UNIVERSITY OF ENGINEERING AND TECHNOLOGY LAHORE

Assignment # 2

Analysis of DFIG with Unbalanced Stator Voltage

Course Title: Control of Electric Machine Drives

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DEPARTMENT OF ELECTRICAL ENGINEERING

EE 535: Control of Electric Machine Drives

Analysis of DFIG with Unbalanced Stator Voltage

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Introduction

This case study presented DFIG sub-synchronous operation during unbalanced stator voltage conditions. Converter control was devised to mitigate unbalance effect of torque and power ripples, while making sure that no reactive power was delivered to the grid by the Stator or DC Link.

Induction Machine dq0-axis Reference Frame Model

A complex vector-based dq0-axis Reference Frame Model was built to demonstrate the dynamics of an induction machine. All variables were in per unit and the model was simulated in synchronous frame of reference. A complex vector was treated as two real variables with the q-axis leading the d-axis by 90°. The rotor speed was fixed at 0.95 p.u. DFIG control relied on stator flux-oriented reference frame, hence stator voltage and flux was aligned with the q-axis (ψ_{qs} = 0 and v_{ds} = 0).

The d-, q- and 0-axis Voltage Equations were

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{0s} \\ v_{qr} \\ v_{qr} \\ v_{0r} \end{bmatrix} = \begin{bmatrix} R_s + \frac{p}{\omega_b} X_s & \frac{\omega_s}{\omega_b} X_s & 0 & \frac{p}{\omega_b} X_m & \frac{\omega_s}{\omega_b} X_s & 0 \\ -\frac{\omega_s}{\omega_b} X_s & R_s + \frac{p}{\omega_b} X_s & 0 & -\frac{\omega_s}{\omega_b} X_m & \frac{p}{\omega_b} X_m & 0 \\ 0 & 0 & R_s + \frac{p}{\omega_b} X_{ls} & 0 & 0 & 0 \\ \frac{p}{\omega_b} X_m & \frac{\omega_s - \omega_r}{\omega_b} X_m & 0 & R_r + \frac{p}{\omega_b} X_r & \frac{\omega_s - \omega_r}{\omega_b} X_r & 0 \\ -\frac{\omega_s - \omega_r}{\omega_b} X_m & \frac{p}{\omega_b} X_m & 0 & -\frac{\omega_s - \omega_r}{\omega_b} X_r & R_r + \frac{p}{\omega_b} X_r & 0 \\ 0 & 0 & 0 & 0 & 0 & R_r + \frac{p}{\omega_b} X_{lr} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \\ i_{qr} \\ i_{dr} \\ i_{0r} \end{bmatrix}$$

DFIG Rotor Side Converter Control

1. Positive Sequence Controller

The output real power and reactive power from stator circuit was controlled via iqr and idr respectively. Feedback controllers were designed to generate the desired dq+ rotor voltages.

$$v_{qr} = r_r i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_{sl}\psi_{dr} = r_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + \omega_{sl}(\sigma L_r i_{dr} + \frac{L_m}{L_s}\psi_{ds})$$

$$v_{dr} = r_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_{sl}\psi_{qr} = r_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - \omega_{sl}\sigma L_r i_{qr}$$

2. Negative Sequence Controller

For a given negative-sequence stator voltage, negative sequence rotor voltage generated by the RSC was used to eliminate the negative sequence rotor current, the negative sequence stator current and the torque pulsation.

$$T_e = T_{edc} + T_{ecos}\cos(2\omega_e t) + T_{esin}\sin(2\omega_e t)$$

$$T_{edc} = \mathrm{K}(\psi_{qs}^{+}\mathrm{i}_{qr}^{+} + \psi_{ds}^{+}\mathrm{i}_{dr}^{+} + \psi_{qs}^{-}\mathrm{i}_{qr}^{-} + \psi_{ds}^{-}\mathrm{i}_{dr}^{-})$$

$$T_{ecos} = K(\psi_{qs}^{+}\mathrm{i}_{qr}^{-} + \psi_{ds}^{+}\mathrm{i}_{dr}^{-} + \psi_{qs}^{-}\mathrm{i}_{qr}^{+} + \psi_{ds}^{-}\mathrm{i}_{dr}^{+})$$

$$T_{esin} = K(\psi_{ds}^{+}\mathrm{i}_{qr}^{-} - \psi_{qs}^{+}\mathrm{i}_{dr}^{-} - \psi_{ds}^{-}\mathrm{i}_{qr}^{+} + \psi_{qs}^{-}\mathrm{i}_{dr}^{+})$$

RSC made $T_{ecos} = 0$ and $T_{esin} = 0$ by controlling $i_{qr-}$and i_{dr-}.

DFIG Grid Side Converter

1. Positive Sequence Controller

The Positive Sequence Controller tracked DC Link Voltage Reference and controlled the Power delivered to grid by GSC. Real power and reactive power were linearly related to i_{qg} and i_{dg} respectively. Hence decoupled real power and reactive power controller was designed to generate the desired grid side converter voltages:

$$v_{qg} = L_g \frac{di_{qg}}{dt} + \omega L_g i_{dg} + v_{qs}$$

$$v_{dg} = L_g \frac{di_{dg}}{dt} - \omega L_g i_{qg}$$

The GSC Filter was modeled as an inductor.

2. Negative Sequence Controller

For negative sequence compensation via GSC, the current controllers of the GSC will measure the network currents, extract the negative sequence components and generate the required negative sequence currents from the GSC for compensation. The reference values of the negative sequence currents come from the measurements of the currents to the grid.

$$i_{gq,ref}^{-} = i_{eq}^{-}$$

$$i_{gd,ref}^{-} = i_{ed}^{-}$$

DC Link Dynamics

The DC-link capacitor dynamics or the relationship between the RSC and the GSC was

$$CV_{DC0}\frac{dV_{DC}}{dt} = -P_r - P_g$$

Conclusion

The converters tracked the desired references and the DFIG continued to export power to grid during the fault. Grid Side Converter compensated the negative sequence currents required in the network during stator voltage imbalance. It also controlled DC Link Voltage and the Power delivered to grid by DC Link. Rotor Side Converter eliminated negative sequence rotor currents, negative sequence stator currents and torque pulsation. It also controlled Active and Reactive Power delivered by stator to grid.

Analysis of DFIG with Unbalanced Stator Voltage

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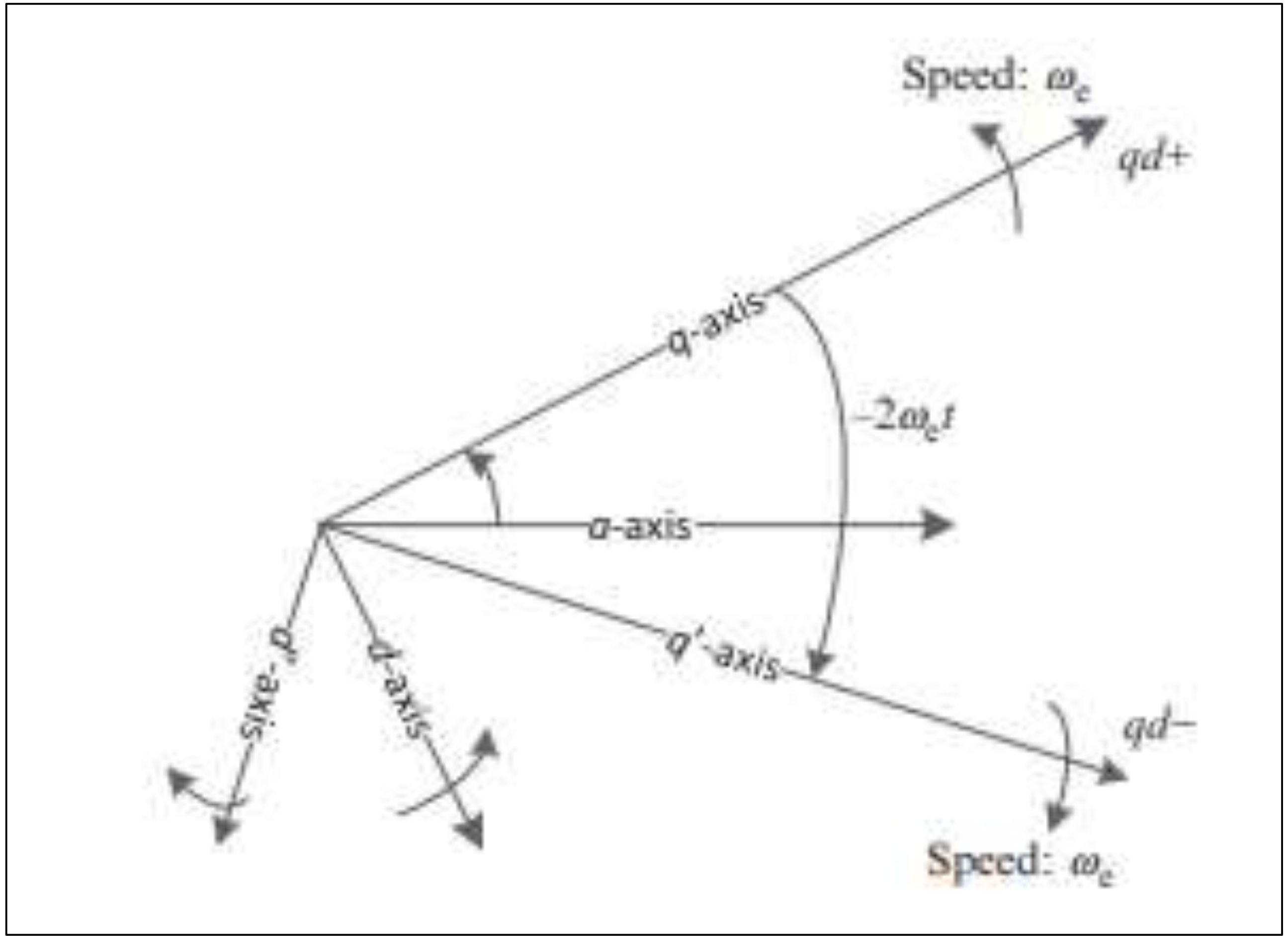
Overview

- Stator Voltage Unbalance causes Positive Sequence Voltage/ Current Components and Negative Sequence Voltage/ Current Components to be disturbed. This causes unwanted Torque Pulsations.
- GSC will compensate the negative sequence currents required in the network during the voltage unbalance. It also controls Power delivered to grid by GSC and DC Link Voltage.
- RSC will eliminate negative sequence rotor currents, negative sequence stator currents and torque pulsation. It also controls Active and Reactive Power delivered by stator.

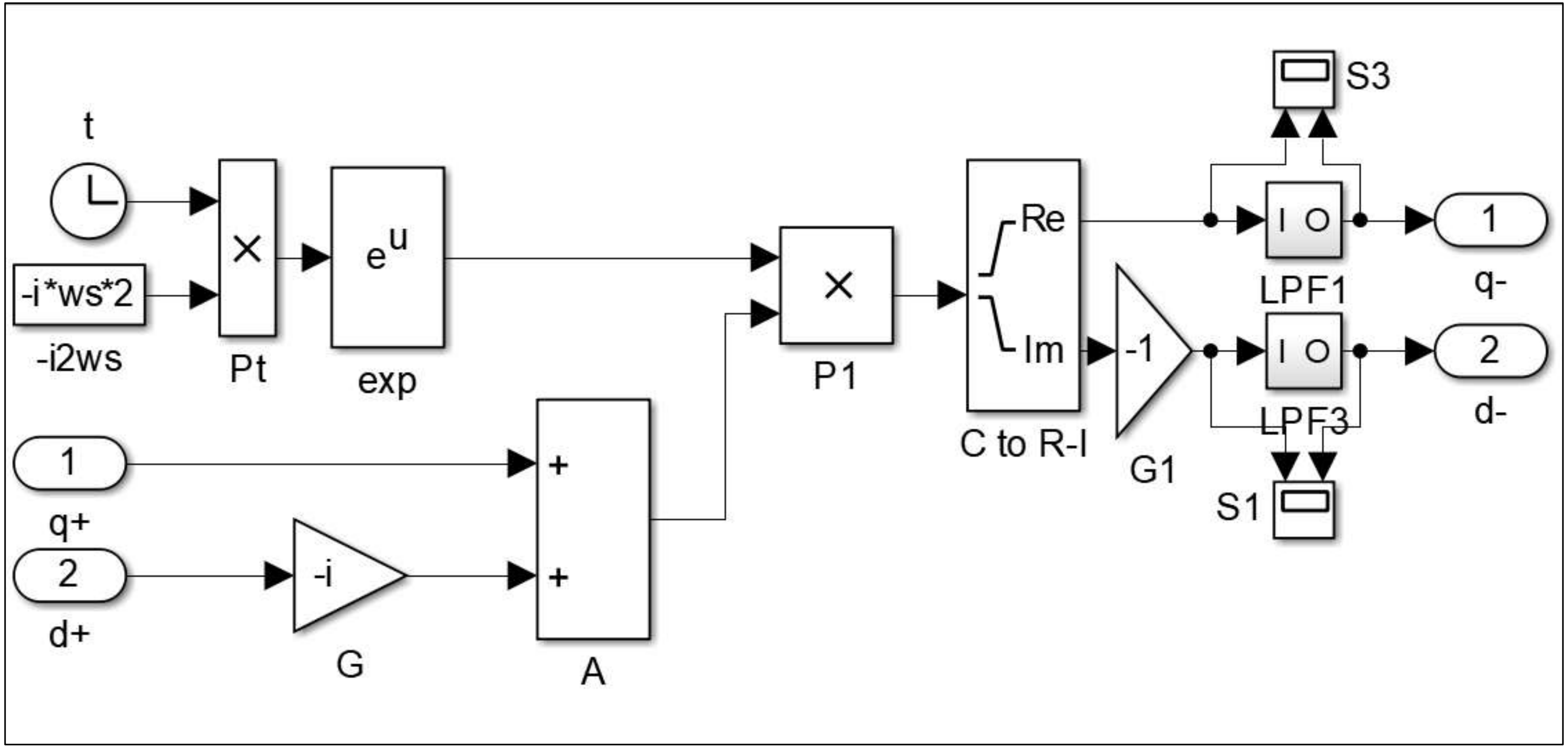
Negative Sequence dq- Components

Negative-sequence components rotate at -ω_e in dq-synchronously rotating reference frame. They are extracted through qd+/qd– transformation:

