University of Idaho
College of Engineering

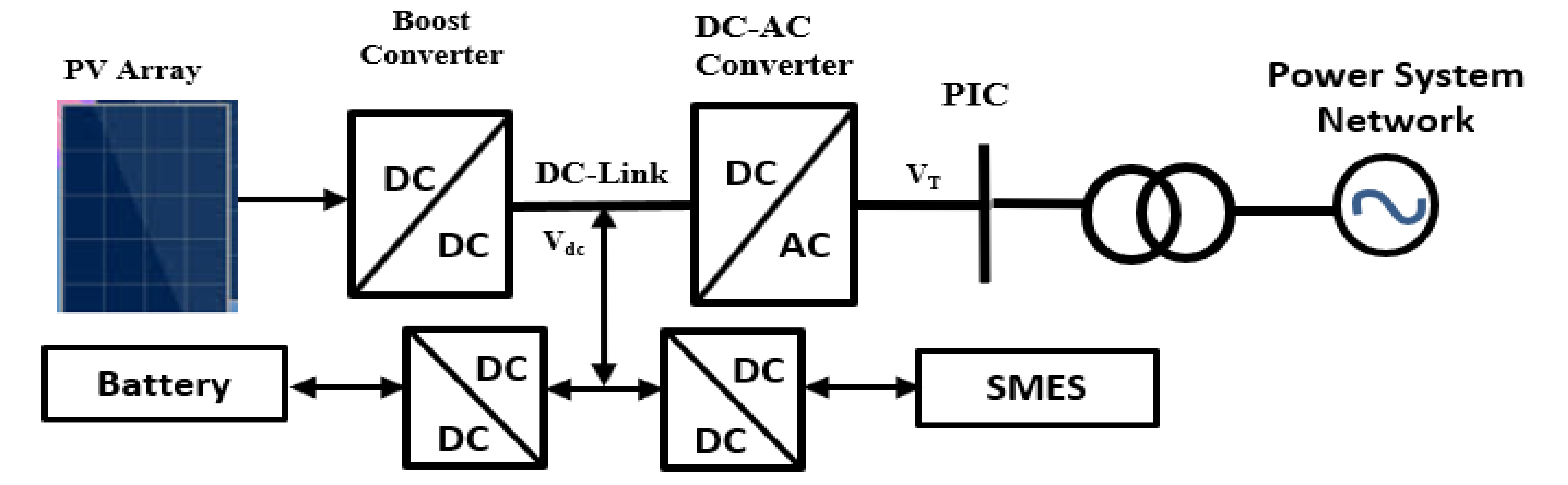
# VIRTUAL SYNCHRONOUS CONTROLLER BASED SMES/BATTERY ENERGY STORAGE SYSTEM

Mahmoud M. Badreldien Prof. Brian K. Johnson

# CONTENTS

# Introduction

- Effect of inertia and damping of SGs on system's stability.
- Effect of inverter-based RERs on system inertia.



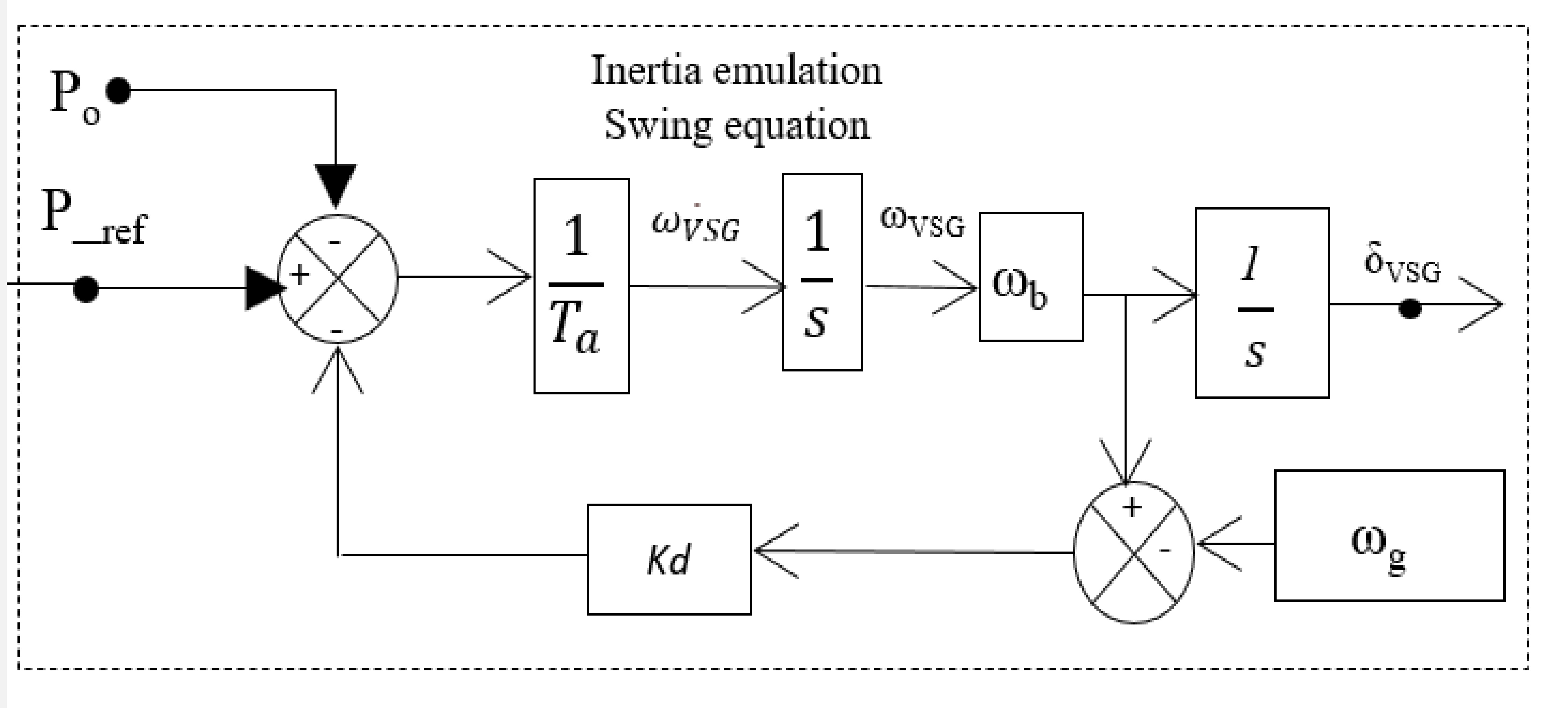

General layout of the proposed system

**This paper would describe:**

- VSG ( Virtual inertia)
- Inverter controller design
- HESS
- Simulation results for different scenarios

