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Parallel Operation of Distributed Generators by Virtual Synchronous Generator Control in Microgrids

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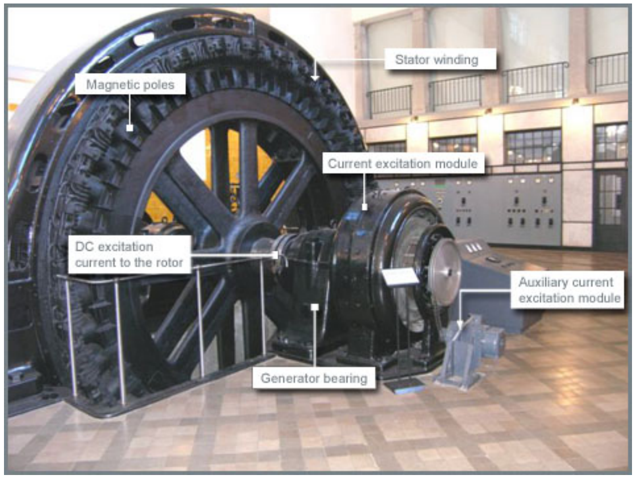
- Introduction
- Parallel Inverters
- Synchronous Generator + Inverter
- Conclusion

Inertial feature of Synchronous Generators

Synchronous Generator



$$W = \frac{1}{2} J \omega_m^2$$

Kinetic Energy of Rotating Mass

$$P_m - P_e = J \omega_m \frac{d\omega_m}{dt} + D(\omega_m - \omega_g)$$

Swing Equation

Frequency fluctuation
under active power transition
limited by the inertia

P_m : Shaft power
P_e : Output power
ω_m : Rotor frequency
ω_g : Grid frequency
J : Moment of inertia
D : Damping factor

DC/AC Inverter

Active Power P

Frequency ω

No intrinsic relation

Undesirable frequency dynamics

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Concept of VSG Control

Conventional Droop Control

Load Sharing

Smooth Transition between Islanding and Grid-connection

+

Swing Equation Emulation

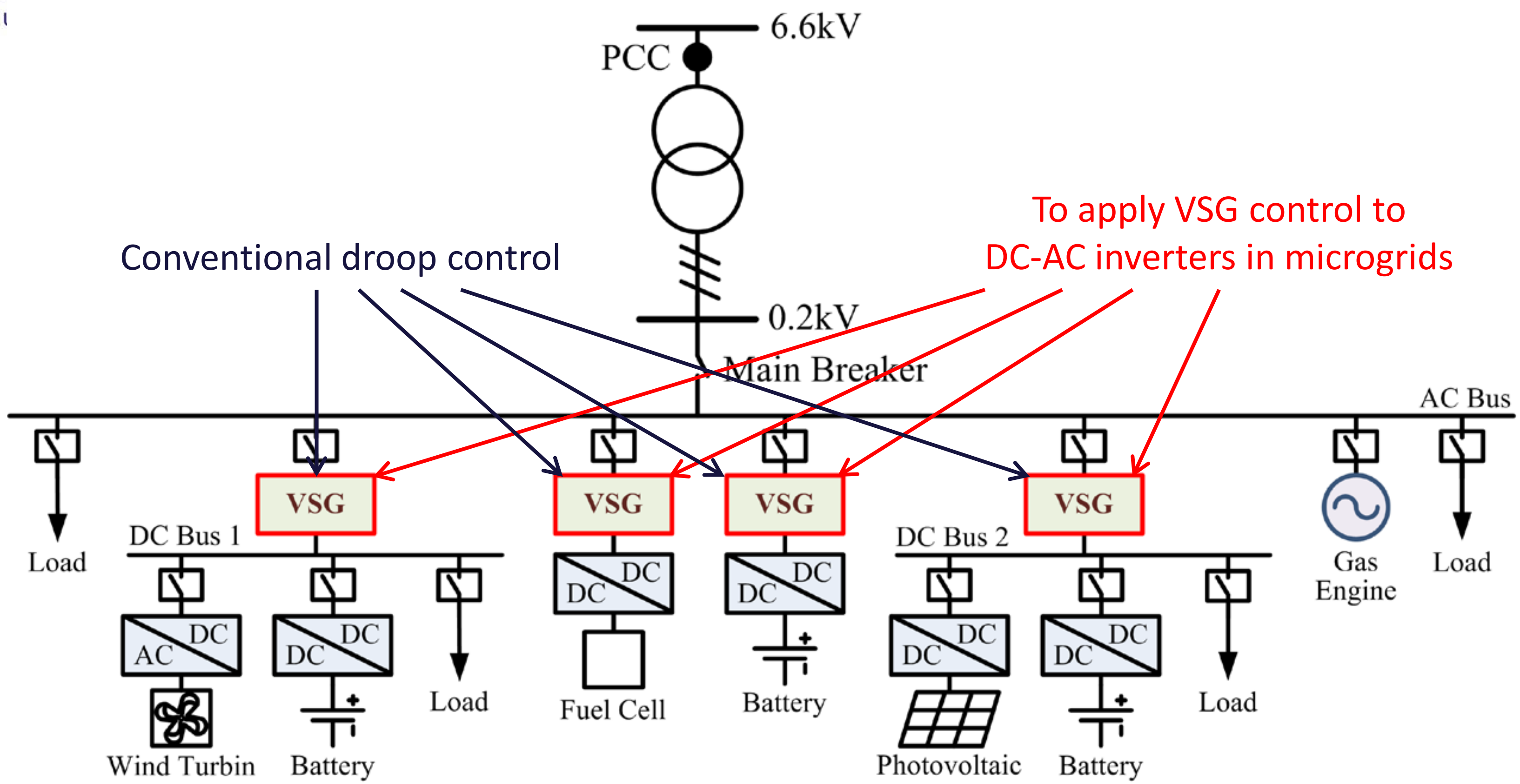
$$P_{in} - P_{out} = J\omega_m \frac{d\omega_m}{dt} + D(\omega_m - \omega_g)$$

Inertia Support

Virtual Synchronous Generator (VSG) Control

A New Concept of **Inverter Control** in **AC Microgrid**

Objectives

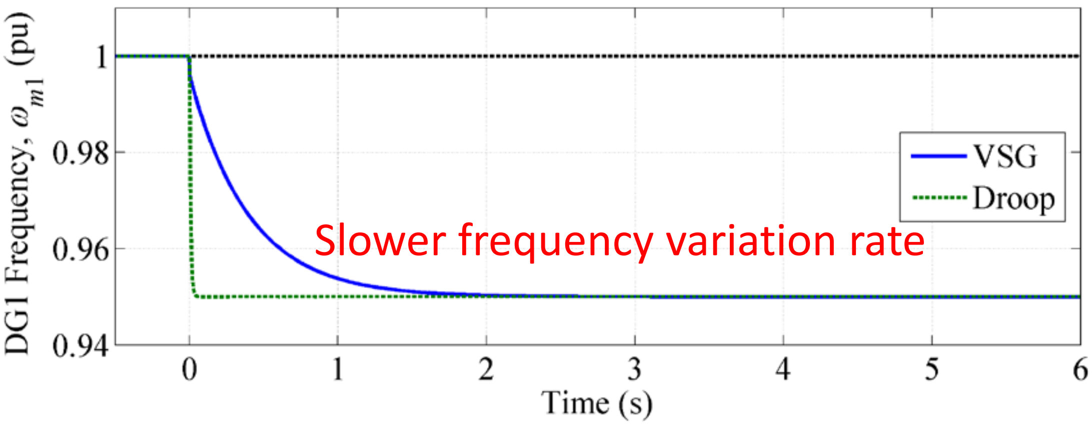


- **Two topics to be discussed**
  - **Parallel Inverters**
  - **Synchronous Generator + Inverter**

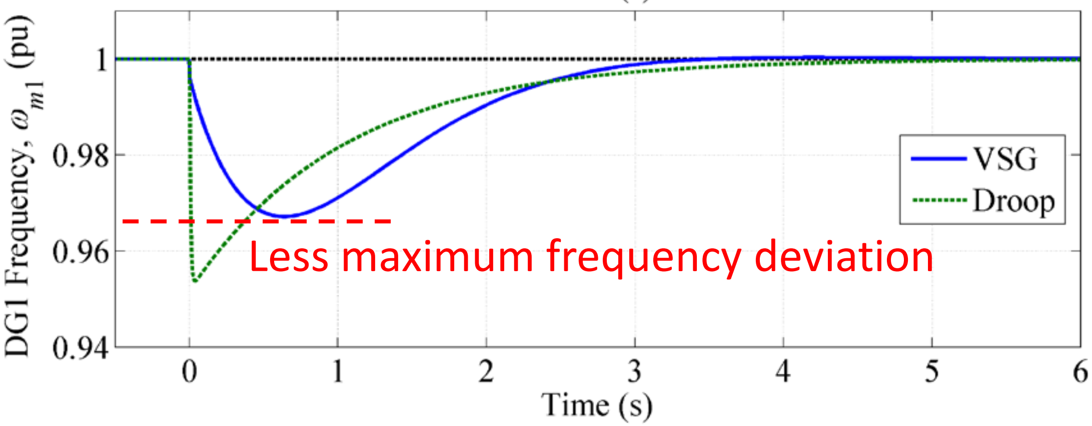
What is the benefit?

Frequency during Loading transition

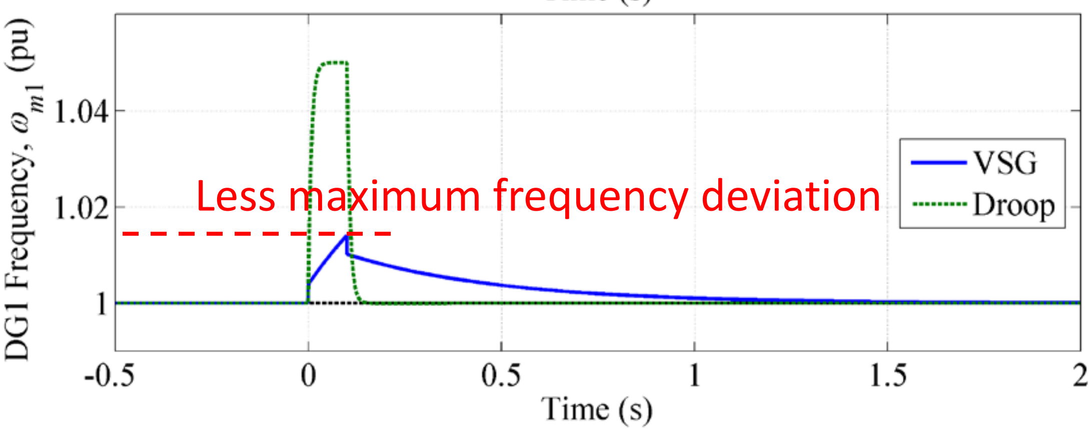
Without Frequency Restoration



With Frequency Restoration



Frequency during Three-phase ground fault cleared in 0.1 s



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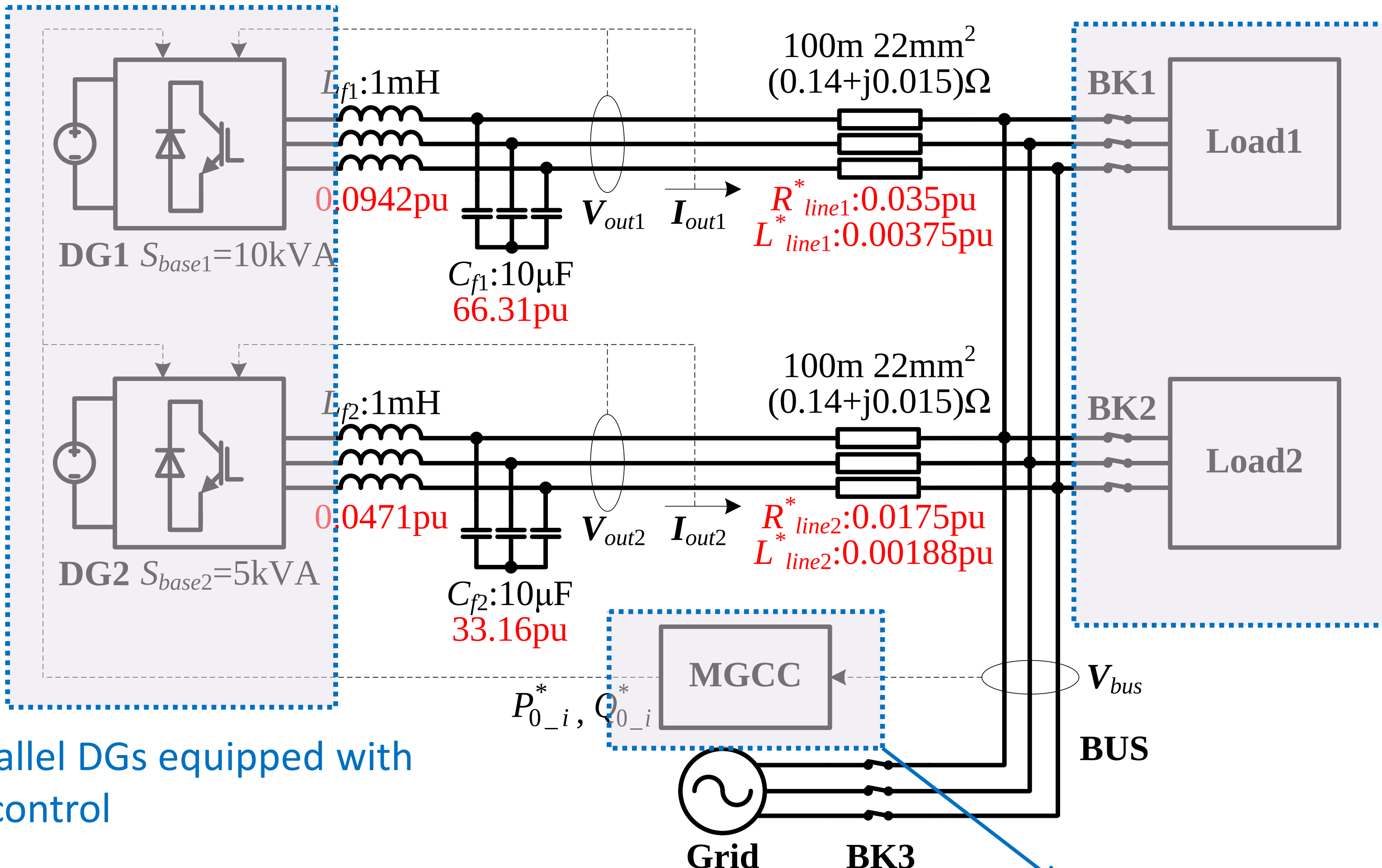
Microgrid: Parallel Inverters

