

Analysis of DFIG with Unbalanced Stator Voltage

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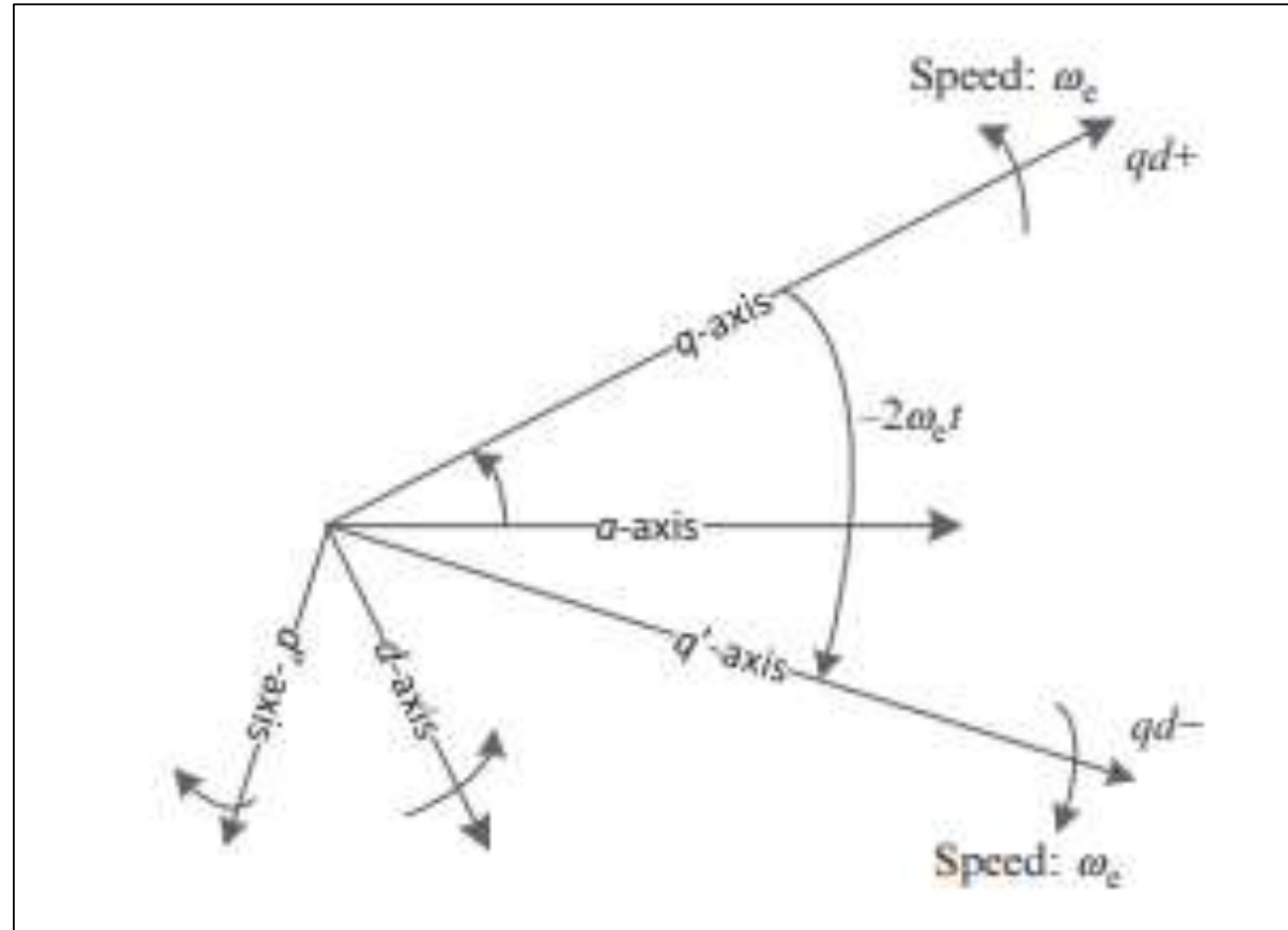
Overview

- 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.

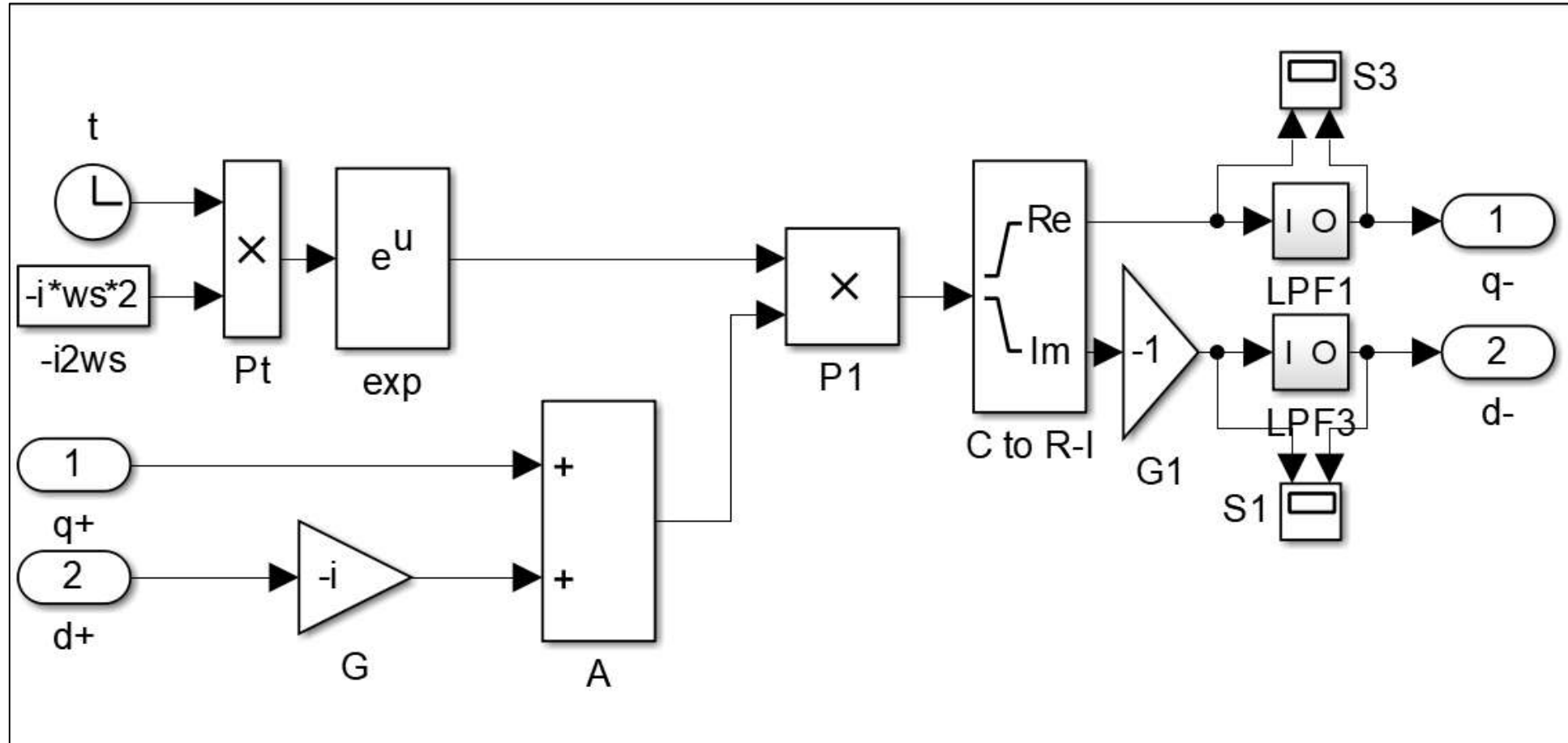
Negative Sequence dq- Components

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

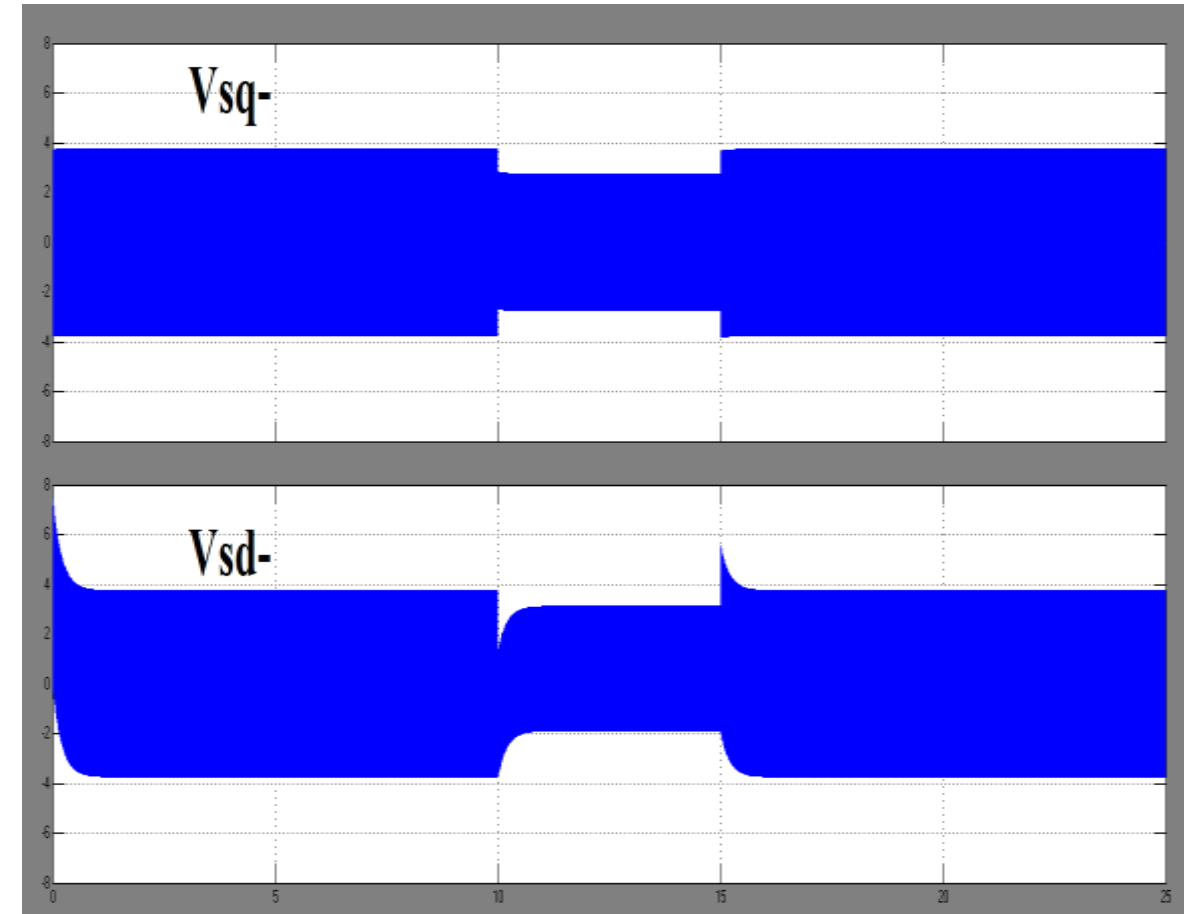
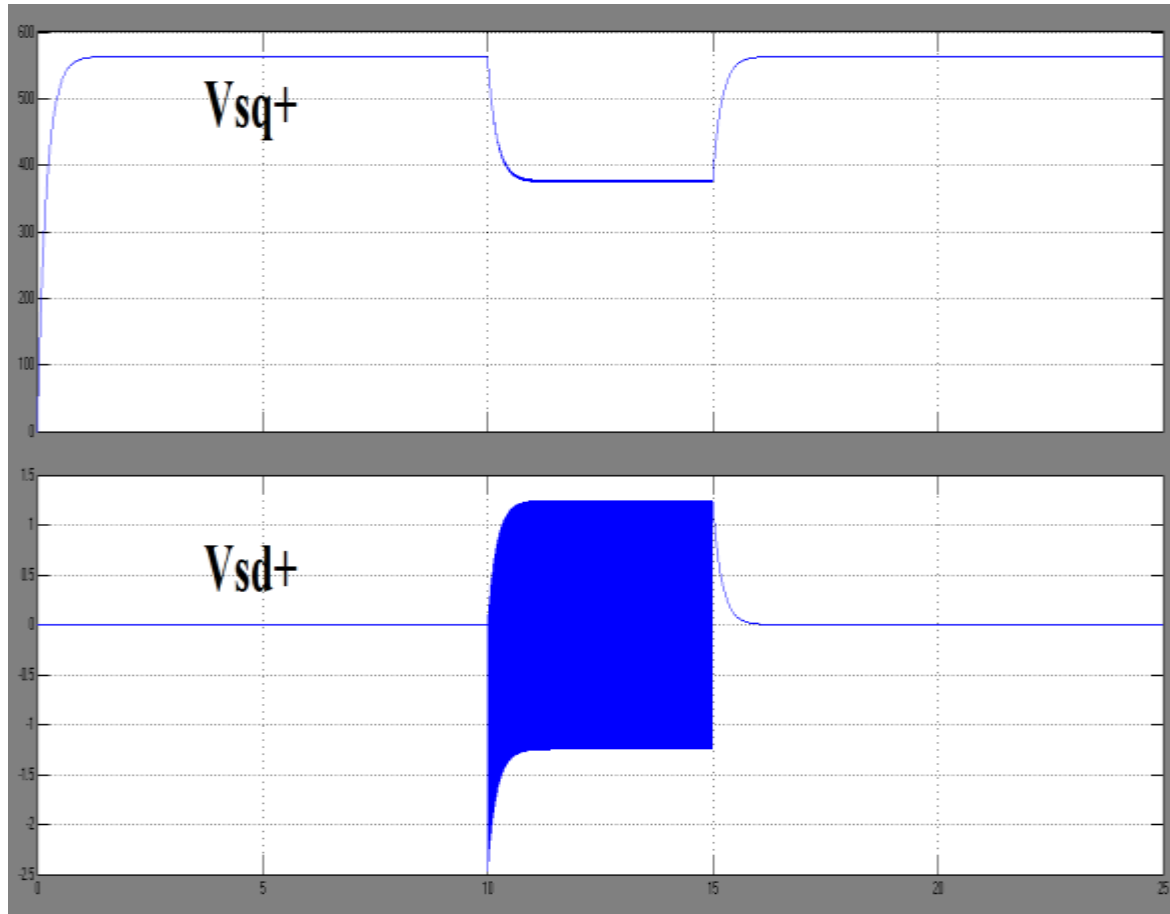
$$[q^- - jd^-] = e^{-j2\omega_e t} \cdot [q^+ - jd^+]$$