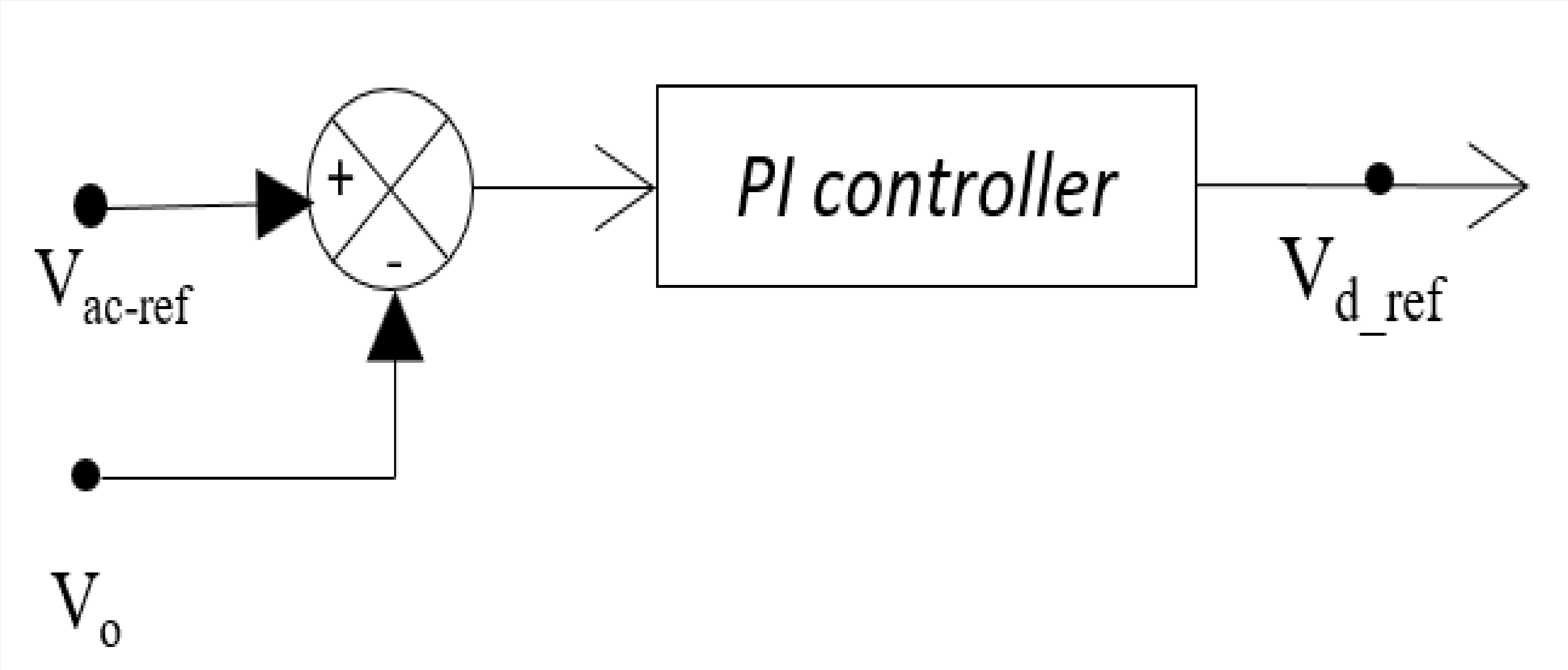
# DC-AC converter controller

Outer loops:
Virtual inertia emulation



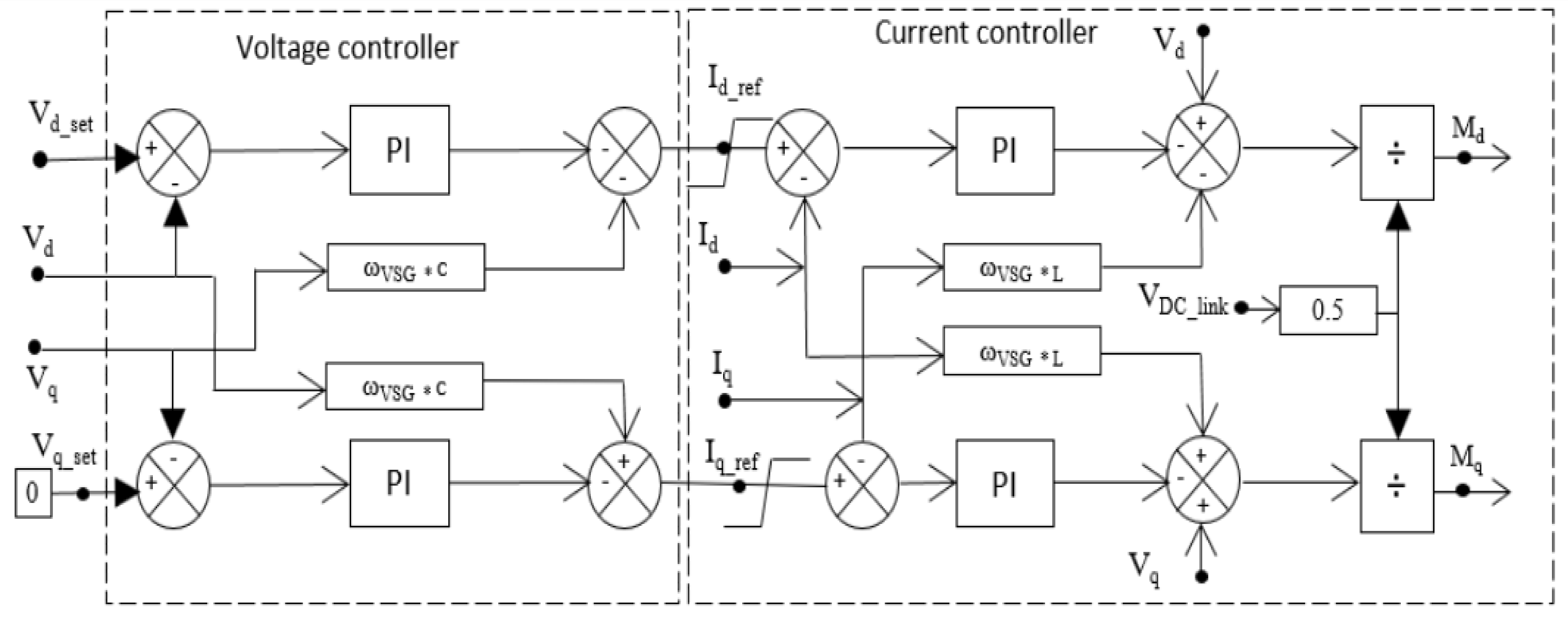

Ta ….Inertia time constant
Kd ….Damping constant

Outer loop:
Terminal voltage Controller



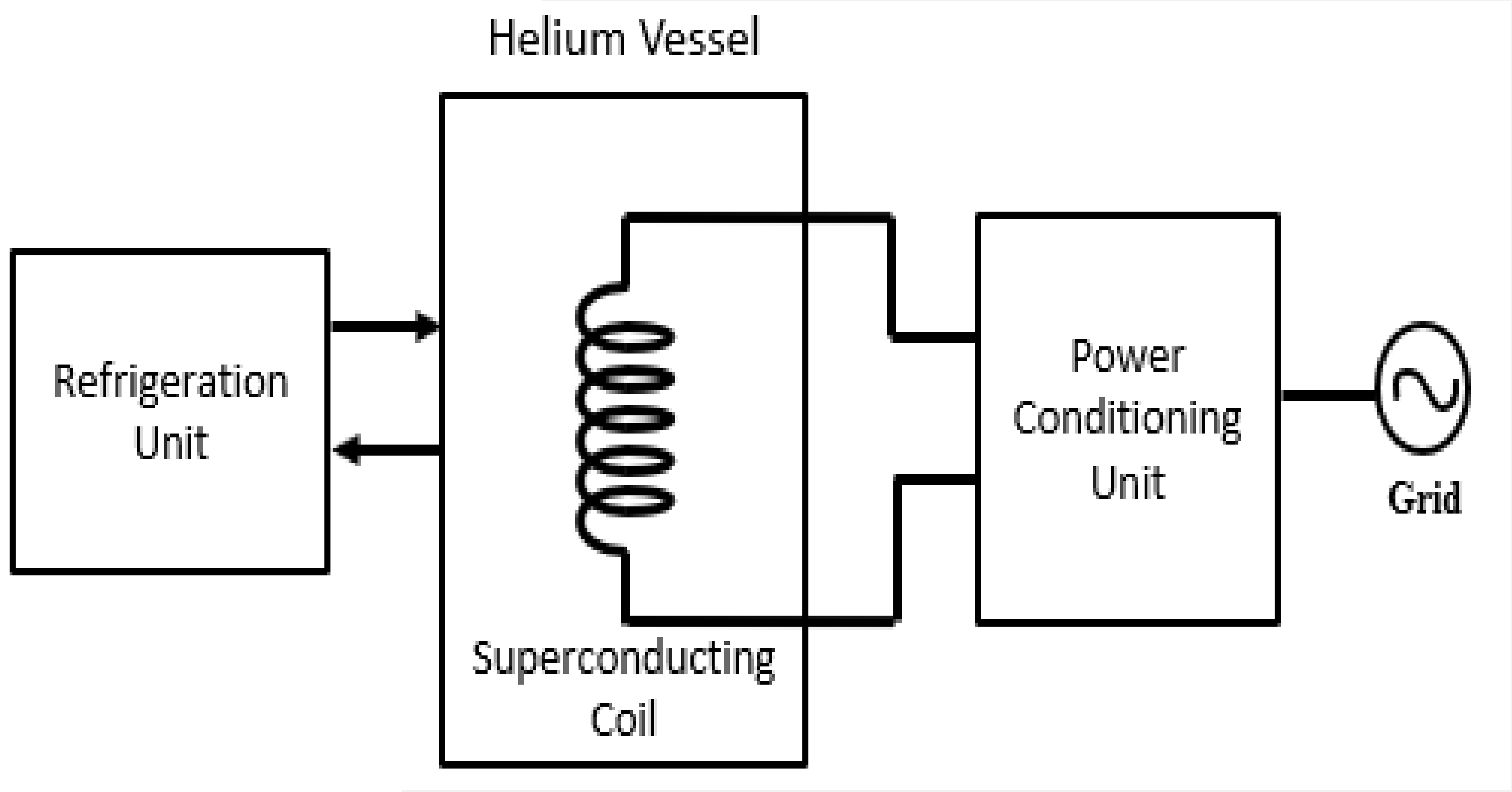
# DC-AC converter controller

## Inner loops

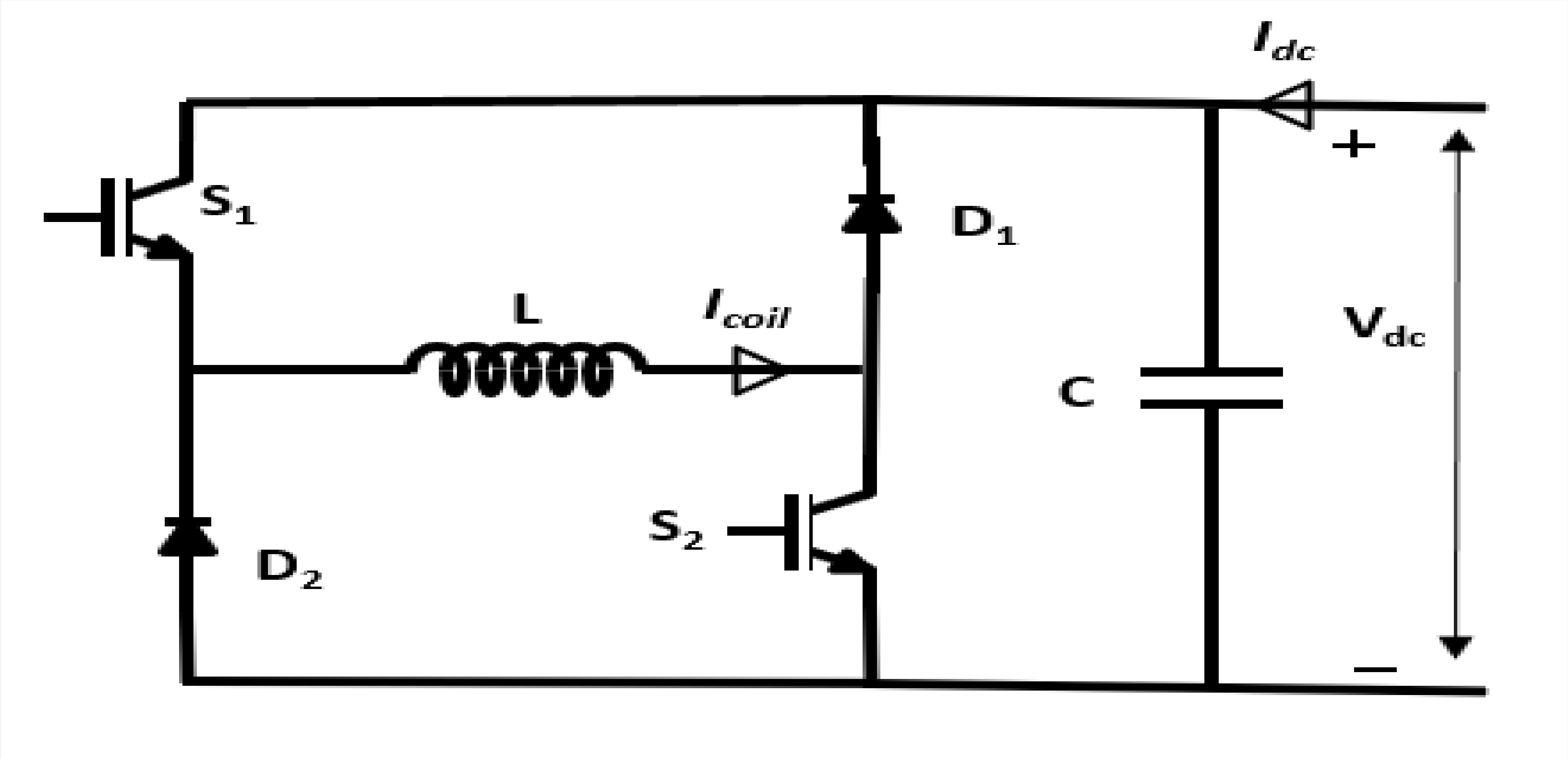



Cascaded voltage and current control loops

# SMES system and controller




Schematic diagram of a SMES system

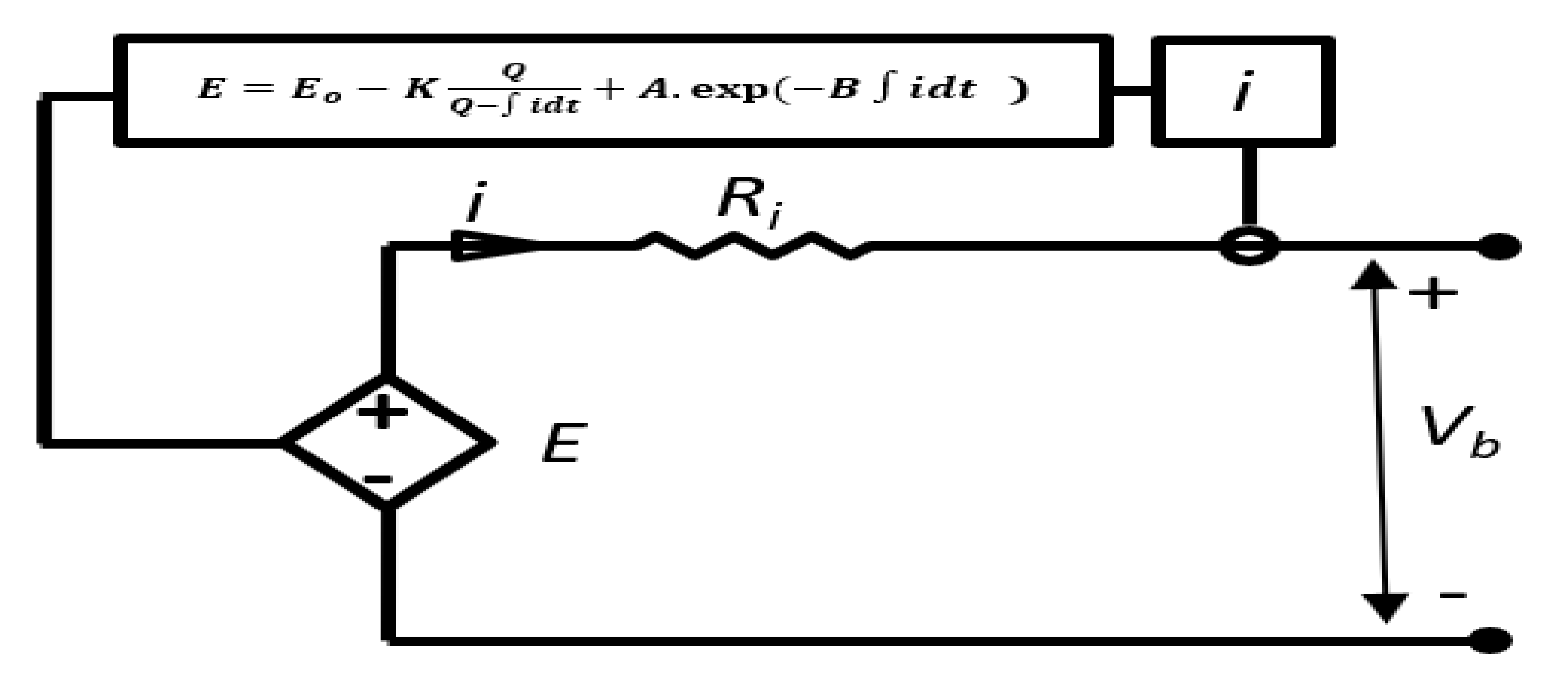



DC-DC chopper of the SMES coil

# Battery storage system and dc-dc converter

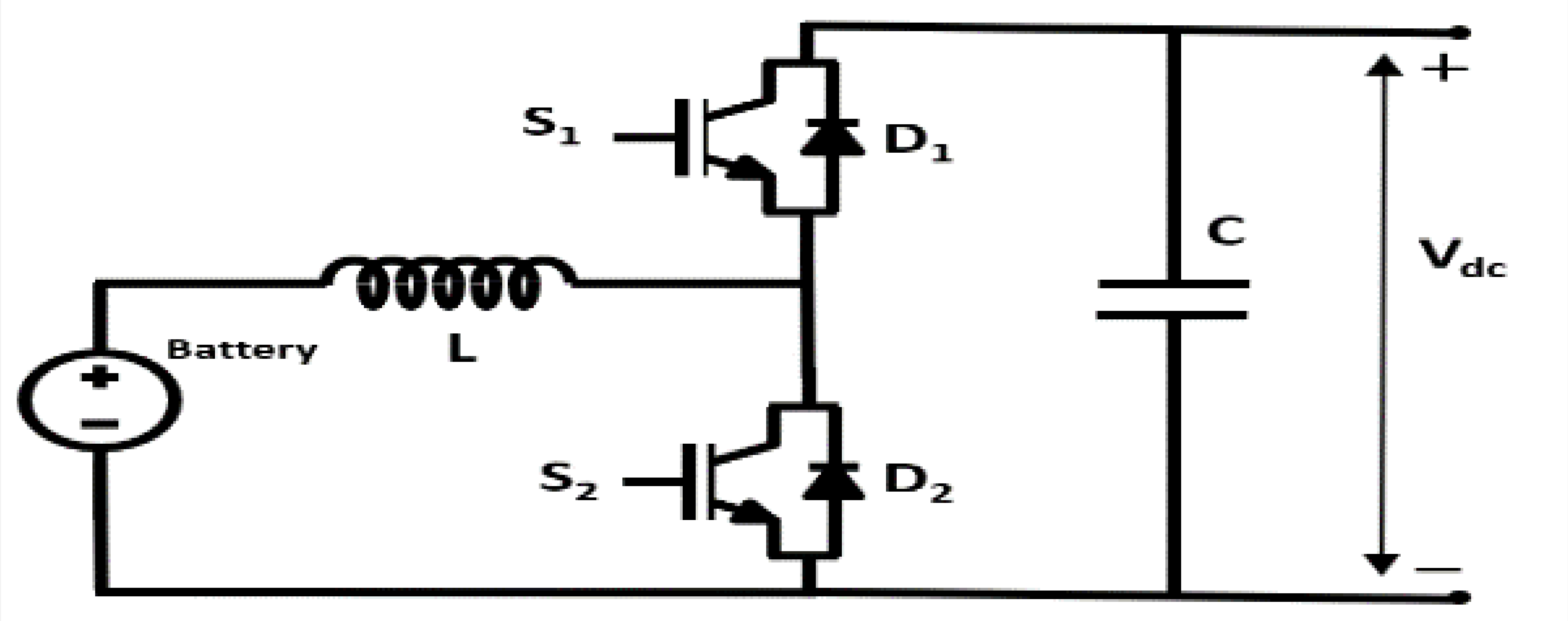
$$E = E_0 - K\left(\frac{Q}{Q - it}\right) + A * e^{-B\int idt}$$

$$V_b = E - R_i * i$$



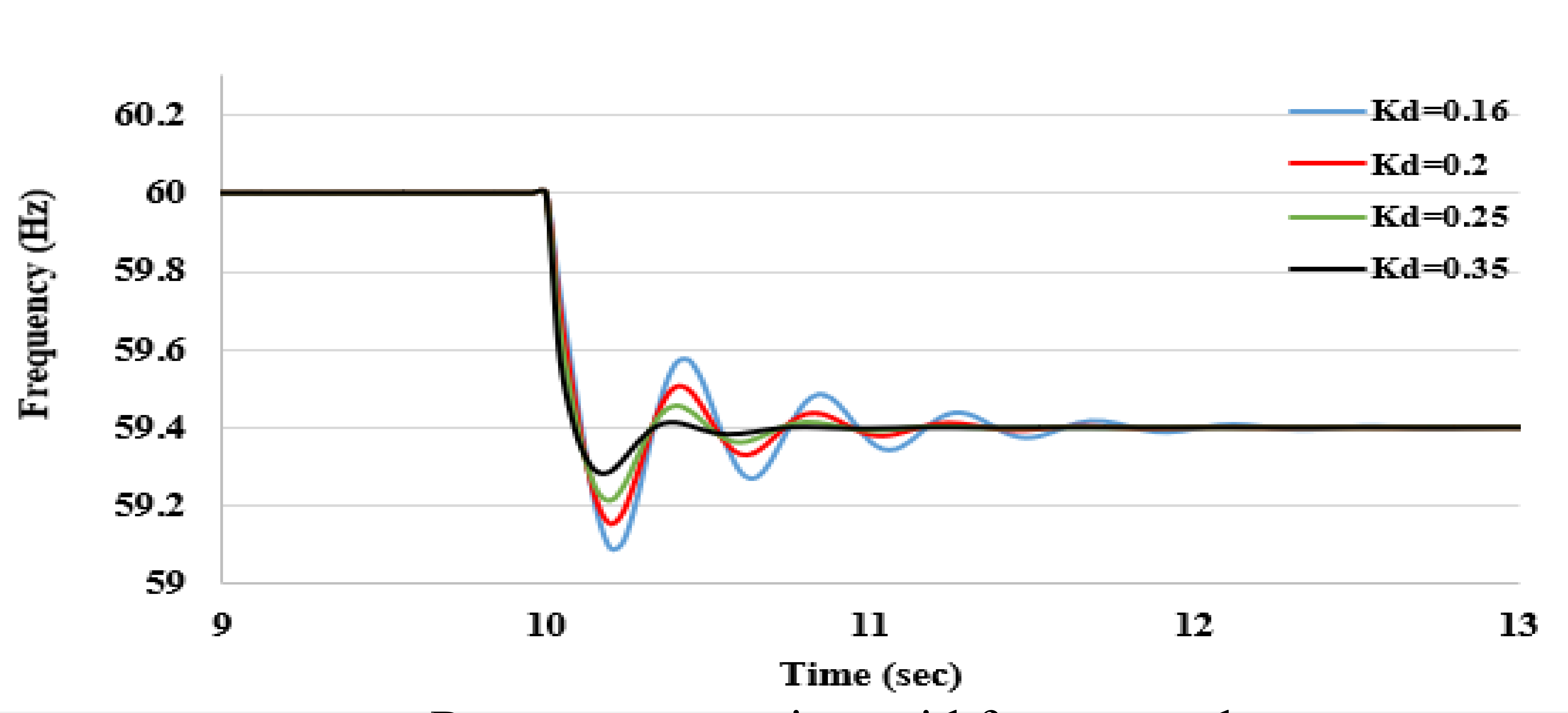

Battery equivalent electric circuit model

## Battery Buck–Boost Converter controller



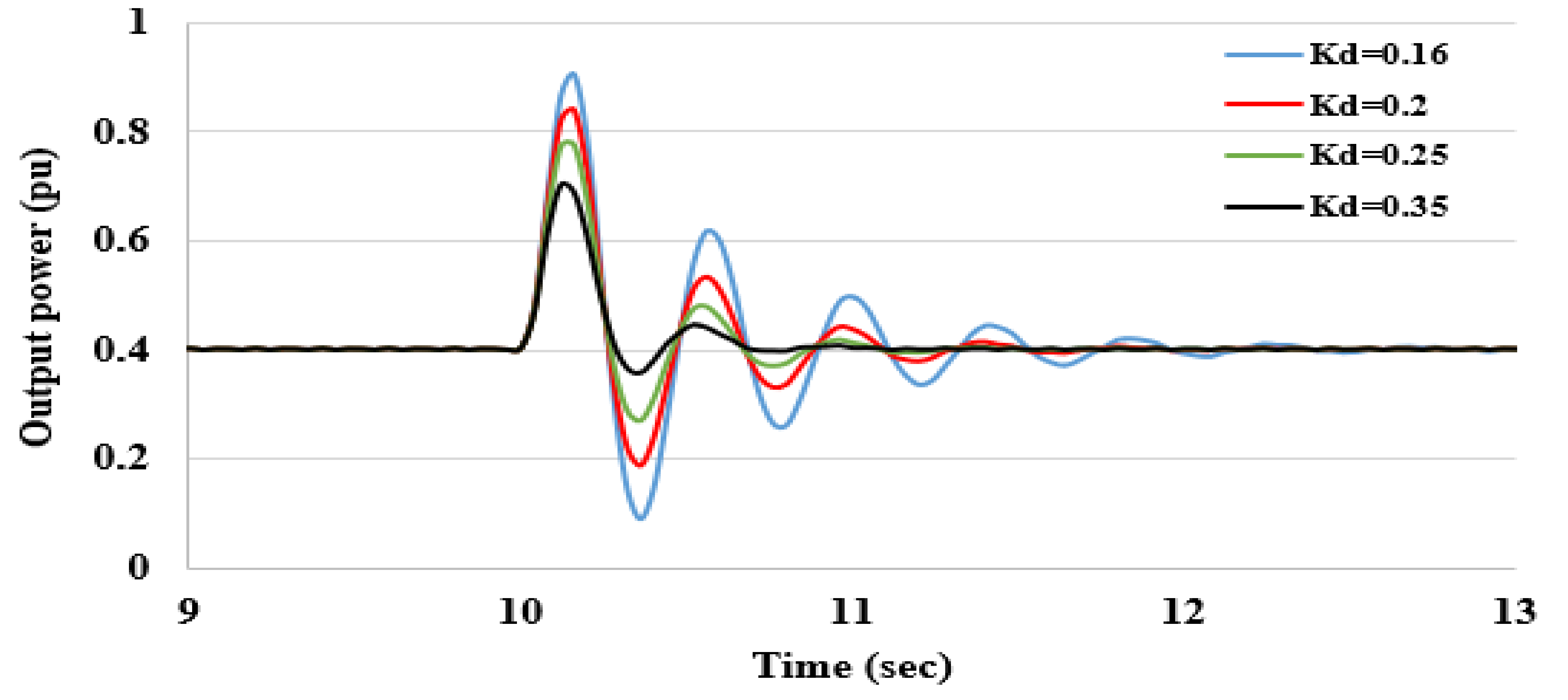

Battery Buck–Boost converter controller

# Simulation results: microgrid frequency drop



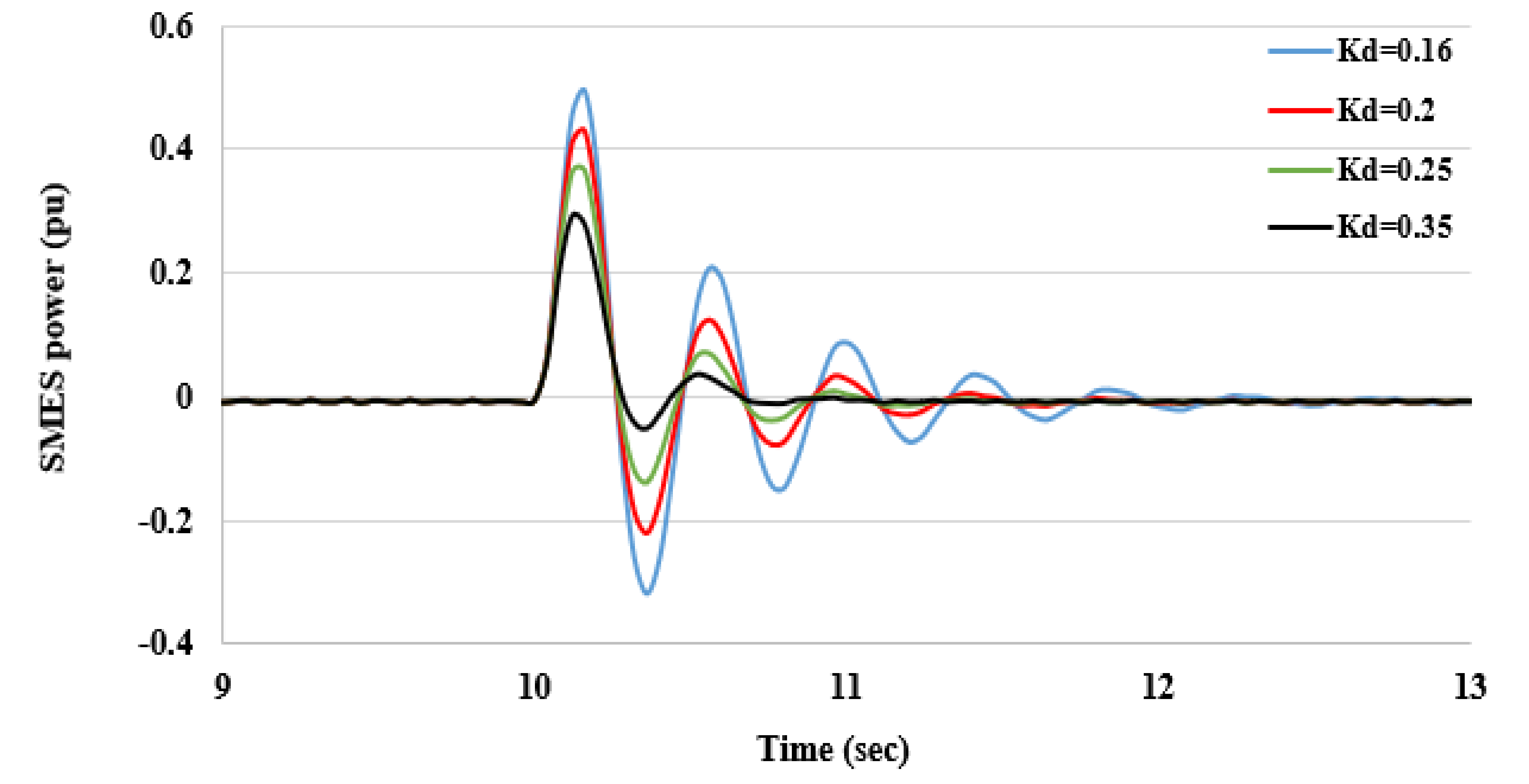

Response to a microgrid frequency drop at different damping constants (Ta=5)

