8.5 Stator Voltage Oriented Control of DFIG WECS

Q. What 2 parameters of grid can be considered constant under normal operating conditions?

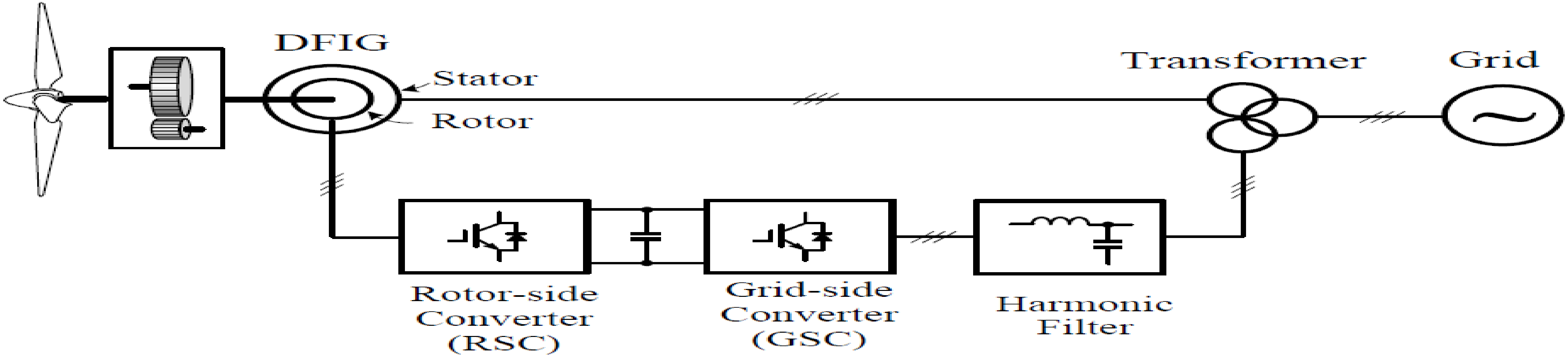
Answer:

1. Voltage &

2. Frequency

8.5.1 Principle of Stator Voltage Oriented Control (SVOC)

- As in DFIG based WECS stator of generator is directly connected to grid, & its voltage & frequency can be considered constant under normal operating conditions.
- It is, therefore, convenient to use Stator Voltage Orientated Control (SVOC) for DFIG.



FOC vs rotor- or stator-flux

- This is in contrast to electric motor drives, where rotor- or stator-flux Field Oriented Controls (FOC) are normally used.

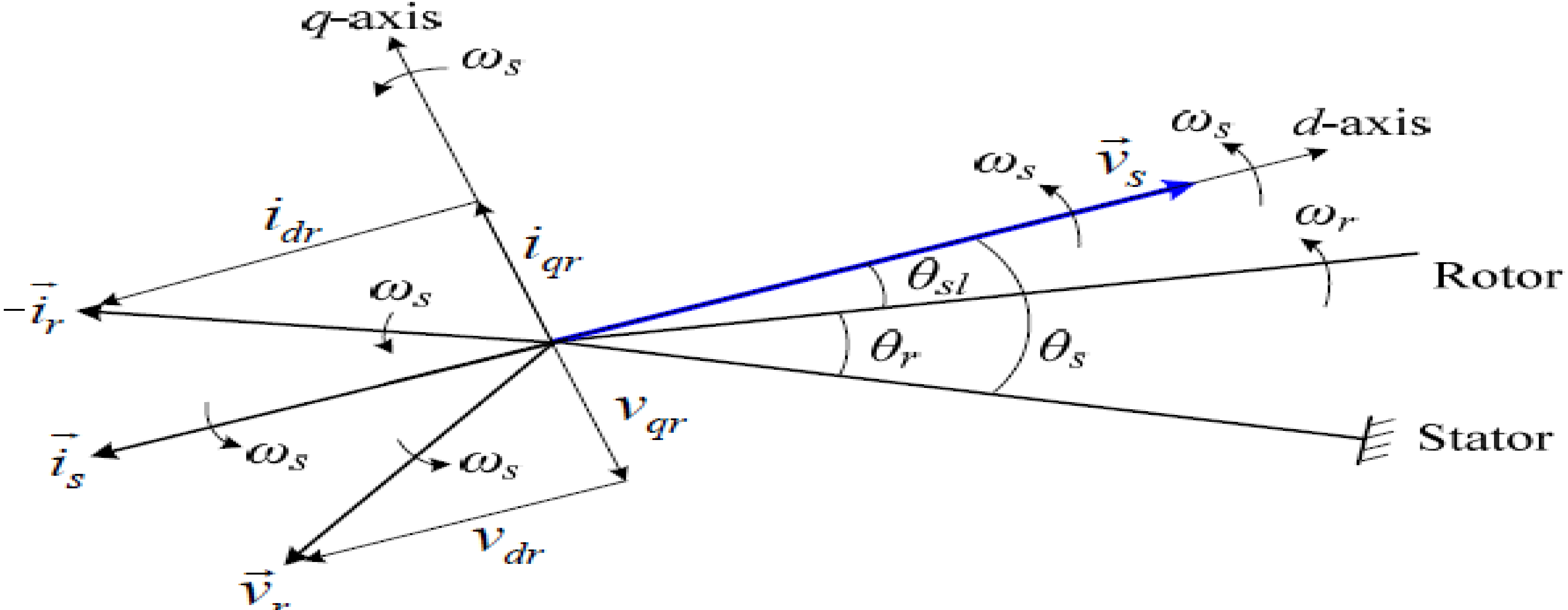
Field-oriented control (FOC)

- Vector control, also called field-oriented control (FOC), is a variable-frequency drive (VFD) control method in which stator currents of a 3-phase AC electric motor are identified as 2 orthogonal components that can be visualized with a vector.
- One component defines magnetic flux of motor, other the torque.
- Control system of drive calculates corresponding current component references from flux & torque references given by drive's speed control.

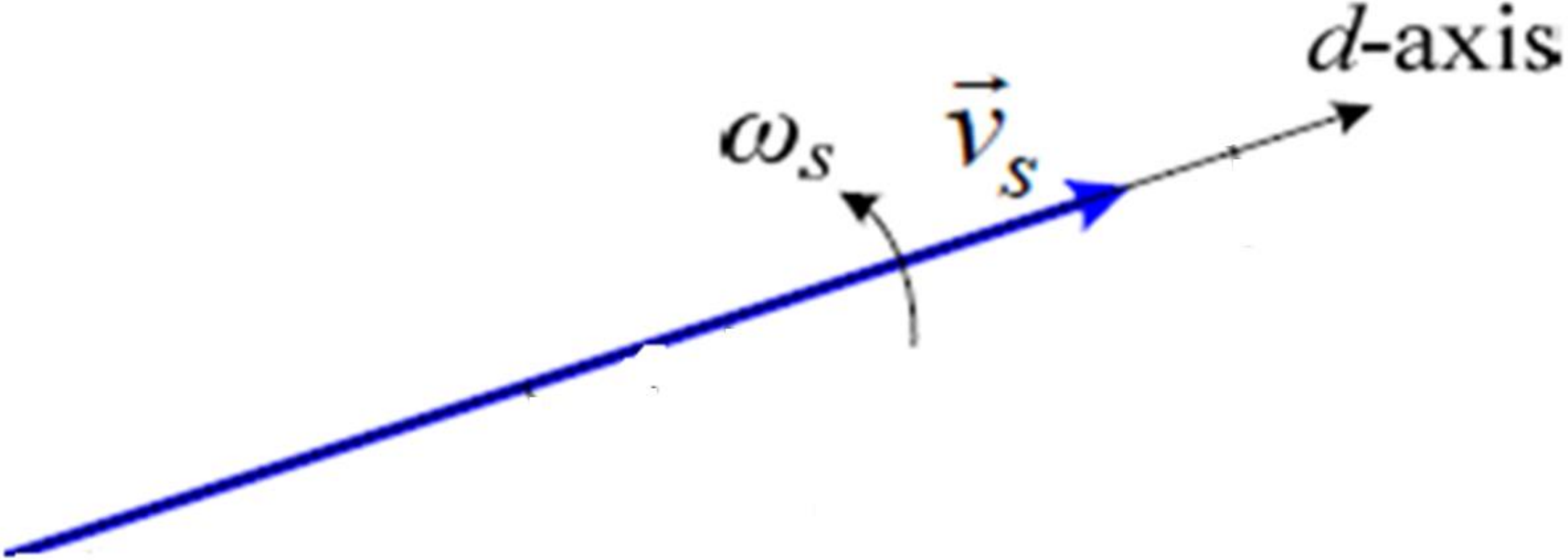
Field-oriented control (FOC)

- Proportional-integral (PI) controllers are used to keep measured current components at their reference values.
- Pulse-width modulation of the variable-frequency drive defines the transistor switching according to the stator voltage references that are the output of the PI current controllers.

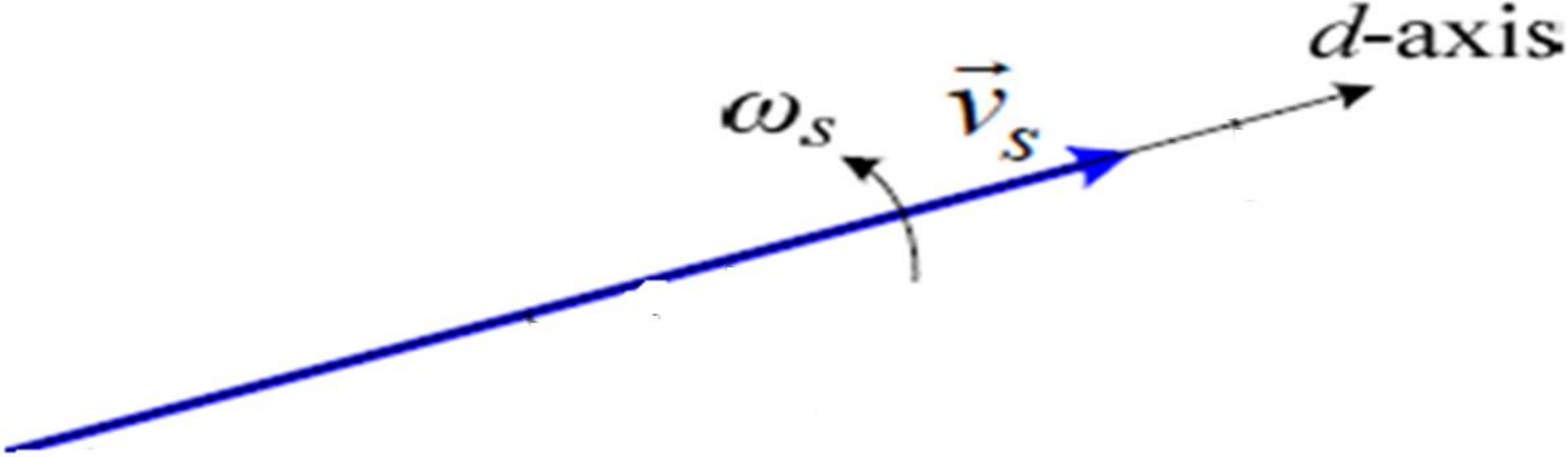
Fig. shows a space vector diagram for DFIG with stator voltage orientated control operating with unity power factor in super-synchronous mode.



Stator voltage orientated control is achieved by aligning *d*-axis of synchronous reference frame with stator voltage vector $\vec{v}_s$

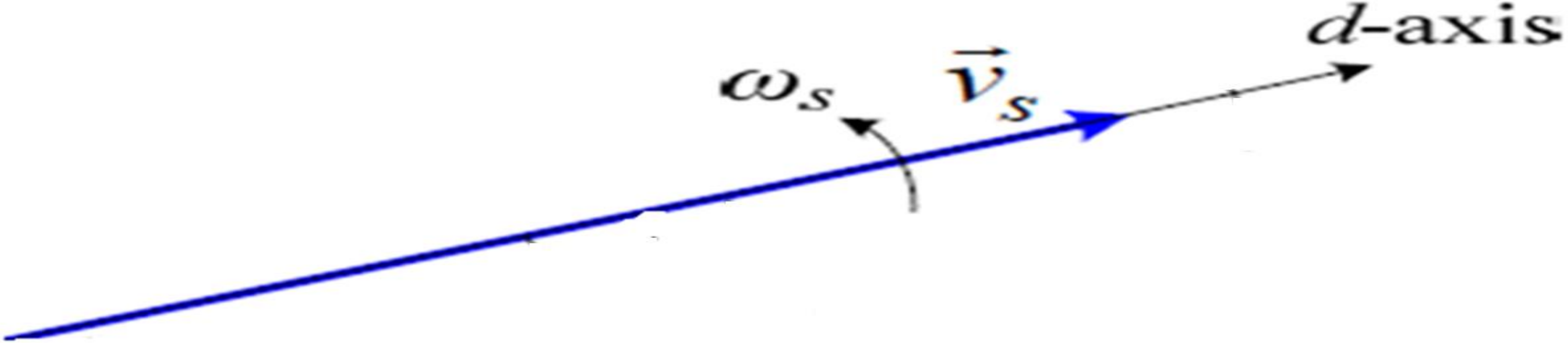


What would be values of v_{qs} =? & v_{ds} =?



As *d*-axis of synchronous reference frame is aligned with stator voltage $\vec{v}_s$ ctor so resultant *d*- & *q*-axis stator voltages are $v_{qs} = 0$ & $v_{ds} = vs$

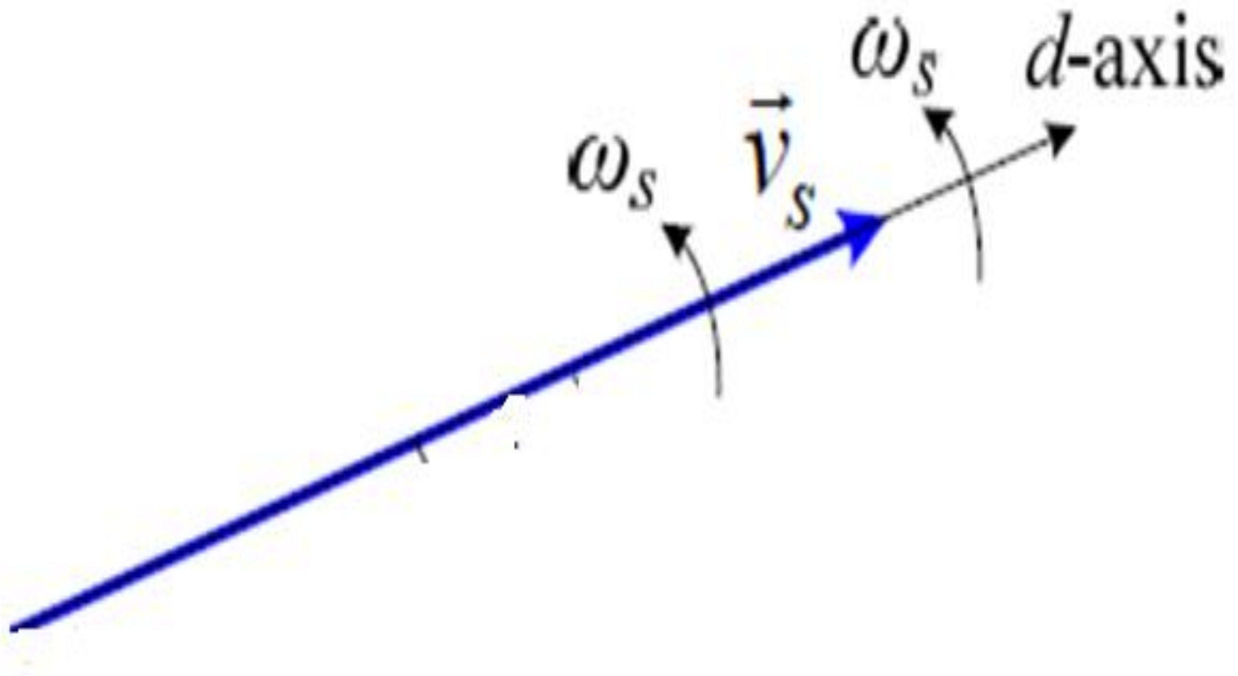
$$v_s^2 = v_{ds}^2 + \cancelto{0}{v_{qs}^2}$$