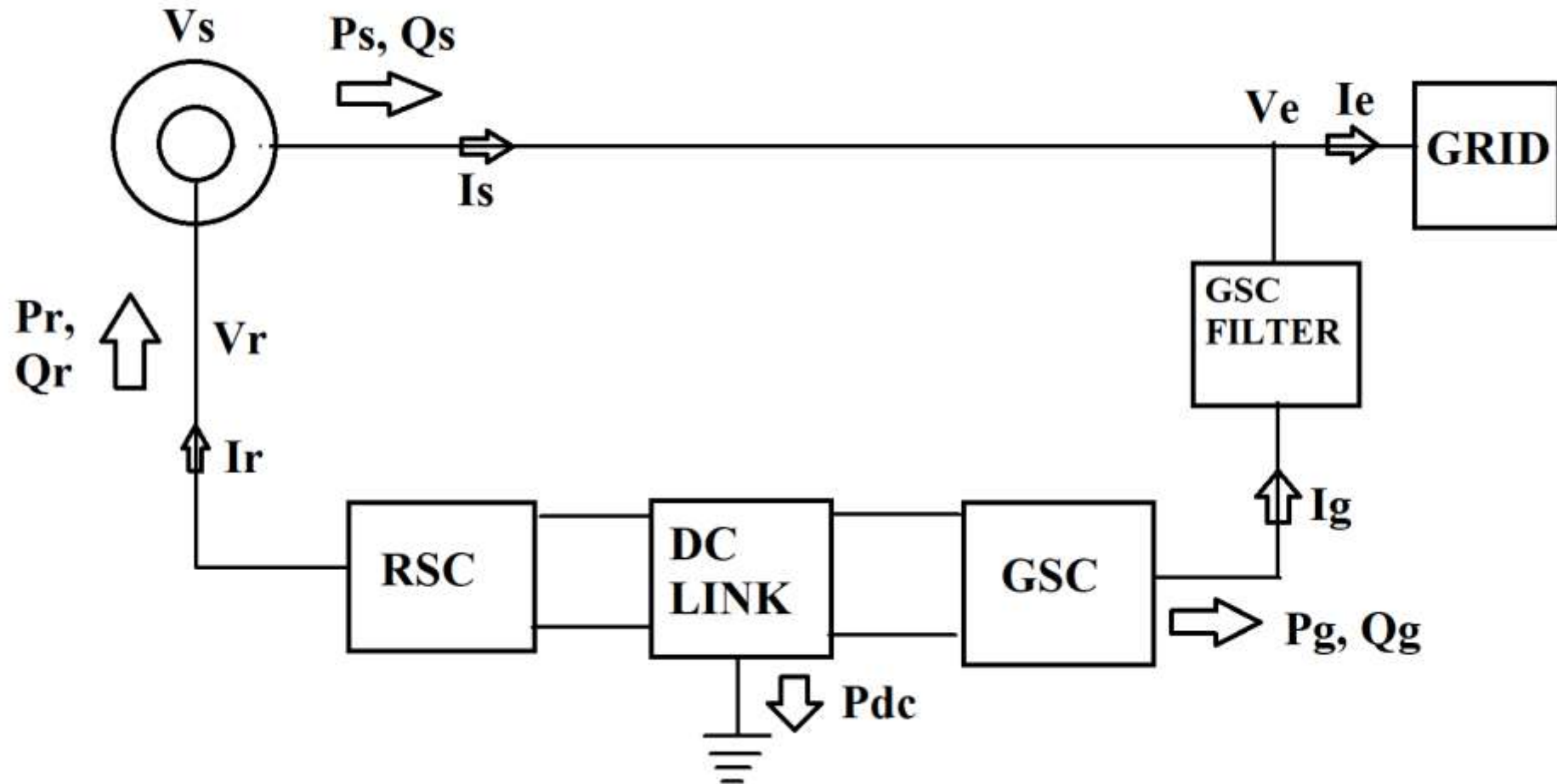
dq+/dq- Transformation



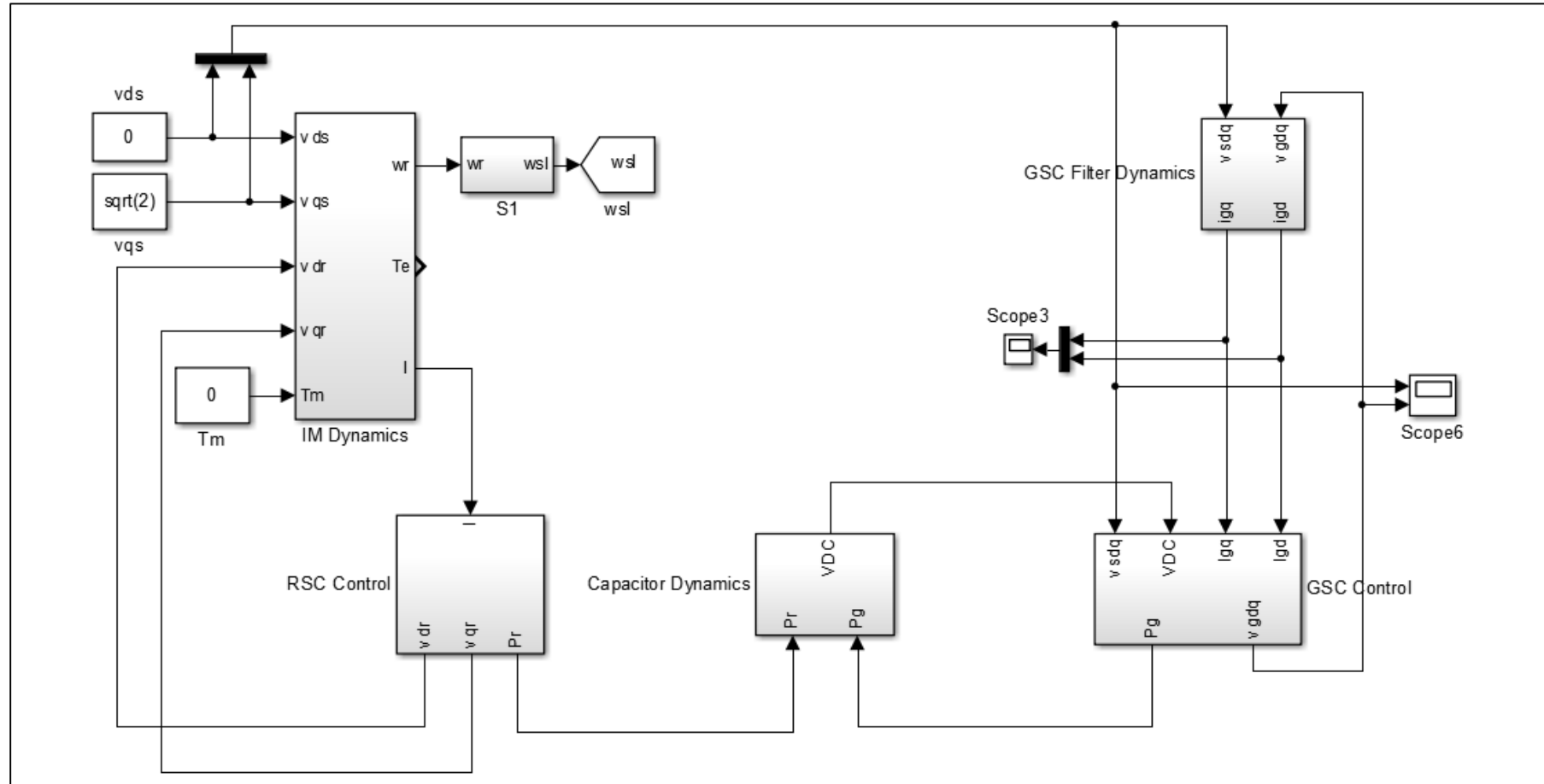
Stator Phase a Voltage Collapses to zero for $t=10\text{s}$ to $t=15\text{s}$