# Simulation results: microgrid frequency drop



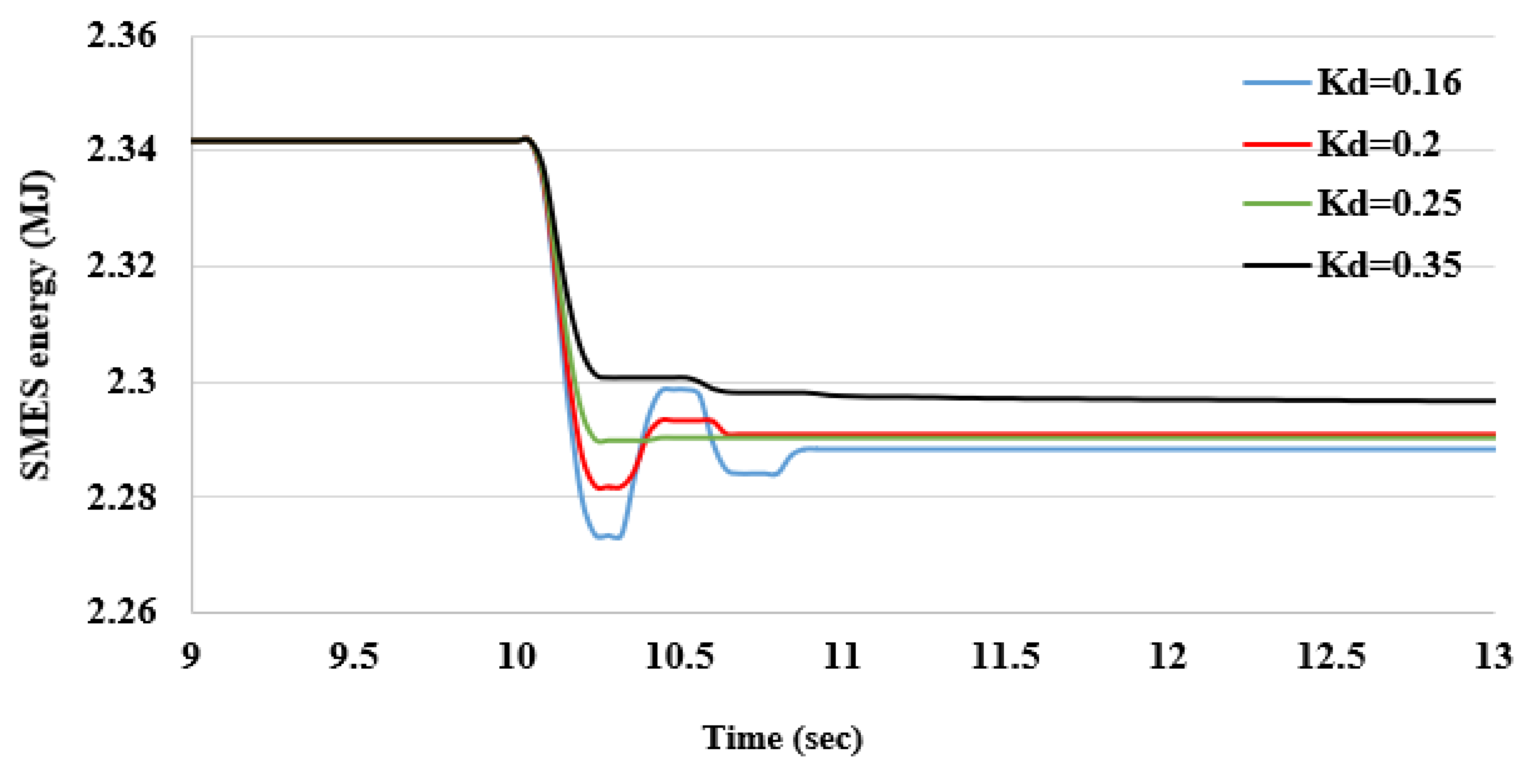

Converter output power at different damping constants in response to a microgrid frequency drop (Ta=5)

# Simulation results: microgrid frequency drop



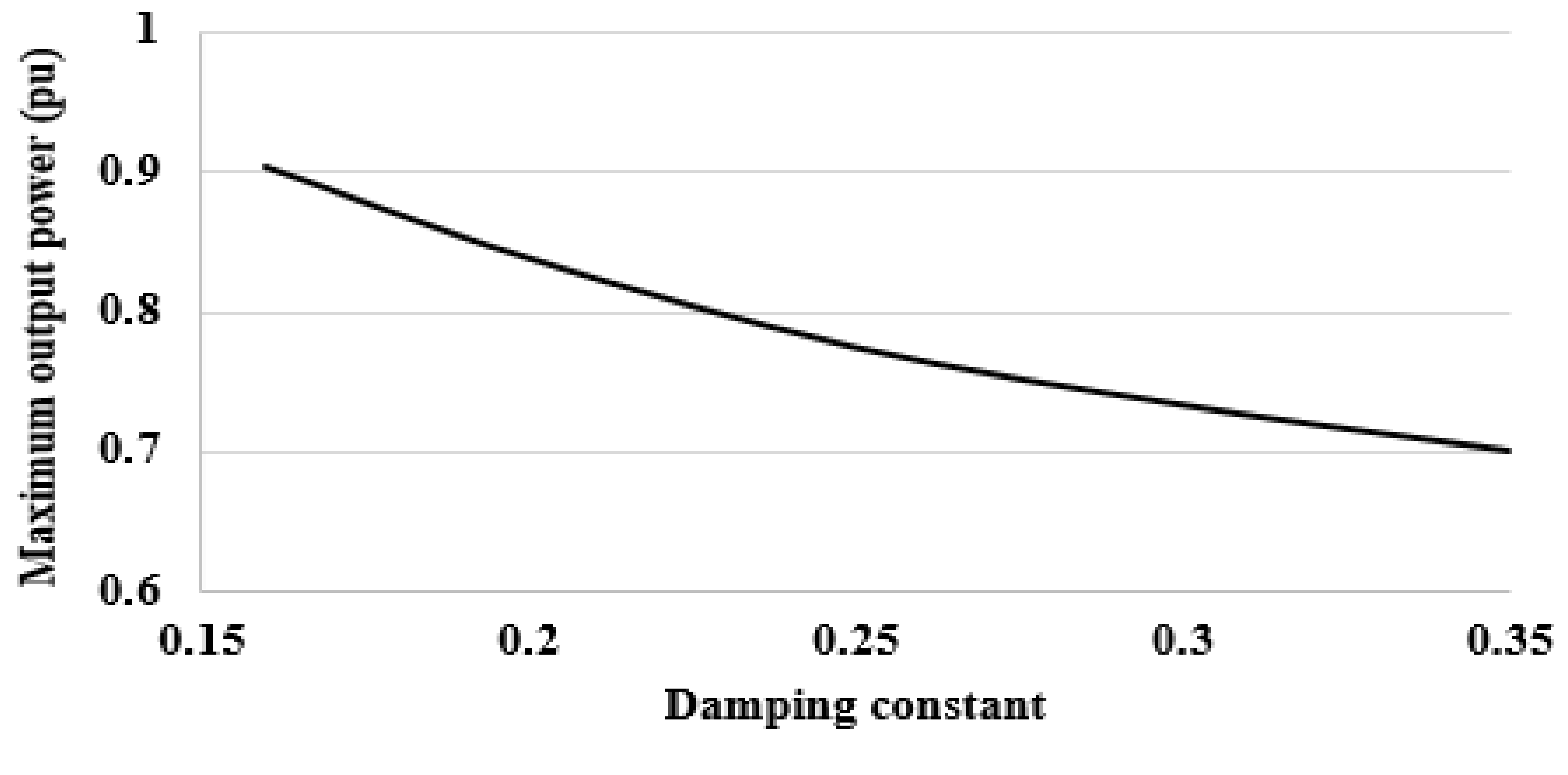

SMES instantaneous power in response to a microgrid frequency drop (Ta=5)

# Simulation results: microgrid frequency drop



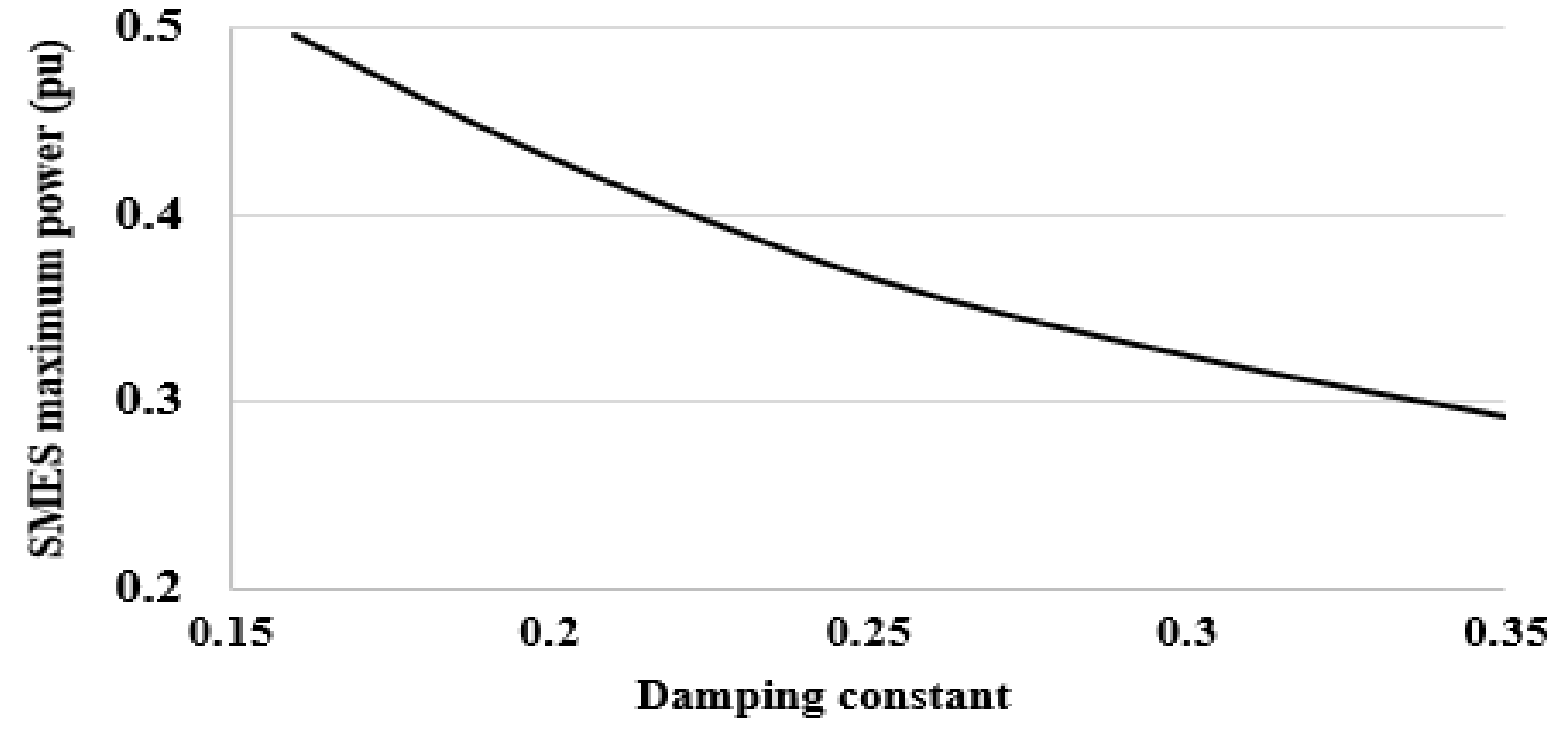

SMES energy at different damping constant in response to a microgrid frequency drop (Ta=5)

# Simulation results: microgrid frequency drop



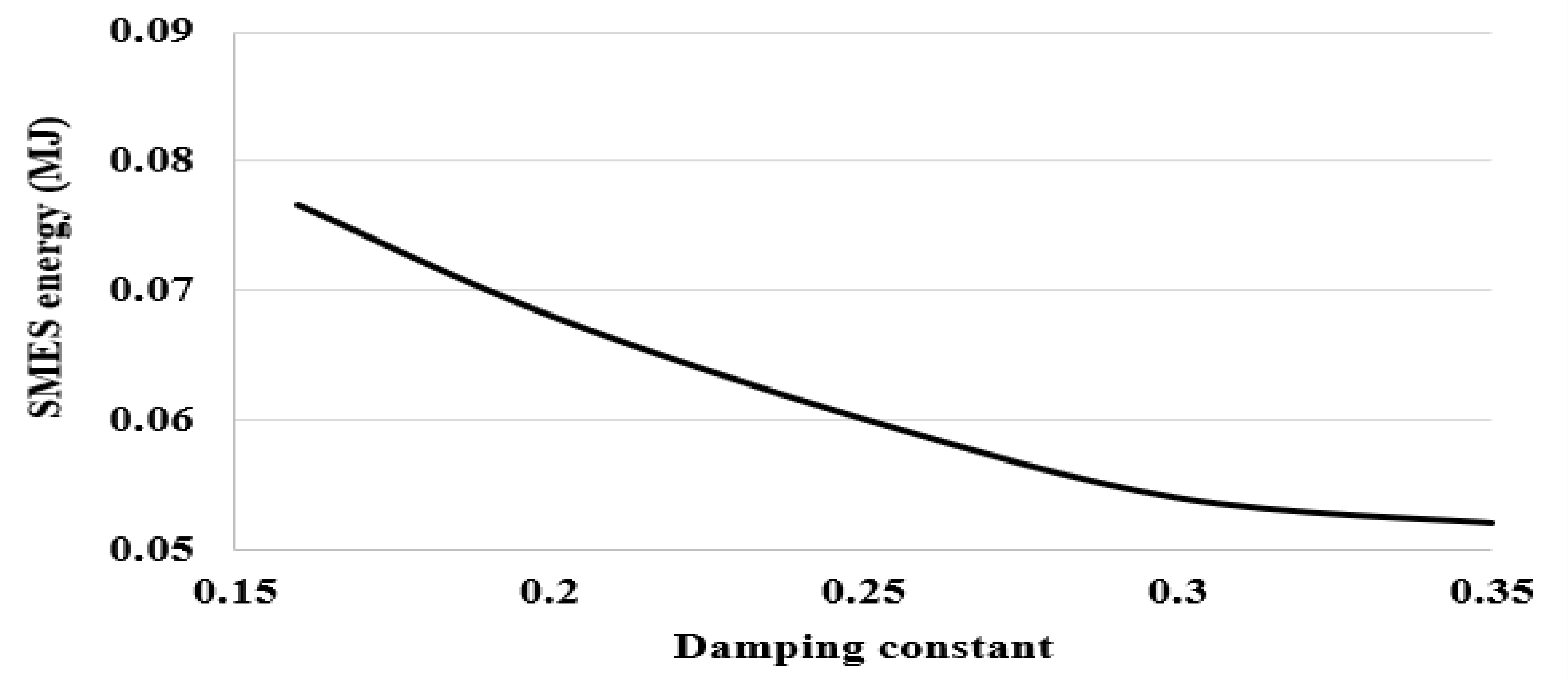

Maximum converter output power versus damping constant in response to a microgrid frequency drop

