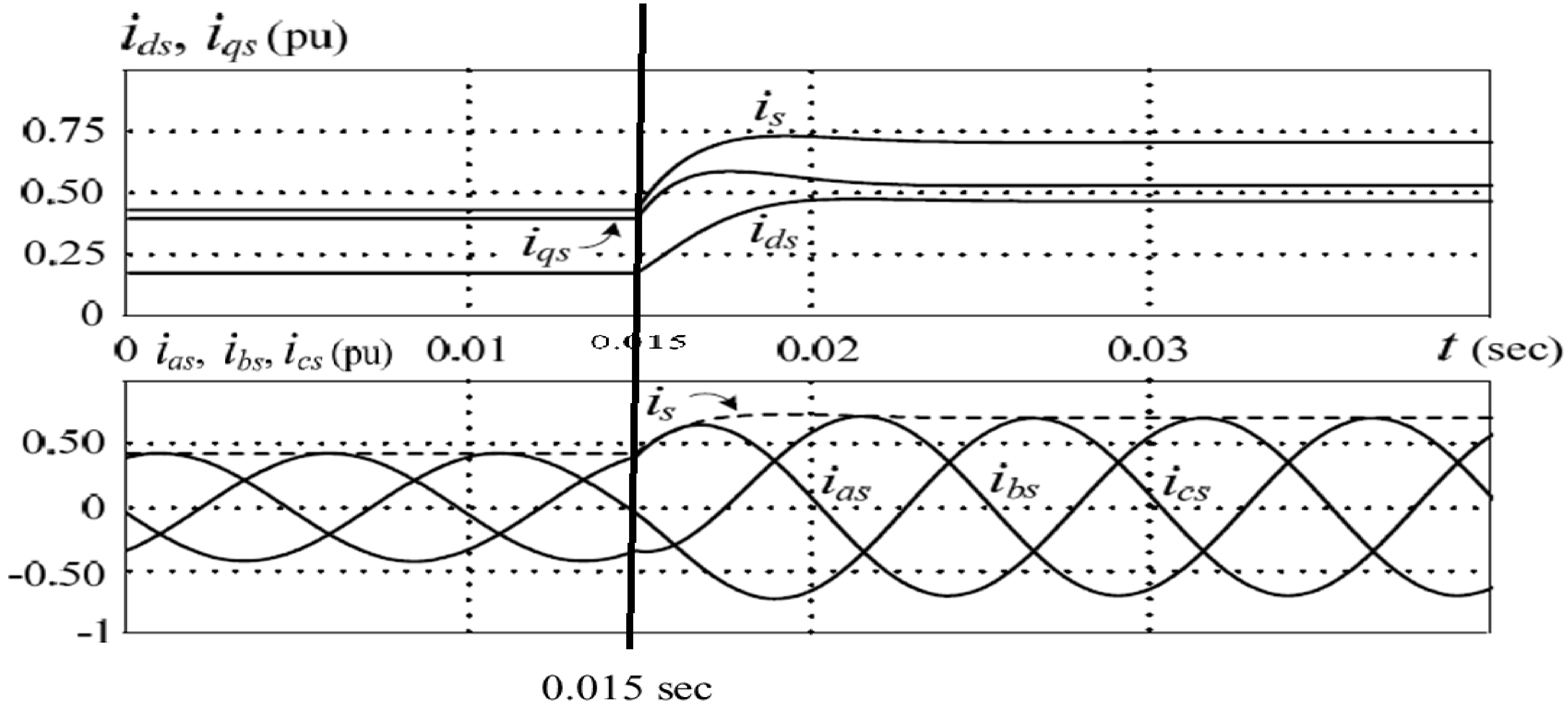


dq-axis stator currents, *ids & iqs*, in synchronous frame are of dc variables, whereas *abc*-axis stator currents, *ias*, *ibs* and *ics*, in stationary frame are sinusoids in steady state.



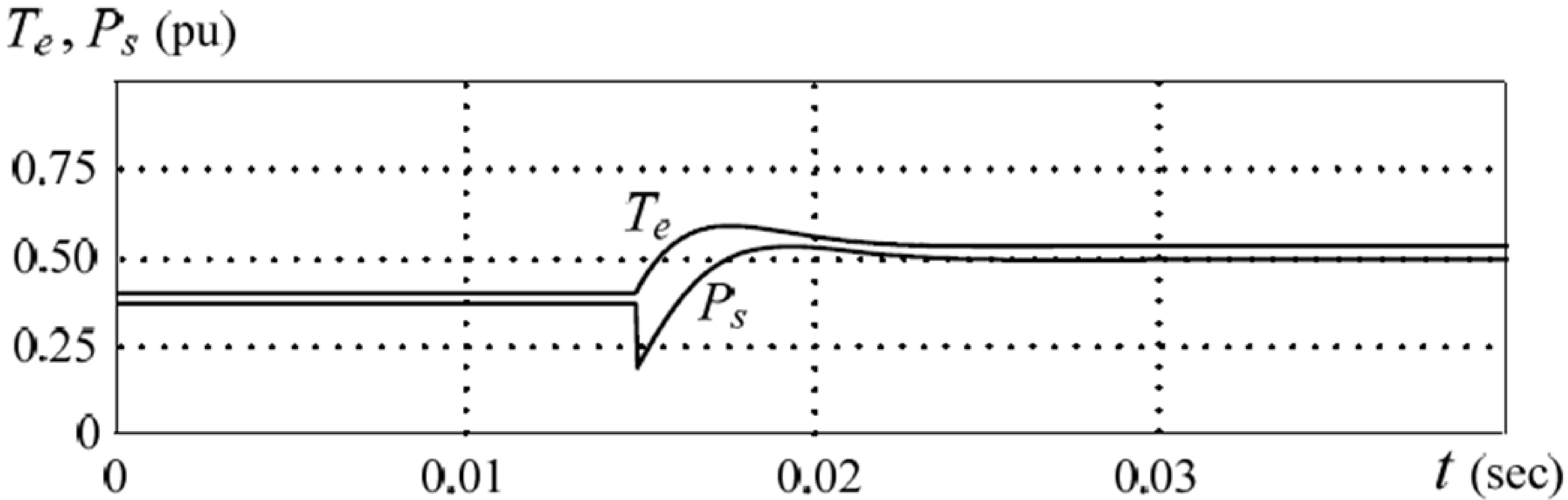
Magnitude of stator current *is*, given by represents peak value of *ias*, *ibs* & *ics*.