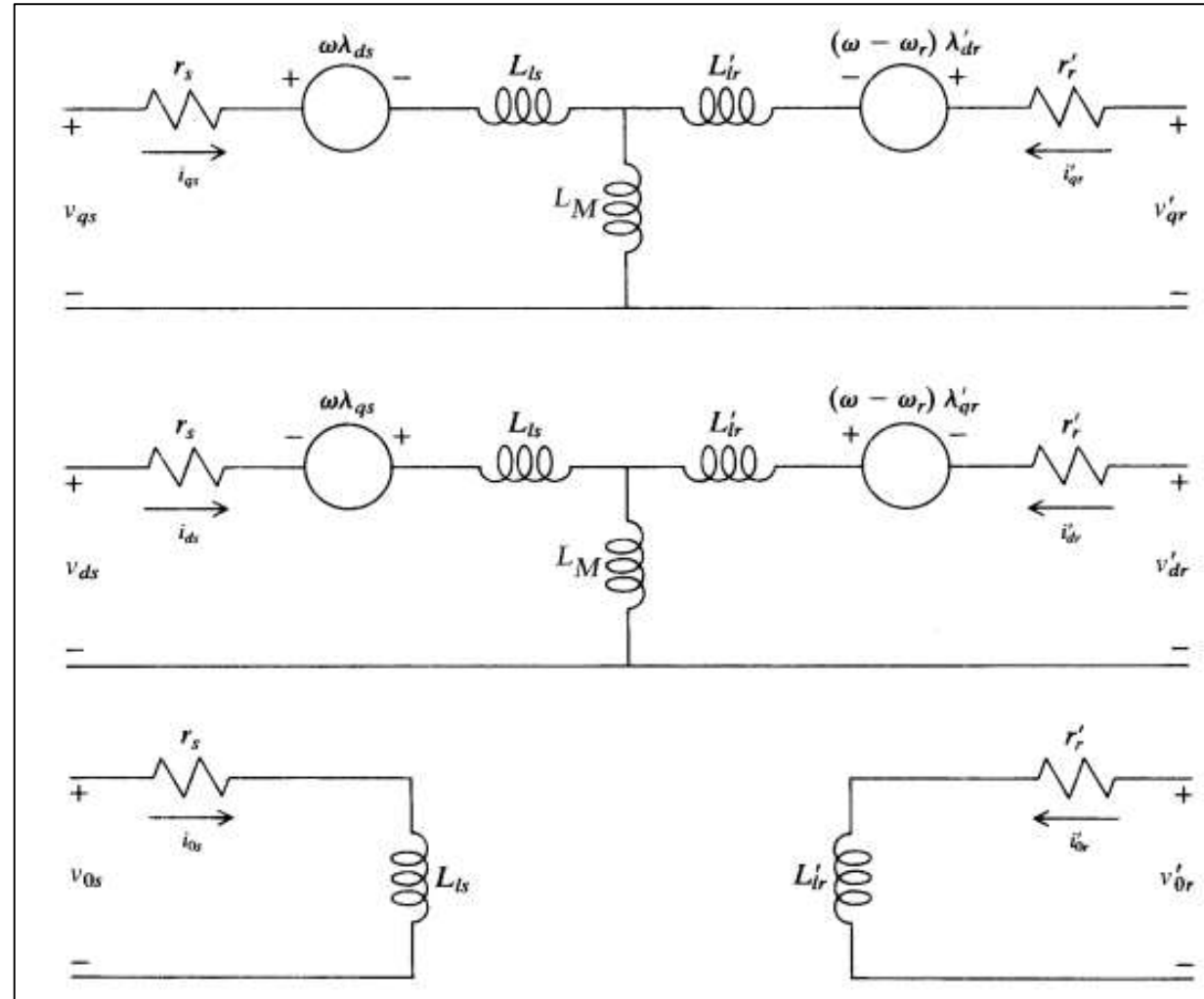
Complete DFIG Model



Complete DFIG Simulation Model



Induction Machine dq0-axis Model



Induction Machine dq0-axis Model Equations

Voltage and Current Equations

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

Motion and Torque Equations

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

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

$$P_{base} = 2 \text{ MW}$$

- Rated Line-Line Voltage

$$V_{rated,LL} = 690 \text{ V}_{rms}$$

- Number of Pole Pairs

$$P = 6$$

- Rated Stator Frequency

$$f_e = 60 \text{ Hz}$$

- Stator Winding Resistance

$$R_s = 0.00488 \text{ p.u.}$$

- Rotor Winding Resistance

$$R_r = 0.00549 \text{ p.u.}$$

- Stator Leakage Reactance

$$X_{ls} = 0.09231 \text{ p.u.}$$

- Rotor Leakage Reactance

$$X_{lr} = 0.09955 \text{ p.u.}$$

- Magnetizing Reactance

$$X_m = 3.95279 \text{ p.u.}$$

$$X_s = X_{ls} + X_m = 4.0451 \text{ p.u.}$$

$$X_r = X_{lr} + X_m = 4.0523 \text{ p.u.}$$

- Inertia Constant

$$H = 3.5 \text{ s}$$

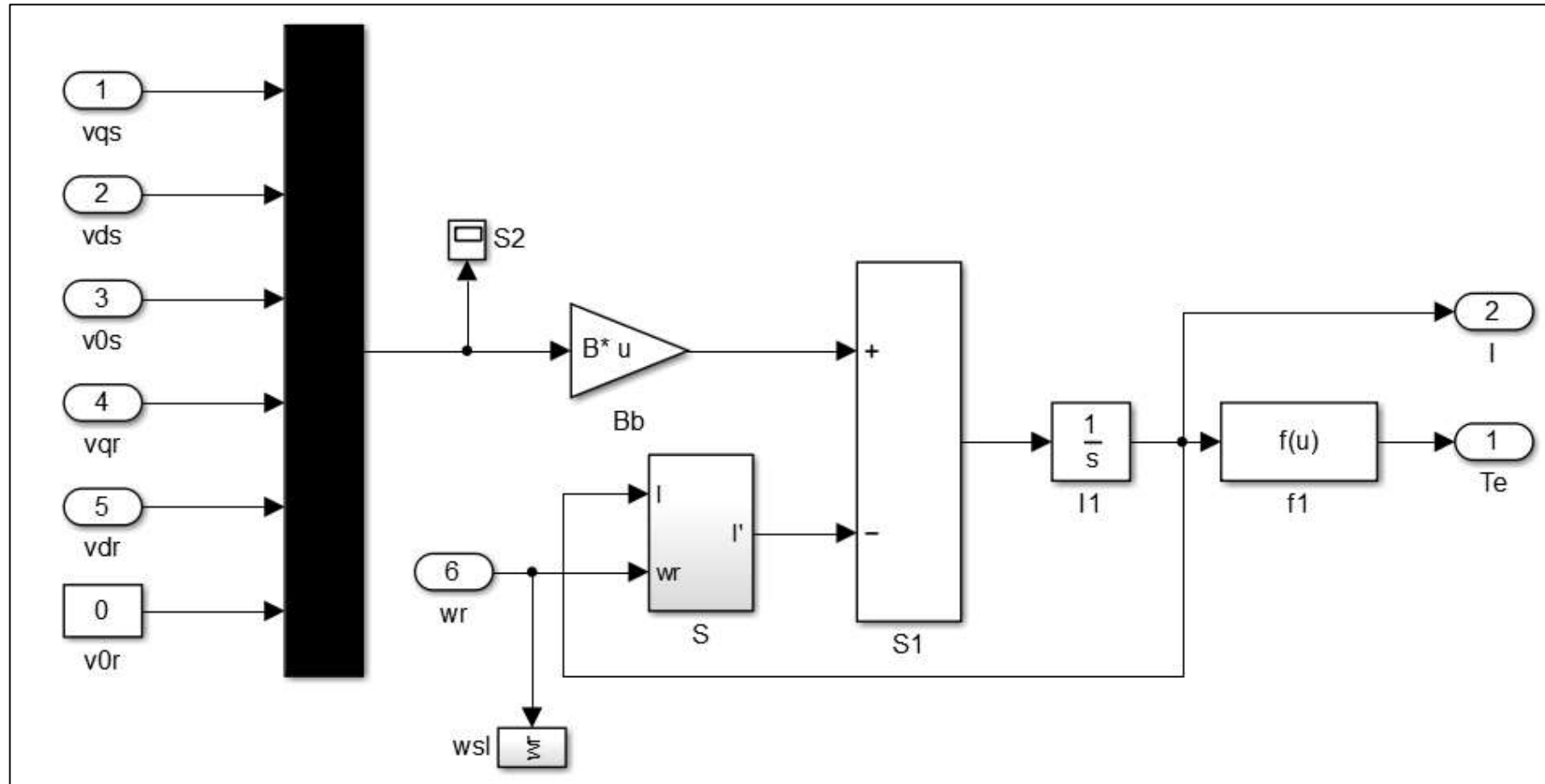
- Base Speed

$$\omega_b = 2\pi f_e = 376.9911 \text{ rad/s}$$

- Synchronous Speed

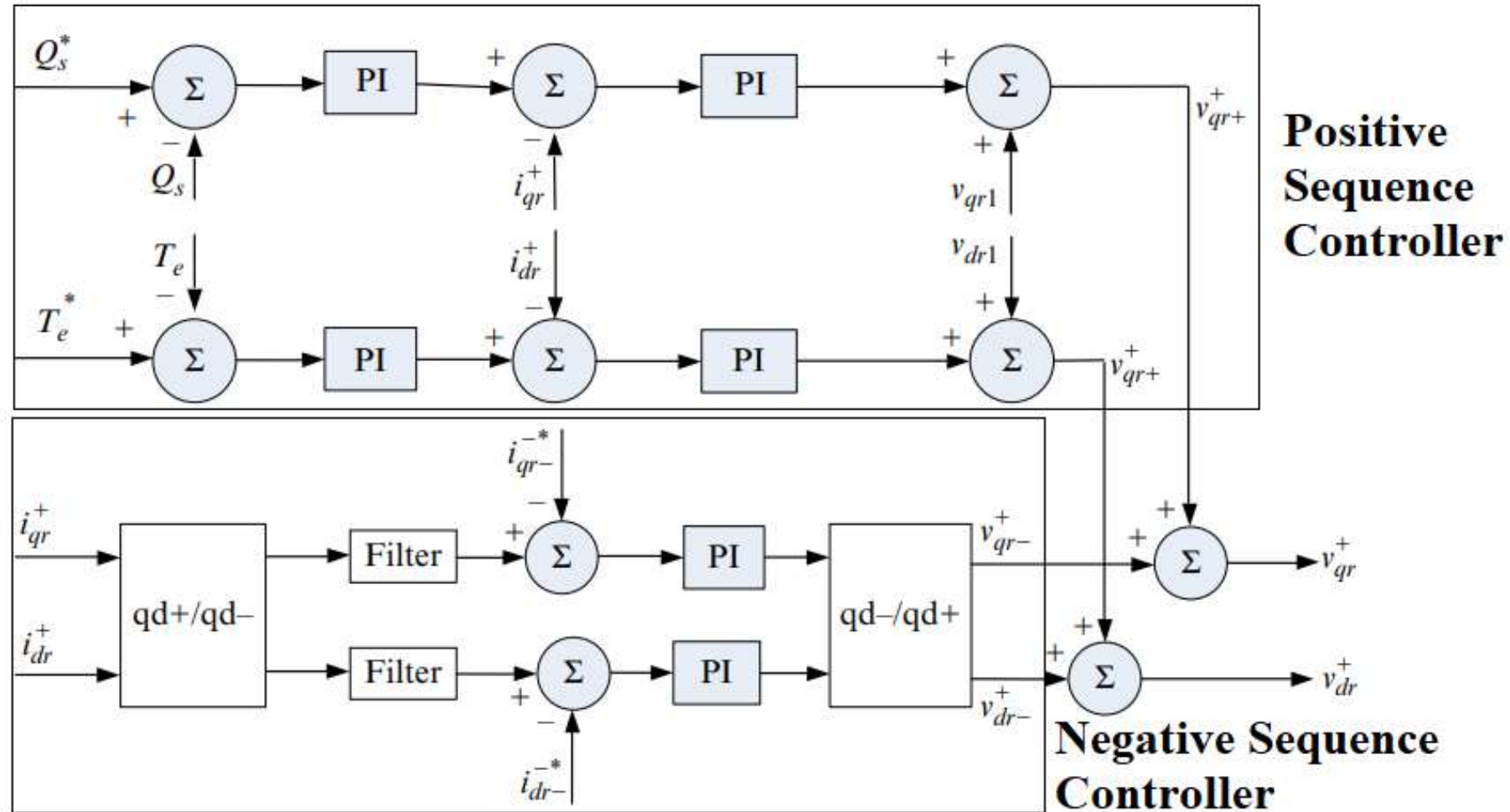
$$\omega_s = \frac{2}{P} 2\pi f_e = 125.6637 \text{ rad/s}$$

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 i_{qr} and i_{dr} respectively.

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

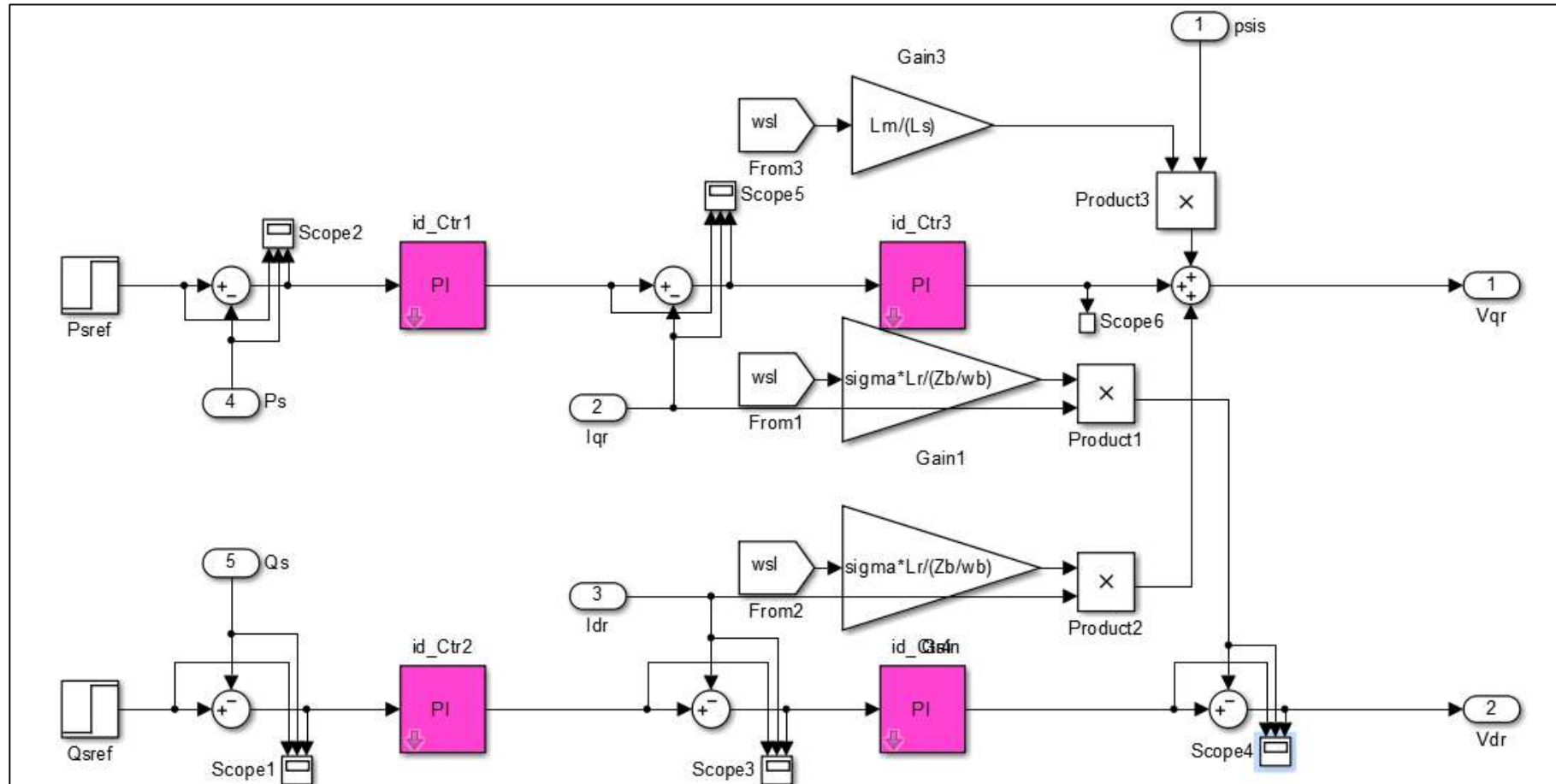
$$Q_s = -\frac{3}{2} (v_{qs} i_{ds} - v_{ds} i_{qs}) = -\frac{3P}{4} \omega_e \psi_{ds} i_{ds}$$

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

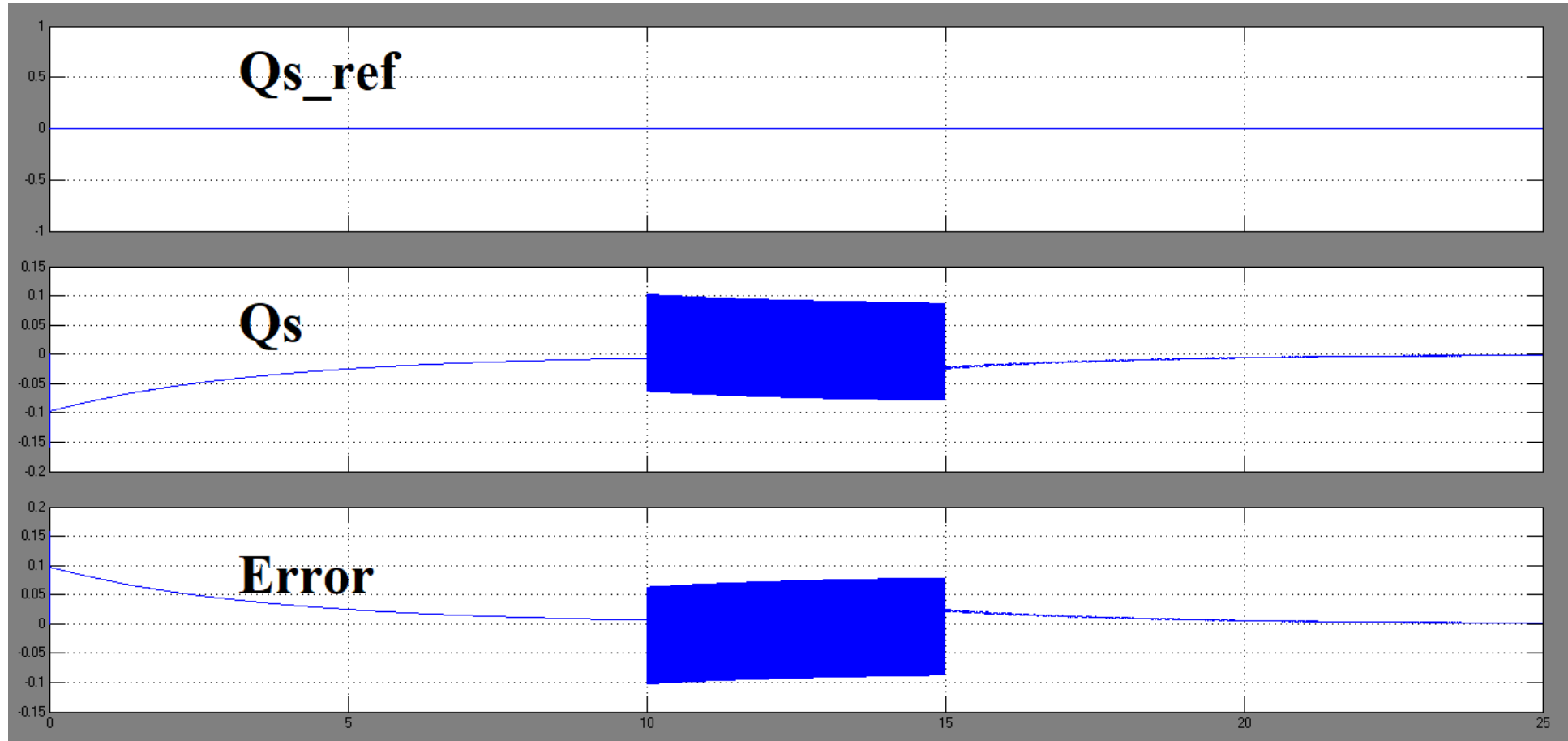
$$v_{qr} = r_r i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_{sl} \psi_{dr} = r_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + \omega_{sl} (\sigma L_r i_{dr} + \frac{L_m}{L_s} \psi_{ds})$$