# Simulation results: microgrid frequency drop



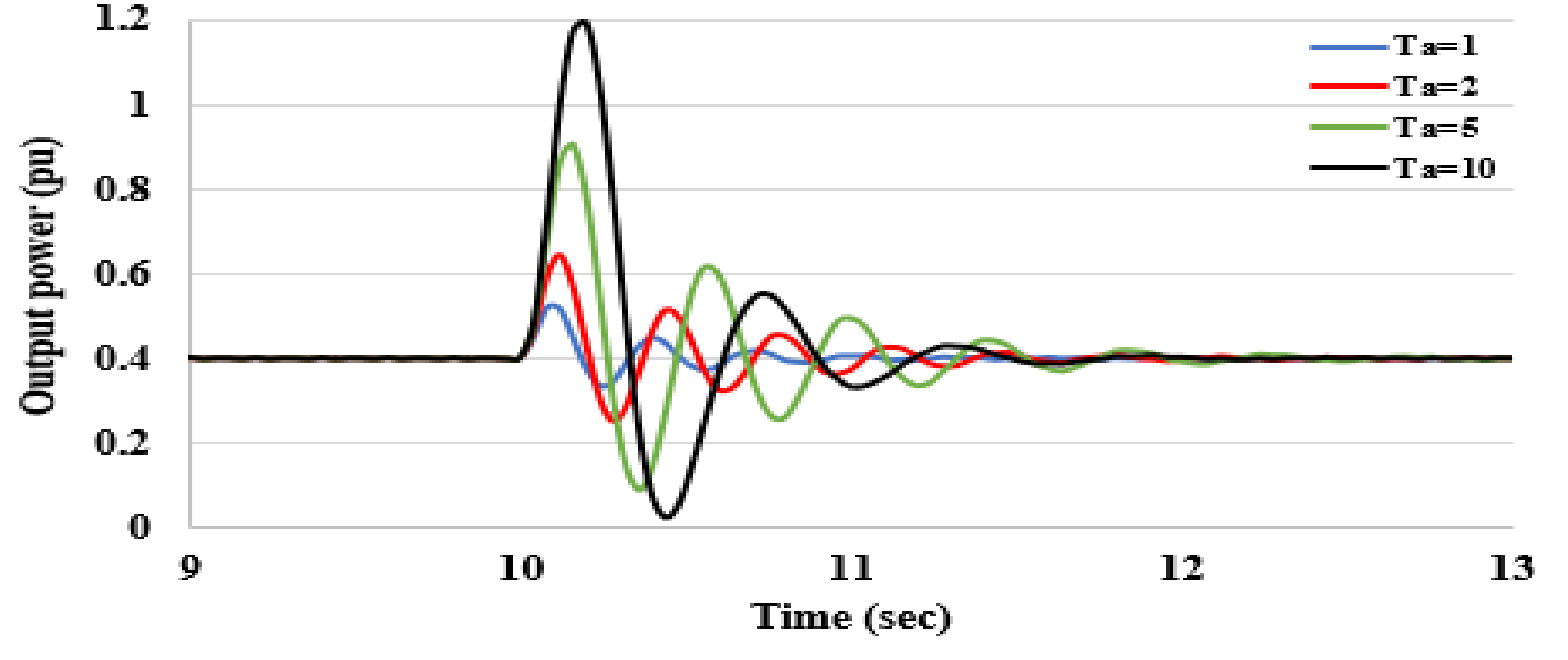

SMES maximum power versus damping constant in response to a microgrid frequency drop

# Simulation results: microgrid frequency drop



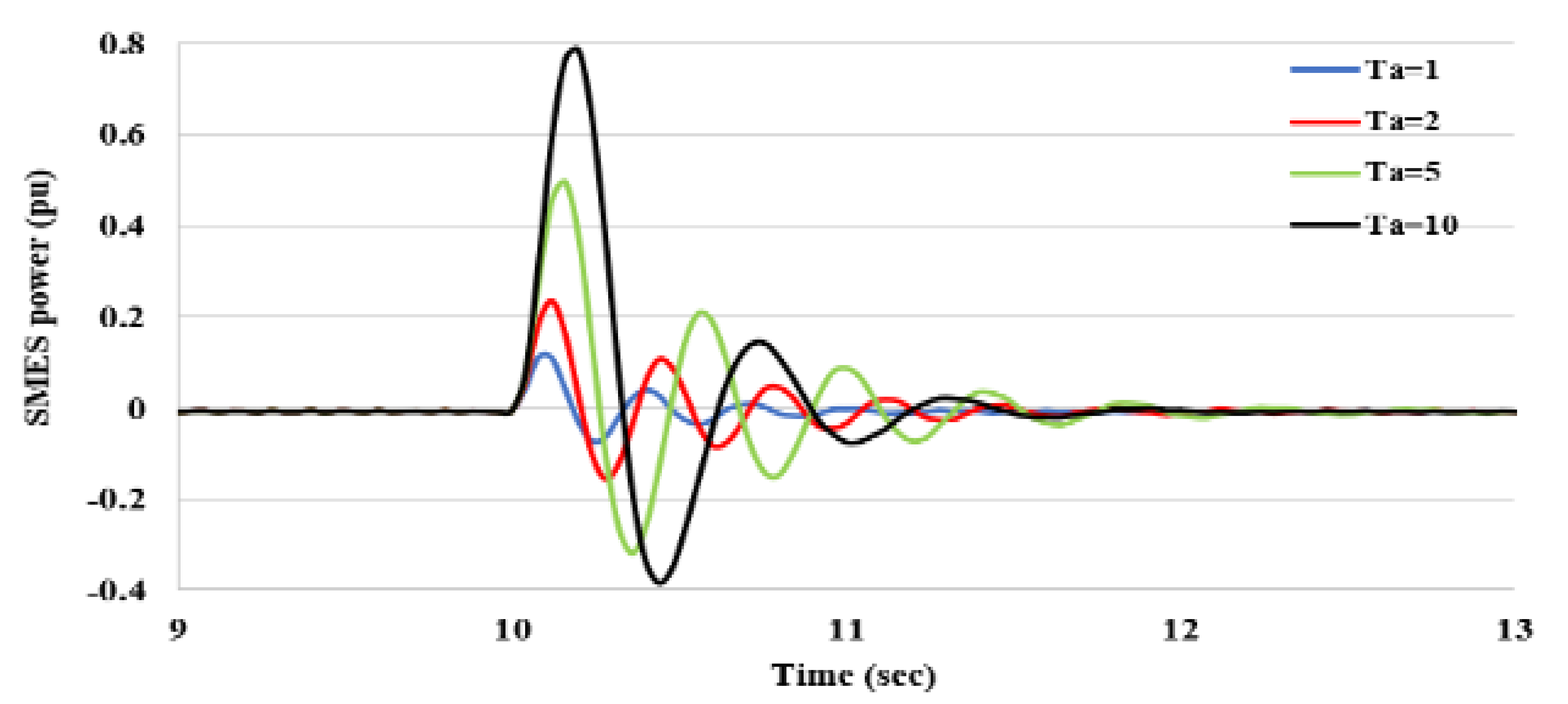

SMES generated energy versus damping constant in response to a microgrid frequency drop

# Simulation results: microgrid frequency drop at different inertia time constants



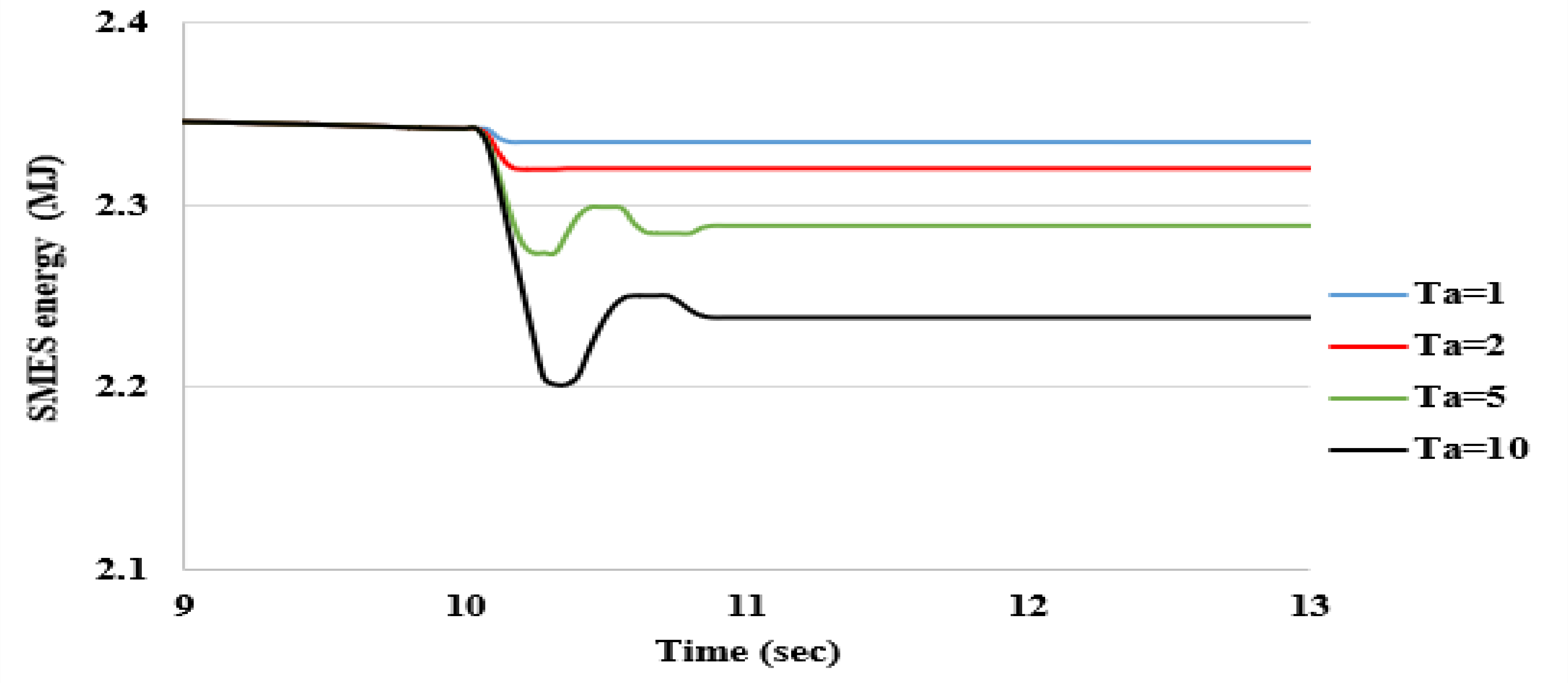

Converter output power at different inertia constants in response to a microgrid frequency drop (Kd=0.16)

# Simulation results: microgrid frequency drop



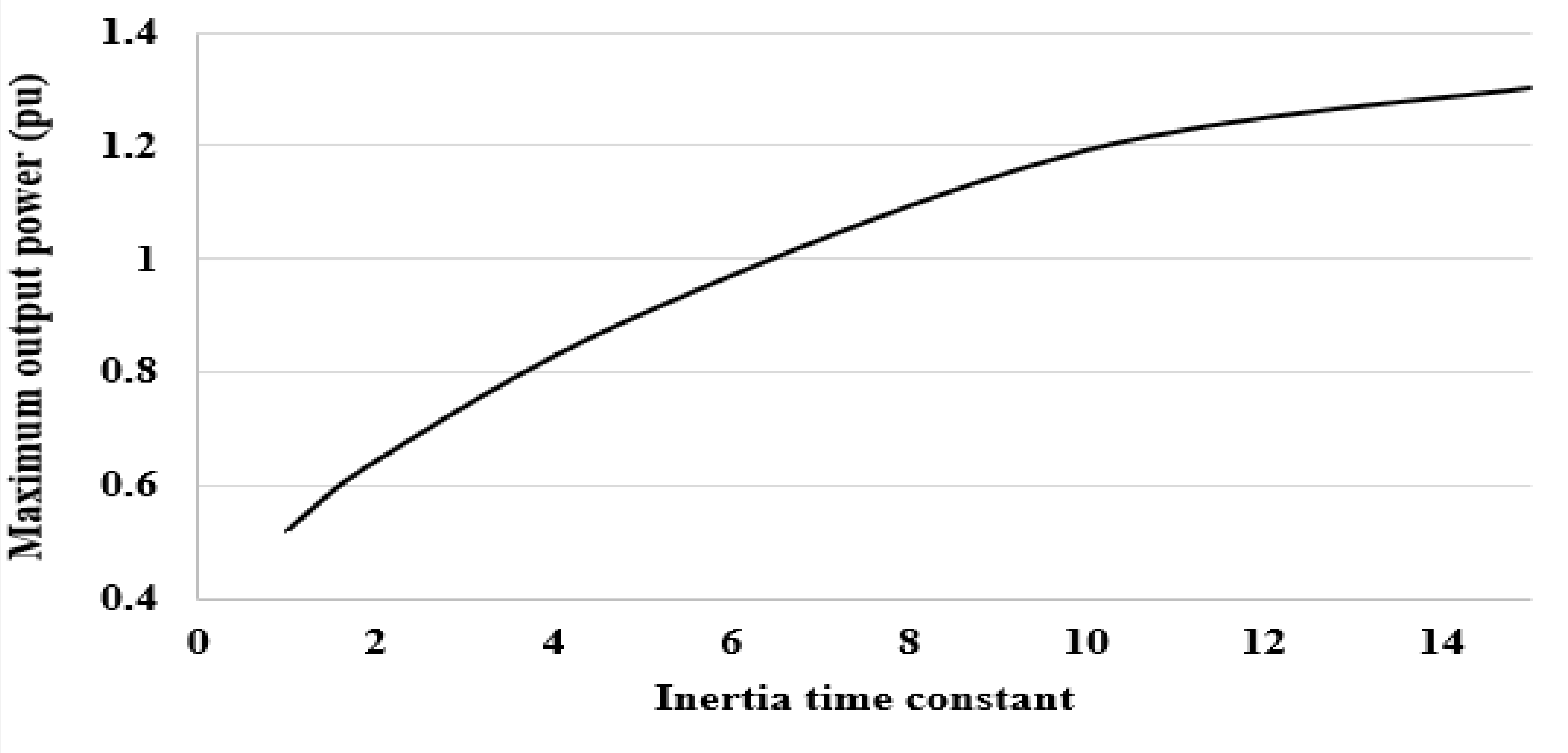

SMES output power at different inertia constants in response to a microgrid frequency drop (Kd=0.16)

# Simulation results: microgrid frequency drop



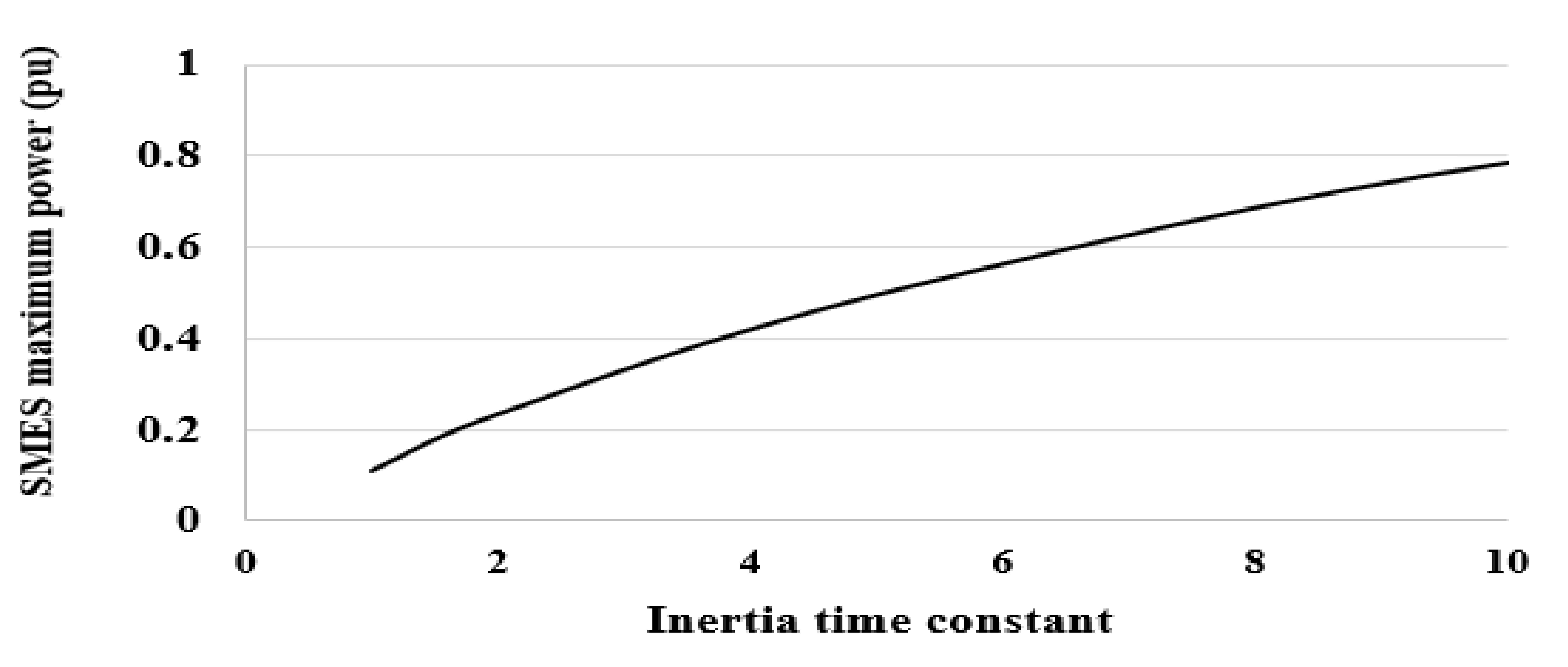

SMES energy at different inertia constants in response to a microgrid frequency drop (Kd=0.16)