$$i_s = \sqrt{i_{qs}^2 + i_{ds}^2}$$



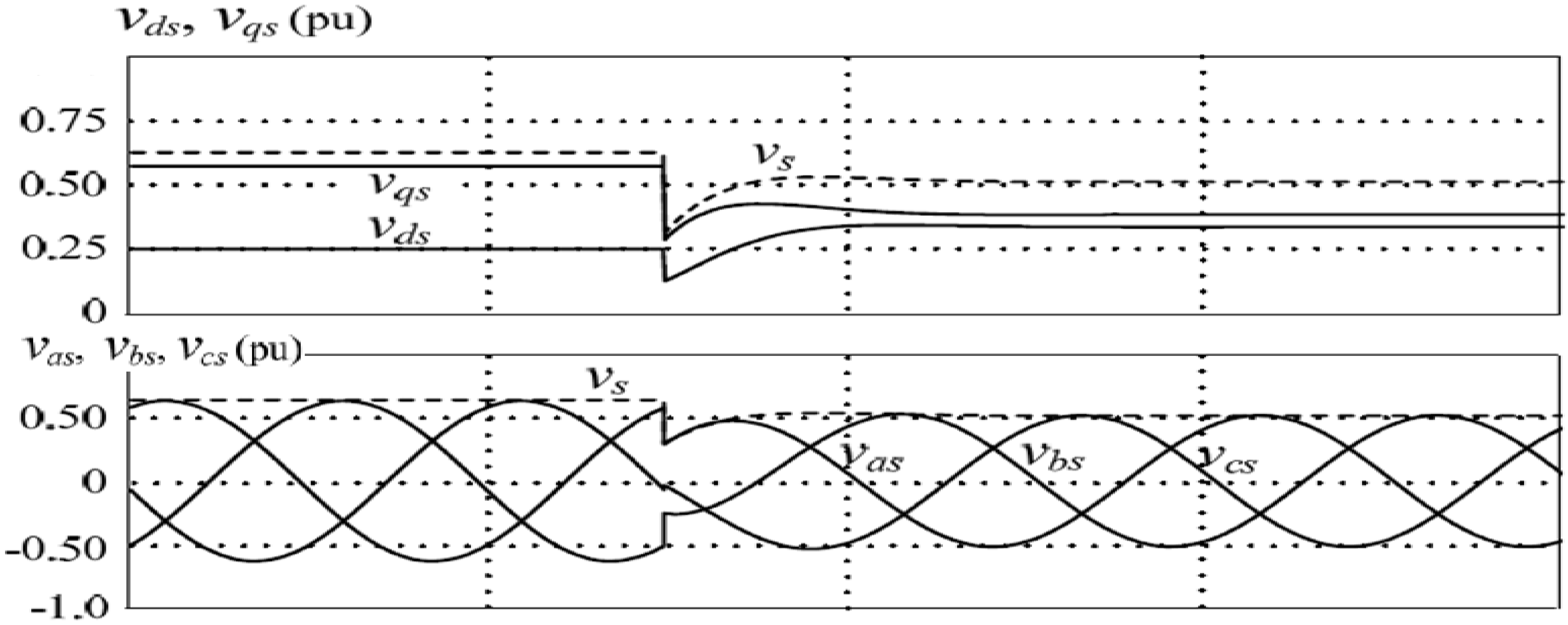
$$T_e = \frac{3P}{2}\left[\lambda_r\, i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right] \qquad T_e = \frac{3P}{2}\left(\lambda_r\, i_{qs}\right)$$

- Electromagnetic torque *Te* & stator active power *Ps* are increased accordingly when system operates at new operating point.



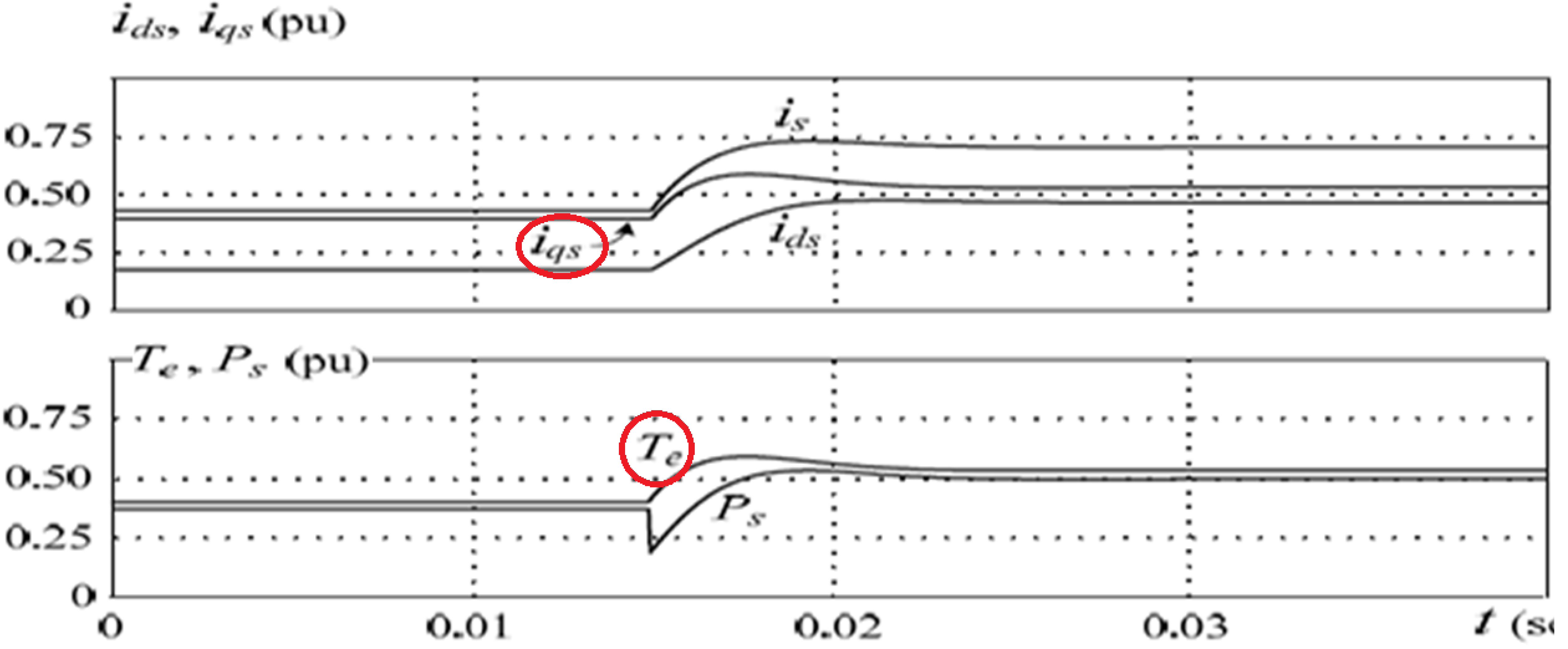
Similar phenomenon can be observed for stator voltages. A decreasing in load resistance results in an increase in stator currents, but stator voltages?