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

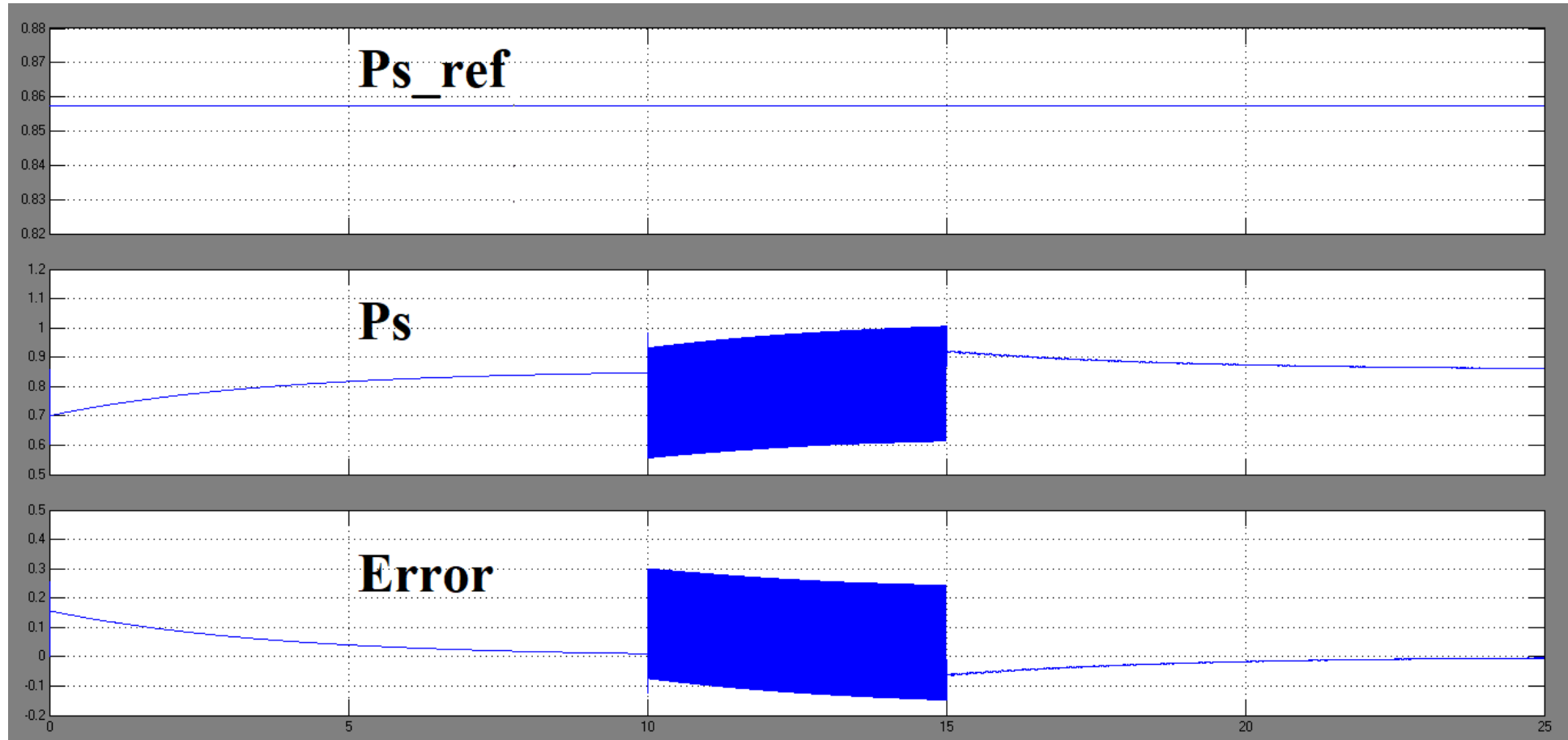
Positive Sequence Controller in RSC



Positive Sequence RSC Control of Stator Power Q_s



Positive Sequence RSC Control of Stator Power P_s



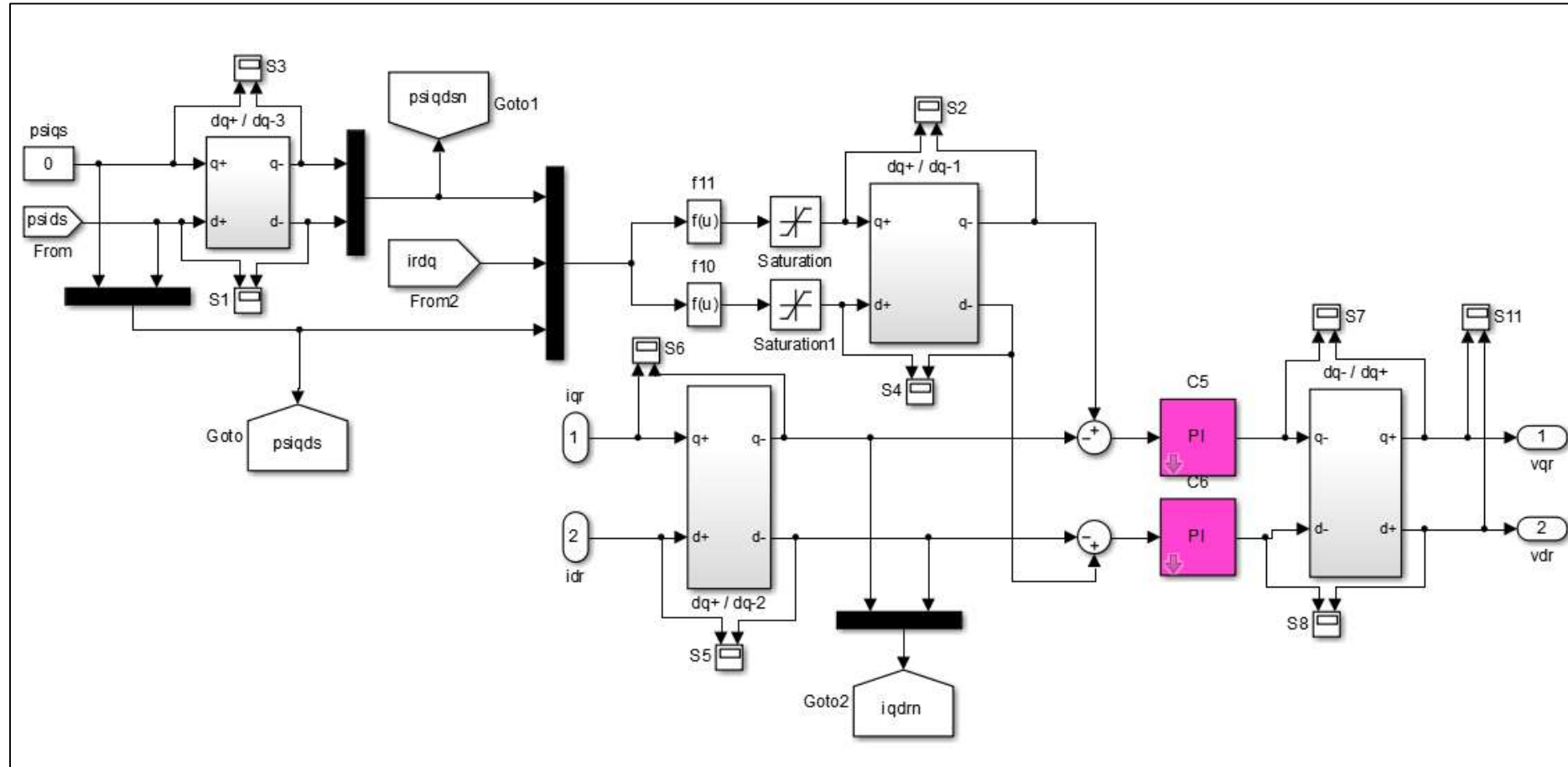
DFIG Rotor Side Converter Negative Sequence Control

- 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.

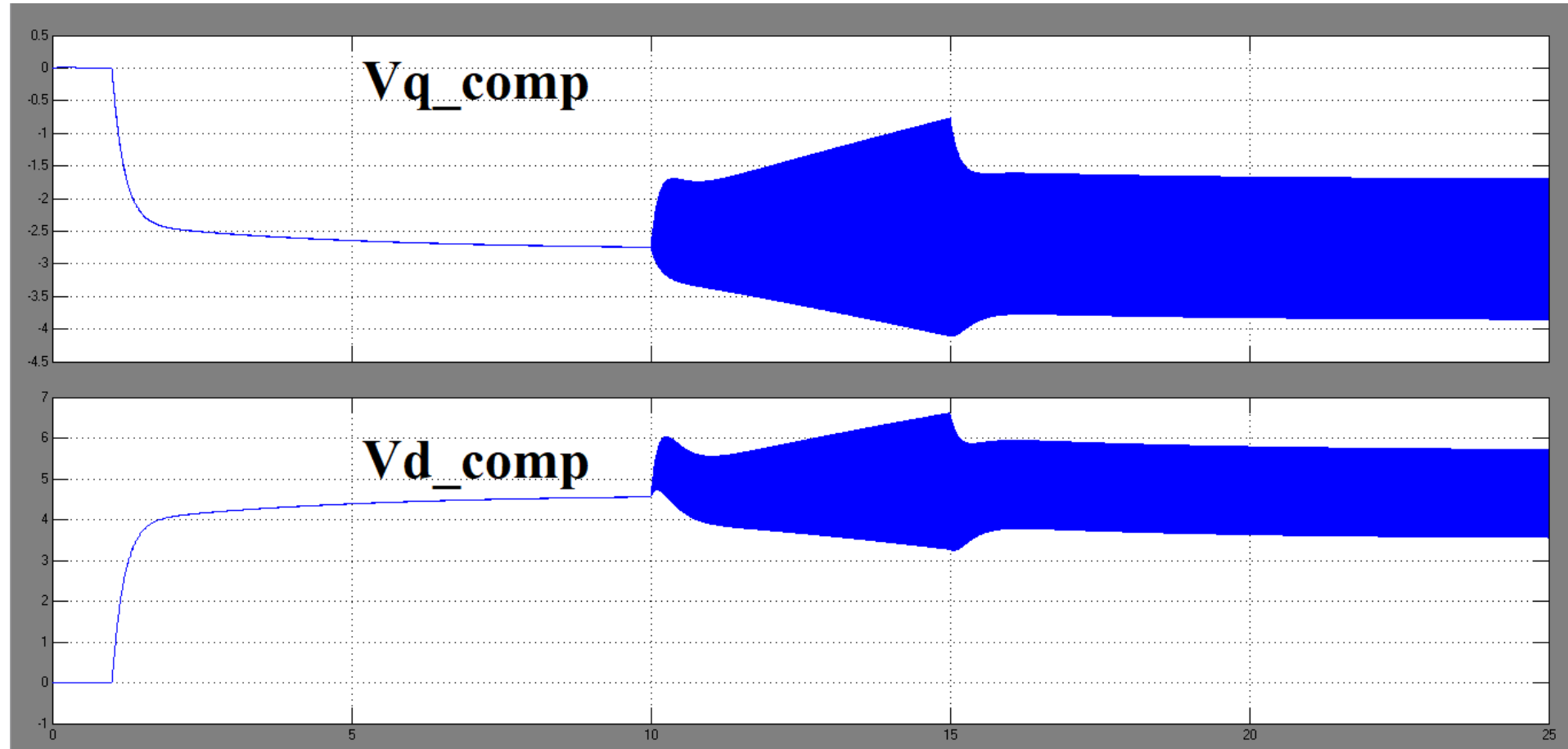
$$\begin{aligned}T_e &= T_{edc} + T_{ecos} \cos(2\omega_e t) + T_{esin} \sin(2\omega_e t) \\T_{edc} &= K(\psi_{qs}^+ i_{qr}^+ + \psi_{ds}^+ i_{dr}^+ + \psi_{qs}^- i_{qr}^- + \psi_{ds}^- i_{dr}^-) \\T_{ecos} &= K(\psi_{qs}^+ i_{qr}^- + \psi_{ds}^+ i_{dr}^- + \psi_{qs}^- i_{qr}^+ + \psi_{ds}^- i_{dr}^+) \\T_{esin} &= K(\psi_{ds}^+ i_{qr}^- - \psi_{qs}^+ i_{dr}^- - \psi_{ds}^- i_{qr}^+ + \psi_{qs}^- i_{dr}^+)\end{aligned}$$