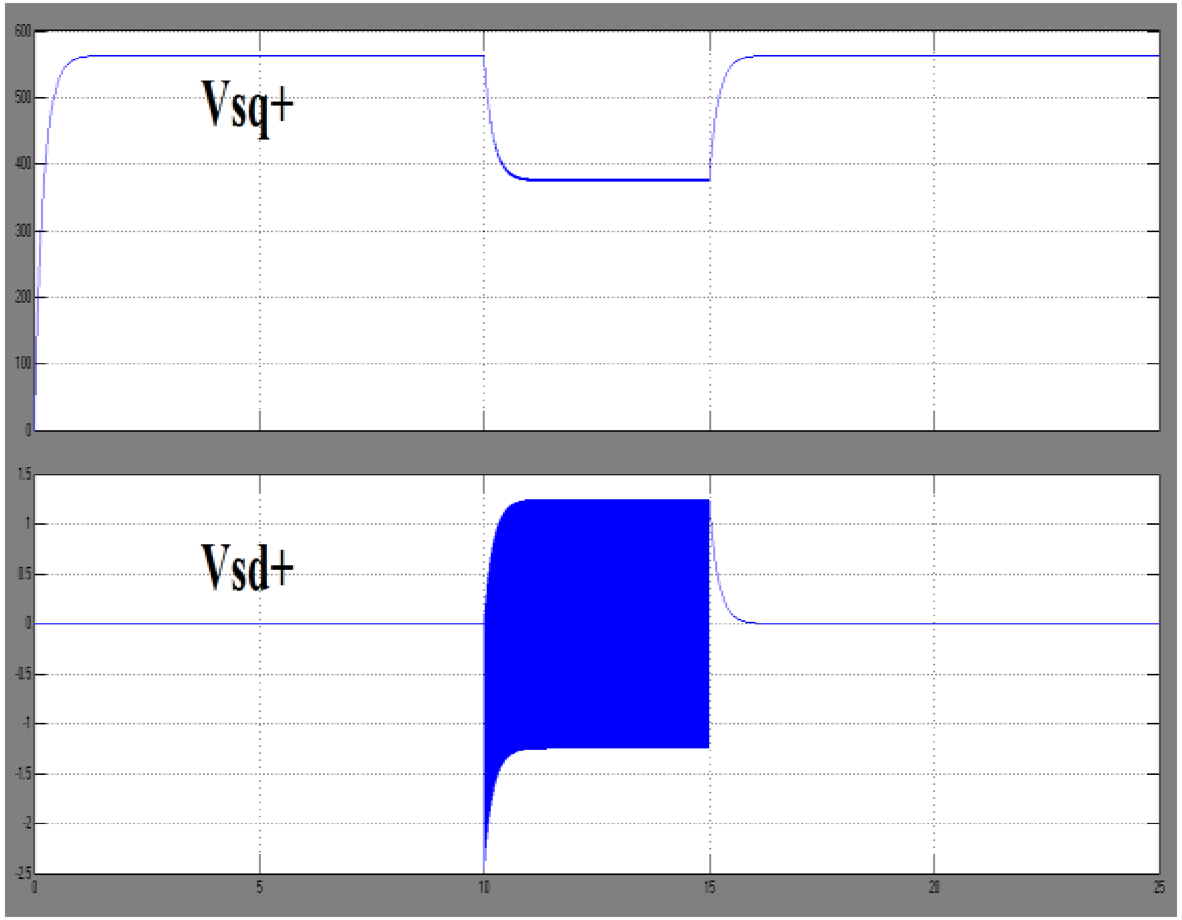
$$[q^- - jd^-] = e^{-j2\omega_e t}.[q^+ - jd^+]$$

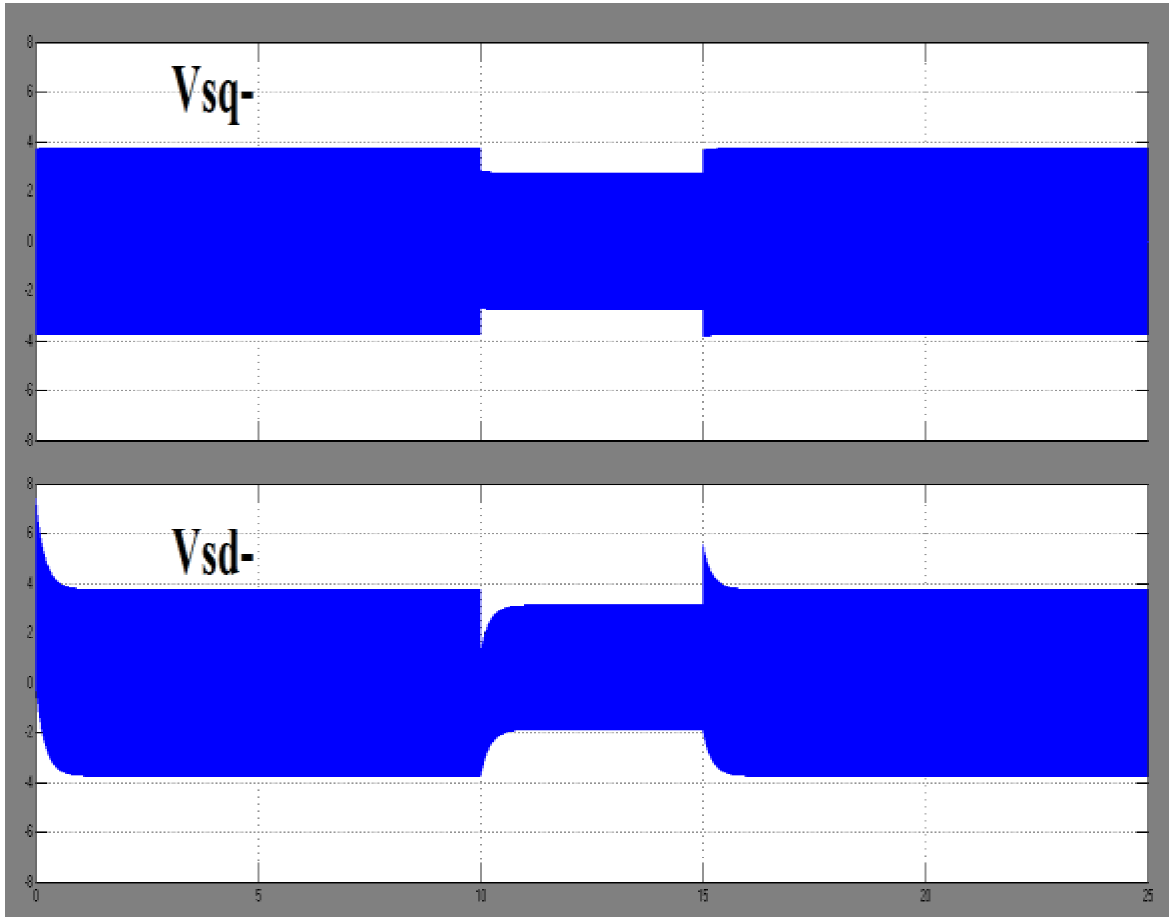


dq+/dq- Transformation

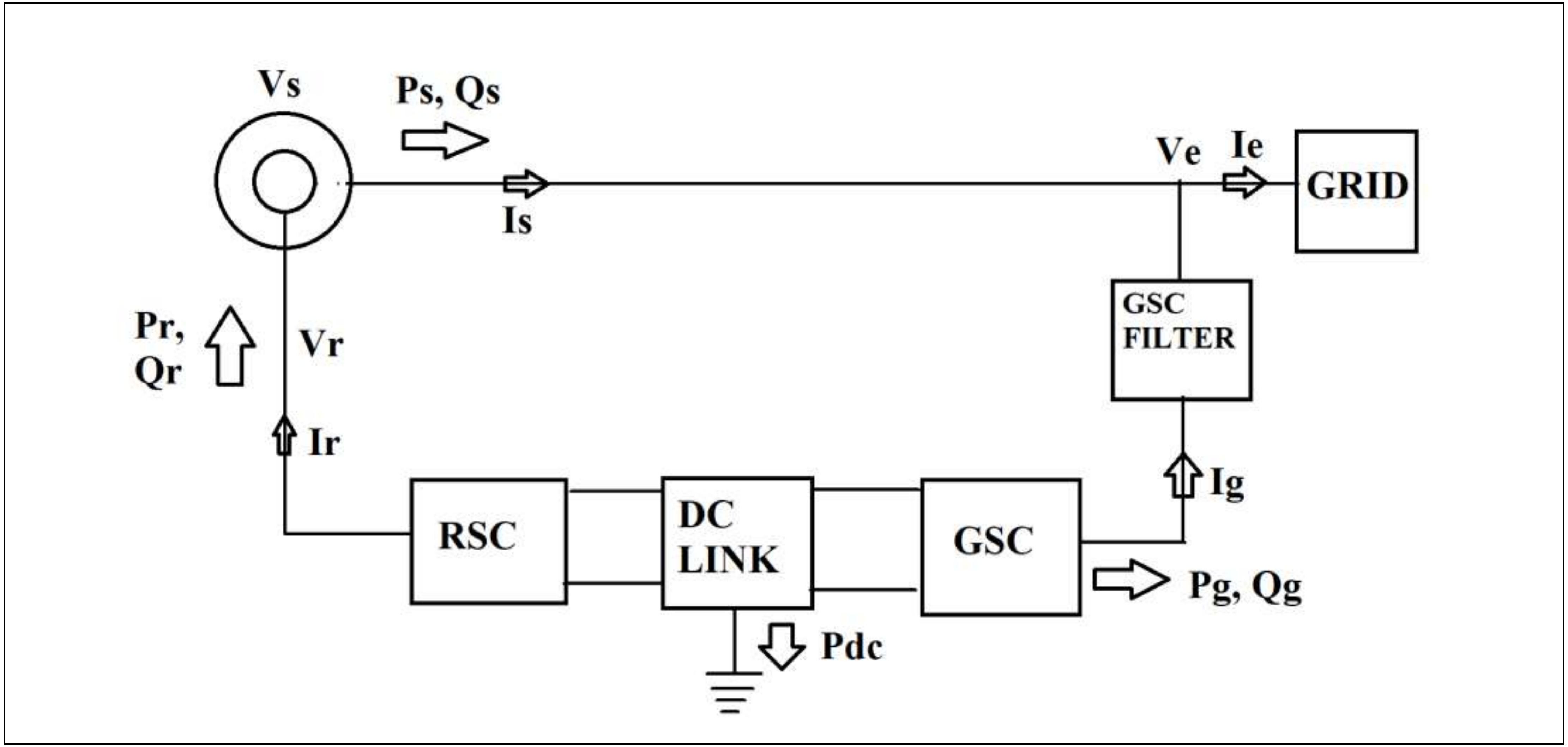


Stator Phase a Voltage Collapses to zero for t=10s to t=15s

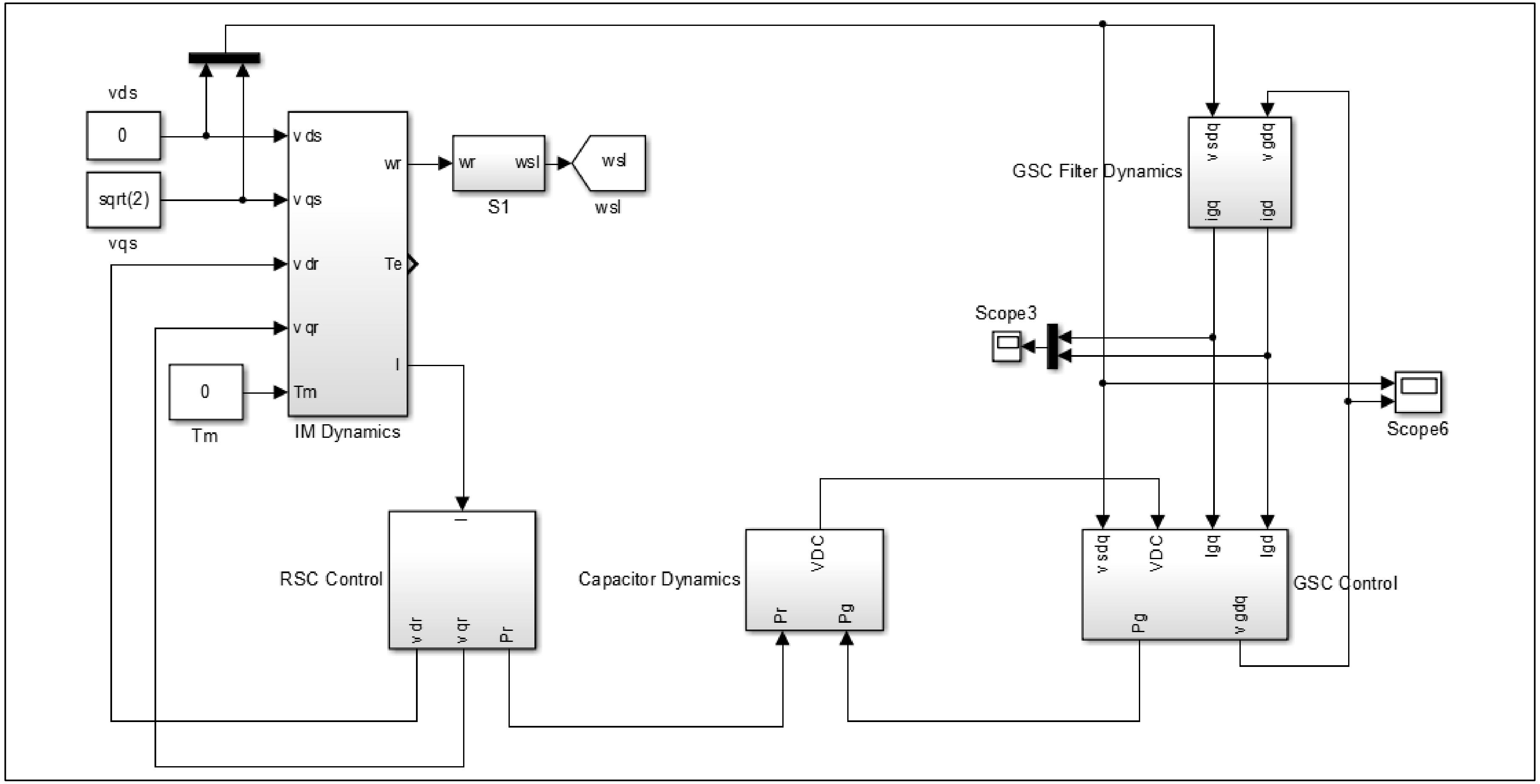




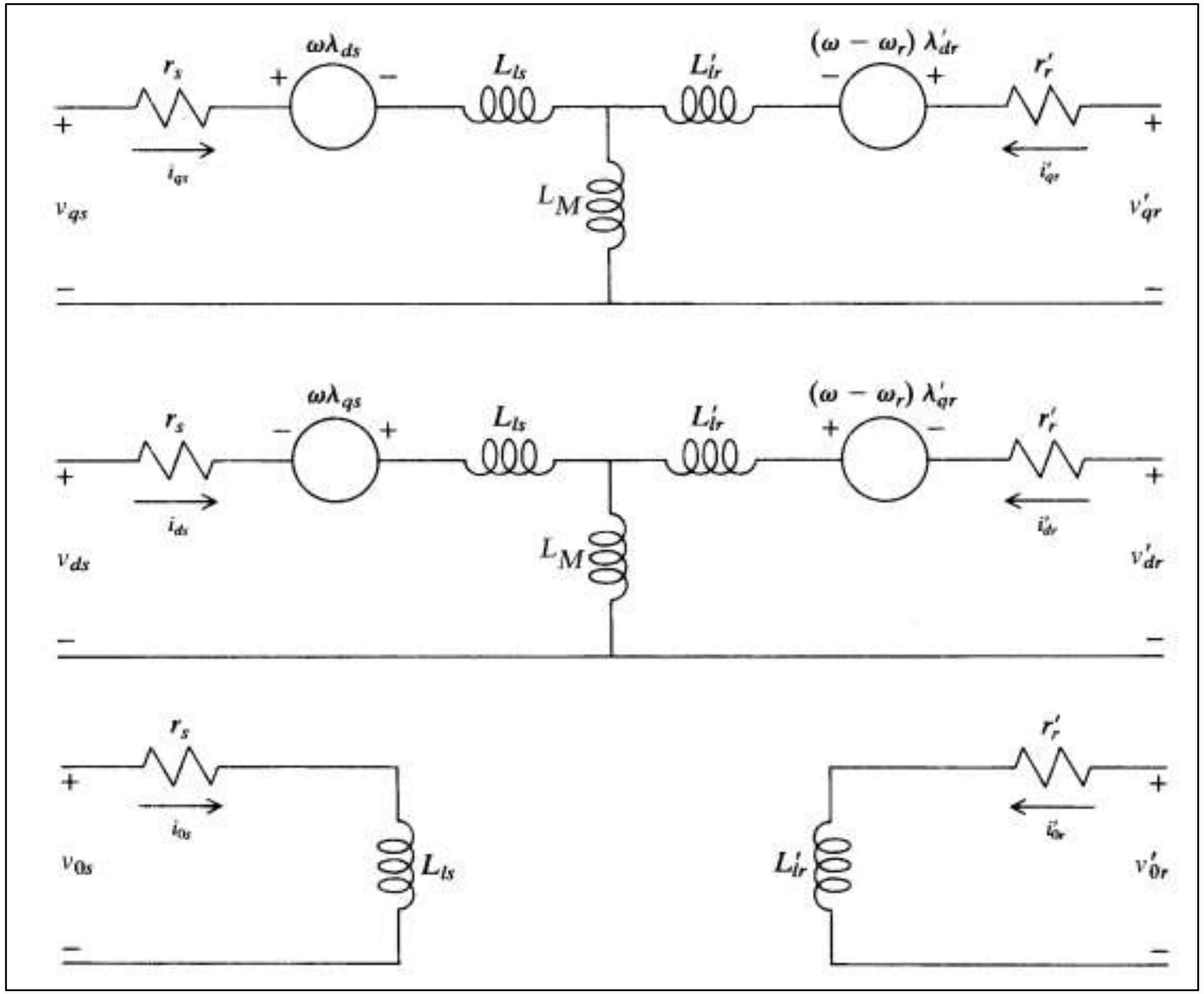
Complete DFIG Model



Complete DFIG Simulation Model



Induction Machine dq0-axis Model



Induction Machine dq0-axis Model Equations

<u>Voltage and Current Equations</u>

- $$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{0s} \\ v_{qr} \\ v_{qr} \\ v_{0r} \end{bmatrix} = \begin{bmatrix} R_s + \frac{p}{\omega_b}X_s & \frac{\omega_s}{\omega_b}X_s & 0 & \frac{p}{\omega_b}X_m & \frac{\omega_s}{\omega_b}X_s & 0 \\ -\frac{\omega_s}{\omega_b}X_s & R_s + \frac{p}{\omega_b}X_s & 0 & -\frac{\omega_s}{\omega_b}X_m & \frac{p}{\omega_b}X_m & 0 \\ 0 & 0 & R_s + \frac{p}{\omega_b}X_{ls} & 0 & 0 & 0 \\ \frac{p}{\omega_b}X_m & \frac{\omega_s - \omega_r}{\omega_b}X_m & 0 & R_r + \frac{p}{\omega_b}X_r & \frac{\omega_s - \omega_r}{\omega_b}X_r & 0 \\ -\frac{\omega_s - \omega_r}{\omega_b}X_m & \frac{p}{\omega_b}X_m & 0 & -\frac{\omega_s - \omega_r}{\omega_b}X_r & R_r + \frac{p}{\omega_b}X_r & 0 \\ 0 & 0 & 0 & 0 & 0 & R_r + \frac{p}{\omega_b}X_{lr} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \\ i_{qr} \\ i_{dr} \\ i_{0r} \end{bmatrix}$$