A decreasing in load resistance results in an increase in stator currents, but stator voltages are reduced mainly due to voltage drop across stator inductances.



Equation indicates that *d*-axis current *ids* in non-salient SG does not contribute to torque production.

$$T_e = \frac{3P}{2}\left(\lambda_r i_{qs}\right)$$

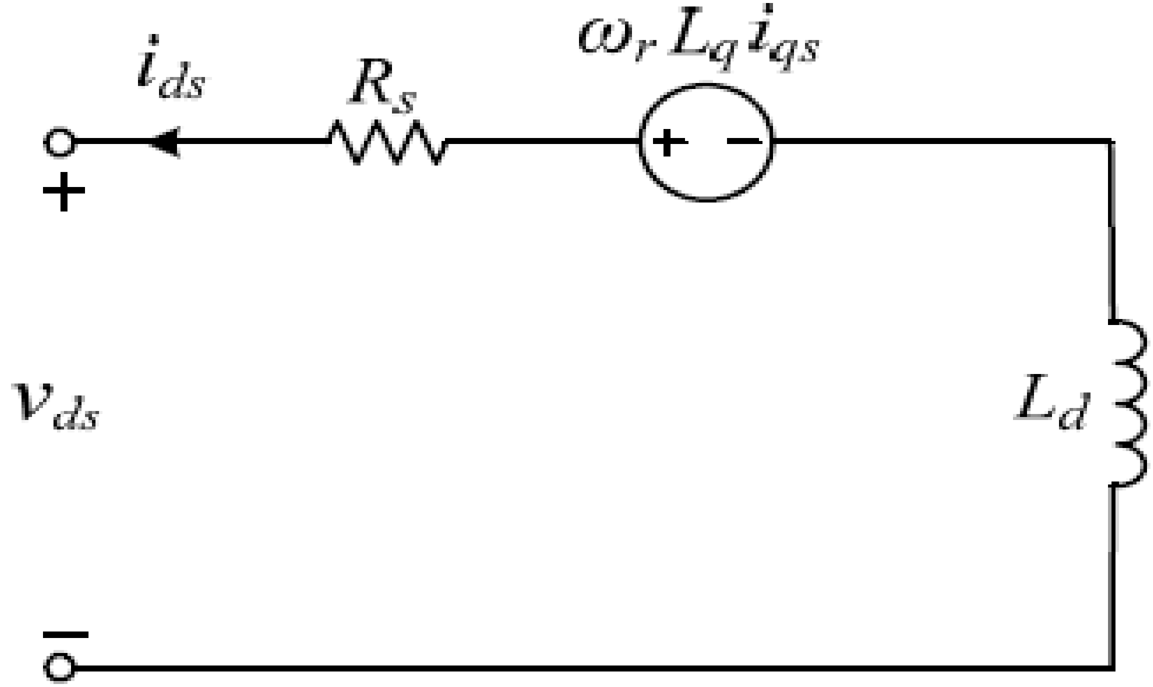


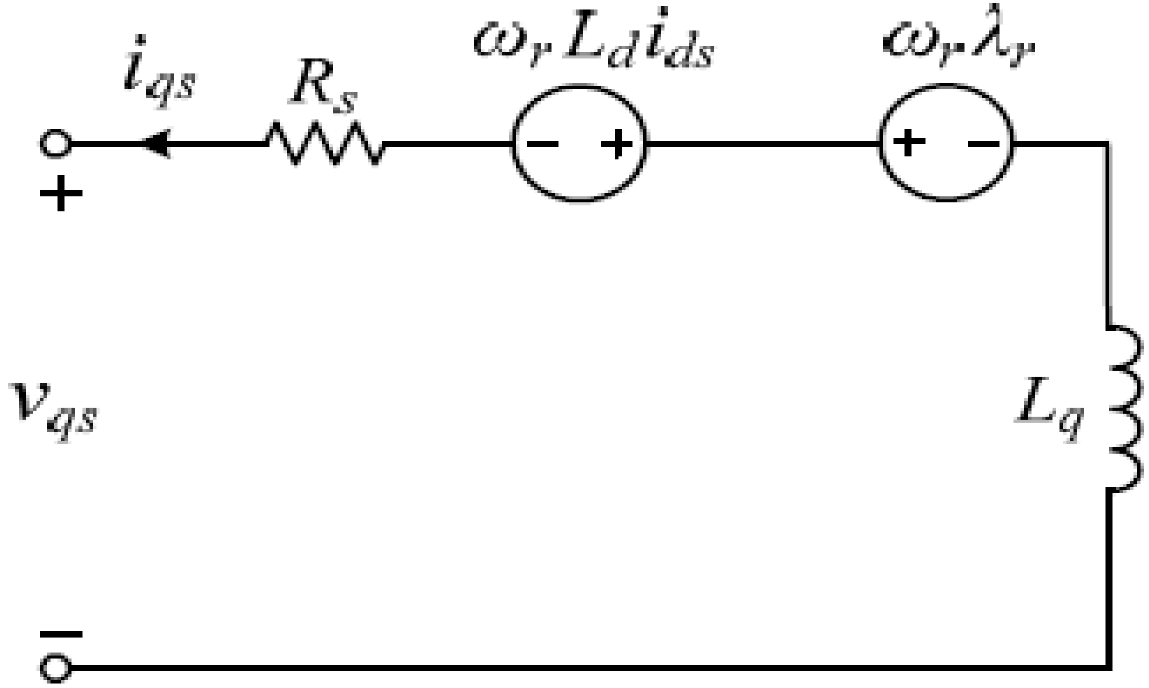
Simulation model for assignment#03due date 19/03

- Re-design the simulation model and verify Fig. 3.4-8 Simulated waveforms for a standalone PMSG system with resistive load.
- Submit report.

3.4.3 Steady-State Equivalent Circuits

- Steady-state model of a synchronous generator provides a useful tool for analysis of generator's steady-state performance.
- SG steady-state model can be developed from its dynamic model shown in Fig.





dq-axis stator currents, *ids* & *iqs*, in rotor flux synchronous reference frame are of dc values in steady state.

- Their derivatives in , *pids* & *piqs*, become 0.