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

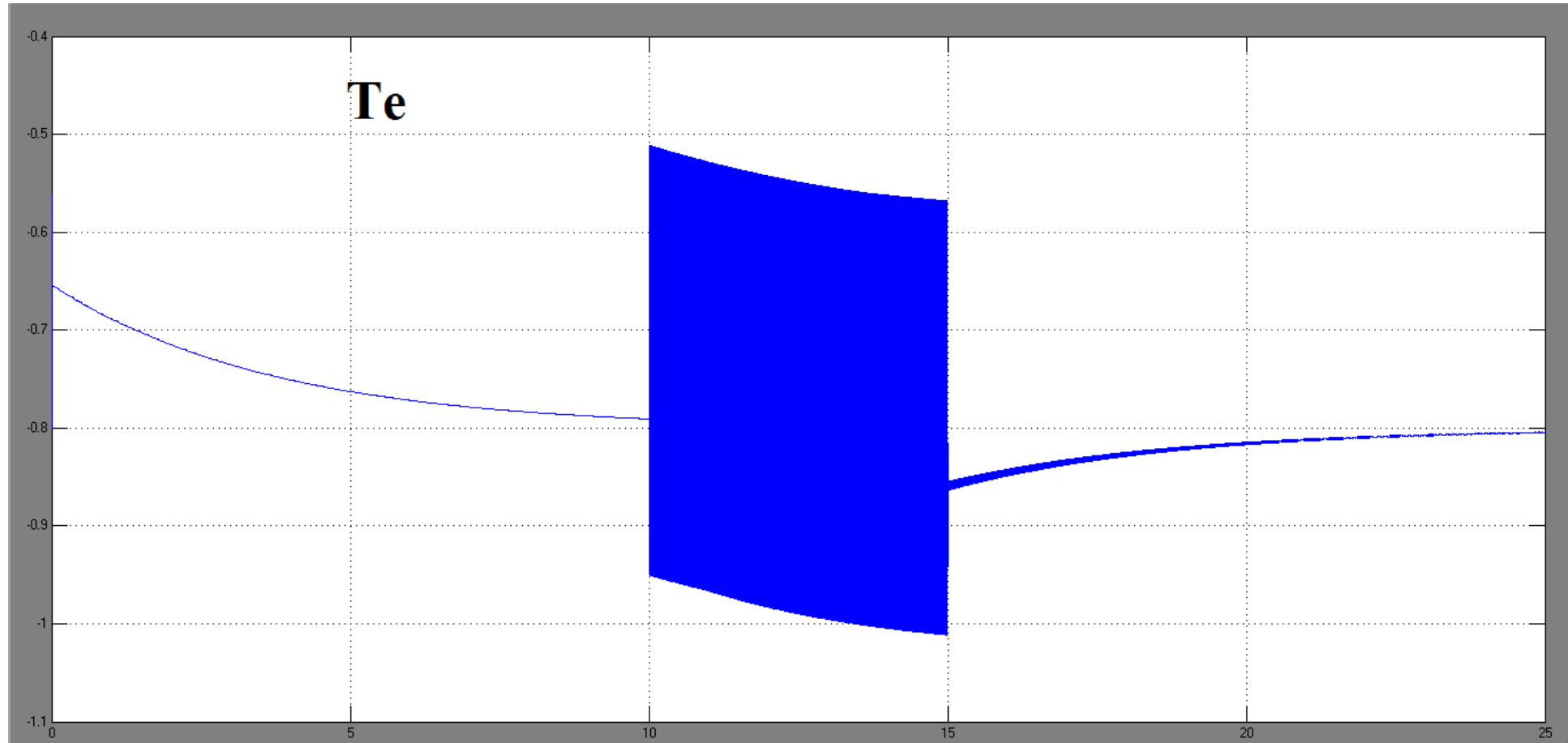
Negative Sequence Controller in RSC



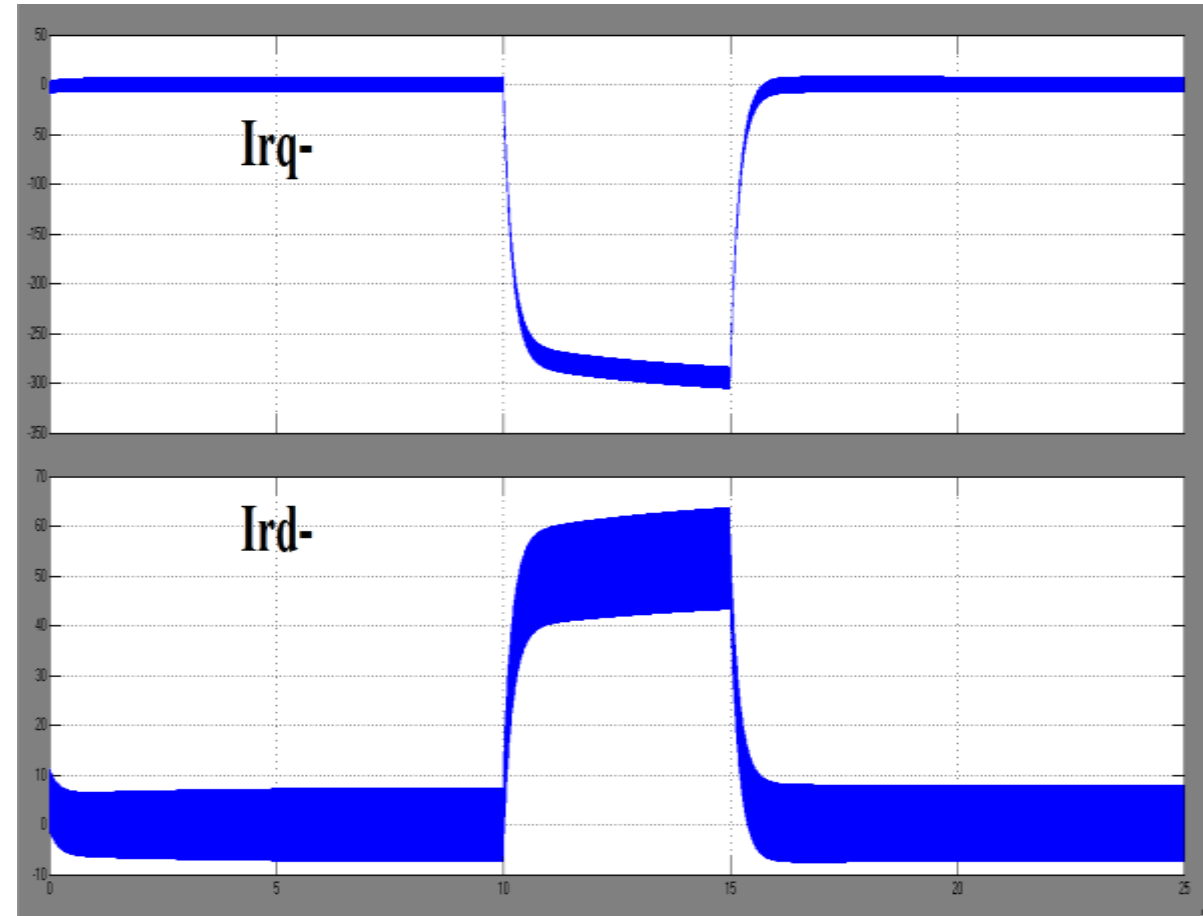
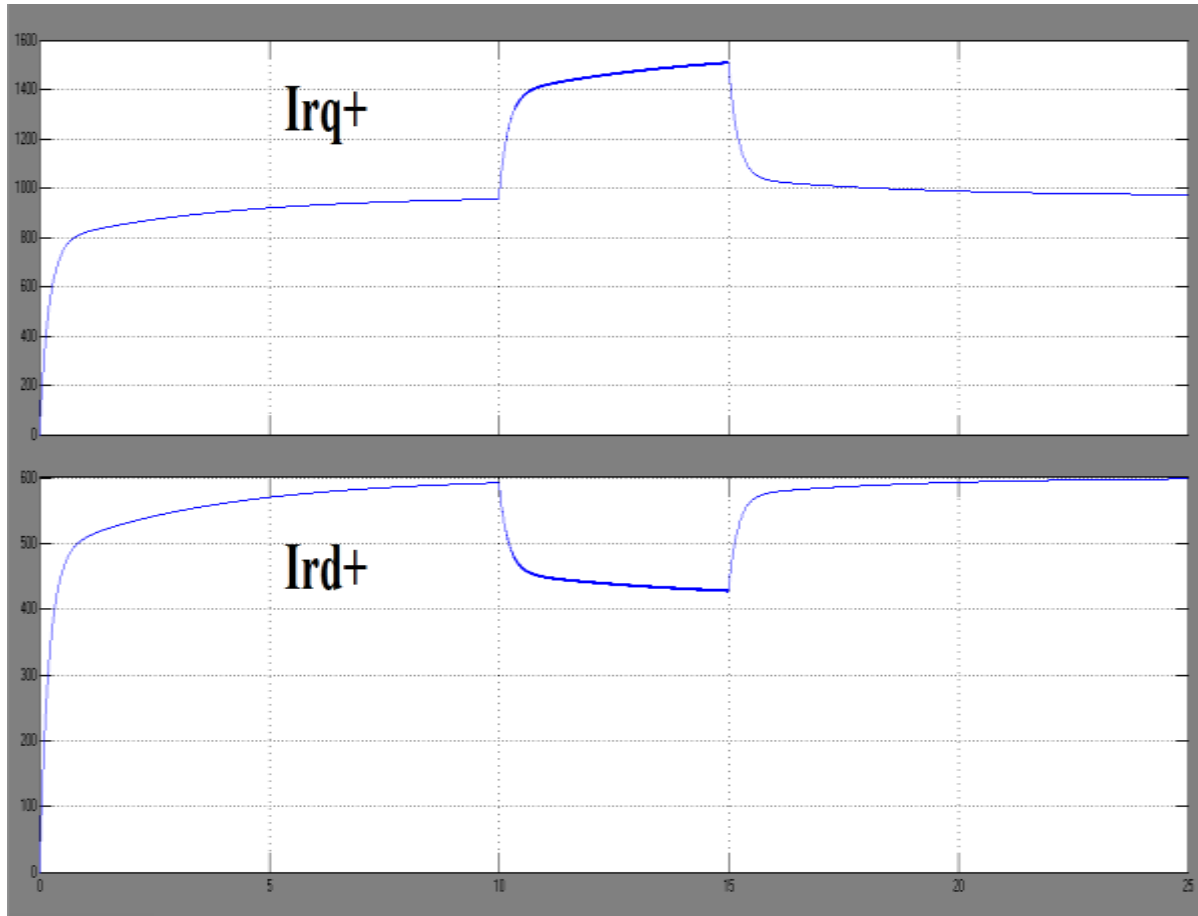
Negative Sequence Compensation via RSC



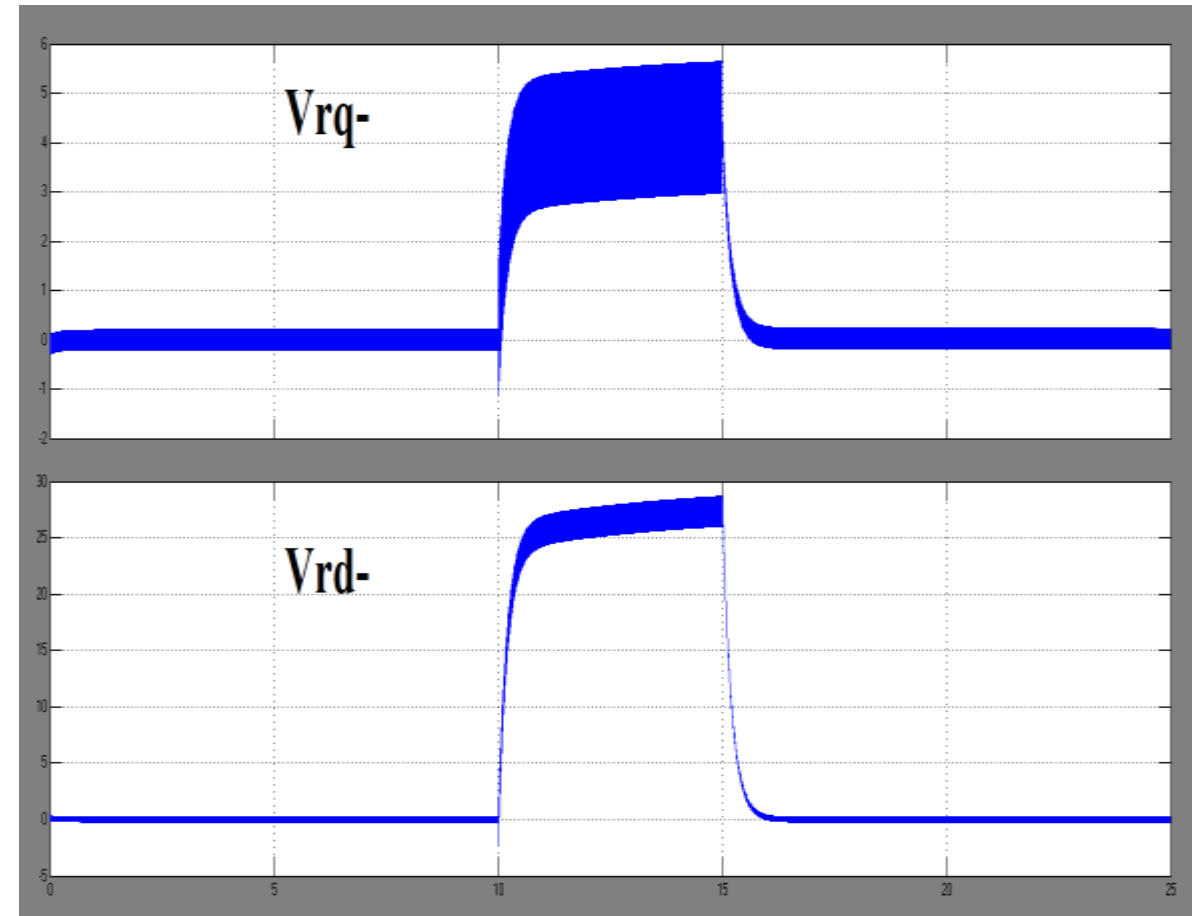
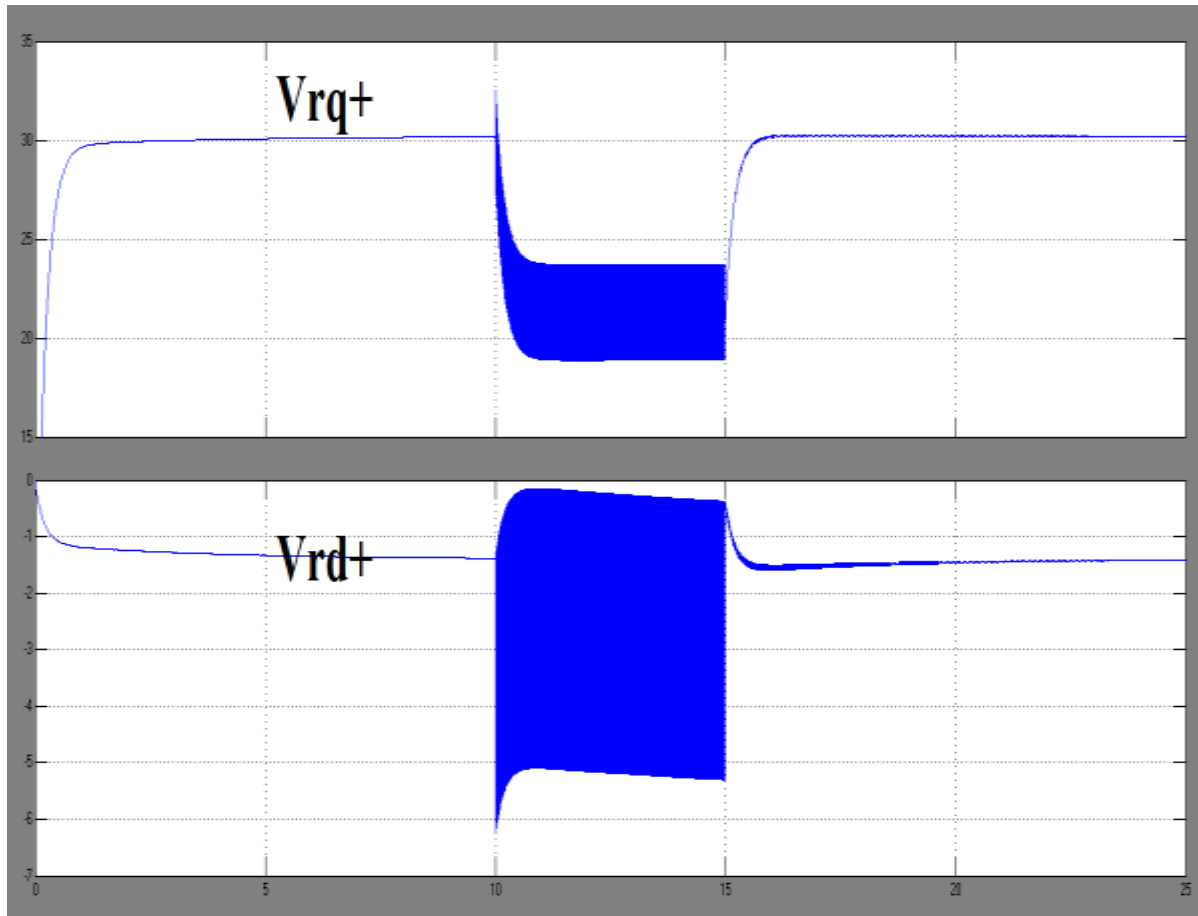
Torque Response