Resultant *d*- & *q*-axis stator voltages are *vqs* = 0 & *vds* = *vs*

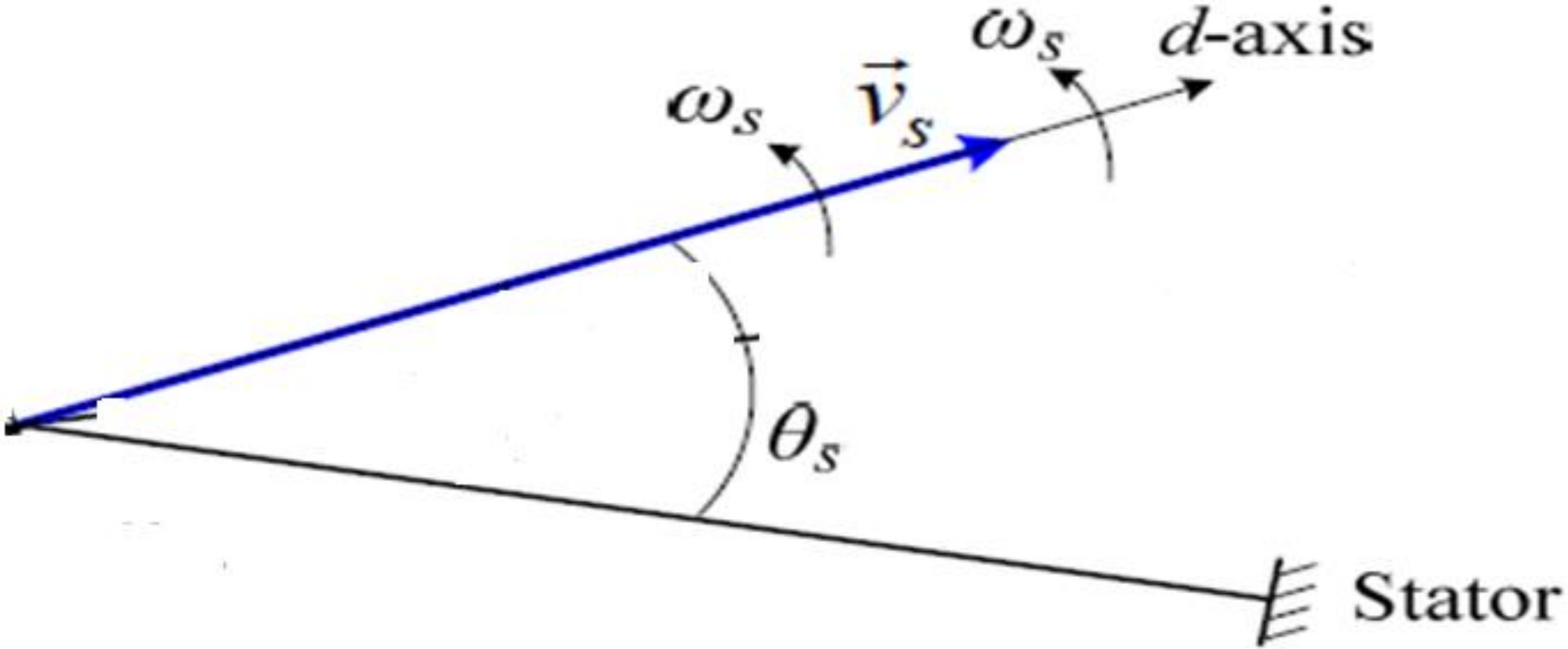
- where *vs* is magnitude of $\vec{v}_s$
- (also peak value of 3-phase stator voltage).
- Rotating speed of the synchronous reference frame is given by

$$\omega_s = 2\pi f_s$$

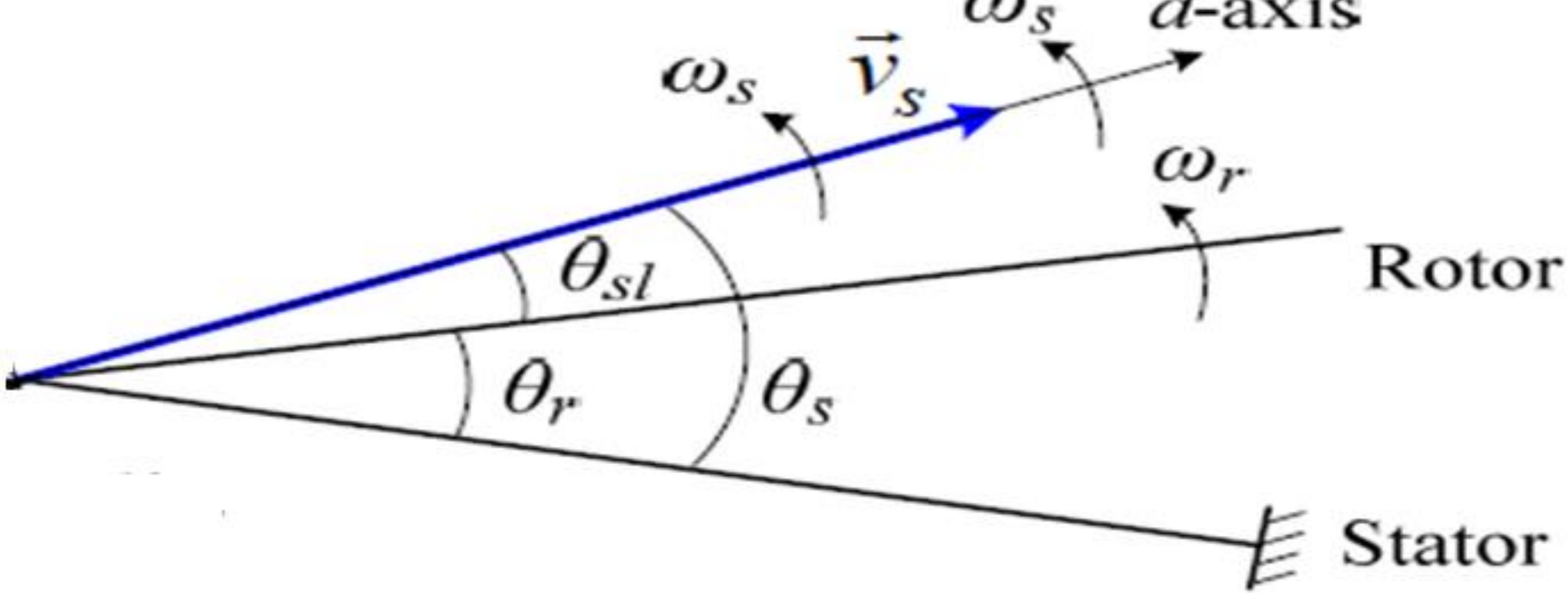


where *fs* is stator frequency of generator (also frequency of grid voltage).

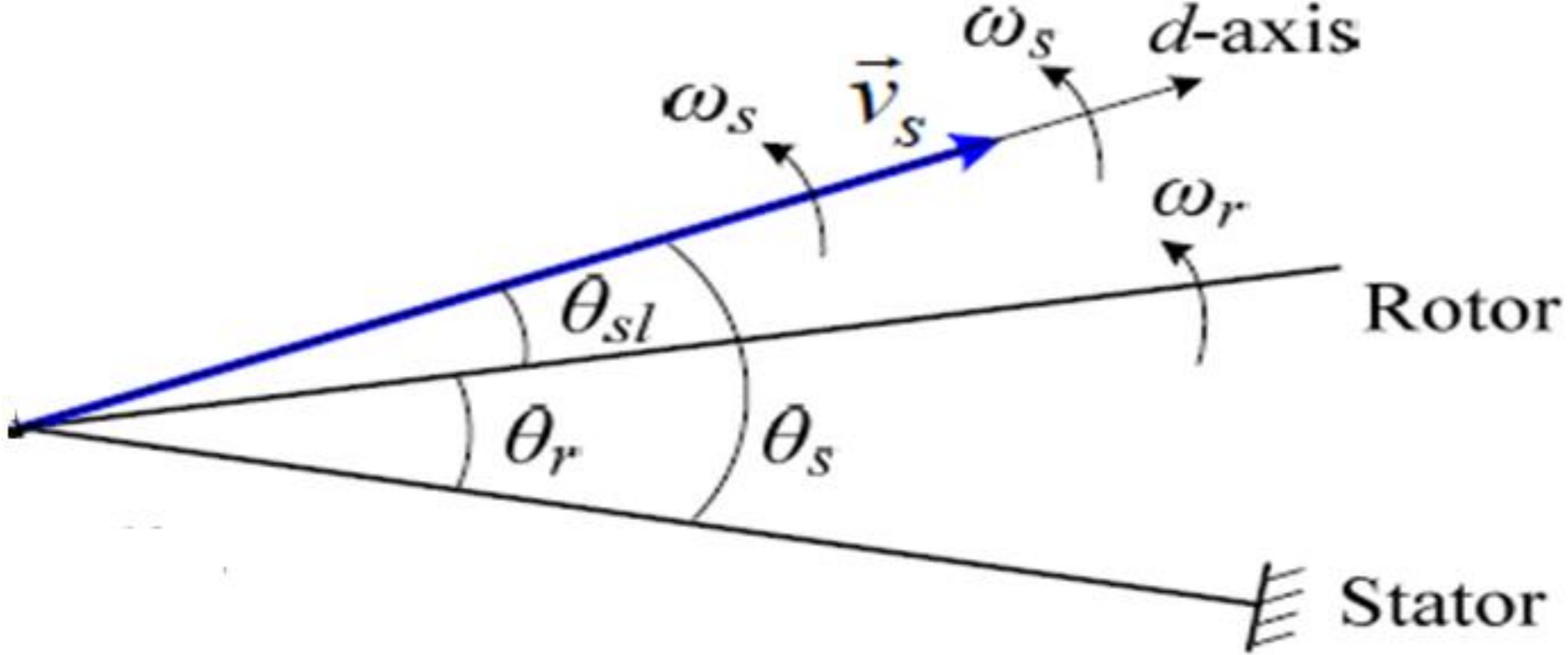
Stator voltage vector angle ϑs is referenced to stator frame, which varies from 0 to 2π when $\vec{v}_s$ rotates 1 revolution in space.



Rotor rotates at speed ω_r. Rotor position angle ϑ_r is also referenced to stator frame.

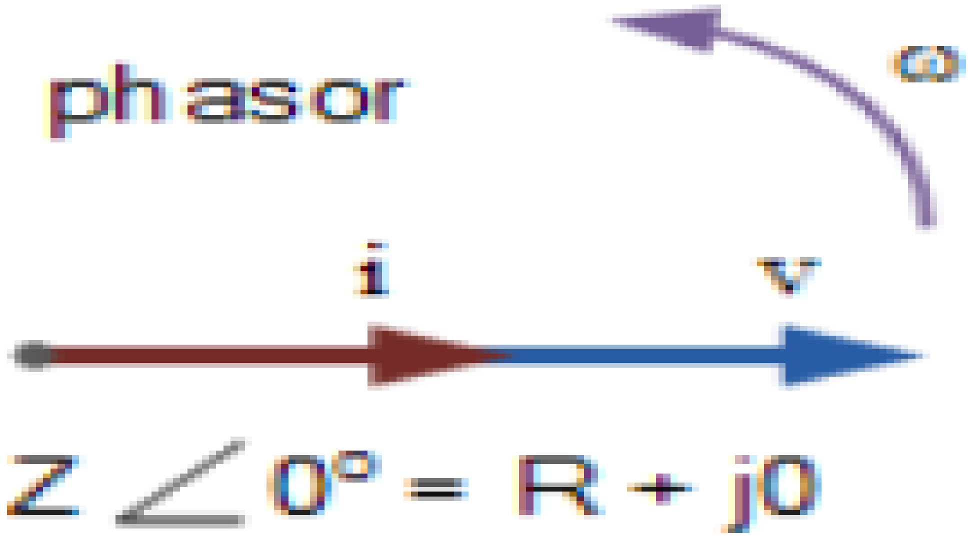


Angle between stator voltage vector $\vec{v}_s$ & rotor is slip angle, defined by $\theta_{sl} = \theta_s - \theta_r$



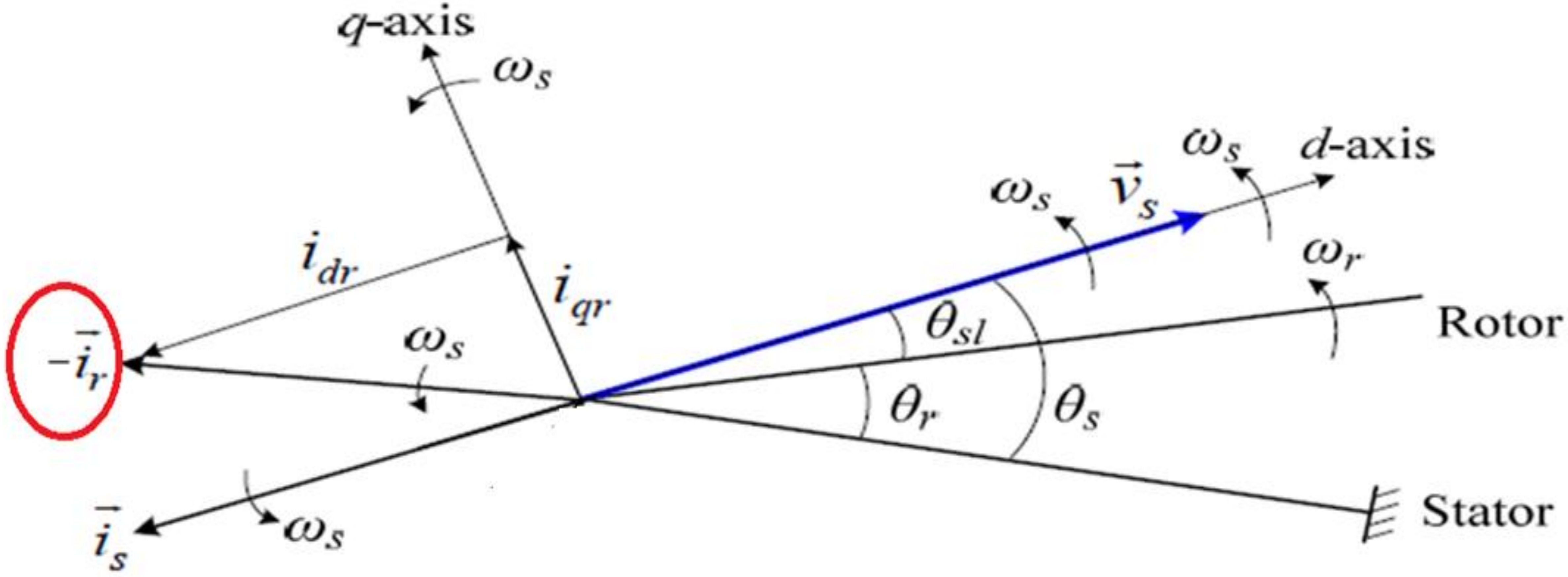
Q. In unity power factor voltage & current vectors can be aligned?

Yes, in unity power factor voltage & current vectors can be aligned

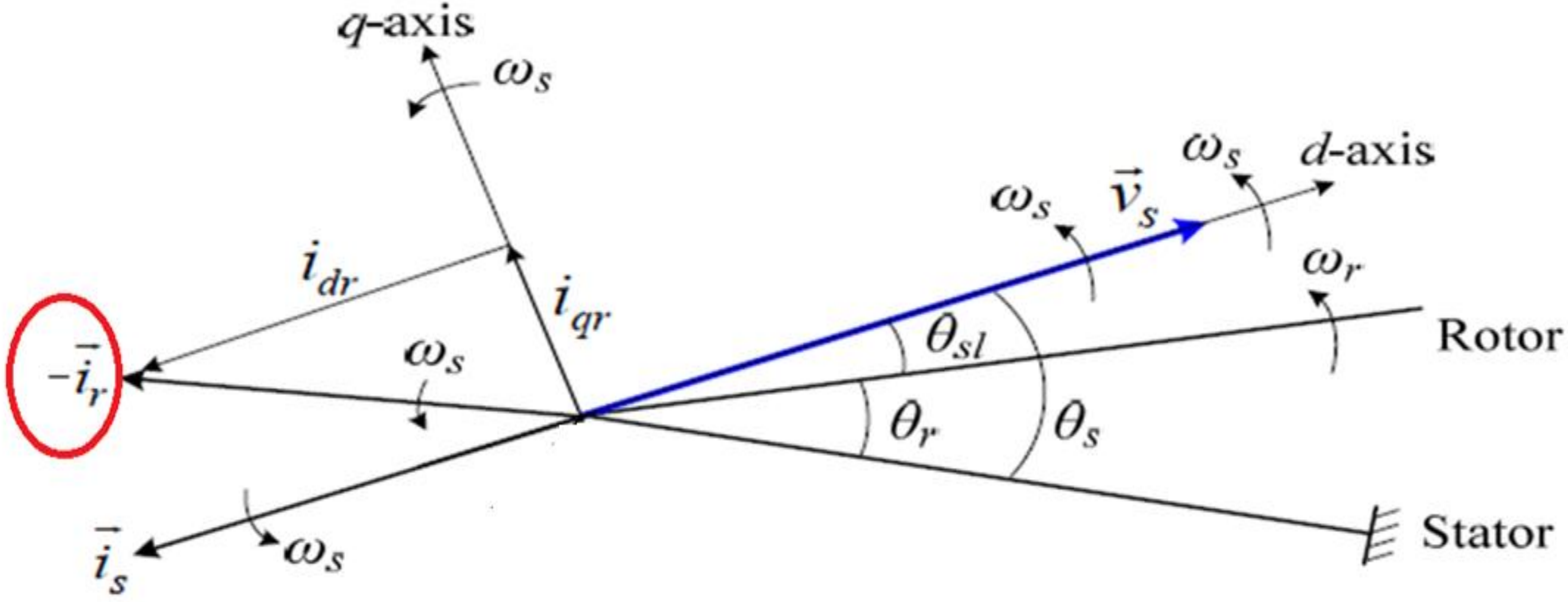


Since DFIG operates with unity power factor, stator current vector $\vec{i}_s$ is aligned with $\vec{v}_s$ but with opposite direction (DFIG in generating mode).