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q p i_{qs} \end{cases}$$

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r \end{cases}$$

Therefore equations that describe steady-state characteristics of synchronous generator are given by

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r \end{cases}$$

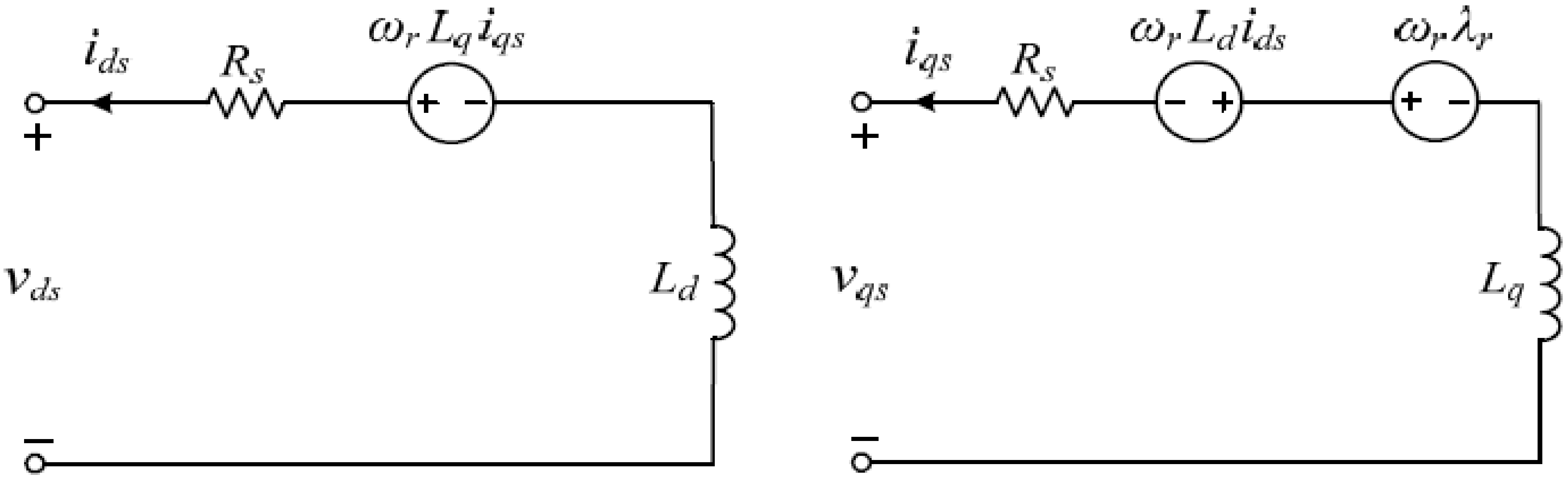
Since *dq*-axis voltages & currents in synchronous frames are all constant dc values in steady state, it is convenient to use them directly for steady-state analysis.

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r \end{cases}$$

Based on eqn, steady-state equivalent design the circuit for synchronous generator?

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r \end{cases}$$

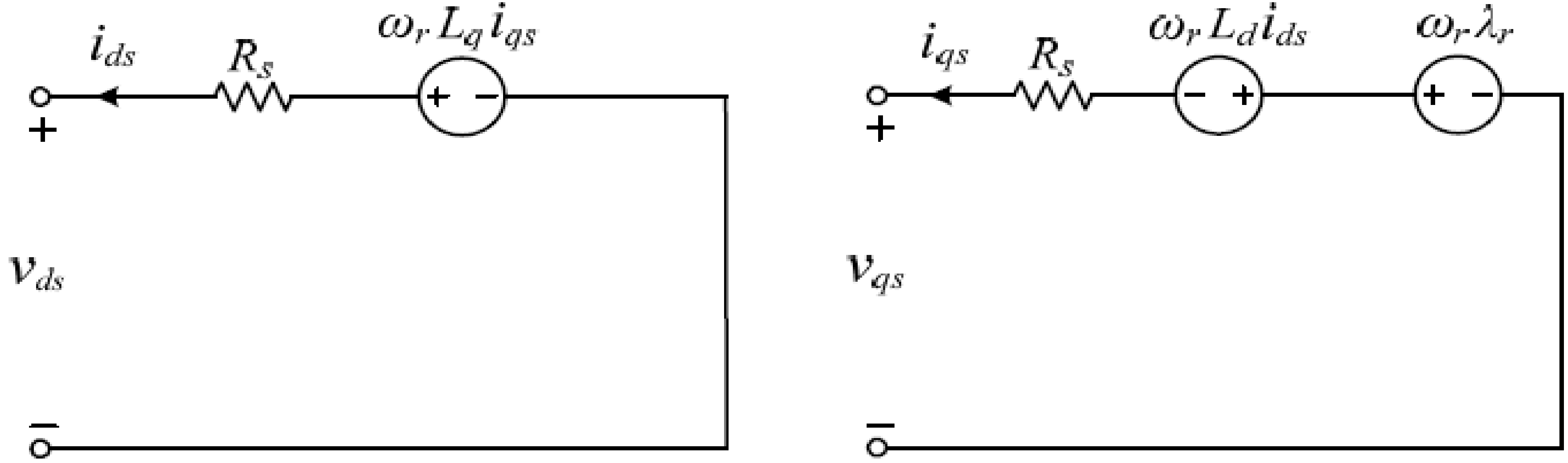
$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r \end{cases}$$



Case Study 3-4

Steady-State Analysis of Standalone SG with *RL* Load

- In this case study, steady-state performance of a standalone salient-pole synchronous generator with an *RL* load is analysed using *dq*-axis steady-state equivalent circuit of Fig.



