Lecture#

4.7 Control of Grid-Connected Inverter

4.7.1 Voltage Oriented Control (VOC)

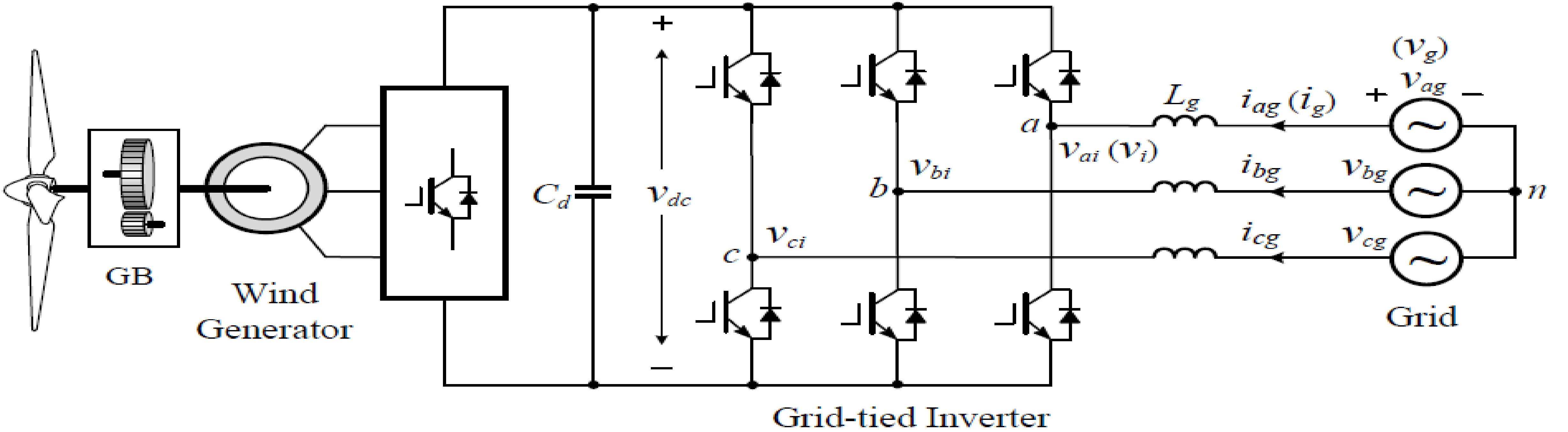
4.7.2 VOC with Decoupled Controller

4.7.3 Operation of Grid-Connected Inverter with VOC & Reactive Power Control

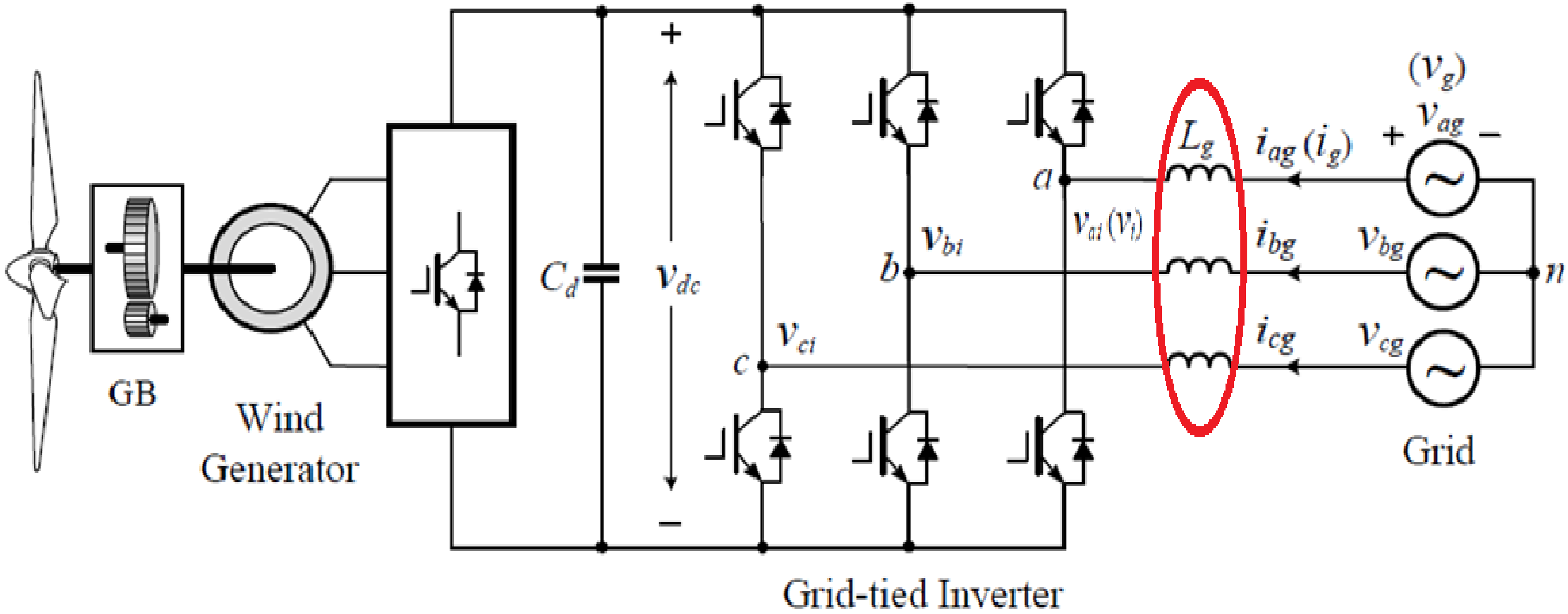
- Numericals:4-17 to 4-19

4.7 Control of Grid-Connected Inverter

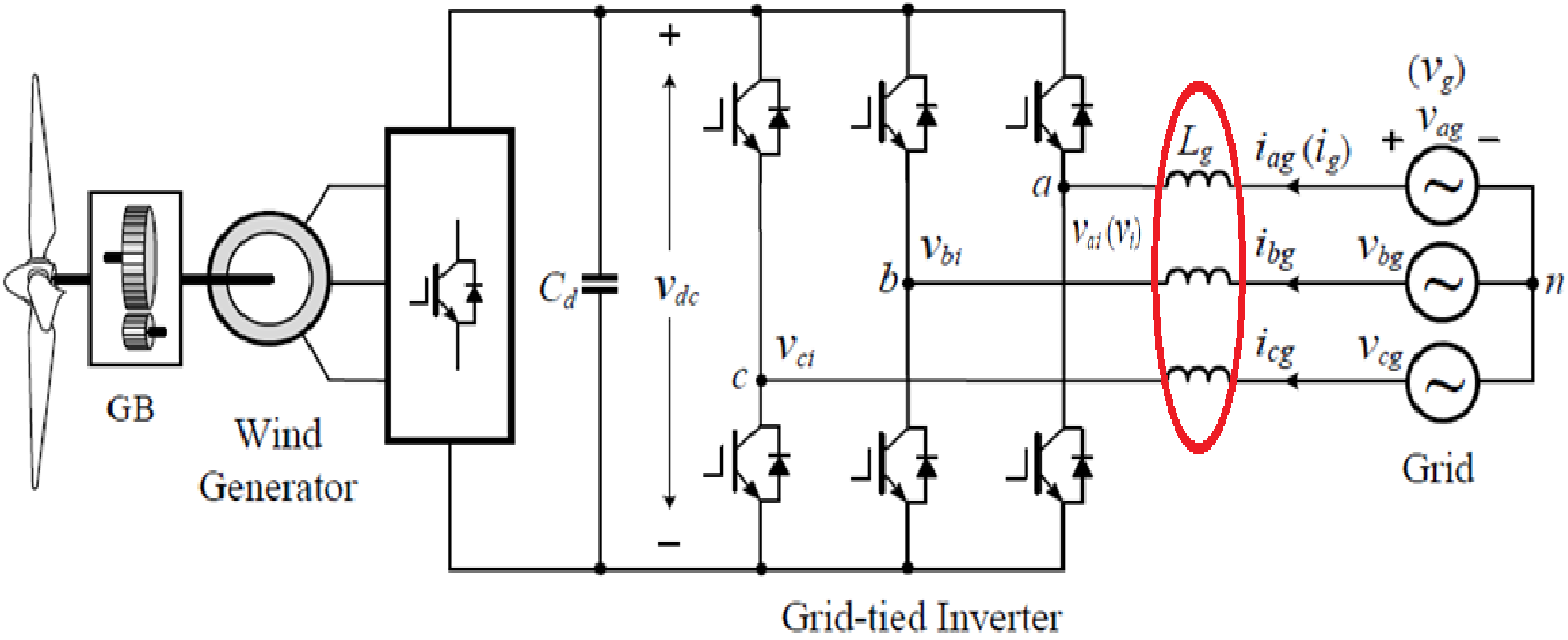
- Most commercial wind turbines deliver generated power to electric grid through power converters.
- A grid-connected (grid-tied) inverter for wind energy applications is shown where 2-level voltage source inverter is used.



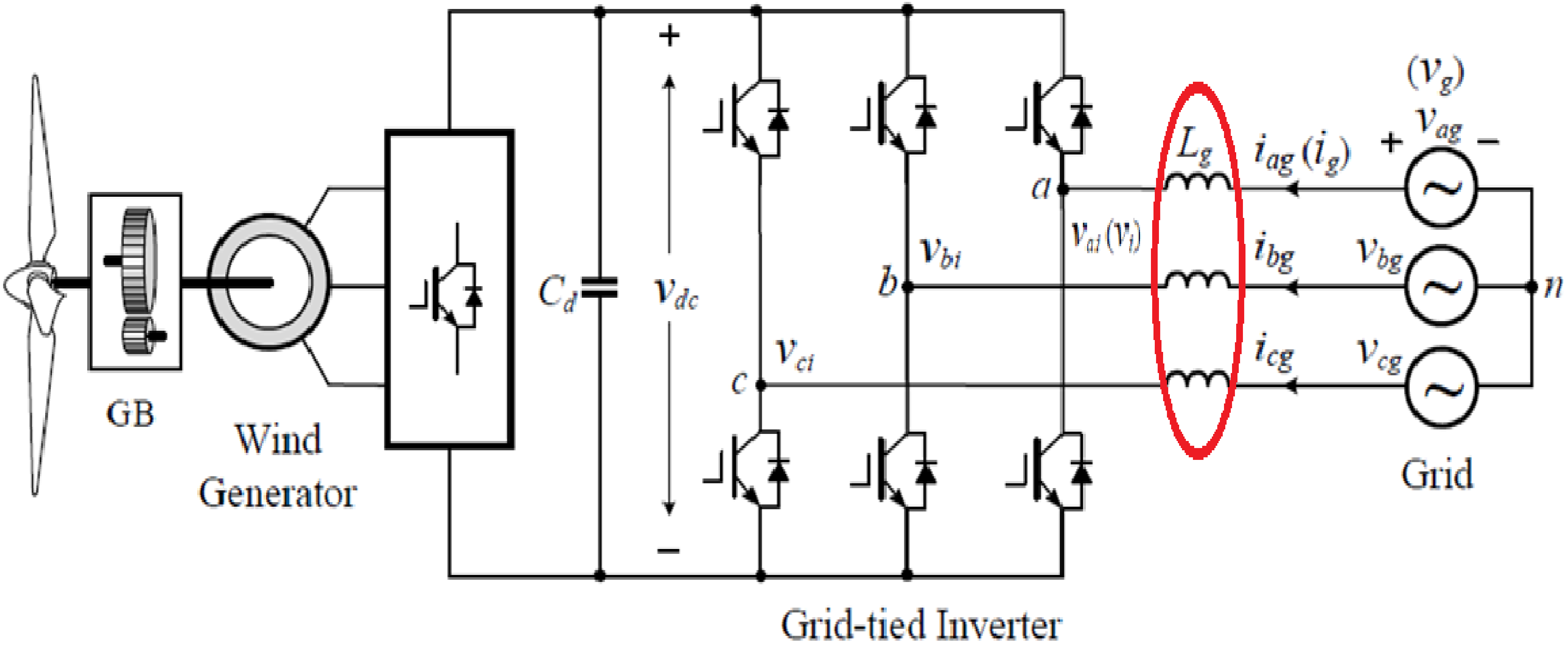
Between inverter & grid a transformer is connected. *Lg* represents leakage inductance of transformer.



Line reactor of 0.05-0.1 per unit, is normally added to system?



Line resistance is negligibly small & has little impact on system performance. It is, therefore, omitted in analysis.



Grid-tied inverter can be modulated by space vector modulation scheme.

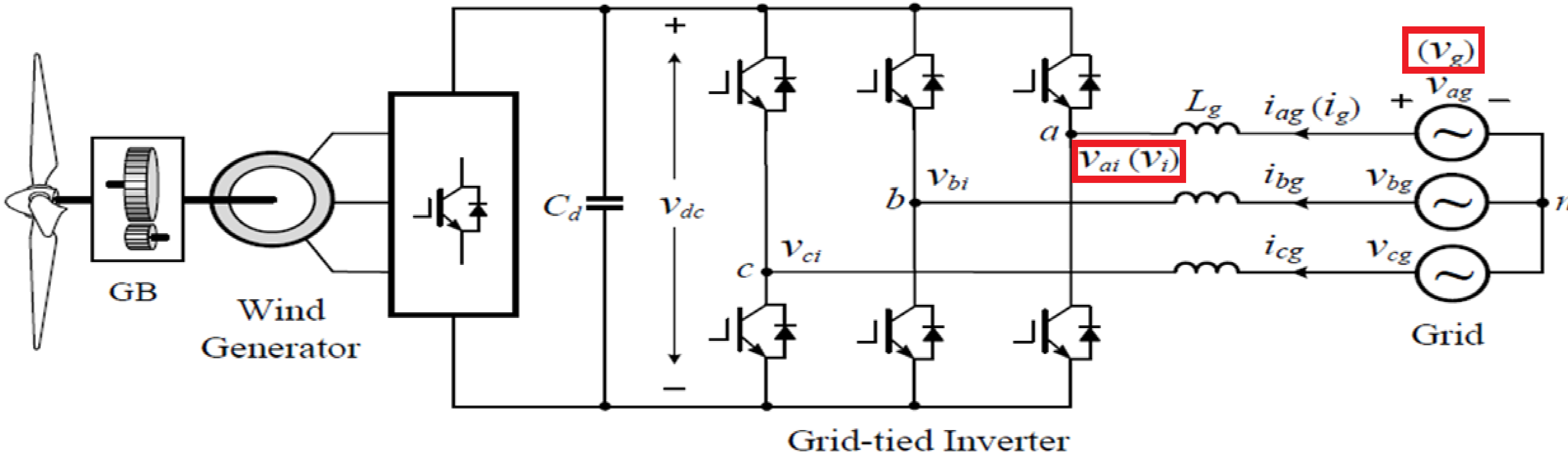
- Inverter is a boost converter by nature & its average dc voltage *Vdc* can be obtained from:

$$V_{dc} = \frac{\sqrt{6}\ V_{ai1}}{m_a} \qquad \text{for } 0 < m_a \leq 1$$

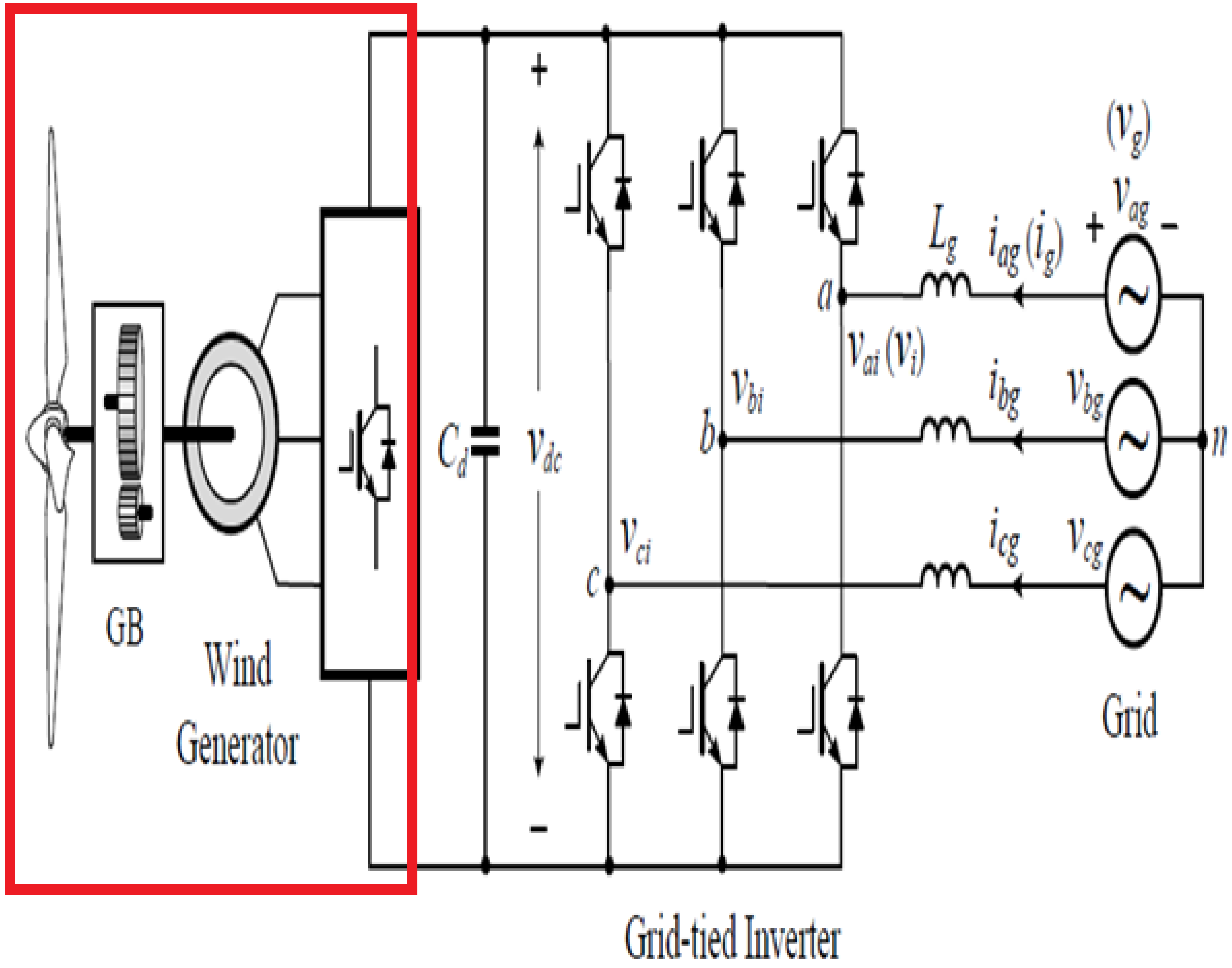
where *ma* is modulation index & *Vai*1 is rms value of fundamental-frequency component of inverter phase-*a* voltage, respectively.

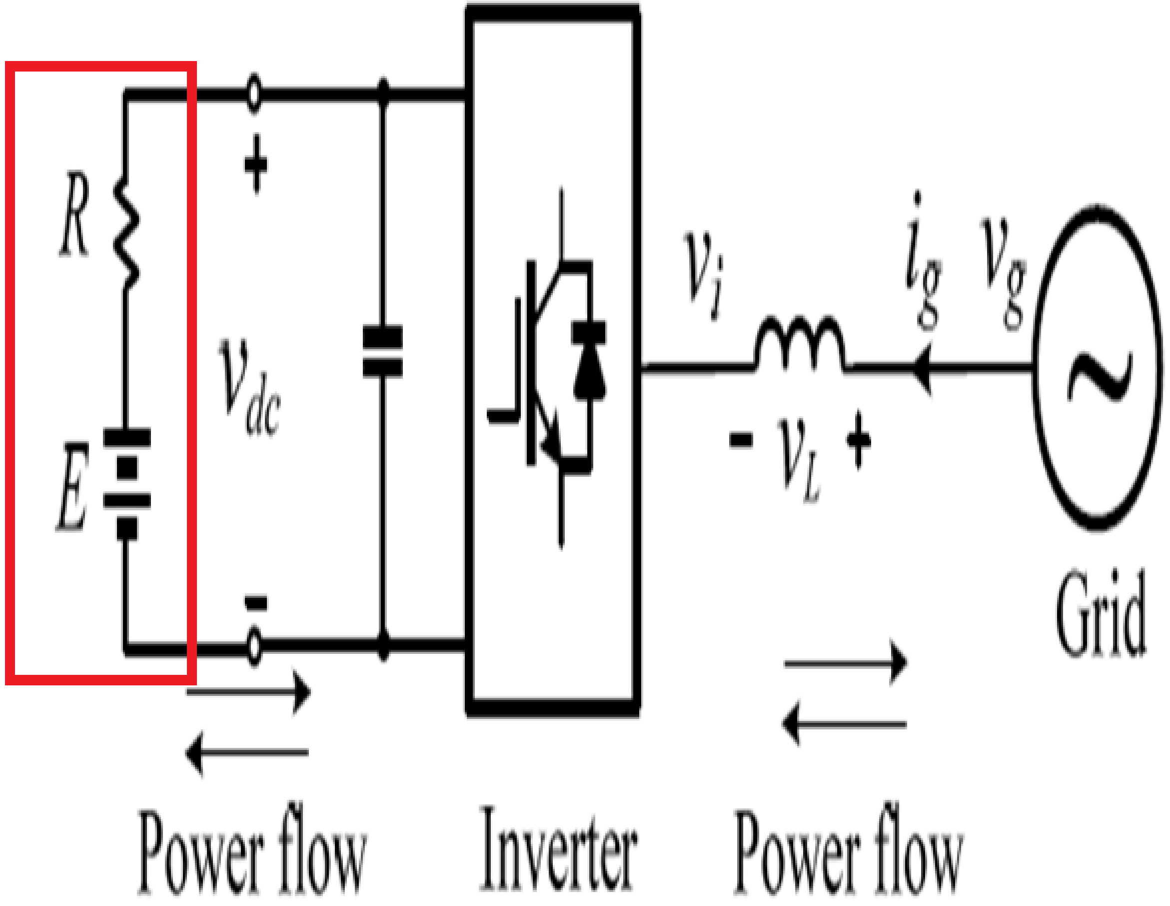
RMS value of fundamental-frequency component of inverter phase-*a* voltage V_{ai1}=rms value of grid phase voltage V_g(which can be considered constant) i.e. V_{ai1}= V_g=K so dc voltage can be boosted to a high value by a small m_a.

$$V_{dc} = \frac{\sqrt{6}\, V_{ai1}}{m_a} = \frac{K}{m_a} \qquad \text{for } 0 < m_a \le 1$$

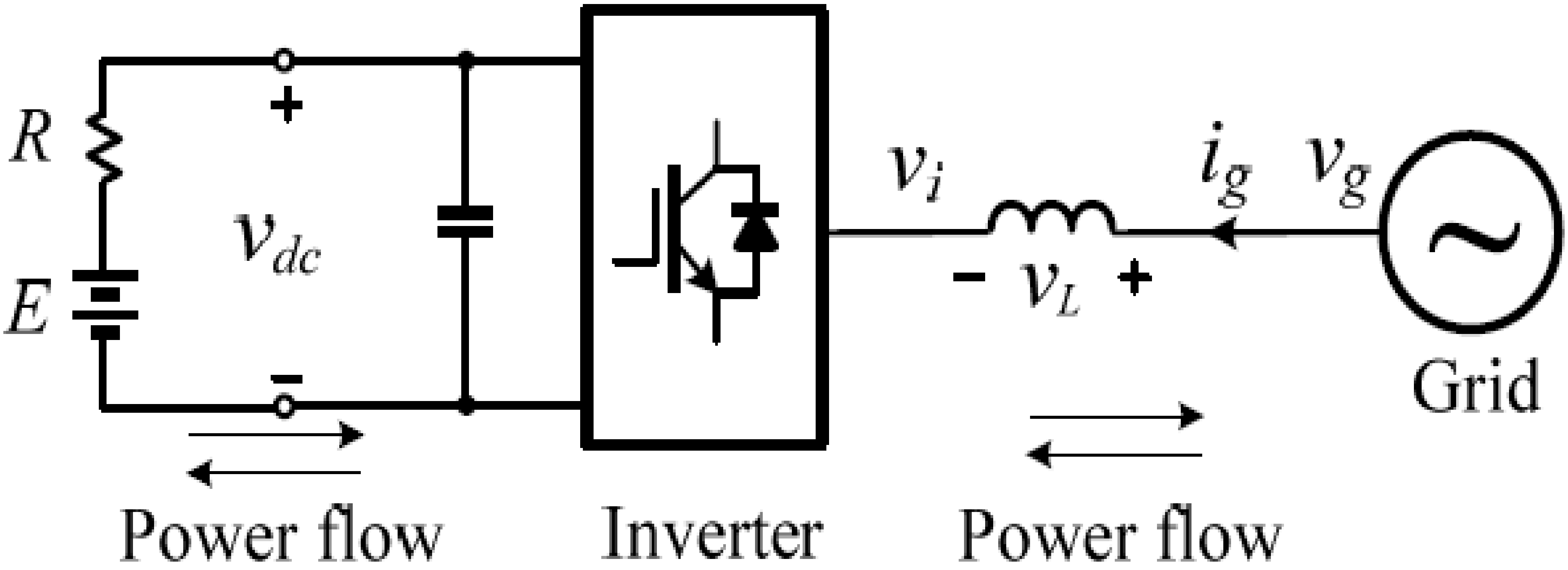


Wind turbine, generator & rectifier can be replaced by a battery in series with a small resistance that represents power losses in system.