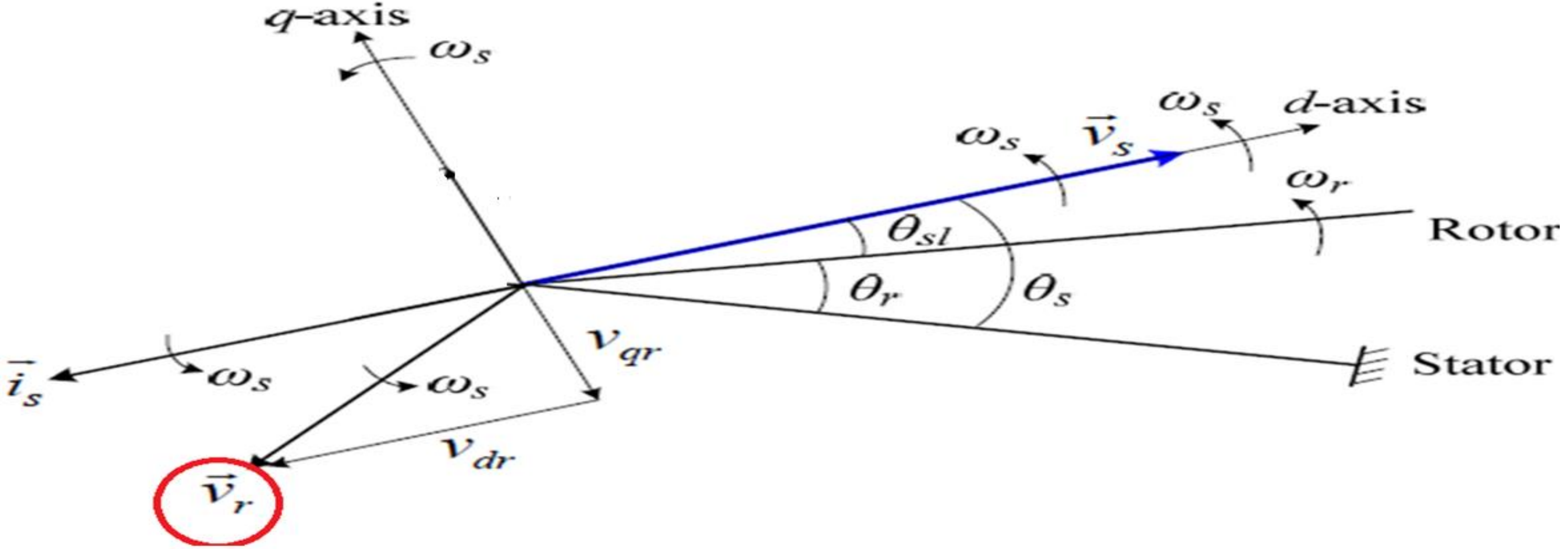
Rotor current vector $\vec{i}_r$ can be resolved into 2 components along *dq* axes: i_{dr} & i_{qr} .



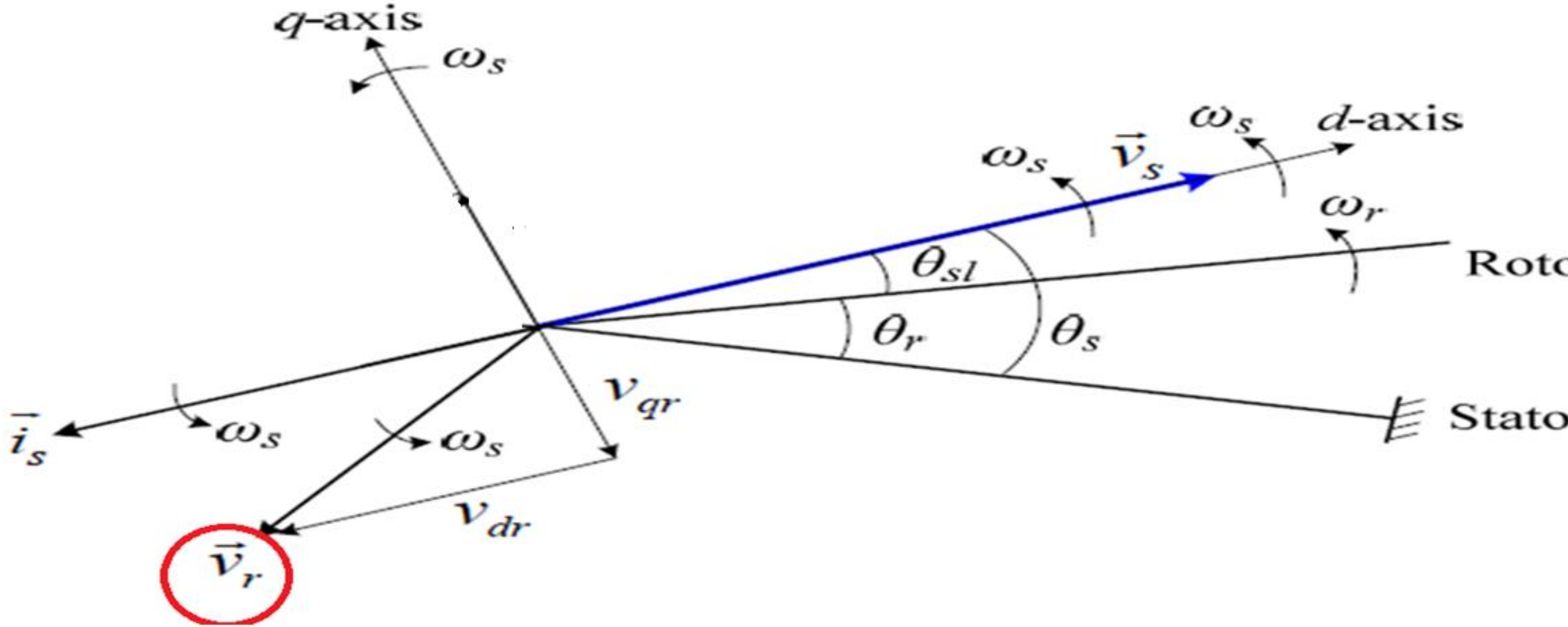
These *dq*-axis components(*idr* & *iqr*) can be controlled independently by rotor converters.



Rotor voltage vector $\vec{v}_r$ can be resolved into 2 components along *dq* axes: v_{dr} & v_{qr}.



These dq-axis(v_{dr} & v_{qr}) components can be controlled independently by rotor converters.



To investigate controllability of electromagnetic torque *Te*, active power *Ps* & reactive power *Qs* by rotor voltage(*Vr*) & rotor current(*ir*).

- DFIG based WECS can be controlled by electromagnetic torque *Te* for speed control or active power *Ps*.

- In contrast to other WECS, electromagnetic torque *Te* of generator, active power *Ps* & reactive power *Qs* of stator are controlled by RSC.

Electromagnetic torque(Te) of generator can be expressed in terms of flux & current:(Write equation)?

Electromagnetic torque (*Te*) of generator can be expressed as:

$$T_e = \frac{3P}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs})$$

$$T_e = \frac{3P}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs})$$

where λds & λqs are *dq*-axis stator flux linkages, given by

$$\begin{cases} \lambda_{ds} = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} = L_s i_{qs} + L_m i_{qr} \end{cases}$$

From which *dq*-axis stator currents are calculated to be

$$\begin{cases} i_{ds} = \dfrac{\lambda_{ds} - L_m i_{dr}}{L_s} \\ i_{qs} = \dfrac{\lambda_{qs} - L_m i_{qr}}{L_s} \end{cases}$$

Substituting
$$\begin{cases} i_{ds} = \dfrac{\lambda_{ds} - L_m i_{dr}}{L_s} \\ i_{qs} = \dfrac{\lambda_{qs} - L_m i_{qr}}{L_s} \end{cases}$$
into

$$T_e = \frac{3P}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs})$$

yields

$$T_e = \frac{3PL_m}{2L_s}(-i_{qr}\lambda_{ds} + i_{dr}\lambda_{qs})$$

$$T_e = \frac{3PL_m}{2L_s}(-i_{qr}\lambda_{ds} + i_{dr}\lambda_{qs})$$

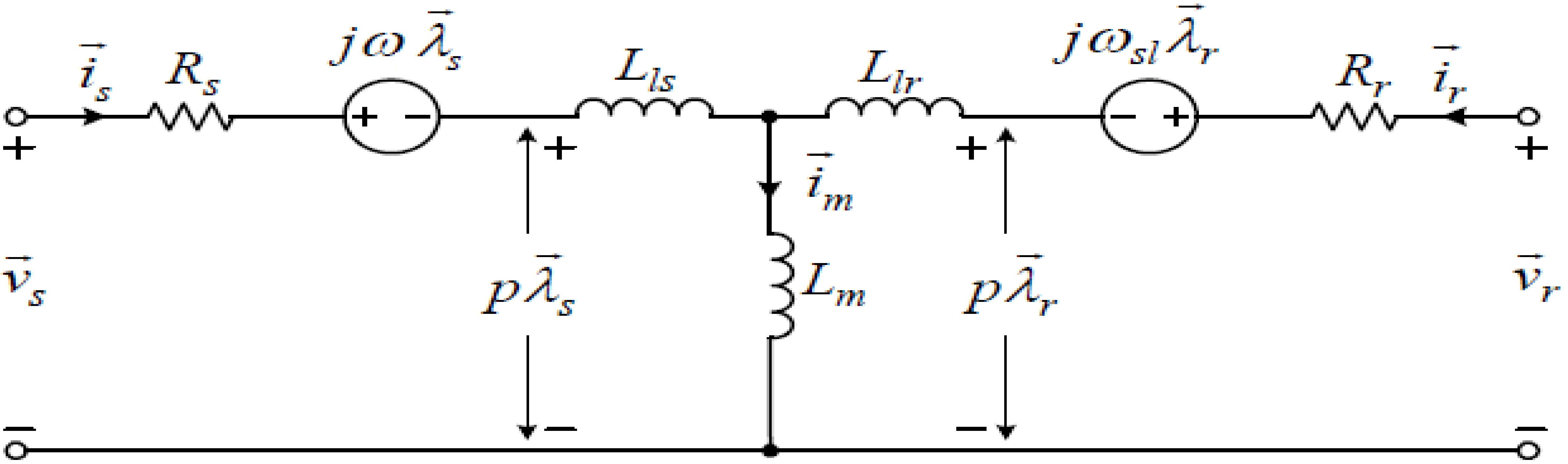
- Above equation indicates that electromagnetic torque(Te) is a function of rotor current(i_{dr} & i_{qr}) & stator flux linkages(λ_{ds} & λ_{qs}).
- In DFIG wind energy system, stator voltage is constant since it is directly connected to grid. Rotor current is controlled by RSC.
- It is thus desirable to find relationship between torque, stator voltage & rotor current.

Voltage equation for stator of generator in synchronous reference frame

$$\vec{v}_s = R_s \vec{i}_s + p\vec{\lambda}_s + j\omega\vec{\lambda}_s$$

Stator voltage vector for steady-state operation of induction generator is

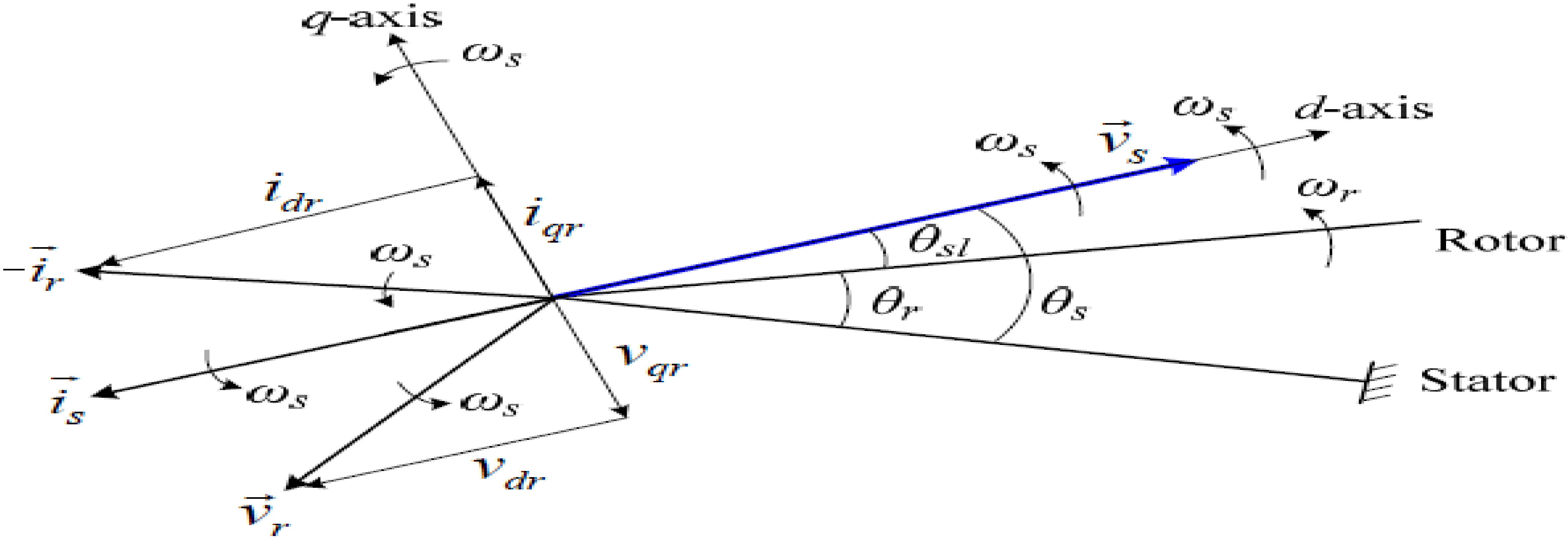
$$\vec{v}_s = R_s \vec{i}_s + j\omega_s \vec{\lambda}_s$$



Dissolved vecto[...] into *dq*-axis:

$$\vec{v}_s = R_s \vec{i}_s + j\omega_s \vec{\lambda}_s$$

$$(v_{ds} + jv_{qs}) = R_s(i_{ds} + ji_{qs}) + j\omega_s(\lambda_{ds} + j\lambda_{qs})$$



Find *dq*-axis stator flux linkages from?