Rotor Currents

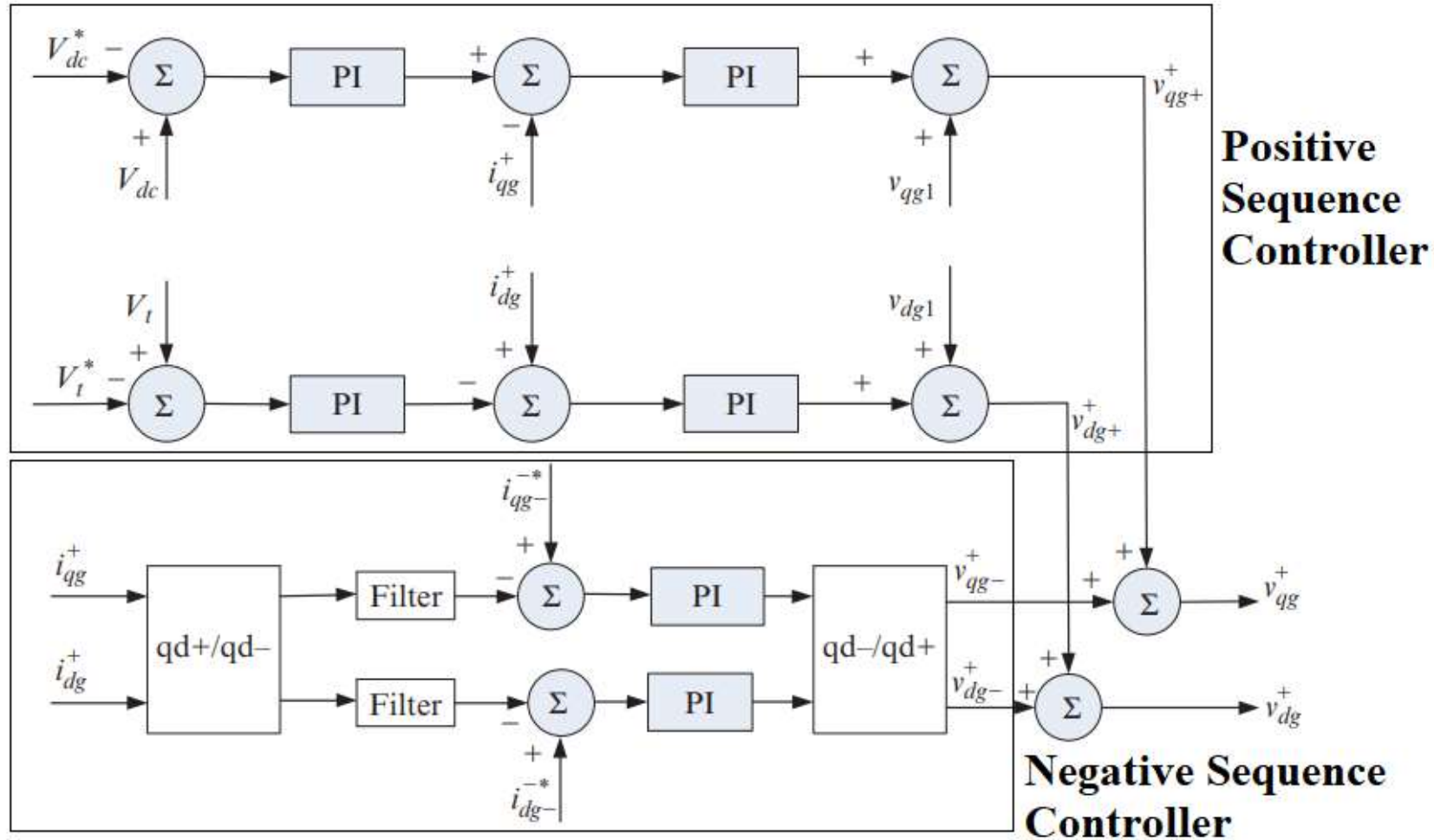


Rotor Voltages



Grid Side Converter

Grid Side Converter



DFIG Grid Side Converter Positive Sequence Control

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

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

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

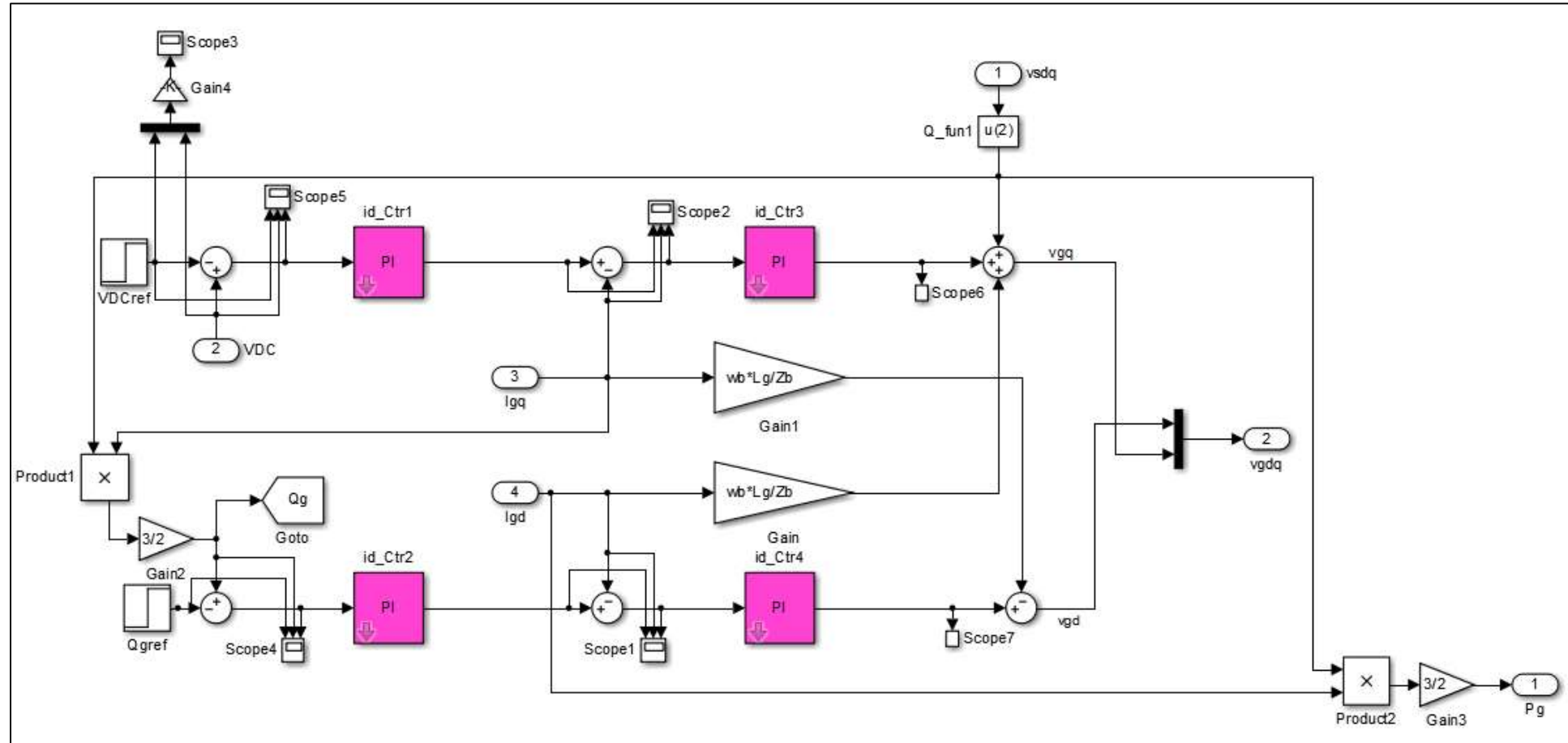
- GSC control takes care of the DC-link voltage as well

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

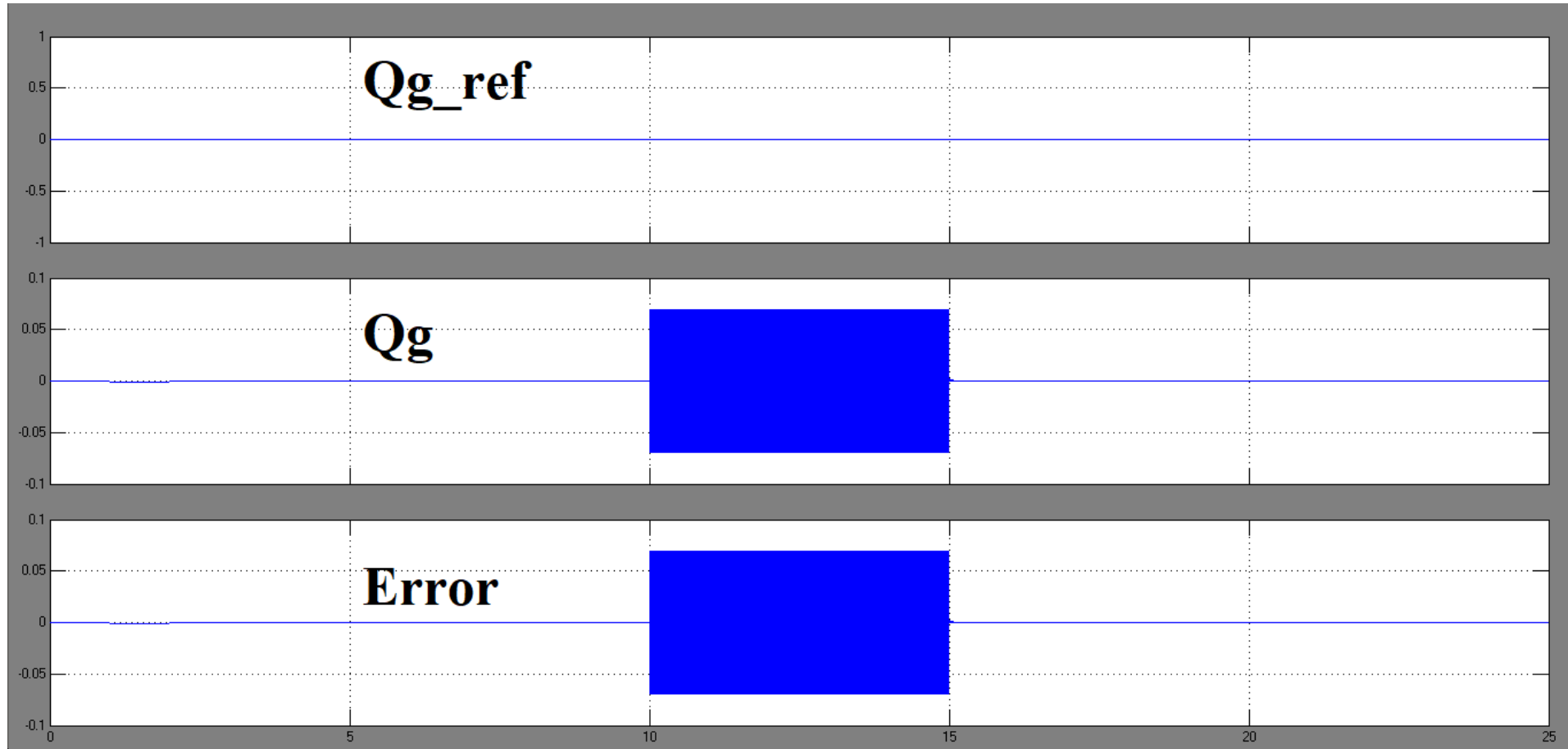
- The GSC output voltage, GSC current, and the coupling point voltage are used to design controller.