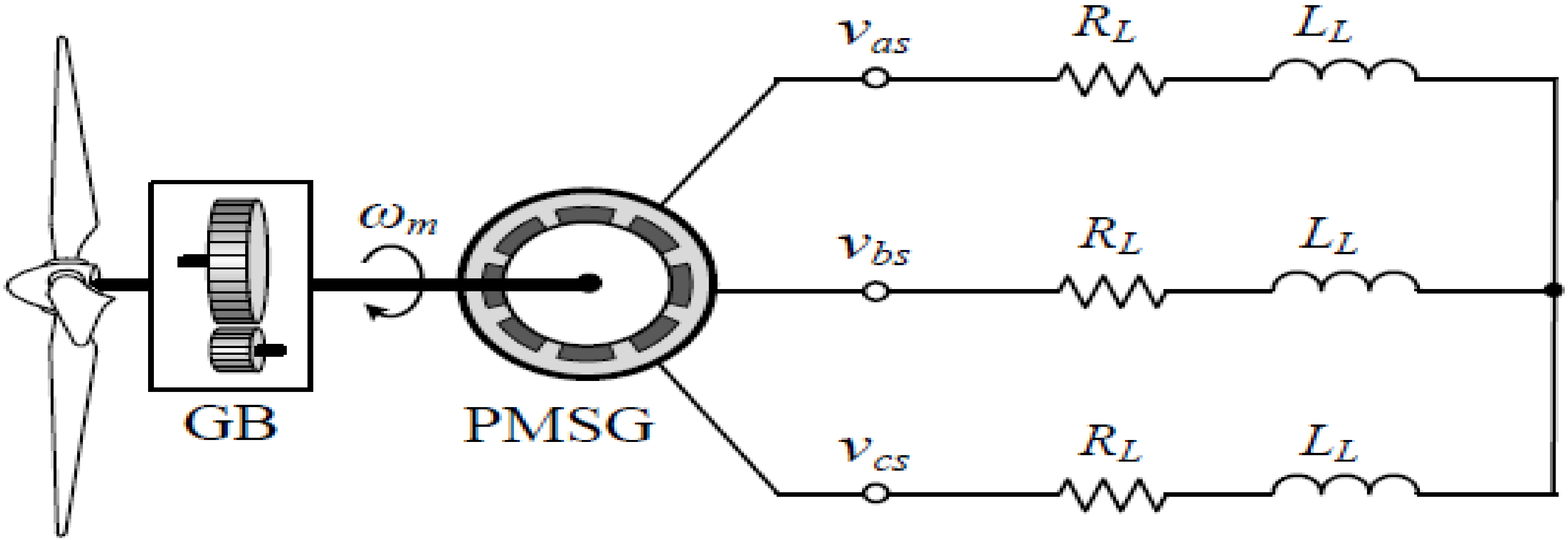
(a) *d*-axis circuit (b) *q*-axis circuit

Table B-12 2.5MW/4000V/40Hz Salient Pole PMSG Parameters

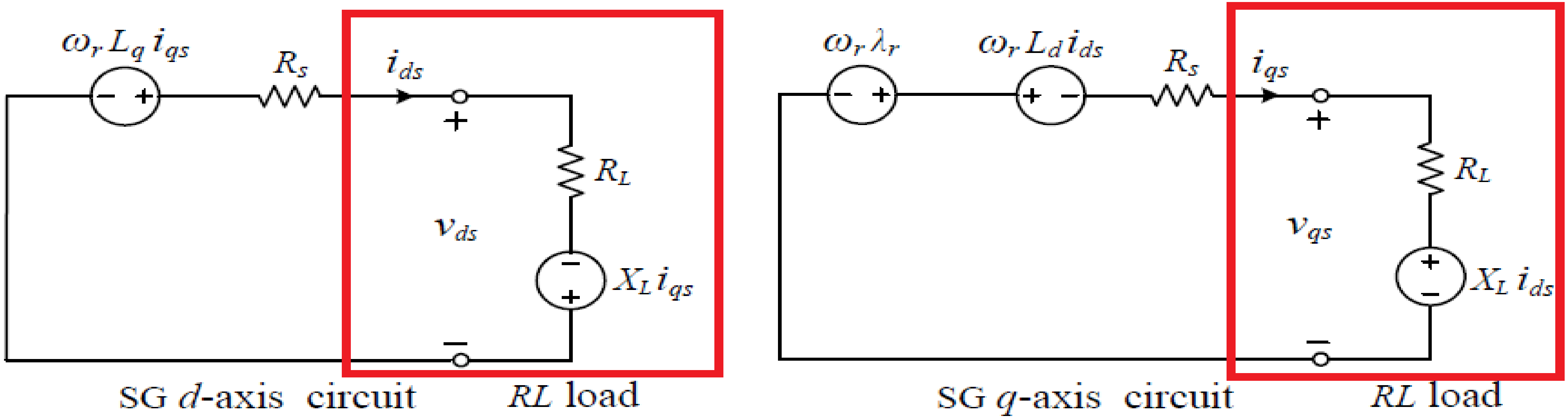
Generator Type	**PMSG, 2.5MW/4000V/40Hz, Salient Pole**	
Rated Mechanical Power	2.5 MW	1.0 pu
Rated Apparent Power	3.383 MVA	1.0 pu
Rated Line-to-line Voltage	4000 V (rms)	
Rated Phase Voltage	2309.4 V (rms)	1.0 pu
Rated Stator Current	485 A (rms)	1.0 pu
Rated Stator Frequency	40 Hz	1.0 pu
Rated Power Factor	0.739	
Rated Rotor Speed	400 rpm	1.0pu
Number of Pole Pairs	6	
Rated Mechanical Torque	59.6831 kN.m	1.0 pu
Rated Rotor Flux Linkage	4.759 Wb (rms)	0.5179 pu
Stator Winding Resistance R_s	24.25 mΩ	0.00513 pu
d-axis Synchronous Inductance L_d	8.9995 mH	0.4782 pu
q-axis Synchronous Inductance L_q	21.8463 mH	1.161 pu
Optimal Angle of Stator Current (with respect to q-axis)	32.784°	
Base Flux Linkage Λ_B	9.1888 Wb (rms)	1.0 pu
Base Impedance Z_B	4.7295 Ω	1.0 pu
Base Inductance L_B	18.818 mH	1.0 pu
Base Capacitance C_B	841.283 μF	1.0 pu

Consider a 2.5MW/4000V/40Hz/400rpm 6-pole salient PMSG, whose parameters are given in Table B-12 in Appendix B.

- Generator operates at rotor speed of 400 rpm & supplies a 3-phase *RL* load of R_L = 4.2855 Ω & L_L = 8.258 mH