<u>Motion and Torque Equations</u>

- $\frac{\omega_r}{\omega_b} = \frac{1}{2HS}(T_e - T_m)$
- $T_e = X_m(i_{qs}i_{dr} - i_{ds}i_{qr})$

Induction Machine dq0-axis Model Equations

- DFIG control relies on stator flux-oriented reference frame

$$v_{ds}=0$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} = 0$$

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} = \psi_s$$

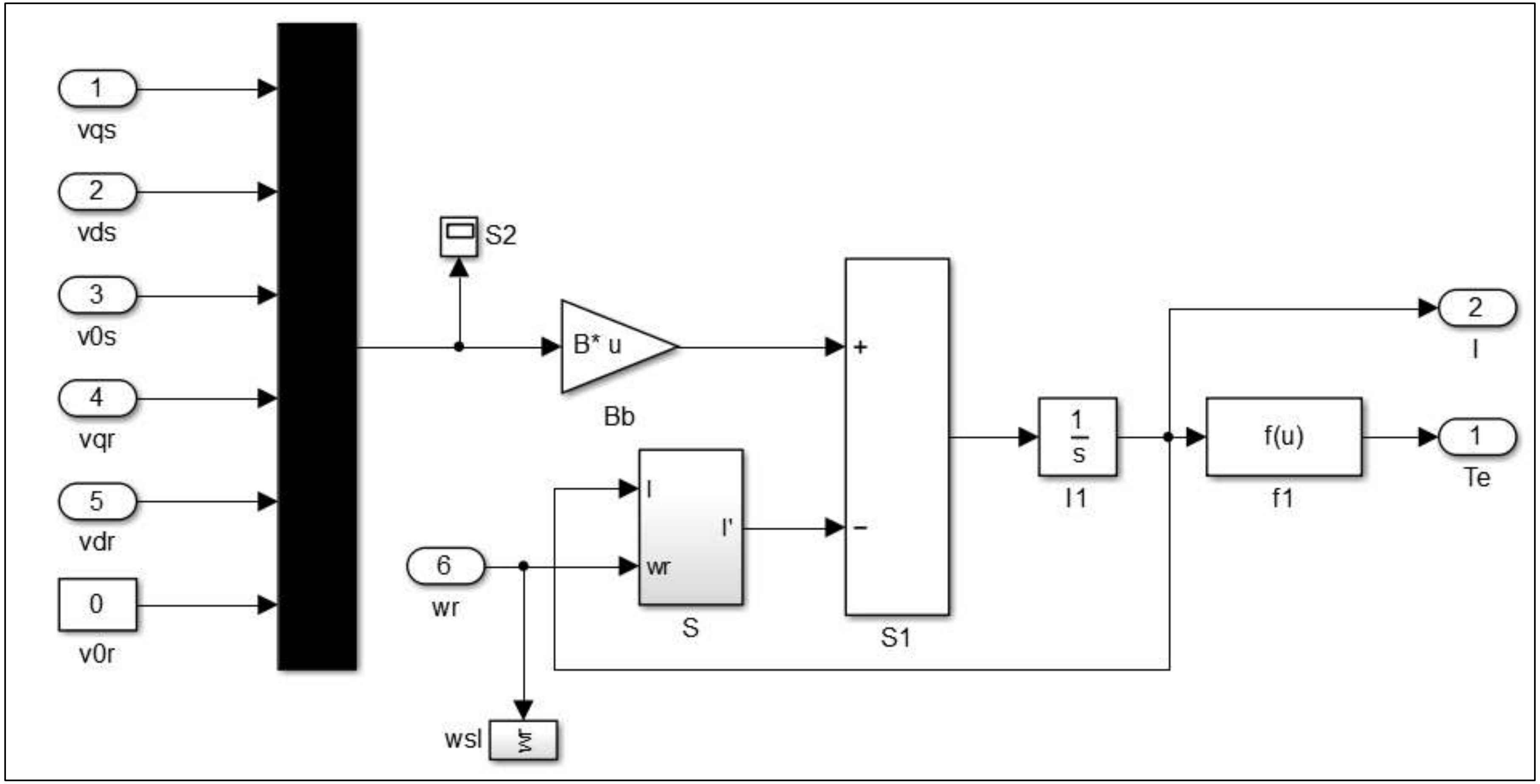
$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} = \left(L_r - \frac{L_m^2}{L_s}\right) i_{qr} = \sigma L_r i_{qr}$$

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} = \sigma L_r i_{dr} + \frac{L_m}{L_s} \psi_{ds}$$

DFIG Machine Constants

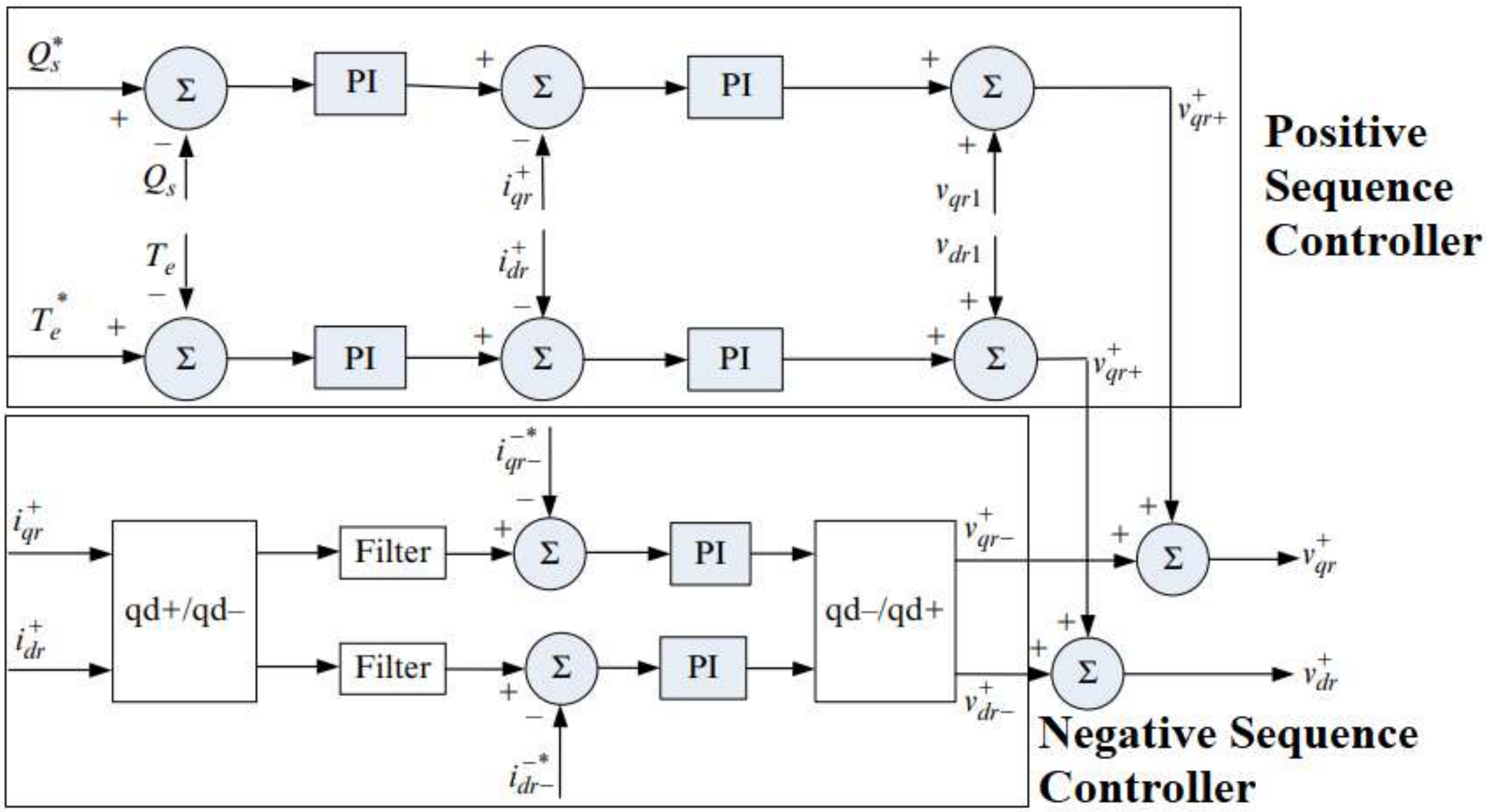
- Rated Power
$$P_{base} = 2\ MW$$
- Rated Line-Line Voltage
$$V_{rated,LL} = 690\ V_{rms}$$
- Number of Pole Pairs
$$P = 6$$
- Rated Stator Frequency
$$f_e = 60\ Hz$$
- Stator Winding Resistance
$$R_s = 0.00488\ p.u.$$
- Rotor Winding Resistance
$$R_r = 0.00549\ p.u.$$
- Stator Leakage Reactance
$$X_{ls} = 0.09231\ p.u.$$
- Rotor Leakage Reactance
$$X_{lr} = 0.09955\ p.u.$$
- Magnetizing Reactance
$$X_m = 3.95279\ p.u.$$
$$X_s = X_{ls} + X_m = 4.0451\ p.u.$$
$$X_r = X_{lr} + X_m = 4.0523\ p.u.$$
- Inertia Constant
$$H = 3.5\ s$$
- Base Speed
$$\omega_b = 2\pi f_e = 376.9911\ rad/s$$
- Synchronous Speed
$$\omega_s = \frac{2}{P} 2\pi f_e = 125.6637\ rad/s$$

Induction Machine Model



Rotor Side Converter

Rotor Side Converter



Rotor Side Converter Positive Sequence Controller

- The output real and reactive power from the stator circuit can be controlled via iqr and idr respectively.

$$P_s = -\omega_e T_e = \frac{3PL_m}{4L_s}\omega_e \psi_{ds} i_{qr}$$

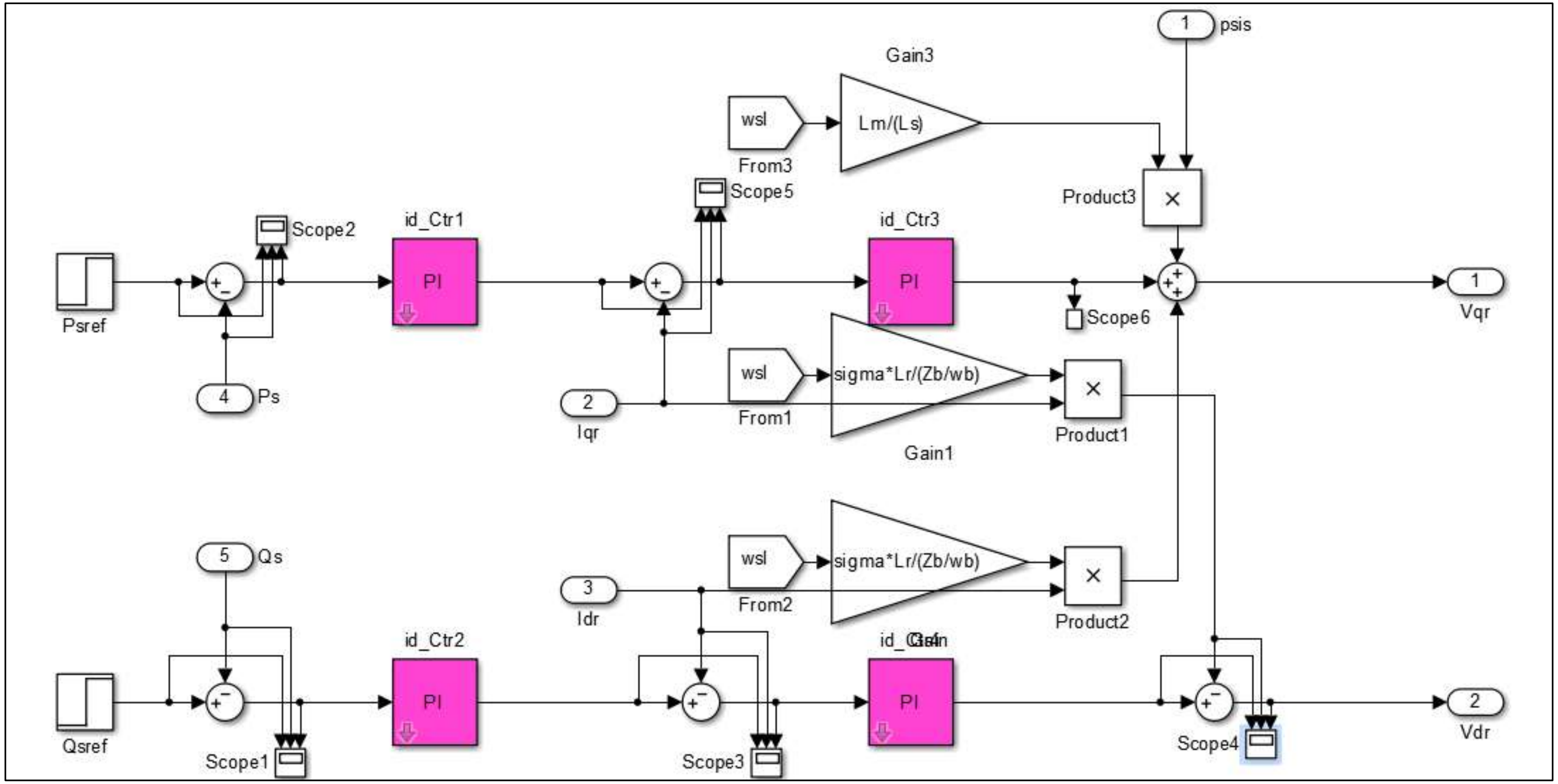
$$Q_s = -\frac{3}{2}\left(v_{qs}i_{ds} - v_{ds}i_{qs}\right) = -\frac{3P}{4}\omega_e \psi_{ds} i_{ds}$$

- The rotor voltages are used to design Positive Sequence RSC controller.