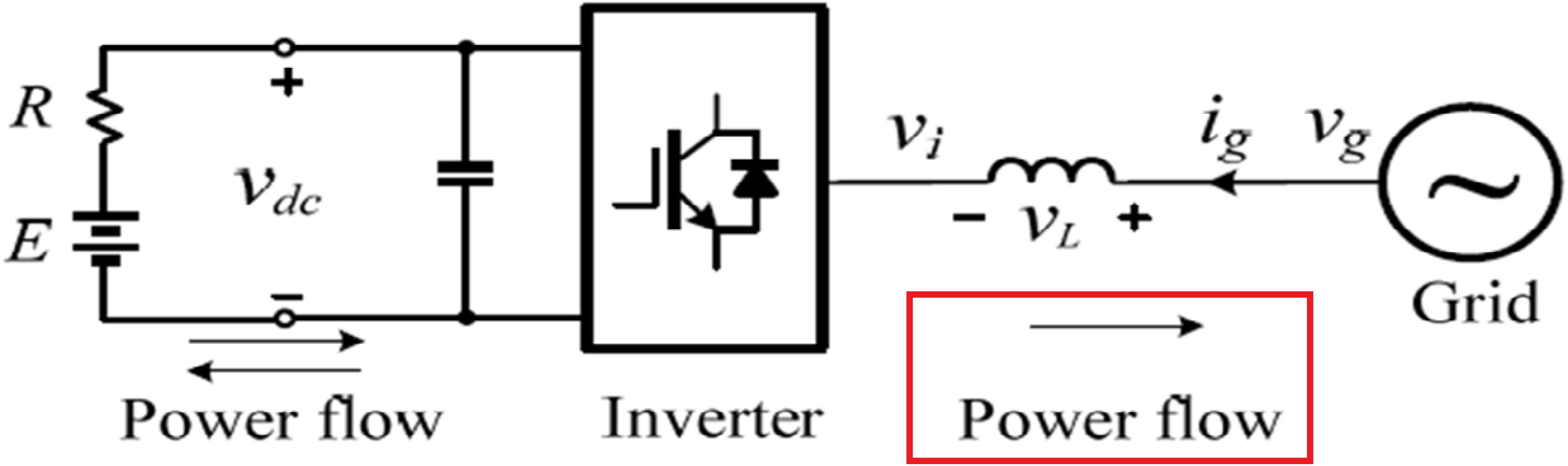
Power flow between inverter & grid is bi-directional. Power can be transferred from grid to dc circuit of inverter, or vice versa.



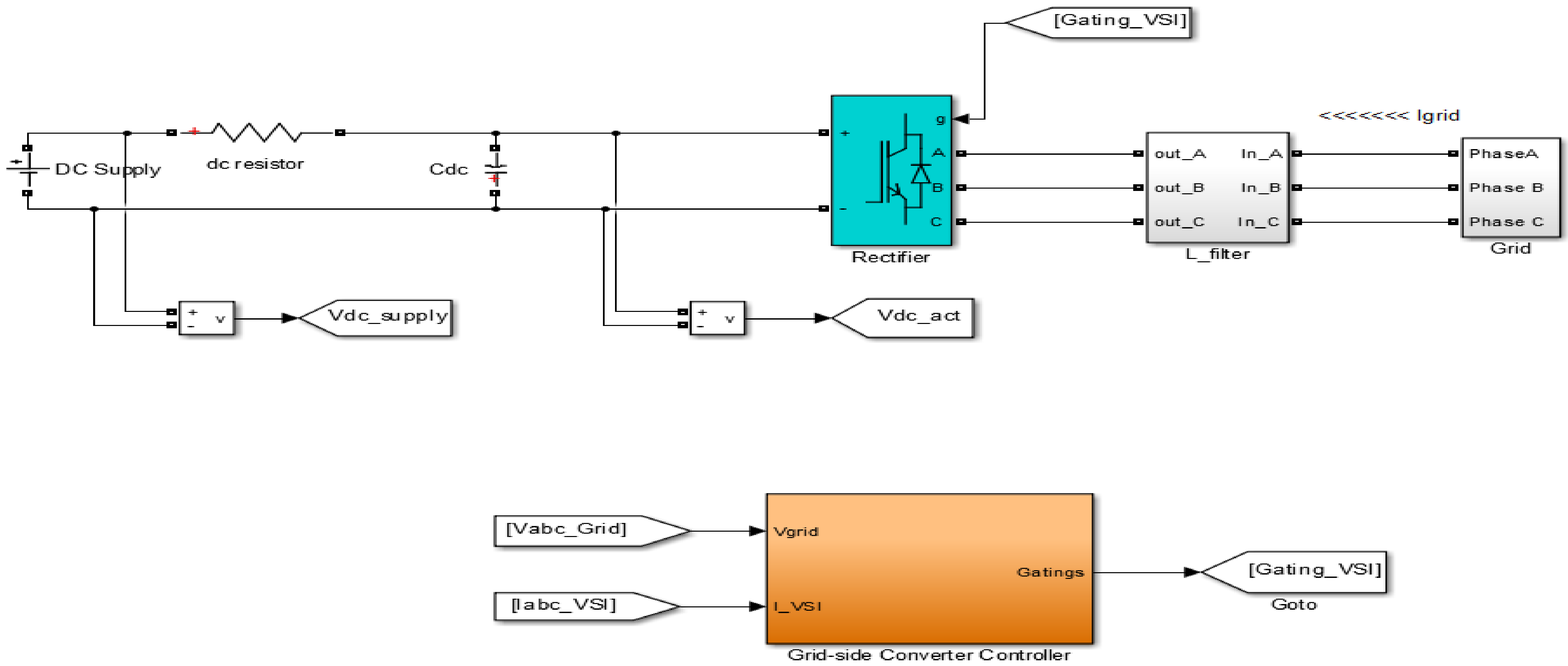
For wind energy applications, power is normally delivered from inverter to grid.

Active power of system delivered to grid: $Pg = 3\ Vg\ Ig \cos \varphi g$

where φg is grid power factor angle: $\varphi g = \angle Vg - \angle Ig$



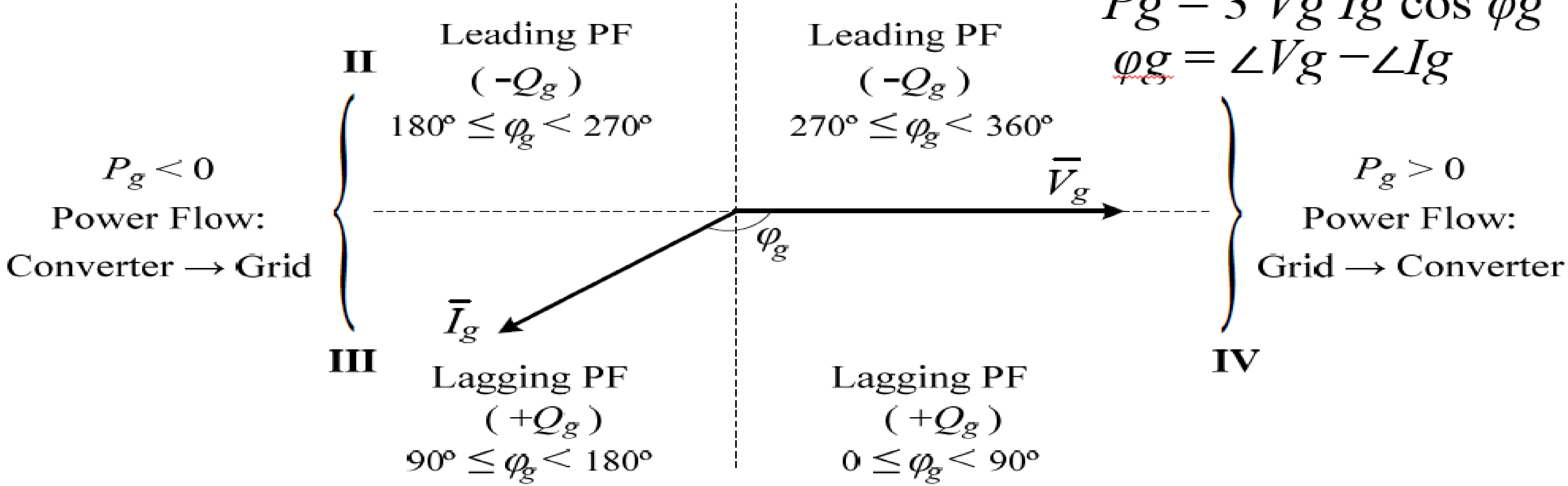
Simulation model



Grid power factor can be unity, leading or lagging

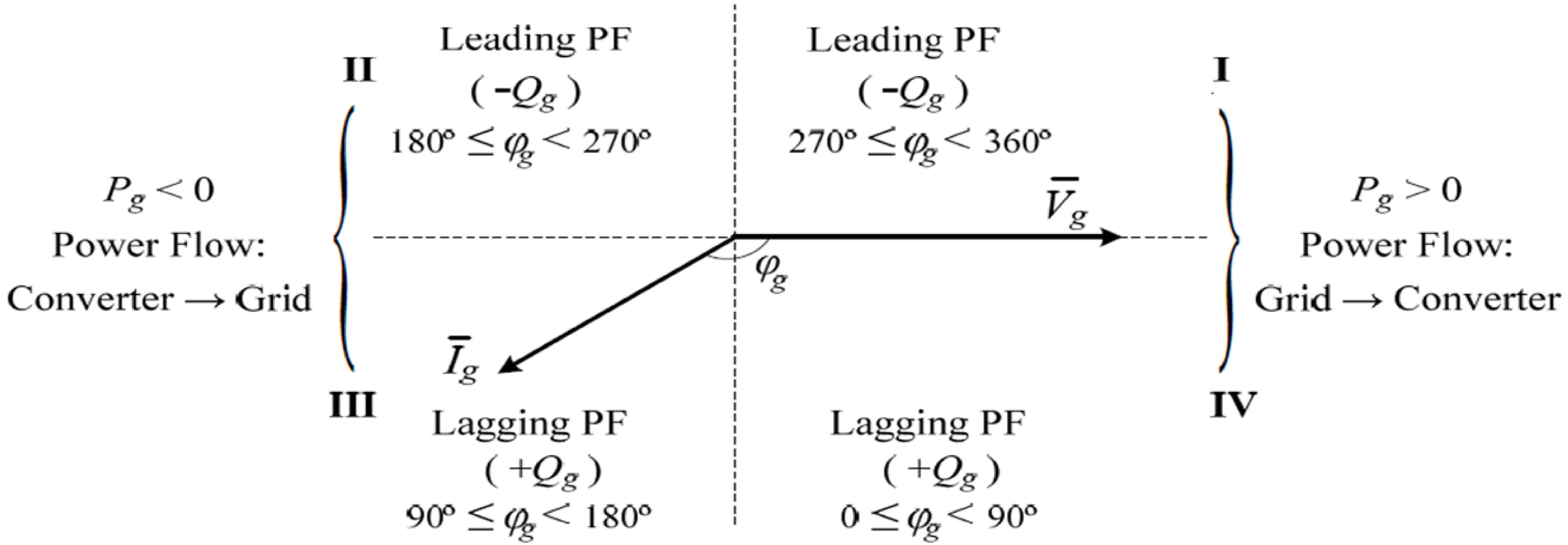
- Wind energy system provide a controllable reactive power to grid to support grid voltage in addition to active power production.

$$Pg = 3\ Vg\ Ig \cos \varphi g$$
$$\varphi g = \angle Vg - \angle Ig$$



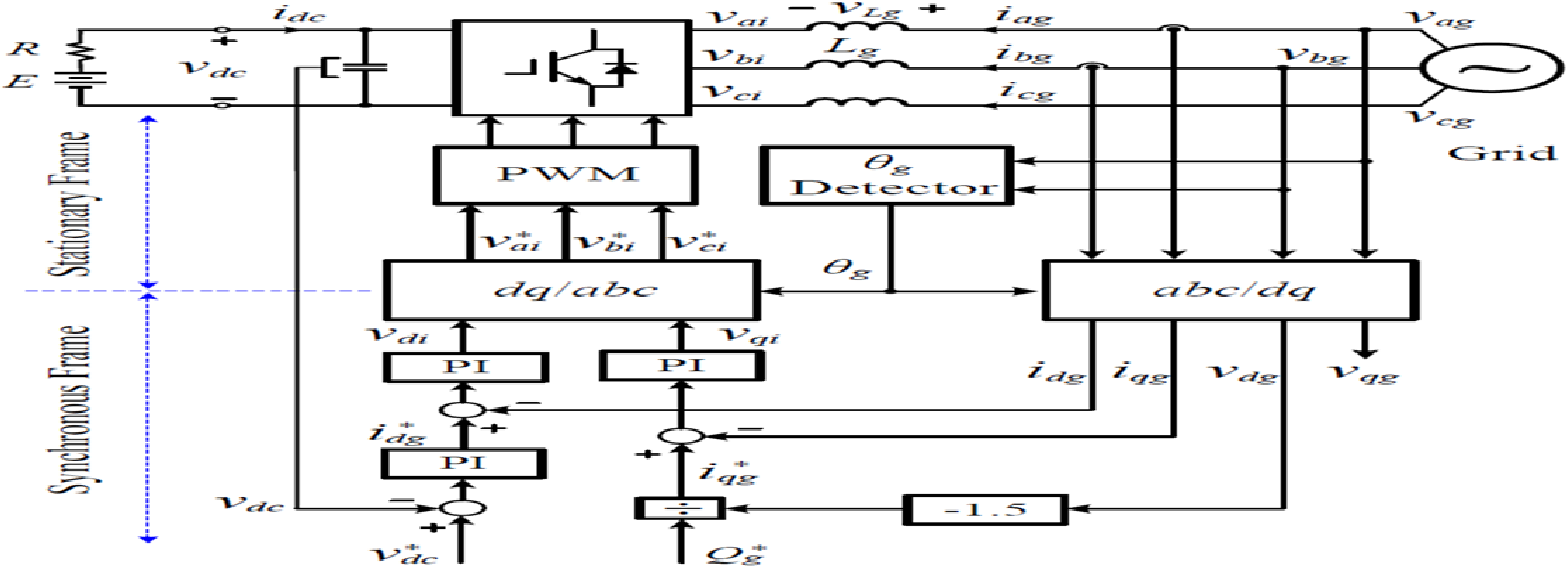
Wind energy system can operate with power factor angle in range of 90º ≤ φg < 270º

$$Pg = 3\ Vg\ Ig \cos \varphi g$$
$$\varphi g = \angle Vg - \angle Ig$$

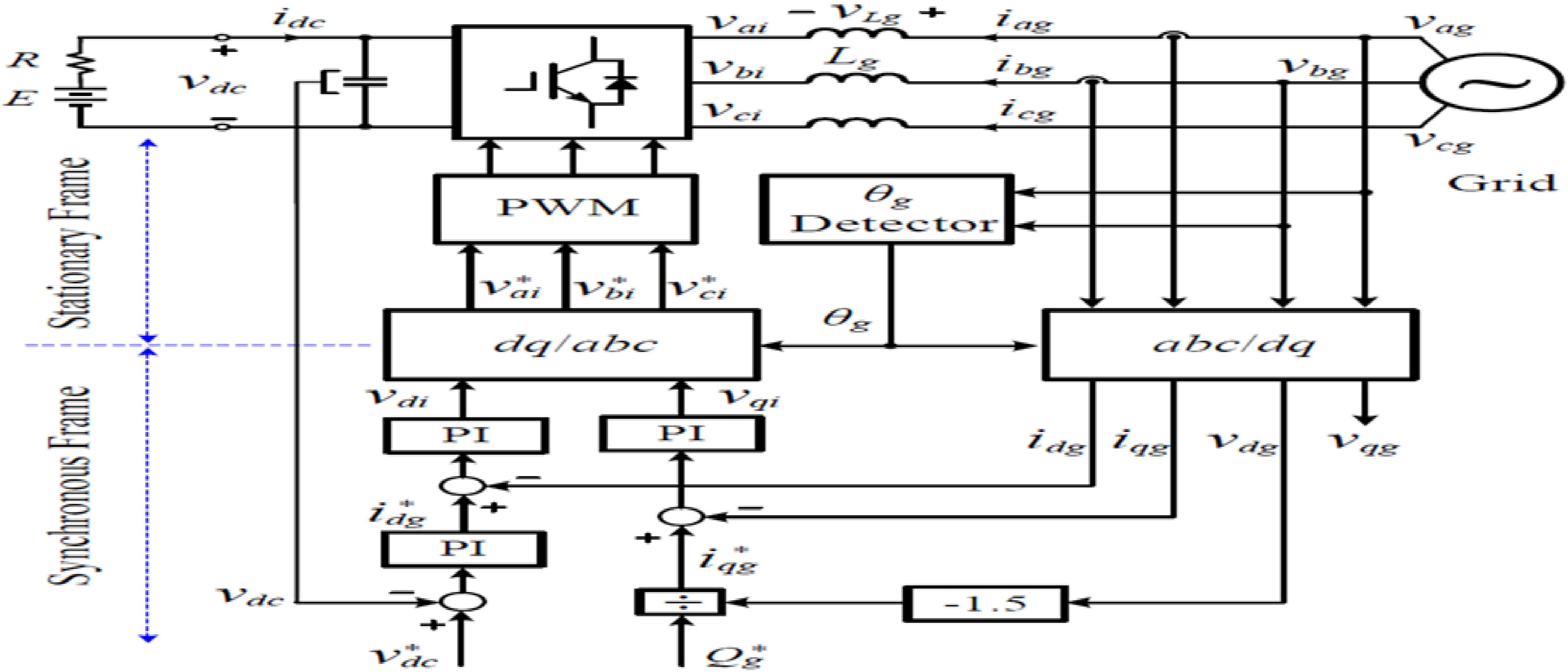


4.7.1 Voltage Oriented Control (VOC)

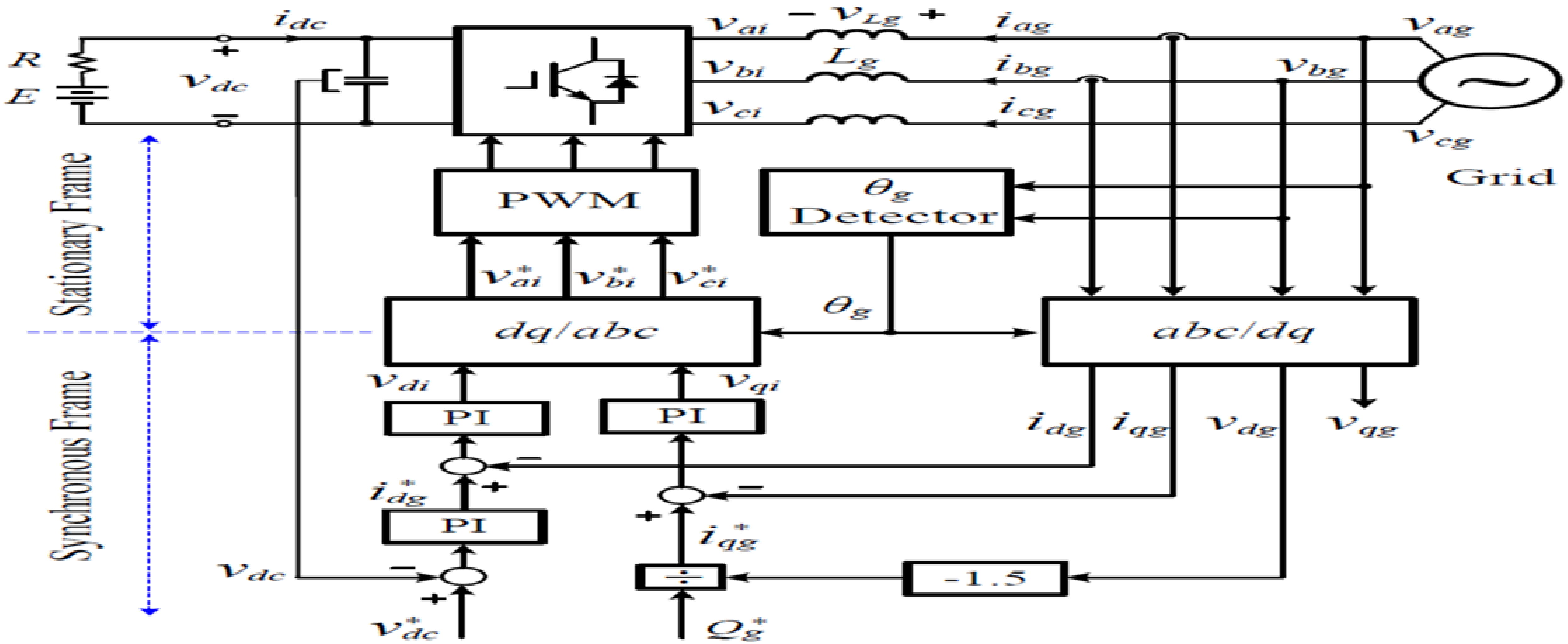
Grid-connected inverter can be controlled with various schemes e.g Voltage Oriented Control (VOC).



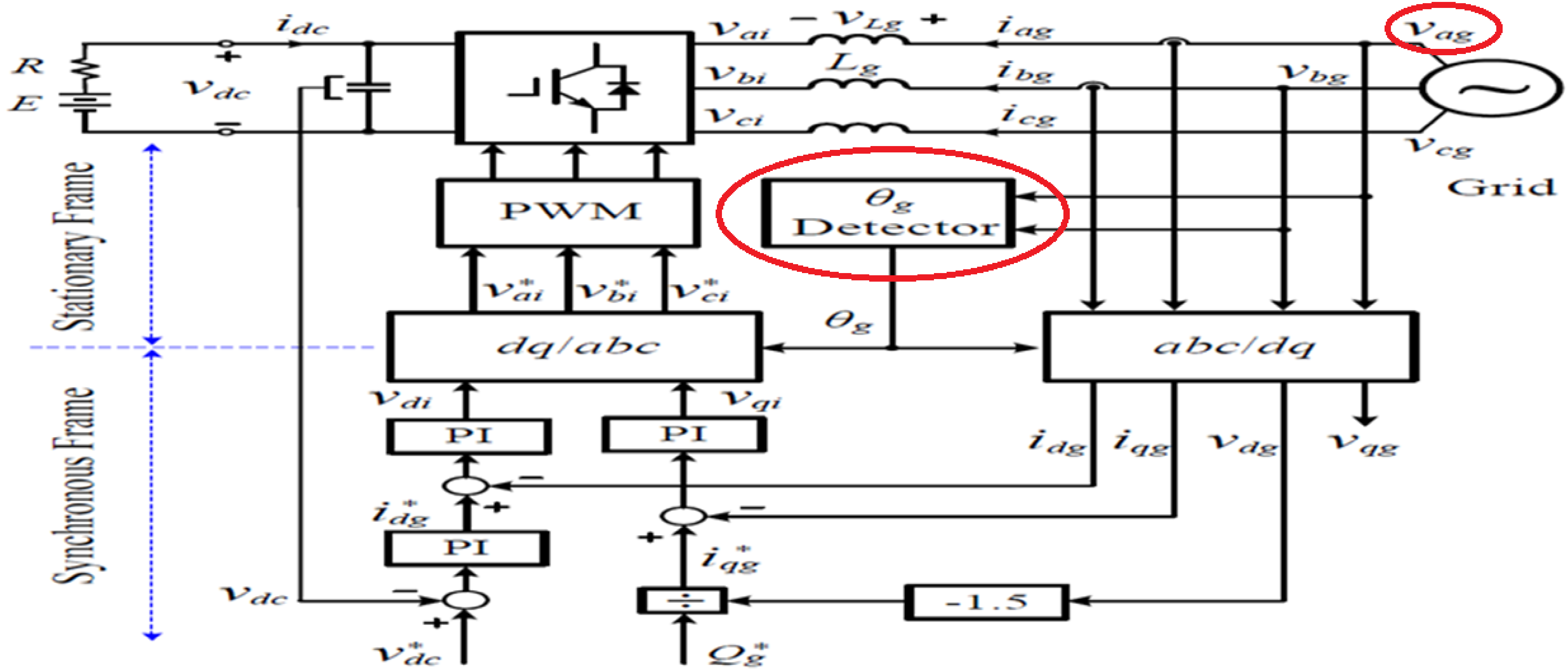
This scheme is based on transformation b/w *abc* stationary reference frame & *dq* synchronous frame.



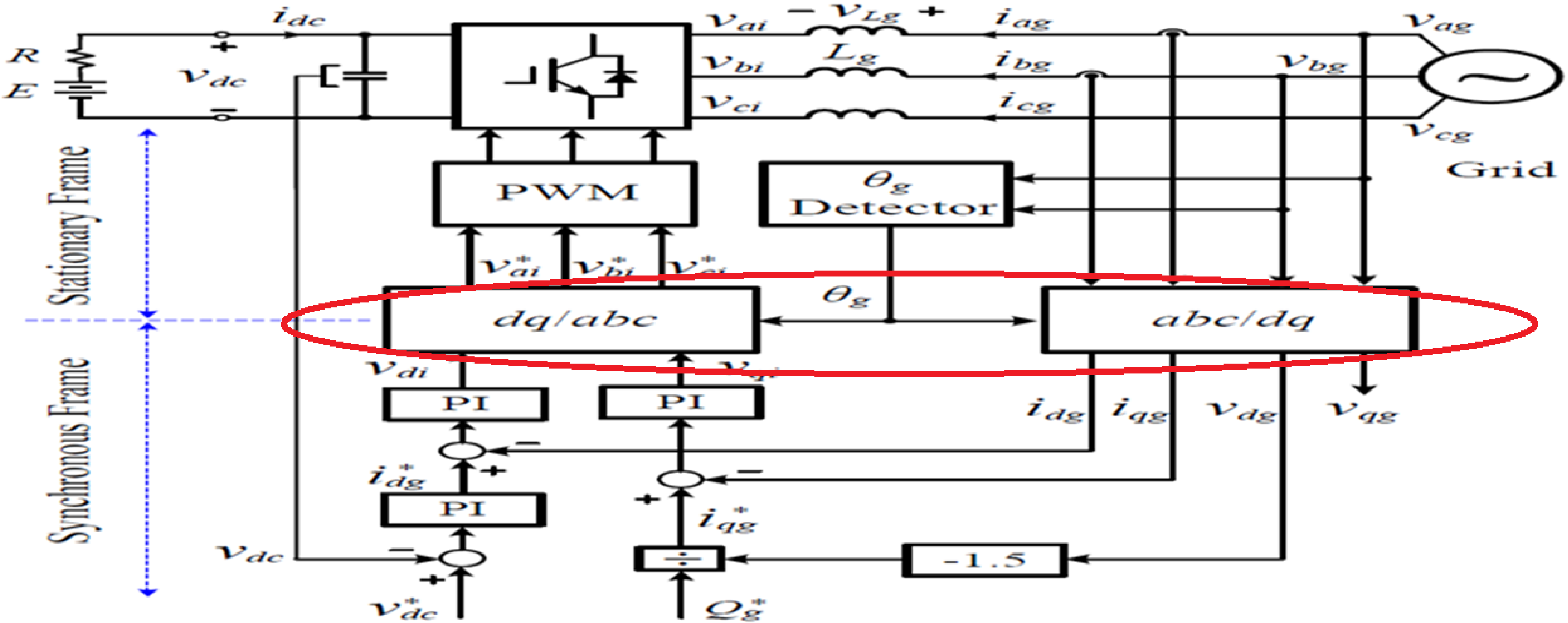
Control algorithm is implemented in grid-voltage synchronous reference frame, where all variables are of dc components in steady state.