$$(v_{ds} + jv_{qs}) = R_s(i_{ds} + ji_{qs}) + j\omega_s(\lambda_{ds} + j\lambda_{qs})$$

$$\begin{cases} \lambda_{ds} = \dfrac{v_{qs} - R_s i_{qs}}{\omega_s} \\ \lambda_{qs} = -\dfrac{v_{ds} - R_s i_{ds}}{\omega_s} \end{cases}$$

dq-axis stator flux linkages

$$\begin{cases} \lambda_{ds} = \dfrac{v_{qs} - R_s i_{qs}}{\omega_s} \\ \lambda_{qs} = -\dfrac{v_{ds} - R_s i_{ds}}{\omega_s} \end{cases}$$

$$v_{ds} + j v_{qs} = R_s(\mathbf{i}_{ds} + \mathbf{j}\mathbf{i}_{qs}) + \mathbf{j}\,\omega_s(\lambda_{ds} + \mathbf{j}\,\lambda_{qs})$$

$$v_{ds} + j v_{qs} = R_s\,\mathbf{i}_{ds} + \mathbf{j}\,R_s\,\mathbf{i}_{qs} + \mathbf{j}\,\omega_s\lambda_{ds} - \omega_s\lambda_{qs}$$

$$v_{ds} = R_s\,\mathbf{i}_{ds} - \omega_s\lambda_{qs}$$

$$\lambda_{qs} = \frac{R_s\,\mathbf{i}_{ds} - v_{ds}}{\omega_s}$$

$$\lambda_{qs} = \frac{-v_{ds} + R_s\,\mathbf{i}_{ds}}{\omega_s}$$

$$v_{qs} = R_s\,\mathbf{i}_{qs} + \omega_s\lambda_{ds}$$

$$\lambda_{ds} = \frac{v_{qs} - R_s\,\mathbf{i}_{qs}}{\omega_s}$$

Substitutin $\begin{cases} \lambda_{ds} = \dfrac{v_{qs} - R_s i_{qs}}{\omega_s} \\ \lambda_{qs} = -\dfrac{v_{ds} - R_s i_{ds}}{\omega_s} \end{cases}$

$$T_e = \frac{3PL_m}{2L_s}(-i_{qr}\lambda_{ds} + i_{dr}\lambda_{qs})$$

gives

$$T_e = \frac{3PL_m}{2\omega_s L_s}(-i_{qr}(v_{qs} - R_s i_{qs}) - i_{dr}(v_{ds} - R_s i_{ds}))$$

$$= \frac{3PL_m}{2\omega_s L_s}(-i_{qr}v_{qs} + R_s i_{qs} i_{qr} + R_s i_{ds} i_{dr} - i_{dr} v_{ds})$$

With *vqs* = 0 for stator voltage oriented control, torque equation can be simplified to

$$T_e = \frac{3PL_m}{2\omega_s L_s}(R_s i_{qs} i_{qr} + R_s i_{ds} i_{dr} - i_{dr} v_{ds})$$

Ignoring stator resistance *Rs*, which is normally very low for large DFIG, torque equation can be further simplified:

$$T_e = \frac{3PL_m}{2\omega_s L_s}(R_s i_{qs} i_{qr} + R_s i_{ds} i_{dr} - i_{dr} v_{ds})$$

$$T_e = -\frac{3PL_m}{2\omega_s L_s} i_{dr} v_{ds}$$

It can be observed from above equation that electromagnetic torque(Te) is a function of *d*-axis rotor current(i_{dr}) & stator voltage(v_{ds}).

Calculation of *dq*-axis rotor currents.

Stator active(P_s) & reactive power(Q_s) can be calculated by

$$\begin{cases} P_s = \dfrac{3}{2}\left(v_{ds} i_{ds} + v_{qs} \overset{0}{\cancel{i_{qs}}}\right) \\ Q_s = \dfrac{3}{2}\left(v_{qs} \overset{0}{\cancel{i_{ds}}} - v_{ds} i_{qs}\right) \end{cases}$$

Using stator voltage oriented control ($v_{qs} = 0$), above equation can be simplified to

$$\begin{cases} P_s = \dfrac{3}{2} v_{ds} i_{ds} \\ Q_s = -\dfrac{3}{2} v_{ds} i_{qs} \end{cases} \quad \text{for } v_{qs} = 0$$

Substitutir $\begin{cases} i_{ds} = \dfrac{\lambda_{ds} - L_m i_{dr}}{L_s} \\ i_{qs} = \dfrac{\lambda_{qs} - L_m i_{qr}}{L_s} \end{cases}$ in $\begin{cases} P_s = \dfrac{3}{2} v_{ds} i_{ds} \\ Q_s = -\dfrac{3}{2} v_{ds} i_{qs} \end{cases}$ for $v_{qs} = 0$

yields

$$\begin{cases} P_s = \dfrac{3}{2} v_{ds} \left(\dfrac{\lambda_{ds} - L_m i_{dr}}{L_s} \right) \\ Q_s = -\dfrac{3}{2} v_{ds} \left(\dfrac{\lambda_{qs} - L_m i_{qr}}{L_s} \right) \end{cases}$$

from which

$$\begin{cases} i_{dr} = -\dfrac{2L_s}{3v_{ds} L_m} P_s + \dfrac{1}{L_m} \lambda_{ds} \\ i_{qr} = \dfrac{2L_s}{3v_{ds} L_m} Q_s + \dfrac{1}{L_m} \lambda_{qs} \end{cases}$$

Substituting stator flux linkages into

$$\begin{cases} \lambda_{ds} = \dfrac{v_{qs} - R_s i_{qs}}{\omega_s} \\ \lambda_{qs} = -\dfrac{v_{ds} - R_s i_{ds}}{\omega_s} \end{cases}$$

$$\begin{cases} i_{dr} = -\dfrac{2L_s}{3v_{ds}L_m} P_s + \dfrac{1}{L_m} \lambda_{ds} \\ i_{qr} = \dfrac{2L_s}{3v_{ds}L_m} Q_s + \dfrac{1}{L_m} \lambda_{qs} \end{cases}$$

gives

$$\begin{cases} i_{dr} = -\dfrac{2L_s}{3v_{ds}L_m} P_s + \dfrac{v_{qs} - R_s i_{qs}}{\omega_s L_m} = -\dfrac{2L_s}{3v_{ds}L_m} P_s - \dfrac{R_s}{\omega_s L_m} i_{qs} \\ i_{qr} = \dfrac{2L_s}{3v_{ds}L_m} Q_s - \dfrac{v_{ds} - R_s i_{ds}}{\omega_s L_m} = \dfrac{2L_s}{3v_{ds}L_m} Q_s + \dfrac{R_s}{\omega_s L_m} i_{ds} - \dfrac{v_{ds}}{\omega_s L_m} \end{cases} \quad \text{for } v_{qs} = 0$$

$$
\begin{cases}
i_{dr} = -\dfrac{2L_s}{3v_{ds}L_m}P_s + \dfrac{v_{qs} - R_s i_{qs}}{\omega_s L_m} = -\dfrac{2L_s}{3v_{ds}L_m}P_s - \dfrac{R_s}{\omega_s L_m}i_{qs} \\
i_{qr} = \dfrac{2L_s}{3v_{ds}L_m}Q_s - \dfrac{v_{ds} - R_s i_{ds}}{\omega_s L_m} = \dfrac{2L_s}{3v_{ds}L_m}Q_s + \dfrac{R_s}{\omega_s L_m}i_{ds} - \dfrac{v_{ds}}{\omega_s L_m}
\end{cases}
\quad \text{for } v_{qs} = 0
$$

Neglecting stator resistance *Rs*, we have

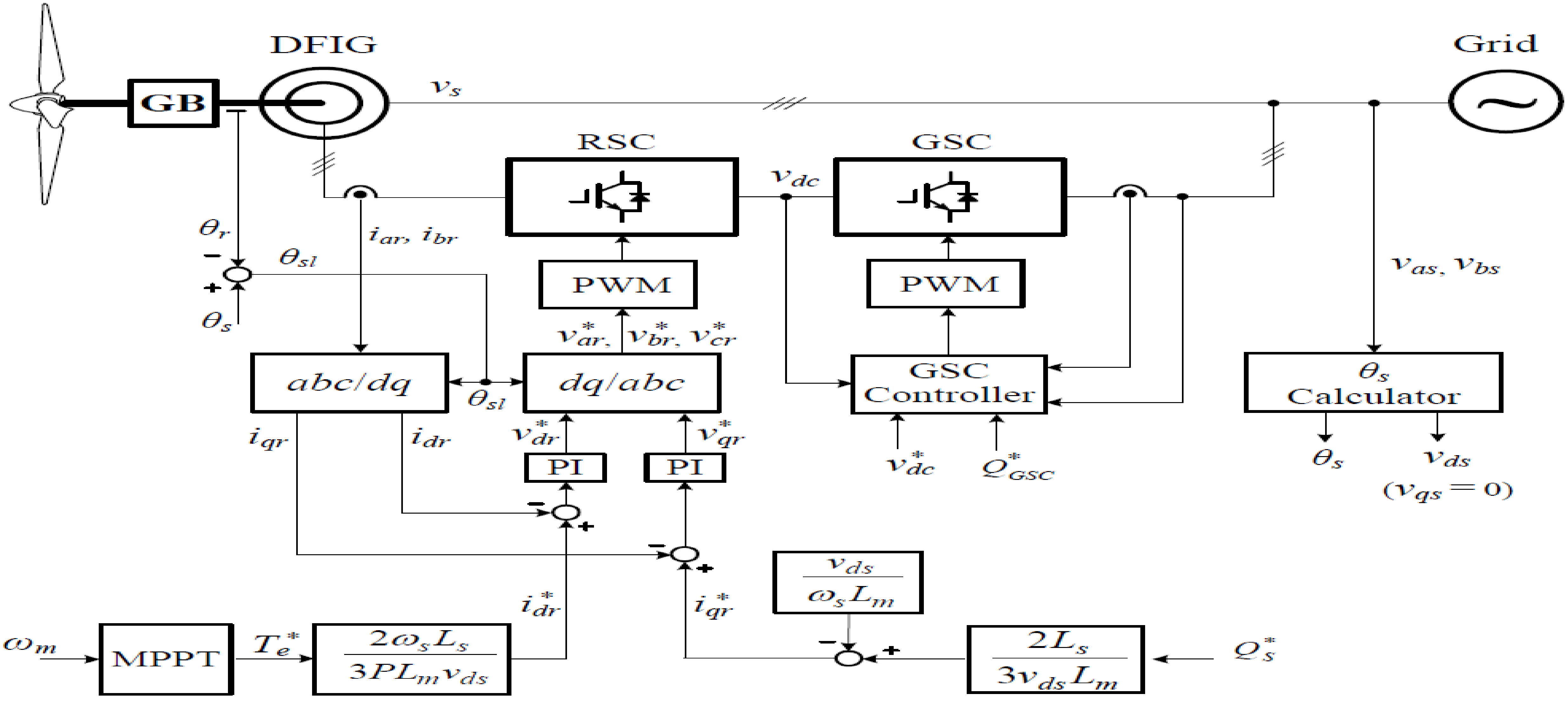
$$
\begin{cases}
i_{dr} = -\dfrac{2L_s}{3v_{ds}L_m}P_s & \text{(a)} \\
i_{qr} = \dfrac{2L_s}{3v_{ds}L_m}Q_s - \dfrac{v_{ds}}{\omega_s L_m} & \text{(b)}
\end{cases}
$$

Equations indicate that for a given stator voltage, stator active power *Ps* & reactive power *Qs* can be controlled by *dq*-axis rotor currents.

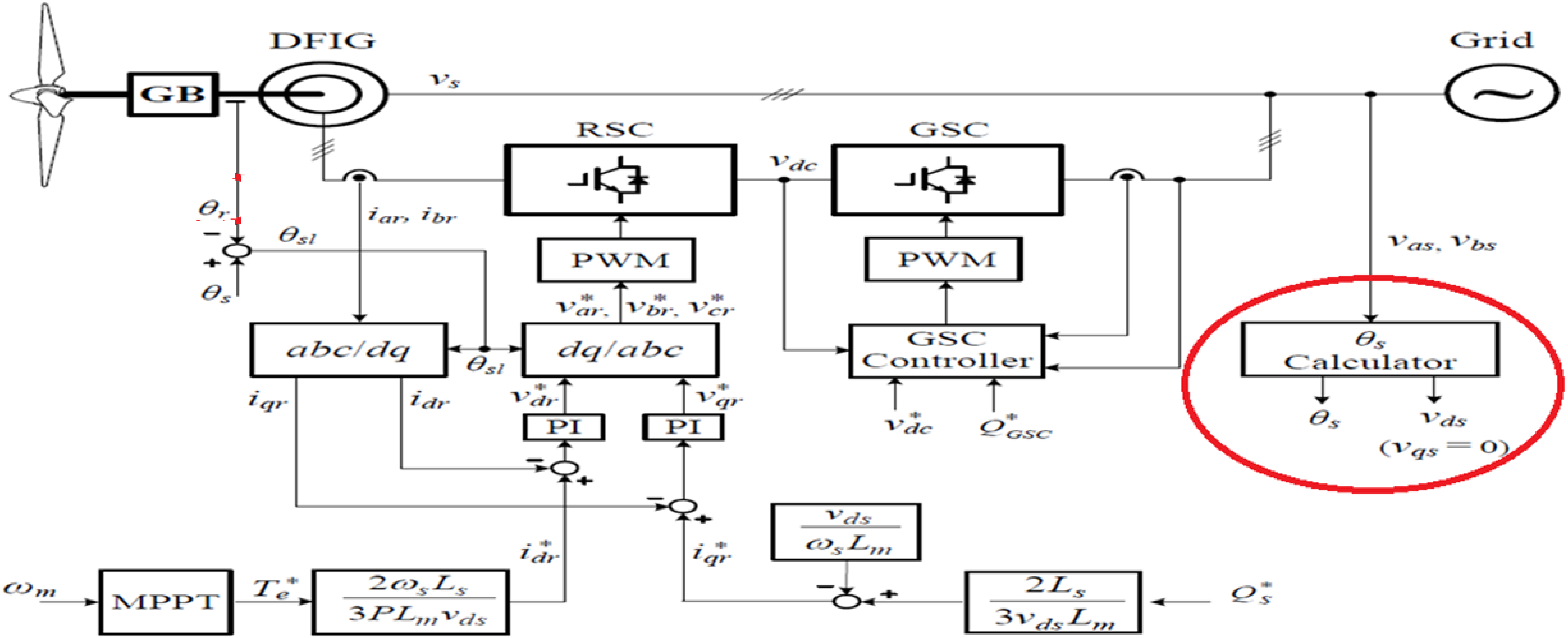
$$\begin{cases} i_{dr} = -\dfrac{2L_s}{3v_{ds}L_m}P_s \\ i_{qr} = \dfrac{2L_s}{3v_{ds}L_m}Q_s - \dfrac{v_{ds}}{\omega_s L_m} \end{cases}$$

8.5.2 System Block Diagram

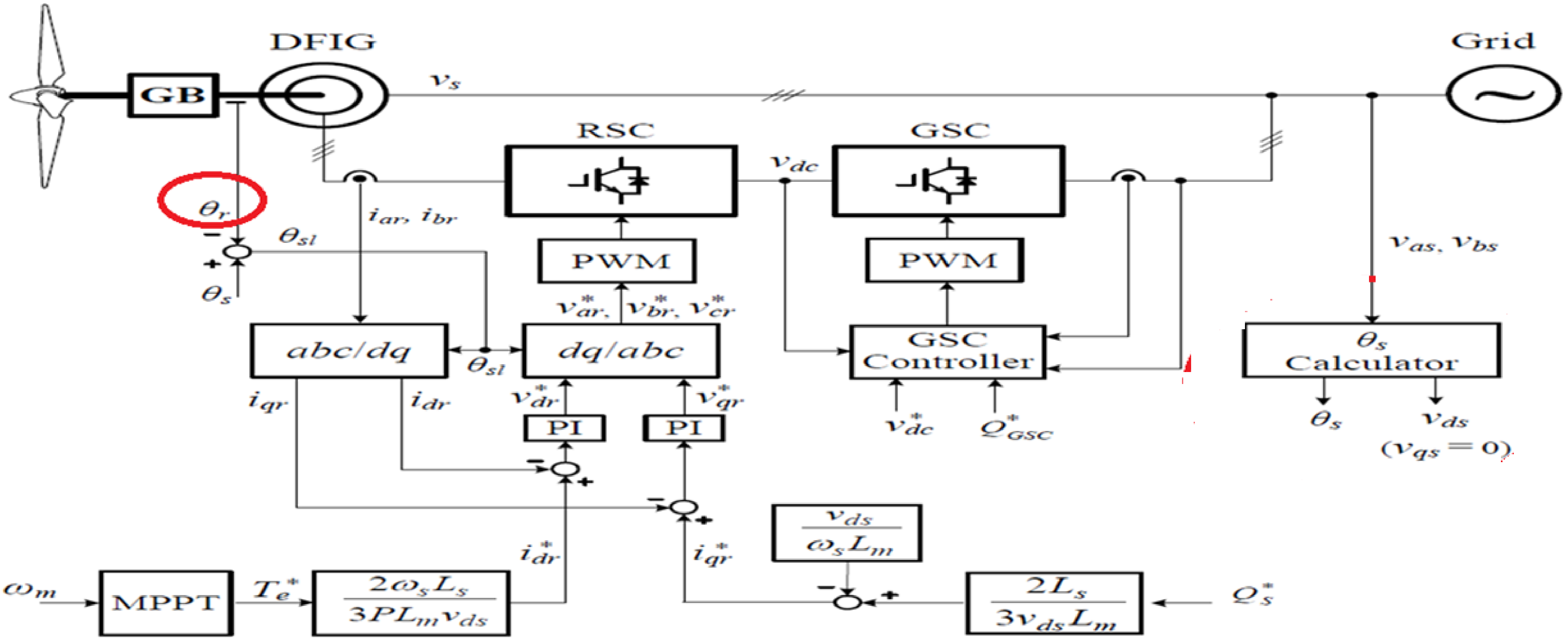
Fig. shows block diagram of DFIG wind energy system with stator voltage oriented control.