# Simulation results: microgrid frequency drop



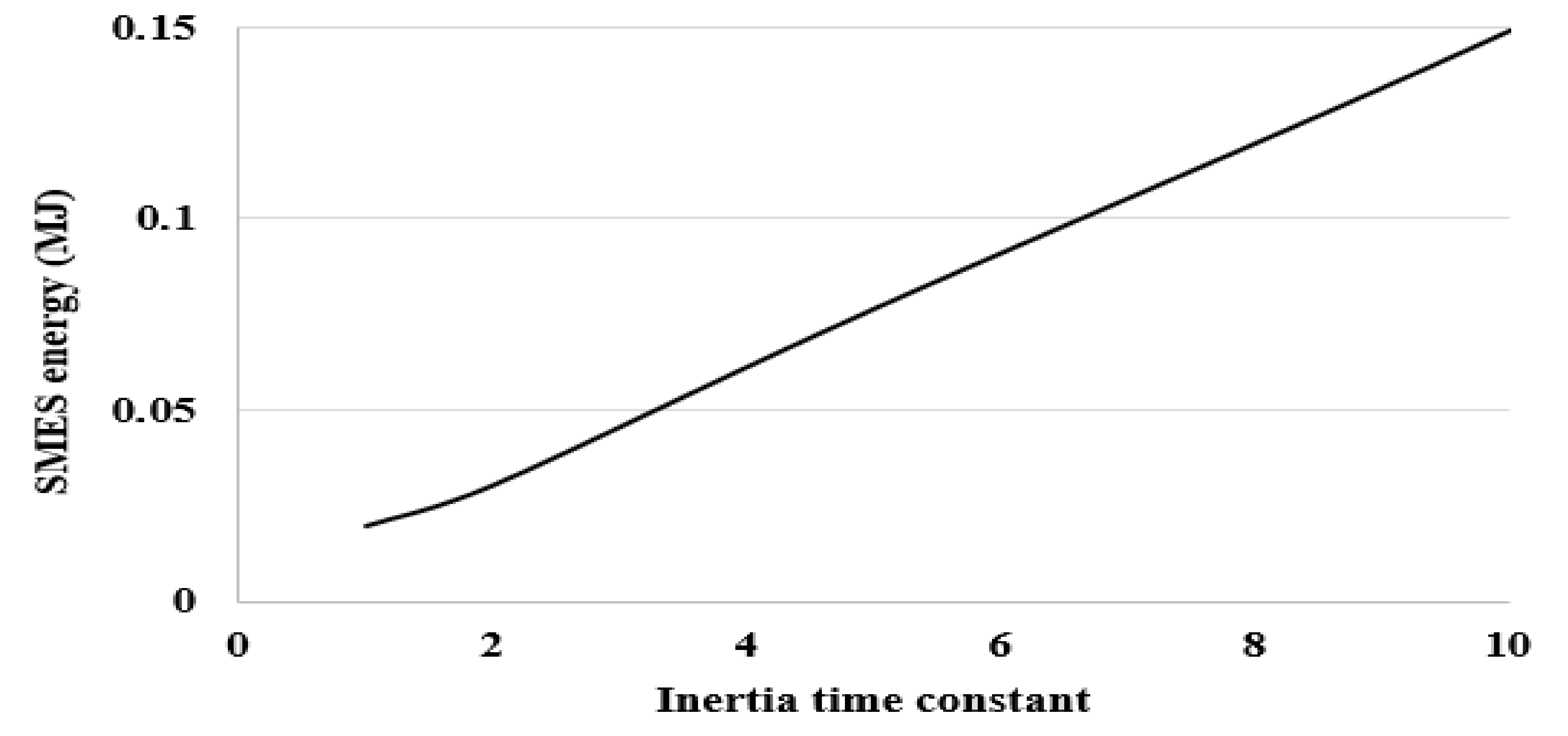

Maximum converter output power versus inertia constants in response to a microgrid frequency drop

# Simulation results: microgrid frequency drop




SMES maximum power versus inertia constants in response to a microgrid frequency drop

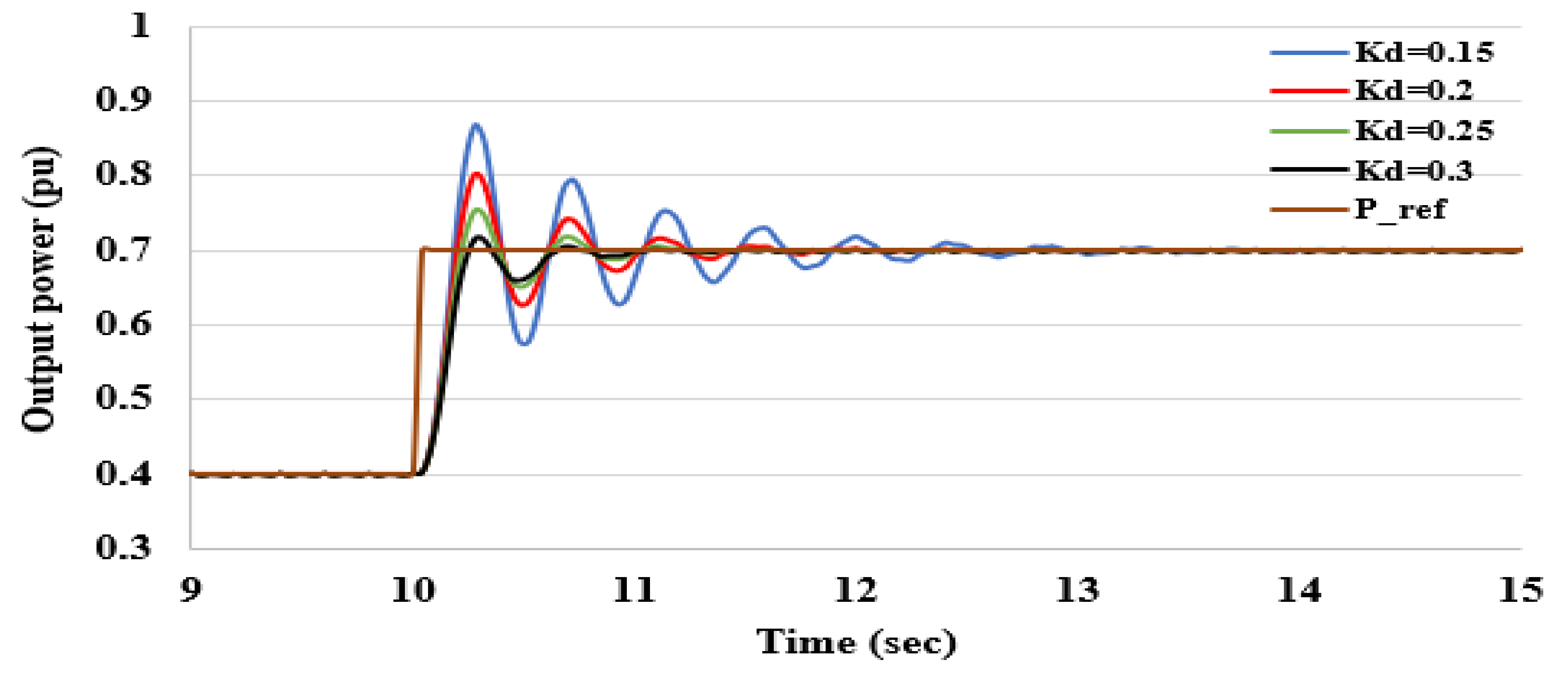
# Simulation results: microgrid frequency drop




SMES energy versus inertia constants in response to a microgrid frequency drop

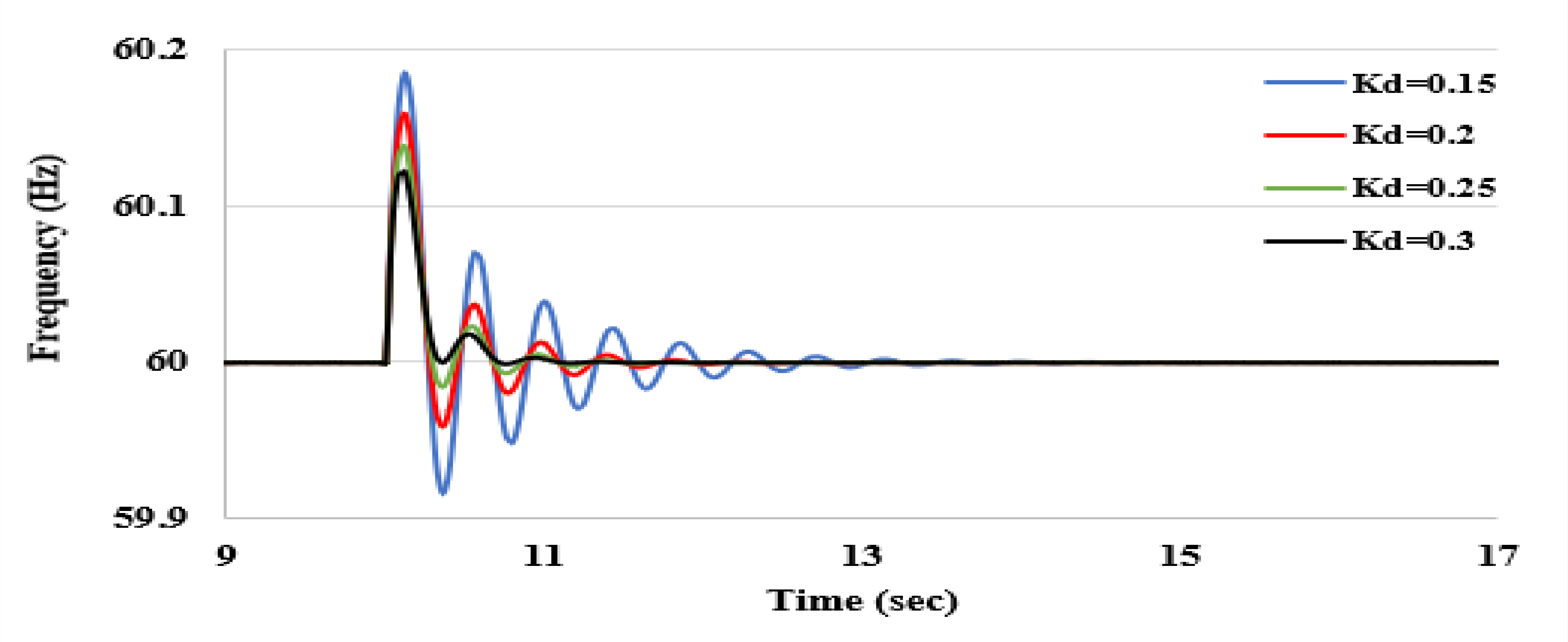
# Simulation results:

**step power setpoint increase** at different damping constants



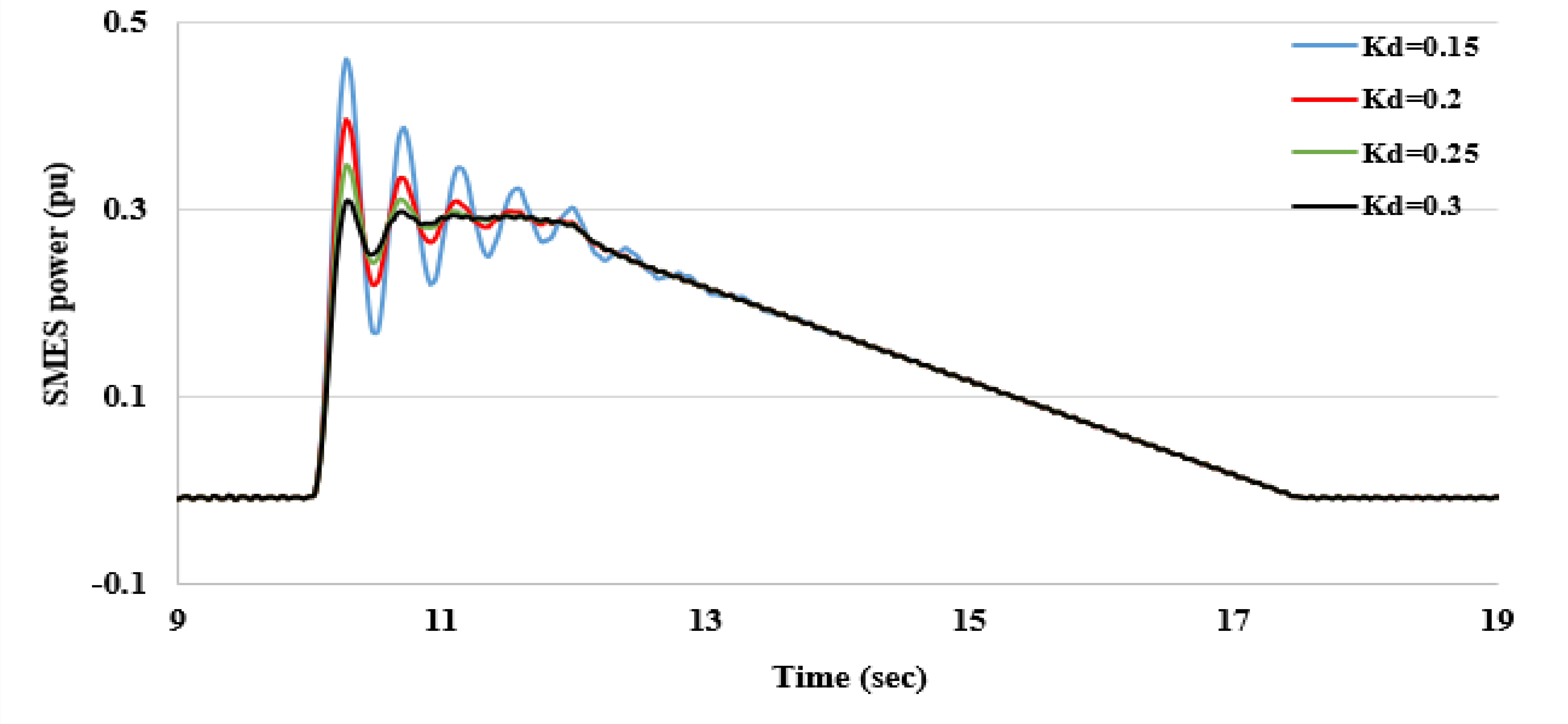

Converter power at different damping constants in response to step power setpoint increase (Ta=6)

# Simulation results: step power setpoint increase



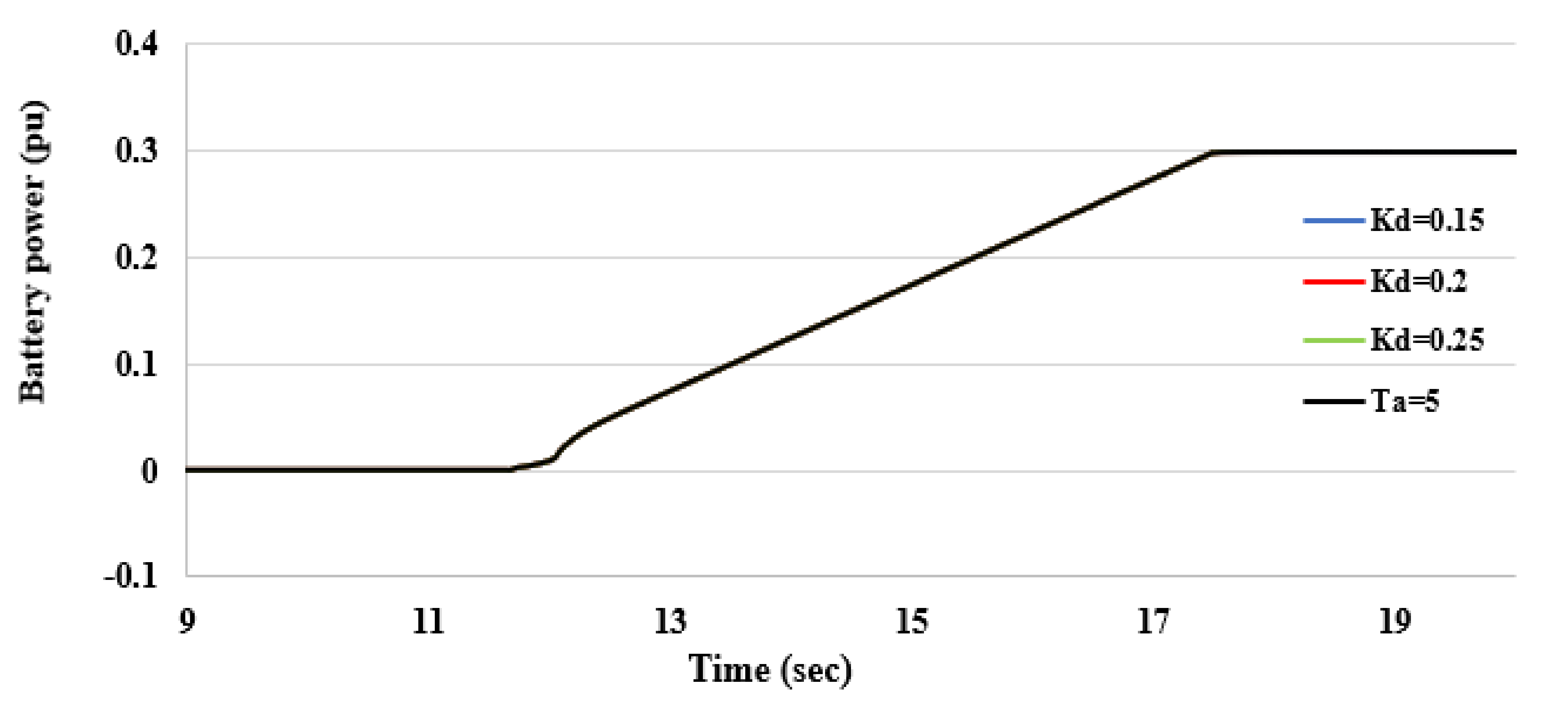

Frequency change at different damping constants in response to step power setpoint increase (Ta=6)