Grid voltage(v_{ag}) is measured & its angle ϑg is detected for voltage orientation.



ϑg is used for transformation of variables from *abc* stationary frame to *dq* synchronous frame through *abc/dq* transformation or *dq/abc* transformation



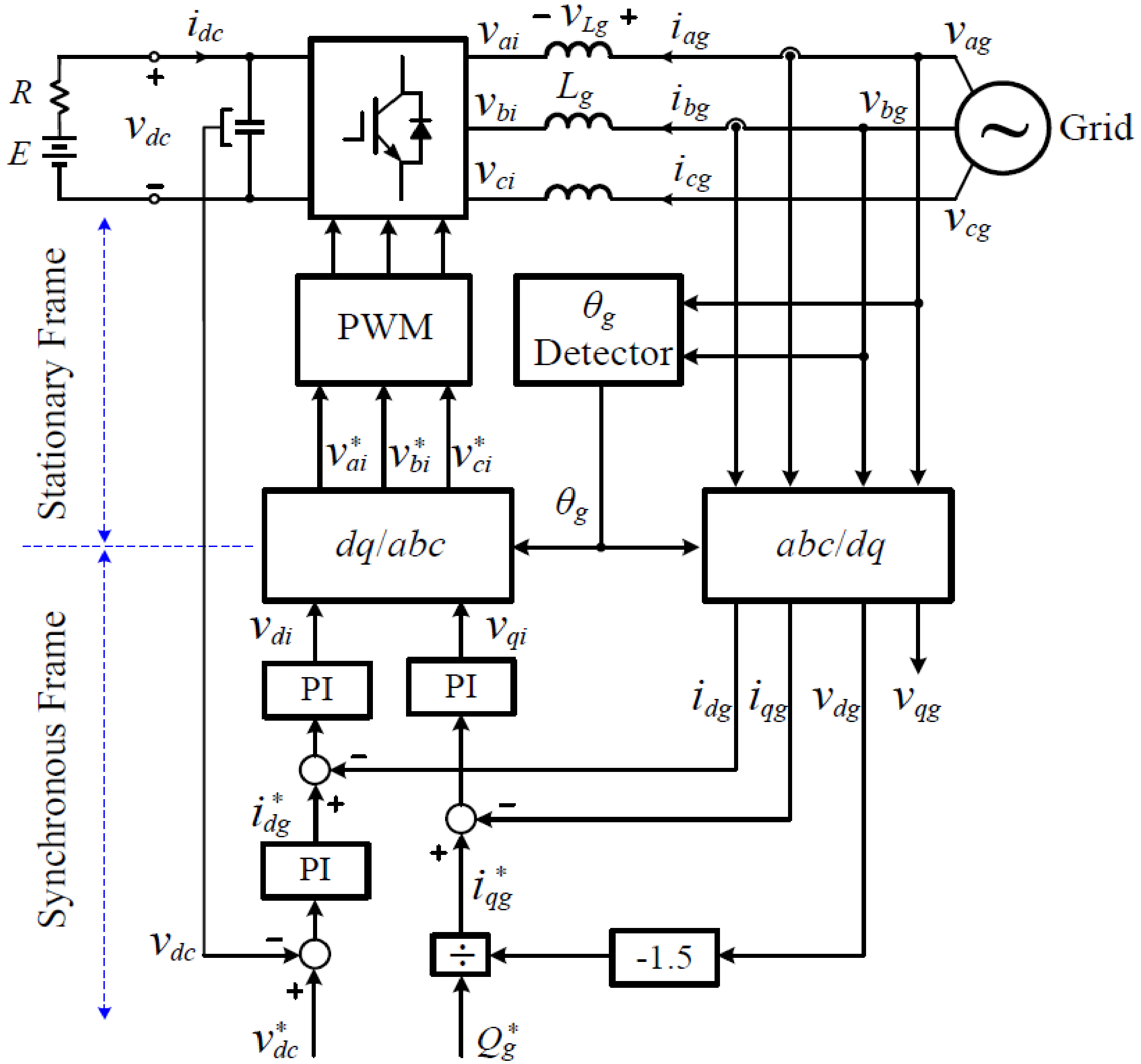
How to detect grid voltage angle ϑg?

Various methods are available to detect grid voltage angle ϑg.

As grid voltages, *vag*, *vbg*, & *vcg* are 3-phase balanced sinusoidal waveforms,

So ϑg can be obtained by:

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



Prove that:

$$\begin{cases} v_\alpha = \dfrac{2}{3}\left(v_{ag} - \dfrac{1}{2}v_{bg} - \dfrac{1}{2}v_{cg}\right) = v_{ag} \\ v_\beta = \dfrac{2}{3}\left(\dfrac{\sqrt{3}}{2}v_{bg} - \dfrac{\sqrt{3}}{2}v_{cg}\right) = \dfrac{\sqrt{3}}{3}\left(v_{ag} + 2v_{bg}\right) \end{cases} \quad \text{for} \quad v_{ag} + v_{bg} + v_{cg} = 0$$

$v\alpha$ can be obtained by $abc/\alpha\beta$ transformation

$$V_\alpha = \frac{2}{3}\left\{V_{ag} - \frac{1}{2}(V_{bg} + V_{cg})\right\}$$

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix}$$

$$V_\alpha = \frac{2}{3}\left\{V_{ag} + \frac{1}{2}V_{ag}\right\}$$

$$V_{ag} + V_{bg} + V_{cg} = 0$$

$$V_\alpha = \frac{2}{3}\left\{\frac{3}{2}V_{ag}\right\}$$

$$V_\alpha = V_{ag}$$

v_β can be obtained by *abc*/*αβ* transformation

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix}$$

$$V_\beta = \frac{2}{3}\left\{\frac{\sqrt{3}}{2}V_{bg} - \frac{\sqrt{3}}{2}V_{cg}\right\}$$

$$V_\beta = \frac{2}{3}\times\frac{\sqrt{3}}{2}\left\{V_{bg} - V_{cg}\right\}$$

$$V_{ag} + V_{bg} + V_{cg} = 0$$

$$-V_{cg} = (V_{ag} + V_{bg})$$

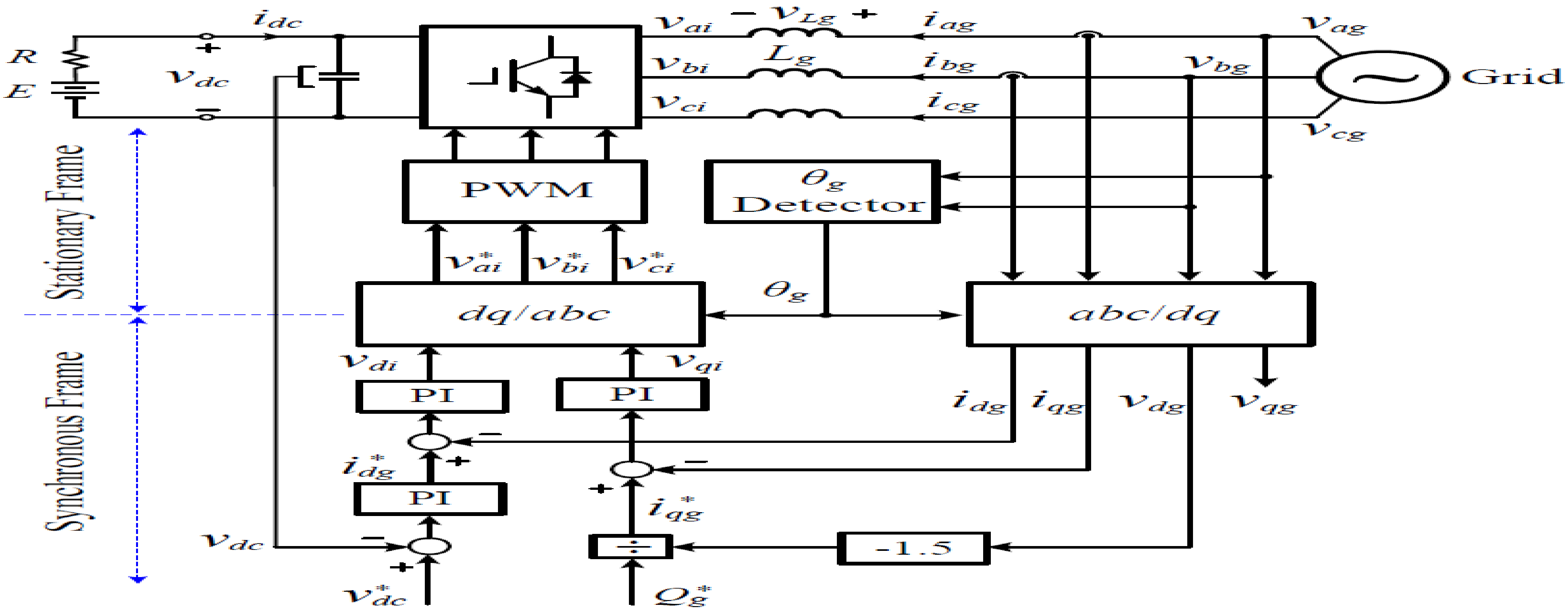
$$V_\beta = \frac{\sqrt{3}}{3}\left\{V_{bg} + V_{ag} + V_{bg}\right\}$$

$$V_\beta = \frac{\sqrt{3}}{3}\left\{2V_{bg} + V_{ag}\right\}$$

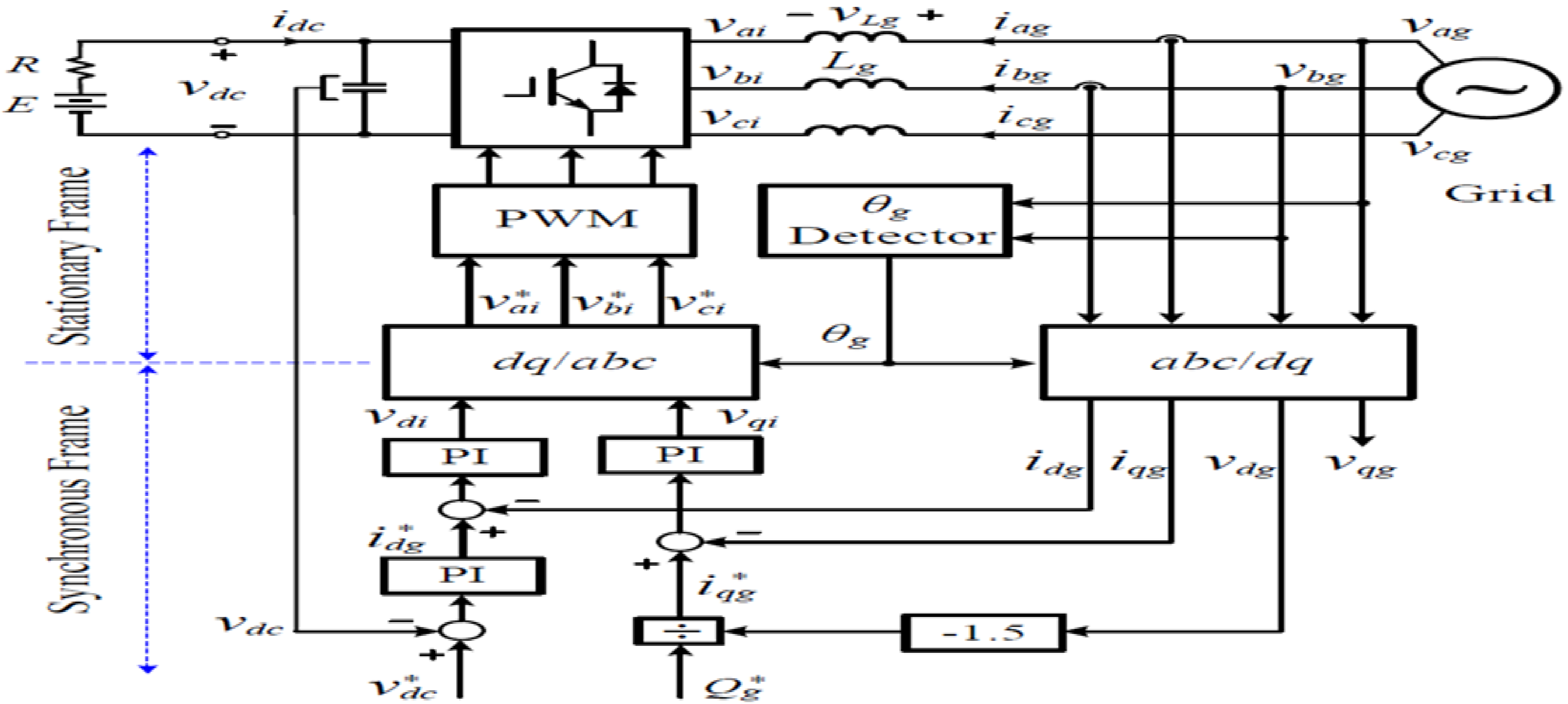
Is there any need to measure phase-*c* grid voltage *vcg*?

$$\begin{cases} v_\alpha = \dfrac{2}{3}\left(v_{ag} - \dfrac{1}{2}v_{bg} - \dfrac{1}{2}v_{cg}\right) = v_{ag} \\ v_\beta = \dfrac{2}{3}\left(\dfrac{\sqrt{3}}{2}v_{bg} - \dfrac{\sqrt{3}}{2}v_{cg}\right) = \dfrac{\sqrt{3}}{3}\left(v_{ag} + 2v_{bg}\right) \end{cases} \quad \text{for} \quad v_{ag} + v_{bg} + v_{cg} = 0$$

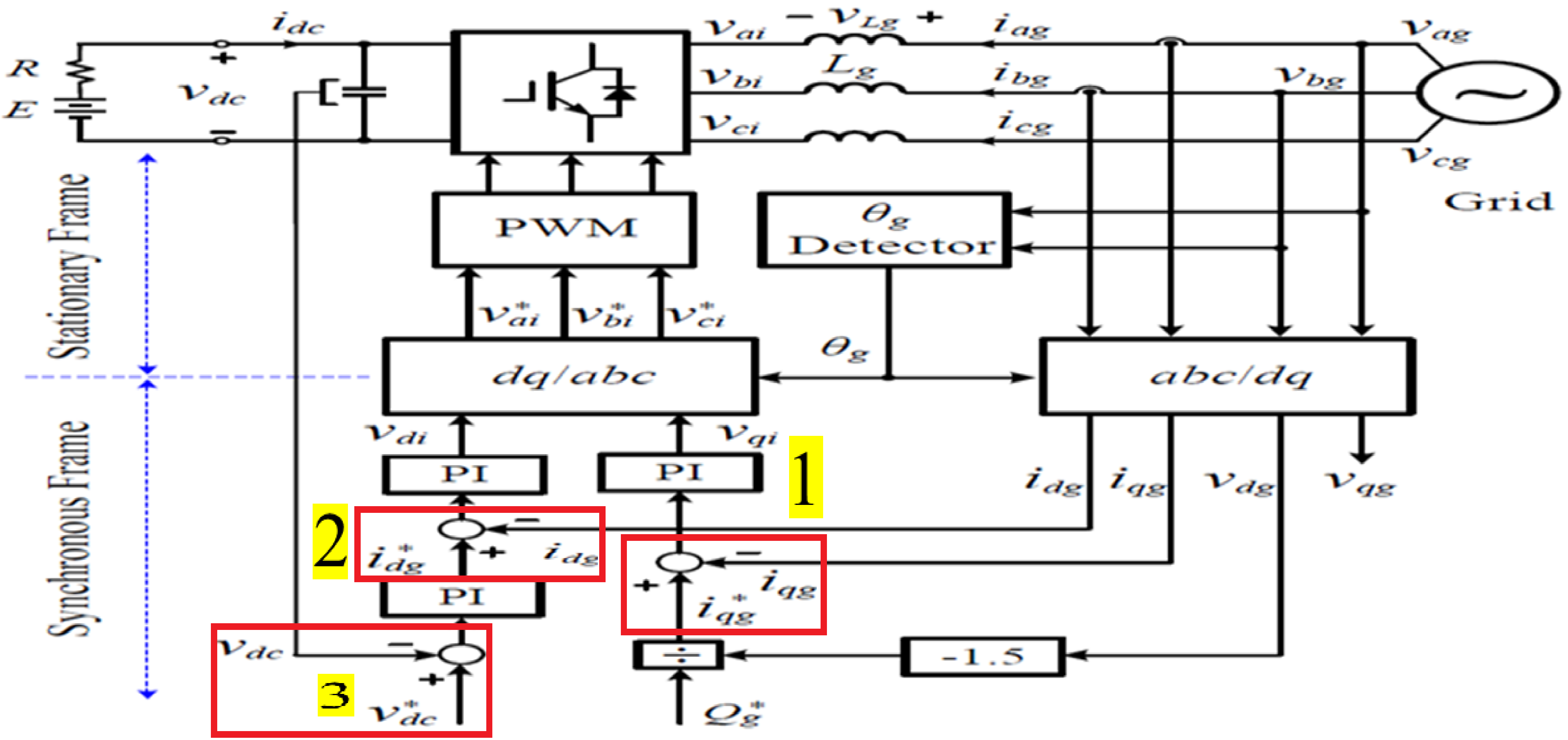
Grid voltage may contain harmonics & be distorted, digital filters or phase looked loop (PLL) may be used for detection of grid voltage angle ϑg.



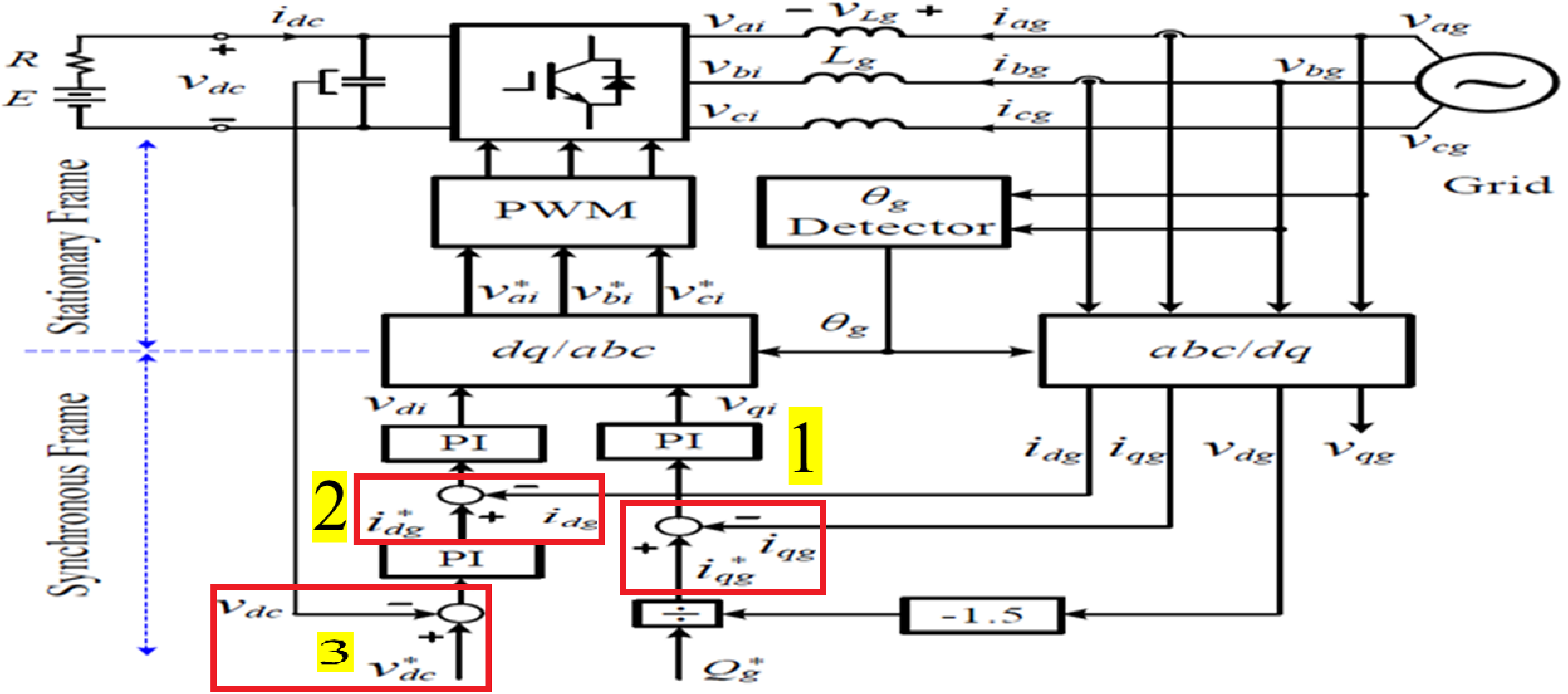
How many Feedback control loops in system?



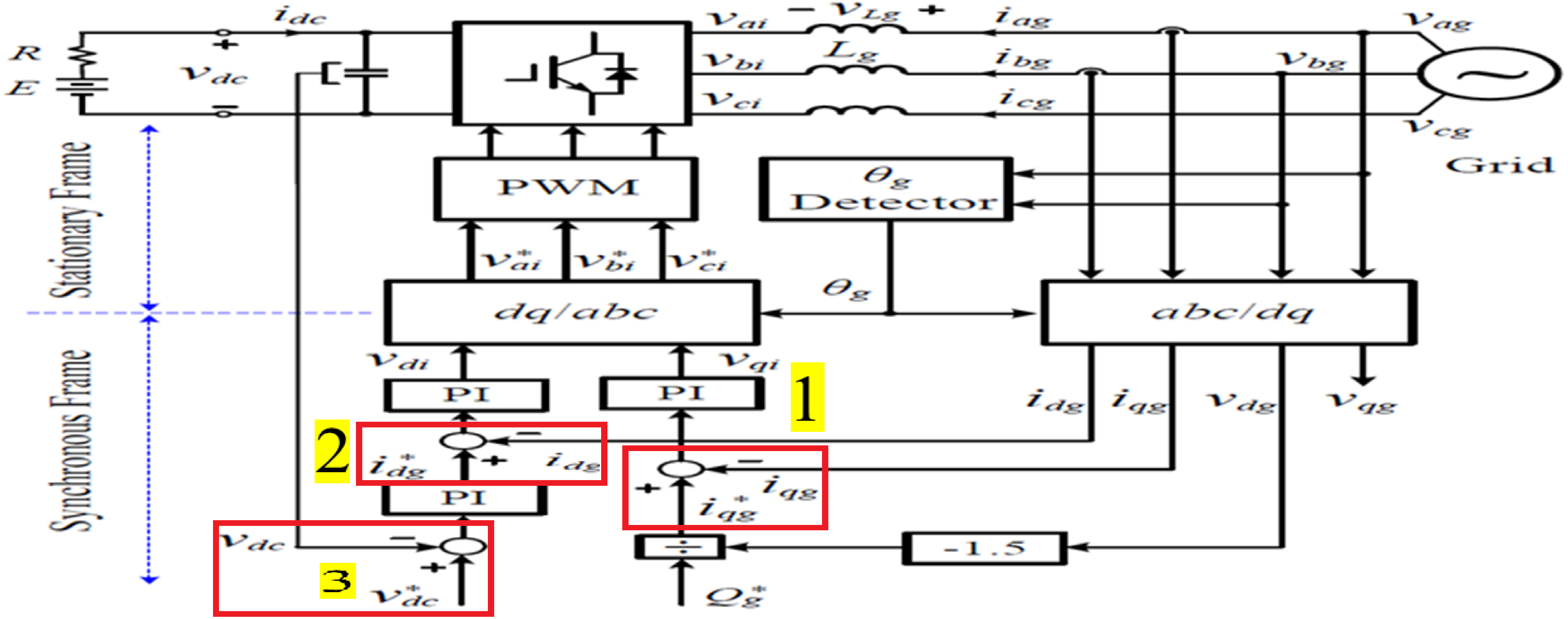
There are 3 feedback control loops in system:



02 inner current loops for accurate control of *dq*-axis currents *idg* & *iqg*

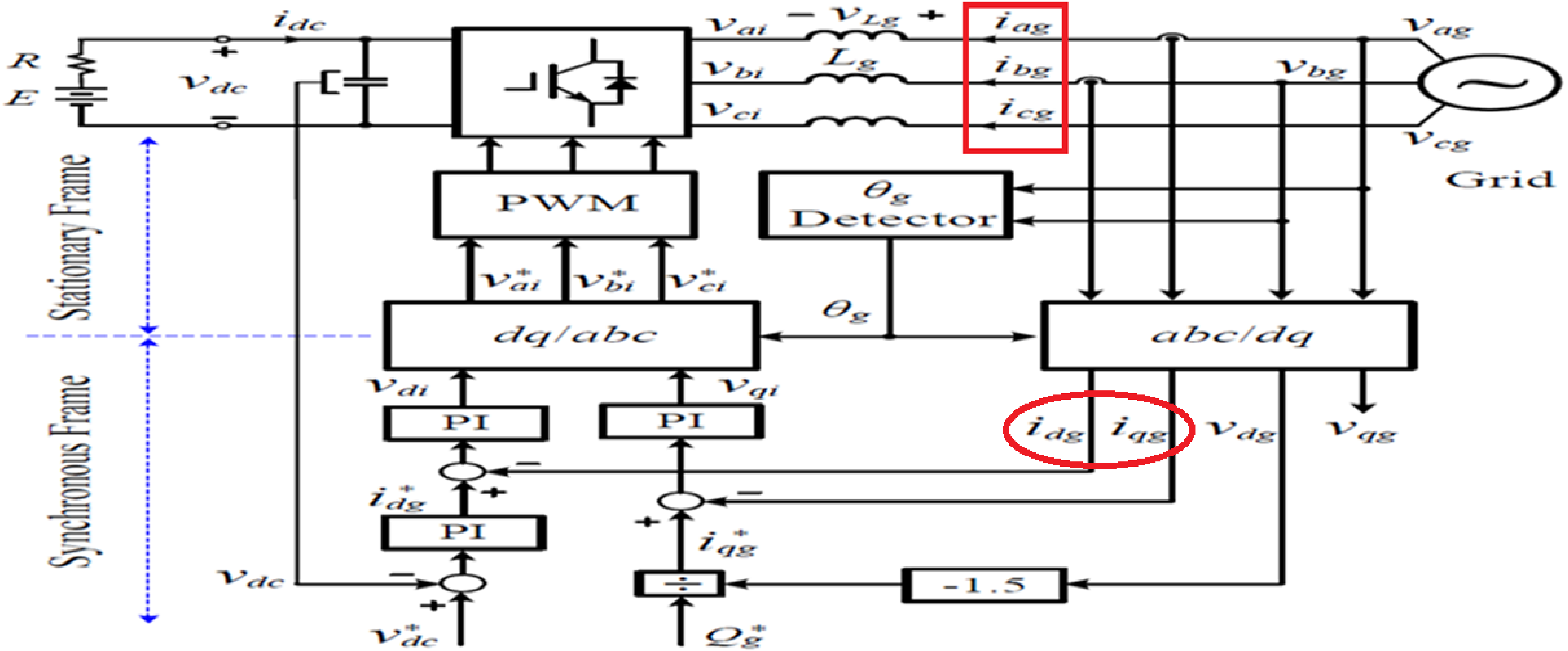


1 outer dc voltage feedback loop for control of dc voltage *vdc*.