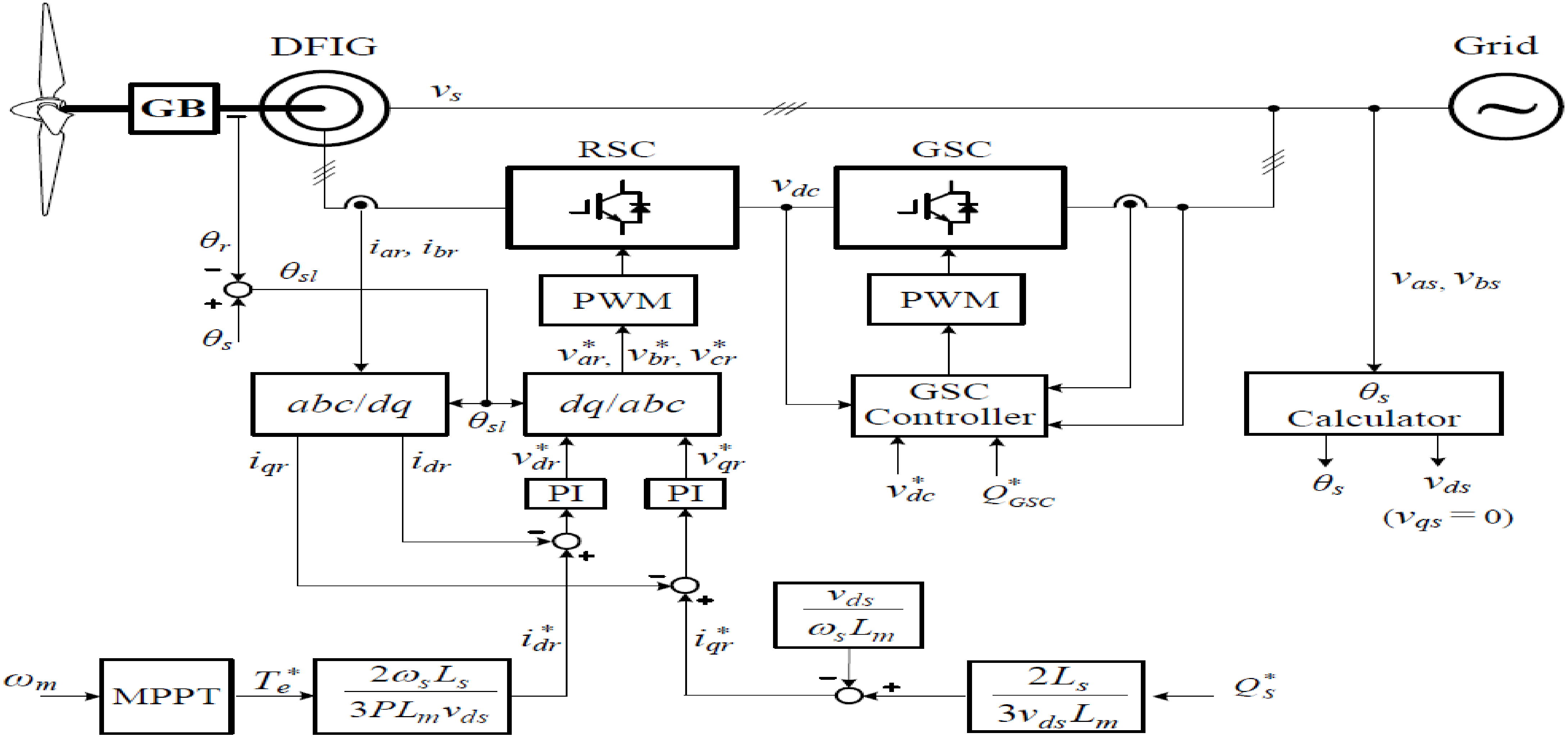
Stator voltage vector angle ϑs is identified by ϑs calculator



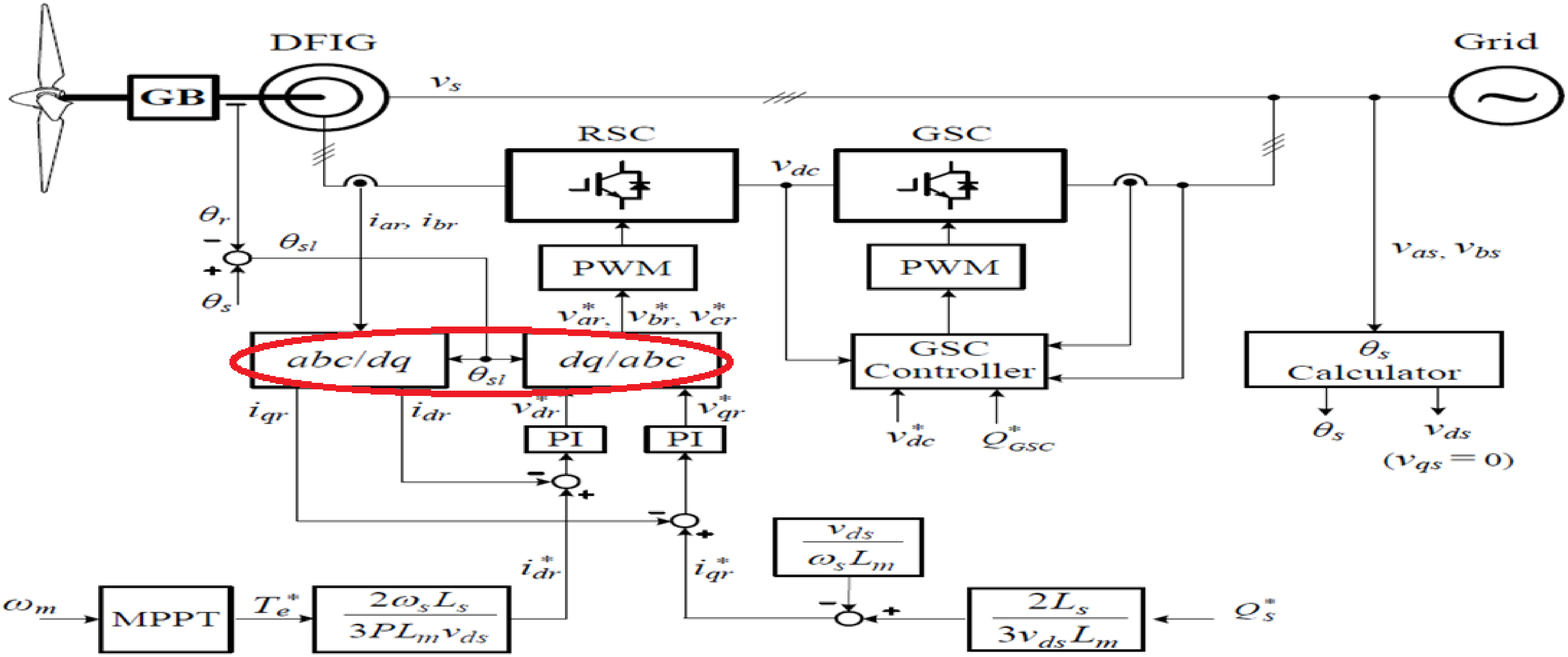
Rotor position angle ϑr is measured by an encoder mounted on shaft of generator.



Slip angle for reference frame transformation is obtained by $\vartheta sl = \vartheta s - \vartheta r$.

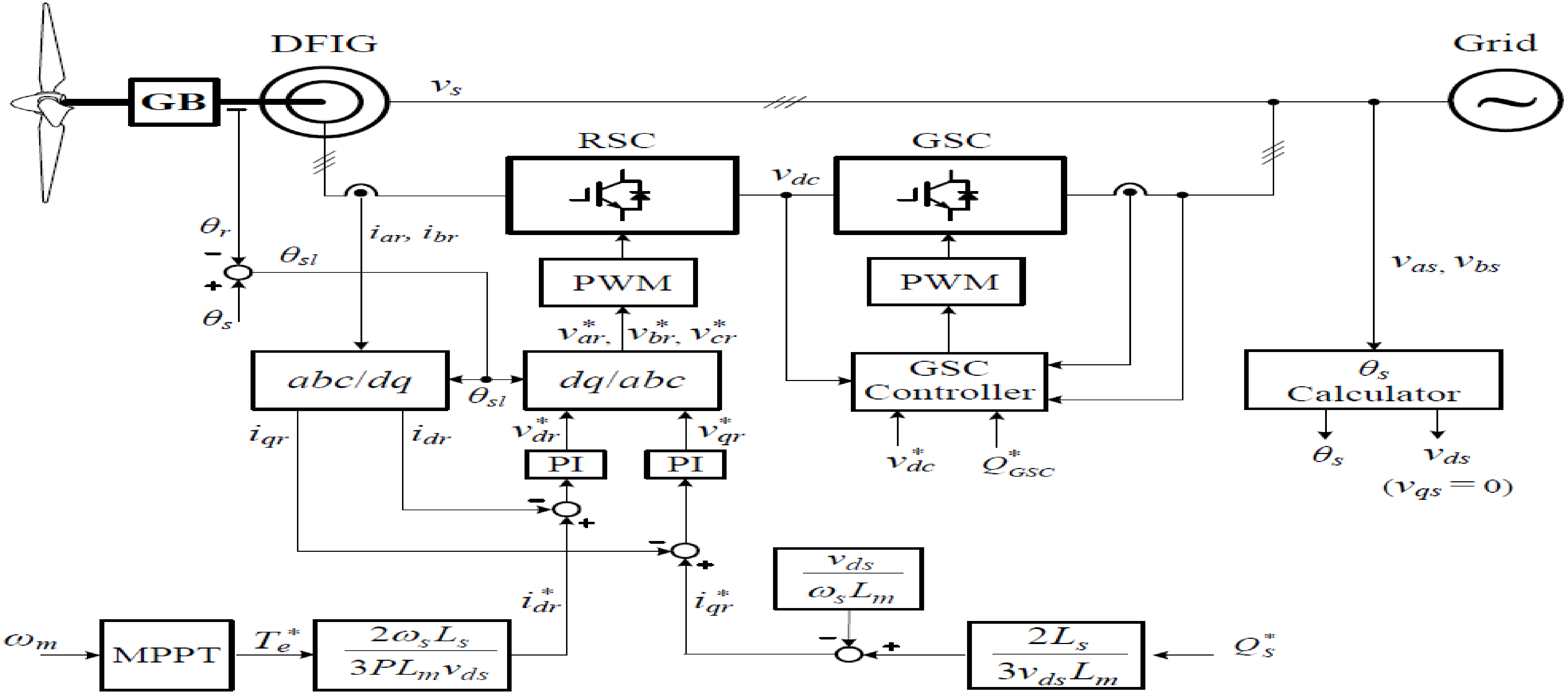


abc/dq & *dq/abc* transformation blocks transform variables in *abc* stationary reference frame to *dq* synchronous reference frame, & vice versa,



Angle of stator voltage vector (ϑs)can be obtained by

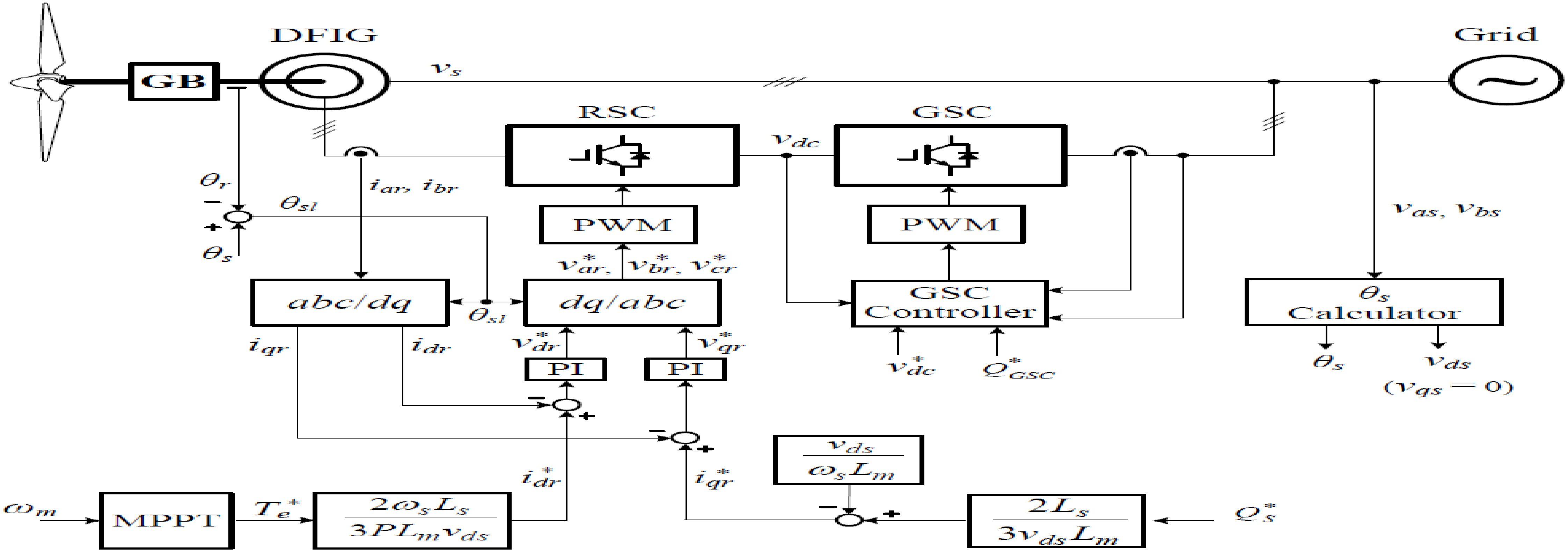
$$\theta_s = \tan^{-1}\frac{v_\beta}{v_\alpha}$$