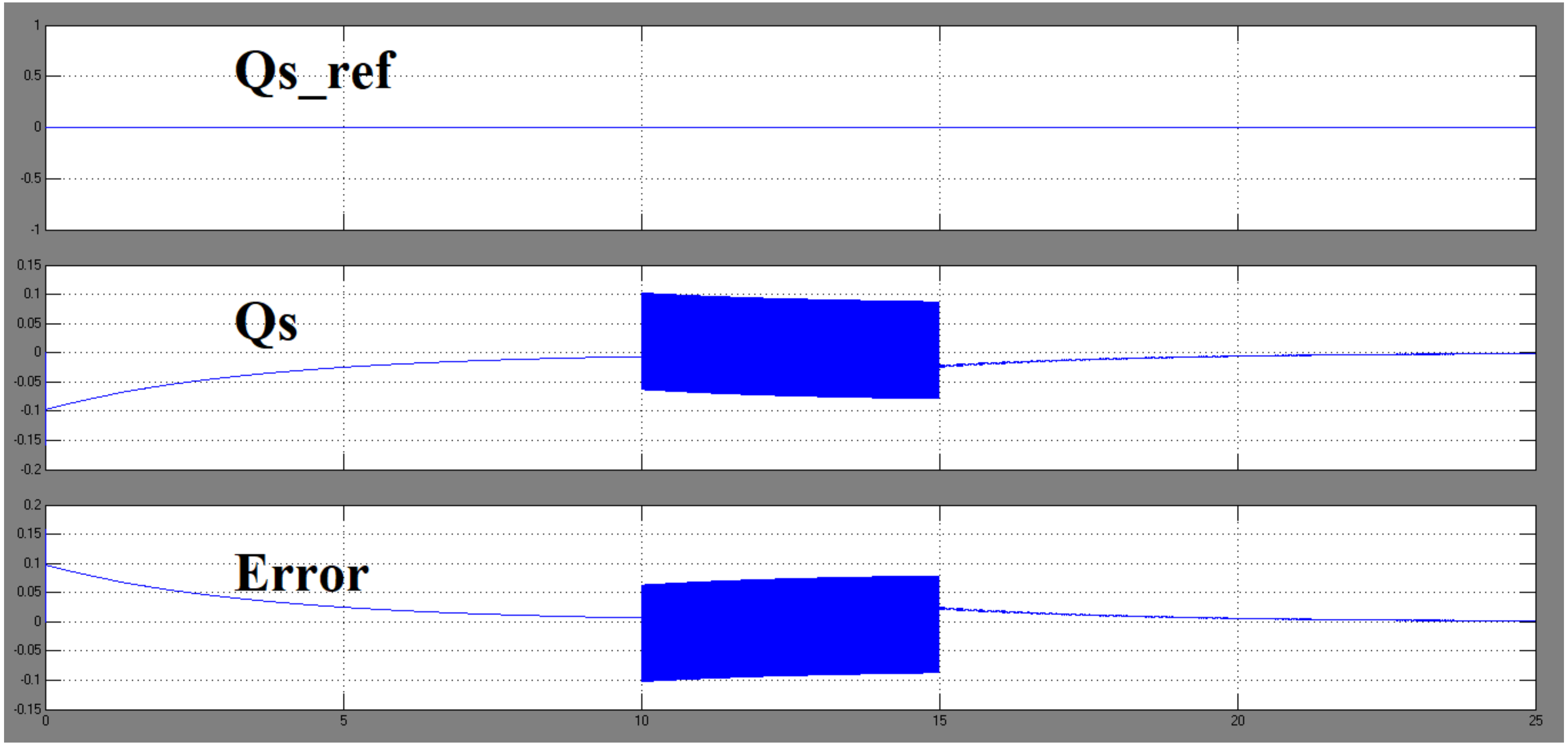
$$v_{qr} = r_r i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_{sl}\psi_{dr} = r_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + \omega_{sl}(\sigma L_r i_{dr} + \frac{L_m}{L_s}\psi_{ds})$$

$$v_{dr} = r_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_{sl}\psi_{qr} = r_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - \omega_{sl}\sigma L_r i_{qr}$$

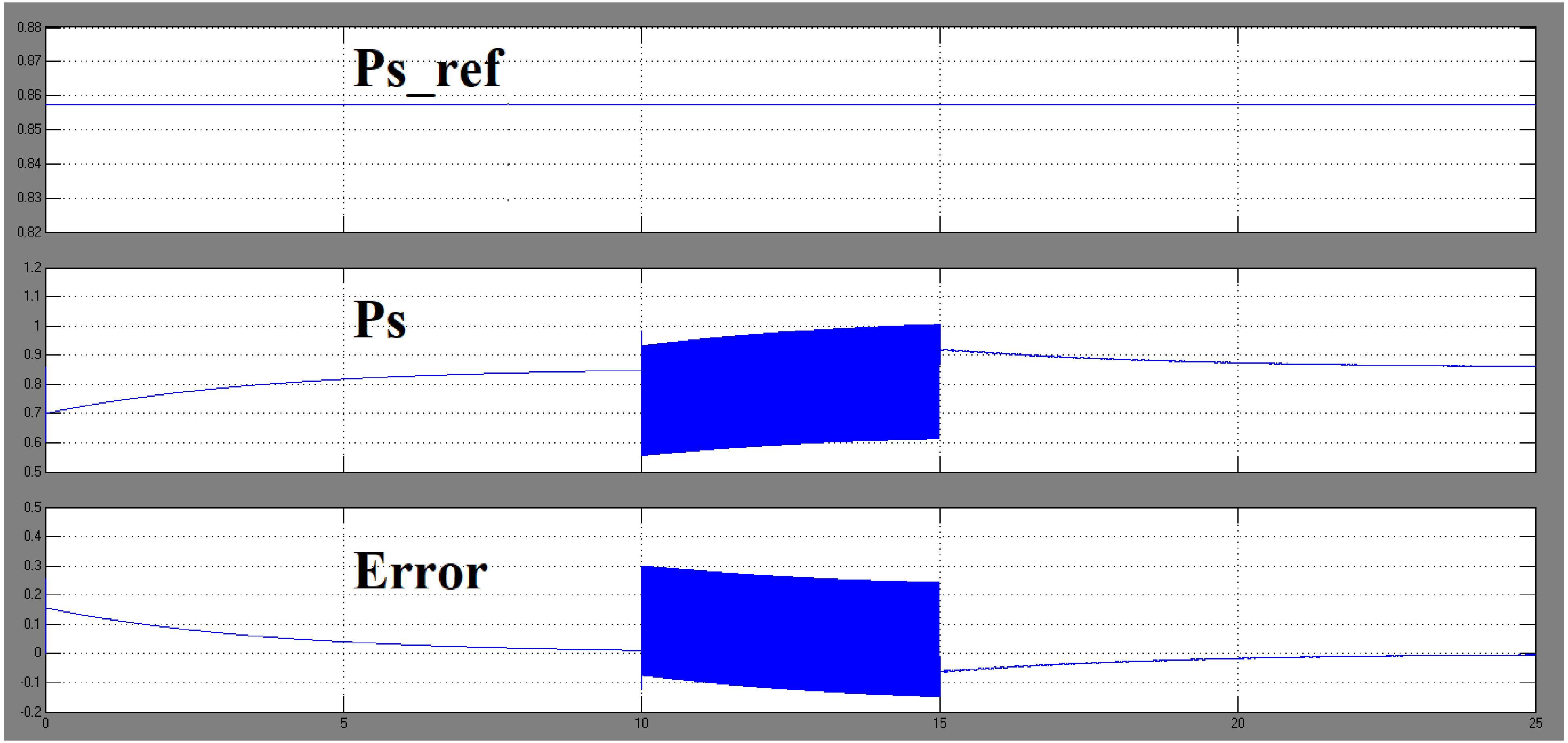
Positive Sequence Controller in RSC



Positive Sequence RSC Control of Stator Power Qs



Positive Sequence RSC Control of Stator Power Ps



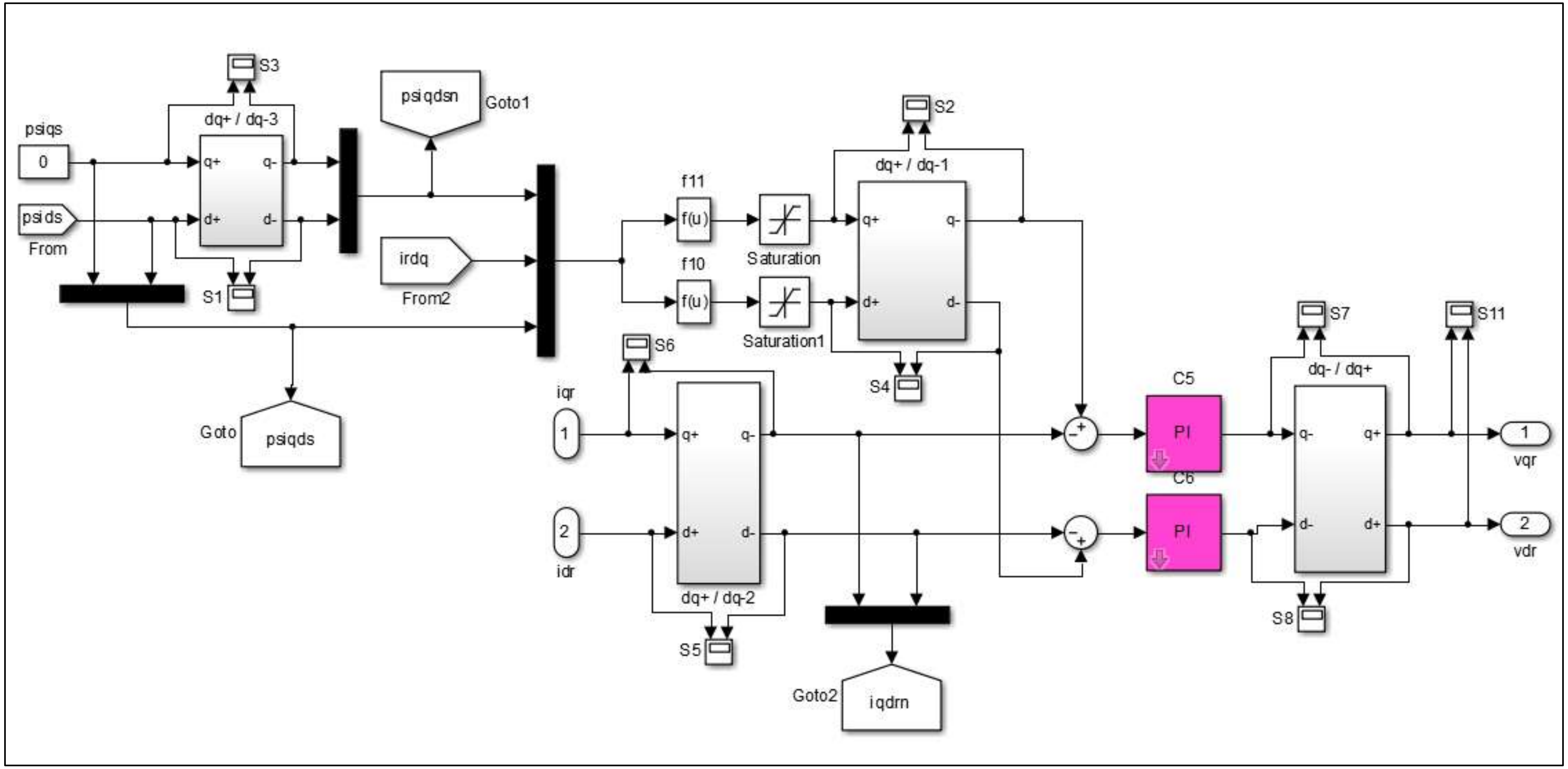
DFIG Rotor Side Converter Negative Sequence Control

- For a given negative-sequence stator voltage, a negative sequence rotor voltage generated by the RSC has the potential to eliminate the negative sequence rotor current, the negative sequence stator current or the torque pulsation.

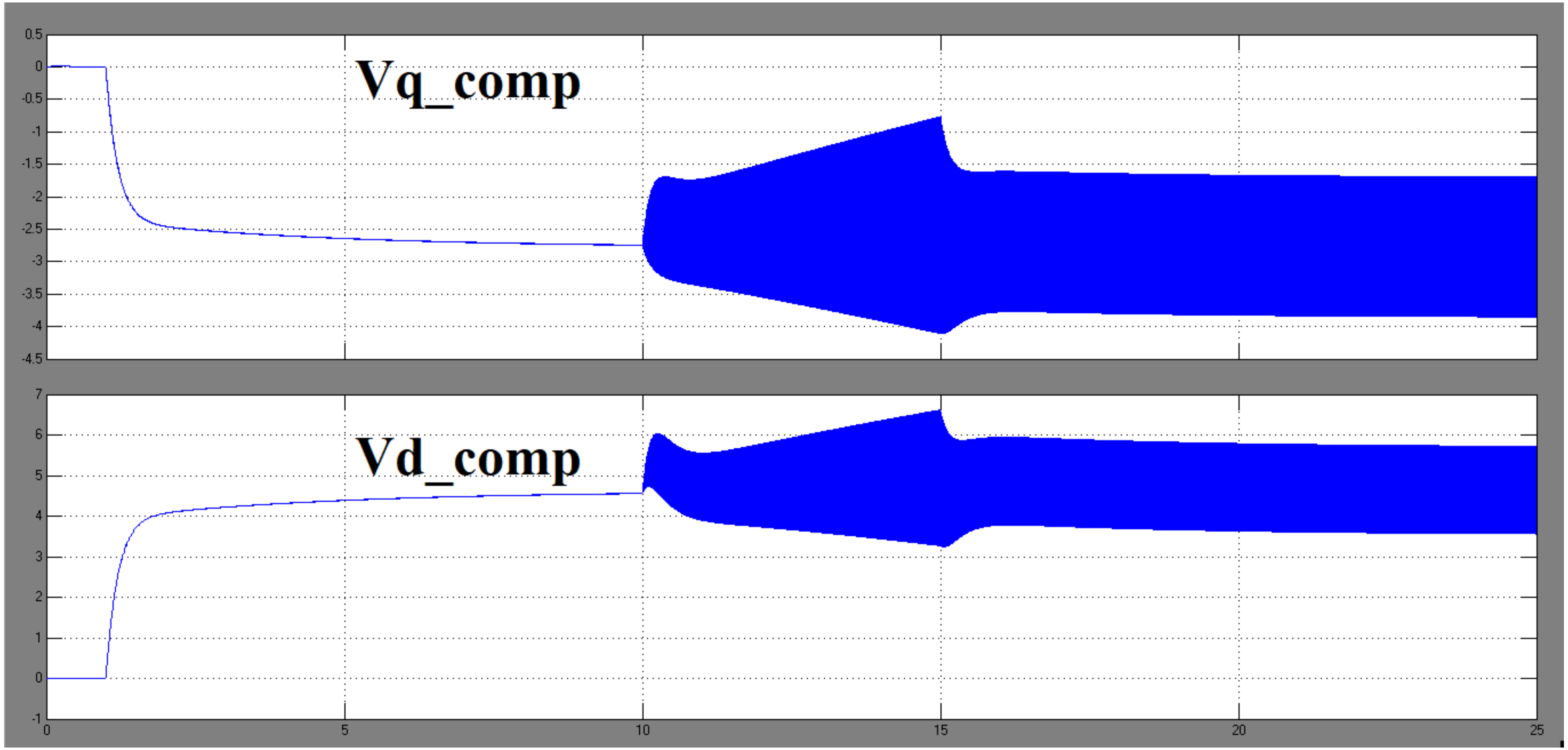
$$T_e = T_{edc} + T_{ecos}\cos(2\omega_e t) + T_{esin}\sin(2\omega_e t)$$
$$T_{edc} = \mathrm{K}(\psi_{qs}^{+} \mathrm{i}_{qr}^{+} + \psi_{ds}^{+} \mathrm{i}_{dr}^{+} + \psi_{qs}^{-} \mathrm{i}_{qr}^{-} + \psi_{ds}^{-} \mathrm{i}_{dr}^{-})$$
$$T_{ecos} = K(\psi_{qs}^{+} \mathrm{i}_{qr}^{-} + \psi_{ds}^{+} \mathrm{i}_{dr}^{-} + \psi_{qs}^{-} \mathrm{i}_{qr}^{+} + \psi_{ds}^{-} \mathrm{i}_{dr}^{+})$$
$$T_{esin} = K(\psi_{ds}^{+} \mathrm{i}_{qr}^{-} - \psi_{qs}^{+} \mathrm{i}_{dr}^{-} - \psi_{ds}^{-} \mathrm{i}_{qr}^{+} + \psi_{qs}^{-} \mathrm{i}_{dr}^{+})$$

- RSC must make $T_{ecos} = 0$ and $T_{esin} = 0$ by controlling $i_{qr-}$and i_{dr-}.