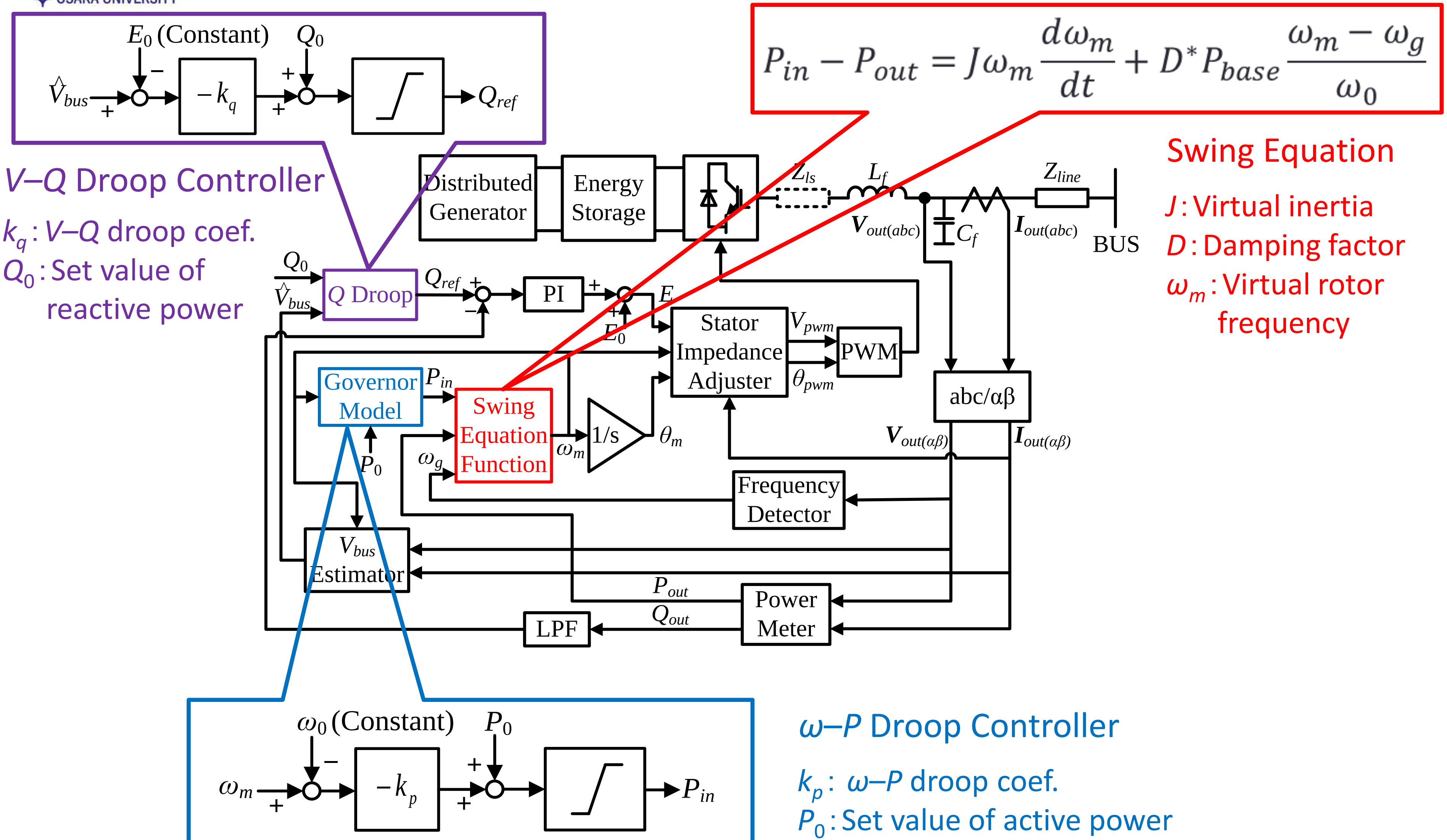
Fluctuated loading



2 parallel DGs equipped with VSG control

Microgrid Central Controller (MGCC)
Frequency and voltage restoration

VSG Control Scheme (Basic Part)



$$P_{in} - P_{out} = J\omega_m \frac{d\omega_m}{dt} + D^* P_{base} \frac{\omega_m - \omega_g}{\omega_0}$$

Swing Equation

J : Virtual inertia

D : Damping factor

ω_m : Virtual rotor frequency

V–Q Droop Controller

k_q : V–Q droop coef.

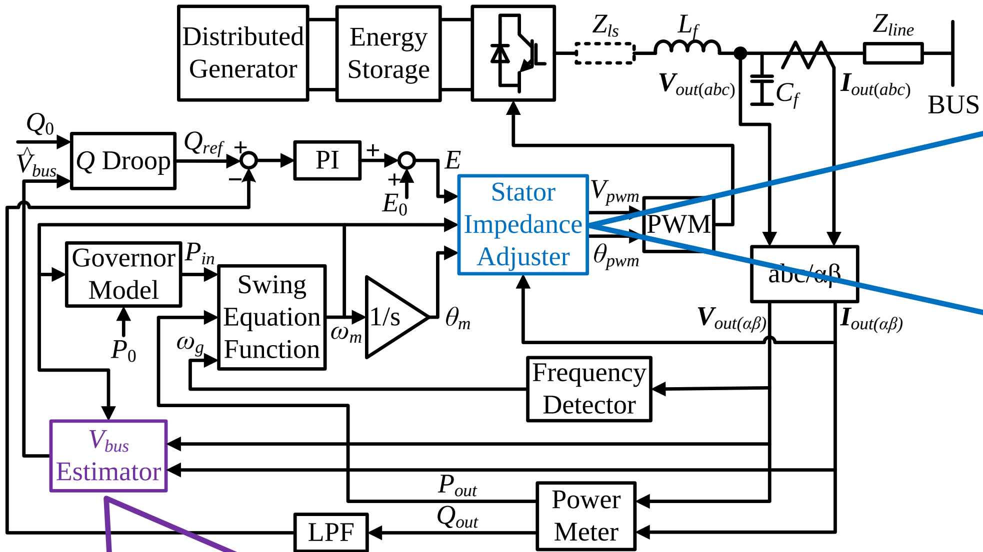
Q_0 : Set value of reactive power

ω–P Droop Controller

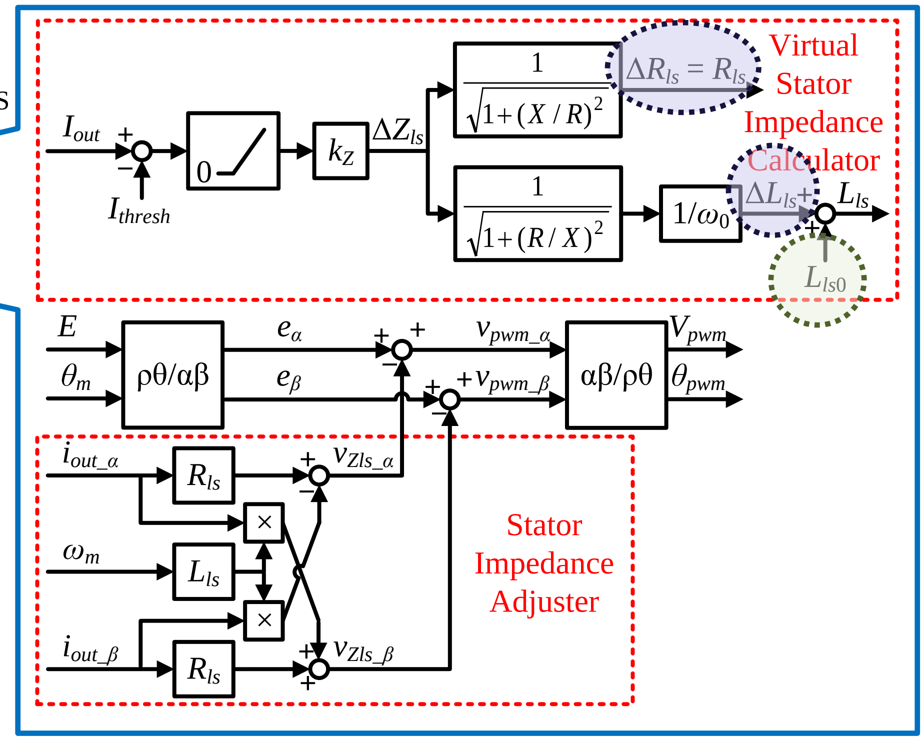
k_p : ω–P droop coef.

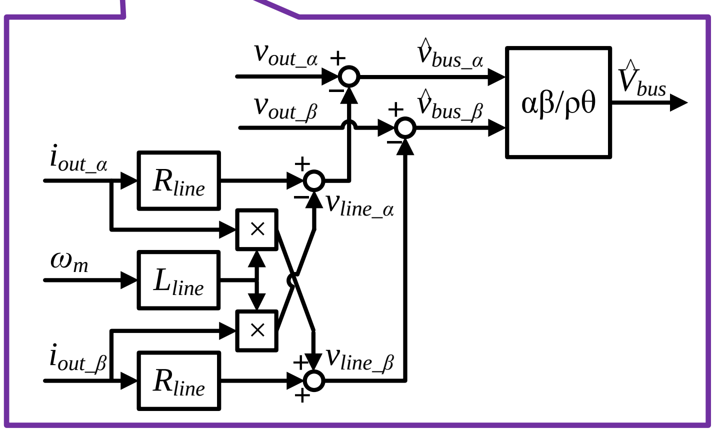
P_0 : Set value of active power

VSG Control Scheme (Enhanced Part)



Stator Impedance Adjuster





Bus voltage estimator

Estimate bus voltage
for proper reactive power sharing

- Constant part
  - Transient power sharing
  - Increased damping
- Transient part
  - Overcurrent limiting

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Control Parameters

Parameter	Value	Parameter	Value
DG1 Power Rating S_{base1}	10 kVA	LPF cut-off Frequency $T_{fp\,i}$	7.96×10^{-3} s
DG2 Power Rating S_{base2}	5 kVA	LPF cut-off Frequency $T_{fq\,i}$	7.96×10^{-3} s
Nominal Voltage E_0	200 V	Q Ctrl. PI Gain $K^*_{pq\,i}$	0.0125 pu
Nominal Frequency ω_0	376.99 rad/s	Q Ctrl. PI Time Constant $T_{iq\,i}$	1.25×10^{-4} s
Inertia Constant M^*_i	8 s	Sec. Ctrl. PI Gain K^*_{psec}	1 pu
Damping Factor D^*_i	17 pu	Sec. Ctrl. PI Time Constant T_{isec}	0.05 s
Set Value of Active Power $P^*_{0\,i}$ (default)	1 pu	DG1 Cont. Virtual Stator Reactor $L_{ls0\,1}$	6.39 mH
Set Value of Reactive Power $Q^*_{0\,i}$ (default)	0 pu	DG2 Cont. Virtual Stator Reactor $L_{ls0\,2}$	13.81 mH
Active Power Droop Coef. $k^*_{p\,i}$	20 pu	Trans. Virtual Stator Imp. Gain $k^*_{Z\,i}$	1.79 pu
Reactive Power Droop Coef. $k^*_{q\,i}$	5 pu	Trans. Virtual Stator Imp. Ratio X/R_i	5