# Simulation results: step power setpoint increase



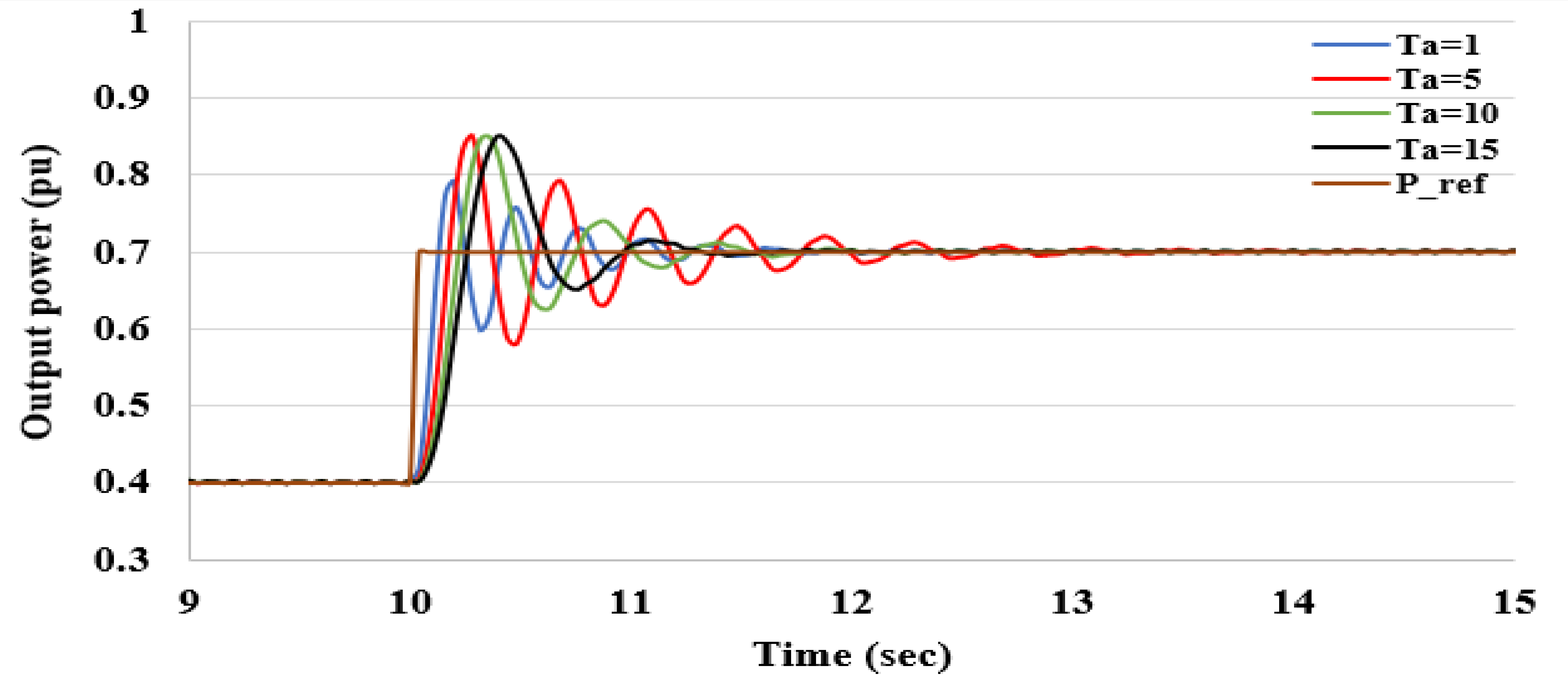

SMES power at different damping constant in response to step power setpoint increase (Ta=6)

# Simulation results: step power setpoint increase



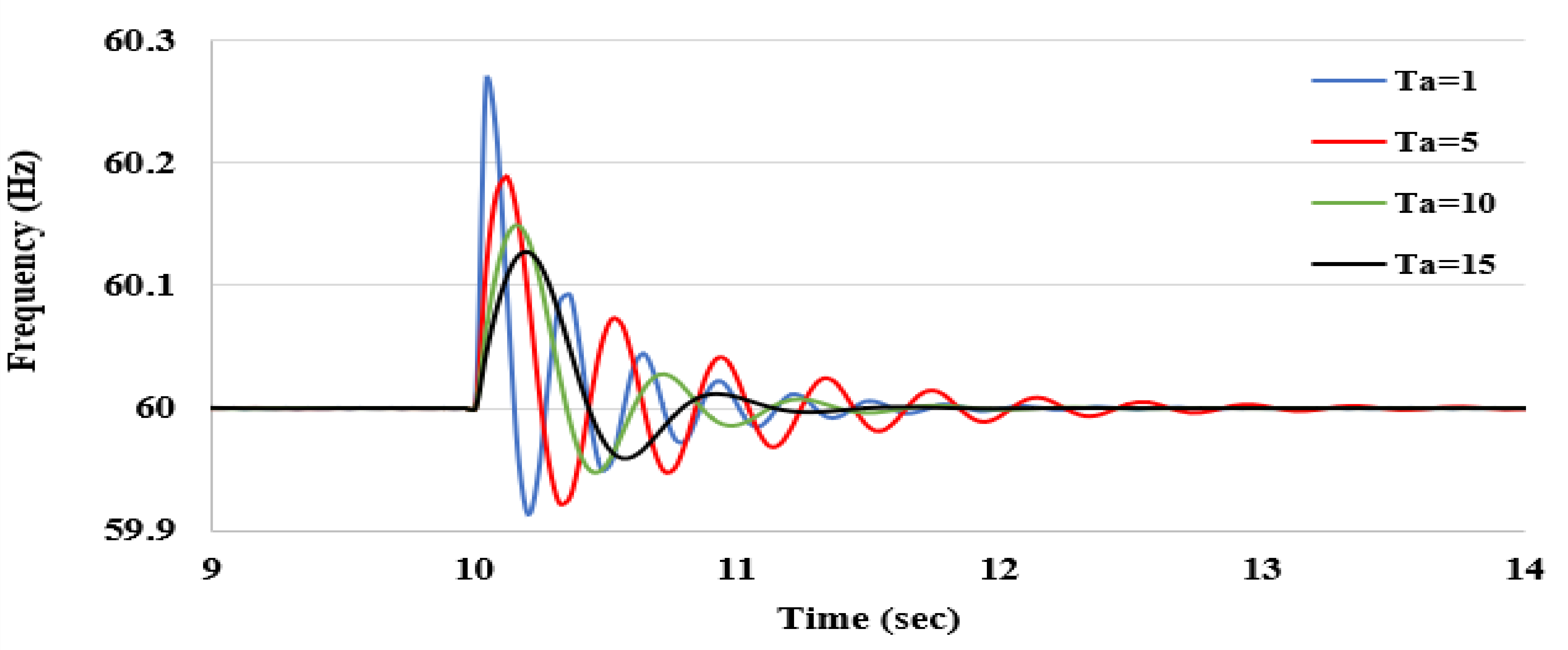

Battery power profile

# Simulation results: step power setpoint increase at different inertia time constants



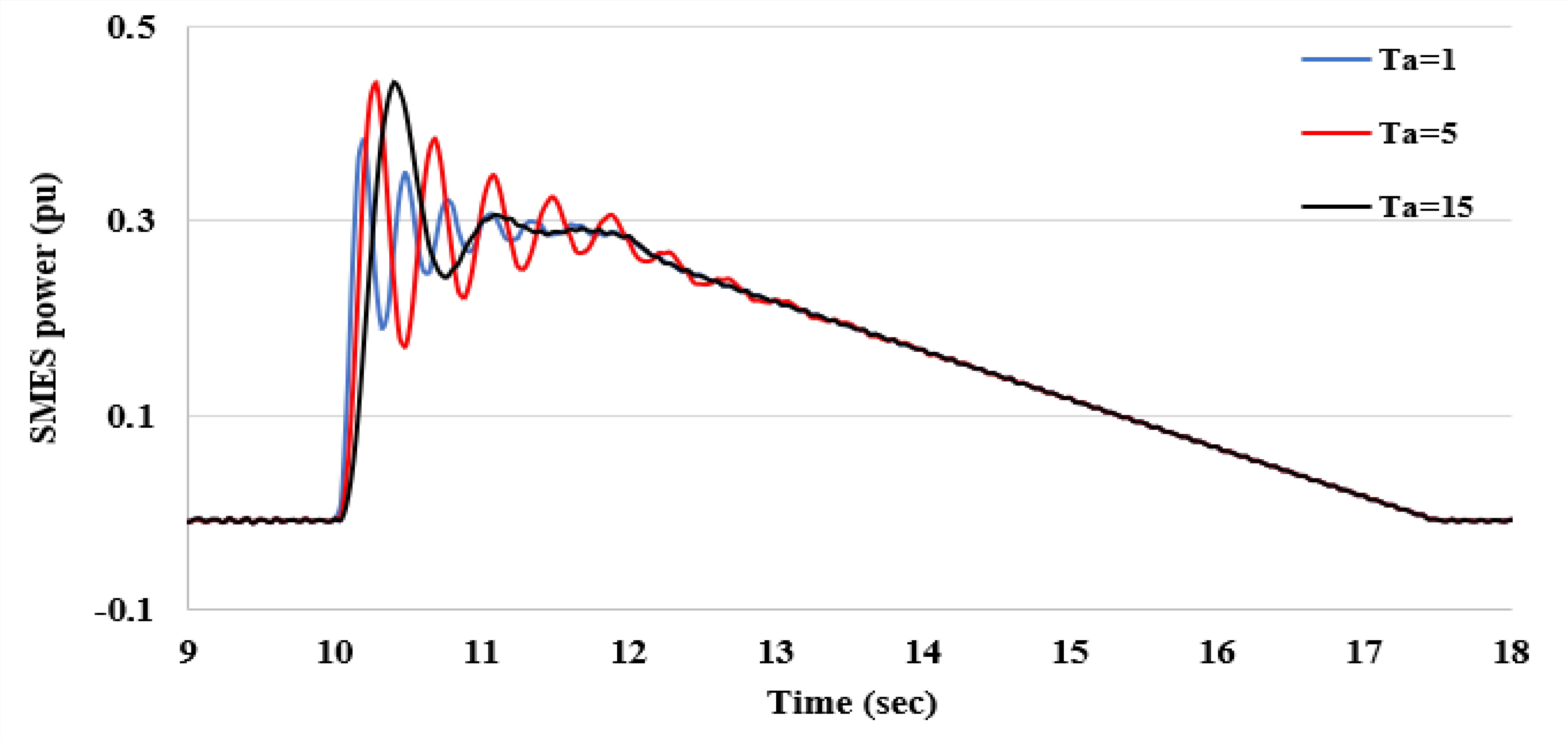

Converter power at different inertia constants in response to step power setpoint increase (Kd=0.16)

# Simulation results: step power setpoint increase



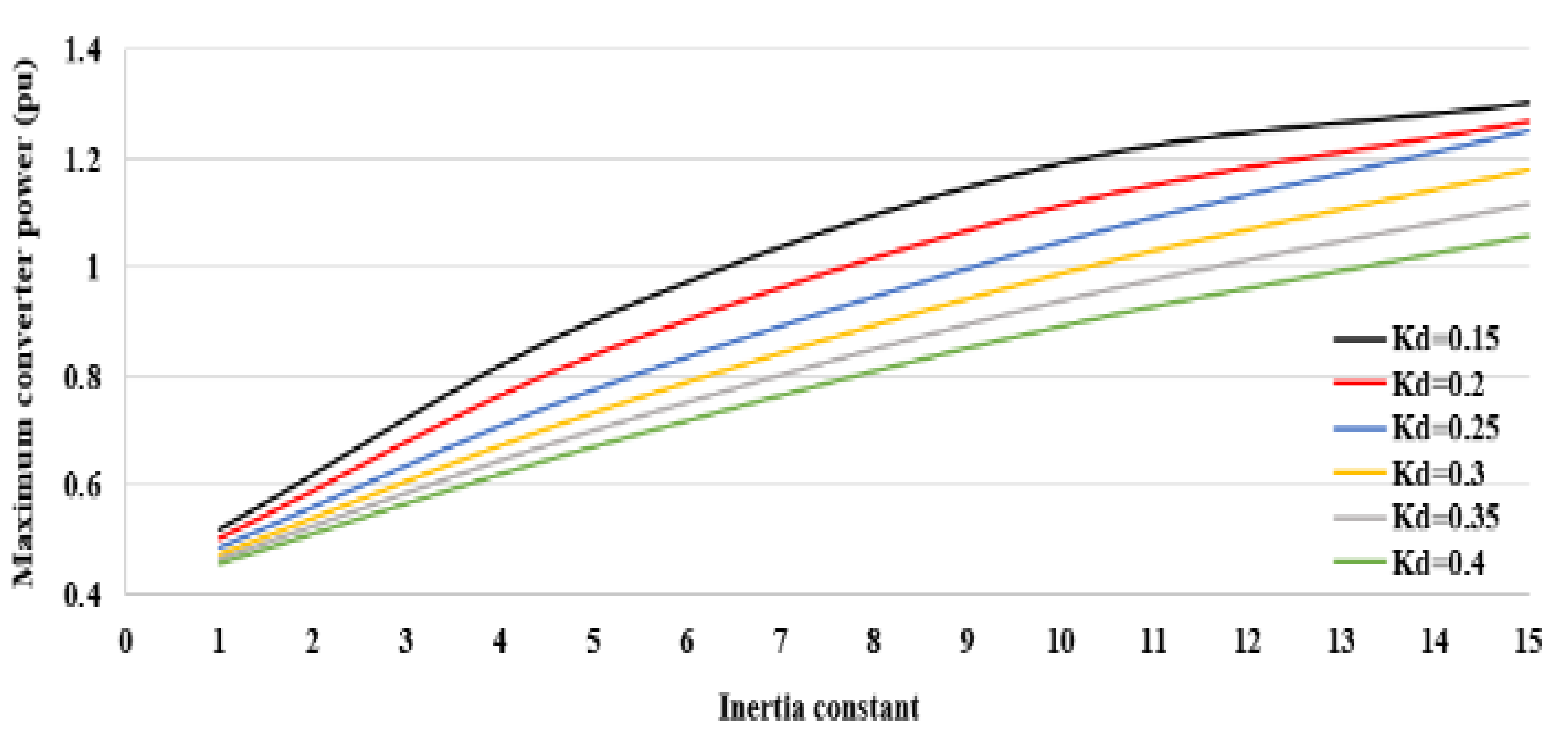

Frequency change at different inertia constants in response to step power setpoint increase (Kd=0.16)

# Simulation results: step power setpoint increase



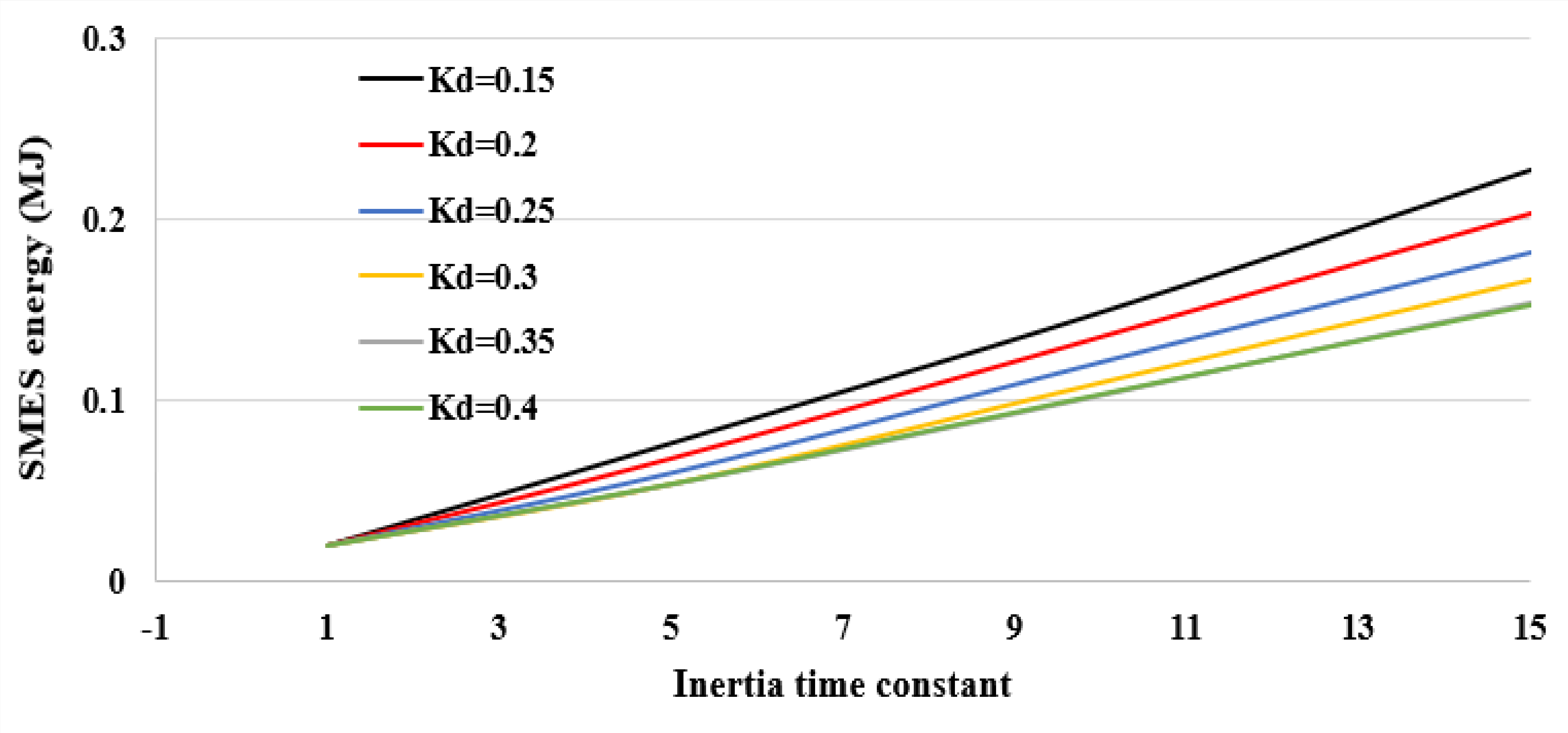

SMES power at different inertia constants in response to step power setpoint increase (Kd=0.16)