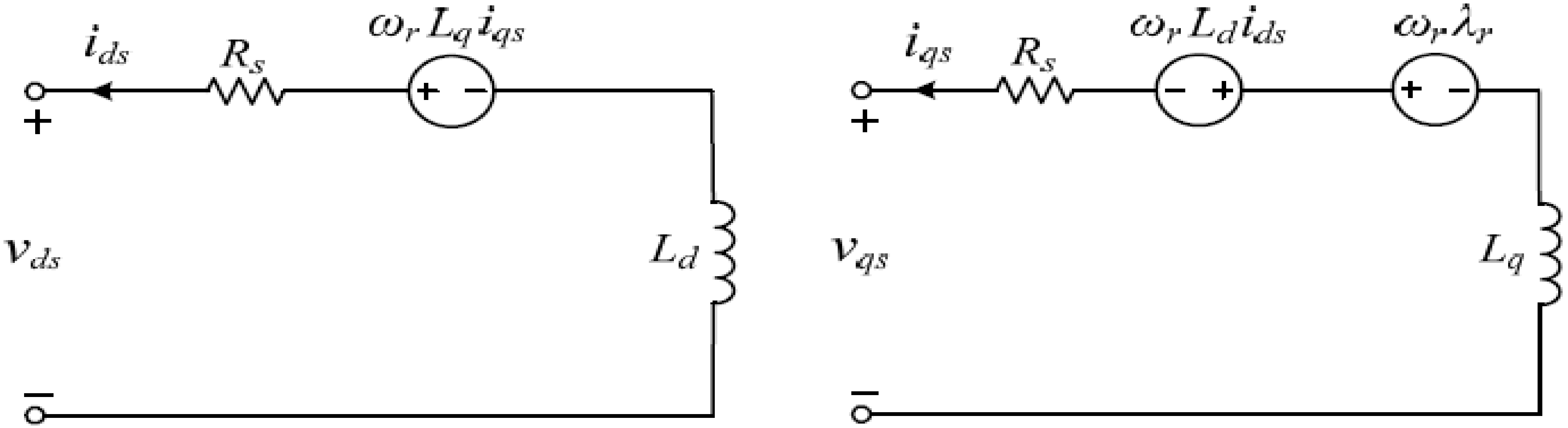
$$\begin{cases} v_{ds} = R_L i_{ds} - \omega_r L_L i_{qs} = R_L i_{ds} - X_L i_{qs} \\ v_{qs} = R_L i_{qs} + \omega_r L_L i_{ds} = R_L i_{qs} + X_L i_{ds} \end{cases}$$



where $X_L i_{qs} = \omega_r L_L i_{qs}$ and $X_L i_{ds} = \omega_r L_L i_{ds}$

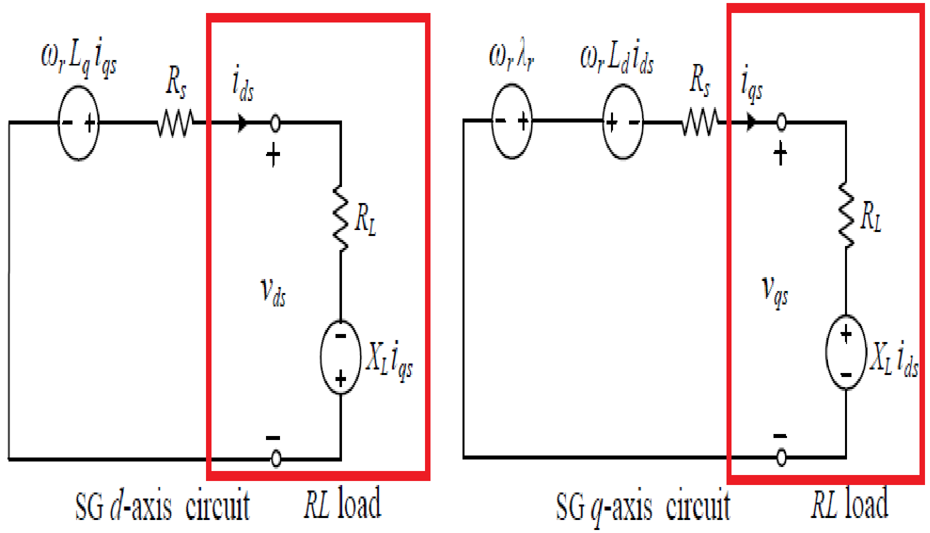
Equations that describe steady-state characteristics of synchronous generator are given by

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r \end{cases}$$



Substituting
$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r \end{cases}$$

into
$$\begin{cases} v_{ds} = R_L i_{ds} - \omega_r L_L i_{qs} \\ v_{qs} = R_L i_{qs} + \omega_r L_L i_{ds} \end{cases}$$



yields

$$\begin{cases} -R_s i_{ds} + \omega_r L_q i_{qs} = R_L i_{ds} - \omega_r L_L i_{qs} & \text{(a)} \\ -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r = R_L i_{qs} + \omega_r L_L i_{ds} & \text{(b)} \end{cases}$$

d-axis stator current i_{ds} in terms of i_{qs} can be obtained from

$$-R_s i_{ds} + \omega_r L_q i_{qs} = R_L i_{ds} - \omega_r L_L i_{qs}$$

d-axis stator current i_{ds} in terms of i_{qs}

$$i_{ds} = \frac{\omega_r (L_L + L_q)}{R_L + R_s} i_{qs}$$

Substituting $$i_{ds} = \frac{\omega_r (L_L + L_q)}{R_L + R_s} i_{qs}$$

into

$$-R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r = R_L i_{qs} + \omega_r L_L i_{ds}$$

Yields?

q-axis current

$$i_{qs} = \frac{\omega_r \lambda_r (R_L + R_s)}{(R_L + R_s)^2 + \omega_r^2 (L_L + L_d)(L_L + L_q)}$$

Rated Rotor Speed	400 rpm
Number of Pole Pairs	6
Rated Rotor Flux Linkage	4.759 Wb (rms)
Stator Winding Resistance R_s	24.25 mΩ
d-axis Synchronous Inductance L_d	8.9995 mH
q-axis Synchronous Inductance L_q	21.8463 mH

where $\omega_r = n_r P 2\pi / 60 = 400 \times 6 \times 2\pi / 60 = 251.33$ rad/sec and $\lambda_r = 6.7302$ Wb