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

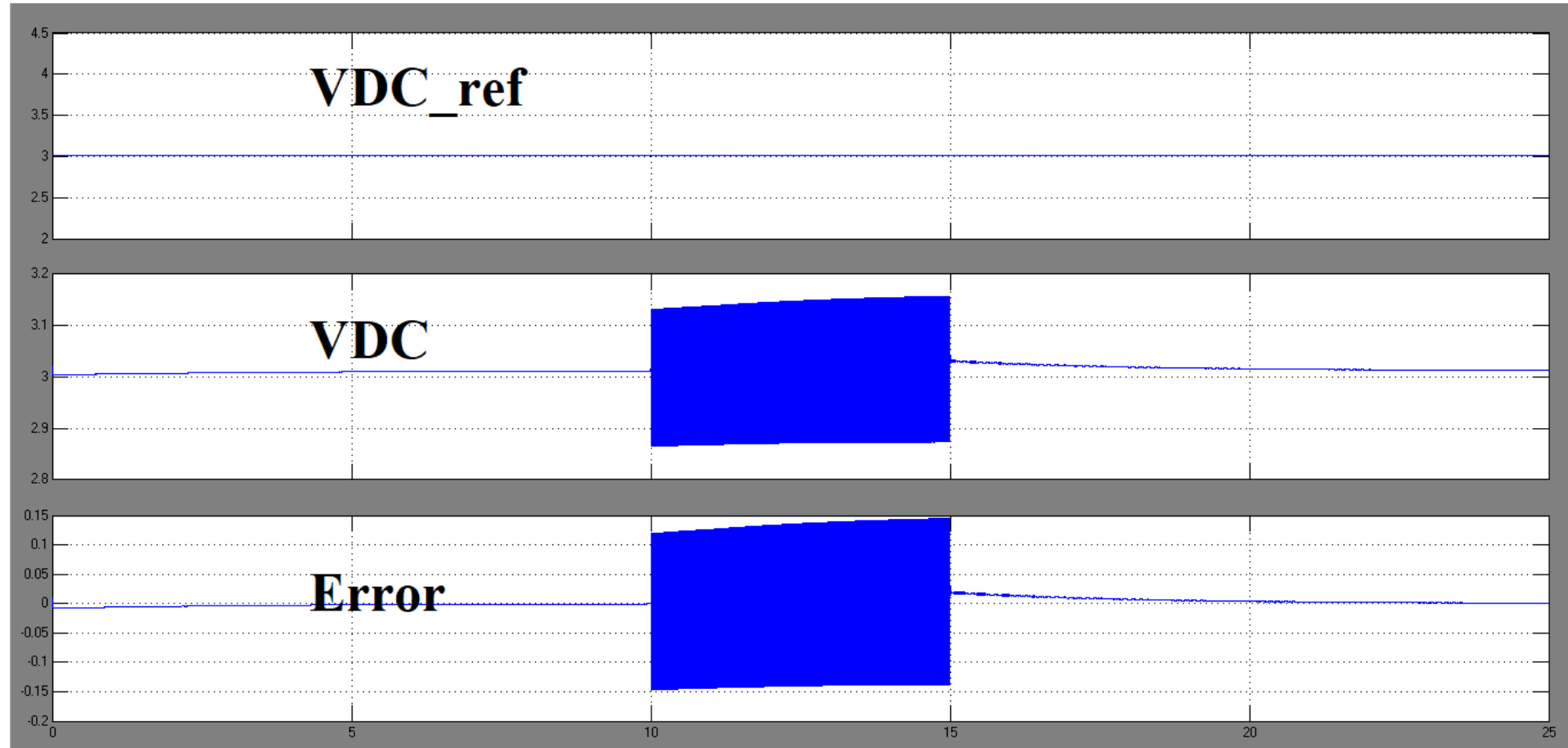
Positive Sequence Controller in GSC



Positive Sequence GSC Control of GSC Power Q_{GSC}



Positive Sequence GSC Control of DC Link Voltage V_{DC}



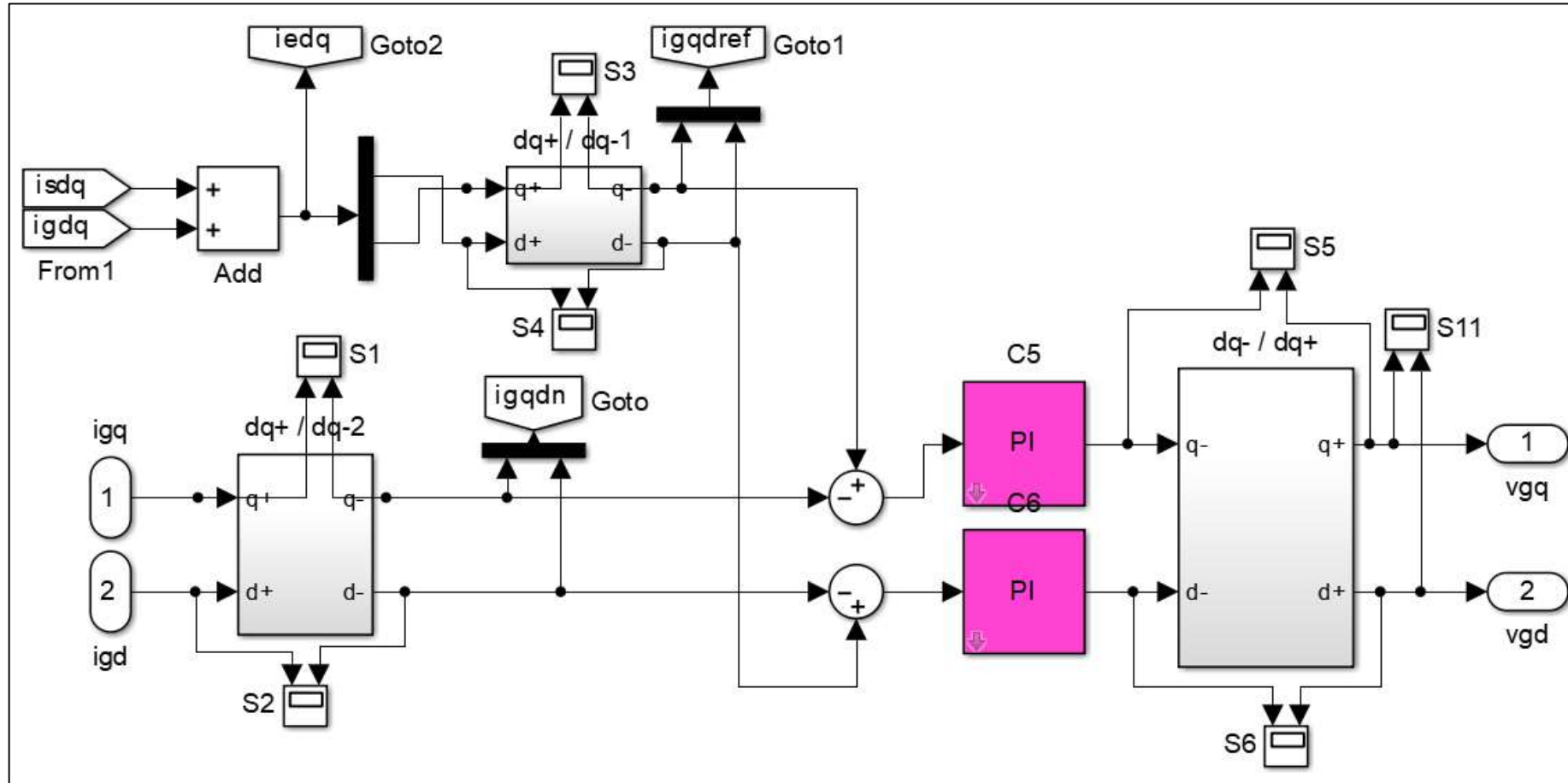
DFIG Grid Side Converter Negative Sequence Control

- 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.

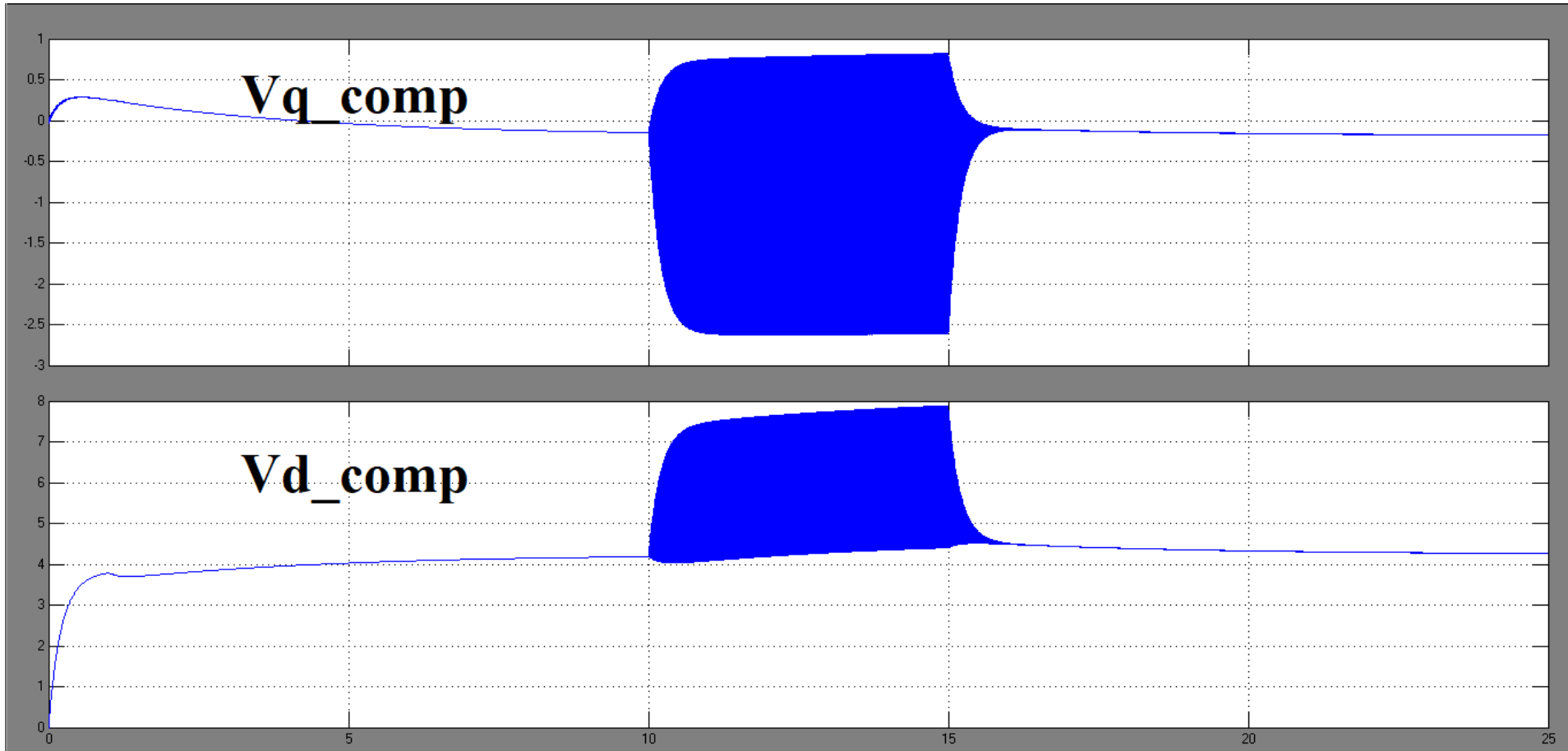
$$i_{gq,ref}^- = i_{eq}^-$$

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

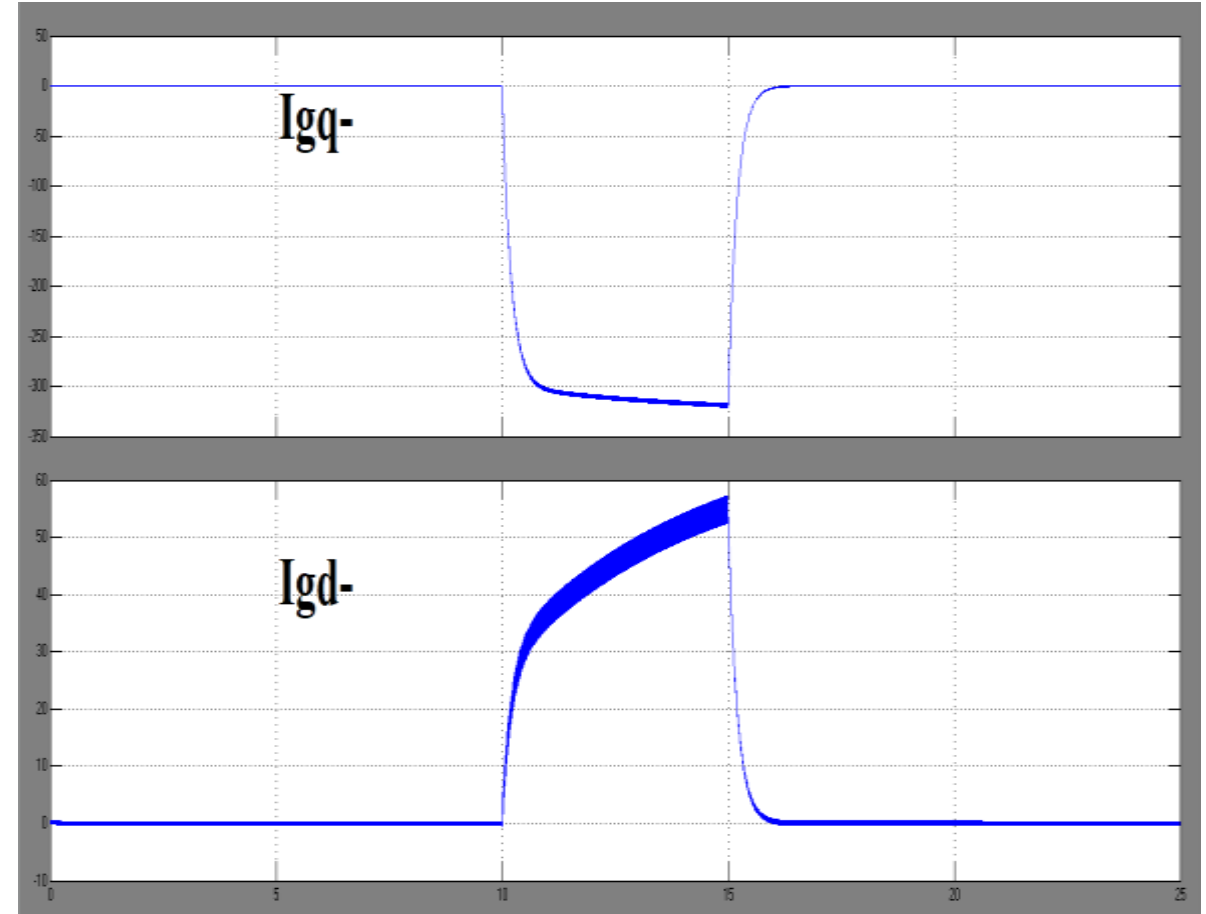
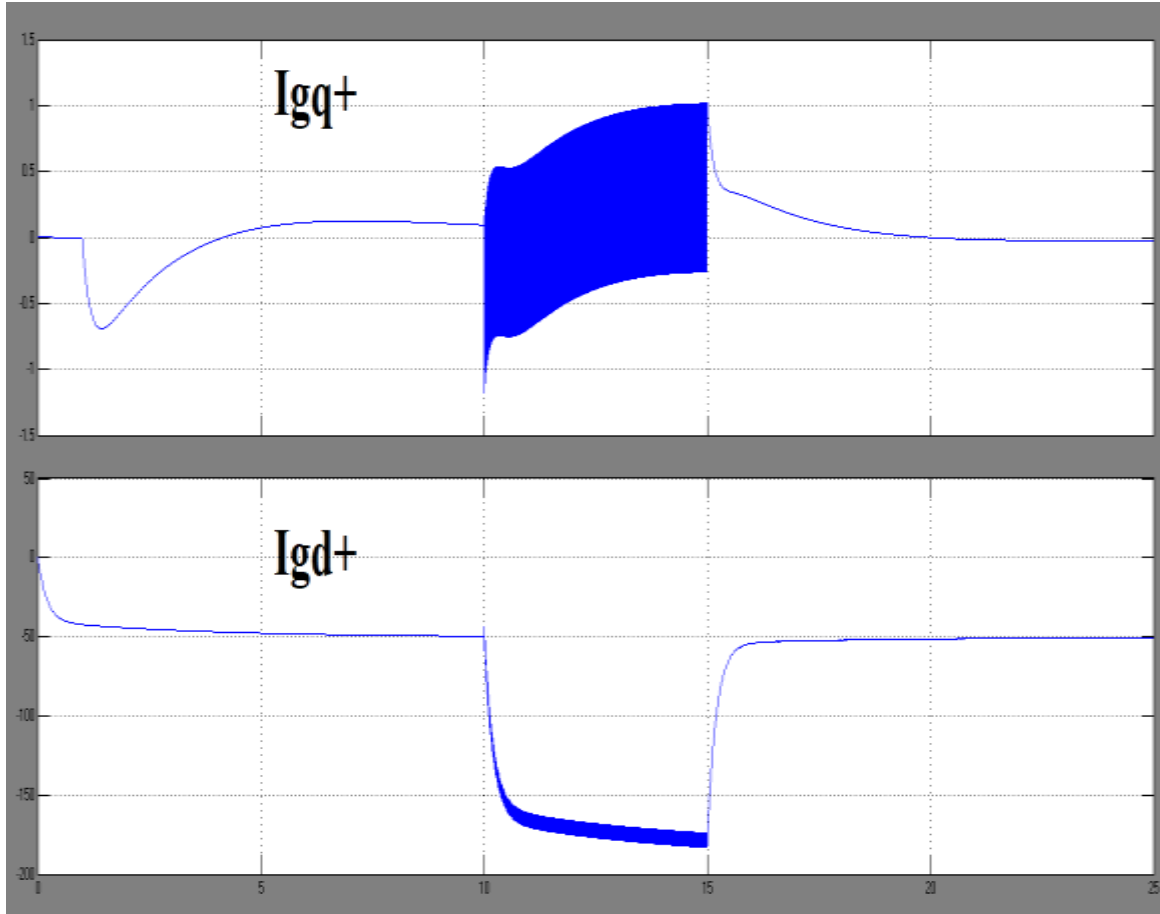
Negative Sequence Controller in GSC