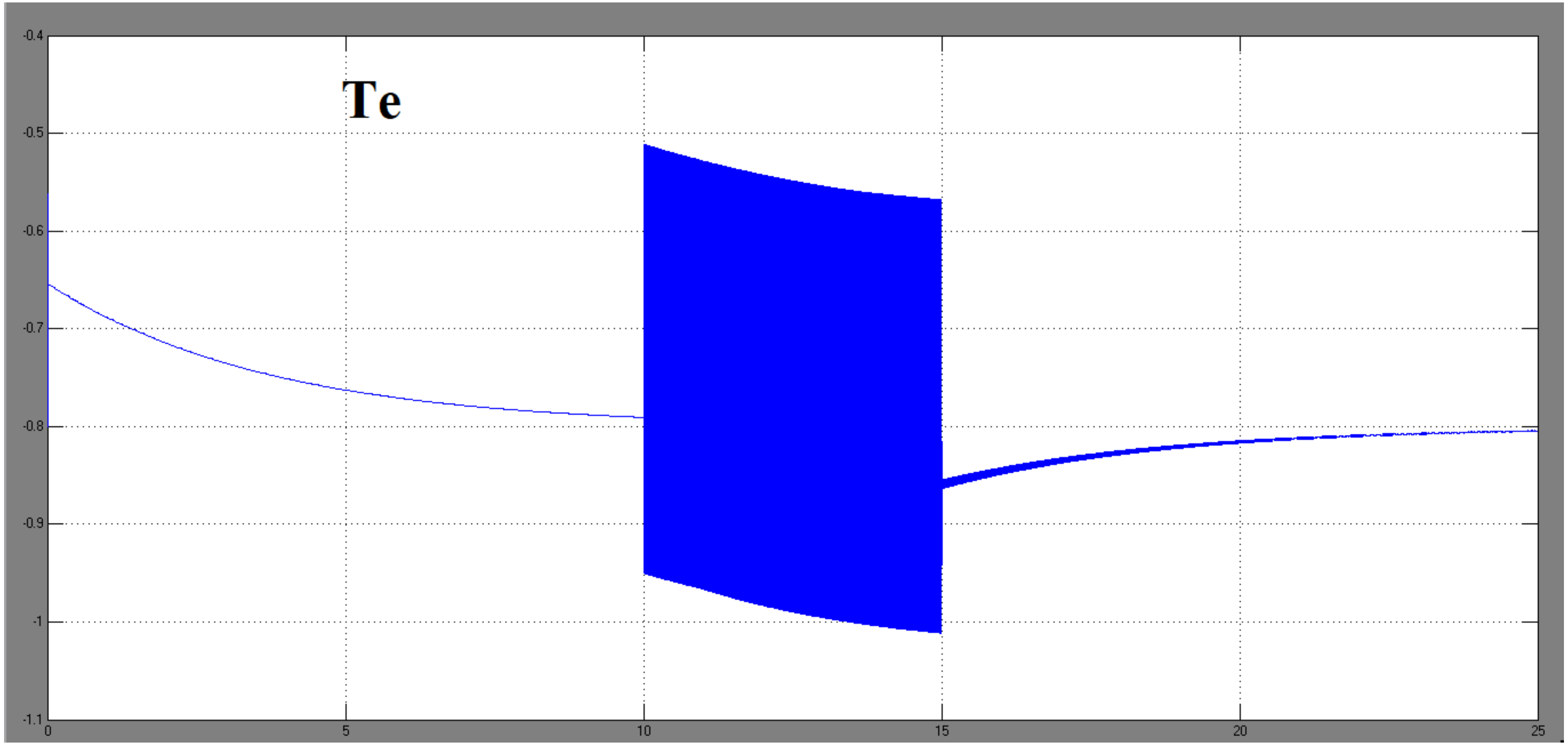
Negative Sequence Controller in RSC



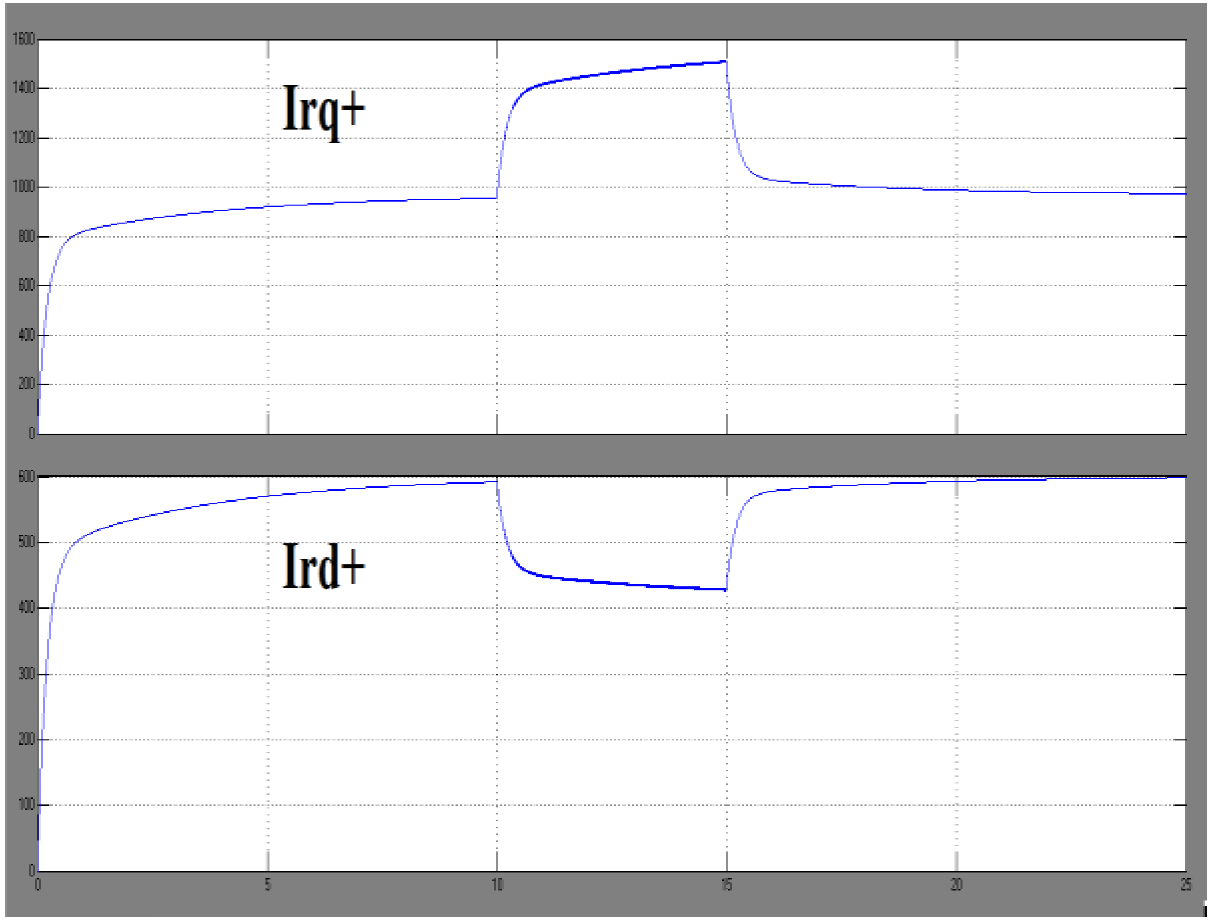
Negative Sequence Compensation via RSC

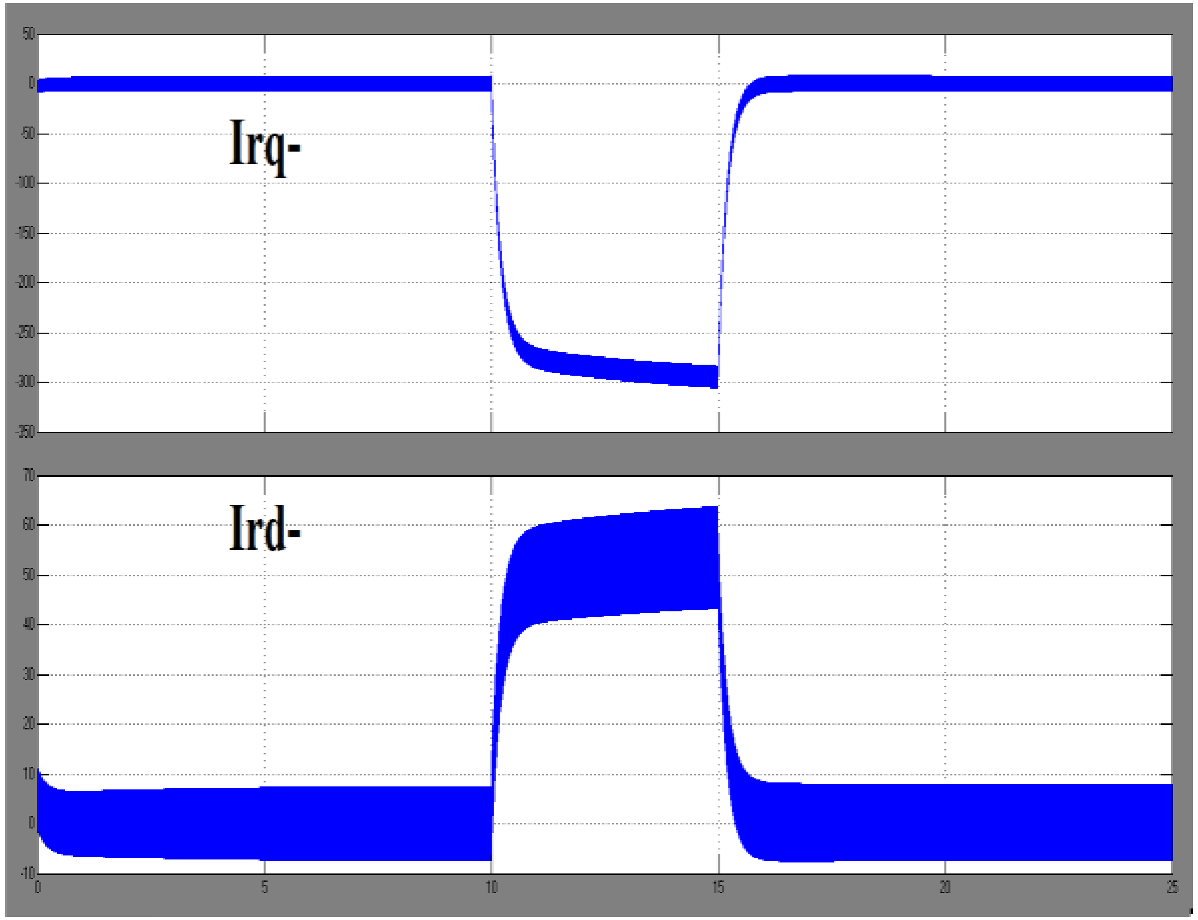


Torque Response

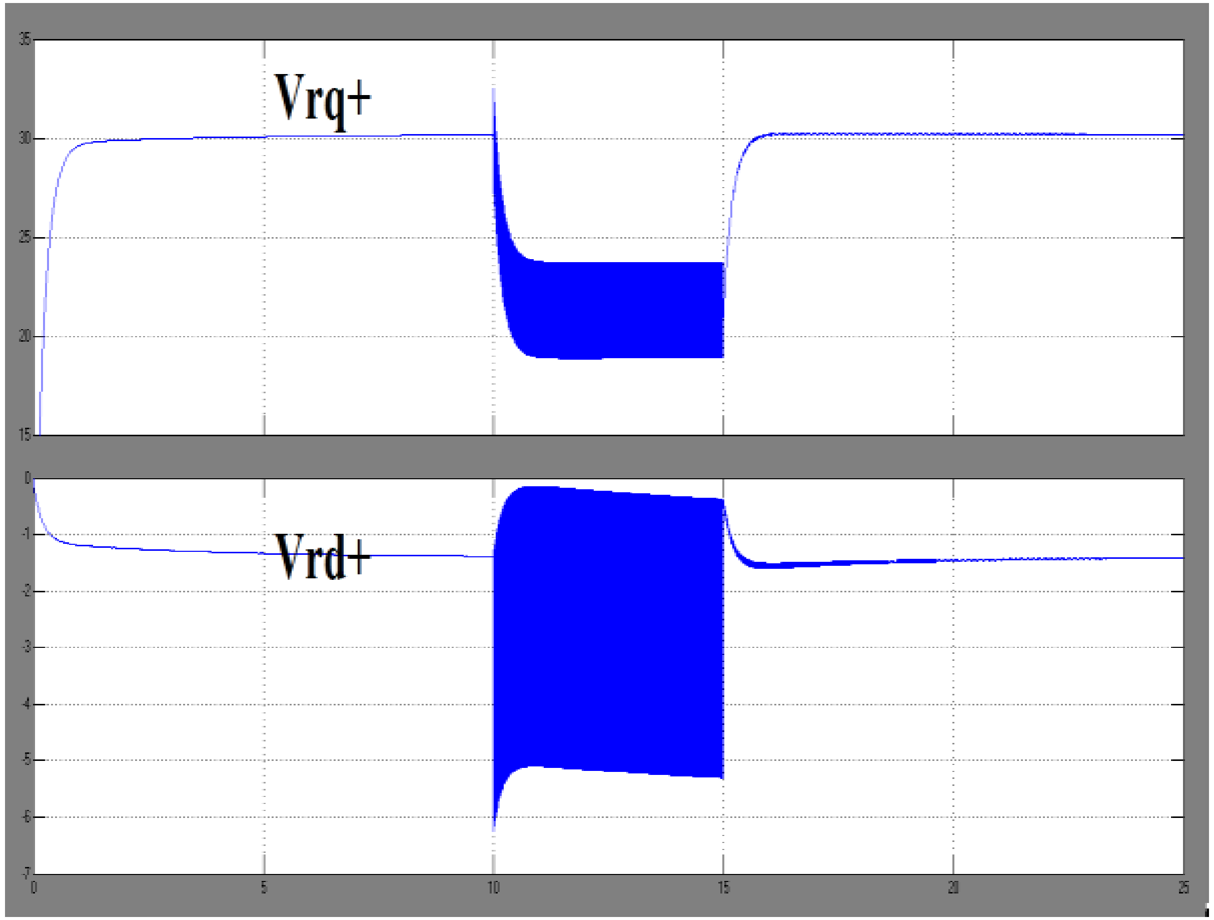


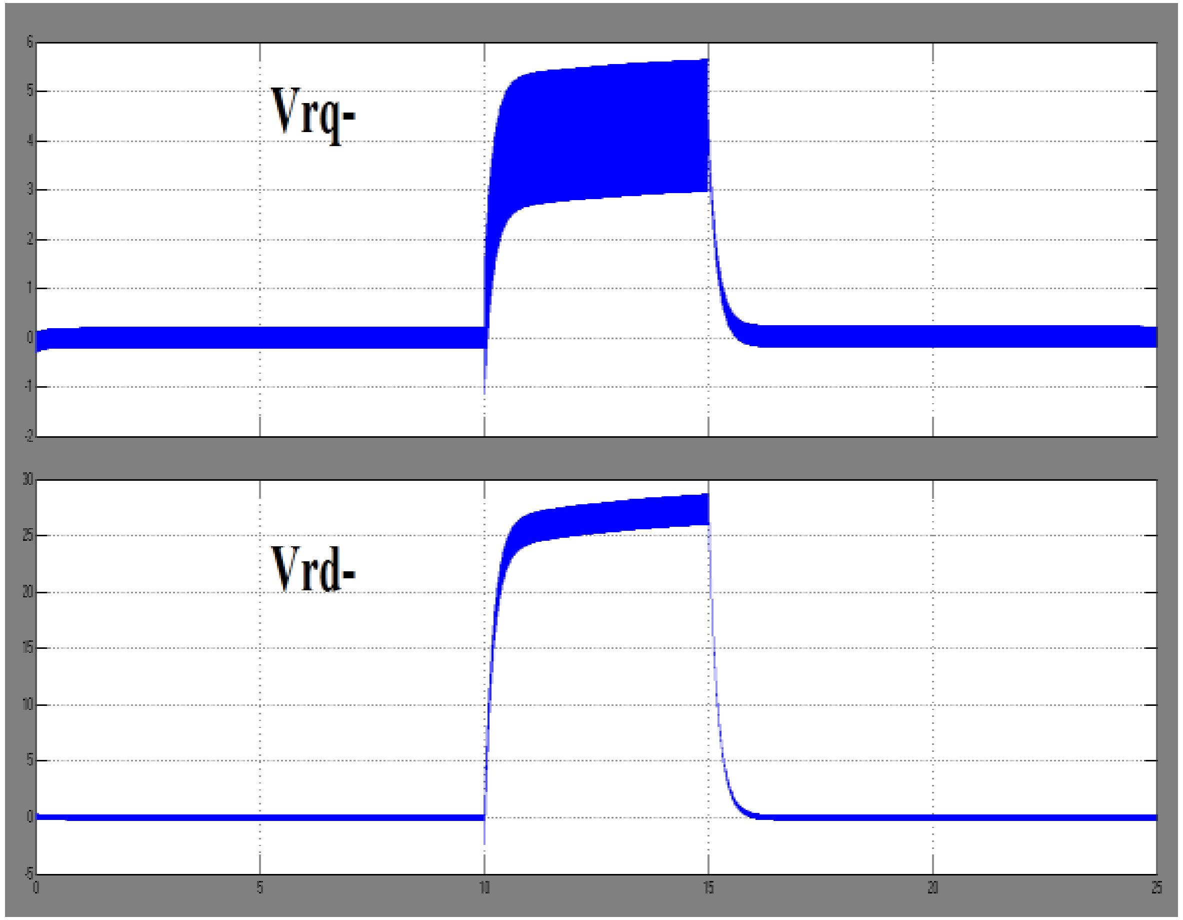
Rotor Currents





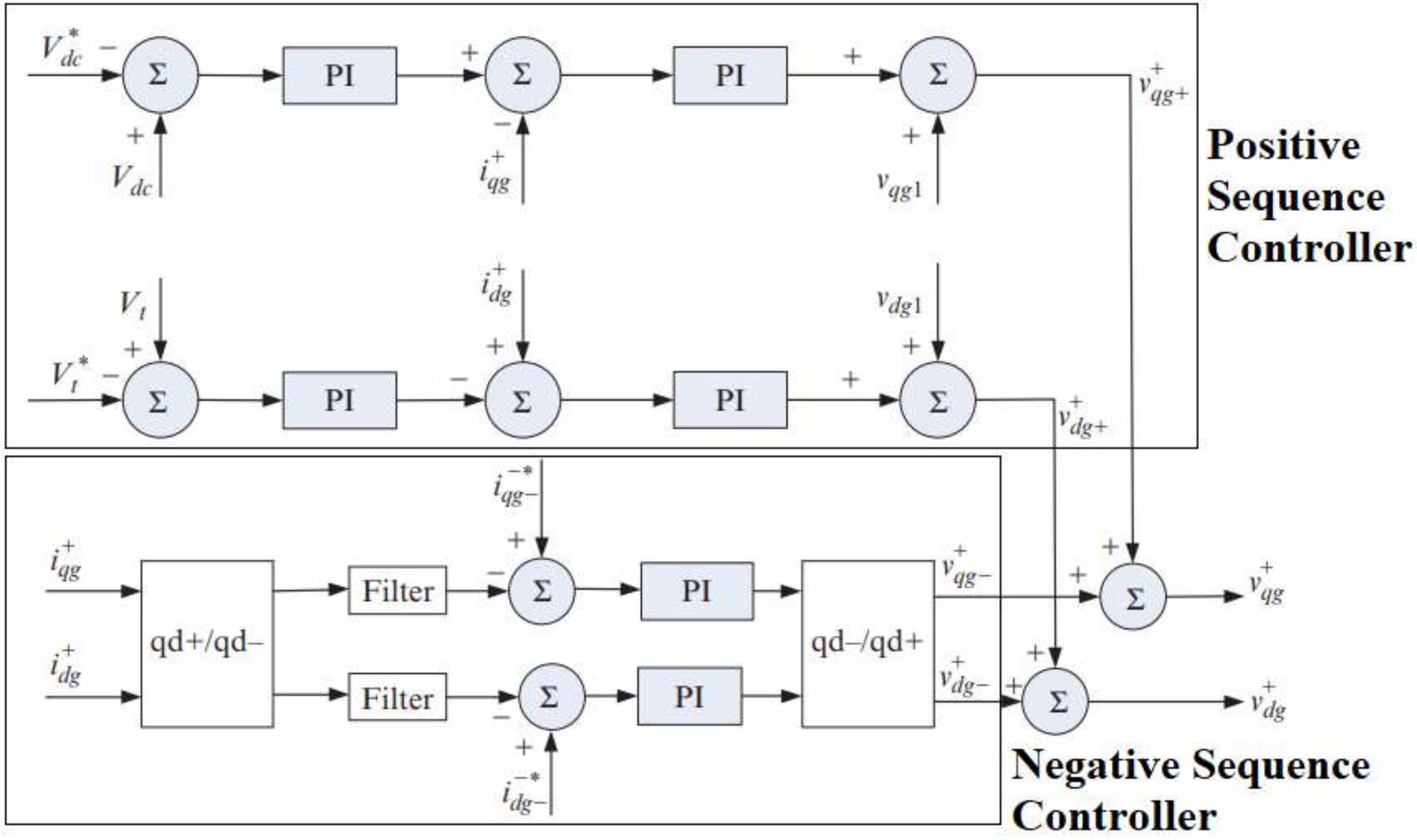
Rotor Voltages





Grid Side Converter

Grid Side Converter



DFIG Grid Side Converter Positive Sequence Control

- The GSC is used for real power and reactive power control