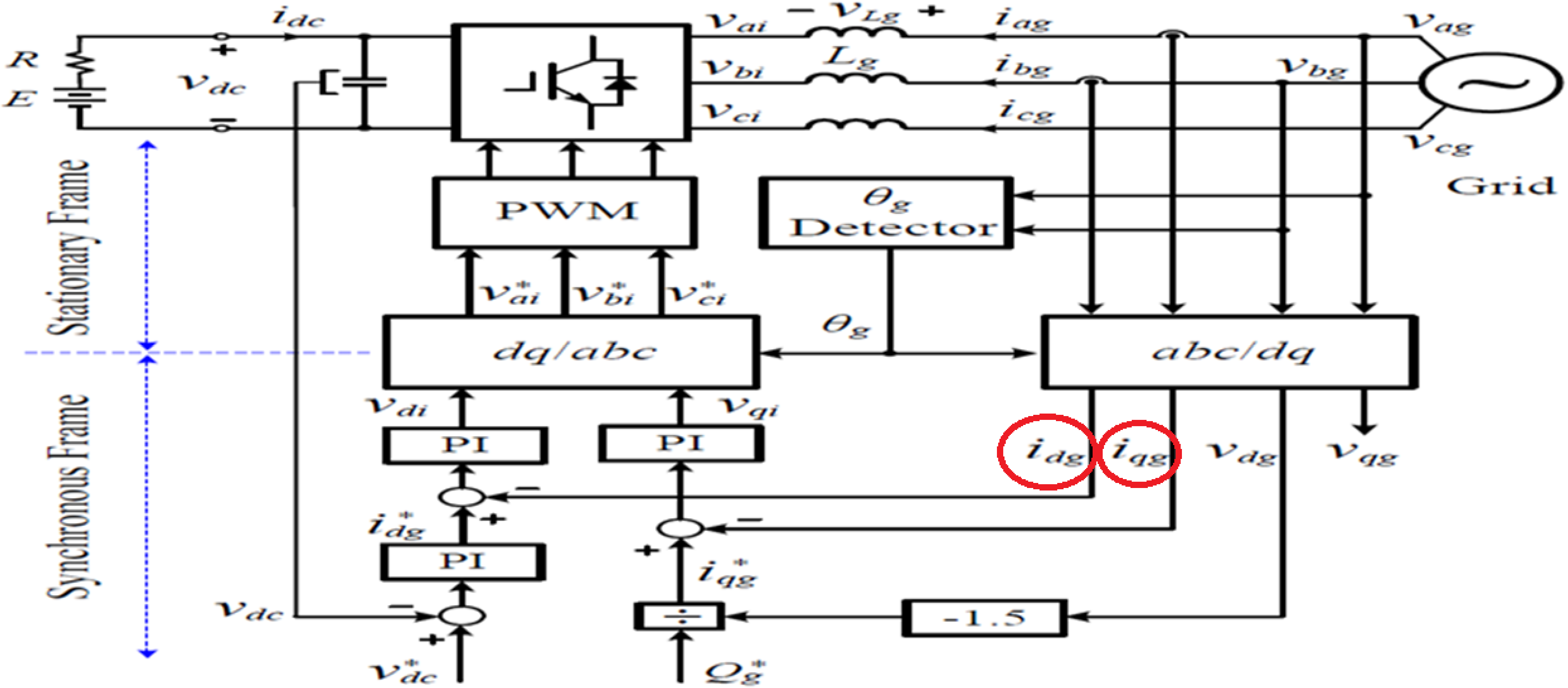


outer dc voltage feedback loop

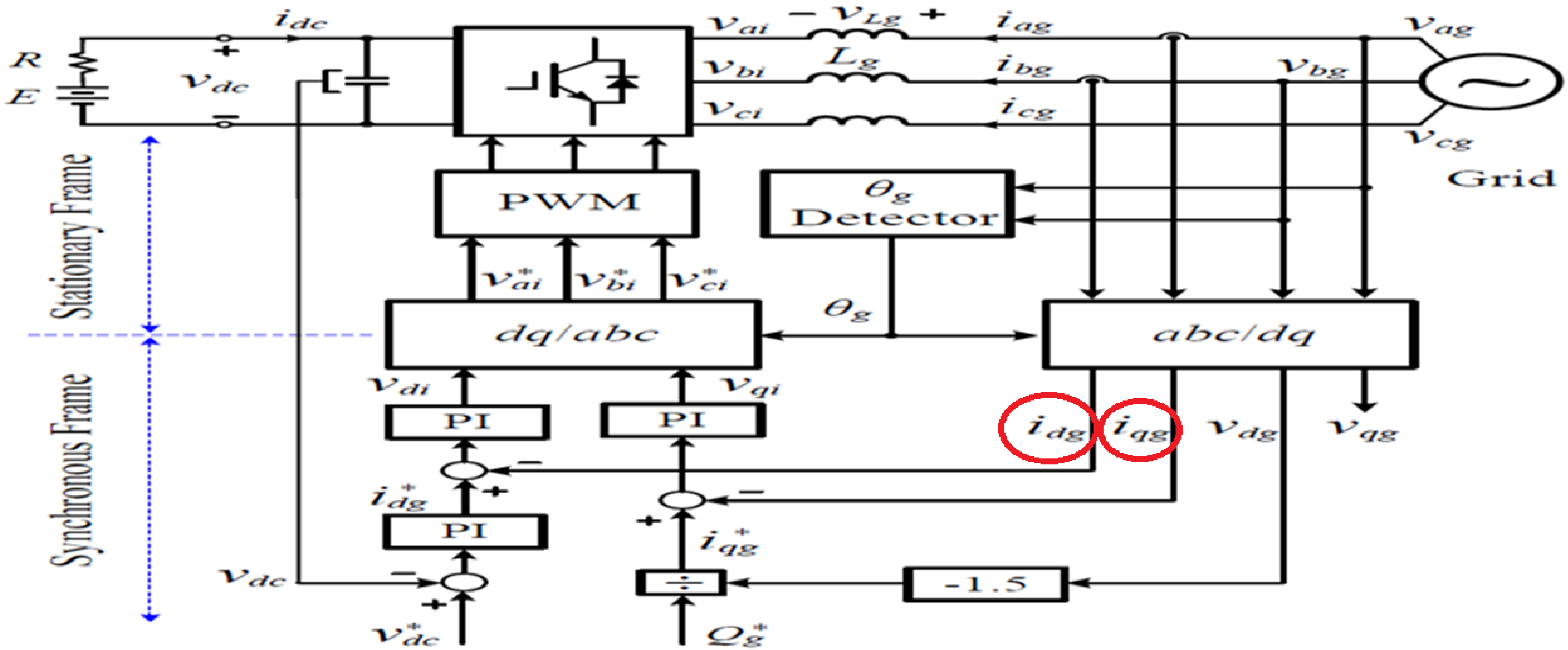
3-phase line currents in *abc* stationary frame i_{ag}, i_{bg} & i_{cg} are transformed to 02-phase currents i_{dg} & i_{qg} in *dq* synchronous frame



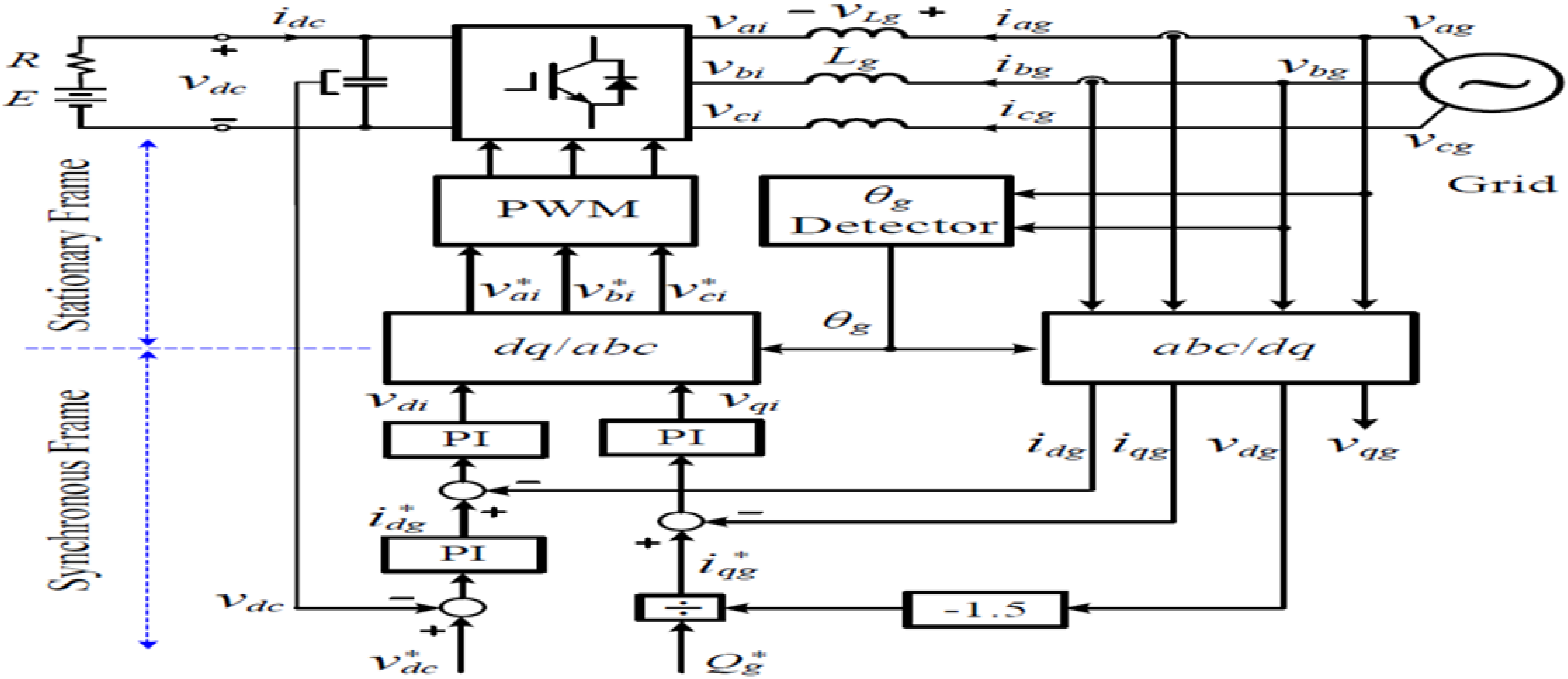
idg & *iqg* are active & reactive components of 3-phase line currents.



Independent control of these 02 components(*idg & iqg*) provides effective means for independent control of system active & reactive power (Pg & Qg) .

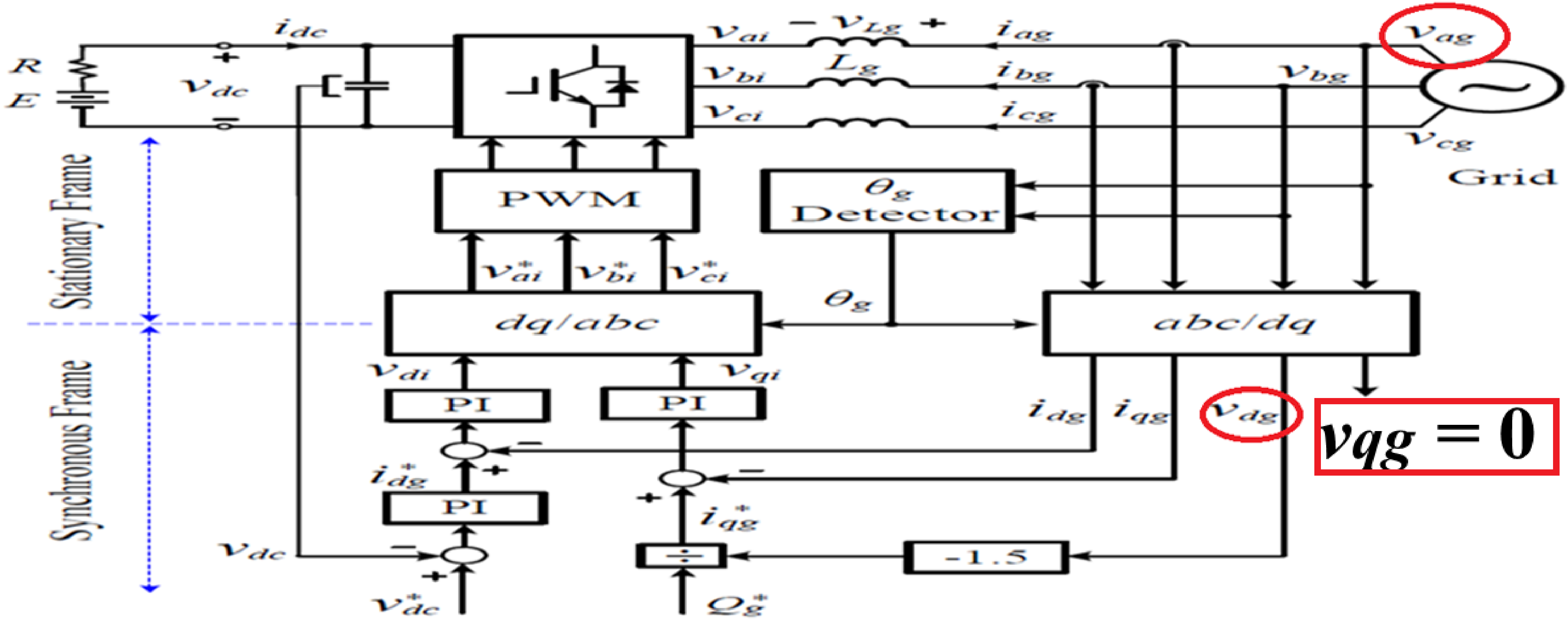


d-axis of synchronous frame(v_{dg}) is aligned with grid voltage vector(v_g) i.e ($v_{dg} = v_g$)



As ($v_{dg} = v_g$) so $\quad v_g^2 = v_{dg}^2 + v_{qg}^2 \quad \cancel{v_g^2} = \cancel{v_g^2} + v_{qg}^2$

Resultant *q*-axis voltage $\boldsymbol{v_{qg} = 0}$



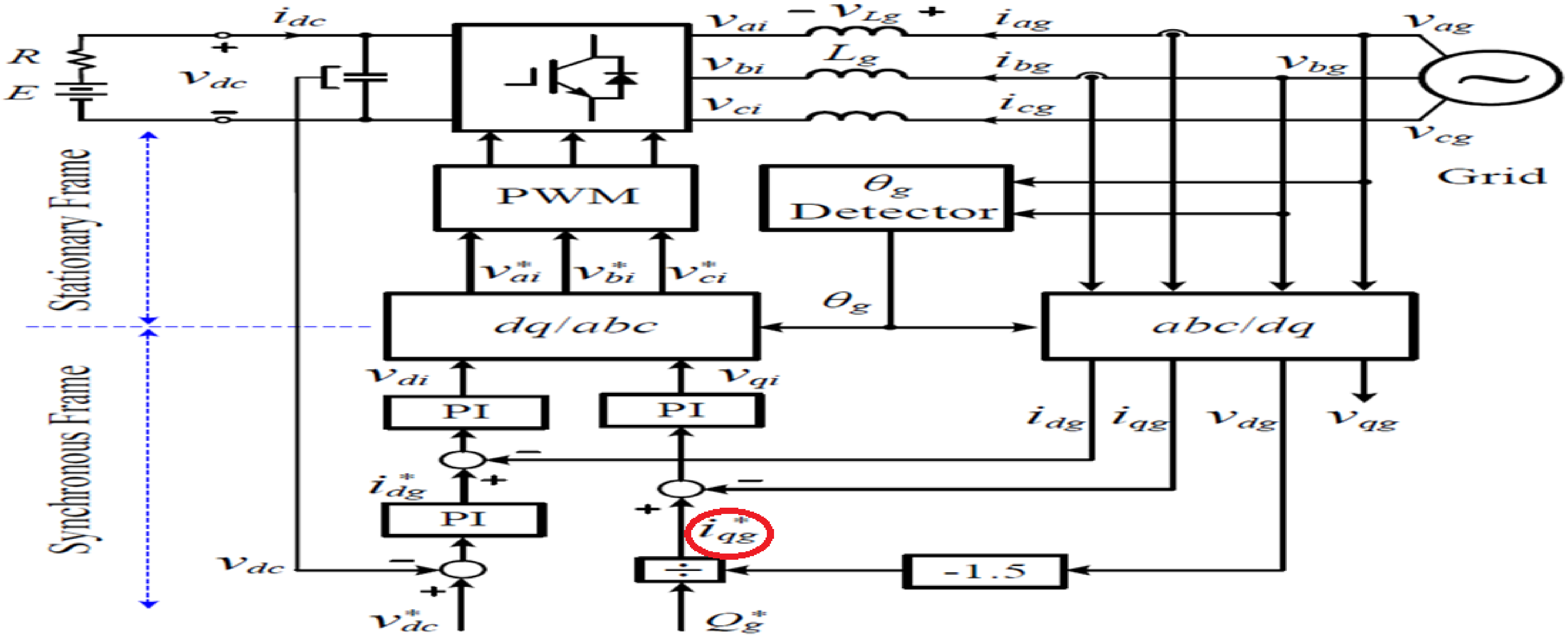
Now active & reactive power of system *(Pg & Qg)* can be calculated by

$$\begin{cases} P_g = \dfrac{3}{2}(v_{dg} i_{dg} + \overset{0}{\cancel{v_{qg} i_{qg}}}) = \dfrac{3}{2} v_{dg} i_{dg} \\ Q_g = \dfrac{3}{2}(\overset{0}{\cancel{v_{qg} i_{dg}}} - v_{dg} i_{qg}) = -\dfrac{3}{2} v_{dg} i_{qg} \end{cases} \quad \text{for } v_{qg} = 0$$

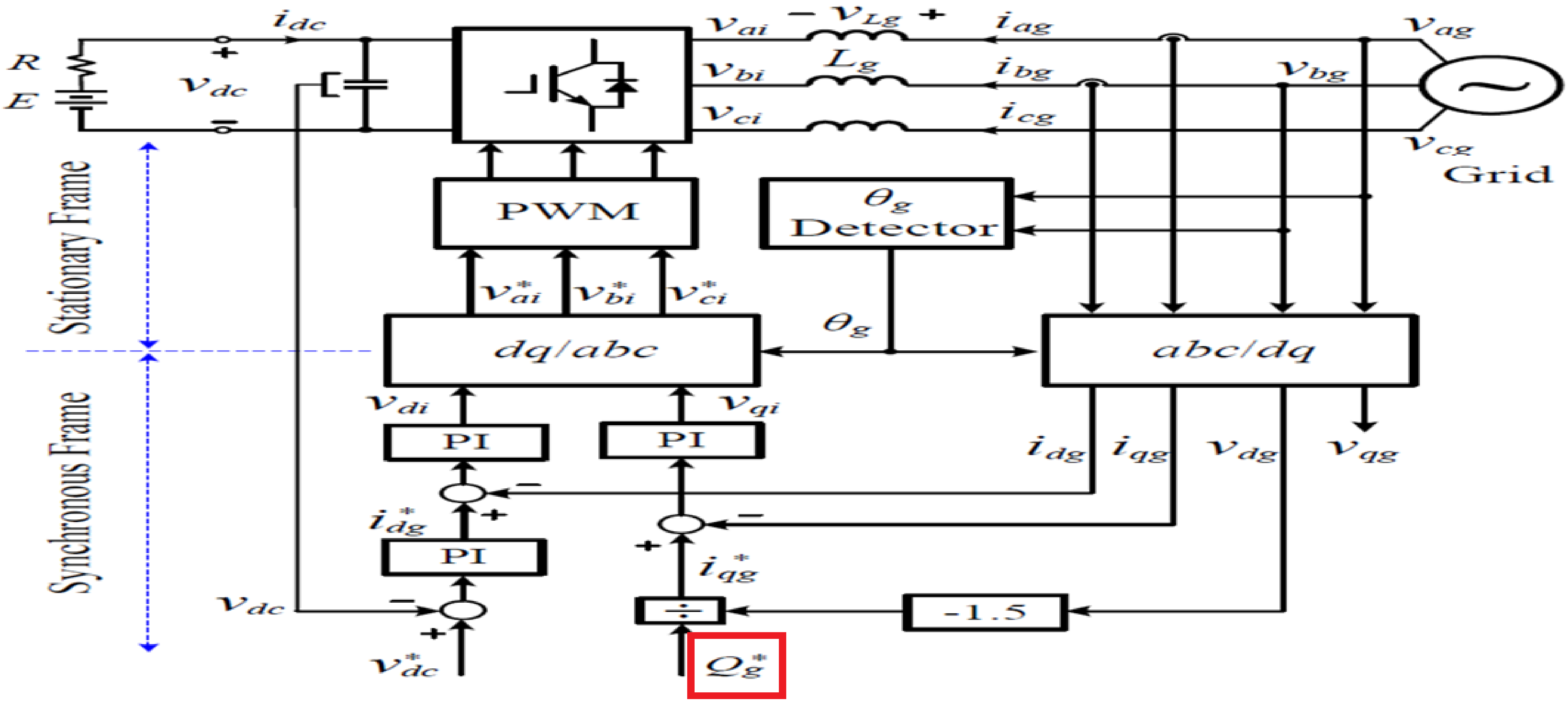
q-axis current reference i_{qg}^* can then be obtained from:

$$Q_g = -\frac{3}{2} v_{dg} i_{qg}$$

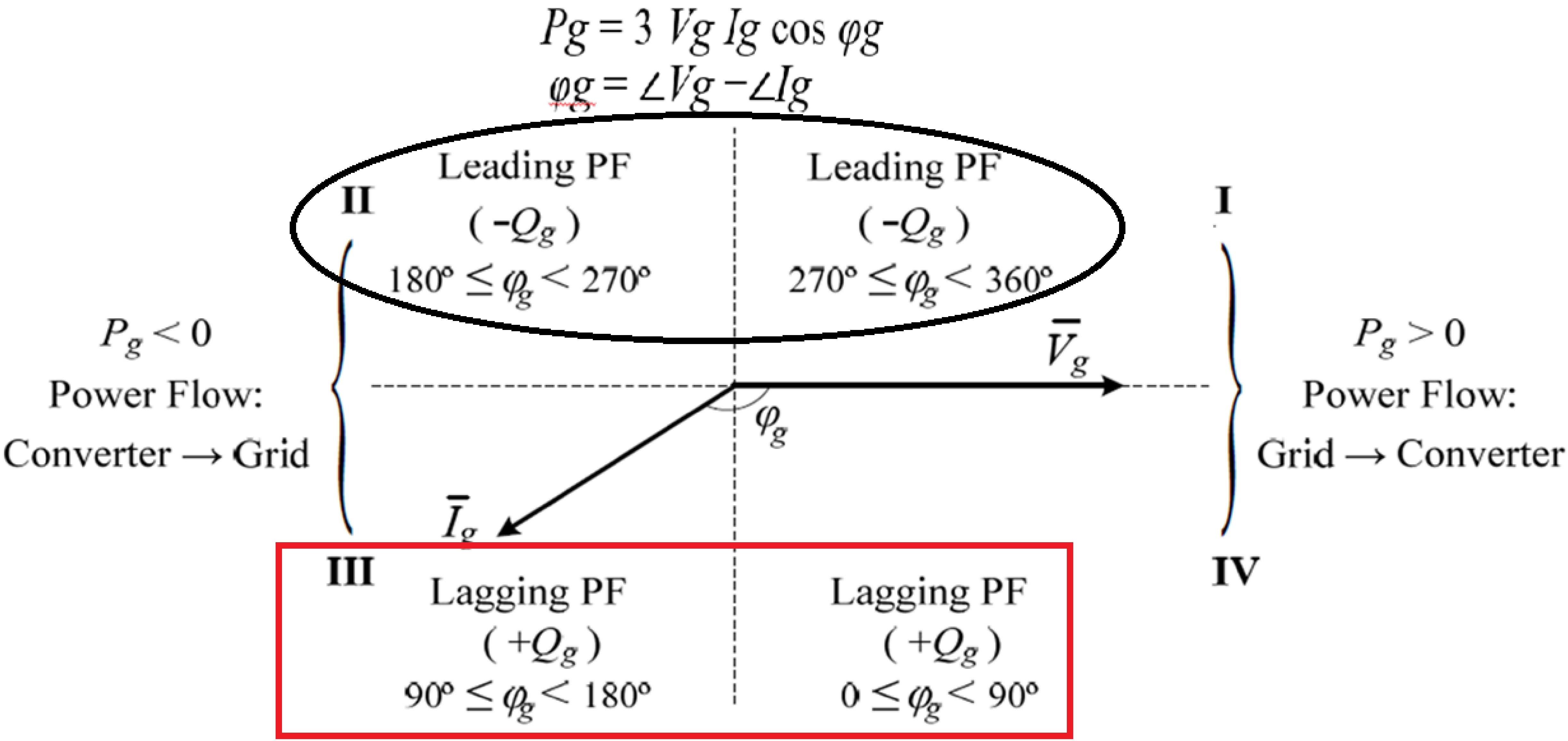
$$i_{qg}^* = \frac{Q_g^*}{-1.5 v_{dg}}$$