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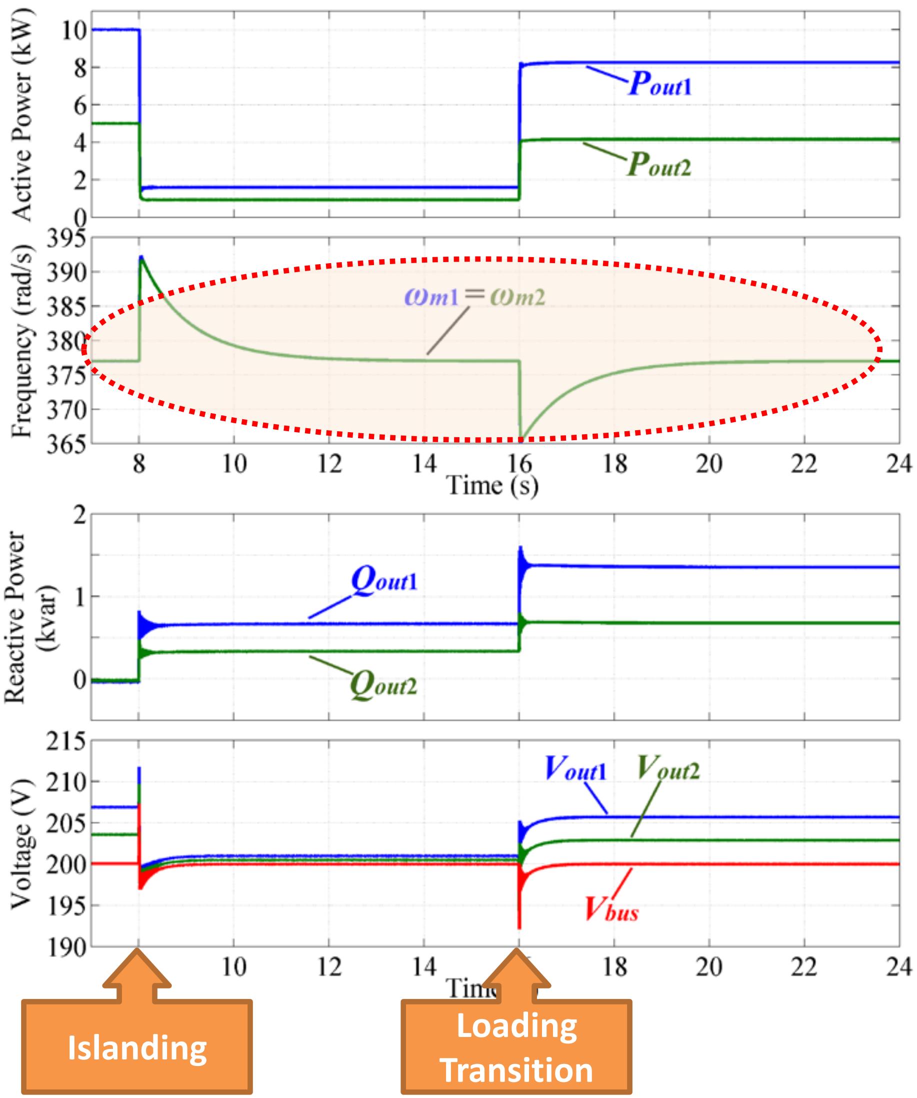
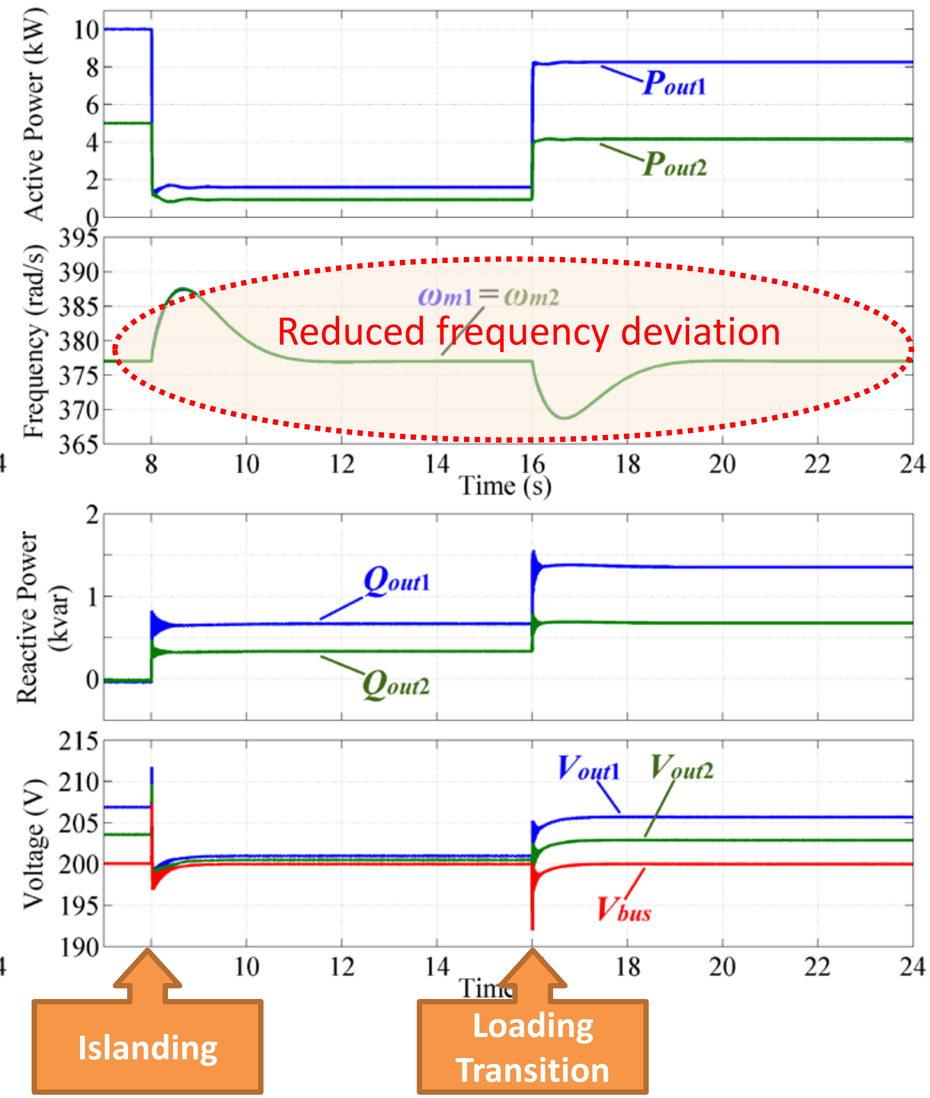
Simulation Results
Loading Transition

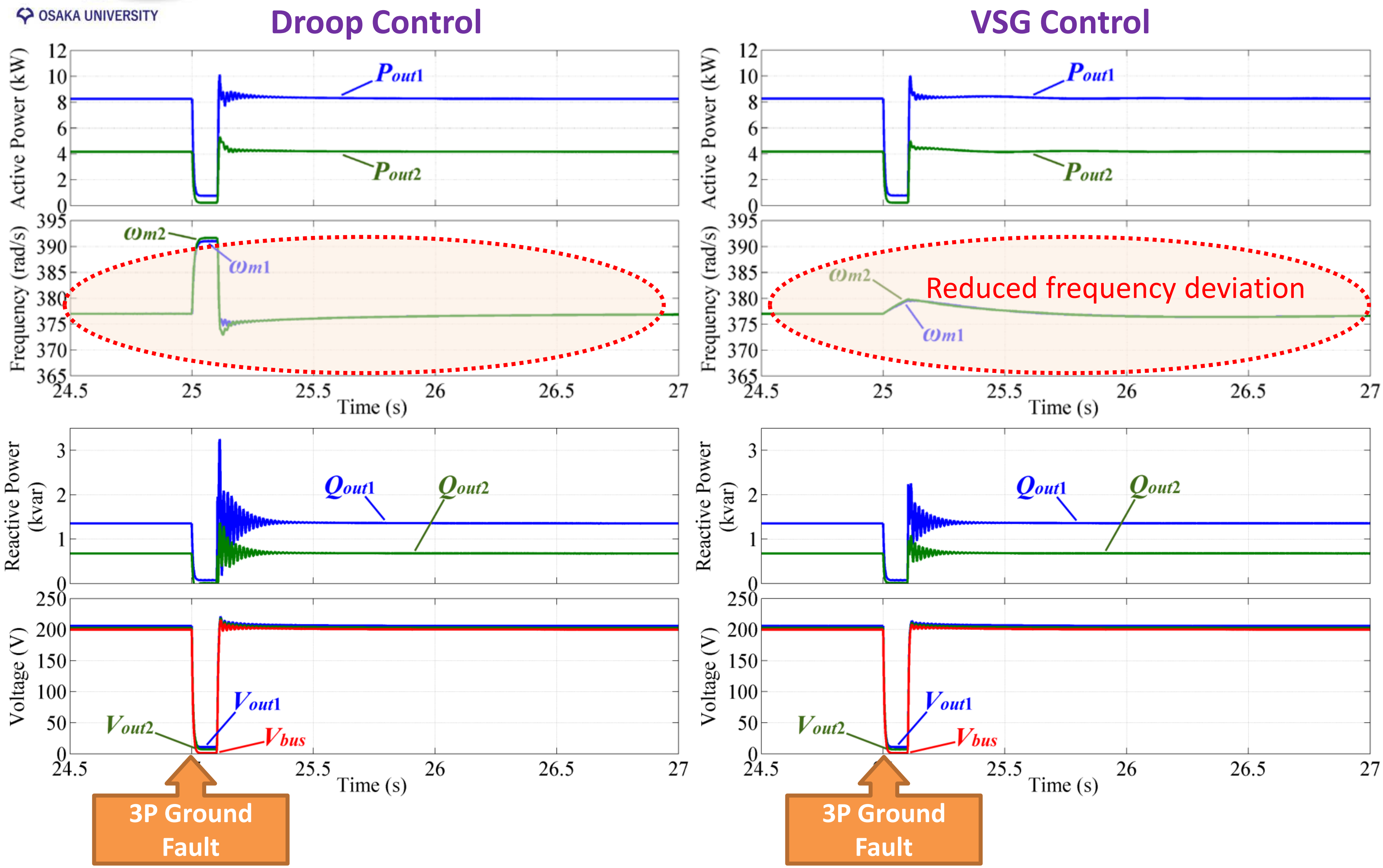
Droop Control



VSG Control



Simulation Results
Three-Phase Ground Fault



Fault Current During Three-Phase Ground Fault

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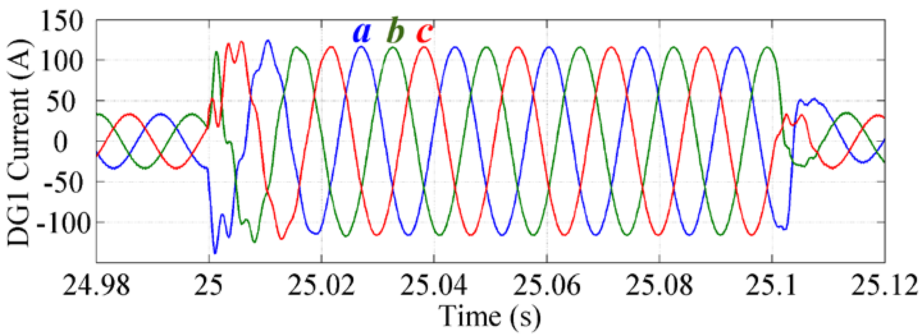
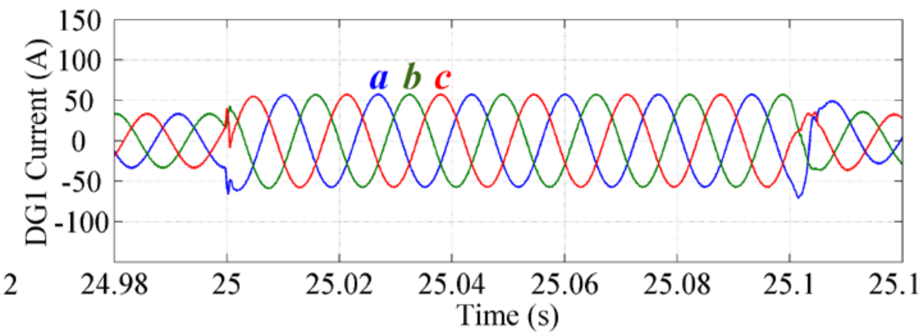
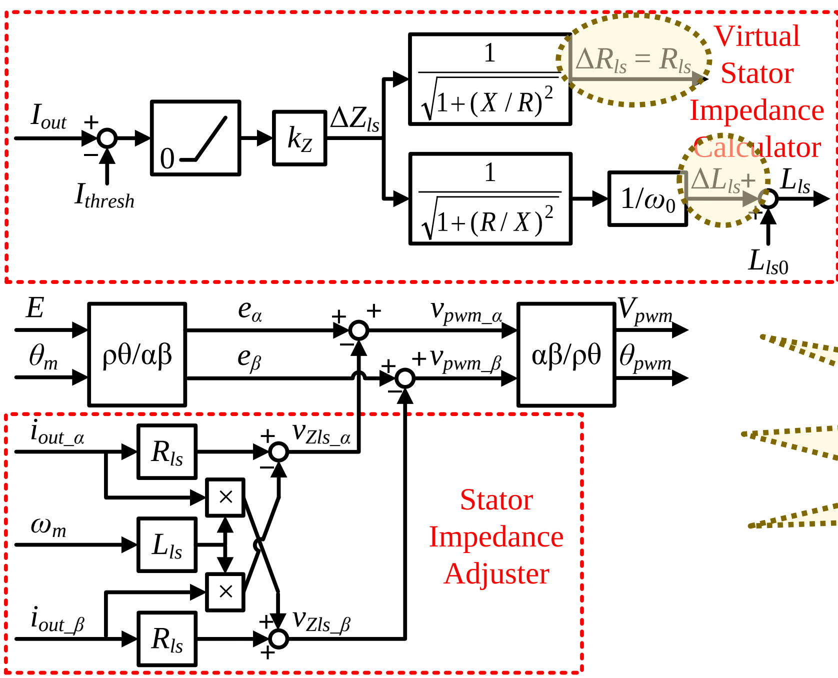
Without Transient Stator Impedance