$$P_g = \frac{3}{2}\left(e_q i_{qg} + e_d i_{dg}\right) = \frac{3}{2} v_{qs} i_{qg}$$

$$Q_g = \frac{3}{2}\left(e_q i_{dg} - e_d i_{qg}\right) = \frac{3}{2} v_{qs} i_{dg}$$

- GSC control takes care of the DC-link voltage as well

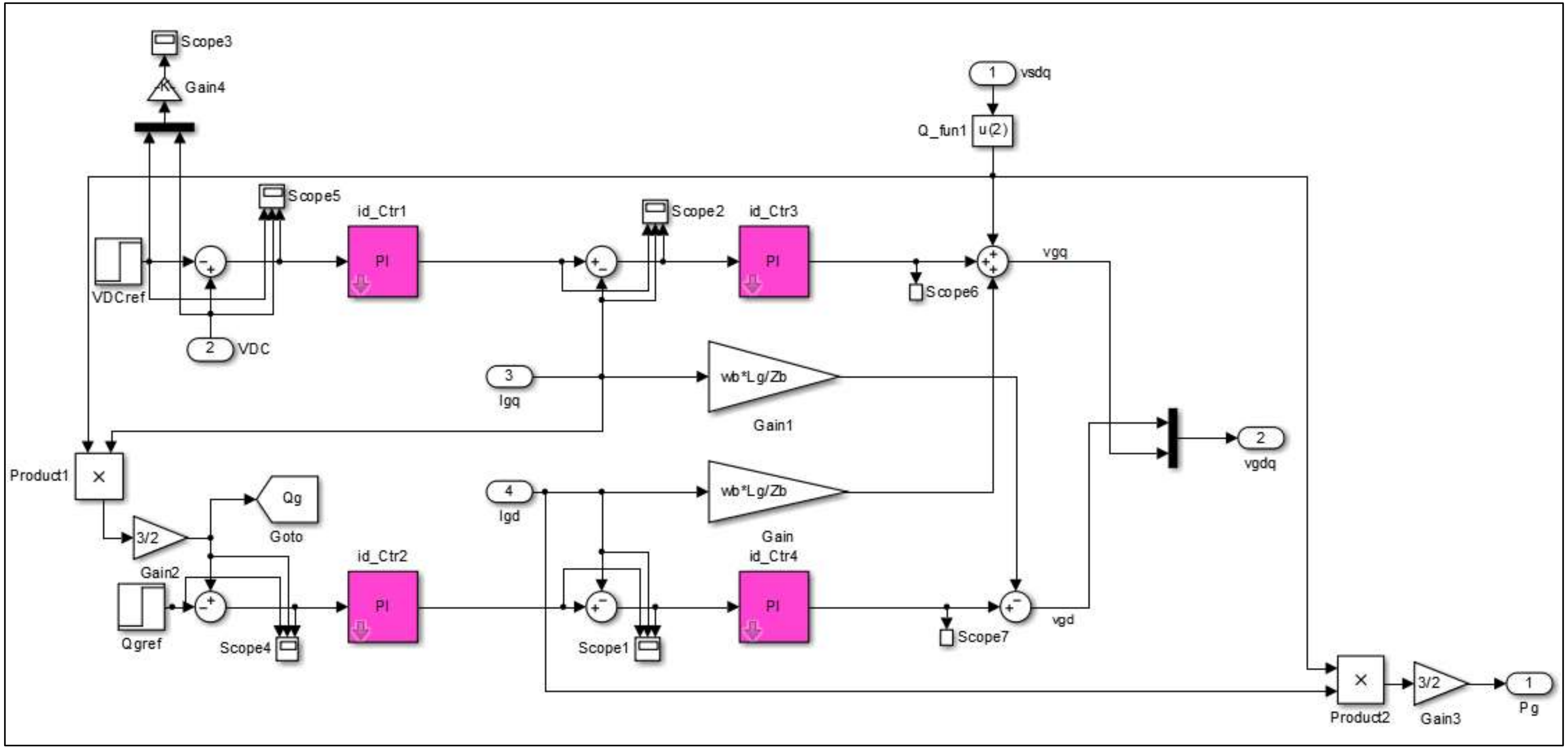
$$\frac{1}{2} C \frac{dV_{DC}^2}{dt} \approx C V_{DC0} \frac{dV_{DC}}{dt} = -P_{RSC} - P_{GSC}$$

- The GSC output voltage, GSC current, and the coupling point voltage are used to design controller.

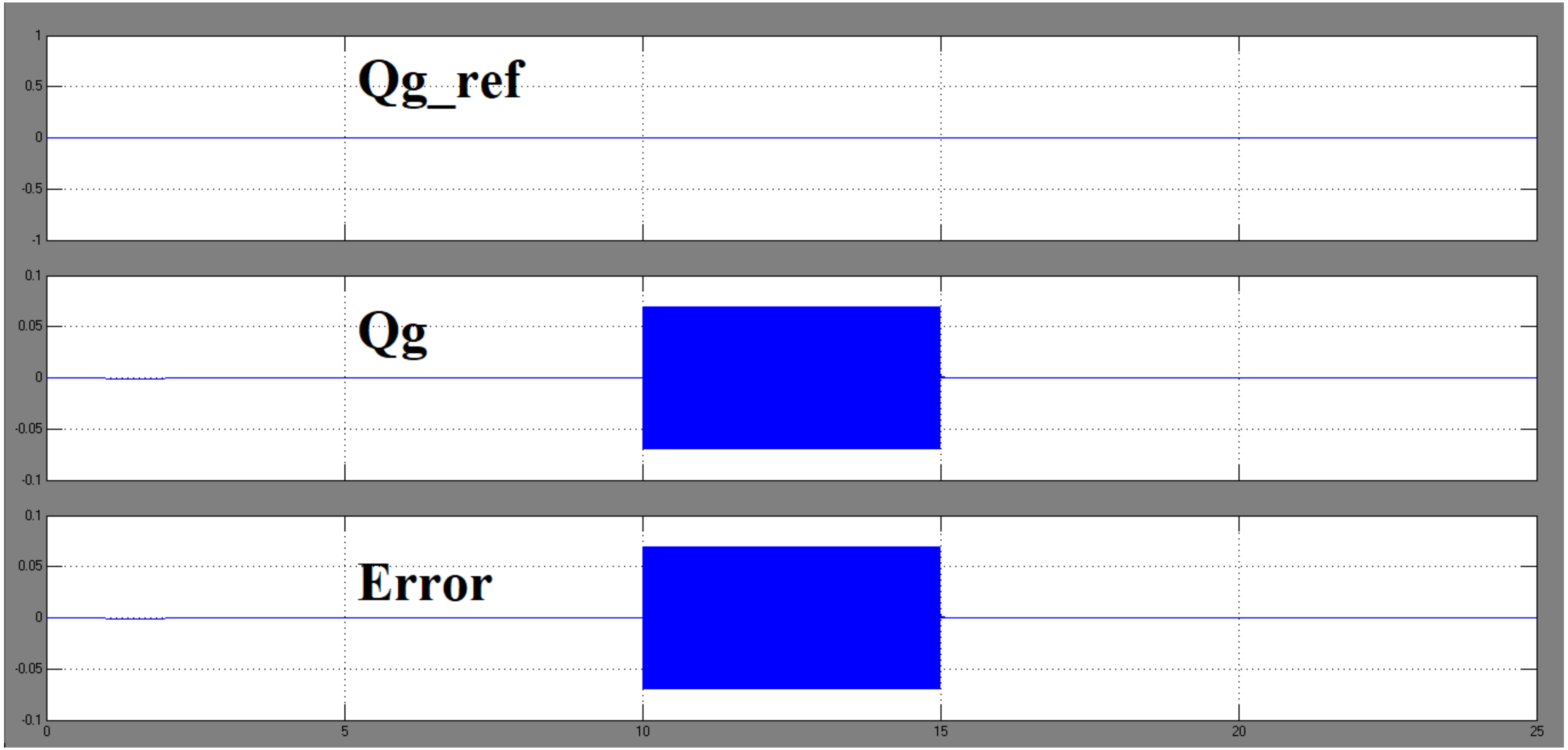
$$v_{qg} = L_g \frac{di_{qg}}{dt} + \omega L_g i_{dg} + v_{qs}$$