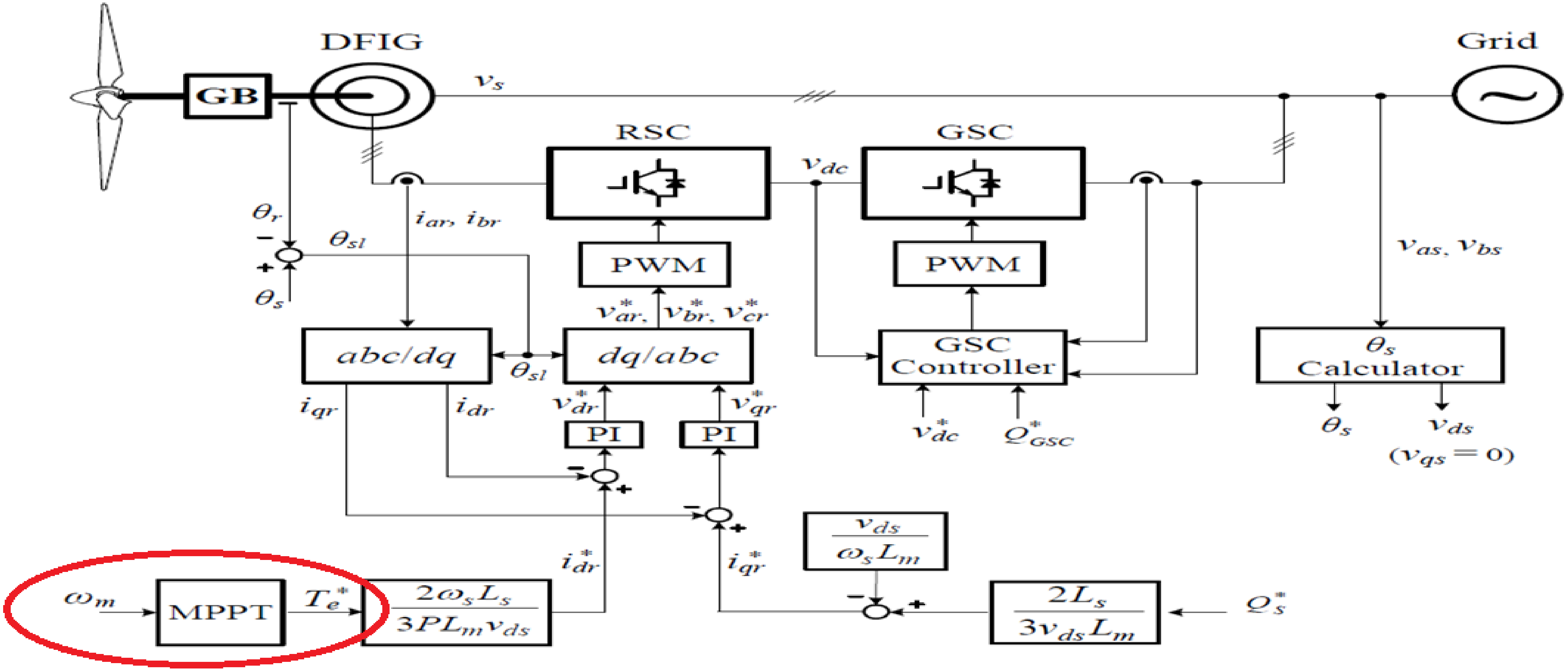
dq-axis stator voltages are give

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix}$$

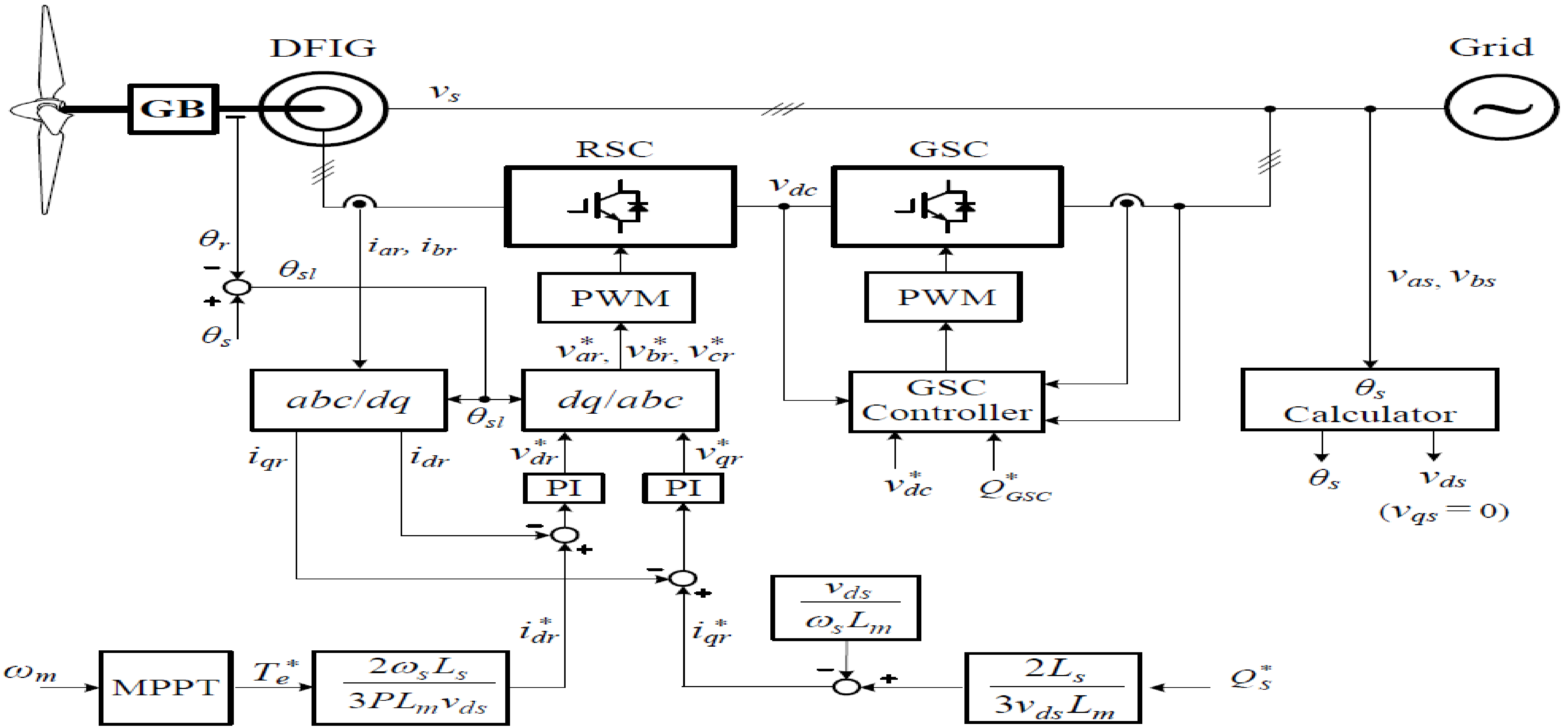
where *vas*, *vbs*, and *vcs* are measured 3-phase stator voltages.



MPPT block generates reference torque T_e^* based on optimal torque method for maximum power point tracking

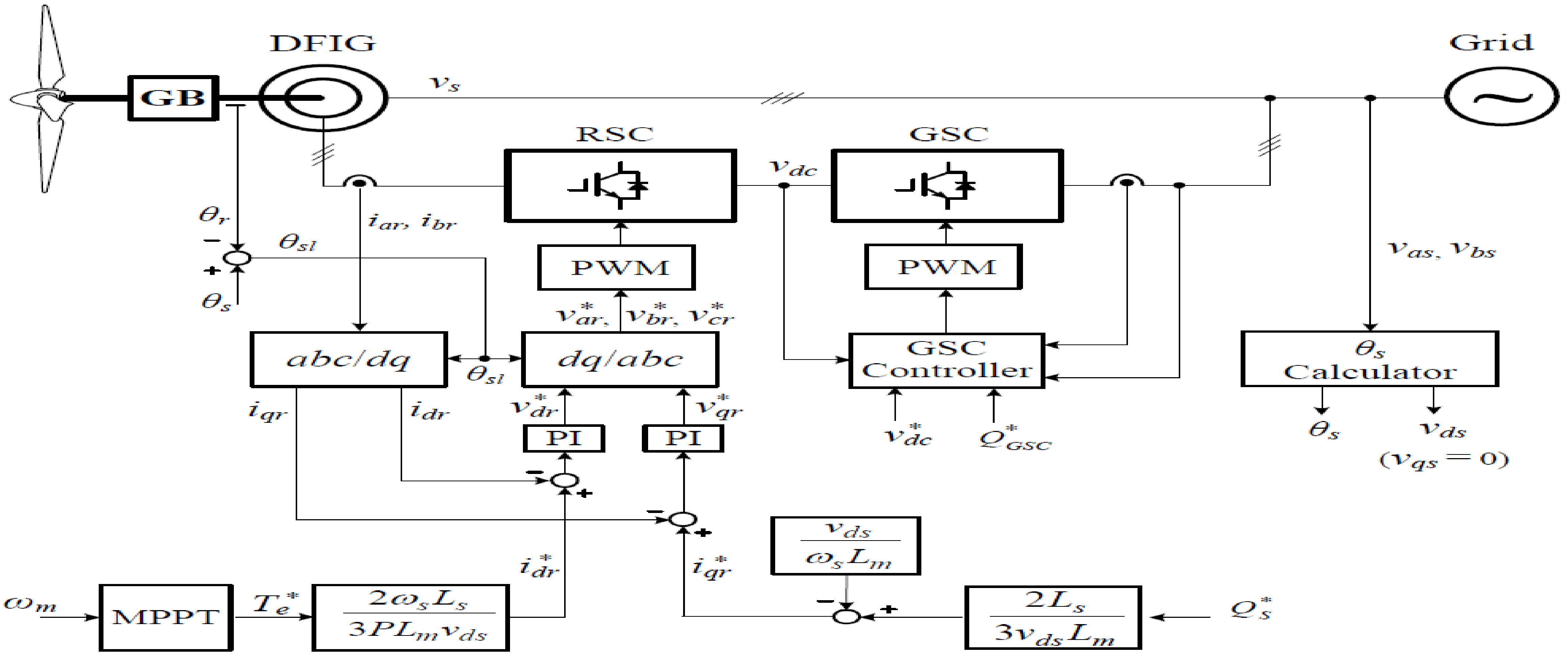


Reference for d-axis rotor current i_{dr}^*, which is torque producing component of rotor current, is calculated b $T_e = -\frac{3PL_m}{2\omega_s L_s} i_{dr} v_{ds}$

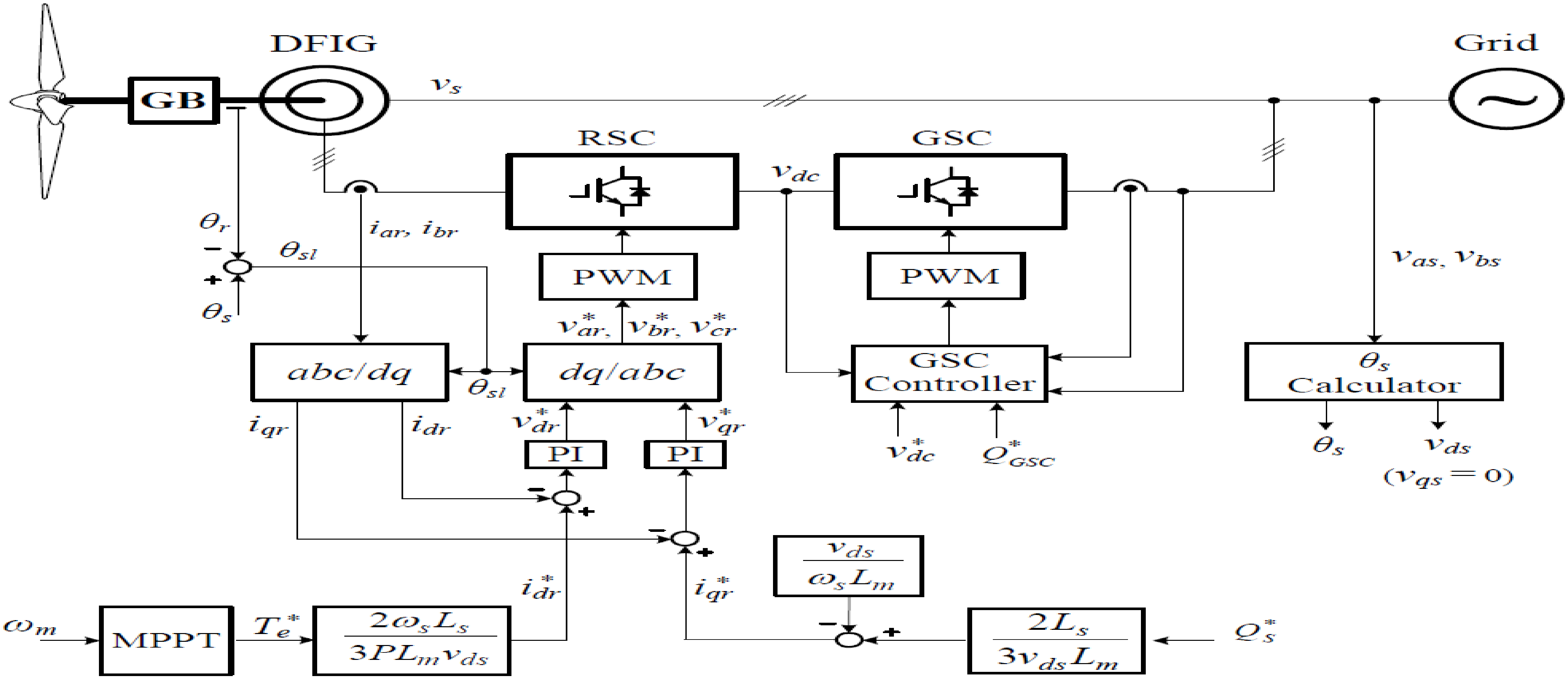


For given stator reactive power reference Q_s^*, q-axis rotor current reference i_{qr}^* is calculated by

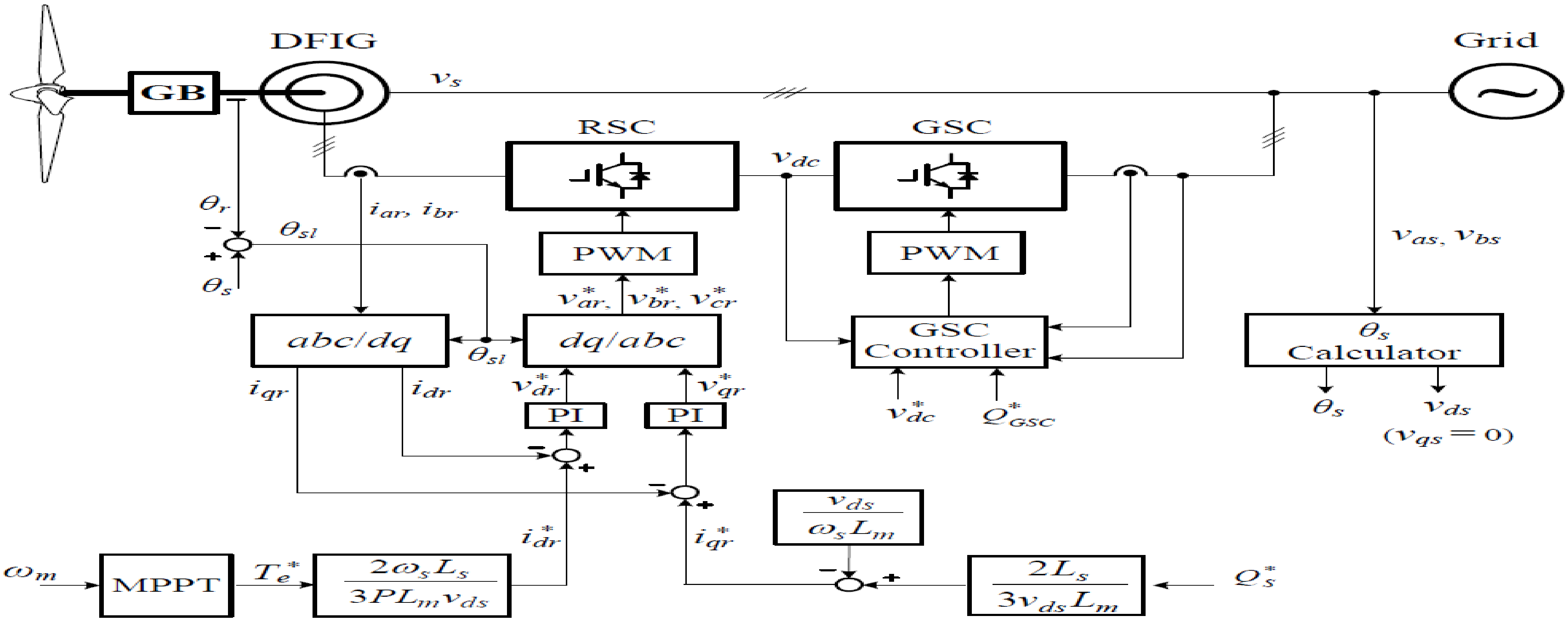
$$i_{qr} = \frac{2L_s}{3v_{ds}L_m}Q_s - \frac{v_{ds}}{\omega_s L_m}$$