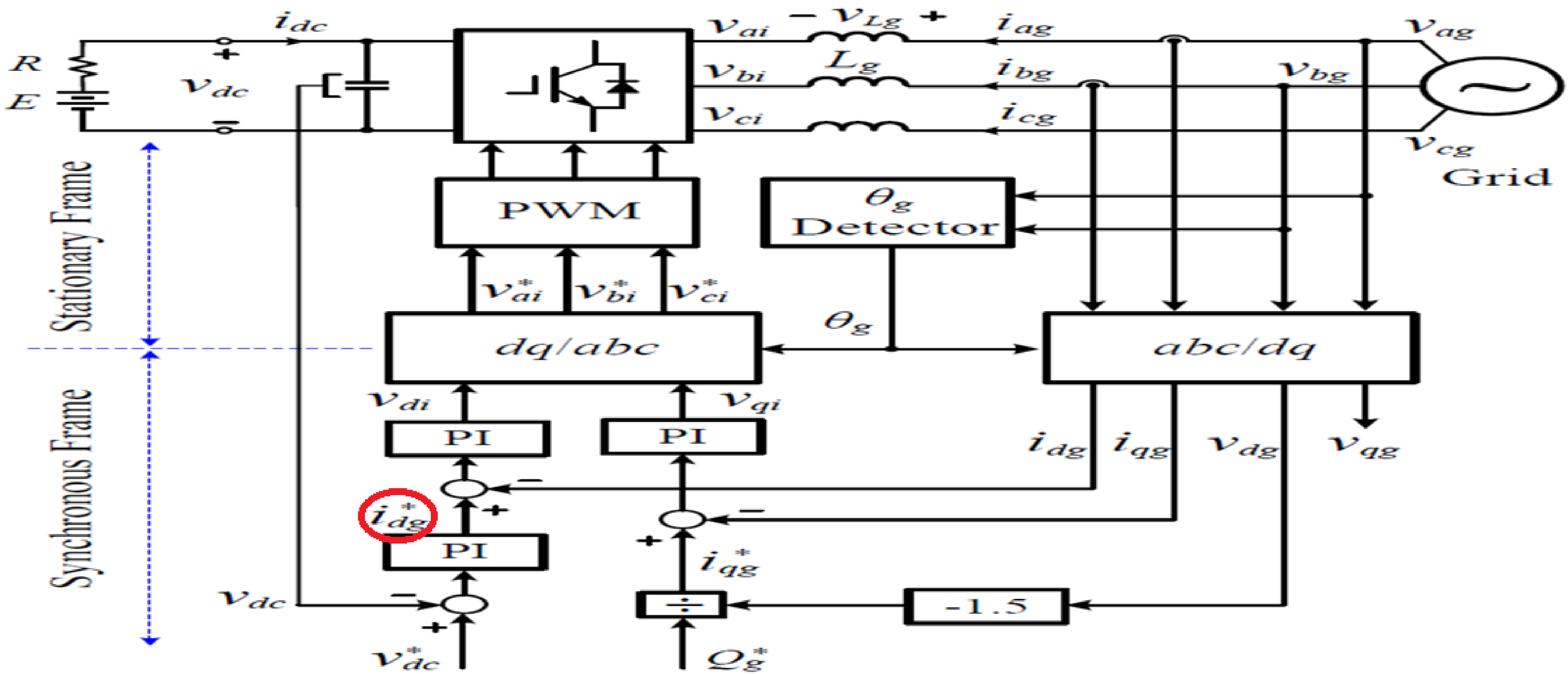
where Q_g^* is reference for reactive power, which can be set to 0 for unity power factor operation



+ve & -ve values of Q_g^*

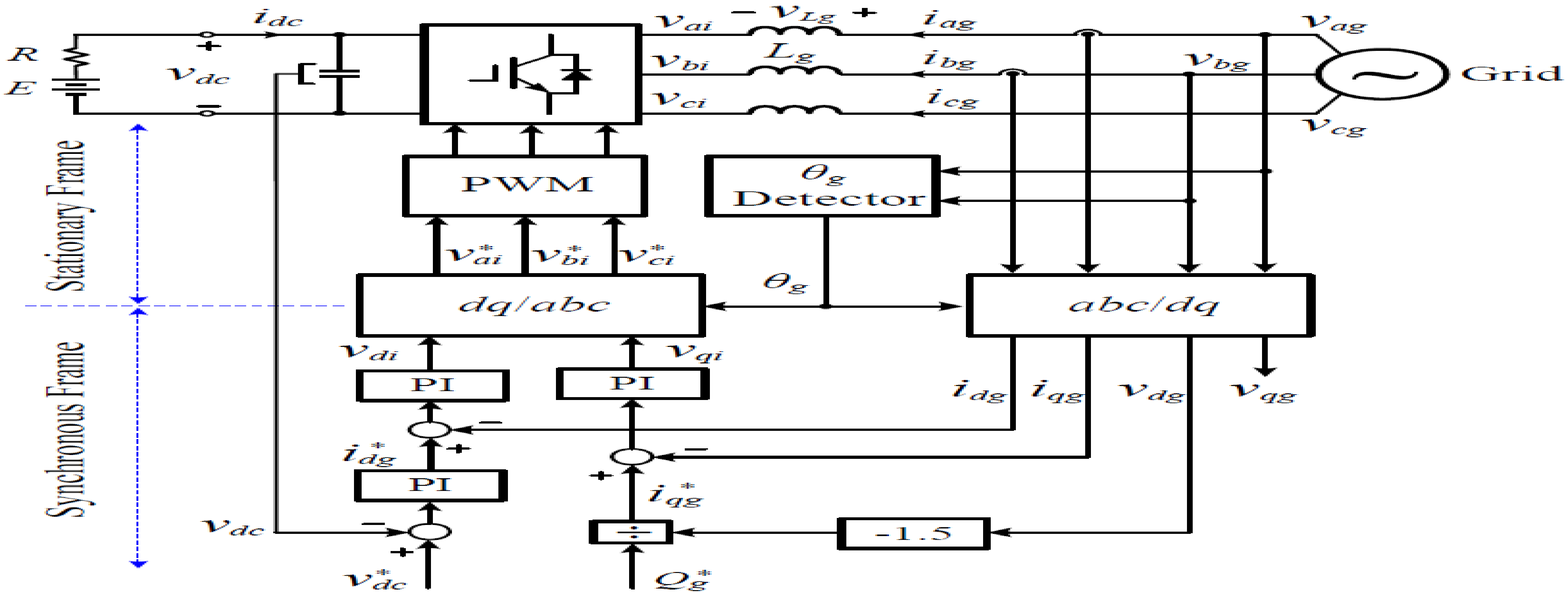


d-axis current reference i_{dg}^*, which represents active power of system, is generated by PI controller for dc voltage control.

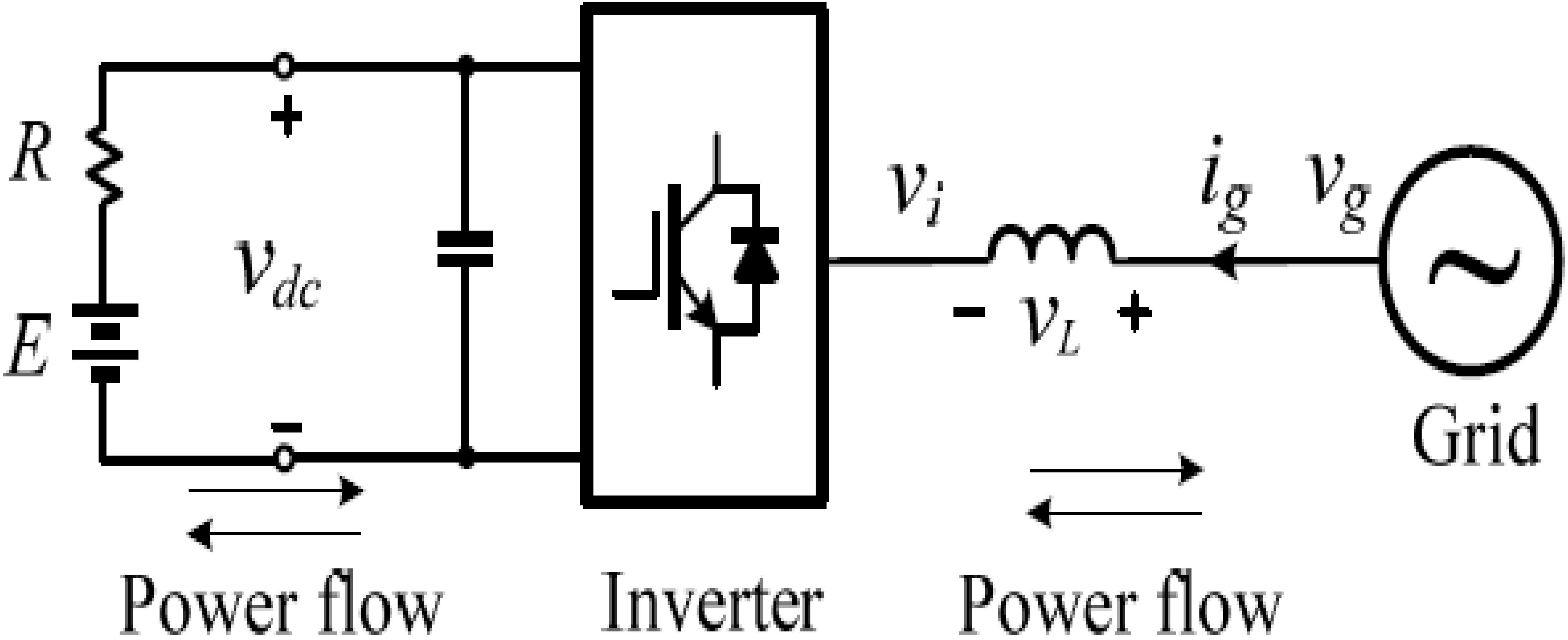


Neglecting losses in inverter, active power on ac side of inverter is equal to dc-side power i.e

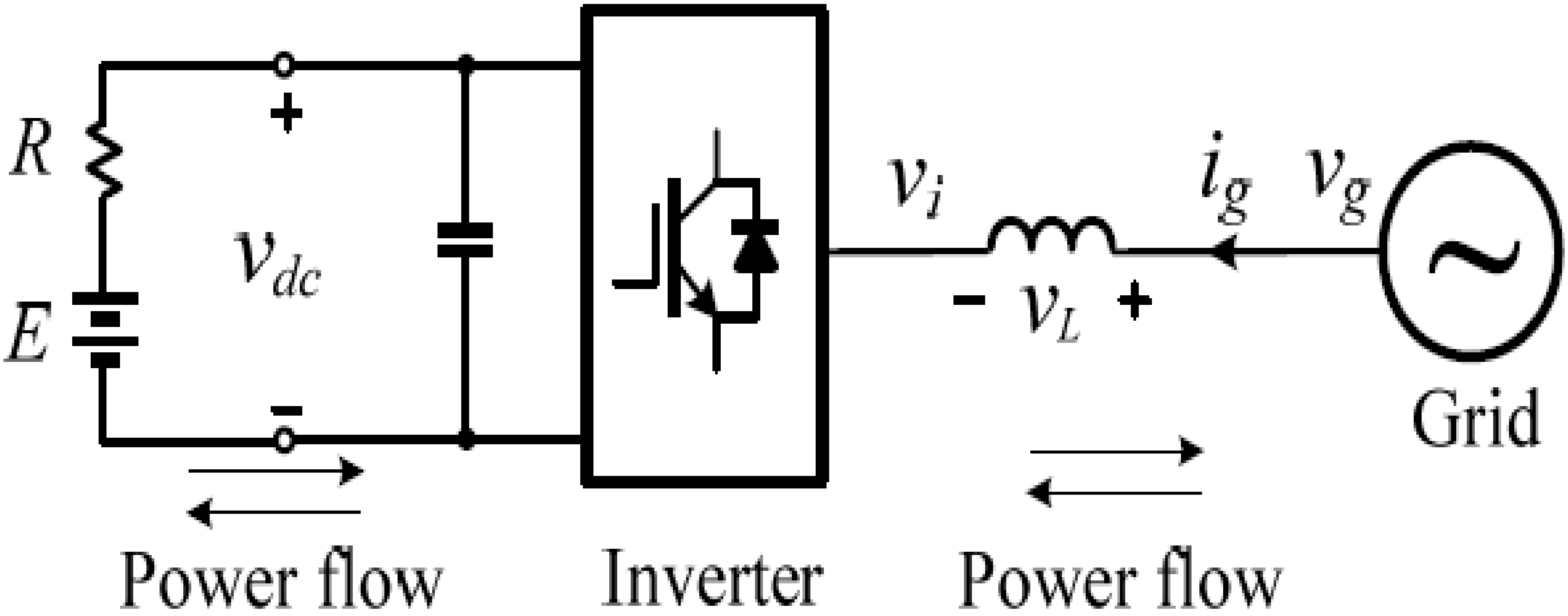
$$P_g = \frac{3}{2} v_{dg} i_{dg} = v_{dc} i_{dc}$$



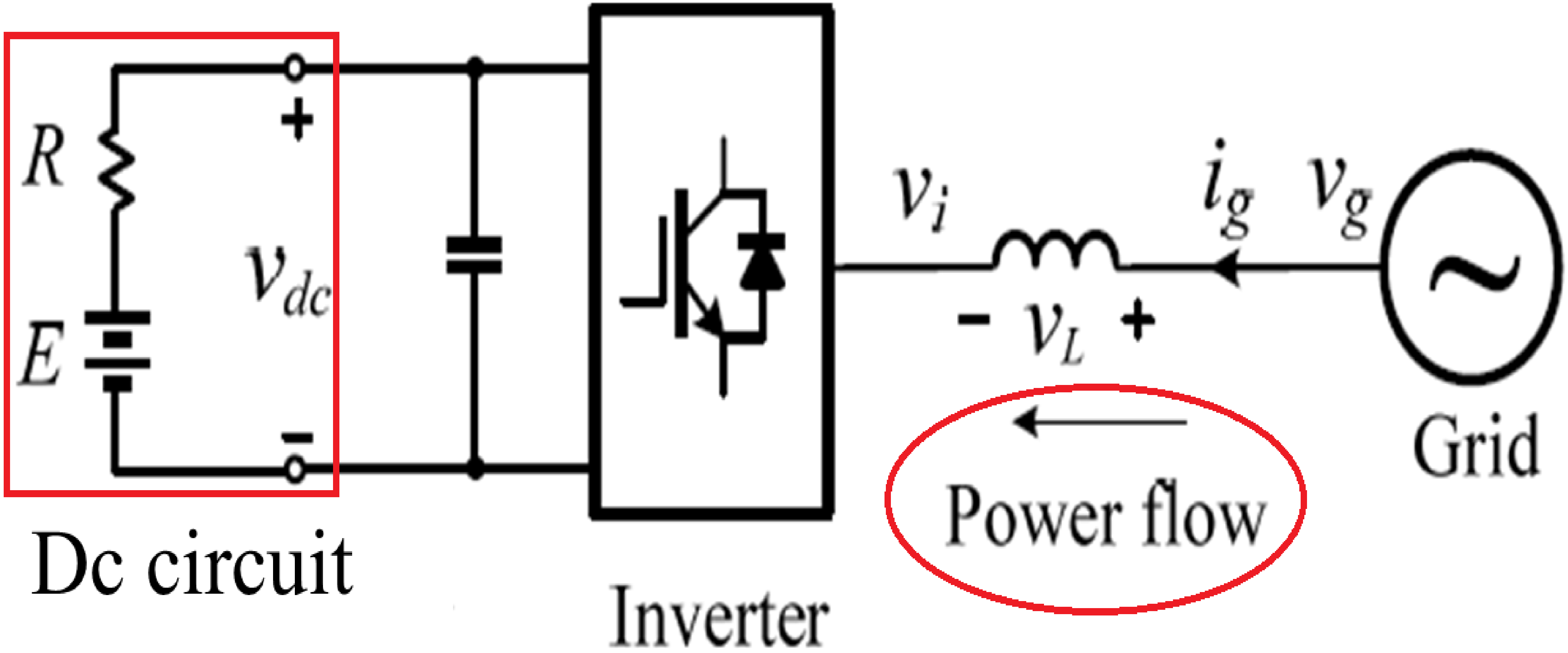
Power flow of inverter system is bidirectional



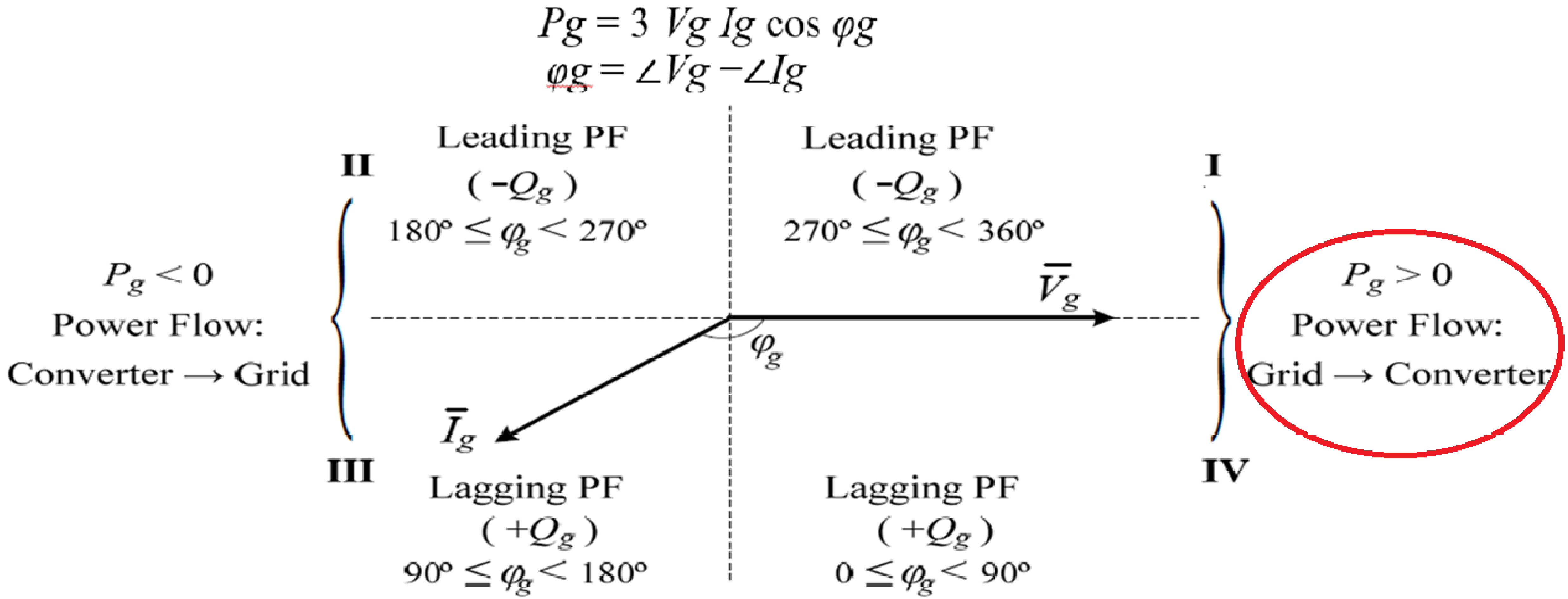
2 operating modes-Rectifying & inverting mode



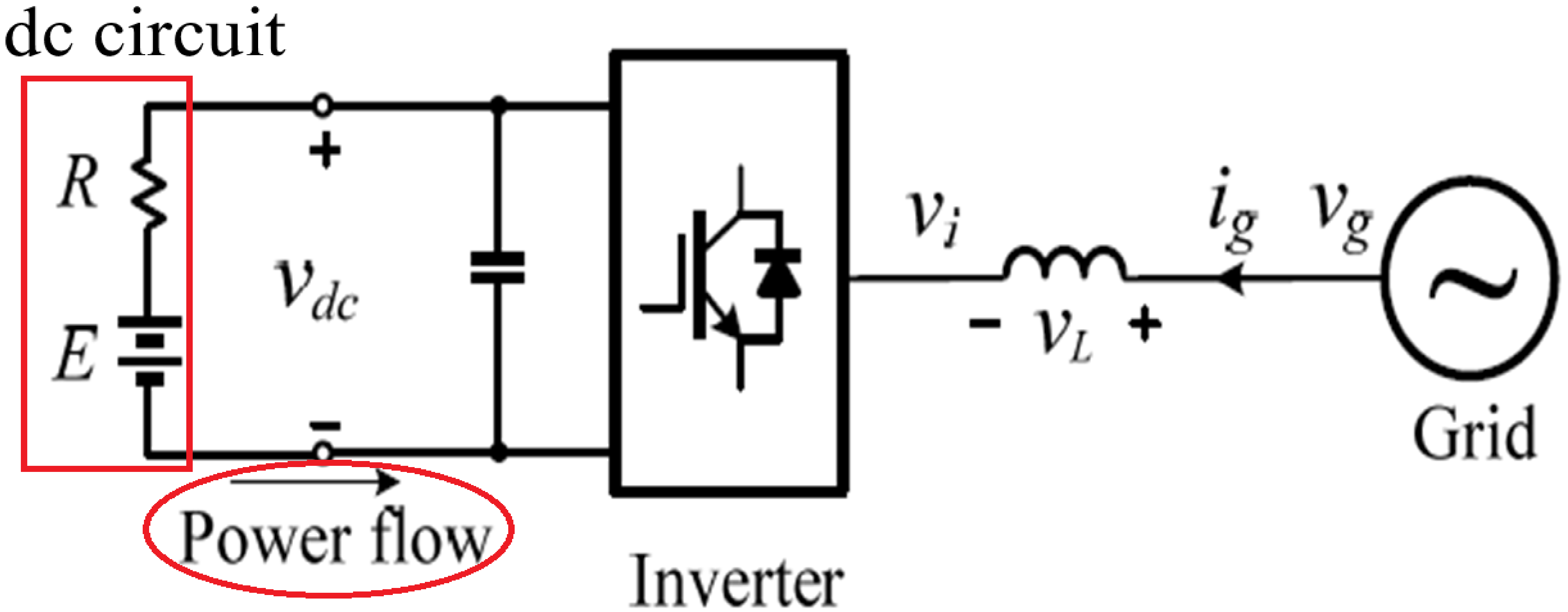
Mode-I When active power is delivered from grid to dc circuit, inverter operates in which mode?



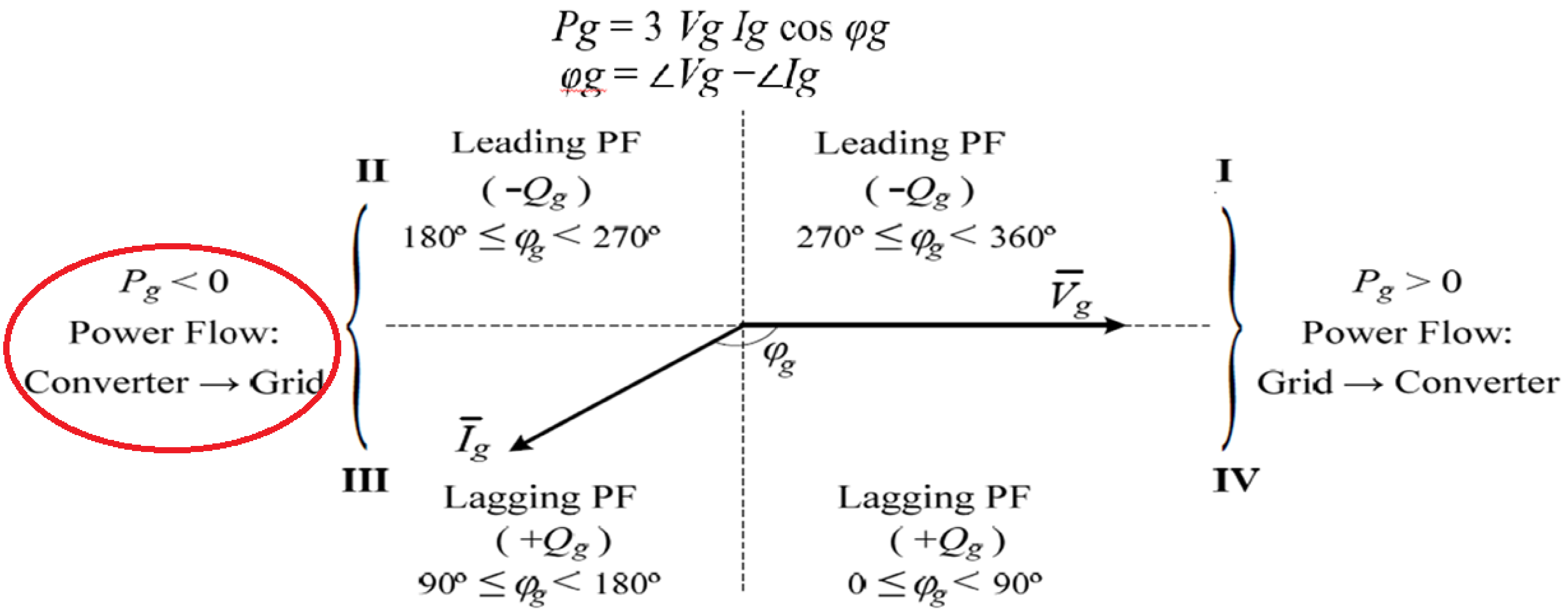
Mode-I When active power is delivered from grid to dc circuit, inverter operates in rectifying mode **& (*Pg* > 0)**



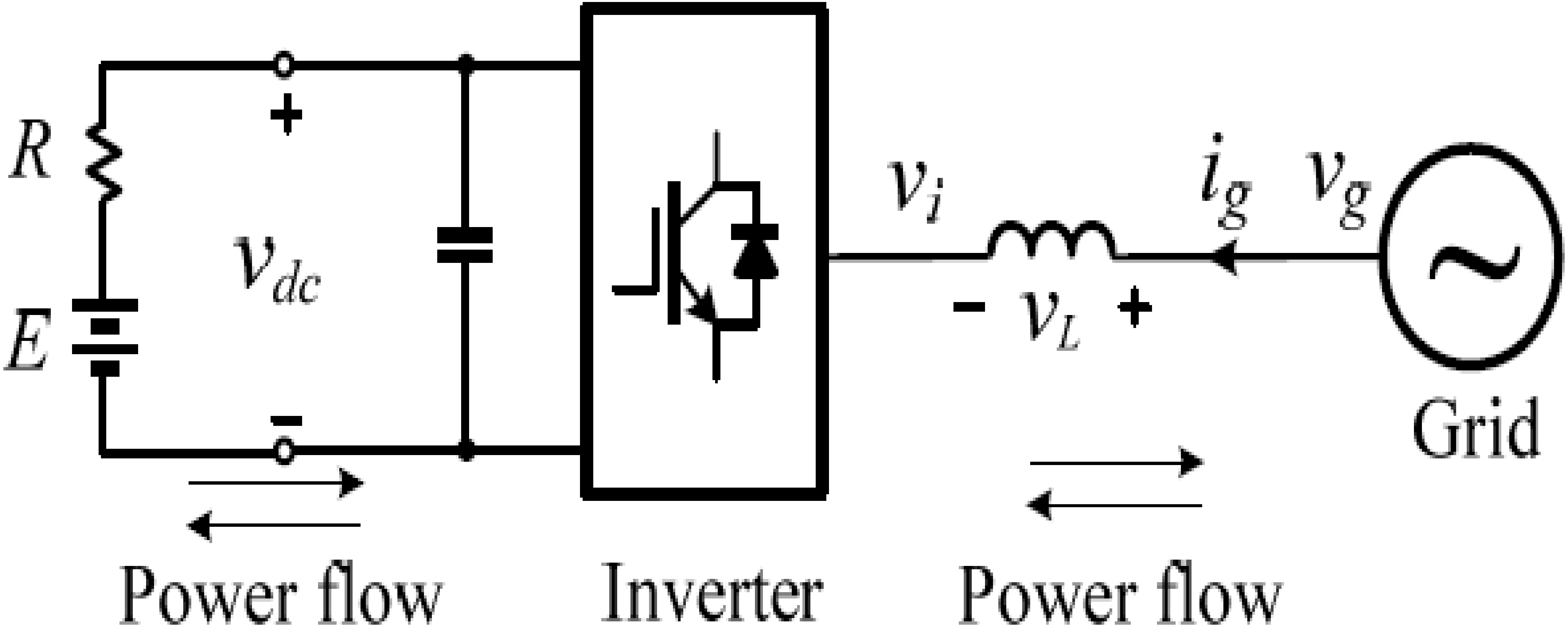
Mode-II When power is transferred from dc circuit to grid, inverter operates in which mode?