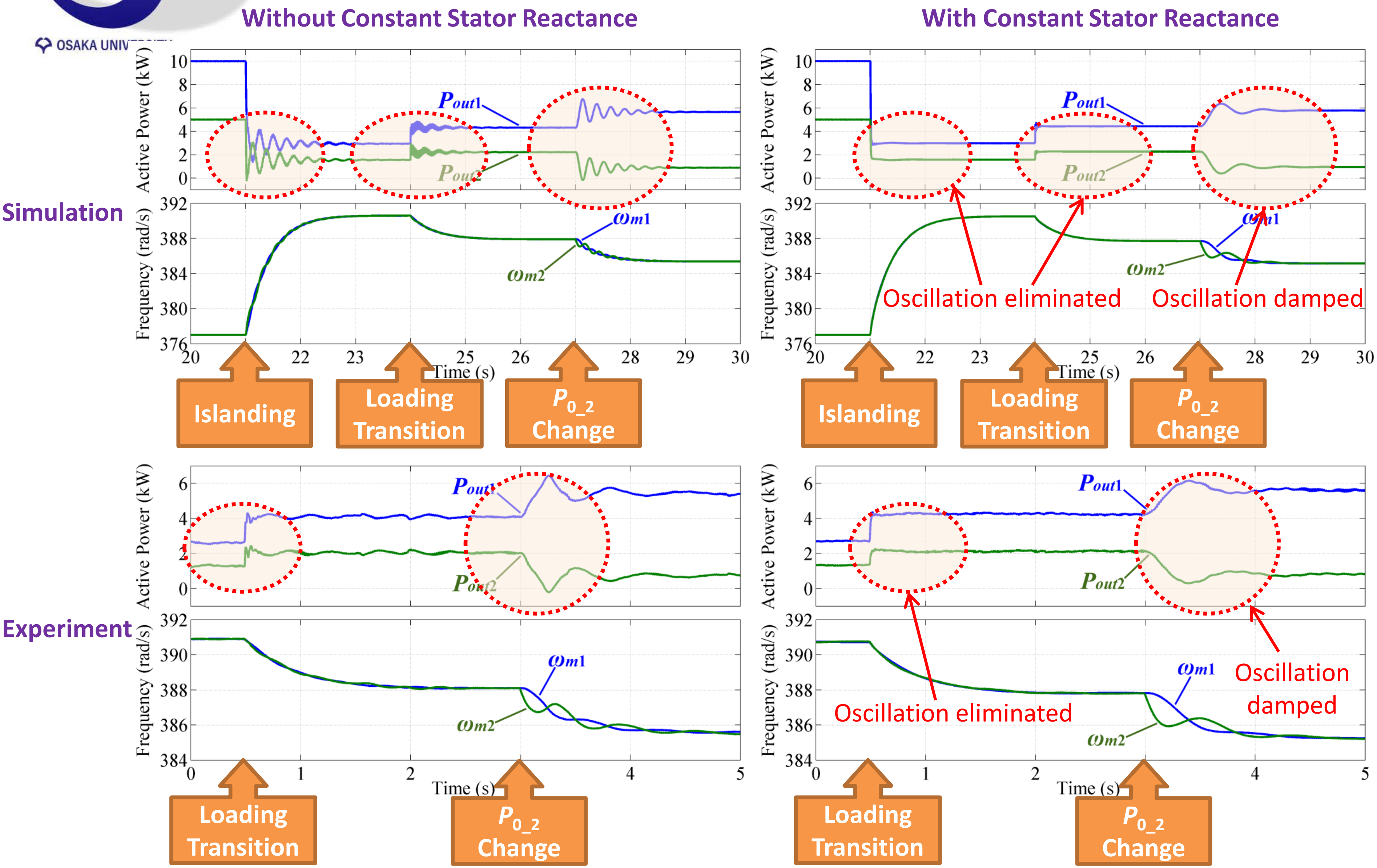
With Transient Stator Impedance





Fault Current is limited by Transient Stator Impedance

Effect of Constant Stator Reactance



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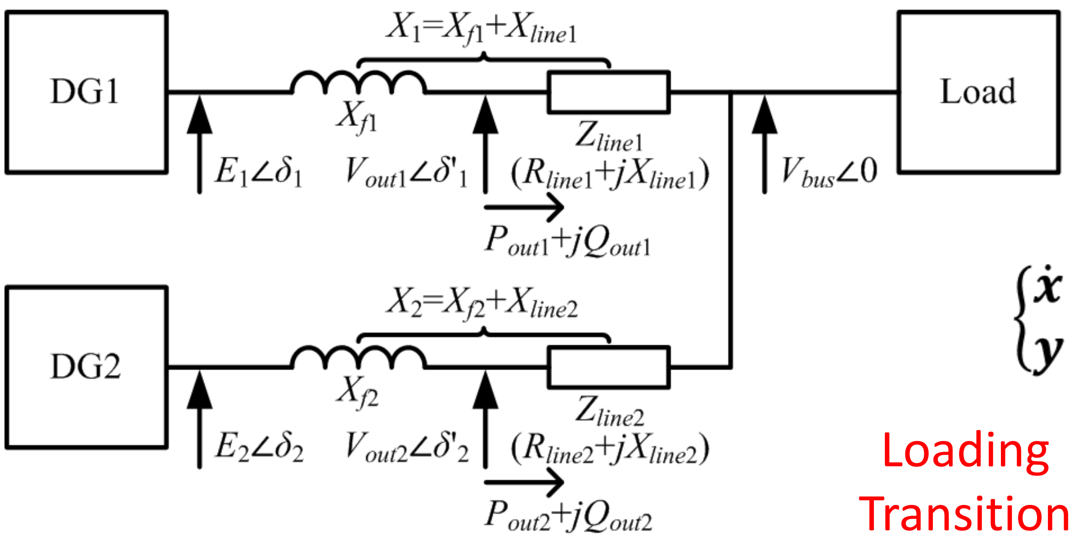
State-Space Model of Islanded Microgrid



$$\begin{cases}\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{Bw} \\ \boldsymbol{y} = \boldsymbol{Cx} + \boldsymbol{Dw}\end{cases}$$

Loading Transition | Change of Active Power Set Value

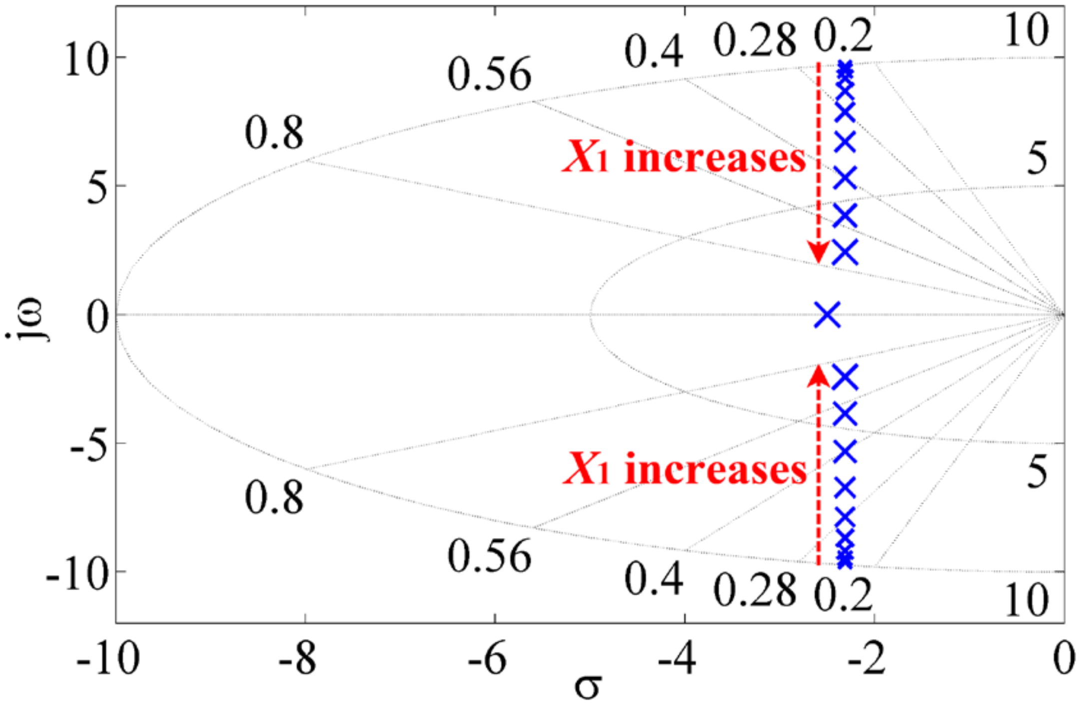
Disturbance: $\boldsymbol{w} = [\Delta P_{load} \quad \Delta P_{0\_1} \quad \Delta P_{0\_2}]^T$

Frequency | Active Power

Output: $\boldsymbol{y} = [\Delta\omega_{m1} \quad \Delta\omega_{m2} \quad \Delta P_{out1} \quad \Delta P_{out2}]^T$

- The damping ratio of oscillation in output parameters is determined by the eigenvalues of state matrix ***A***

Relation between Output Reactance and Damping Ratio



Radial lines : Damping ratio ζ
Circle lines : Damped natural frequency ω_n

- Total output reactance X increases
  - ⇒Damping ratio ζ increases

Oscillation can be damped by increasing output reactance

Transient Load Sharing

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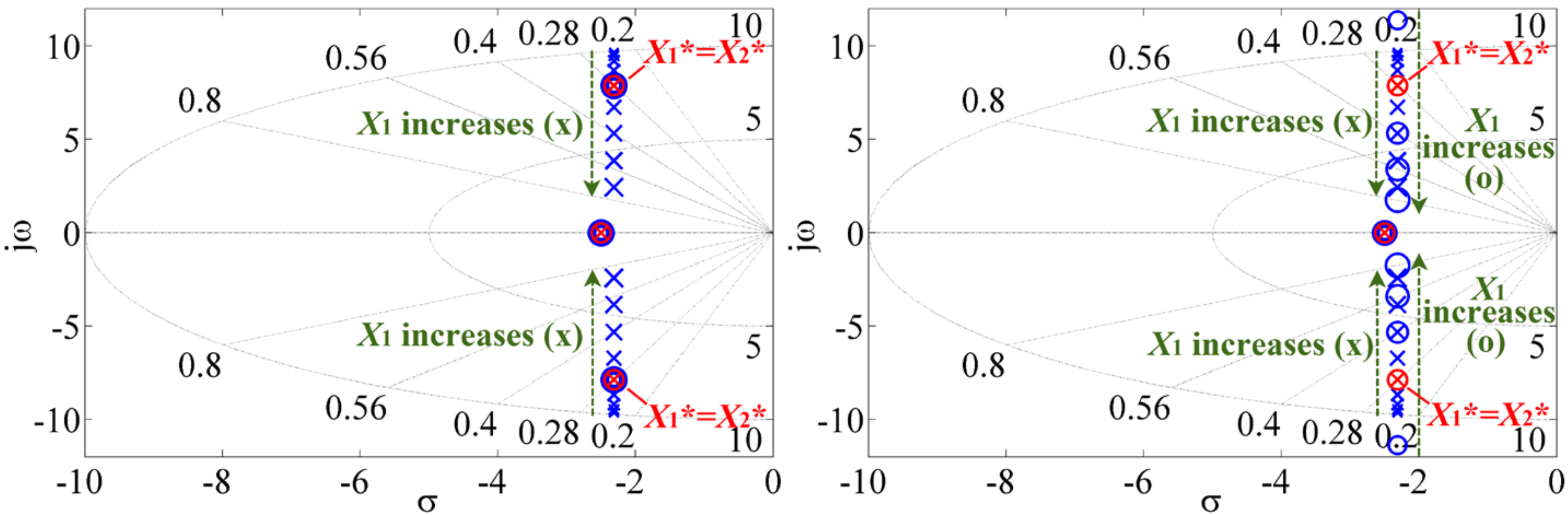
Poles and Zeros of $\frac{\Delta P_{out1}}{\Delta P_{load}}$ Poles and Zeros of $\frac{\Delta P_{out2}}{\Delta P_{load}}$

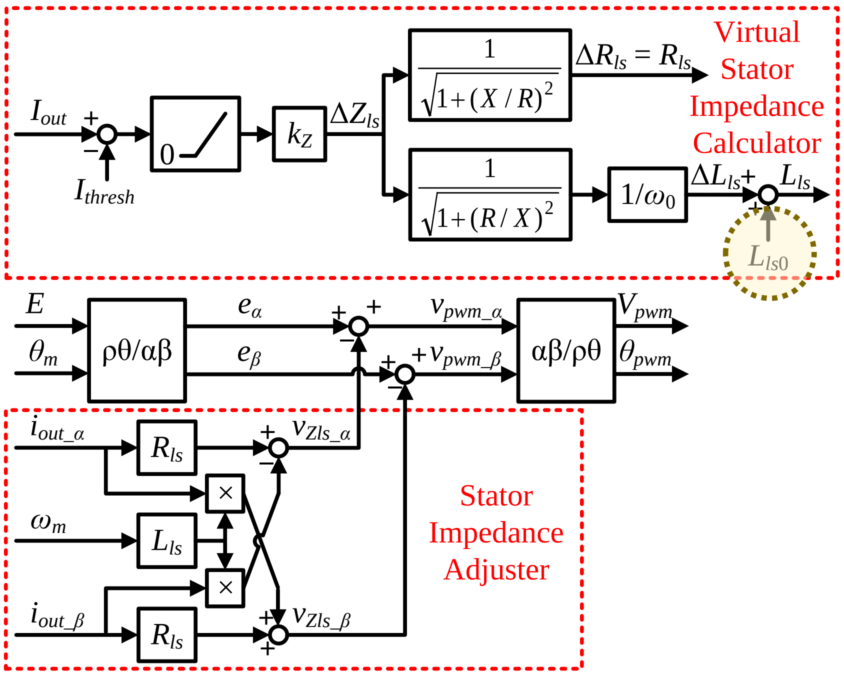


$X_i^* = \frac{X_i P_{basei}}{V_{basei}^2}$ is the total output reactance of ith VSG in per unit value

- When the disturbance is a loading transition
  - If the total output reactance of each VSG is of the same per unit value, poles are cancelled by zeros and oscillation is eliminated

Design of Constant Stator Reactance

- How to design L_{ls0} to avoid oscillation?
  - Large value to provide damping
  - Same total output reactance for all VSG in parallel