$$v_{dg} = L_g \frac{di_{dg}}{dt} - \omega L_g i_{qg}$$

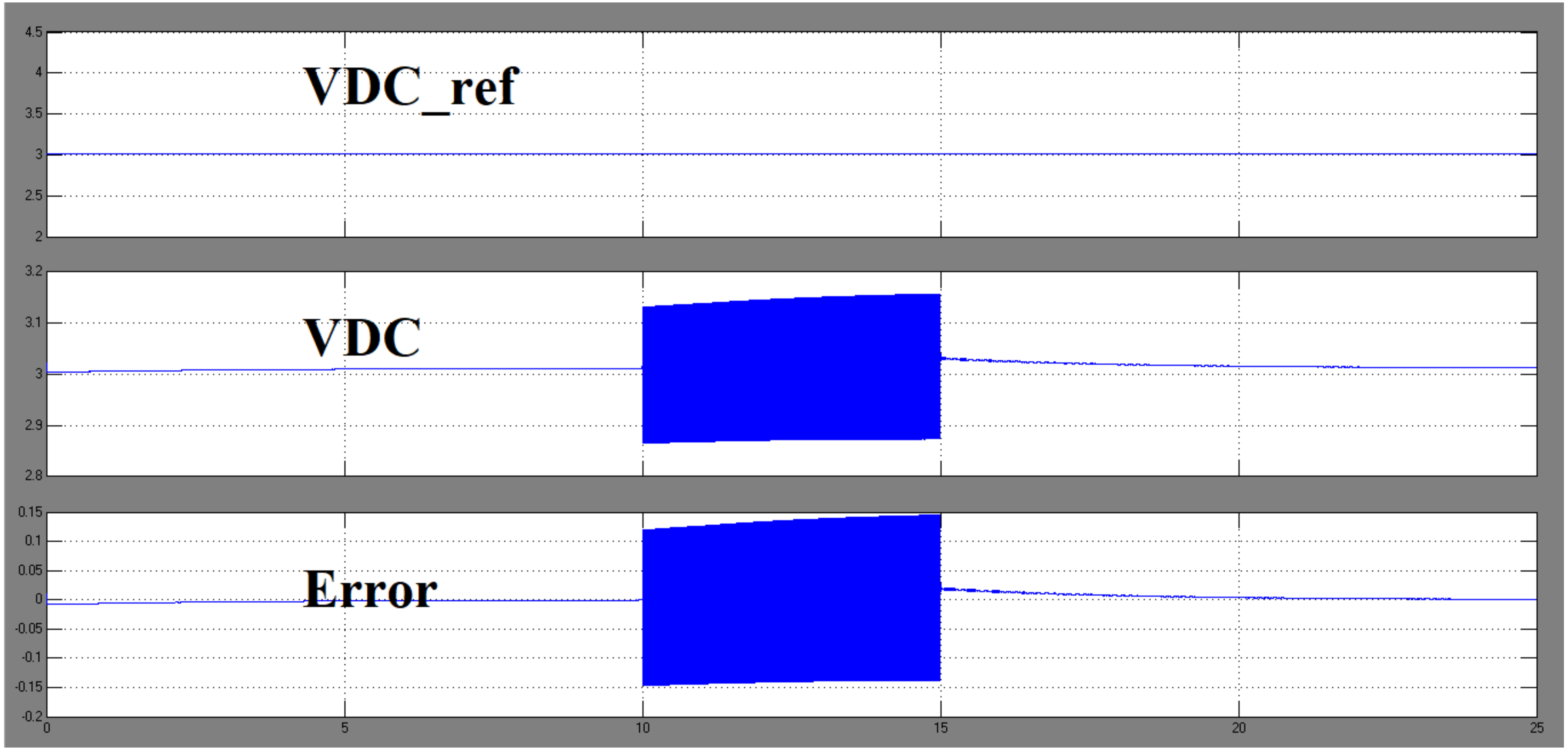
Positive Sequence Controller in GSC



Positive Sequence GSC Control of GSC Power Q_GSC



Positive Sequence GSC Control of DC Link Voltage VDC



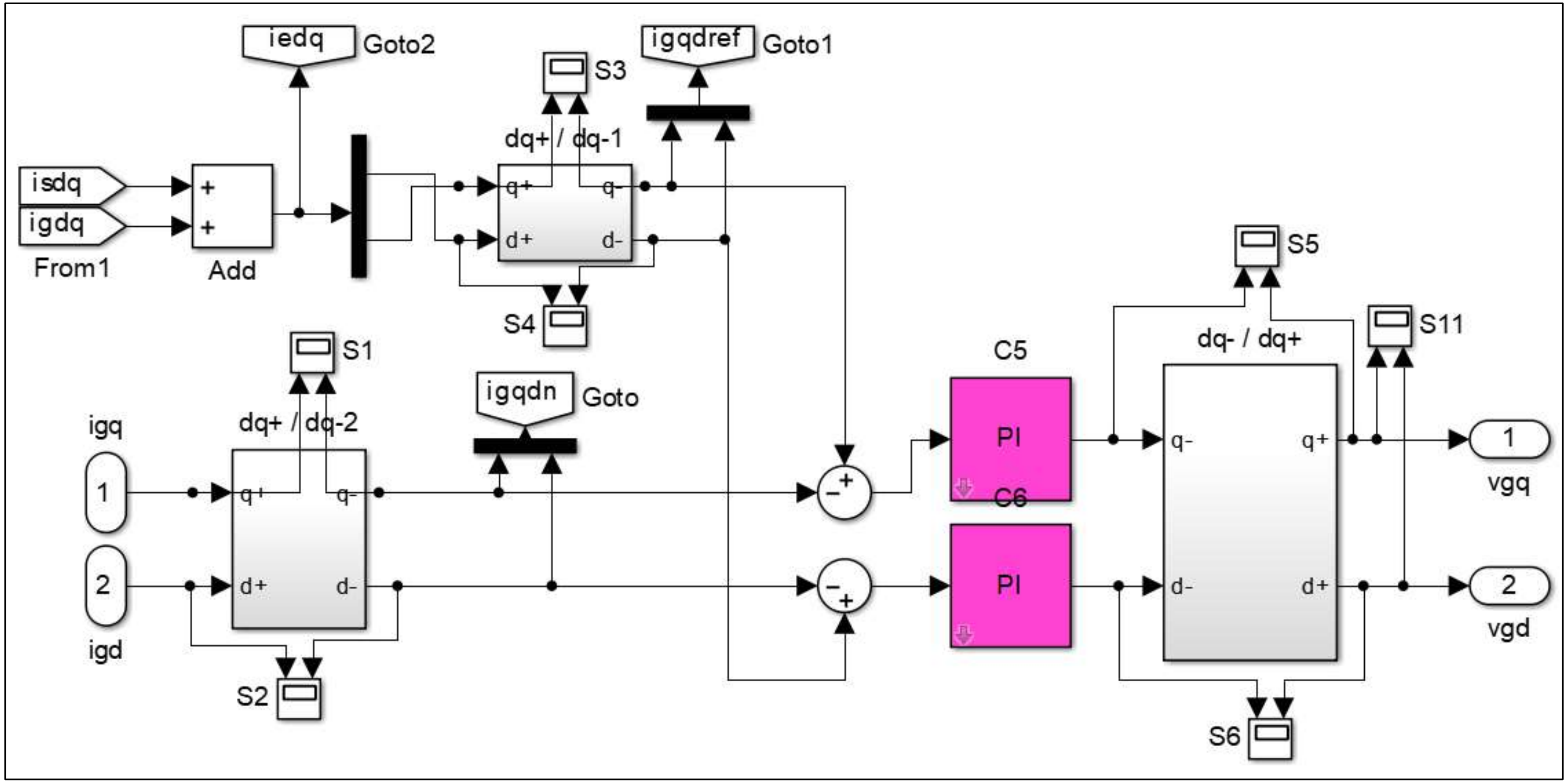
DFIG Grid Side Converter Negative Sequence Control

- For negative sequence compensation via GSC, the current controllers of the GSC will measure the network currents, extract the negative sequence components and generate the required negative sequence currents from the GSC for compensation.
- The reference values of the negative sequence currents come from the measurements of the currents to the grid.