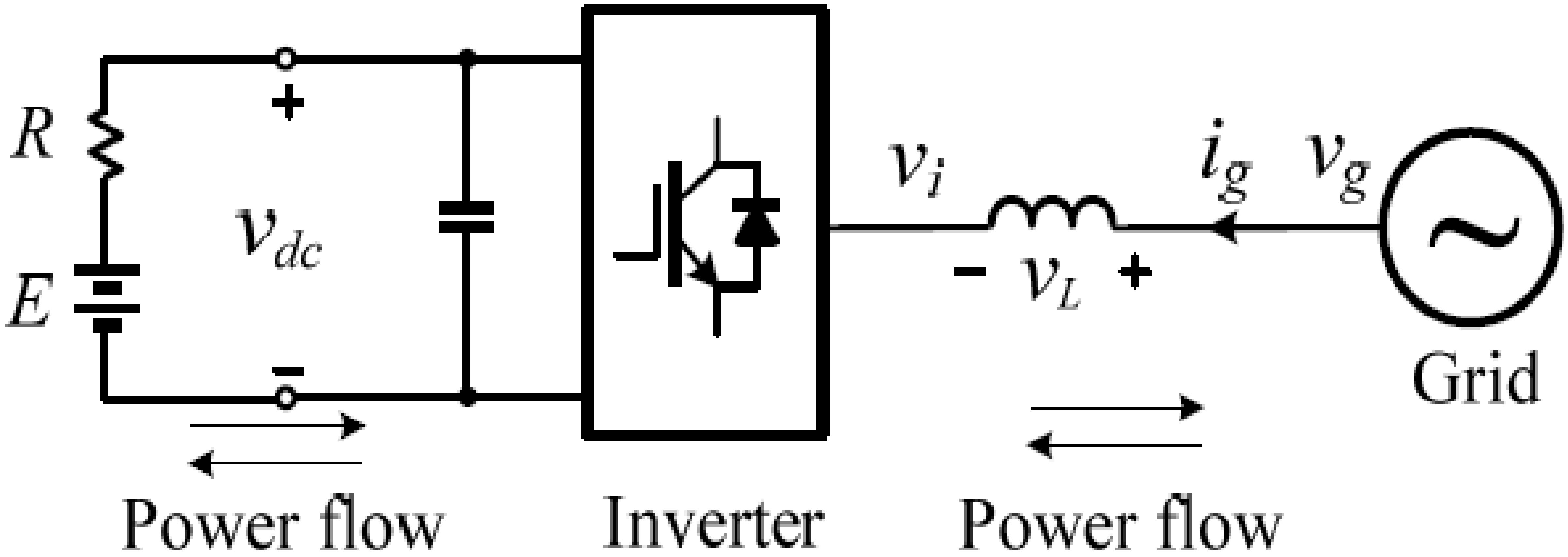
Mode-II When power is transferred from dc circuit to grid, inverter operates in inverting mode & ($Pg < 0$)



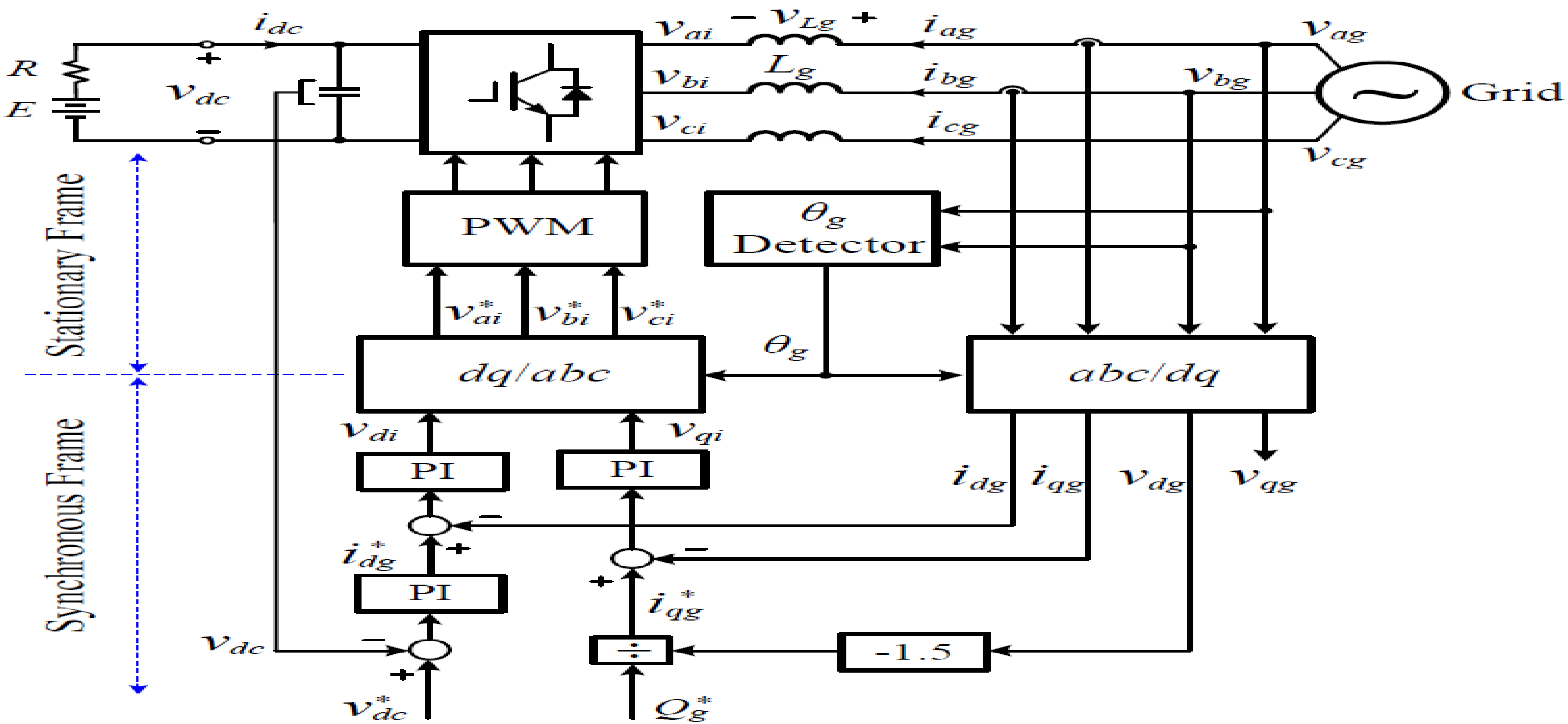
Control system will automatically switch between 2 operating modes & no extra measures should be taken for controller.



To study bidirectional power flow, dc load of inverter can be modelled by a resistor *R* in series with a battery *E*

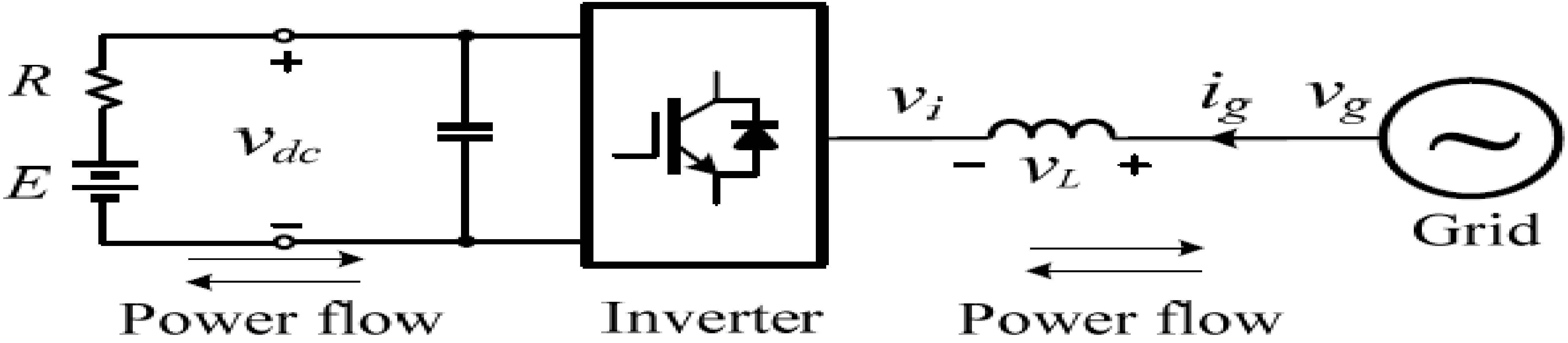


Average dc voltage *Vdc* of inverter is set by its reference & is kept constant by PI controller



Direction of power flow is set by difference between *E* & *Vdc* according to following conditions:

$$\begin{cases} E < V_{dc} \;\rightarrow\; I_{dc} > 0 \;\rightarrow\; P_g > 0 \;\rightarrow \text{Power from grid to load (rectifying mode)} \\ E > V_{dc} \;\rightarrow\; I_{dc} < 0 \;\rightarrow\; P_g < 0 \;\rightarrow \text{Power from load to grid (inverting mode)} \\ E = V_{dc} \;\rightarrow\; I_{dc} = 0 \;\rightarrow\; P_g = 0 \;\rightarrow \text{No power flow between the dc circuit and the grid} \end{cases}$$



To determine an appropriate dc voltage reference v_{dc}^{*} one should take system transients & possible grid voltage variations into account.

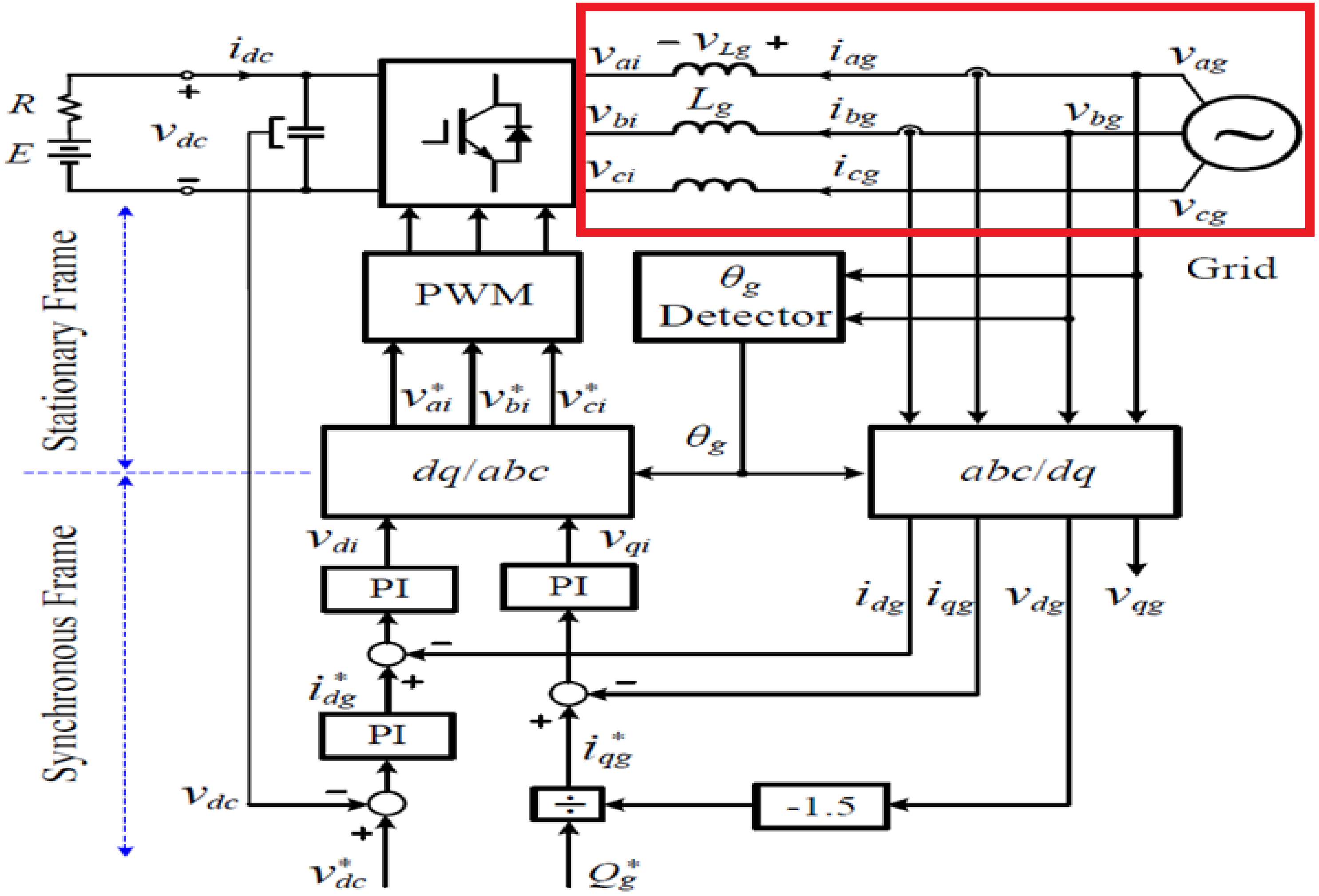
- Assuming that when inverter operates under rated conditions, modulation index *ma*=0.8. Dc reference voltage can then be set by:

$$V_{dc}^{*} = \frac{\sqrt{6}V_{ai1}}{m_a} = \frac{\sqrt{6}}{0.8} = 3.06\,\text{pu} \qquad (V_{ai1} = 1\text{pu})$$

which gives around 20% voltage margin for adjustment during transients & grid voltage variations.

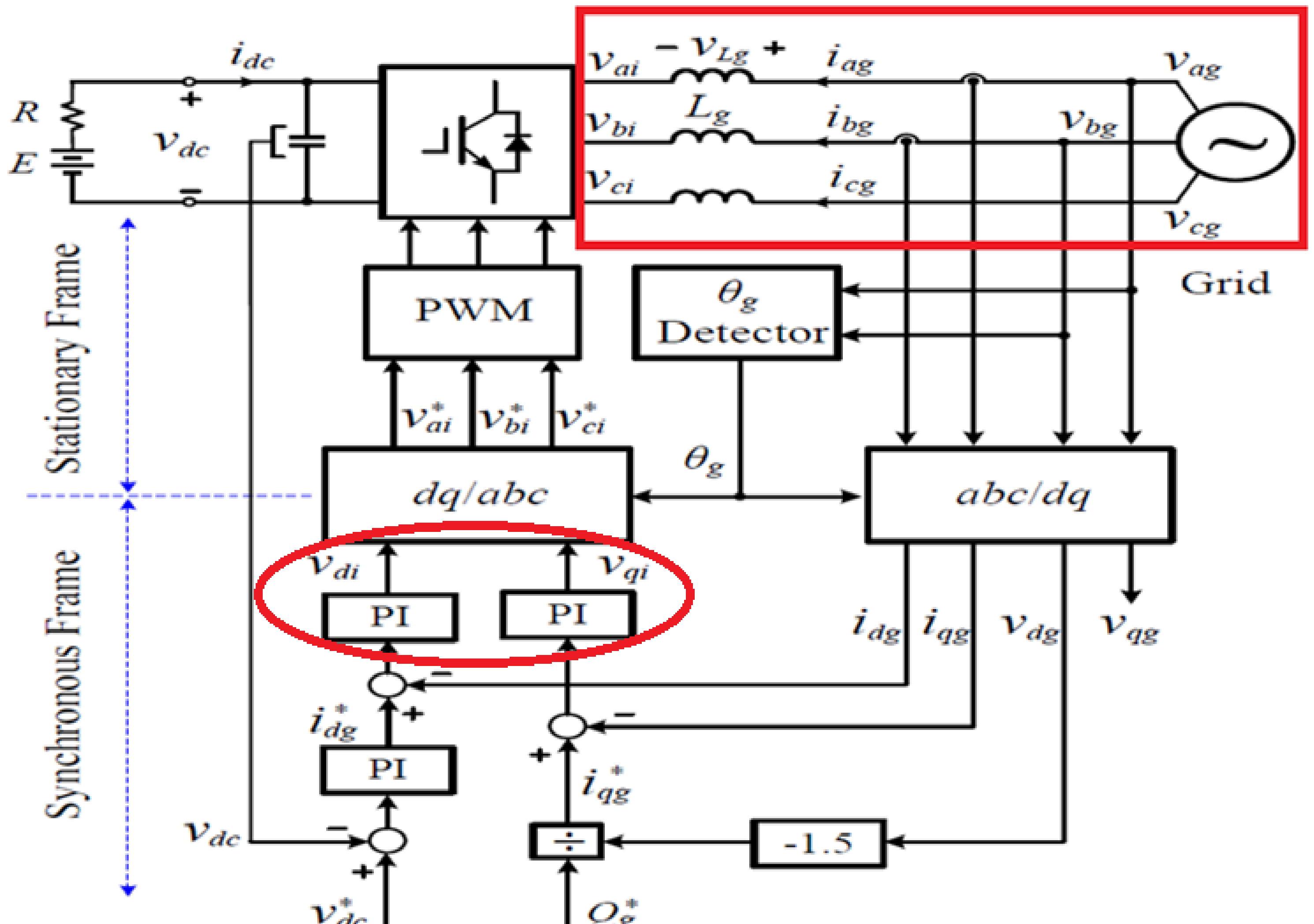
4.7.2 VOC with Decoupled Controller

State equation for grid-side circuit of inverter in *abc* stationary reference frame can be expressed as:



$$
\begin{cases}
\dfrac{di_{ag}}{dt} = \left(v_{ag} - v_{ai}\right) / L_g \\
\dfrac{di_{bg}}{dt} = \left(v_{bg} - v_{bi}\right) / L_g \\
\dfrac{di_{cg}}{dt} = \left(v_{cg} - v_{ci}\right) / L_g
\end{cases}
$$

Equations can be transformed into *dq* synchronous reference frame where controllers for *dq*-axis currents are of PI type. Output of decoupled controller are v_{di} & v_{qi} respectively:



$$
\begin{cases}
\dfrac{di_{ag}}{dt} = (v_{ag} - v_{ai})/L_g \\
\dfrac{di_{bg}}{dt} = (v_{bg} - v_{bi})/L_g \\
\dfrac{di_{cg}}{dt} = (v_{cg} - v_{ci})/L_g
\end{cases}
$$

$$
\begin{cases}
\dfrac{di_{dg}}{dt} = \left(v_{dg} - v_{di} + \omega_g L_g i_{qg}\right)/L_g \\
\dfrac{di_{qg}}{dt} = \left(v_{qg} - v_{qi} - \omega_g L_g i_{dg}\right)/L_g
\end{cases}
$$

where ωg is speed of synchronous reference frame, which is also angular frequency of grid

- $\omega_g L_g i_{qg}$ & $\omega_g L_g i_{dg}$ are induced "speed voltages" due to transformation of 3-phase inductance L_g from stationary reference frame to synchronous frame.

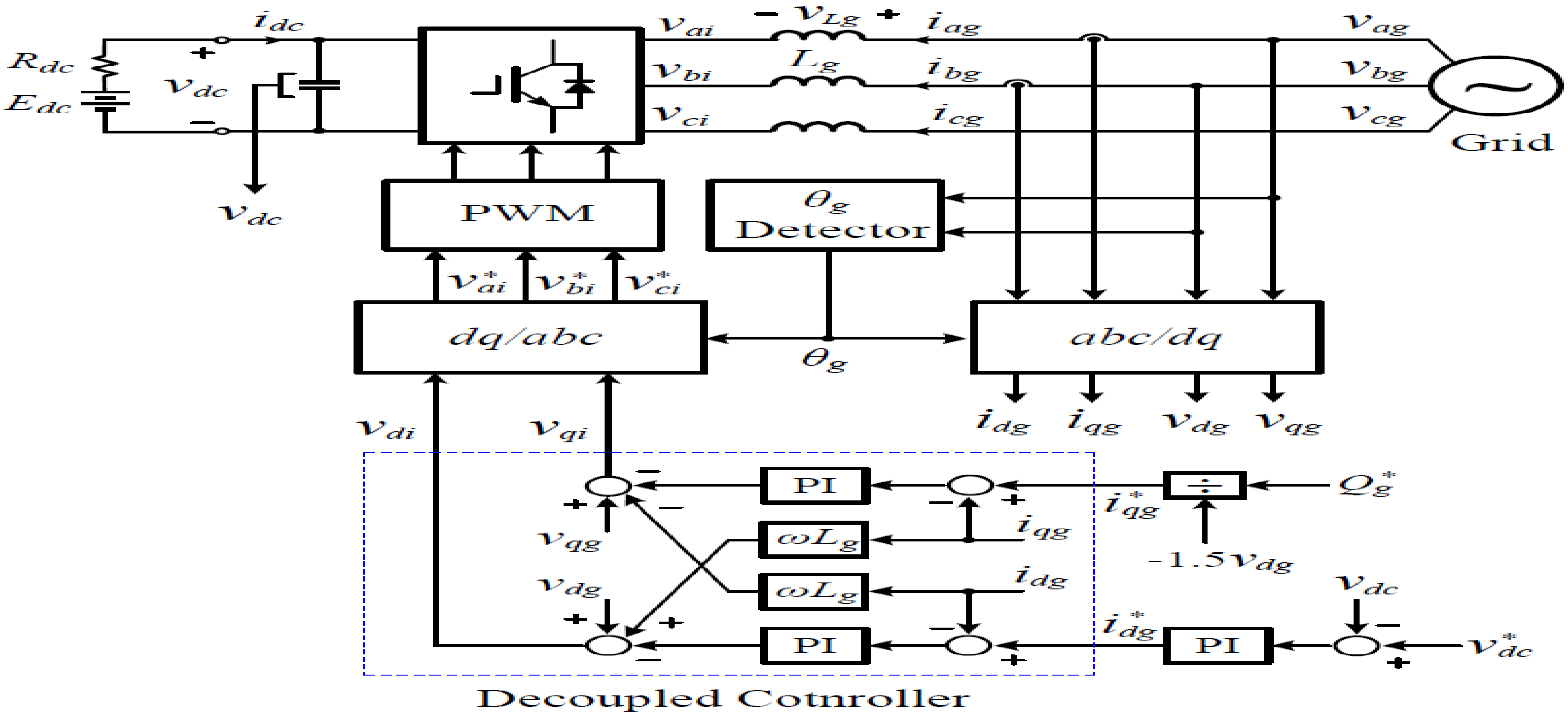
$$\begin{cases} \dfrac{di_{dg}}{dt} = \left(v_{dg} - v_{di} + \omega_g L_g \, i_{qg}\right) / \, L_g \\ \dfrac{di_{qg}}{dt} = \left(v_{qg} - v_{qi} - \omega_g L_g \, i_{dg}\right) / \, L_g \end{cases}$$

Equation illustrates that derivative of *d*-axis line current i_{dg} is related to both *d*- & *q*-axis variables, so is *q*-axis current i_{qg}.

$$\begin{cases} \dfrac{di_{dg}}{dt} = (v_{dg} - v_{di} + \omega_g L_g i_{qg}) / L_g \\ \dfrac{di_{qg}}{dt} = (v_{qg} - v_{qi} - \omega_g L_g i_{dg}) / L_g \end{cases}$$

- This indicates that system control is “cross-coupled”, which may lead to difficulties in controller design & unsatisfactory dynamic performance.

To solve the problem, a decoupled controller shown in Fig. can be implemented.



As the controllers for *dq*-axis currents are of PI type, output of decoupled controller:

$$\begin{cases} v_{di} = -(k_1 + k_2 / S)\left(i_{dg}^* - i_{dg}\right) + \omega_g L_g i_{qg} + v_{dg} \\ v_{qi} = -(k_1 + k_2 / S)\left(i_{qg}^* - i_{qg}\right) - \omega_g L_g i_{dg} + v_{qg} \end{cases}$$

where ($k1 + k2 /S$) is the transfer function of the PI controller.