$$\boxed{X = X_{ls0} + X_f + X_{line} = 0.7\text{pu}}$$

$$(X_{ls0} = \omega_m L_{ls0})$$

X : Total output reactance

X_{ls} : Virtual stator reactance

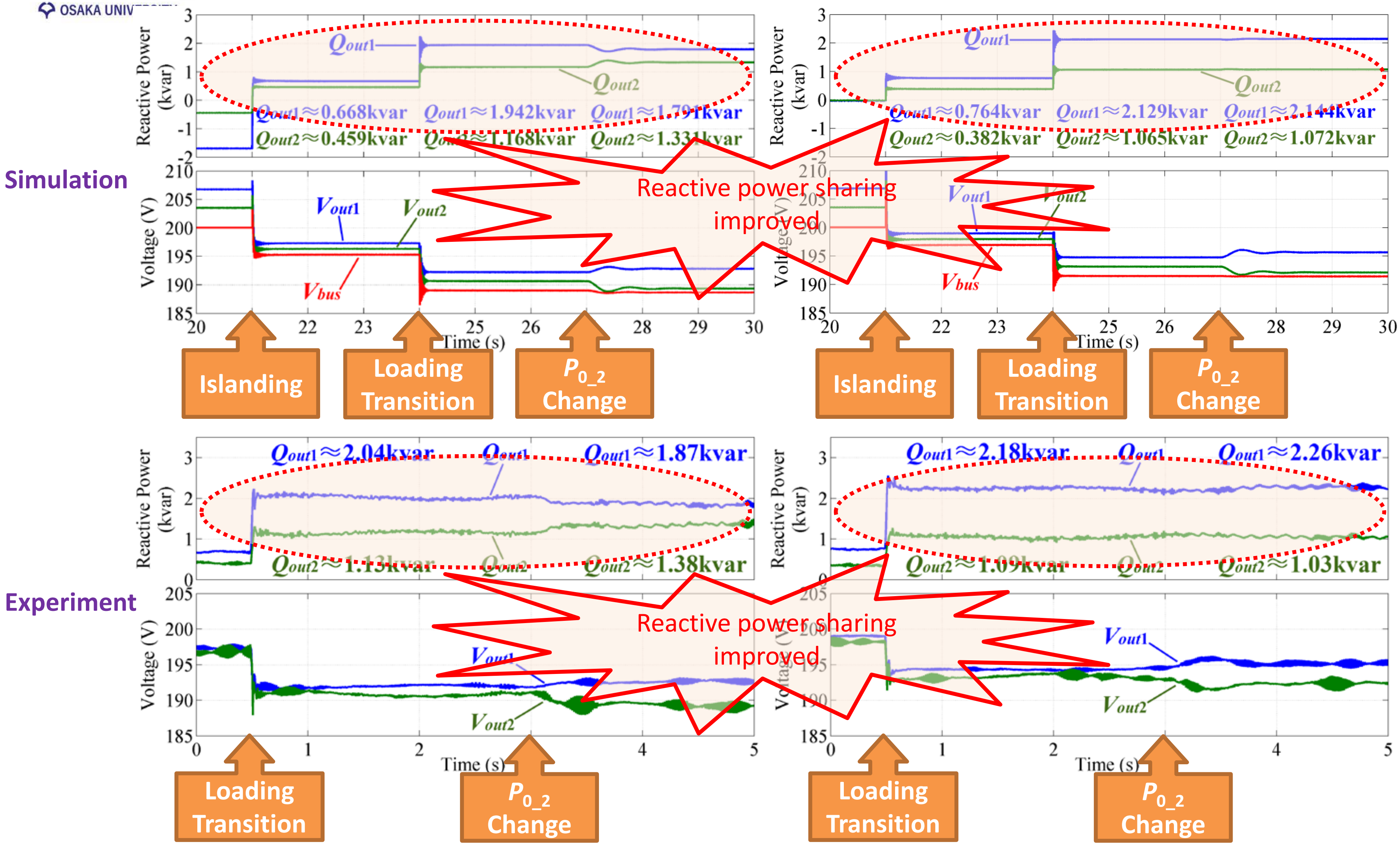
X_f : Filter reactance

X_{line} : Line reactance

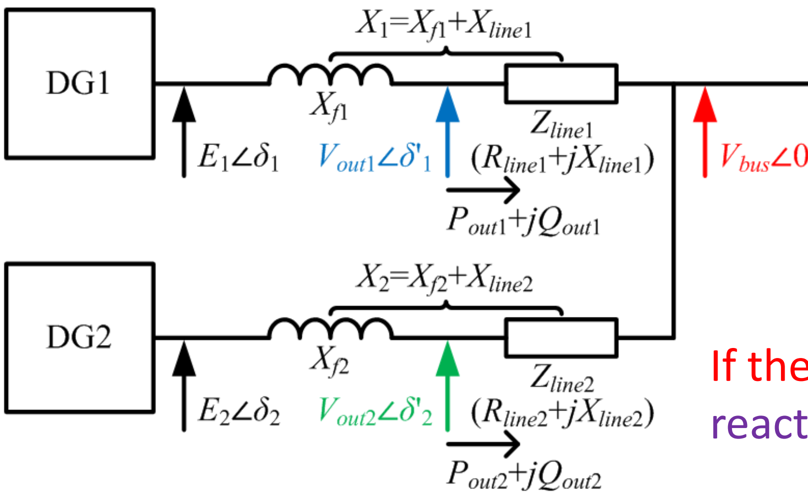
Effect of Constant Stator Reactance

Without Constant Stator Reactance

With Constant Stator Reactance



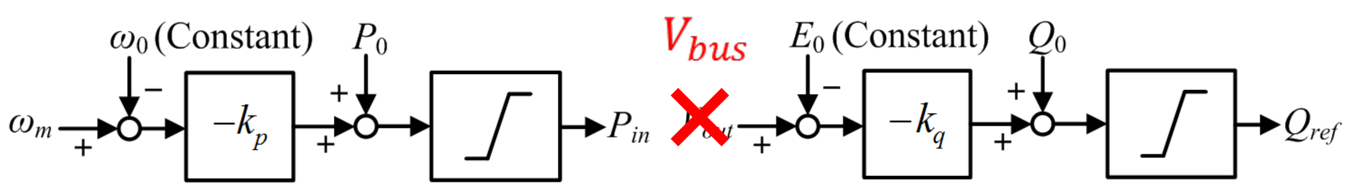
Cause of Poor Reactive Power Sharing



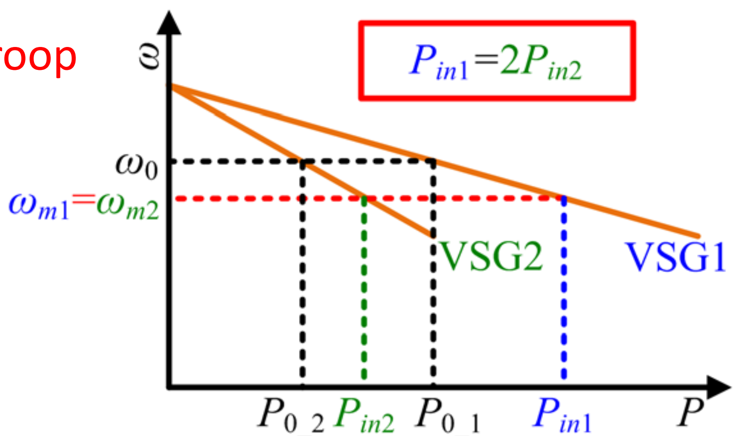
V_{out} : Output voltage of DG

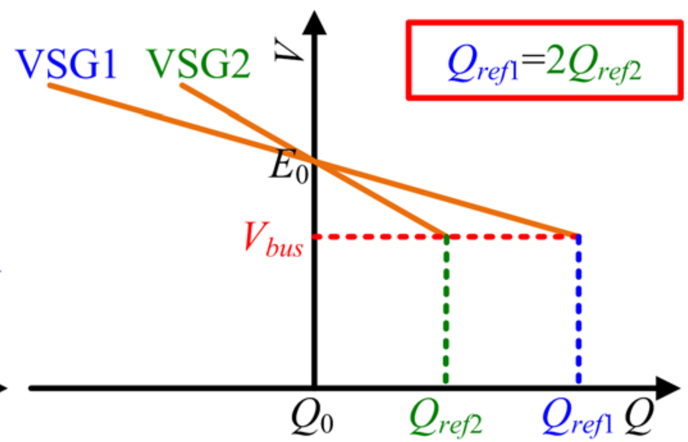
V_{bus} : Bus voltage

If the input of droop controller is equal,
reactive power should be shared properly



ω–P Droop





V–Q Droop

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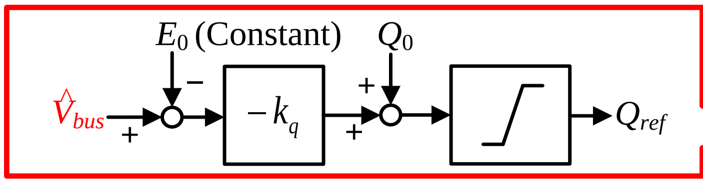
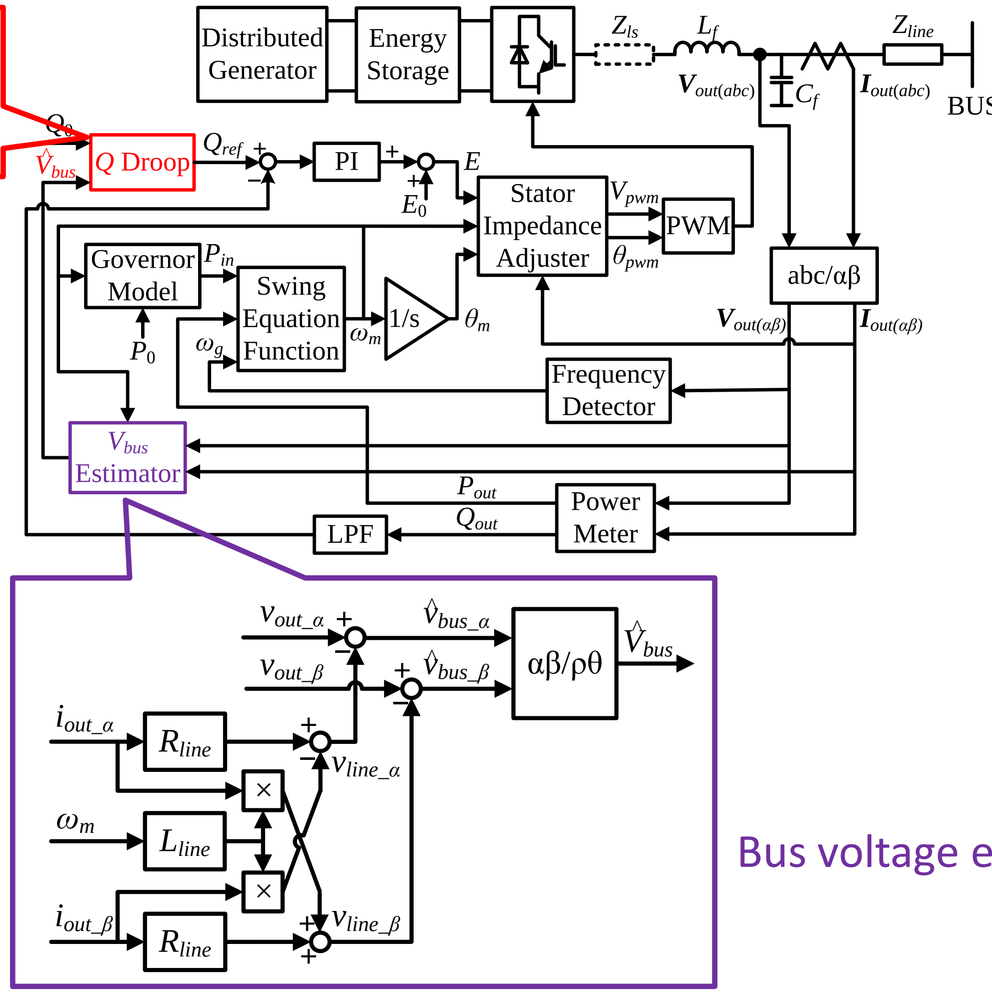
Bus Voltage Estimator for Proper Reactive Power Sharing



V–Q Droop Controller

k_q : V–Q droop coef.

Q_0 : Set value of reactive power



Bus voltage estimator

Estimate bus voltage
for proper reactive power sharing

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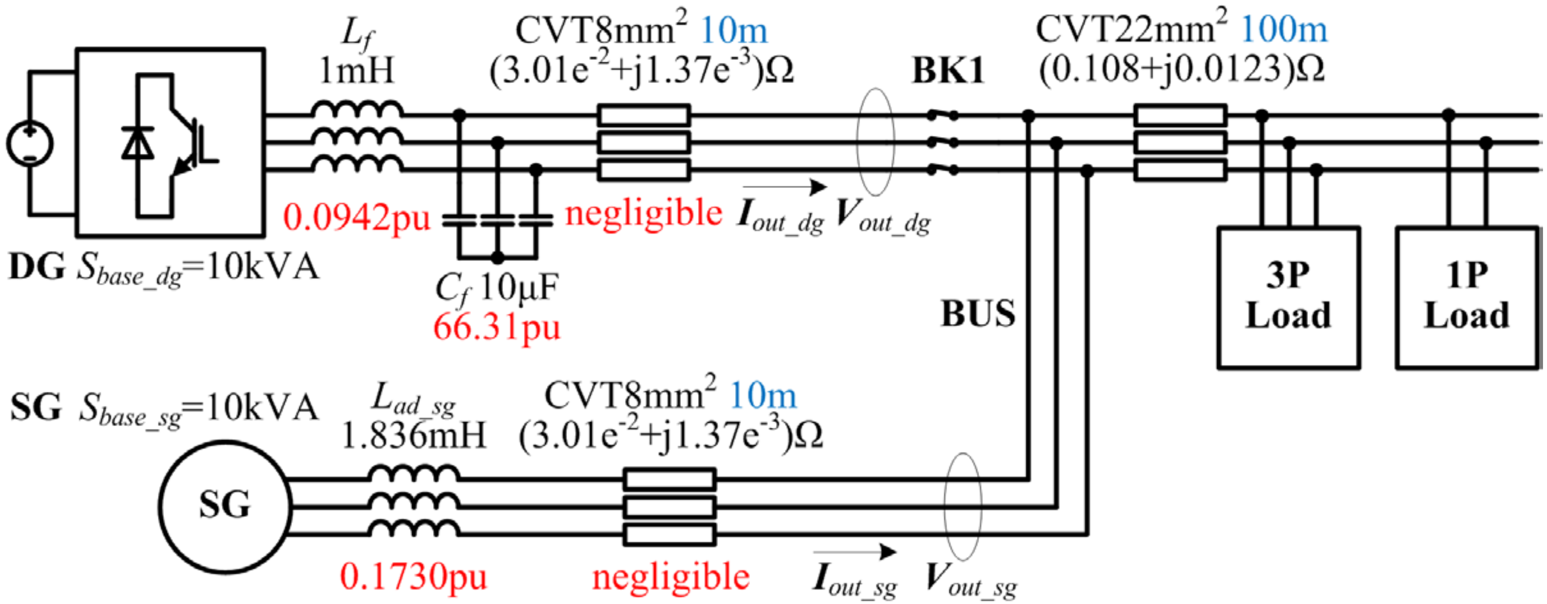
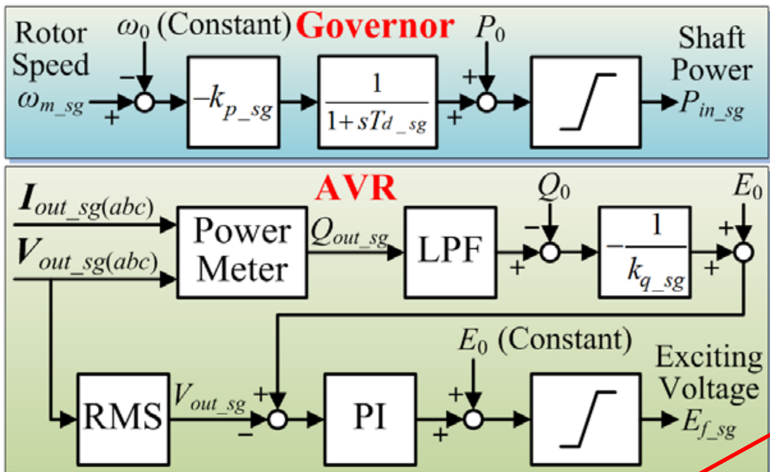
Microgrid: SG + Inverter