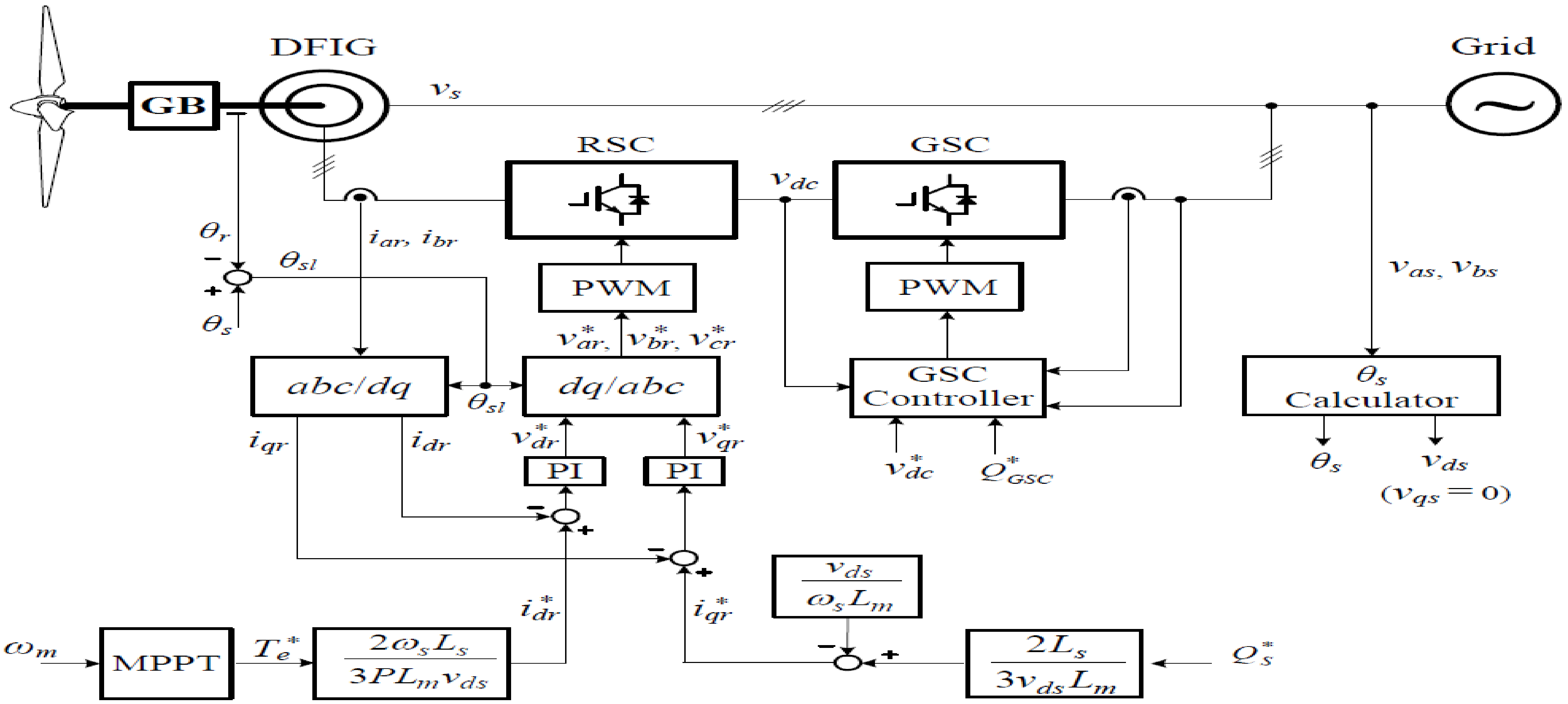
Reference *dq*-axis currents i_{dr}^* and i_{qr}^*, are then compared to measured values, i_{dr} and i_{qr} & errors passed through PI controllers.



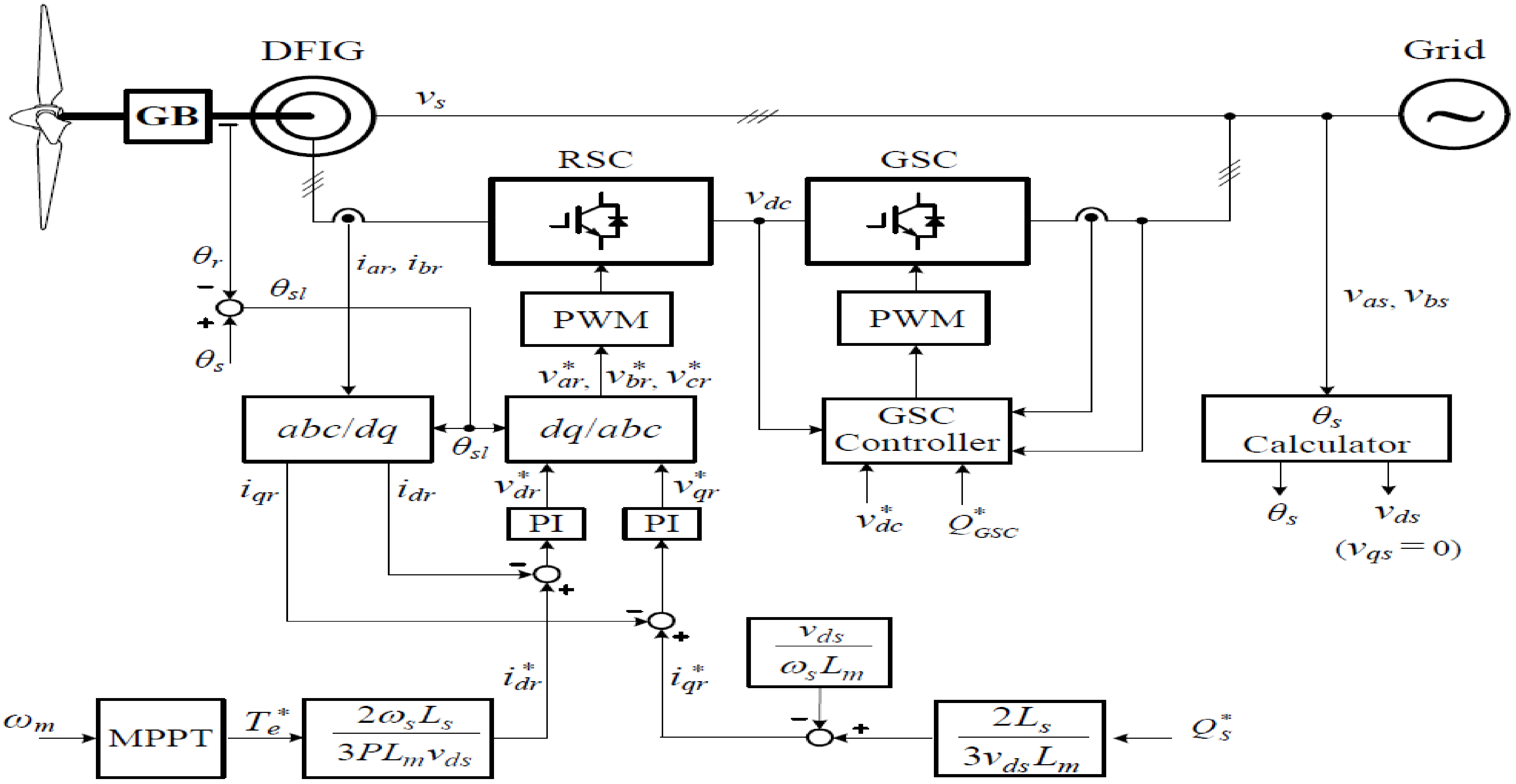
Output of PI controllers, v_{dr}^* and v_{qr}^*, are *dq*-axis rotor voltage references in synchronous frame, which are transformed into a 3-phase reference for rotor voltages, v_{ar}^*, v_{br}^* and v_{cr}^*, in stationary frame



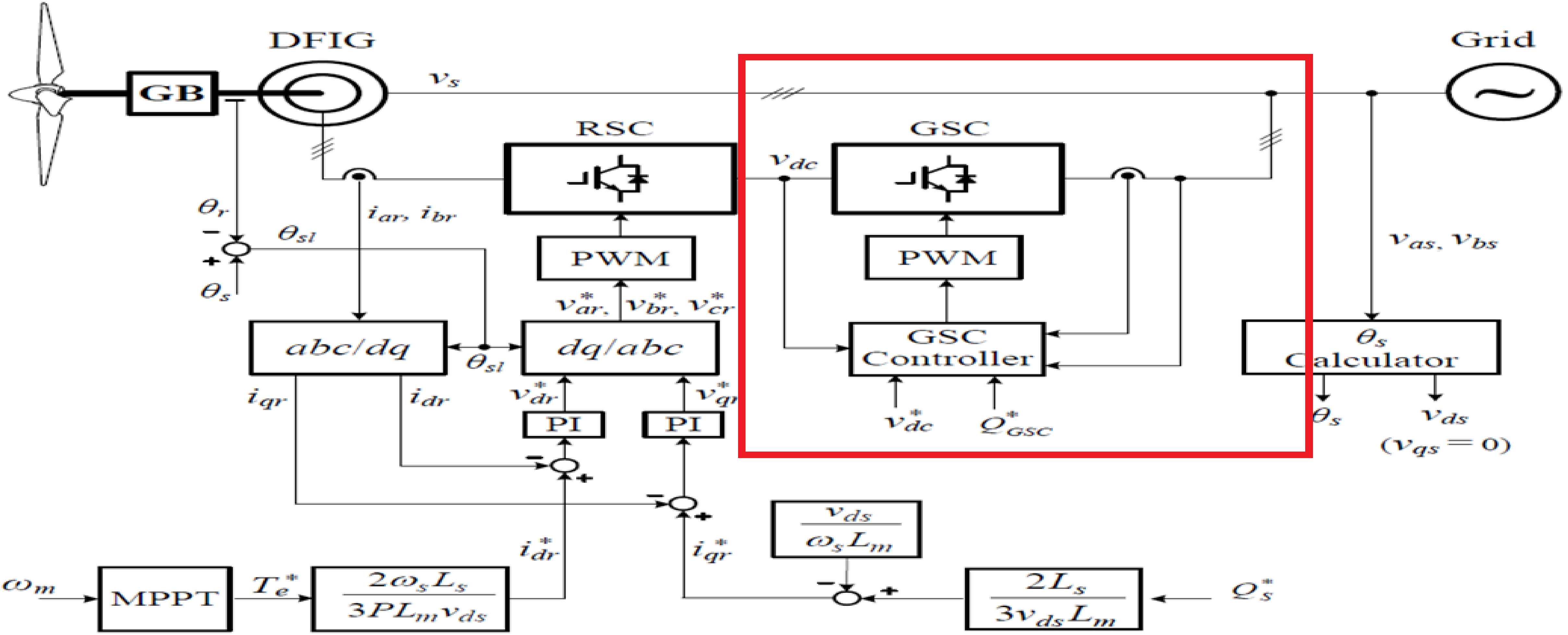
Rotor reference voltages v_{ar}^*, v_{br}^* and v_{cr}^* can serve as 3-phase modulating waveforms in carrier based modulation schemes or be converted into a reference space vector for Space Vector Modulation (SVM).



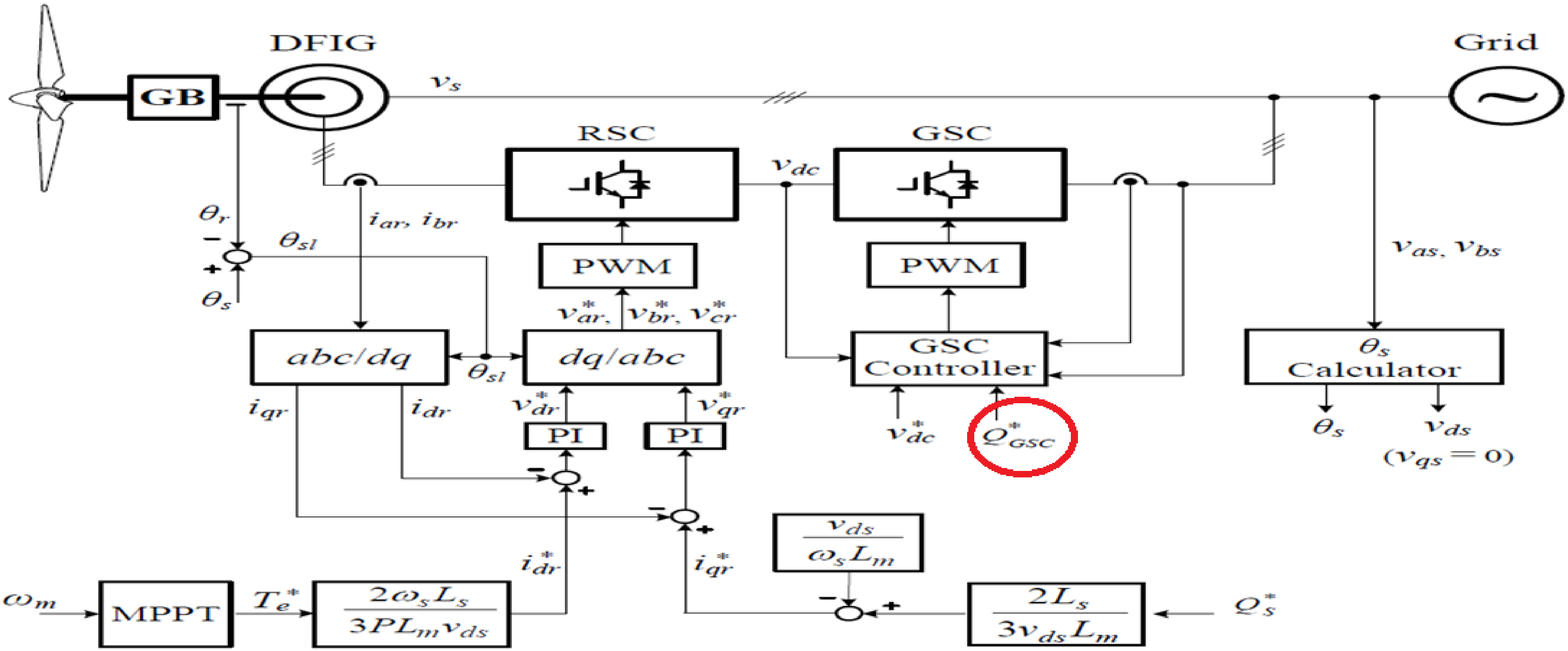
PWM block generates gating signals for rotor-side converter.



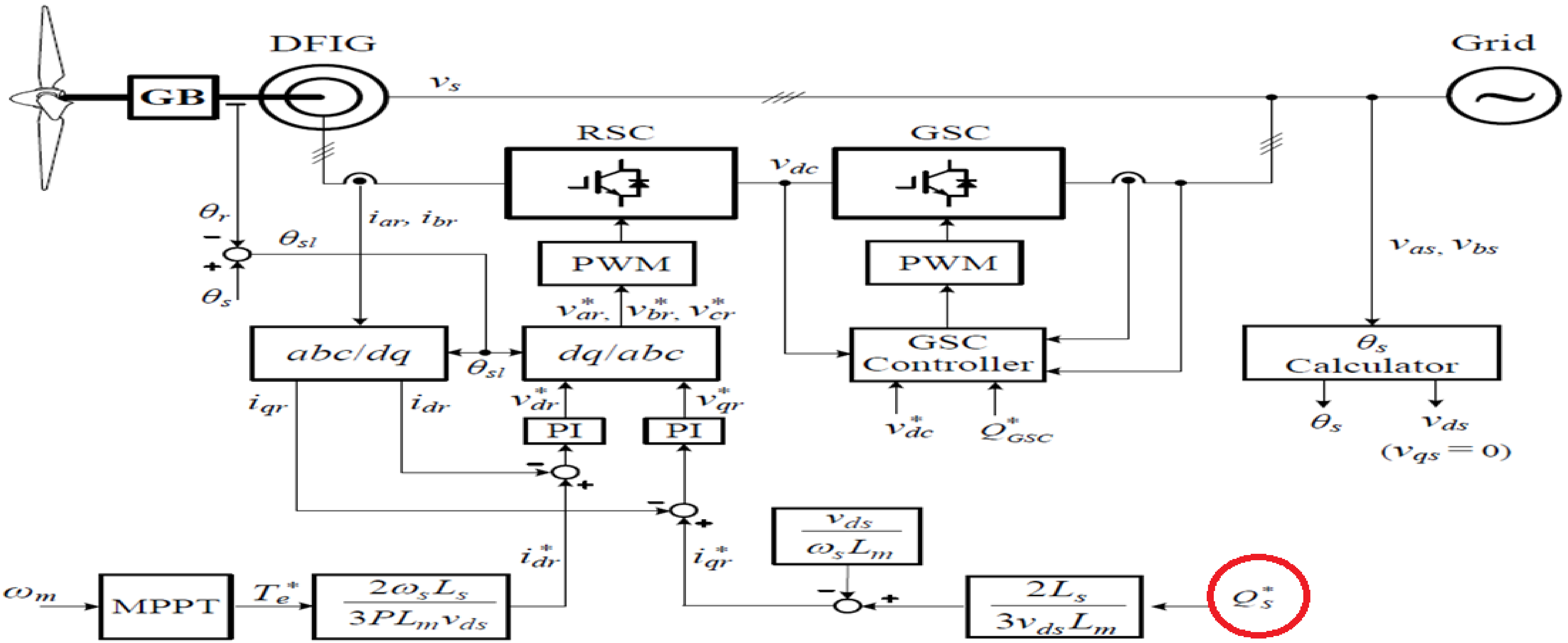
Grid-side converter performs 2 main functions: 1) keeps dc link voltage v_{dc} constant 2) provides reactive power to grid when required.