# Simulation results:



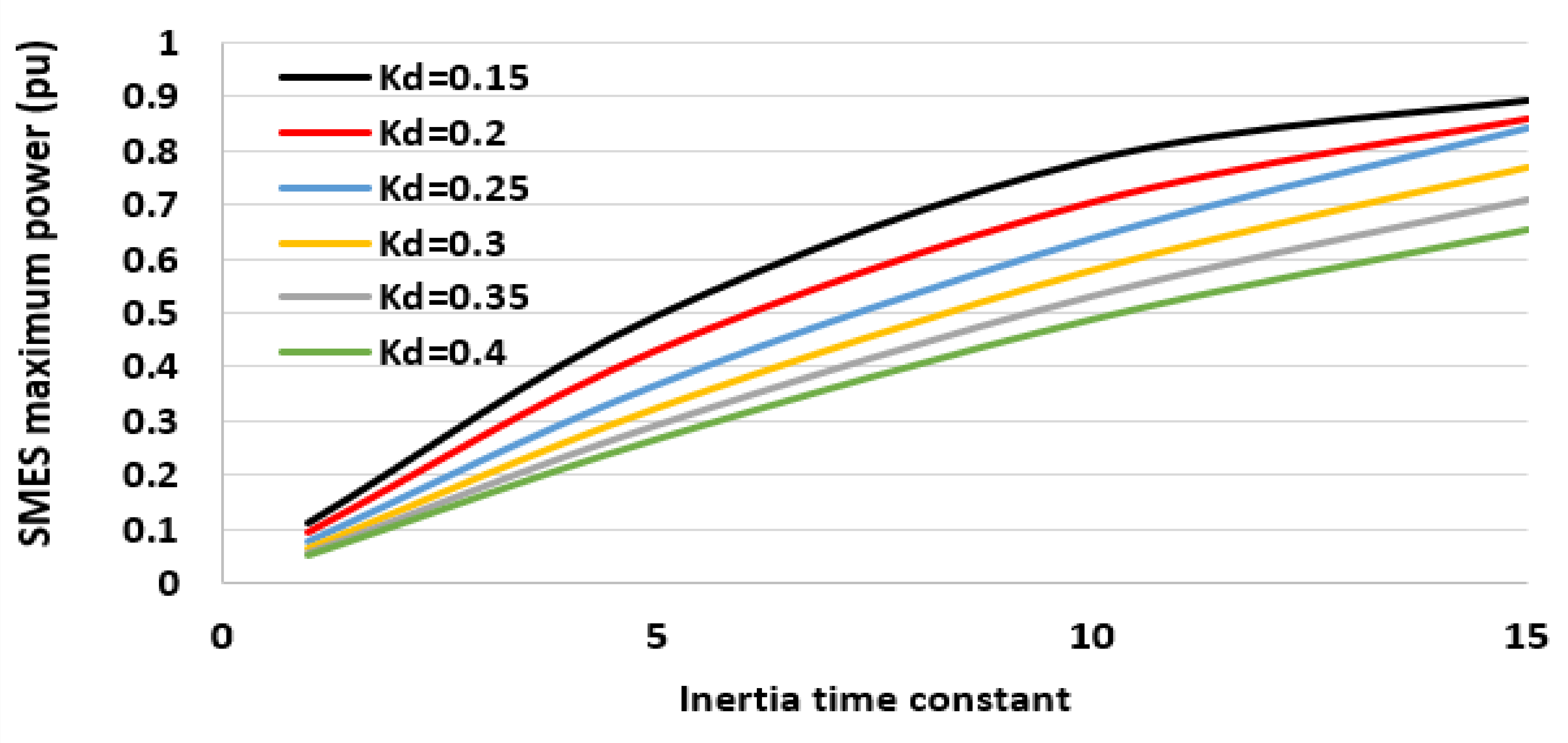

Converter output power at different inertia and damping constants

# Simulation results:




SMES energy at different inertia and damping constants

# Simulation results:




SMES maximum power at different inertia and damping constants

# Conclusion

- Frequency fluctuation depend on the rotor inertia and damping coefficients of CSGs.
- VSG-based controlled inverter combined with ESS can emulate the behavior of CSG
- VSG supports the system frequency and improve system performance ( RoCoF - frequency nadir).
- The impact of different values of constants affect the ratings of the converter and the ESS.
- The converter and the ESS power and energy increases when the inertia time constant increases
- The converter and the ESS power and energy increases when the damping constant decreases
- Supplementing the battery with the SMES
  - Reduces the number of charging and discharging cycles of the battery.
  - Reduces the stress on the battery system
  - Increases its lifetime
- VSG controllers can promote exploiting and expanding RERs in microgrids.

# THANK YOU FOR ATTENTION

# QUESTIONS

For any questions, please contact me at:

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College of Engineering

# MODERN CONTROL OF SMART POWER GRIDS

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# CONTENTS

# Personal information

| Ph.D. Degree | |
|---|---|
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| **Advisor** | Prof. Brian K. Johnson |

| Master degree | |
|---|---|
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| **Department** | Electrical Power and Energy Department |
| **Specialization** | Electrical Engineering |
| **Year** | 2015 |

| Bachelor’s Degree | |
|---|---|
| **College** | Military Technical College |
| **Department** | Electrical Power and Energy Department |
| **Year** | 2007 |

# Introduction

## Problem Definition

- Increasing number of converter-based RERs.
- The total system inertia is reduced.
- The system is vulnerable to frequency and voltage stability problems in case of disturbances.

# Introduction

## Objective

- Increasing the system inertia.
- Controlling the active and reactive power and the terminal voltage.

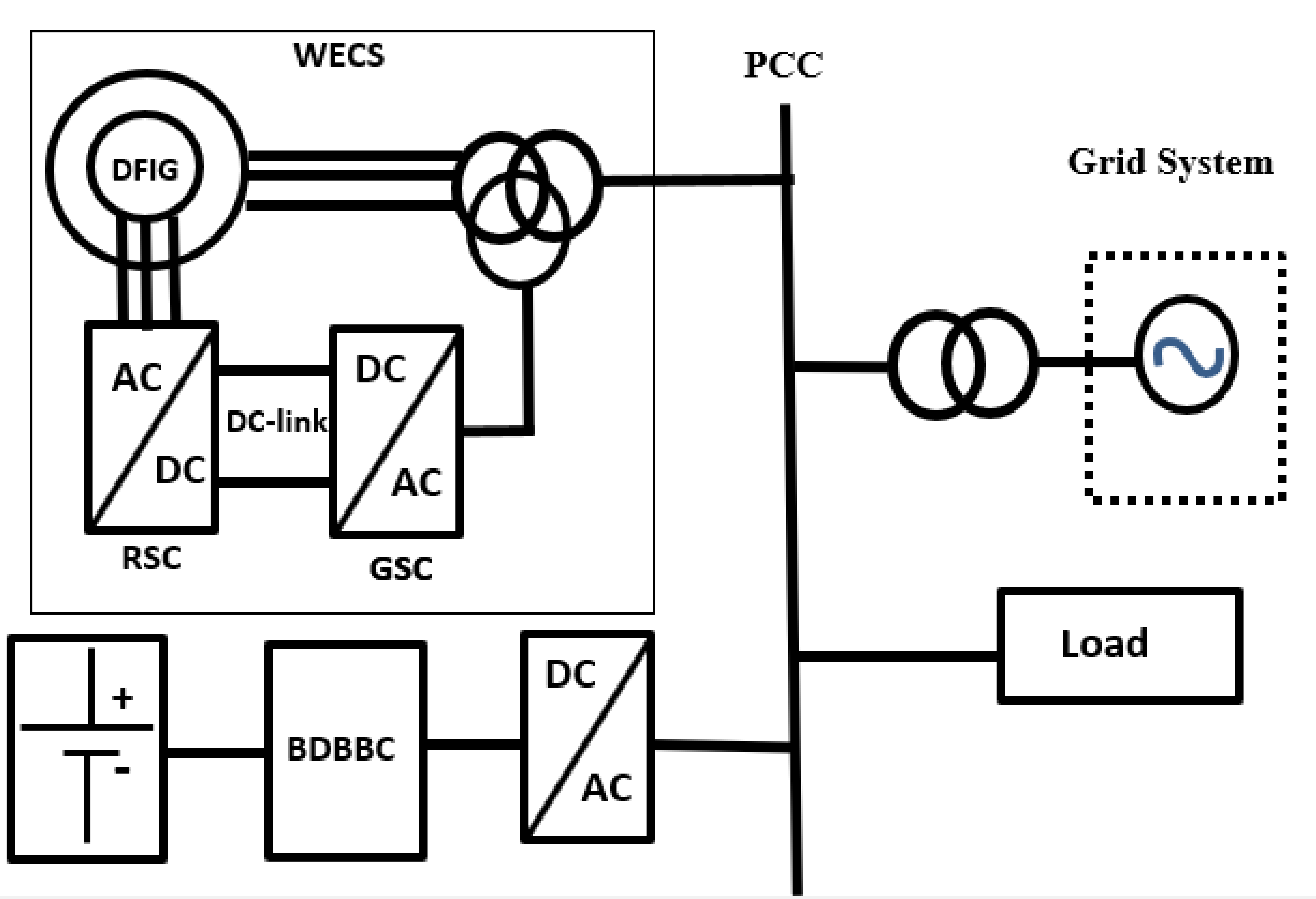
**Goals:**

- Creating virtual inertia, emulating and enhancing features of the conventional SG (Inertia and damping).
- Describing the effects of inertia and damping constants on system performance and ratings.
- Developing a hybrid energy storage system that can provide
  - High power and energy capabilities
  - High and low rate of change of power fluctuations responses

# Introduction:

- **Literature survey**
  - RERs (WECS, PV), ESSs, Control requirements, VI techniques.
- **Modelling of the system components using PSCAD/EMTDC.**
- **Controlling the active and reactive power, and terminal voltage of the systems.**
- **Using HESS (Batteries and SMES (Superconducting Magnetic Energy Storage)).**

## Modelling and Control of Type 3 WECS Combined with BESS




Layout of the proposed WECS system

**Published in:**

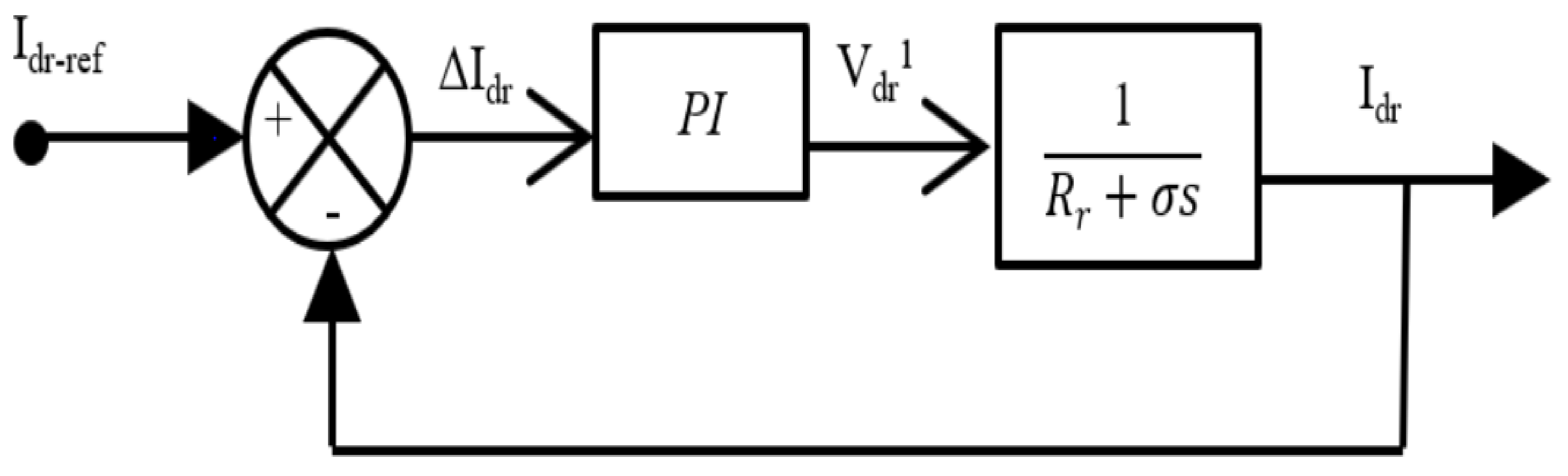
**The 53rd North American Power Symposium 2021/ IEEE**

# Type 3 WECS controller design:
# Rotor side converter controller

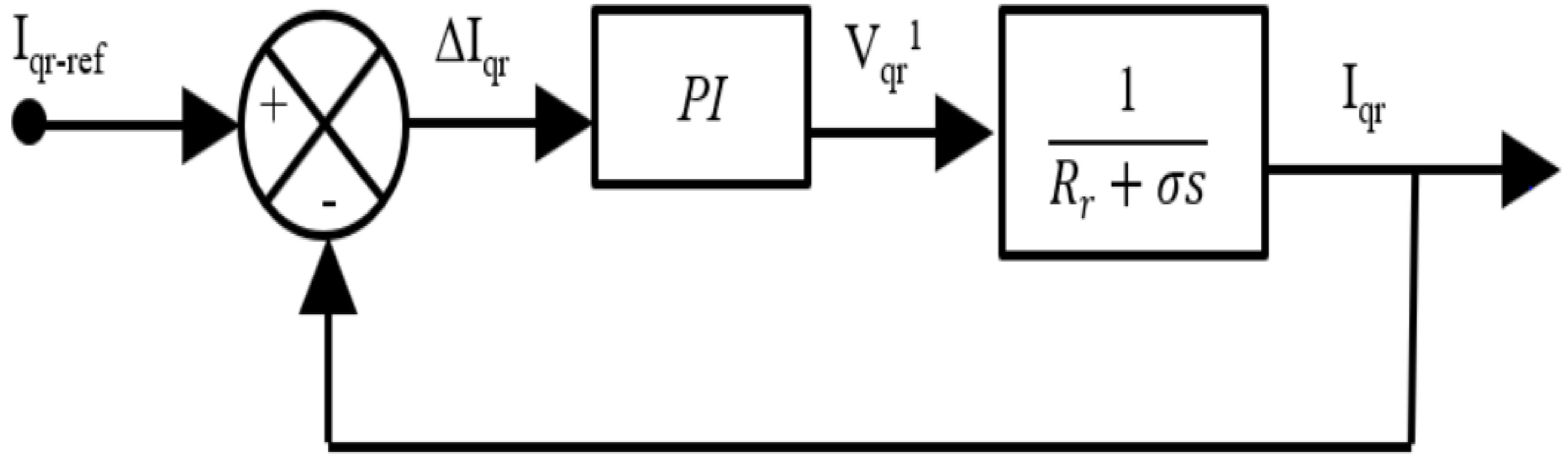
$$P_s = (-3\, L_m/2\, L_s)\,(V_{ds}\, I_{dr})$$
$$Q_s = (-3\, L_m/2\, L_s) V_{ds}(I_m - I_{qr})$$

-Outer Loops

-Inner Loops




RSC, d-axis current controller




RSC, q-axis current controller

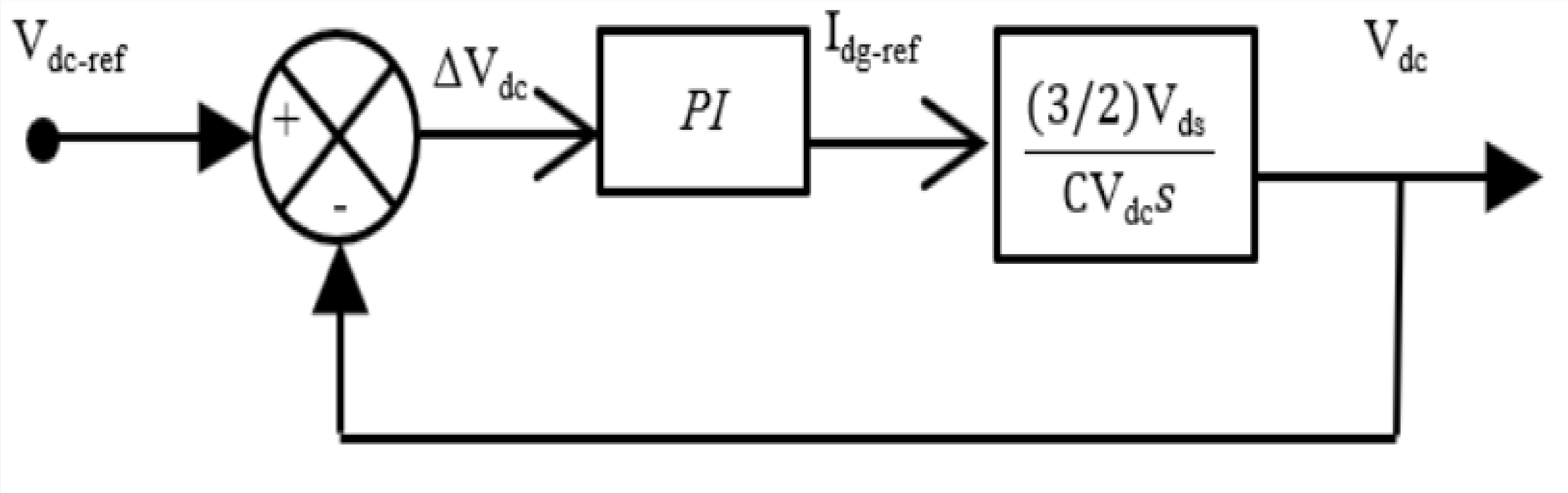
$$V_{dr-ref} = V_{dr}^1 - S\,\omega_s (L_r\, I_{qr} + L_m I_{qs})$$

$$V_{qr-ref} = V_{qr}^1 + S\,\omega_s (L_r\, I_{dr} + L_m I_{ds})$$

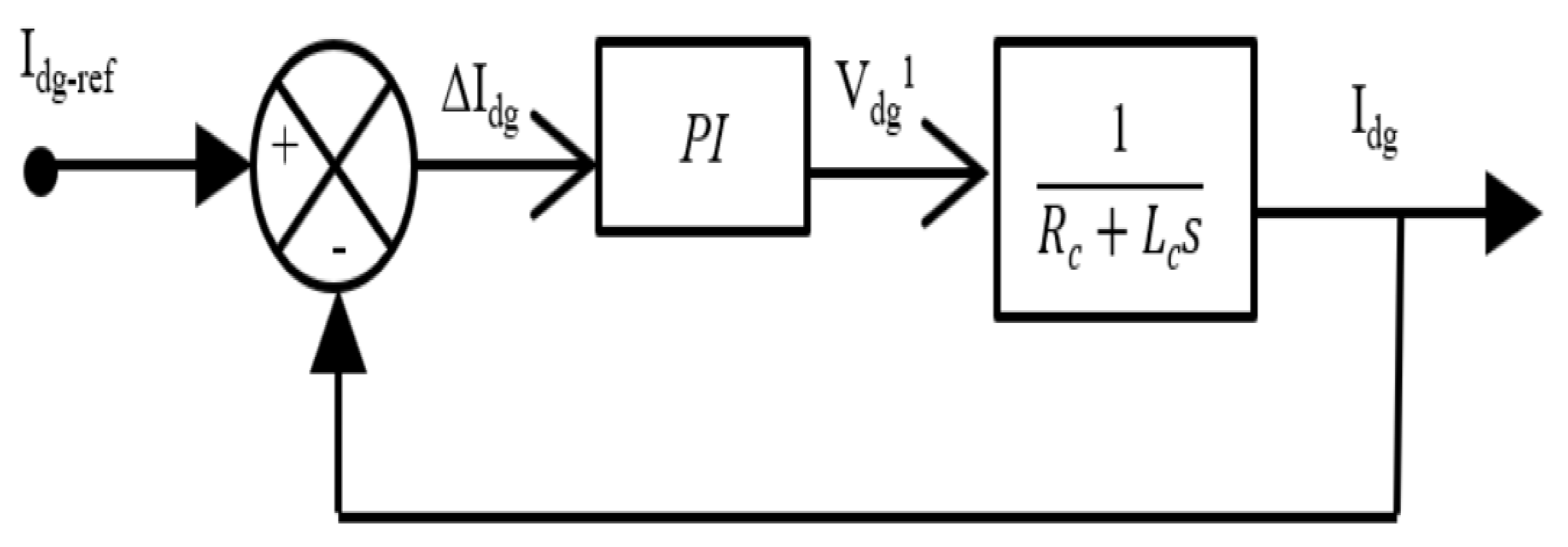
# Type 3 WECS controller design:
# Grid side converter controller