- Stand-alone microgrid in remote area
- SG (10 kVA): Round-rotor moved by gas engine
- DG (10 kVA): Photovoltaic panels
- Load: Three-phase loads and single-phase Loads

Issues of Small Rating SG

SG Controller



Poor inertia

SG Parameters

Parameter	Value	Parameter	Value
Rated voltage E_0	200 V	Set value of active power $P^*_{0\_sg}$	1 pu
Rated power S_{base_sg}	10 kVA	Set value of reactive power $Q^*_{0\_sg}$	0 pu
Nominal frequency ω_0	376.99 rad/s	$\omega - P$ droop coefficient $k^*_{p\_sg}$	20 pu
Inertia constant M^*_{sg}	0.16 s	$V - Q$ droop coefficient $k^*_{p\_sg}$	5 pu
AVR PI K^*_{pAVR}	20 pu	Governor time constant T_{d_sg}	1 s
AVR PI T_{iAVR}	0.025 s	AVR LPF cut-off frequency	20 Hz

Impedance Model							
$X^*_d = X^*_q$	0.219 pu	$X'^*_d = X'^*_q$	0.027 pu	$X''^*_d = X''^*_q$	0.01 pu		
T'_{do}	6.55 s	T''_{do}	0.039 s	T'_{qo}	0.85 s	T''_{qo}	0.071 s

Slow governor response

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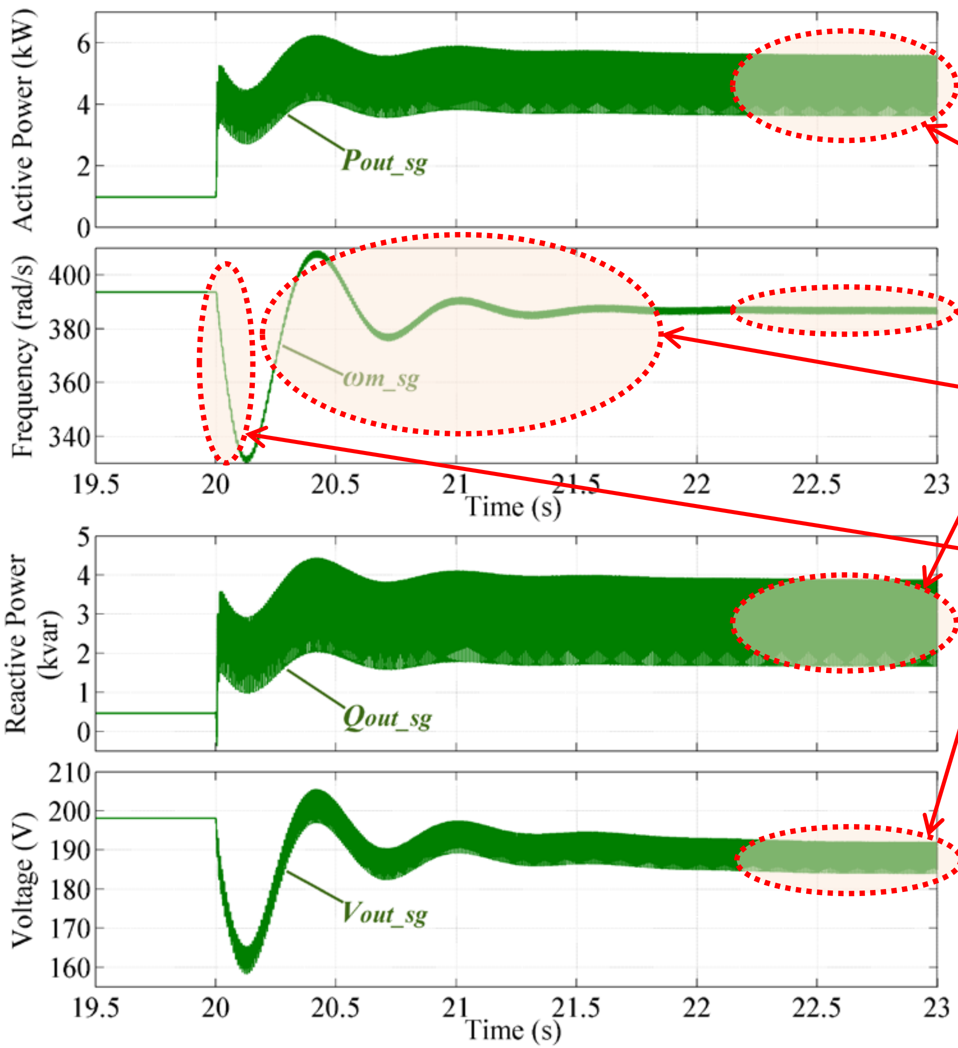
Simulation of Single SG Operation

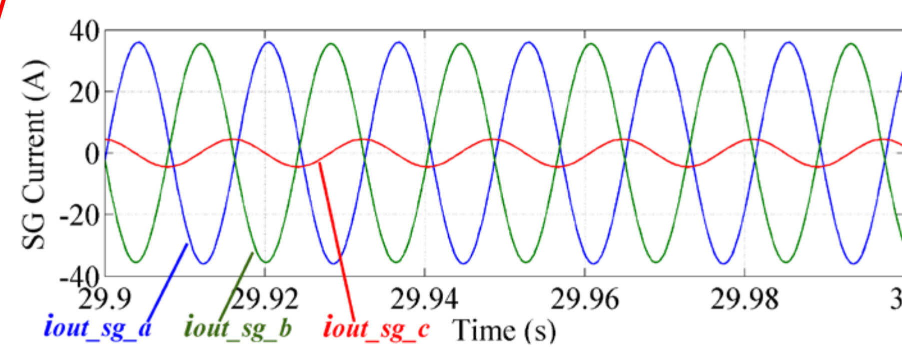
Initial loading : 3P 1 kW, 0.5 kvar
Connected loading : 1P 4.8 kW, 2.1 kvar

Ripples due to 3P unbalance introduced by 1P loading

Slow governor response cannot restore this frequency drop immediately

Rotor frequency decreased rapidly due to poor inertia





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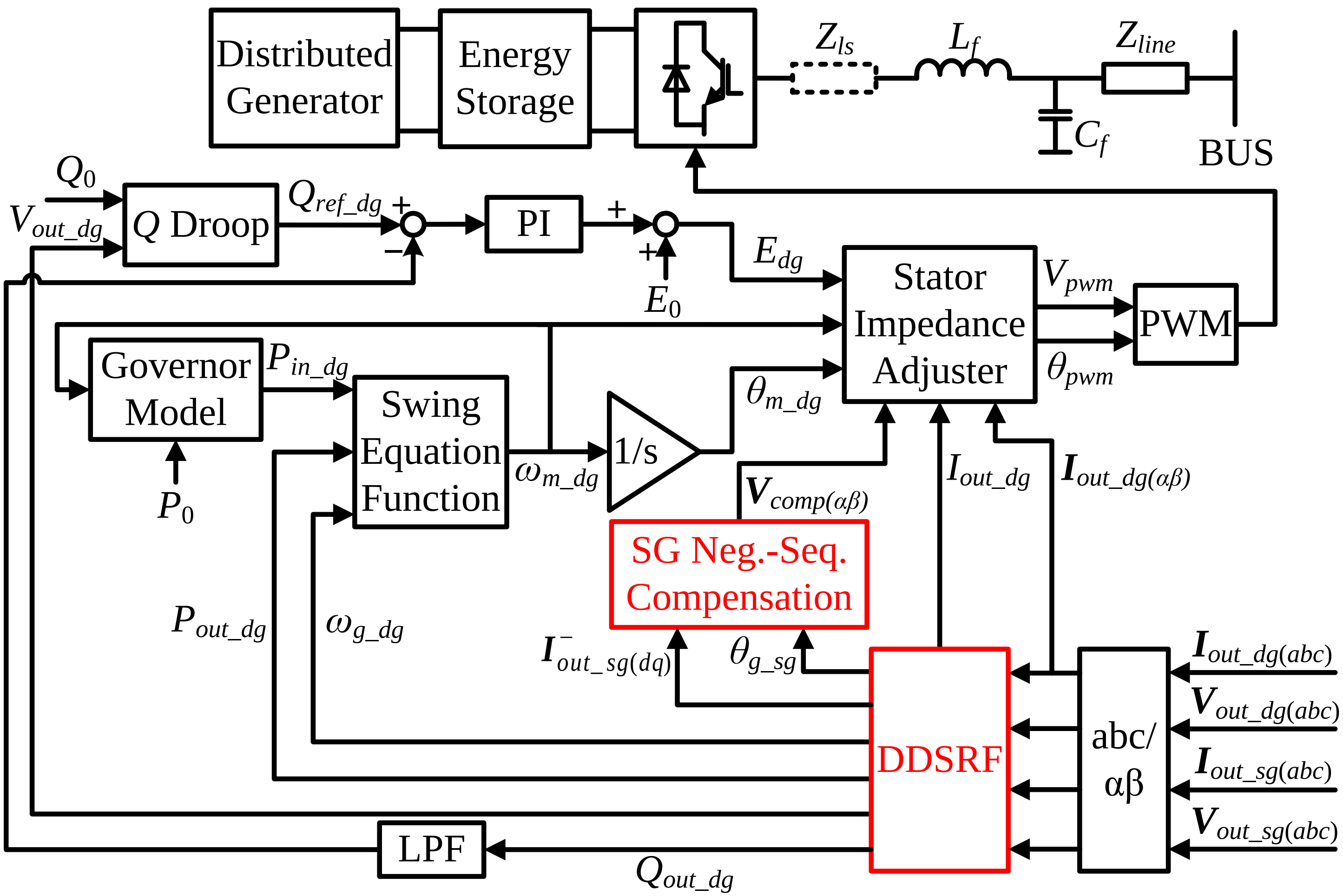
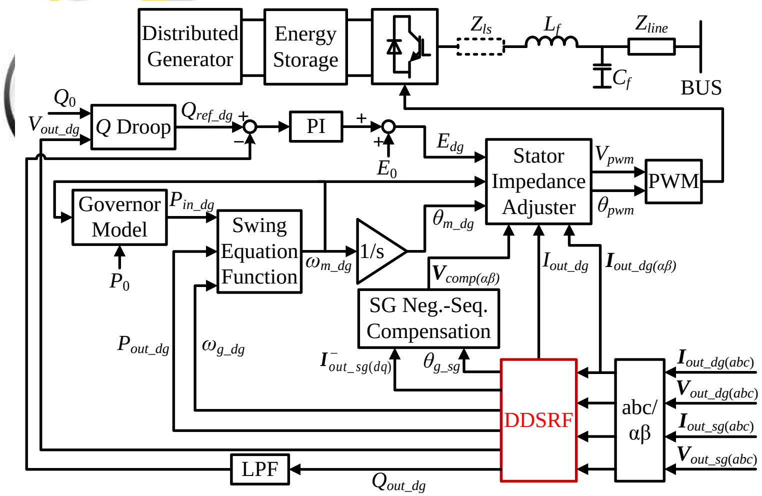
Control Requirements of DG

- 1. Reduce SG rotor frequency deviation
  - If SG rotor frequency drop below 90%, SG may be unstable
  - Virtual Synchronous Generator (VSG) Control
    - Generate virtual inertia to provide transient frequency support
    - Share active and reactive power with the SG
- 2. Eliminate Negative-Sequence Current from SG
  - Prevent SG from overheating and torsional stresses
  - Active power filter (APF)
- 3. Both 1+2 should be realized in ONE inverter

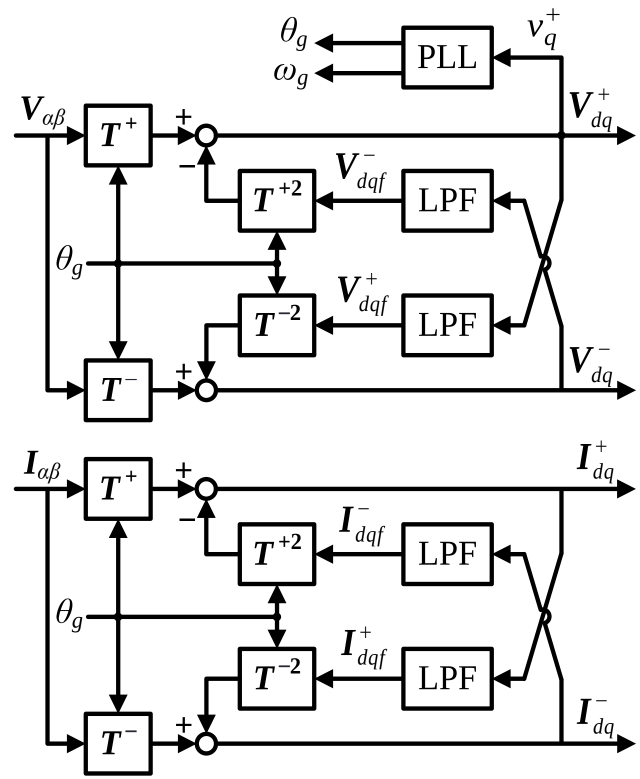
Proposed Modified VSG Control



DDSRF



Double Decoupled Synchronous Reference Frame (DDSRF) Decomposition



$\boldsymbol{T}^{\pm} = \boldsymbol{T}(\pm\theta_g)$ and $\boldsymbol{T}^{\pm 2} = \boldsymbol{T}(\pm 2\theta_g)$

$$\boldsymbol{T}(\theta_g) = \begin{bmatrix} \cos\theta_g & \sin\theta_g \\ -\sin\theta_g & \cos\theta_g \end{bmatrix}$$

- Applied to both DG and SG voltage and current to extract positive and negative sequence components
- Output power, voltage and current of DG are calculated from only positive sequence components
  - Prevent ripples due to negative sequence from entering the controller

$$P_{out\_dg} = v^{+}_{out\_dg\_d} i^{+}_{out\_dg\_d} + v^{+}_{out\_dg\_q} i^{+}_{out\_dg\_}$$