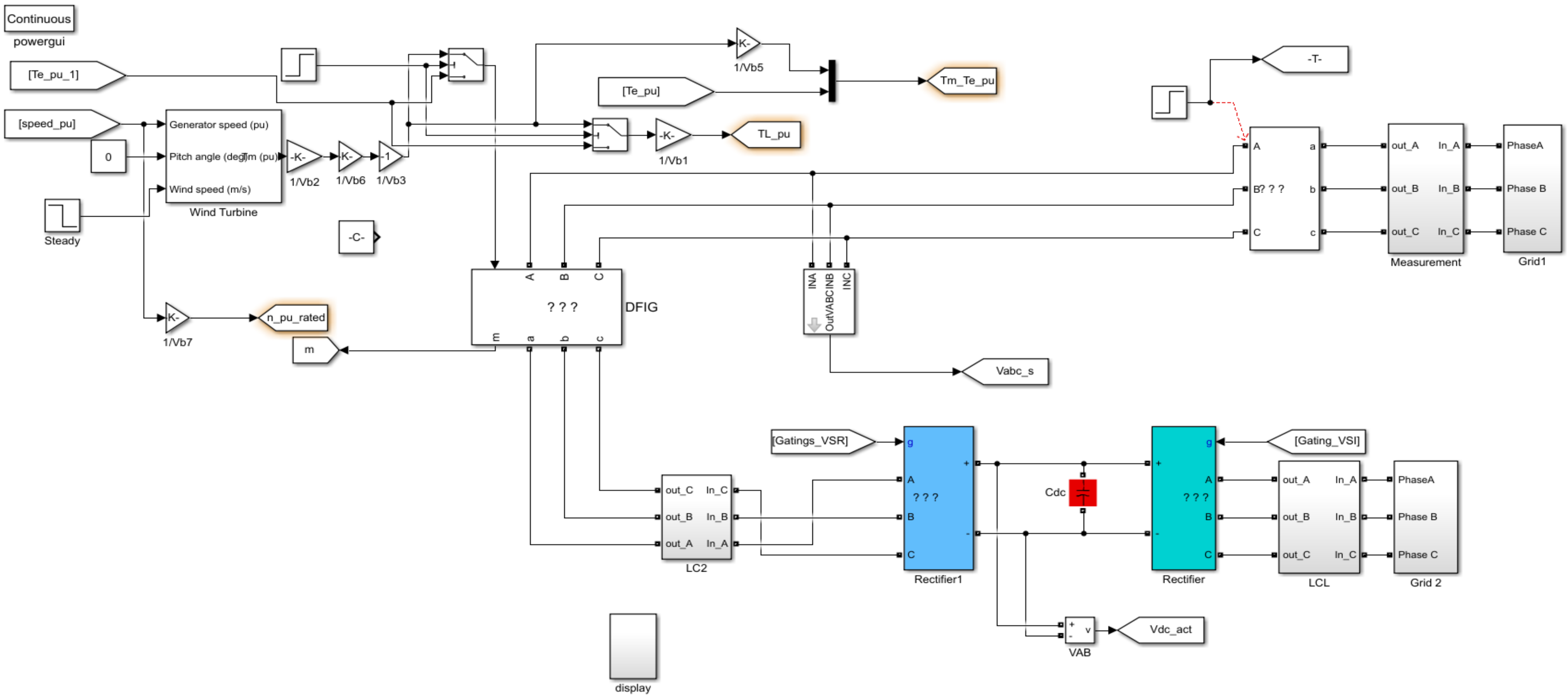
Reactive power reference Q^*_{GSC}, can be set to 0, for unity power factor operation of converter.



Overall power factor of DFIG wind energy system is then controlled by rotor-side converter through its reference Q_s^*



Simulation model for Mini-Project#04



8-22 (Solved Problem) A 6.0MW/4000V/50Hz/1170rpm DFIG wind energy system operates with stator voltage oriented control (SVOC). The parameters of the generator are given in Table B-8 of Appendix B. Generator operates with an MPPT scheme and its stator power factor is 0.95 leading. At a wind speed of 9.23 m/s, the generator operates at 0.7692 pu rotor speed. The stator voltage *Vs* is kept at its rated value of 4000 / 3 by the stator voltage oriented controller. The corresponding equivalent resistance *Req* and reactance *Xeq* for the rotor side converter are found to be –0.29334Ω & –0.27413 Ω , respectively. Calculate the following:

a) generator mechanical torque and power,

b) rms stator and rotor currents,

c) the *dq*-axis stator and rotor voltages,

d) the *dq*-axis stator and rotor currents,

e) The *dq*-axis stator flux linkages and electromagnetic torque of DFIG, and

f) The stator active and reactive powers.

Solution:

a) Rotor mechanical & electrical speeds:

$$\omega_m = \omega_{m,R} \times \omega_{m,\mathrm{pu}} = 1170(2\pi)/60 \times 0.7692 = 94.25 \text{ rad/sec} \quad (900 \text{ rpm})$$

$$\omega_r = \omega_m \times P = 94.25 \times 3 = 282.75 \text{ rad/sec}$$

Slip can be calculated by:

$$s = (\omega_s - \omega_r) / \omega_s = (314.16 - 282.75) / 314.16 = 0.1$$

Generator mechanical torque at 0.7692pu rotor speed:

$$T_m = T_{m,R} \times (\omega_{m,\mathrm{pu}})^2 = -48971 \times \left(0.7692\right)^2 = -28977\ \mathrm{N.m}$$

Rated mechanical power:

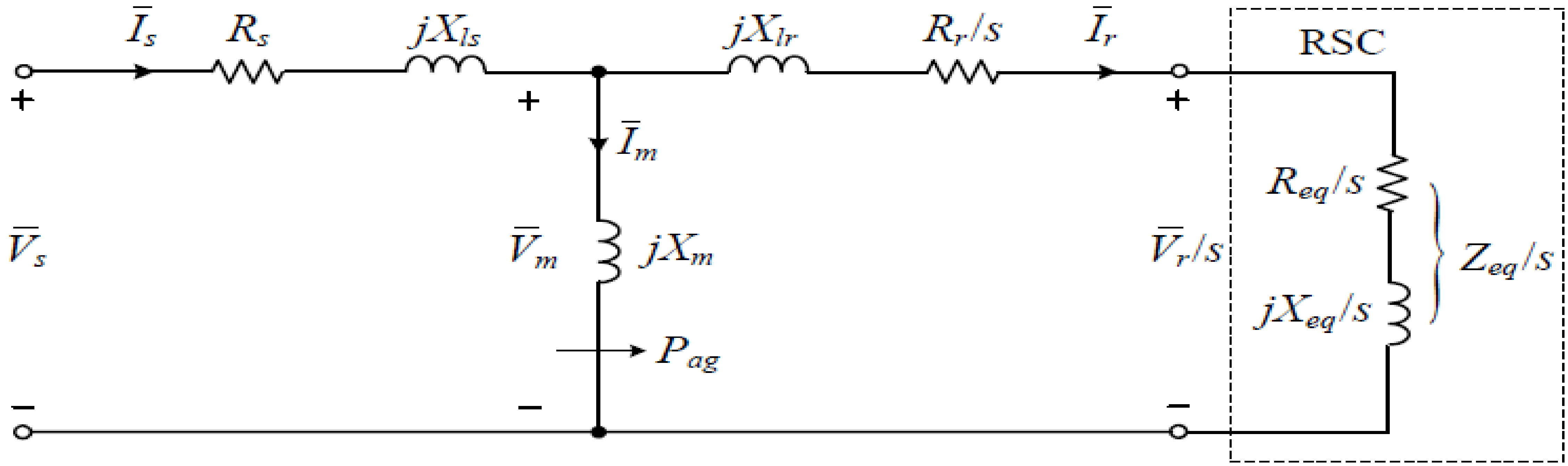
$$P_{m,R} = \omega_{m,R} \times T_{m,R} = 1170(2\pi)/60 \times (-48971) = -6000 \times 10^3 \text{ W}$$

Generator mechanical power at 0.7692pu rotor speed:

$$P_m = P_{m,R} \times (\omega_{m,\text{pu}})^3 = -6000 \times 10^3 \times (0.7692)^3 = -2731 \times 10^3 \text{ W}$$

b) Selecting stator voltage as a reference phasor, stator voltage is: $V_s = 4000/\ 3\angle 0° = 2309.4\angle 0°$ V (rms)

Equivalent impedance of DFIG based on Fig.



$$\bar{Z}_s = R_s + jX_{ls} + jX_m // (\frac{R_r}{s} + jX_{lr} + \frac{R_{eq}}{s} + j\frac{X_{eq}}{s}) = 5.009\angle -161.8^\circ\ \Omega \quad \text{for } s = 0.1$$

Stator current can be calculated by

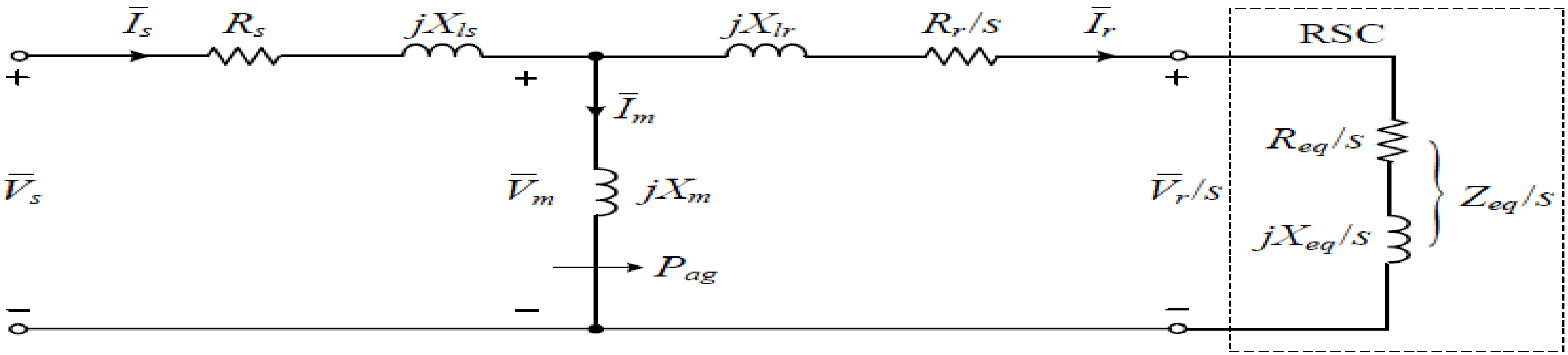
$$\bar{I}_s = \frac{\bar{V}_s}{\bar{Z}_s} = \frac{4000/\sqrt{3}\angle 0°}{5.009\angle -161.8°} = 461.03\angle 161.8°\text{ A} = 461.03\angle -198.2°\text{ A (rms)}$$

Alternatively, the rms stator current using simplified expression:

$$I_s = \frac{|T_m|\omega_s / P}{3V_s \cos\varphi_s} = \frac{28977 \times 2\pi \times 50 / 3}{3 \times (4000/\sqrt{3}) \times 0.95} = 461.04 \text{ A (rms)}$$

Rotor current can be calculated by

$$\bar{I}_r = \frac{jX_m \bar{I}_s}{jX_m + \left(\frac{R_r}{s} + jX_{lr}\right) + \left(\frac{R_{eq}}{s} + j\frac{X_{eq}}{s}\right)} = 616.54\angle 135.7^\circ \text{ A (rms)}$$



c) The equivalent impedance for the rotor side converter:

$$\overline{Z}_{eq} = \overline{V}_r / \overline{I}_r = -0.29334 - j0.27413 = 0.4015\angle -136.94^\circ \ \Omega \ \text{(given)}$$

The rotor voltage:

$$\overline{V}_r = \overline{Z}_{eq} \times \overline{I}_r = 247.54\angle -1.22^\circ \ \text{V (rms)}$$

The *dq*-axis stator voltages can be given by

- $V_{ds} = V_s$ = 2309.4 V (rms)

  V_{qs} = 0 V (rms)

The dq-axis rotor voltages can be given by

$$V_{dr} = V_r \cos\angle V_r \;= 247.54 \times \cos(-1.22°) = -247.48 \;\text{ V (rms)}$$

$$V_{qr} = V_r \sin\angle V_r \;= 247.54 \times \sin(-1.22°) = -5.26 \;\text{ V (rms)}$$

d) The *dq*-axis stator currents can be given by

$$I_{ds} = I_s \cos\angle I_s \; = 461.04 \times \cos(-198.2°) = -438 \text{ A (rms)}$$

$$I_{qs} = I_s \sin\angle I_s \; = 461.04 \times \sin(-198.2°) = 143.96 \text{ A (rms)}$$

The *dq*-axis rotor currents can be given by

$$I_{dr} = I_r \cos\angle I_r = 616.54 \times \cos(135.7°) = -441.42 \text{ A (rms)}$$

$$I_{qr} = I_r \sin\angle I_r = 616.54 \times \sin(135.7°) = 430.43 \text{ A (rms)}$$

e) The *dq*-axis stator flux linkages can be calculated by

$$\Lambda_{ds} = \frac{V_{qs} - R_s I_{qs}}{\omega_s} = -0.0123 \ \ \text{Wb (rms)}$$

$$\Lambda_{qs} = -\frac{V_{ds} - R_s I_{ds}}{\omega_s} = -7.3885 \ \ \text{Wb (rms)}$$

The electromagnetic torque developed by the DFIG can be given by

$$T_e = -T_m = -\frac{3PL_m}{2\omega_s L_s} i_{dr} v_{ds} =$$

$$= -\frac{3 \times 3 \times 25.908 \times 10^{-3}}{2 \times 2 \times \pi \times 50 \times 26.139 \times 10^{-3}} (\sqrt{2} \times -441.42 \times \sqrt{2} \times 2309.4) = 28946 \text{ N.m}$$

f) The stator active and reactive power of the DFIG can be calculated by

$$P_s = \frac{3}{2} v_{ds} i_{ds} = \frac{3}{2} \times \sqrt{2} \times 2309.4 \times \sqrt{2} \times -438 = -3034.5 \times 10^3 \text{ W}$$

$$Q_s = -\frac{3}{2} v_{ds} i_{qs} = -\frac{3}{2} \times \sqrt{2} \times 2309.4 \times \sqrt{2} \times 143.96 = -997.38 \times 10^3 \text{ VAR}$$

Alternatively, the stator active and reactive power can be calculated by

$$P_s = 3V_sI_s\cos\varphi_s = 3\times 2309.4\times 438\times\cos(198.2°) = -3034.5\times 10^3 \text{ W}$$

$$Q_s = 3V_sI_s\sin\varphi_s = 3\times 2309.4\times 438\times\sin(198.2°) = -997.38\times 10^3 \text{ VAR}$$

8-23 Repeat Problem 8-22 when the DFIG operates with 0.9188 pu rotor speed and stator power factor of 0.95 lagging. The corresponding equivalent resistance *Req* & reactance *Xeq* for the rotor side converter are found to be 0.24398Ω and 0.04478 Ω respectively.

Answers:

a) $T_m = -41341\ \text{N.m}$, $P_m = -4653.9\times10^3\ \text{W}$ b) $\bar{I}_s = 657.76\angle-161.8°\ \text{A (rms)}$, $\bar{I}_r = 636\angle172.9°\ \text{A (rms)}$

b) $V_{ds} = 2309.4\ \text{V (rms)}$, $V_{qs} = 0\ \text{V (rms)}$, $V_{dr} = -157.5\ \text{V (rms)}$, $V_{qr} = -9.09\ \text{V (rms)}$

c) $I_{ds} = -624.87\ \text{A (rms)}$, $I_{qs} = -205.39\ \text{A (rms)}$, $I_{dr} = -631.13\ \text{A (rms)}$, $I_{qr} = 78.58\ \text{A (rms)}$

d) $\Lambda_{ds} = 0.0176\ \text{Wb (rms)}$, $\Lambda_{qs} = -7.4045\ \text{Wb (rms)}$, $T_e = 41386\ \text{N.m}$

e) $P_s = -4329.2\times10^3\ \text{W}$, $Q_s = 1422.9\times10^3\ \text{VAR}$