Substituting

$$\begin{cases} v_{di} = -(k_1 + k_2 / S)\left(i_{dg}^* - i_{dg}\right) + \omega_g L_g i_{qg} + v_{dg} \\ v_{qi} = -(k_1 + k_2 / S)\left(i_{qg}^* - i_{qg}\right) - \omega_g L_g i_{dg} + v_{qg} \end{cases}$$

into

$$\begin{cases} \dfrac{di_{dg}}{dt} = \left(v_{dg} - v_{di} + \omega_g L_g \, i_{qg}\right) / L_g \\ \dfrac{di_{qg}}{dt} = \left(v_{qg} - v_{qi} - \omega_g L_g \, i_{dg}\right) / L_g \end{cases}$$

yields

$$\begin{cases} \dfrac{di_{dg}}{dt} = (k_1 + k_2 / S)\left(i_{dg}^* - i_{dg}\right) / L_g \\ \dfrac{di_{qg}}{dt} = (k_1 + k_2 / S)\left(i_{qg}^* - i_{qg}\right) / L_g \end{cases}$$

$$\begin{cases} \dfrac{di_{dg}}{dt} = (k_1 + k_2 / S)\left(i_{dg}^* - i_{dg}\right) / L_g \\ \dfrac{di_{qg}}{dt} = (k_1 + k_2 / S)\left(i_{qg}^* - i_{qg}\right) / L_g \end{cases}$$

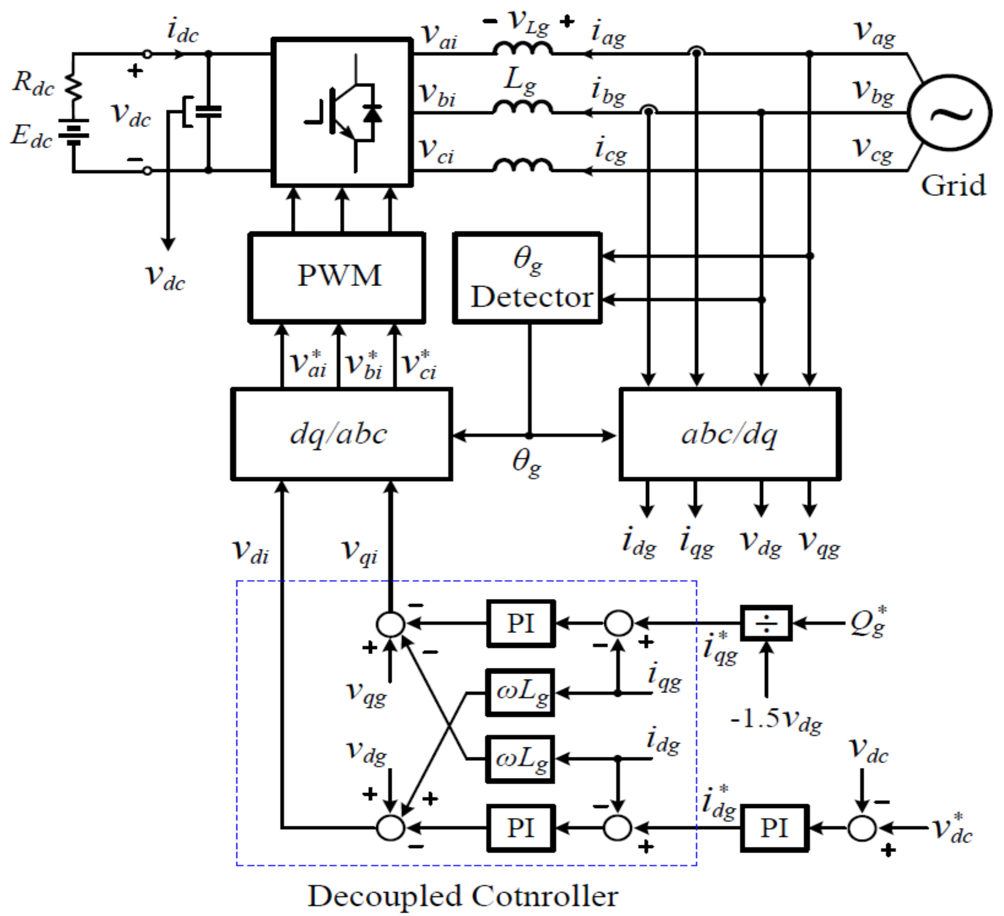
- Above equation indicates that control of *d*-axis grid current i_{dg} is decoupled, involving only *d*-axis components, so is *q*-axis current i_{qg}.
- Decoupled control makes design of PI controllers more convenient, & system is easier to be stabilized.

4.7.3 Operation of Grid-Connected Inverter with VOC and Reactive Power Control

- The operation of the grid-tied inverter with VOC and reactive power control is analyzed through a case study:

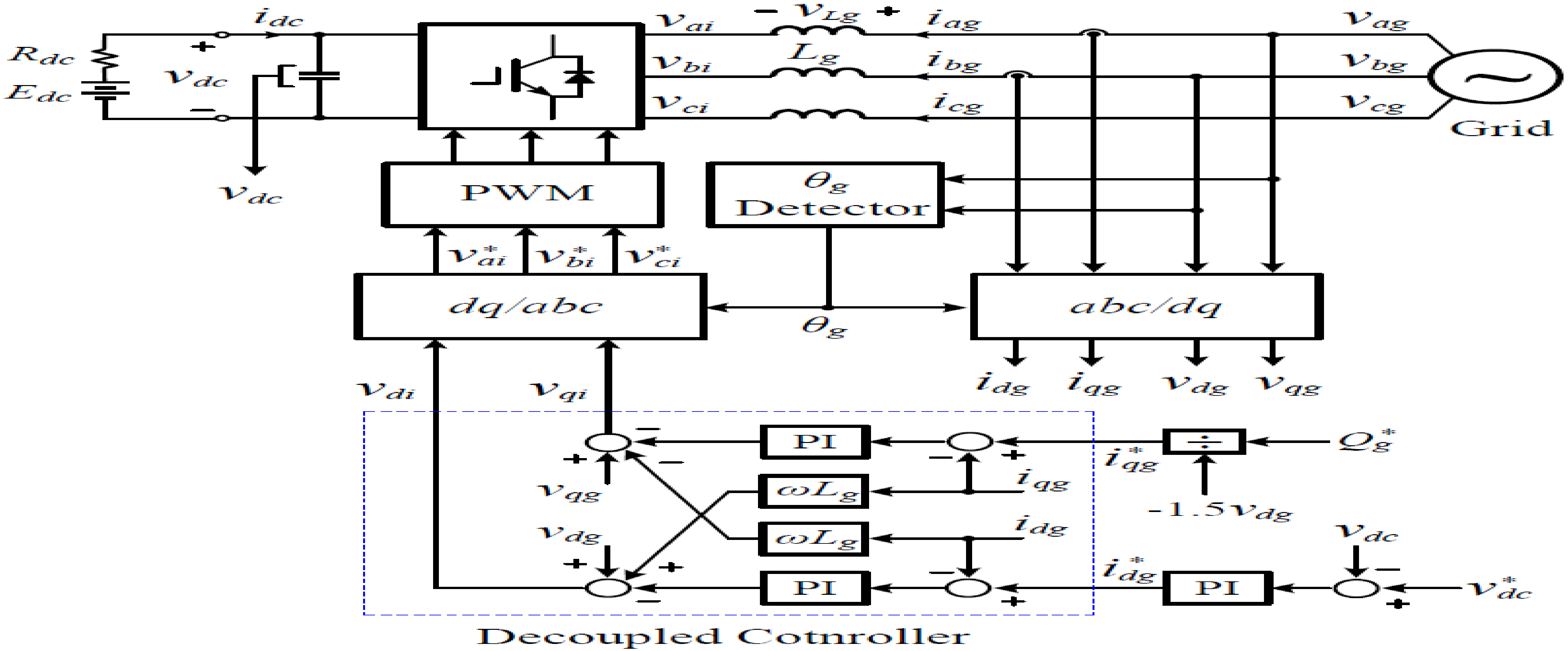
Case Study 4-6 Operation and Analysis of Grid-connected Inverter

- Consider a 2.3MW/690V grid-connected inverter.
- This inverter is controlled by the VOC scheme with a decoupled PI controller as shown in Fig.



Dc reference is set to 1220V=3.06 pu as specified by

$$V_{dc}^{*} = \frac{\sqrt{6}V_{ai1}}{m_a} = \frac{\sqrt{6}}{0.8} = 3.06\,\text{pu} \qquad (V_{ai1} = 1\text{pu})$$

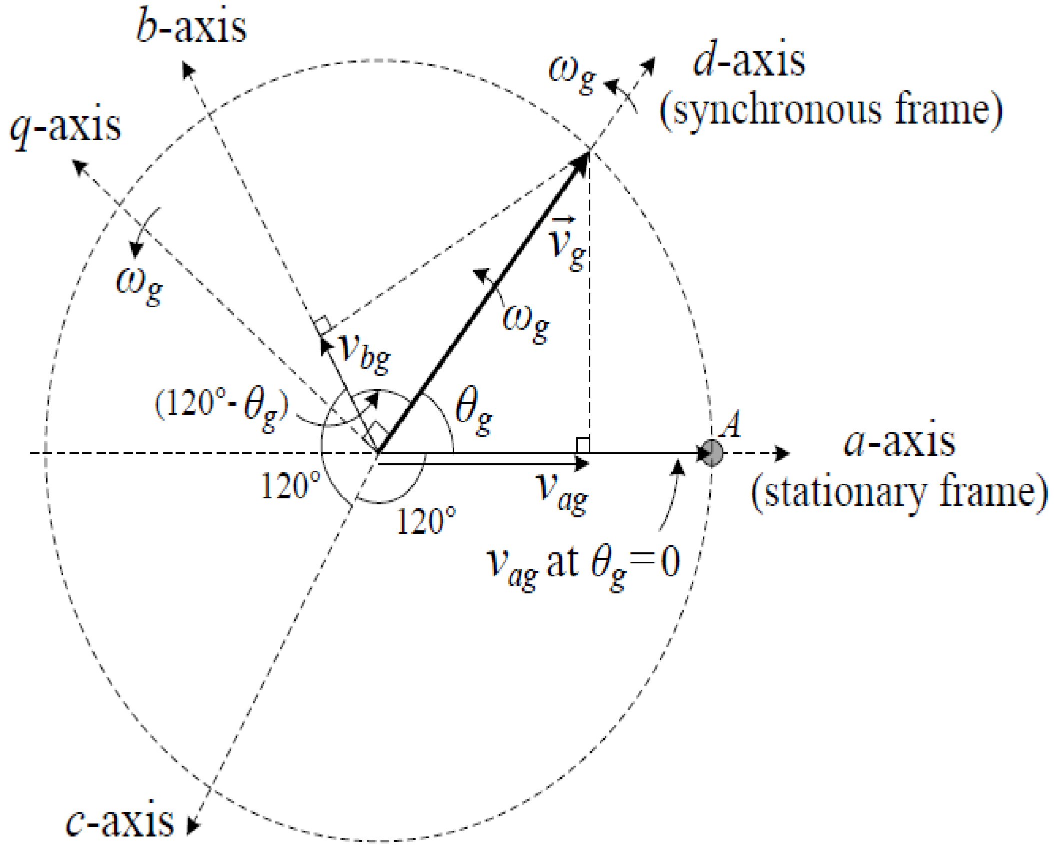


The system parameters and operating conditionsof grid-connected inverter are given in Table

Inverter ratings	2.3MW/690V/1924.5A	
Control scheme	VOC with decoupled PI controller	Fig. 4.7-4
System input references	v_{dc}^*	1220V (3.062 pu)
	Q_g^*	Adjustable
Inverter	Converter type	Two-level VSC
	Modulation scheme	Space vector modulation
	Switching frequency	2.04kHz
DC link circuit	Resistance R	0.0207 Ohms (0.1 pu)
	Battery E	1259 V (3.16 pu)
Electric grid	Grid voltage/frequency	690V/60Hz
	Line inductance	0.1098 mH (0.2 pu)
Reference Frame Transformation	*abc/dq* and *dq/abc* transformation	Eqs. (3.2-1) and (3.2-2), Chapter 3

Fig. illustrates the space vector diagram for the grid voltage vector $\vec{v}_g$

- With the VOC scheme, $\vec{v}_g$ is aligned with the *d*-axis of the synchronous frame, and
- rotates in space at the synchronous speed of *ωg*, which is also the grid angular frequency given by: $\omega_g = 2\pi f_g$
- where *fg* is the frequency of the grid voltage.



- The q-axis voltage v_{qg} of the space vector $\vec{v}_g$ is 0, and d-axis voltage v_{dg} is equal to v_g, which is the magnitude (peak value) of $\vec{v}_g$

- The angle ϑ_g of the vector is referenced to the a-axis of the stationary frame.

Based on $\vec{v}_g$ and ϑg in Fig., the 3-phase grid voltage in the stationary frame reconstructed by

$$\begin{cases} v_{ag} = v_g \cos\theta_g = v_g \cos\omega_g t \\ v_{bg} = v_g \cos\left(\theta_g - 120^\circ\right) = v_g \cos\left(\omega_g t - 120^\circ\right) \\ v_{cg} = v_g \cos\left(\theta_g - 240^\circ\right) = v_g \cos\left(\omega_g t - 240^\circ\right) \end{cases}$$

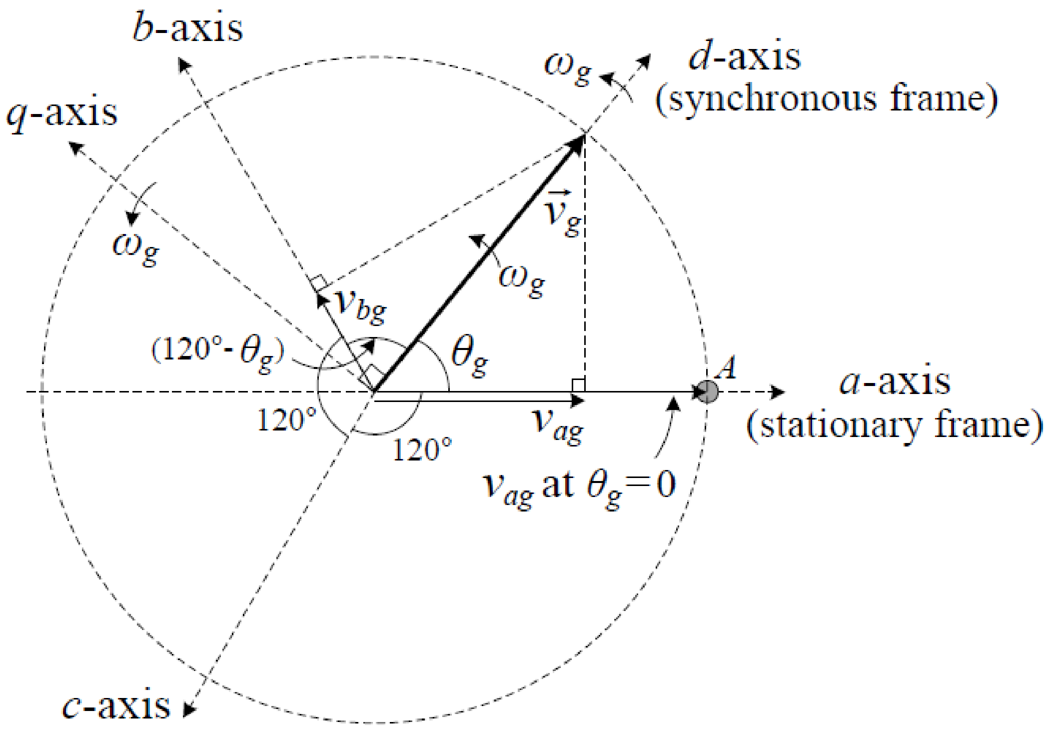
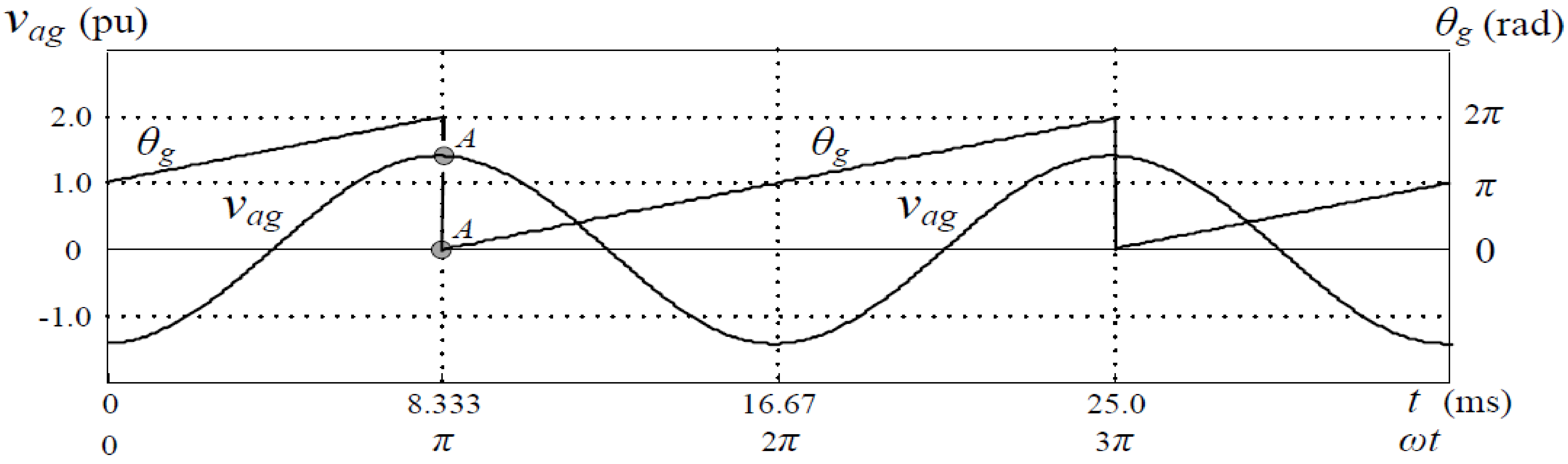
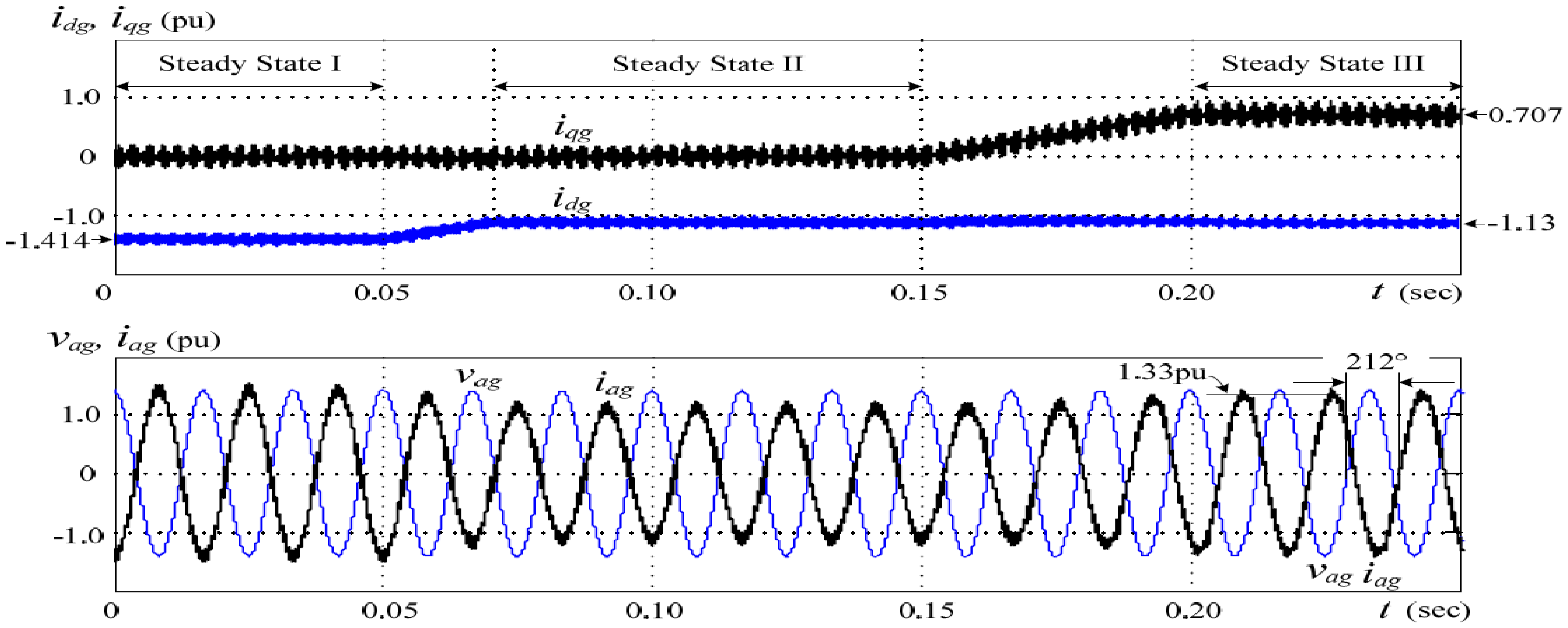


Fig. shows the waveforms of the phase-*a* grid voltage *vag* and the space angle ϑg .

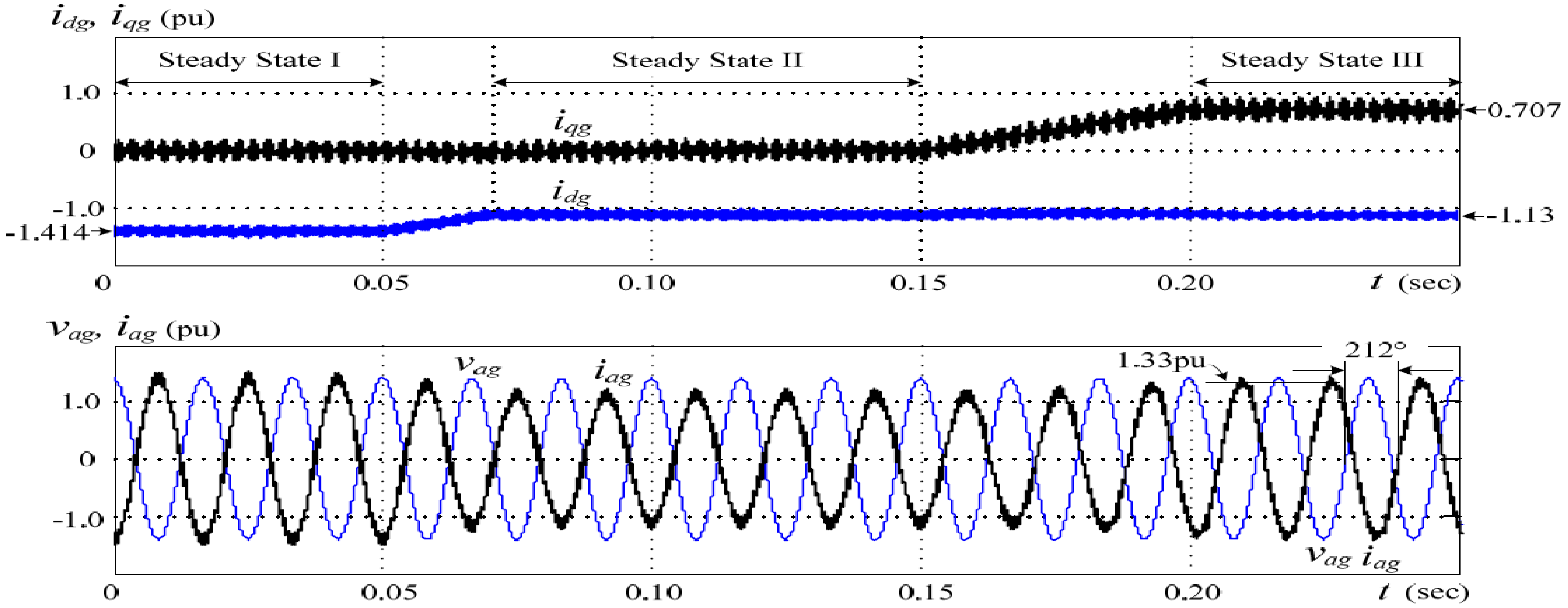
- When $\vec{v}_g$ rotates in space, ϑg and *vag* varies from 0 to 2π periodically.
- When ϑg is equal to 0, *vdg* reaches its peak value as shown at Point *A* in Fig.



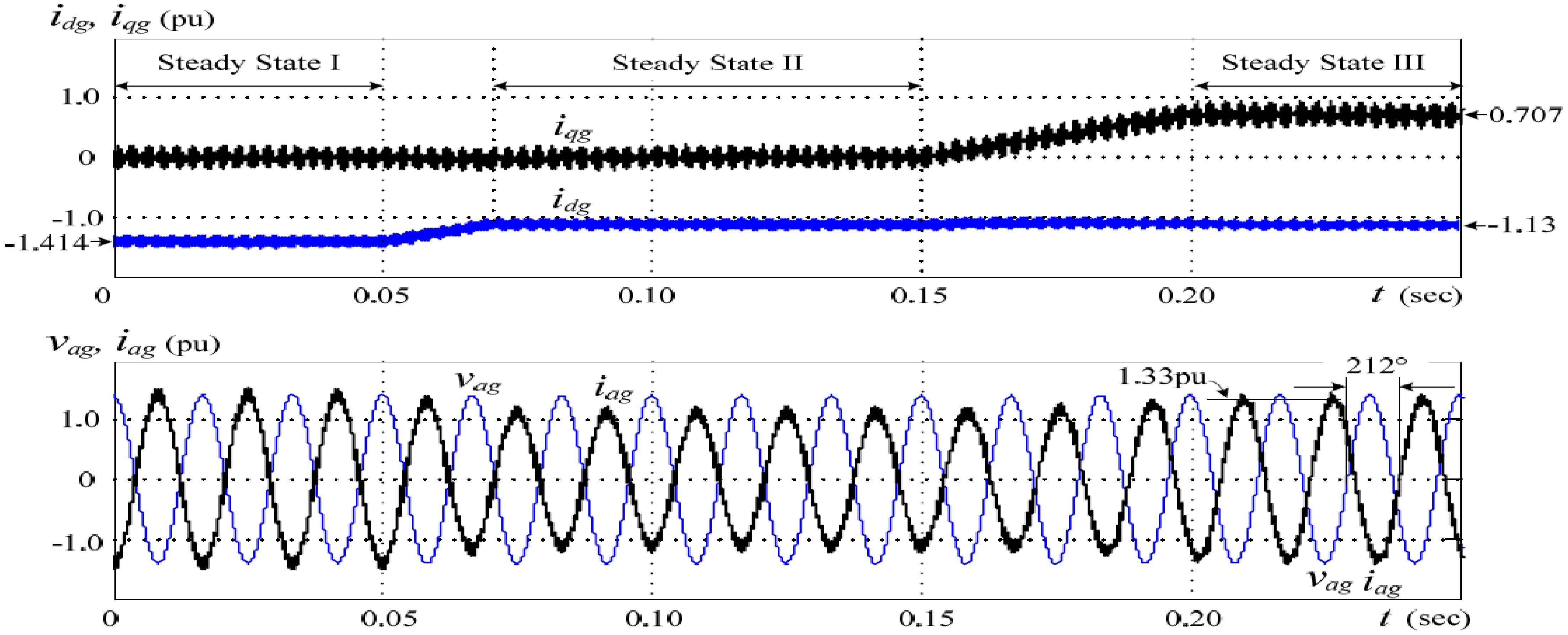
Transient waveforms of inverter are shown, where inverter initially delivers rated active power (*Pg* = -1 pu) and 0 reactive power (*Qg* = 0) to grid.