$R_L = 4.2855\ \Omega$ & $L_L = 8.258$ mH

$i_{qs} = 141.85$ A

q-axis current

$$i_{ds} = \frac{\omega_r(L_L + L_q)}{R_L + R_s} i_{qs}$$

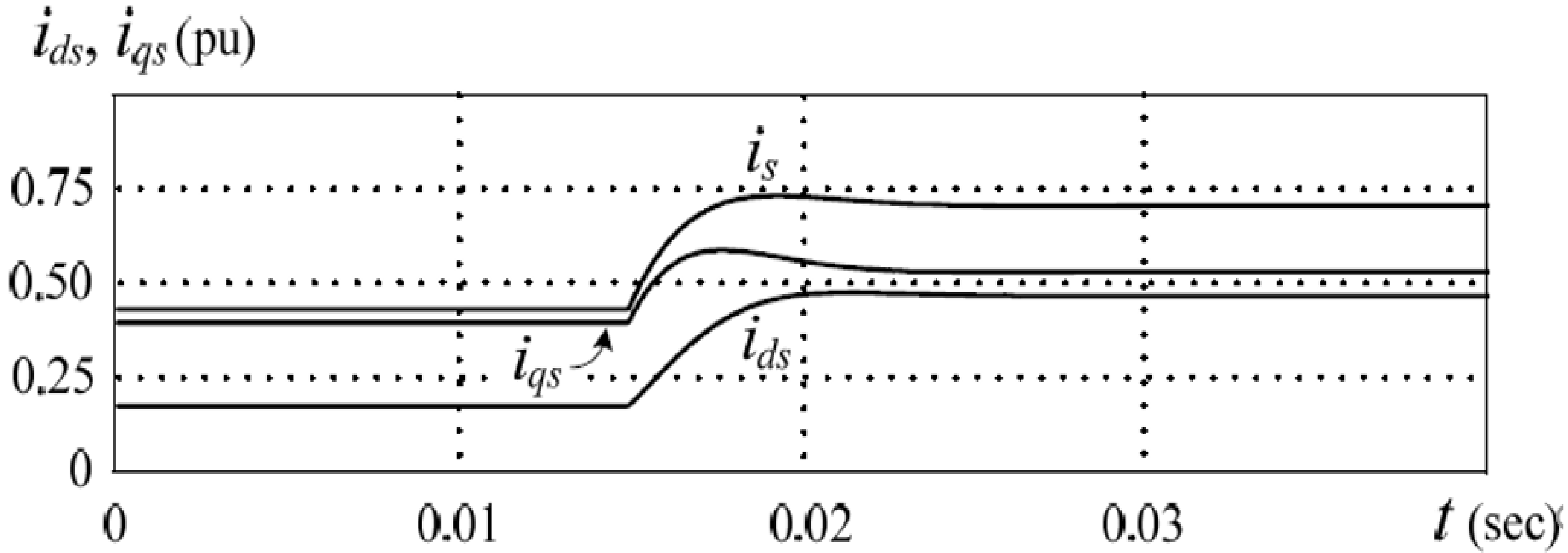
Rated Rotor Speed	400 rpm
Number of Pole Pairs	6
Rated Rotor Flux Linkage	4.759 Wb (rms)
Stator Winding Resistance R_s	24.25 mΩ
d-axis Synchronous Inductance L_d	8.9995 mH
q-axis Synchronous Inductance L_q	21.8463 mH

where $\omega_r = n_r P 2\pi / 60 = 400 \times 6 \times 2\pi / 60 = 251.33 \text{ rad/sec}$ and $\lambda_r = 6.7302 \text{ Wb}$

$R_L = 4.2855\ \Omega$ & $L_L = 8.258$ mH $\quad i_{qs} = 141.85$ A $\quad i_{ds} = 249.0$ A

Rms stator current is evaluated by

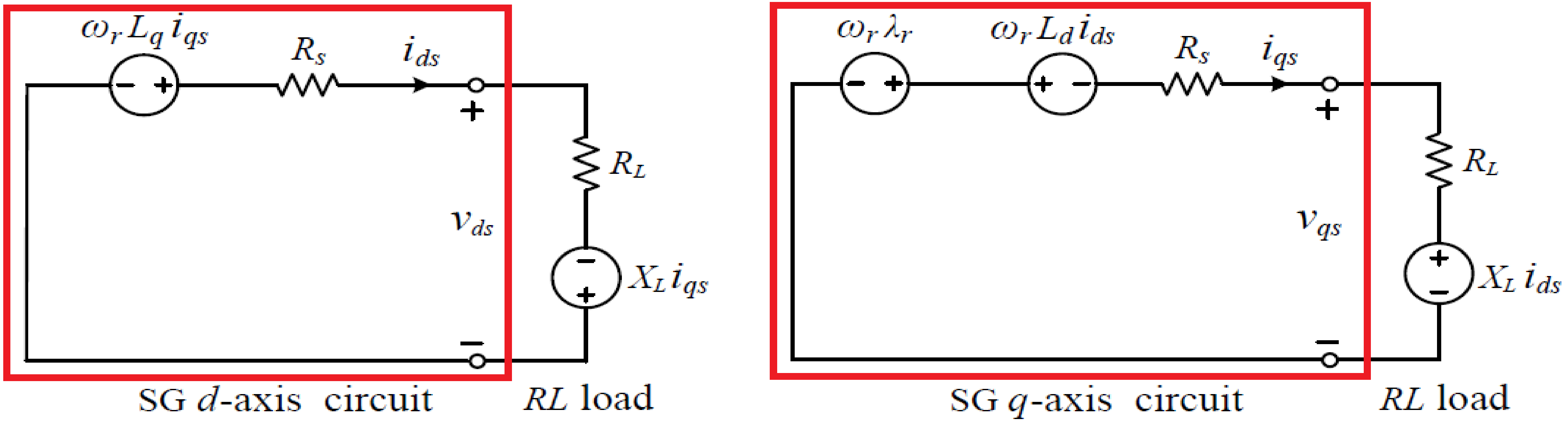
$$i_{ds} = 249.0\ \text{A} \quad i_{qs} = 141.85\ \text{A} \quad I_s = \sqrt{i_{ds}^2 + i_{qs}^2} / \sqrt{2} = 202.7\text{A}$$



$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} = 772.9 \text{ V} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r = 1124.7 \text{ V} \end{cases}$$

$i_{ds} = 249.0$ A $\qquad \omega_r = 251.33$ rad/sec $\qquad R_s = 24.25$ mΩ

$i_{qs} = 141.85$ A $\qquad \lambda_r = 6.7302$ Wb



Rms stator voltage is then calculated by

$$\begin{cases} v_{ds} = 772.9\text{ V} \\ v_{qs} = 1124.7\text{ V} \end{cases}$$

$$V_s = \sqrt{v_{ds}^2 + v_{qs}^2} / \sqrt{2} = 965.0\text{V}$$

which is also rms value of 3-phase stator voltages *Vas*, *Vbs* & *Vcs*.

Electromagnetic torque of generator is obtained by

$$T_e = \frac{3}{2} P\left(\lambda_r\, i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right) = 12.7\ \text{kN.m}$$

$i_{ds} = 249.0\ \text{A}$ $\lambda_r = 6.7302\ \text{Wb}$

$i_{qs} = 141.85\ \text{A}$

d-axis Synchronous Inductance L_d	8.9995 mH
q-axis Synchronous Inductance L_q	21.8463 mH