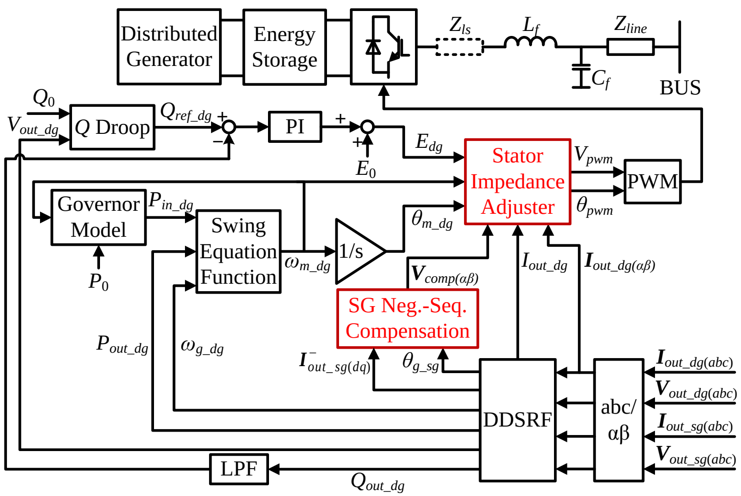
$$Q_{out\_dg} = -v^{+}_{out\_dg\_d} i^{+}_{out\_dg\_q} + v^{+}_{out\_dg\_q} i^{+}_{out\_dg\_d}$$

$$V_{out\_dg} = \sqrt{(v^{+}_{out\_dg\_d})^2 + (v^{+}_{out\_dg\_q})^2}$$

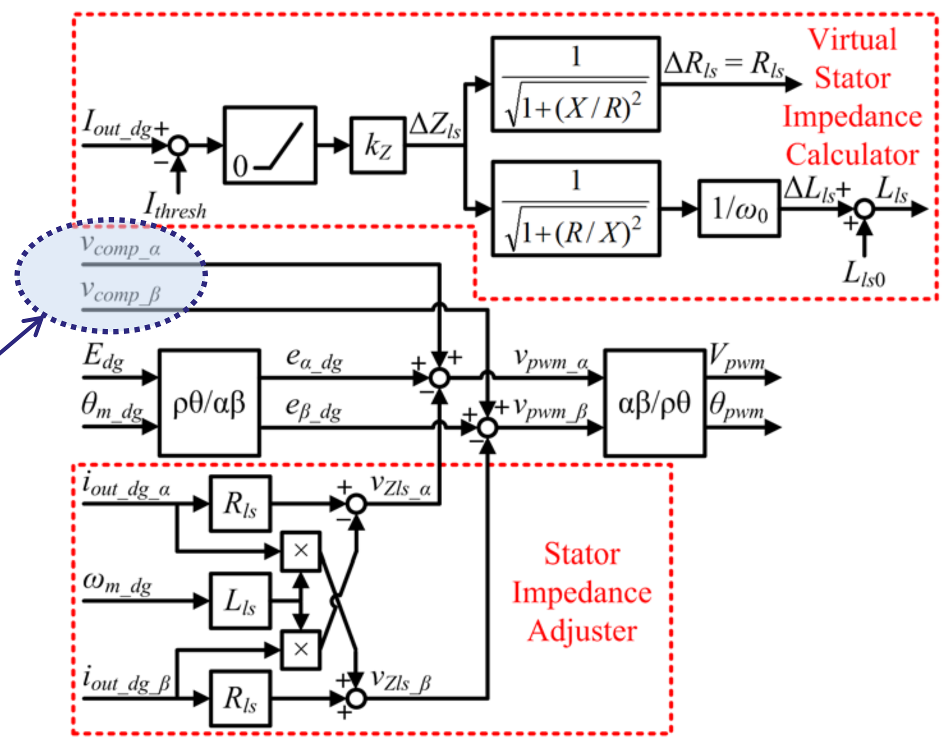
$$I_{out\_dg} = \sqrt{(i^{+}_{out\_dg\_d})^2 + (i^{+}_{out\_dg\_q})^2}$$

LPF: 1st order low pass filter (cut-off frequency 40 Hz)

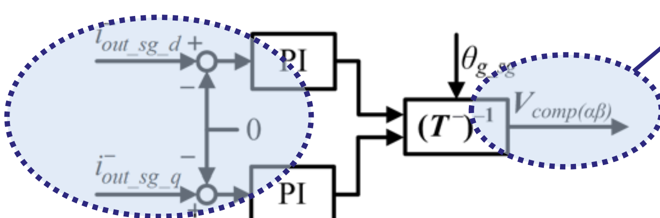
SG Neg.-Seq. Compensation



Stator Impedance Adjuster



SG Neg.-Seq. Compensation



Control SG Neg.-Seq. to 0

Parameter Design of Inverter

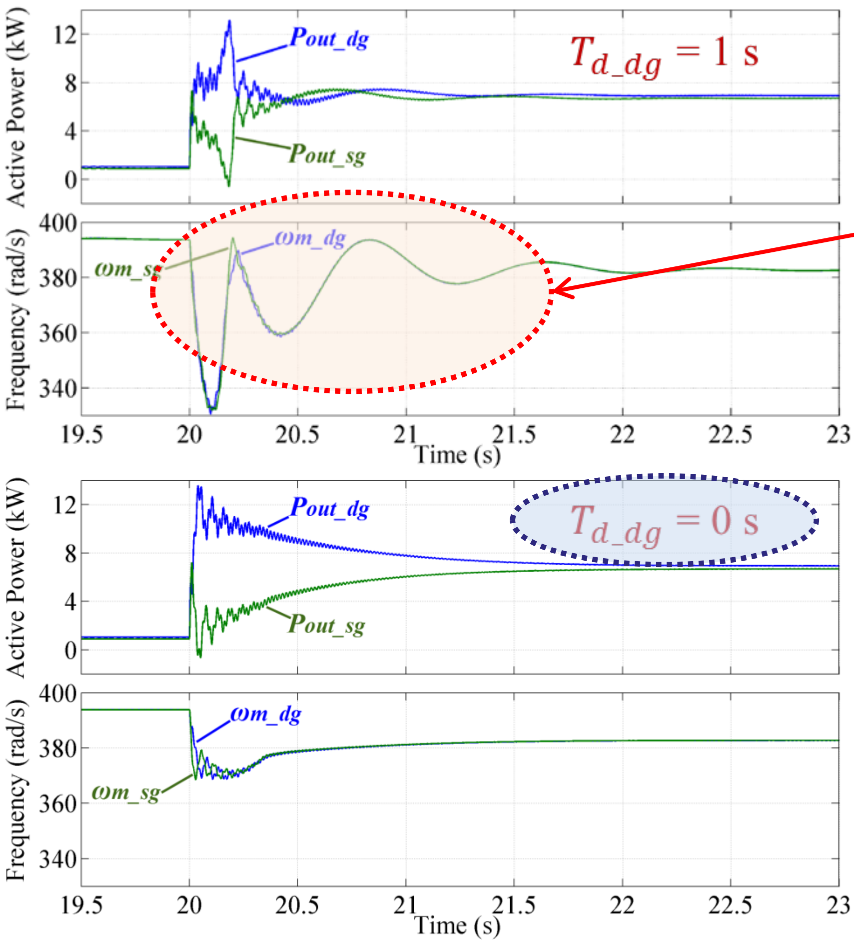
Parameter	Value	Parameter	Value
Rated voltage E_0	200 V	Set value of active power $P^*_{0\_dg}$	1 pu
Rated power S_{base_dg}	10 kVA	Set value of reactive power $Q^*_{0\_dg}$	0 pu
Nominal frequency ω_0	376.99 rad/s	$\omega - P$ droop coefficient $k^*_{p\_dg}$	20 pu
Inertia constant M^*_{dg}	0.16 s	$V - Q$ droop coefficient $k^*_{q\_dg}$	5 pu
Damping factor D^*_{dg}	8.7 pu	Governor time constant T_{d_dg}	0 s
Constant virtual stator inductance L_{ls0}	1.122 mH	Transient virtual stator impedance gain k^*_Z	0.69 pu
SG output reactor L_{ad_sg}	1.836 mH	Transient virtual stator impedance X/R ratio	5
PI Controller for Reactive Power			
K^*_{pq}	0.05 pu	T_{iq}	1.25×10^{-2} s
PI Controller for SG Neg.-Seq. Compensation			
$K^*_{p\_neg}$	0.1 pu	T_{i_neg}	0.01 s
Cut-off frequency of LPF for Q_{out_dg}			20 Hz

All parameters in red should be set equal to SG in per unit value to ensure proper transient and steady power sharing

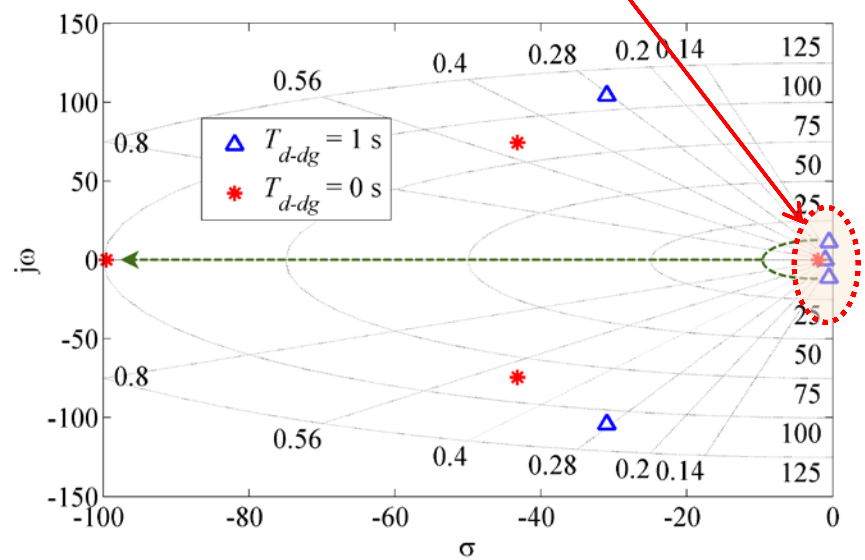
Design of Parameters in blue will be discussed in detail

Governor Time Constant T_{d_dg}

Set equal to SG in order to share transient active power?



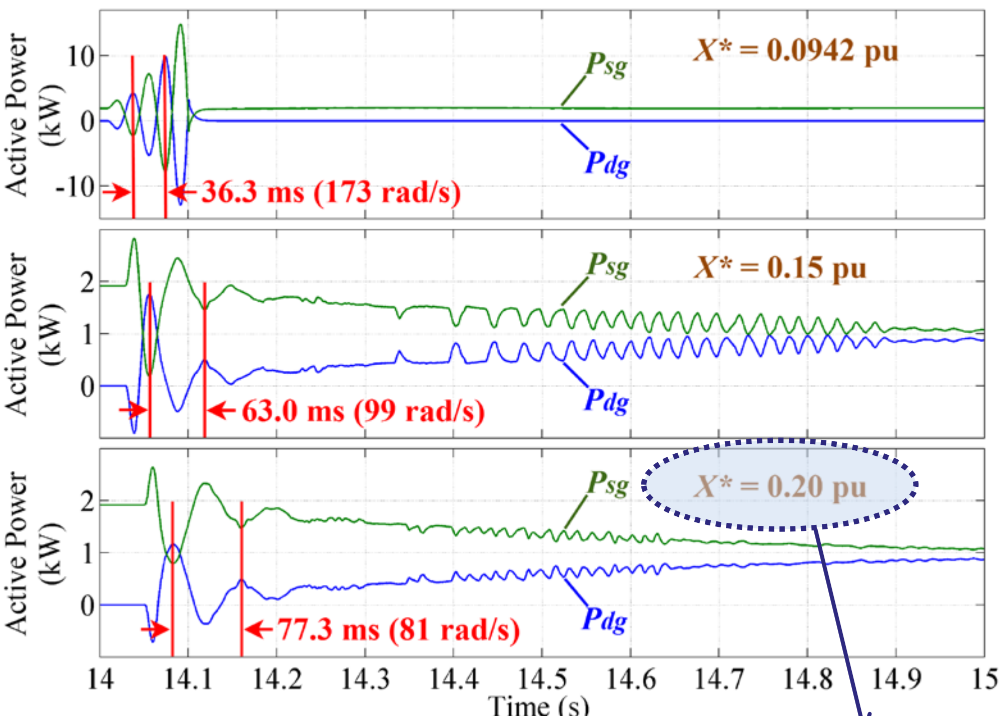
Low frequency oscillation indicated by oscillatory conjugated eigenvalues

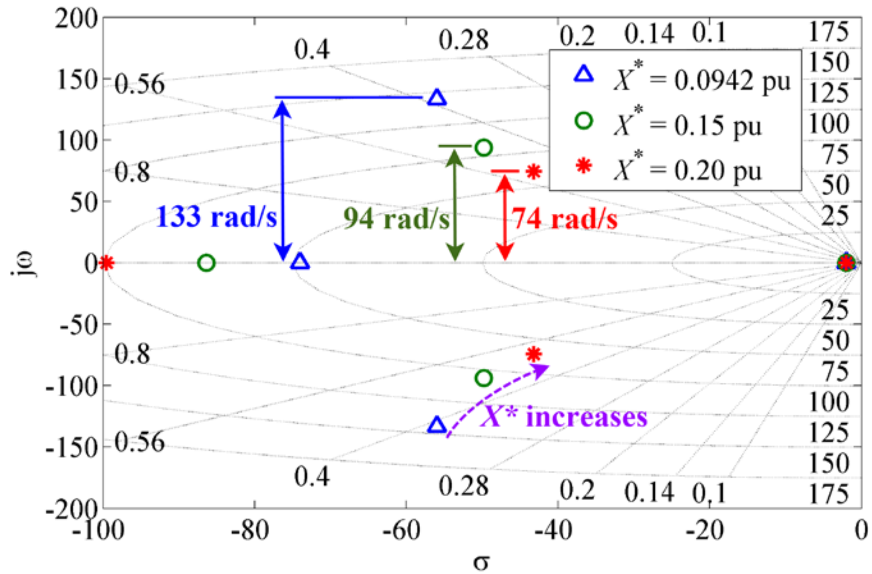


Constant Virtual Stator Inductance

Output reactance of DG and SG should be set equal to share transient power, but how about the value?