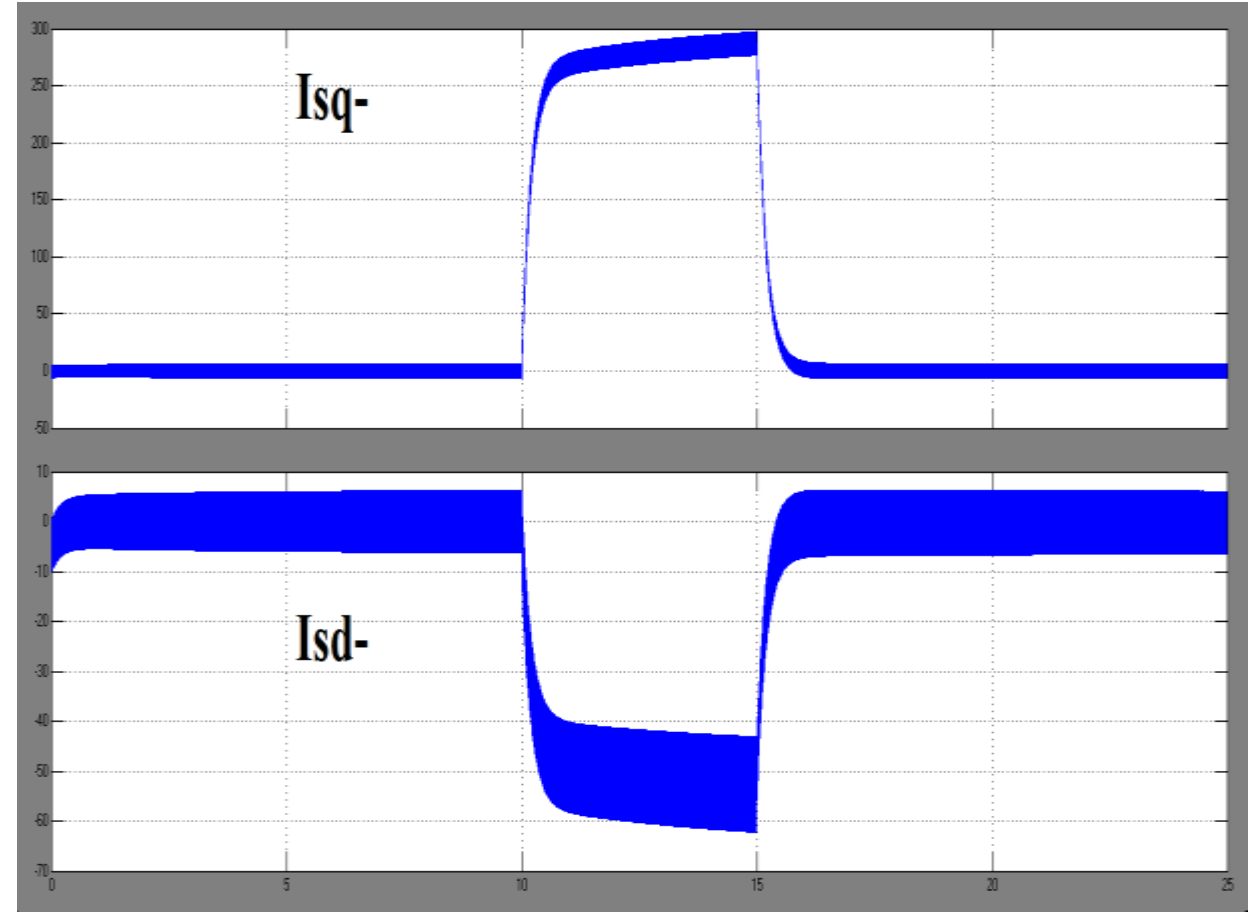
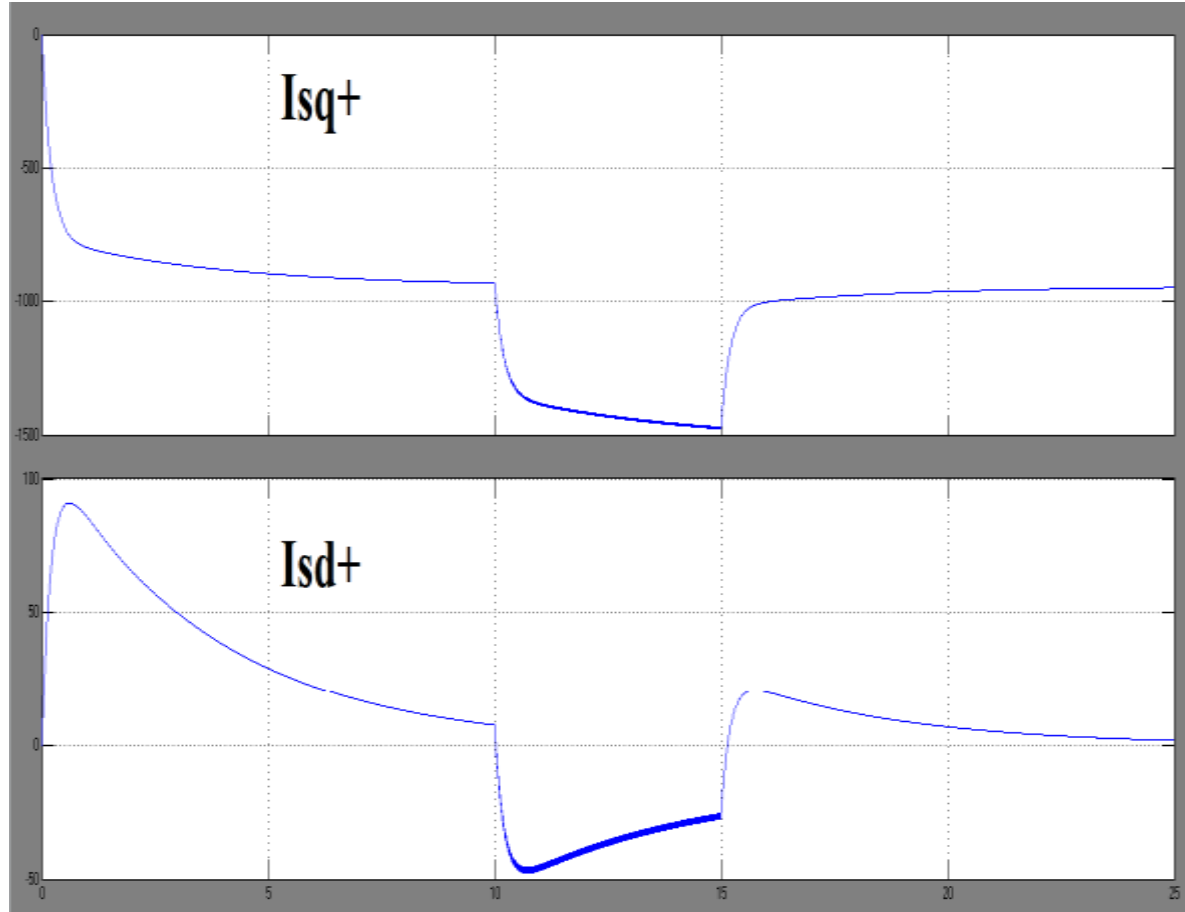
Negative Sequence Compensation via GSC



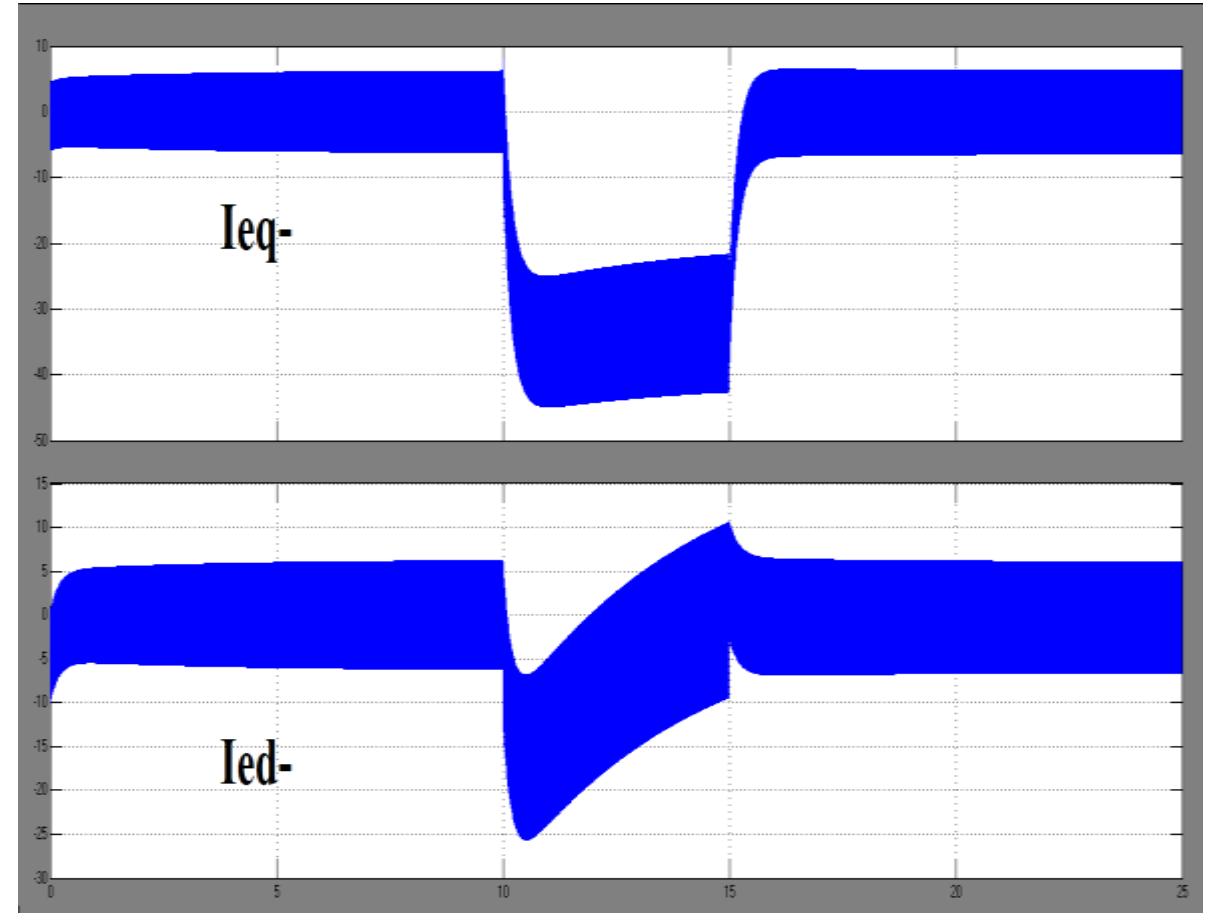
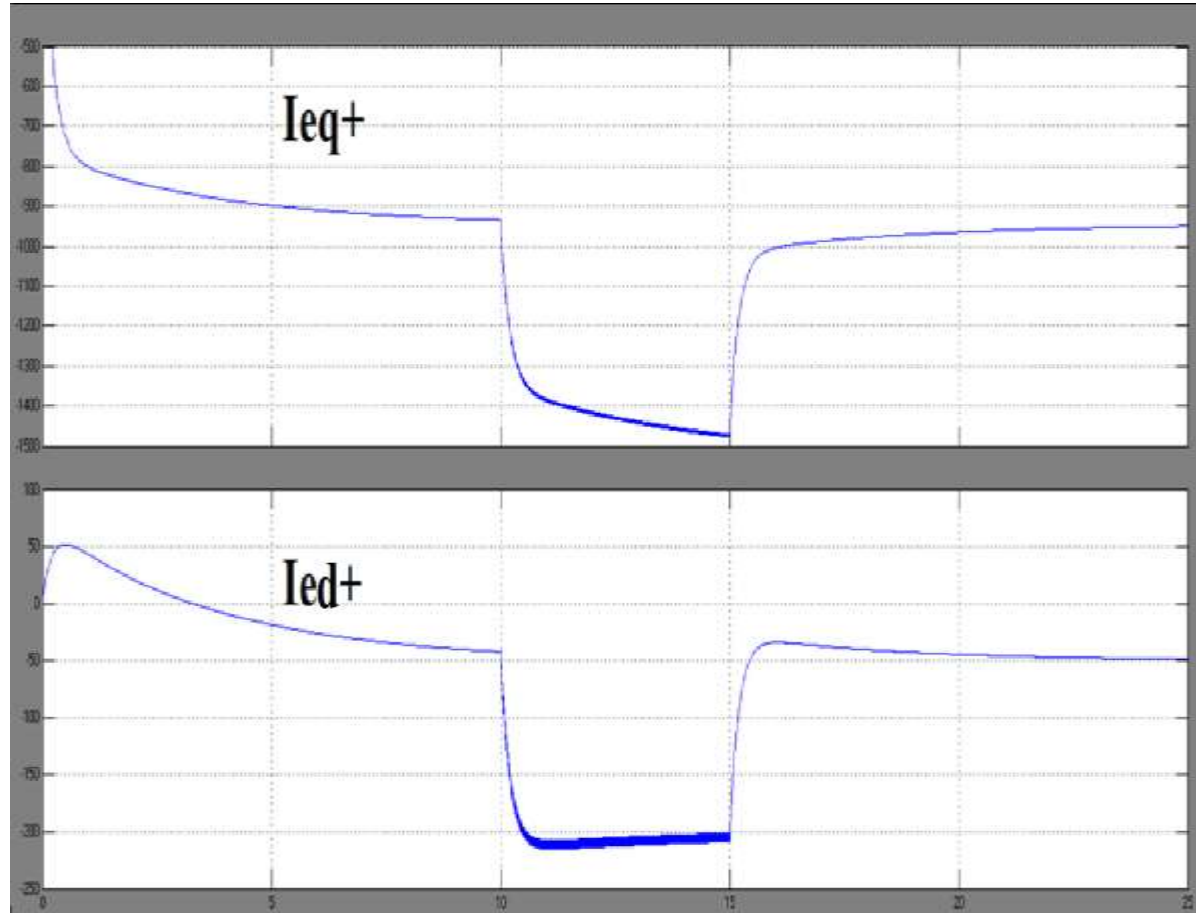
GSC Currents



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

- L. Fan and Z. Miao, *Modeling and Analysis of Doubly Fed Induction Generator Wind Energy Systems*, Elsevier Ltd., 2015, 1-78.
- 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.