Mechanical power of generator is

$$P_m = T_m \omega_m = T_e \omega_r / P = 531.0\,\text{kW}$$

$$\omega_r = 251.33\,\text{rad/sec} \quad T_e = 12.7\,\text{kN.m} \quad P = 6$$

Stator winding loss is

$$P_{cu,s} = 3I_s^2 R_s = 3.0\,\mathrm{kW}$$

$$R_s = 24.25\ \mathrm{m}\Omega$$

$$I_s = 202.7\,\mathrm{A}$$

Active power delivered to load is calculated by subtracting stator winding losses from mechanical power

$$P_L = P_m - P_{cu,s} = 528.0\,\mathrm{kW}$$

$$P_{cu,s} = 3.0\,\mathrm{kW}$$

$$P_m = 531.0\,\mathrm{kW}$$

Load power factor angle is

$$\varphi_L = \tan^{-1}\left(\frac{\omega_r L_L}{R_L}\right) = 25.8^\circ$$

$\omega_r = 251.33 \text{ rad/sec}$ $R_L = 4.2855\ \Omega$ & $L_L = 8.258$ mH

from which load power factor is

$$PF_L = \cos(\varphi_L) = 0.9$$

Alternatively, load active & reactive power can be obtained by

$$\begin{cases} P_L = 1.5(v_{ds}i_{ds} + v_{qs}i_{qs}) = 528.0\,\mathrm{kW} \\ Q_L = 1.5(v_{qs}i_{ds} - v_{ds}i_{qs}) = 255.7\,\mathrm{kVA} \end{cases}$$

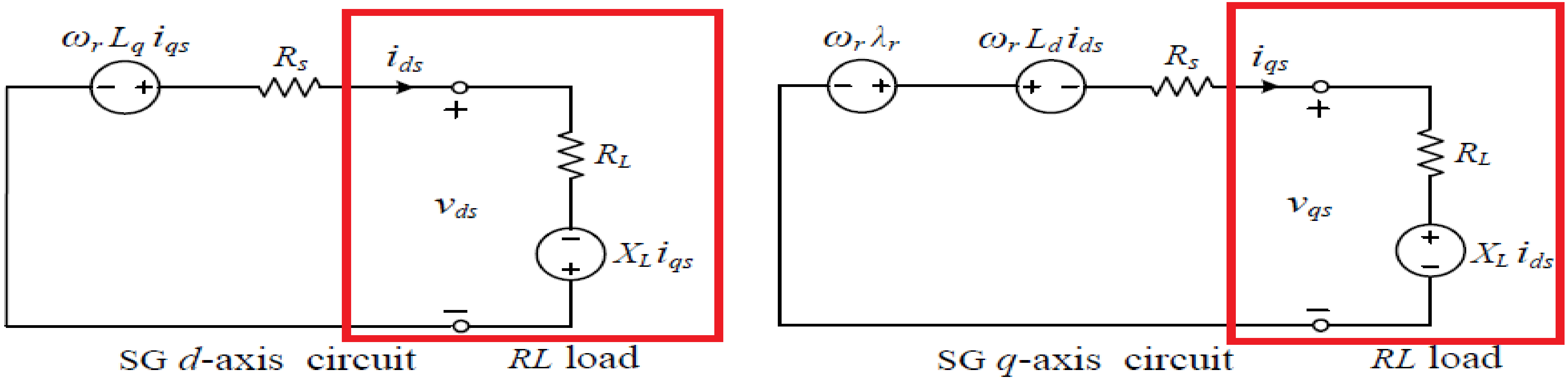
$$\begin{cases} v_{ds} = 772.9\,\mathrm{V} \quad i_{ds} = 249.0\,\mathrm{A} \\ v_{qs} = 1124.7\,\mathrm{V} \quad i_{qs} = 141.85\,\mathrm{A} \end{cases}$$

From which load power factor is

$$PF_L = \frac{P_L}{\sqrt{P_L^2 + Q_L^2}} = 0.9 \qquad \begin{cases} P_L = 528.0\,\mathrm{kW} \\ Q_L = 255.7\,\mathrm{kVA} \end{cases}$$

dq-axis stator voltages can also be calculated from load conditions

$$\begin{cases} v_{ds} = R_L i_{ds} - \omega_r L_L i_{qs} = R_L i_{ds} - X_L i_{qs} = 772.9\ \text{V} \\ v_{qs} = R_L i_{qs} + \omega_r L_L i_{ds} = R_L i_{qs} + X_L i_{ds} = 1124.7\ \text{V} \end{cases}$$



Phase angles of stator voltage & current are given by

$$\begin{cases} \theta_v = \tan^{-1}\left(v_{qs} / v_{ds}\right) = 55.5^\circ \\ \theta_i = \tan^{-1}\left(i_{qs} / i_{ds}\right) = 29.7^\circ \end{cases}$$

$$\begin{cases} v_{ds} = 772.9\ \text{V} & i_{ds} = 249.0\ \text{A} \\ v_{qs} = 1124.7\ \text{V} & i_{qs} = 141.85\ \text{A} \end{cases}$$

Rms stator voltage is then calculated by

$$\begin{cases} v_{ds} = 772.9\ \text{V} \\ v_{qs} = 1124.7\ \text{V} \end{cases}$$

$$V_s = \sqrt{v_{ds}^2 + v_{qs}^2} \,/\, \sqrt{2} = 965.0\text{V}$$

which is also rms value of 3-phase stator voltages *Vas*, *Vbs* & *Vcs*.

The rms stator current is evaluated by

$i_{ds} = 249.0\ \text{A}$ $\qquad$ $i_{qs} = 141.85\ \text{A}$

$$I_s = \sqrt{i_{ds}^2 + i_{qs}^2} / \sqrt{2} = 202.7\text{A}$$

which is rms value of 3-phase stator currents I_{as}, I_{bs} and I_{cs}

from which stator voltage & current phasors can be defined by

$$\begin{cases} \overline{V}_s = V_s \angle \theta_v = 965.0\angle 55.5° \text{ V} \\ \bar{I}_s = I_s \angle \theta_i = 202.7\angle 29.7° \text{ A} \end{cases}$$

Load power factor angle & power factor angle are

$$\begin{cases} \varphi_L = \theta_v - \theta_i = 25.8^\circ \\ PF_L = \cos\varphi_L = 0.9 \end{cases}$$

$$\begin{cases} \theta_v = 55.5^\circ \\ \theta_i = 29.7^\circ \end{cases}$$

Finally, active load power *PL* can be calculated by

$$P_L = 3V_s \breve{I}_s \cos\varphi_L = 528.0\,\text{kW}$$

$$\begin{cases} \overline{V}_s = 965.0\ \text{V} \\ \bar{I}_s = 202.7\ \text{A} \end{cases} \qquad \cos\varphi_L = 0.9$$

Assuming that rotational losses P_{rot} of generator account for 0.5% (12.5 kW) of rated generator power, efficiency of generator is

$$\eta = \frac{P_L}{P_m + P_{rot}} = \frac{528.0}{531.0 + 12.5} = 0.972$$

Efficiency of PMSG

- Permanent magnet synchronous generators usually have higher efficiency than other types of generators due to?

Use of permanent magnets for rotor flux generation.