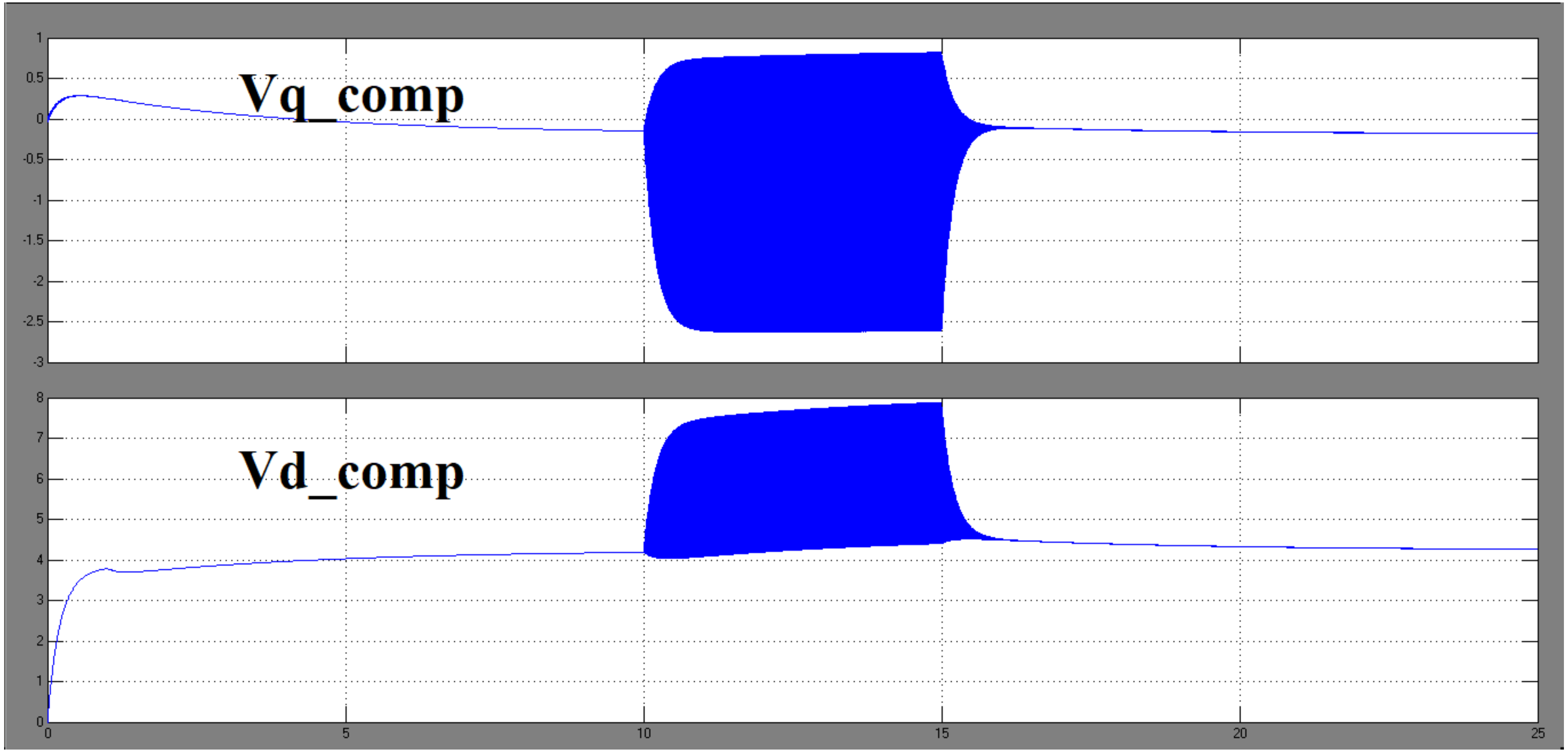
$$i_{gq,ref}^{-} = i_{eq}^{-}$$

$$i_{gd,ref}^{-} = i_{ed}^{-}$$

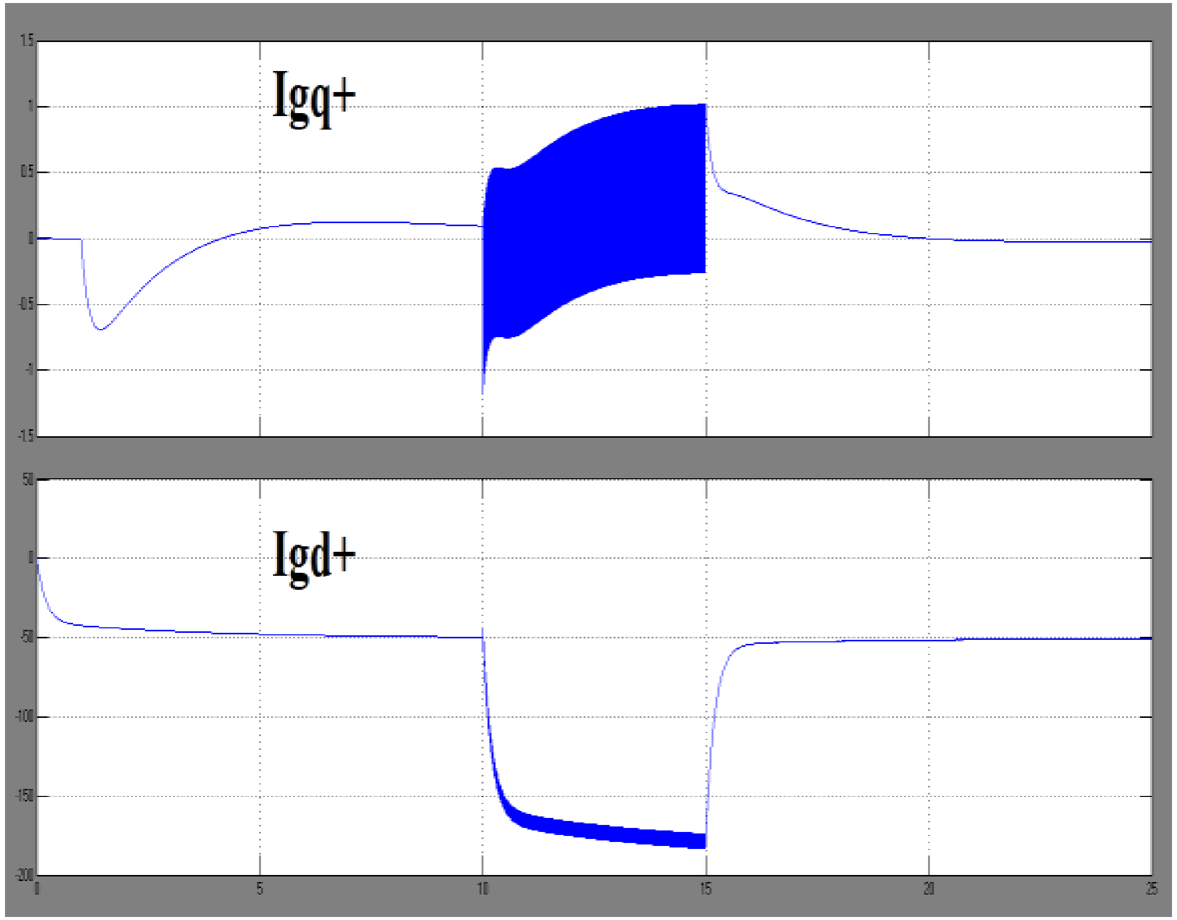
Negative Sequence Controller in GSC

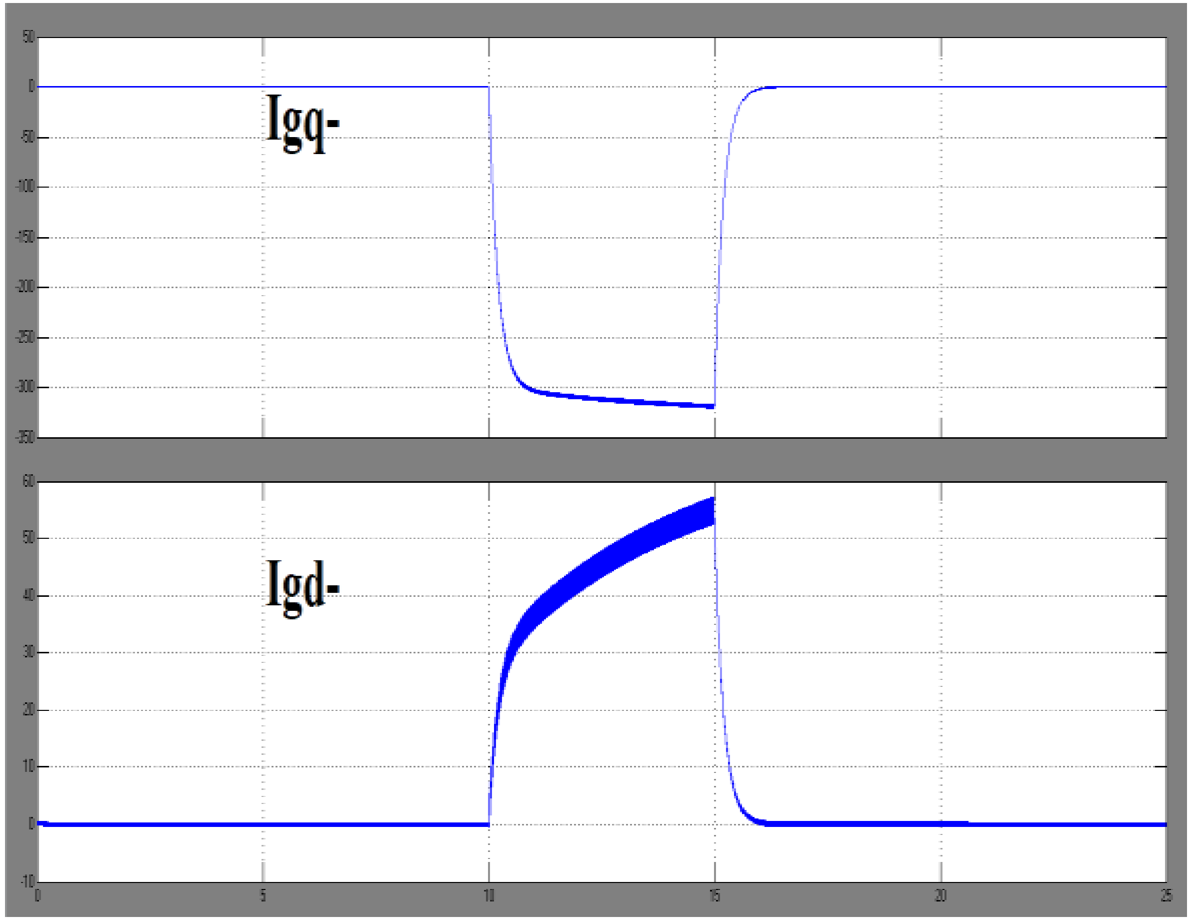


Negative Sequence Compensation via GSC

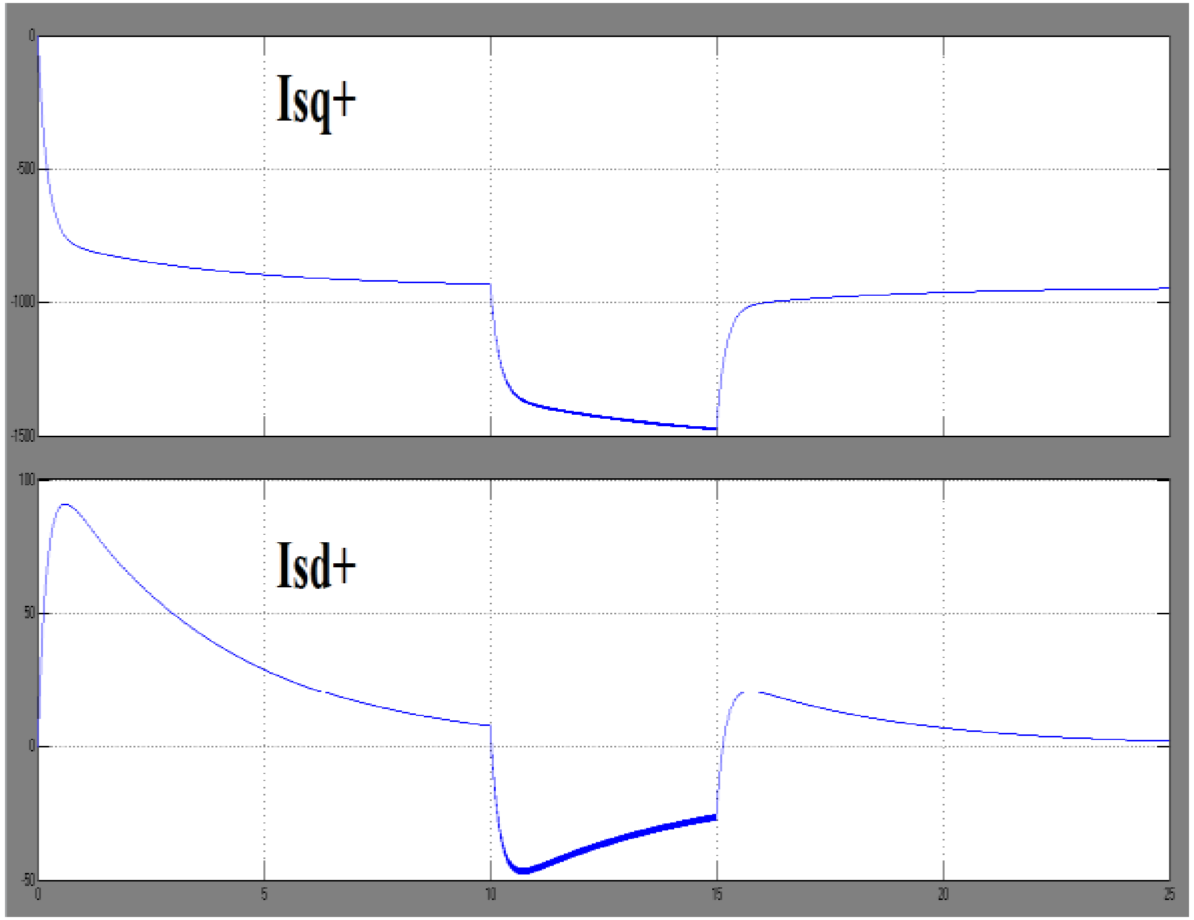


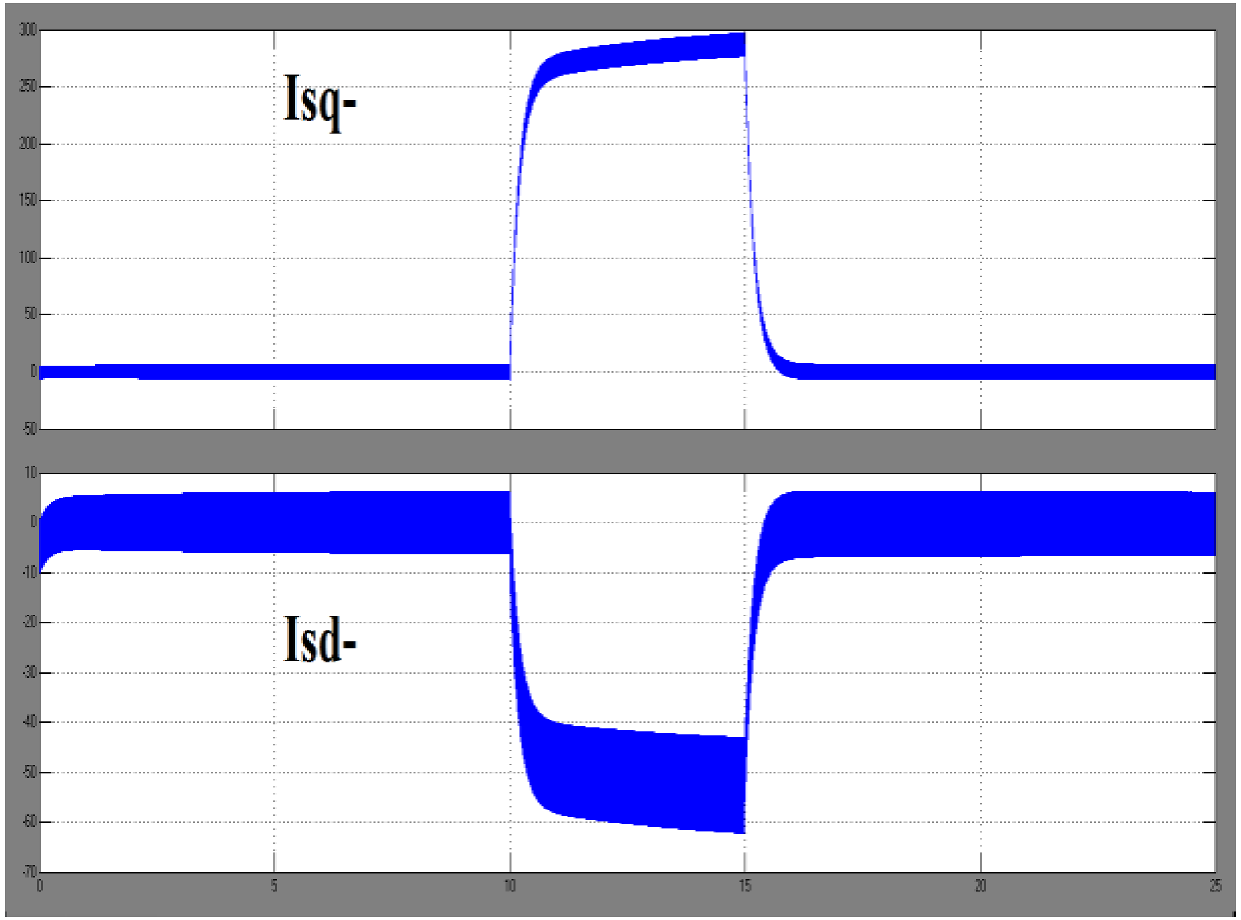
GSC Currents



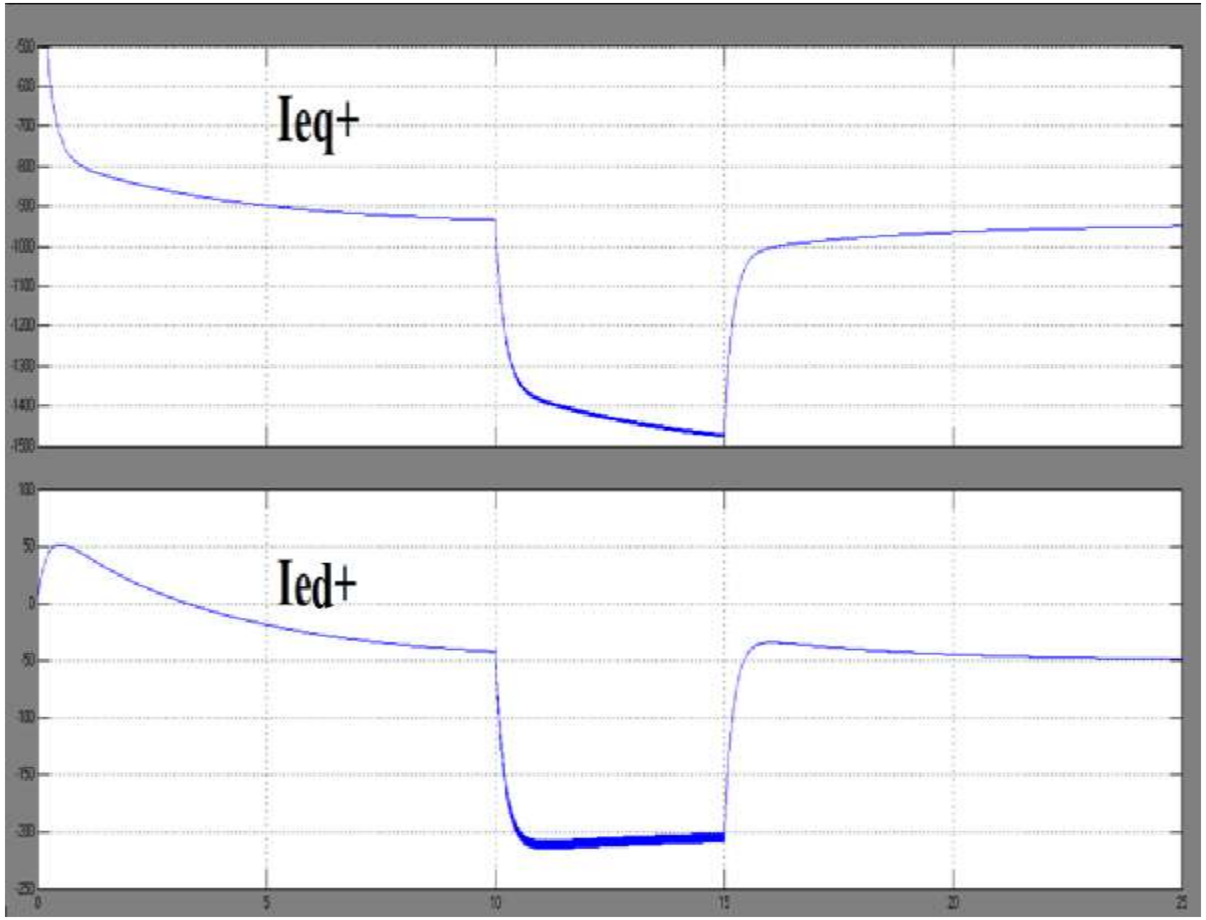


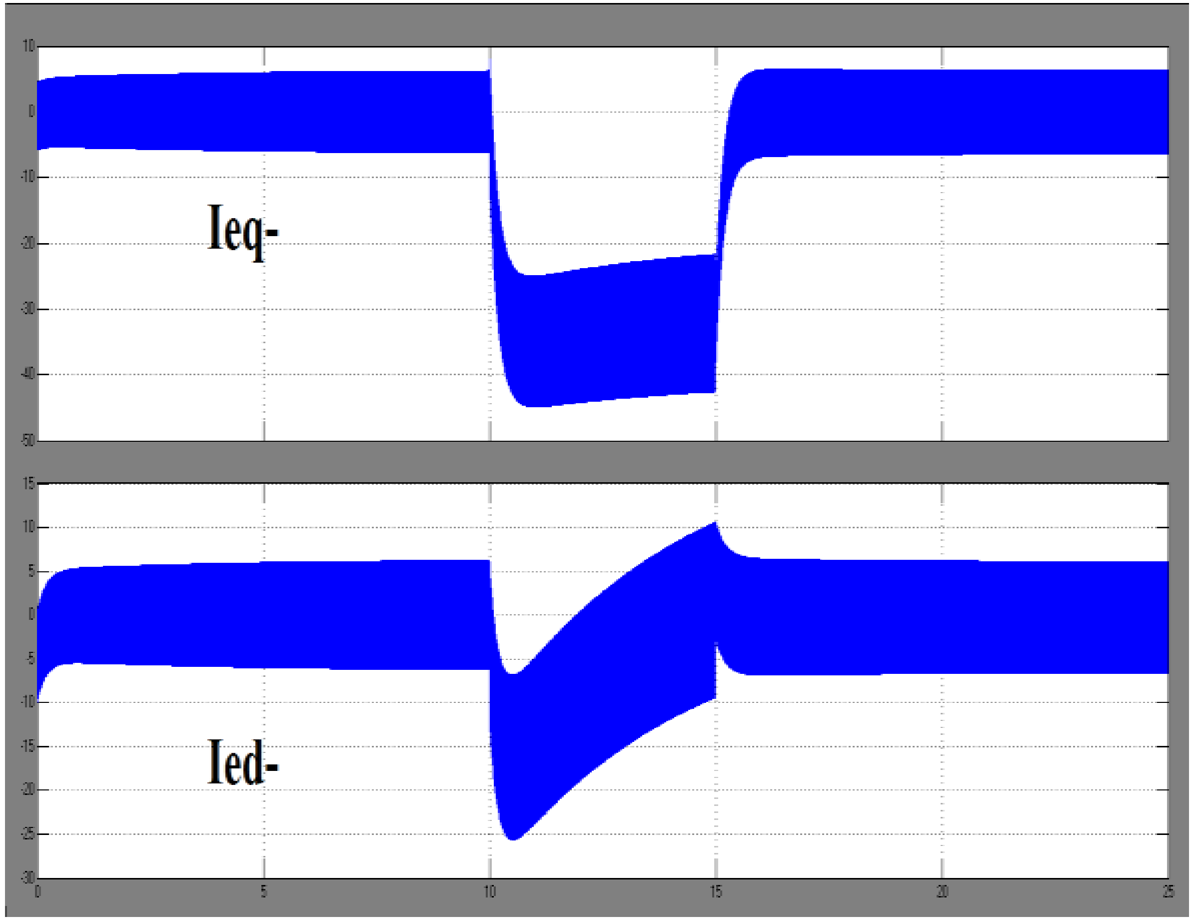
Stator Currents





Grid Currents





Summary

- Due to unbalanced stator voltage conditions, negative-sequence components in stator currents induce a high frequency component $(\omega e+\omega m)$ or $(2-s)\omega e$ in rotor currents and pulsations at $2\omega e$ frequency in electromagnetic torques.
- GSC compensates the negative sequence currents required in the network during any unbalanced operation. It also controls Power delivered to grid by GSC and DC Link Voltage.
- RSC has the potential to eliminate negative sequence rotor currents, negative sequence stator currents or torque pulsation. It also controls Active and Reactive Power delivered by stator.

References

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- R. Pena, J. Clare, G. Asher, *Doubly fed induction generator using back-to-back pwm converters and its application to variable-speed wind-energy generation*, IEEE Proc. Electr. Power Appl. 143(3), 1996, 231-241.
- R. Pena, R. Cardenas, E. Escobar, *Control system for unbalanced operation of stand-alone doubly fed induction generators*, IEEE Trans. Energy Convers. 22(2), 2007, 544-545.