Connection of DG

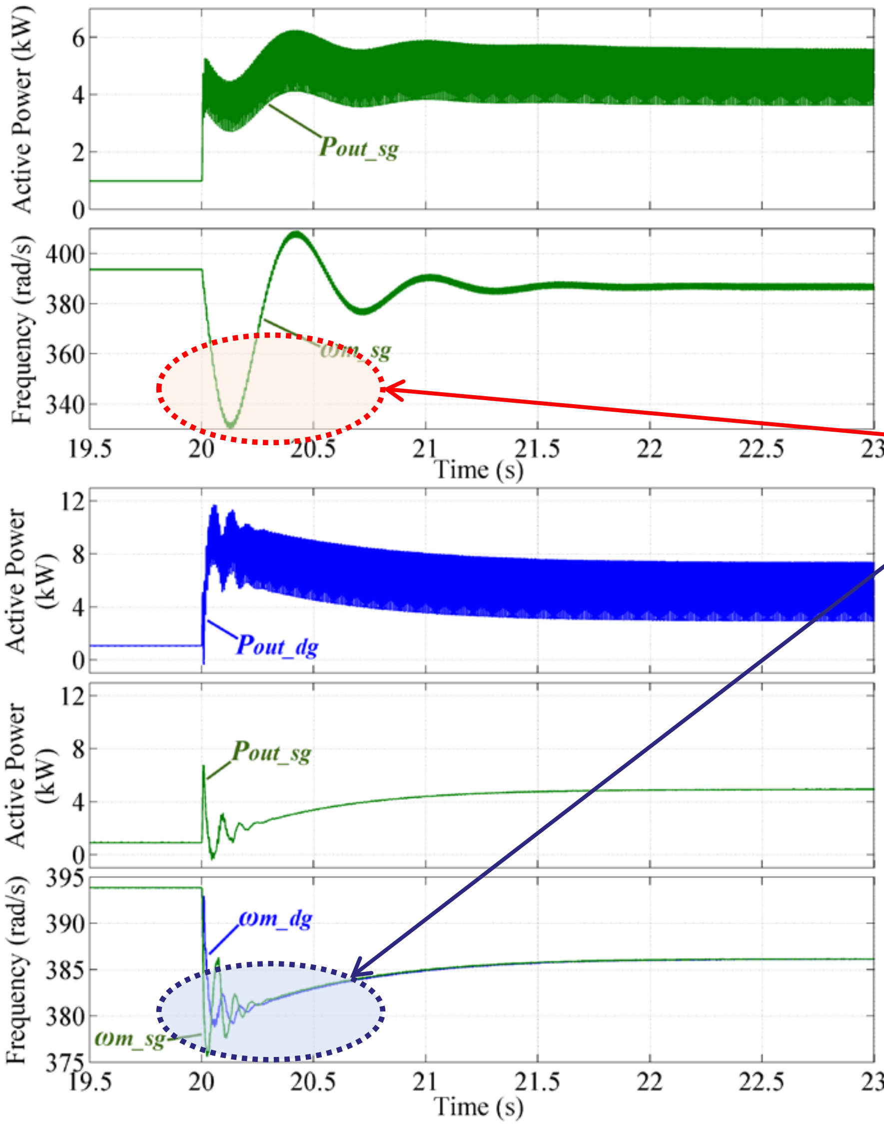




Realized by tuning virtual stator inductance L_{ls0} for DG and adding an additional output reactor L_{ad_sg} for SG

Simulation of 1P Loading Transition

SG only



Initial loading : 3P 1 kW, 0.5 kvar
Connected loading : 1P 4.8 kW, 2.1 kvar

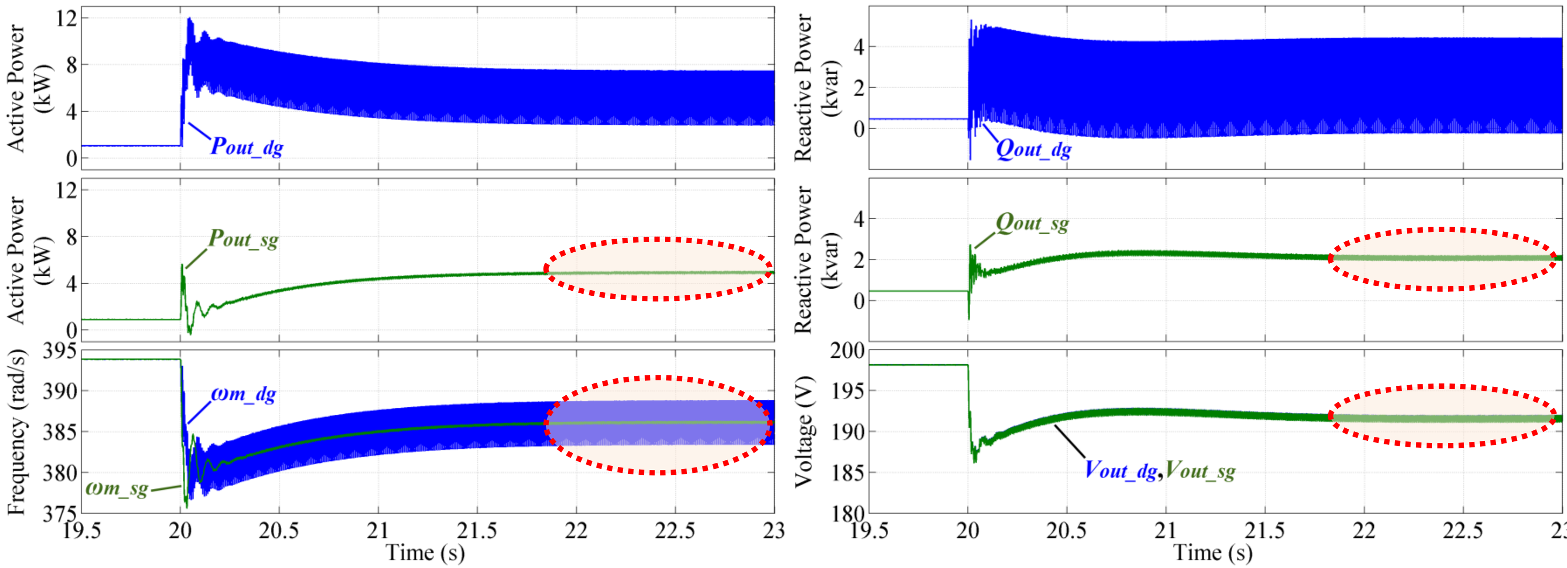
Improved SG rotor frequency deviation
(Frequency Support of VSG)

SG + VSG

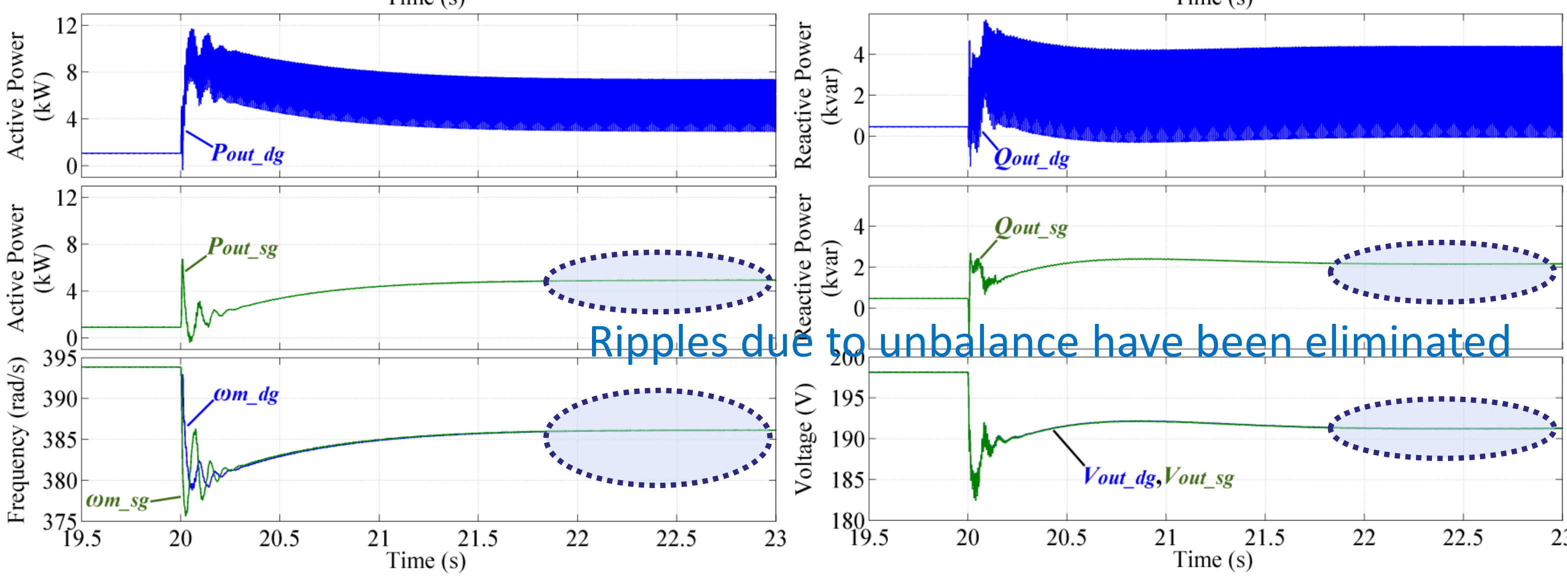
Initial loading : 3P 2 kW, 1 kvar
Connected loading : 1P 9.6 kW, 4.2 kvar
(2x of SG only case)

Simulation of 1P Loading Transition

w/o DDSRF and SG Neg. Seq.



with DDSRF and SG Neg. Seq.

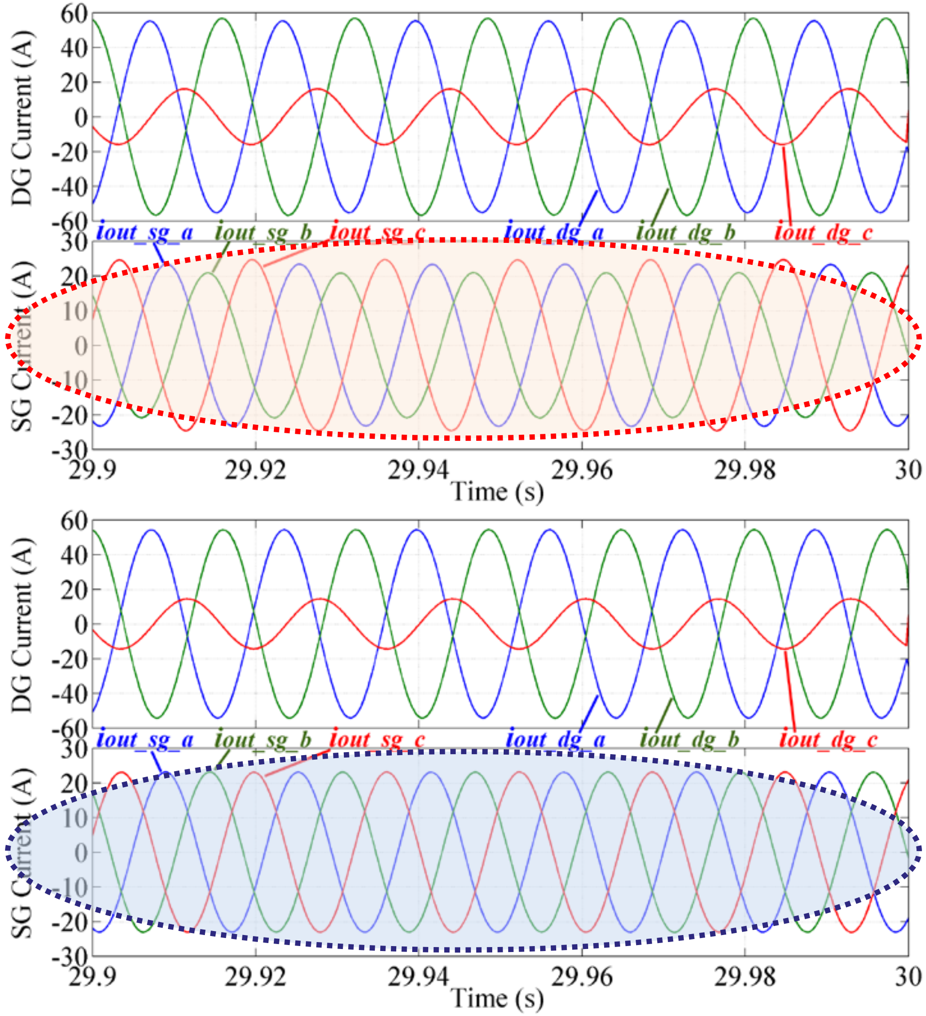


Ripples due to unbalance have been eliminated

Phase Current

w/o DDSRF and
SG Neg. Seq.

with DDSRF and
SG Neg. Seq.



Balanced SG current

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- Parallel Inverters
- Synchronous Generator + Inverter
- Conclusion

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Conclusion

Conclusion

- VSG control can provide inertia support for microgrids, leading to less fluctuant frequency
- Parallel inverters and SG + inverter operations were established, and several related issues were solved

Future Plan

- Operation of Multiple SGs + Multiple inverters

Thank you for your kind attention!

For more details, please refer to:

- J. Liu, Y. Miura, H. Bevrani, and T. Ise, “Enhanced virtual synchronous generator control for parallel inverters in microgrids,” *IEEE Transactions on Smart Grid*., doi: 10.1109/TSG.2016.2521405.
- J. Liu, Y. Miura, T. Ise, J. Yoshizawa, and K. Watanabe, “Parallel operation of a synchronous generator and a virtual synchronous generator under unbalanced loading condition in microgrids,” *8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, Hefei, China, 2016, pp. 3741-3748.
- J. Liu, Y. Miura, and T. Ise, “Power quality improvement of microgrids by virtual synchronous generator control,” *10th Electric Power Quality and Supply Reliability Conference (PQ2016)* , Tallinn, Estonia, 2016.