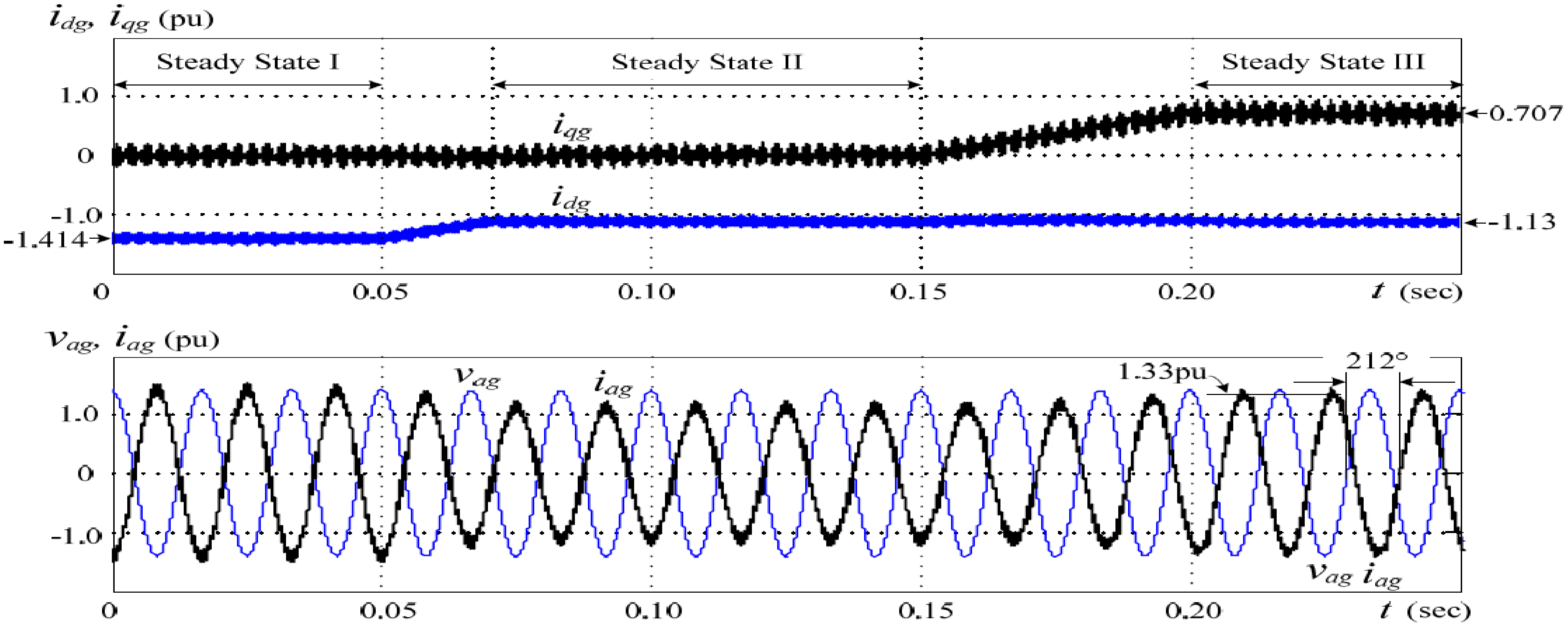
Ignoring all the ripples (produced by current harmonics), the d-axis current idg =-1.41 pu (rated) and 0 q-axis current iqg=0.



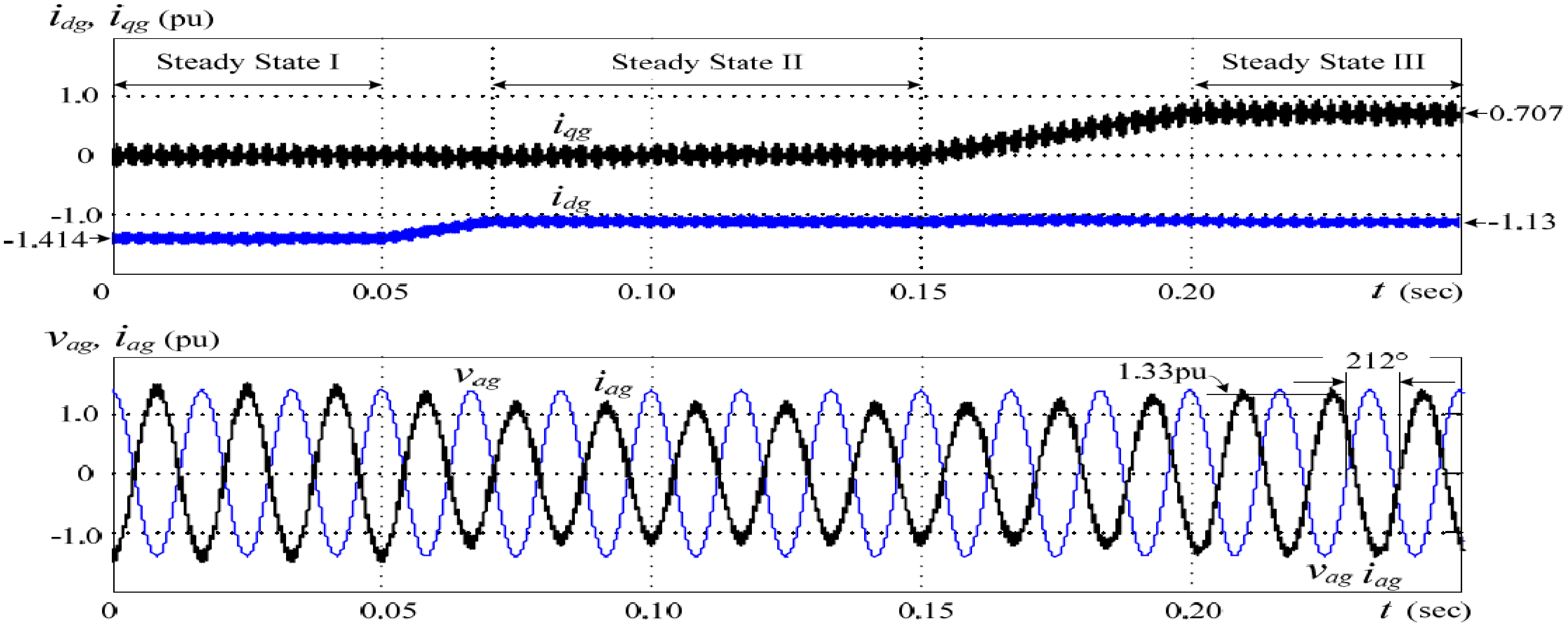
Corresponding waveforms of phase-*a* grid voltage and current during transient are also shown.



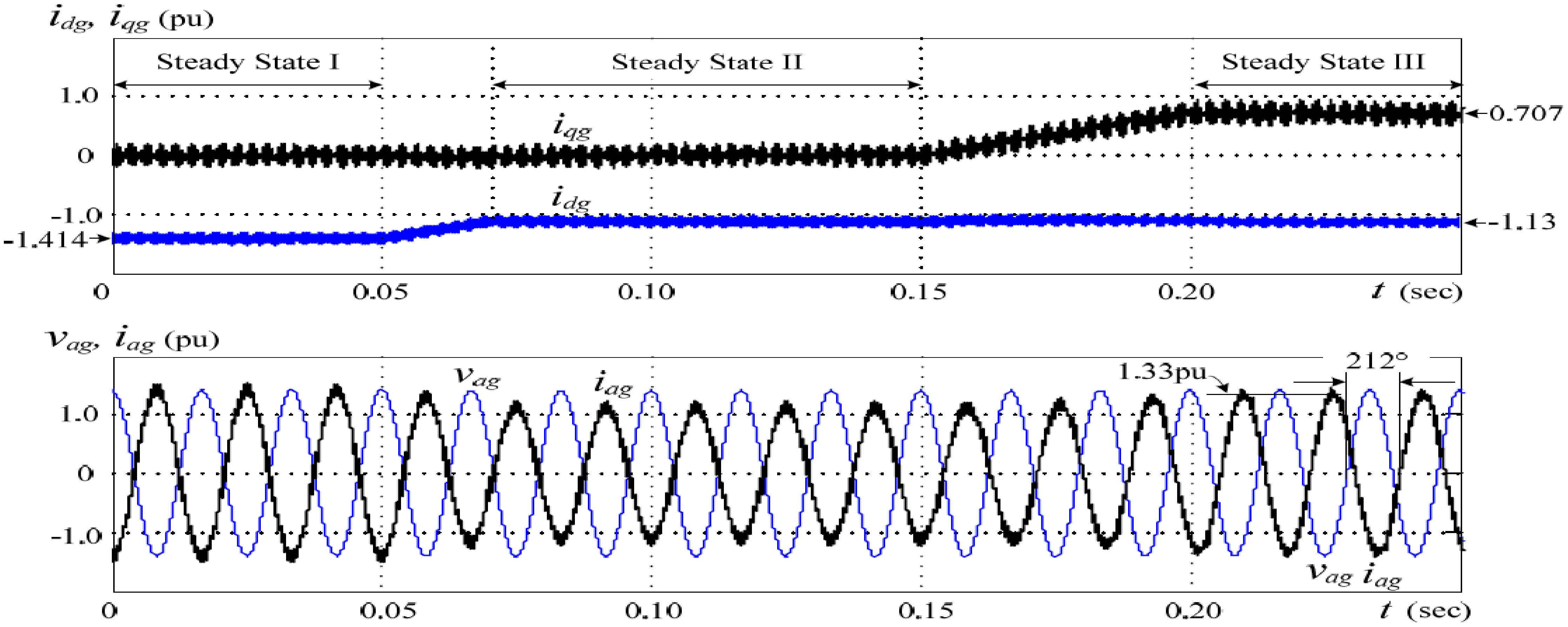
At t = 0.05 sec, battery voltage E starts to reduce such that active power to grid is reduced to 0.8pu around t = 0.075 sec, which leads reduction of the d-axis current from its rated value to -1.13pu (2 ×0.8).



q-axis current remains unchanged during transients due to decoupled control of active and reactive power.



Magnitude of the phase-*a* grid current *iag* is reduced, but kept out of phase with its voltage.



At t = 0.15 sec, reference for reactive power Qg^* starts to vary from 0 to -0.5pu, demanding a leading power factor operation.

- q-axis current i_{qg} reaches 0.707pu at t = 0.20 sec, which is ½ of rated value. The d-axis current is almost kept constant during the

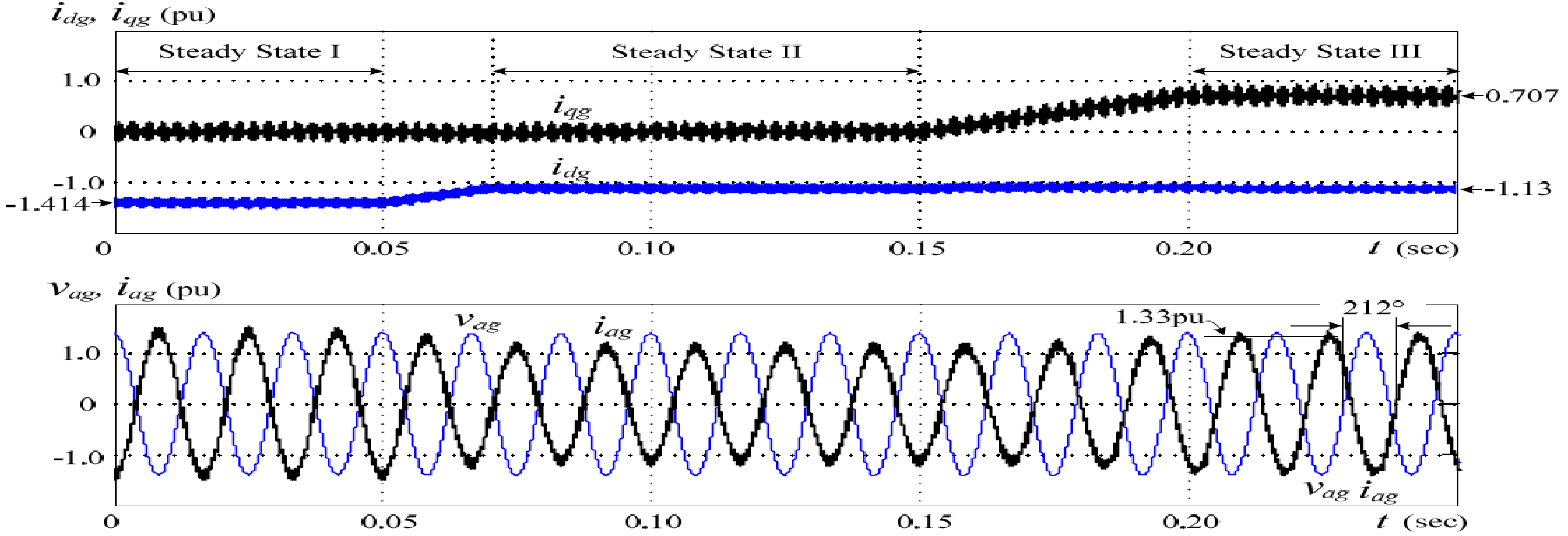
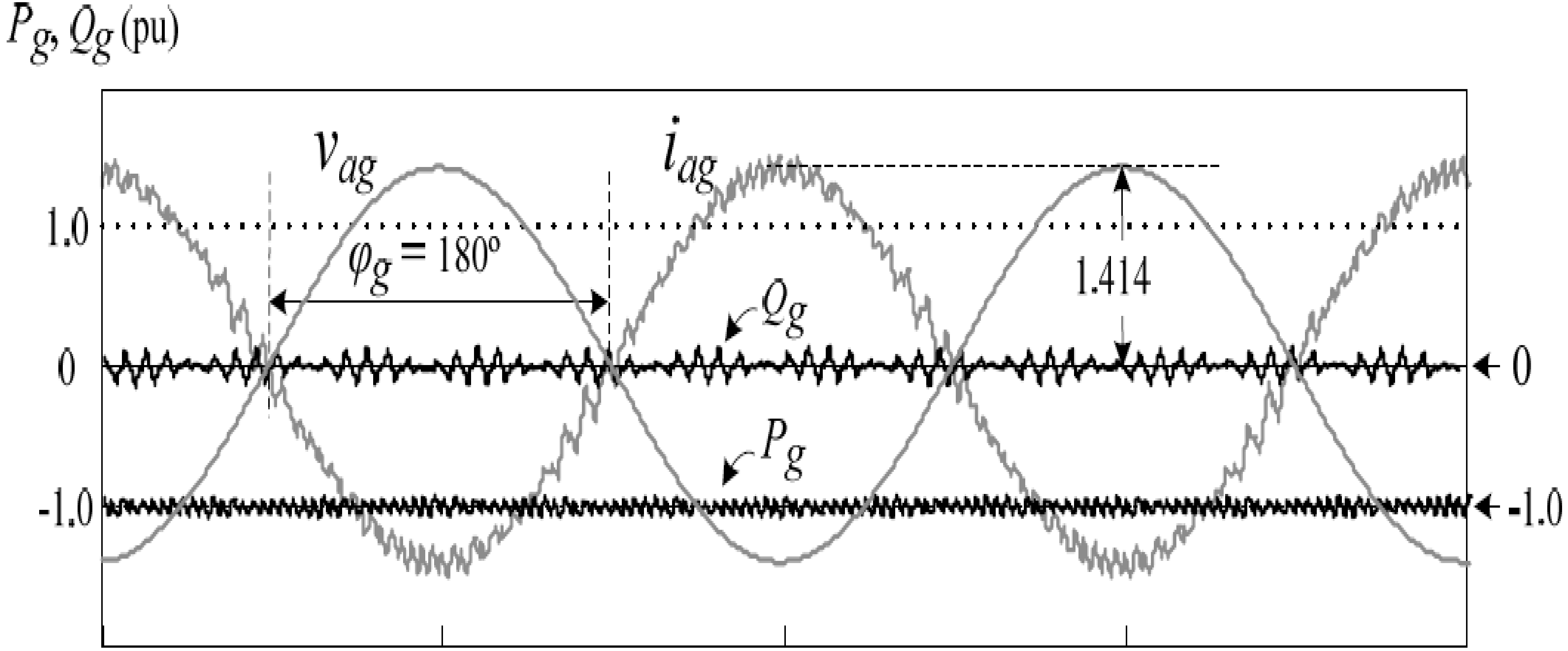


Fig. shows simulated waveforms of inverter operating in Steady State I

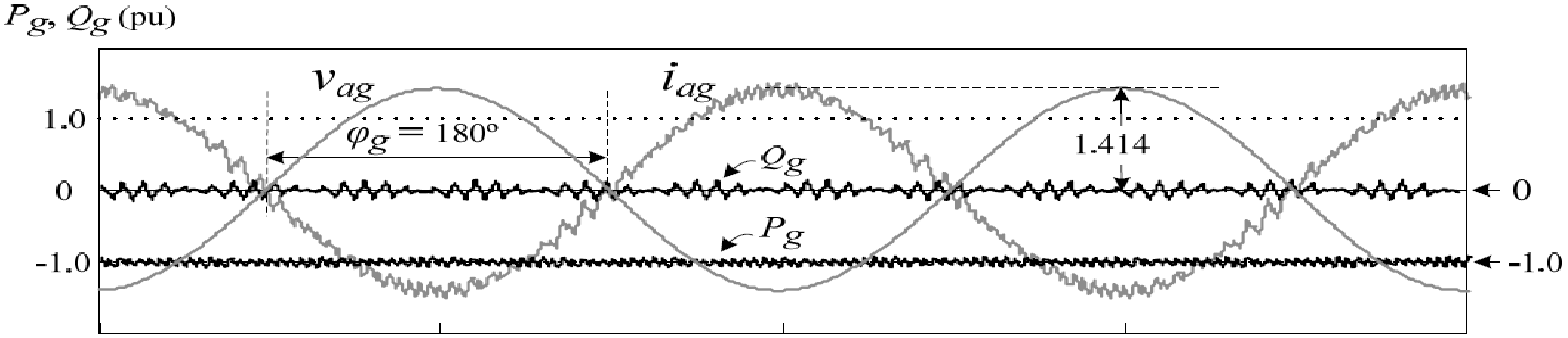


(a) Steady-state operation I

Peak value of the phase-*a* grid current *iag* is 1.41 pu (rated). Grid current *iag* is out of phase with its voltage *vag*. Active power delivered to grid is

$$P_g = V_{ag} I_{ag} \cos\varphi_g = \frac{i_{ag}}{\sqrt{2}} \times \frac{v_{ag}}{\sqrt{2}} \times \cos 180^\circ = -1\text{pu}$$

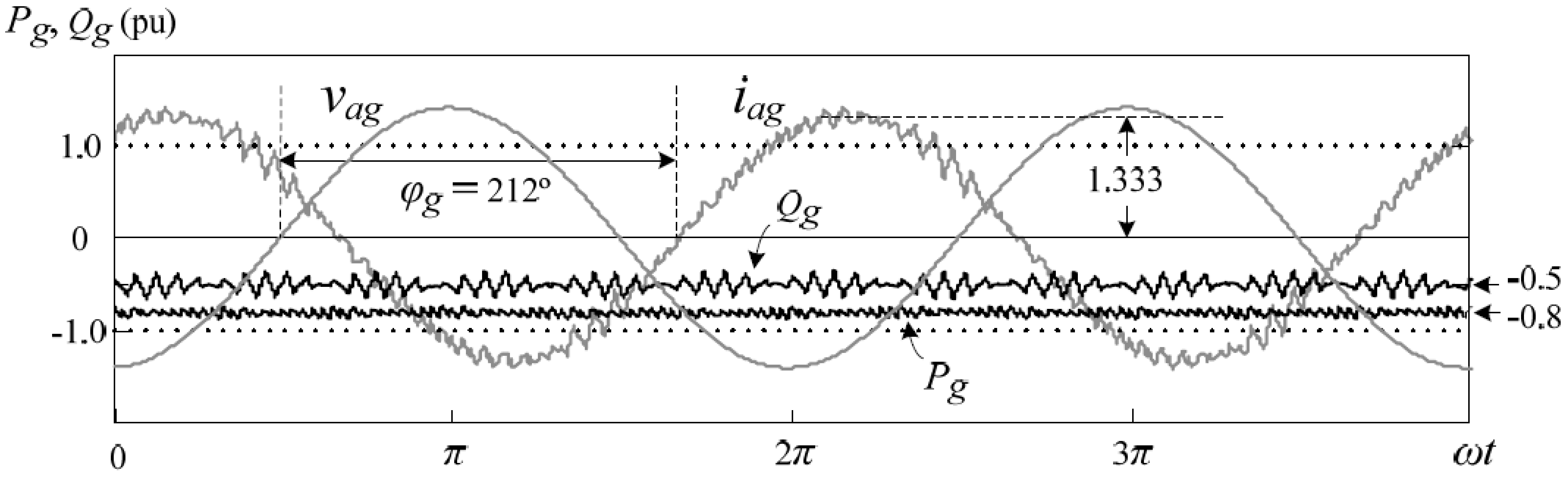
-ve value in above equation indicates that inverter delivers the active power to grid.



(a) Steady-state operation I

Fig. shows simulated waveforms when system reaches Steady State III .

- Measured phase-*a* current *iag*=1.33 pu, which lags phase-*a* voltage *vag* by 212°.

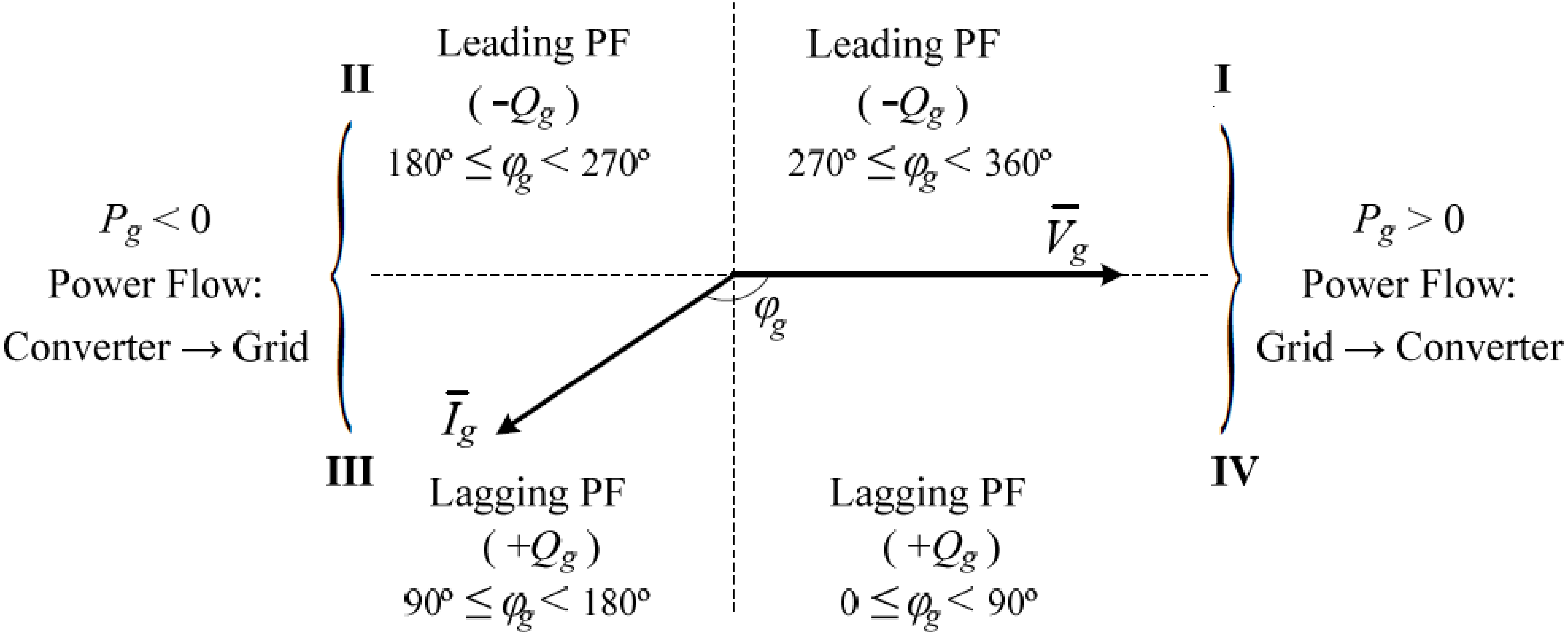


Active and reactive power to the grid can be calculated by

$$P_g = V_{ag} I_{ag} \cos\varphi_g = \frac{1.333}{\sqrt{2}} \times \frac{1.414}{\sqrt{2}} \times \cos 212^\circ = -0.8\text{pu}$$

$$Q_g = V_{ag} I_{ag} \cos\varphi_g = \frac{1.333}{\sqrt{2}} \times \frac{1.414}{\sqrt{2}} \times \sin 212^\circ = -0.5\text{pu}$$

-ve reactive power indicates that inverter operates with leading (capacitive) power factor, which corresponds to operation in Quadrant II of Fig.



b) Phasor digram and PF

In the practical WECS

- Capacitive leading power operation is often required to support the grid voltage.