-Outer Loops

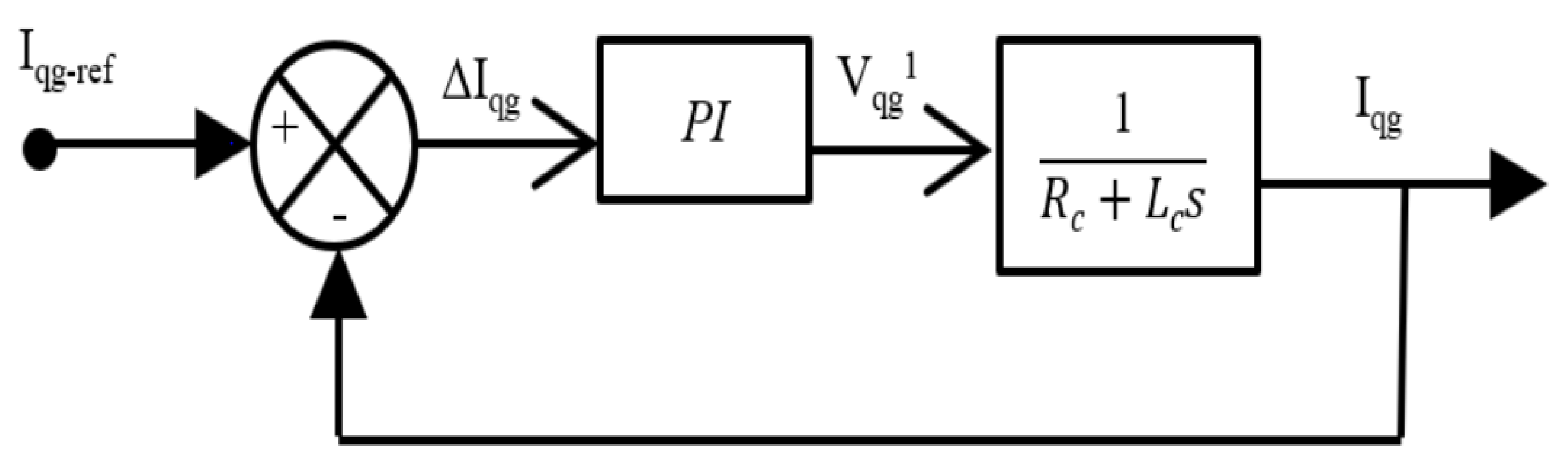
-Inner Loops




GSC, dc voltage control block diagram




GSC, d-axis current controller




GSC, q-axis current controller

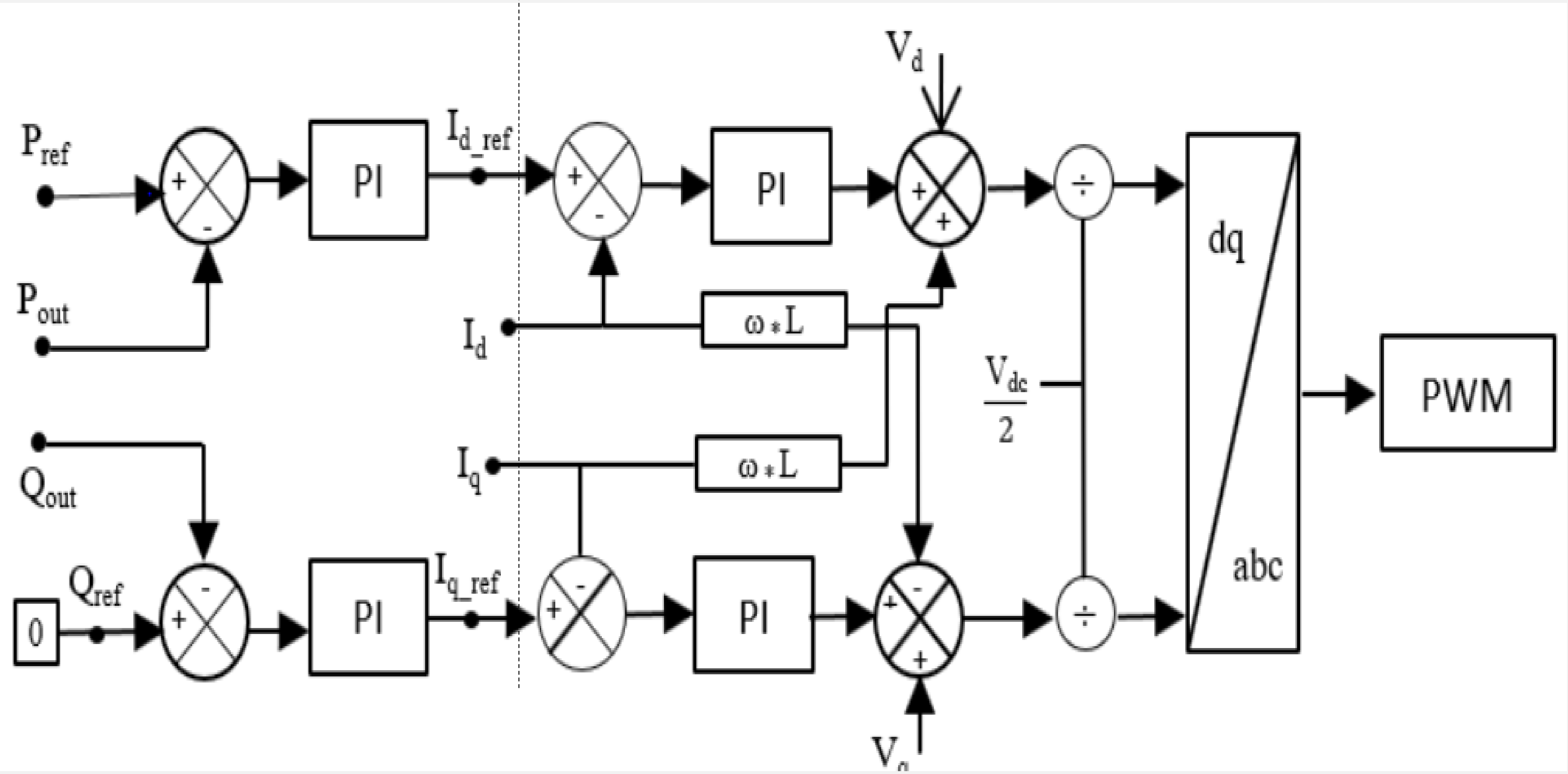
$$V_{dg} = V_{ds} - V_{dg}^{1} + \omega_s L_c I_{qg}$$

$$V_{qg} = V_{qs} - V_{qg}^{1} - \omega_s L_c I_{dg}$$

# DC-AC converter controller

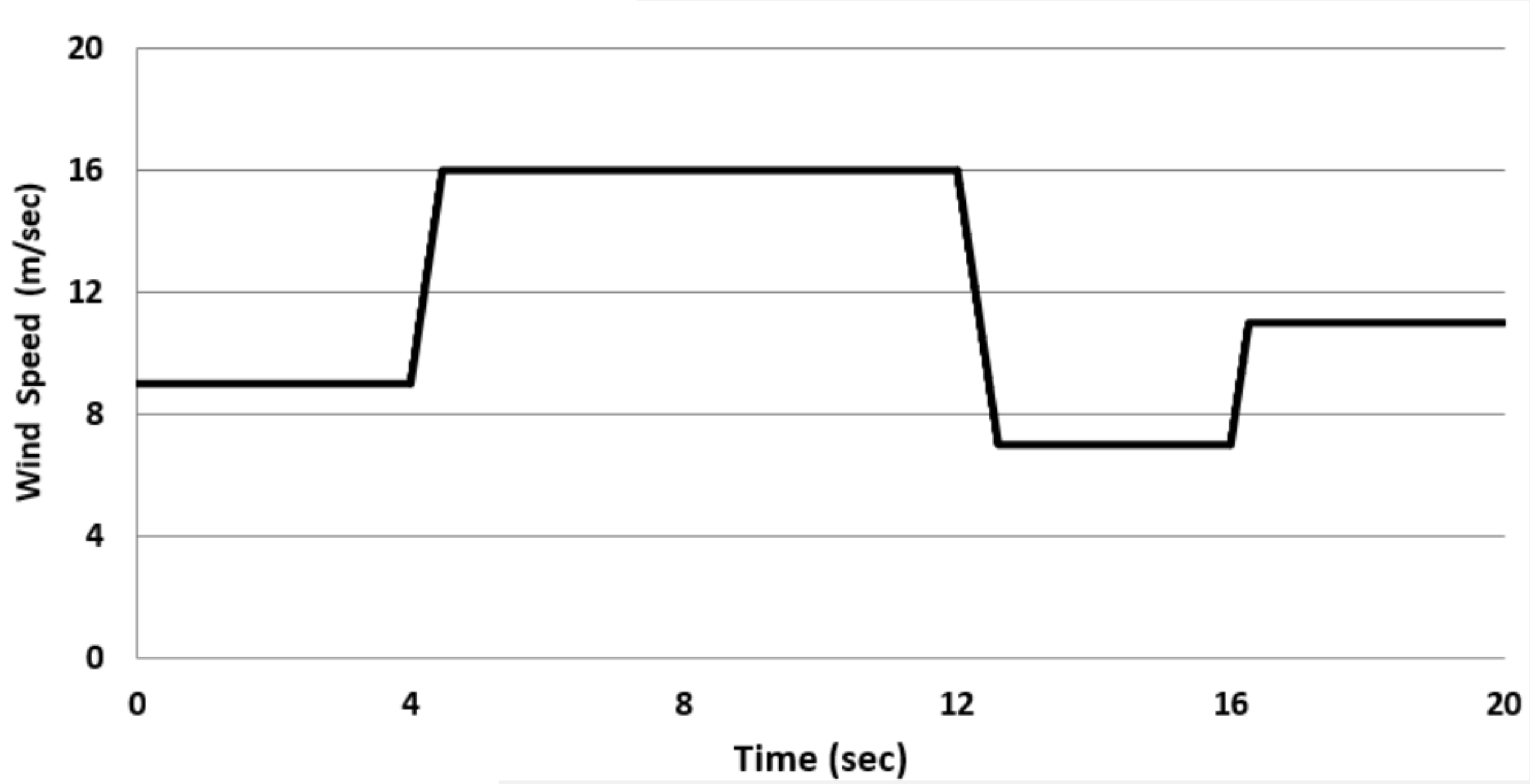
-Outer loops

-Inner loops

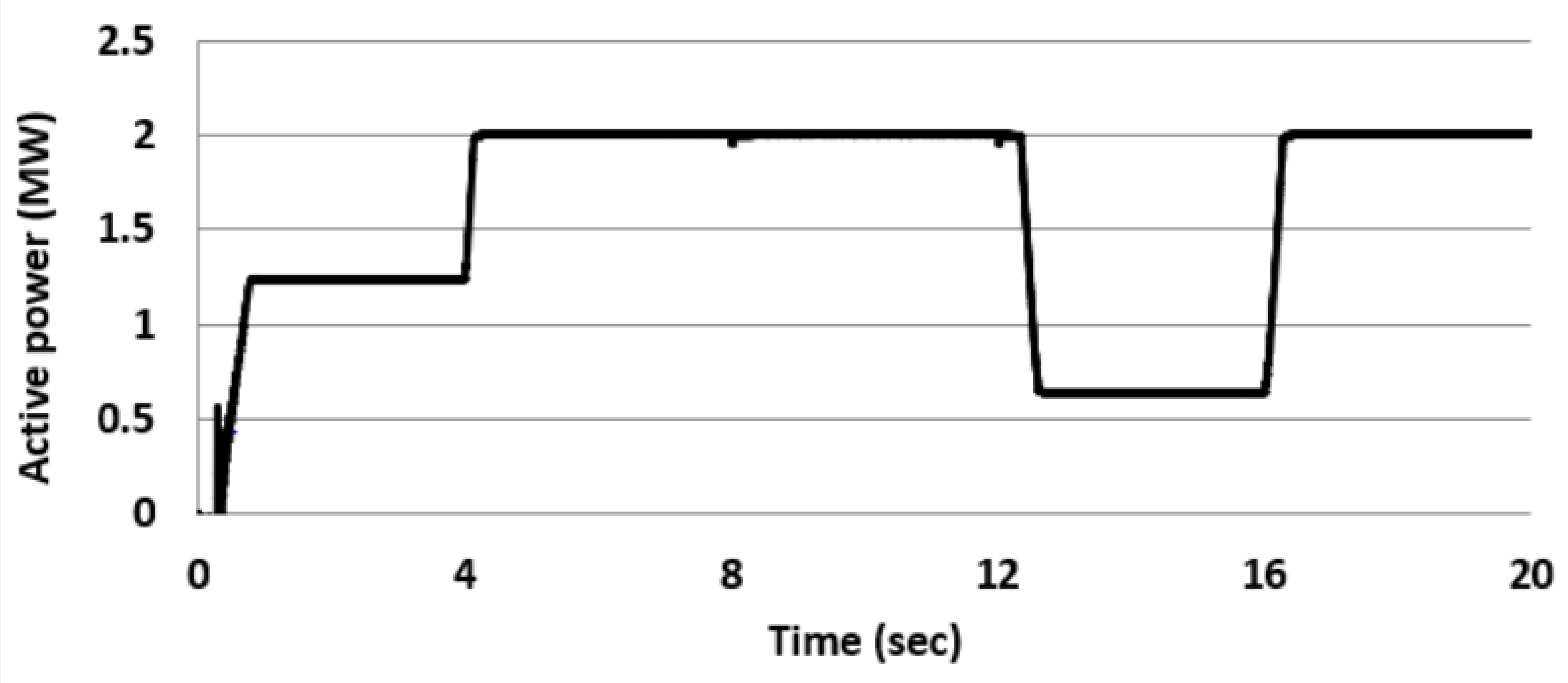



Battery dc-ac converter controller

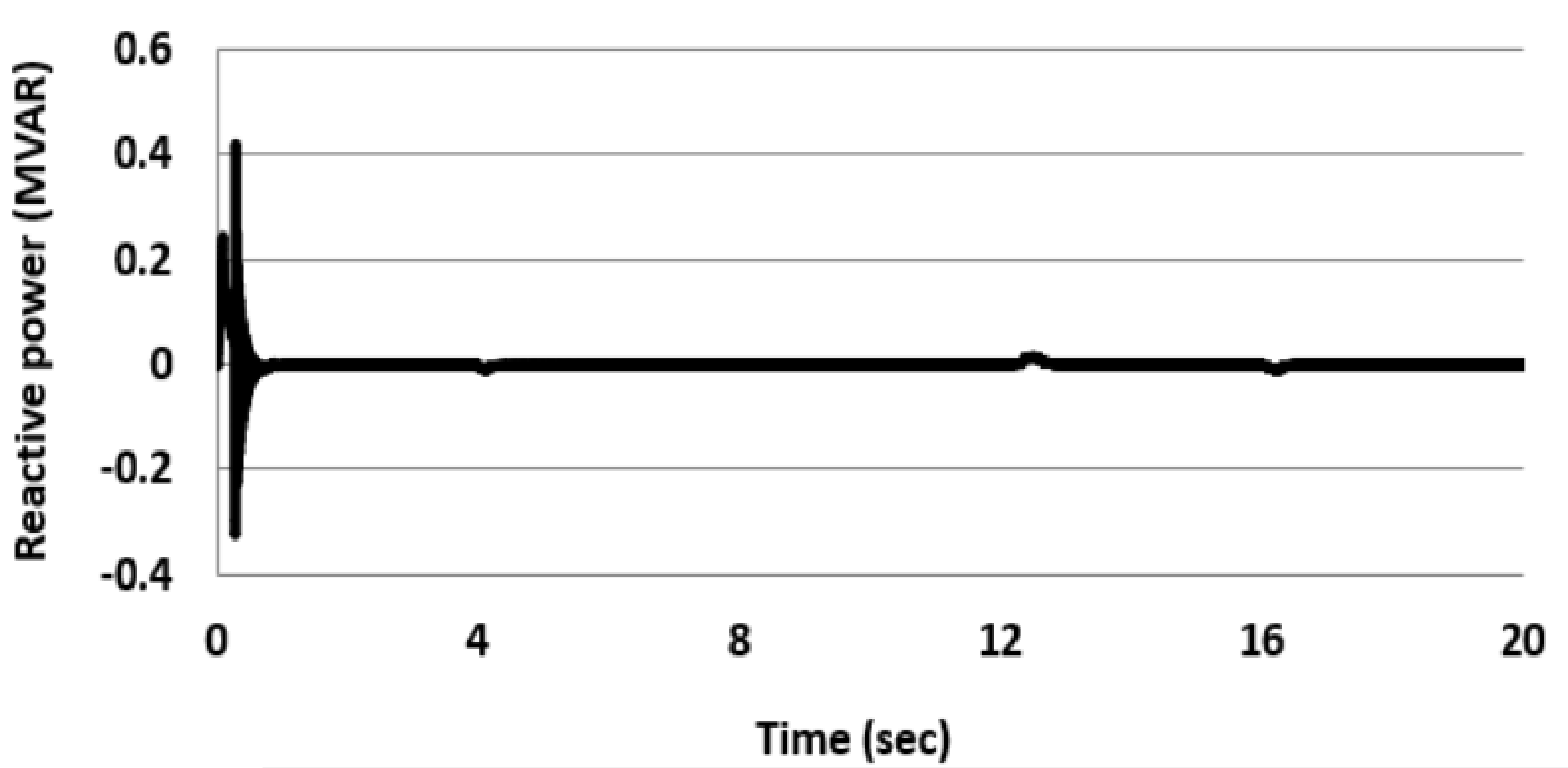
# Simulation of WECS: active and reactive power profile



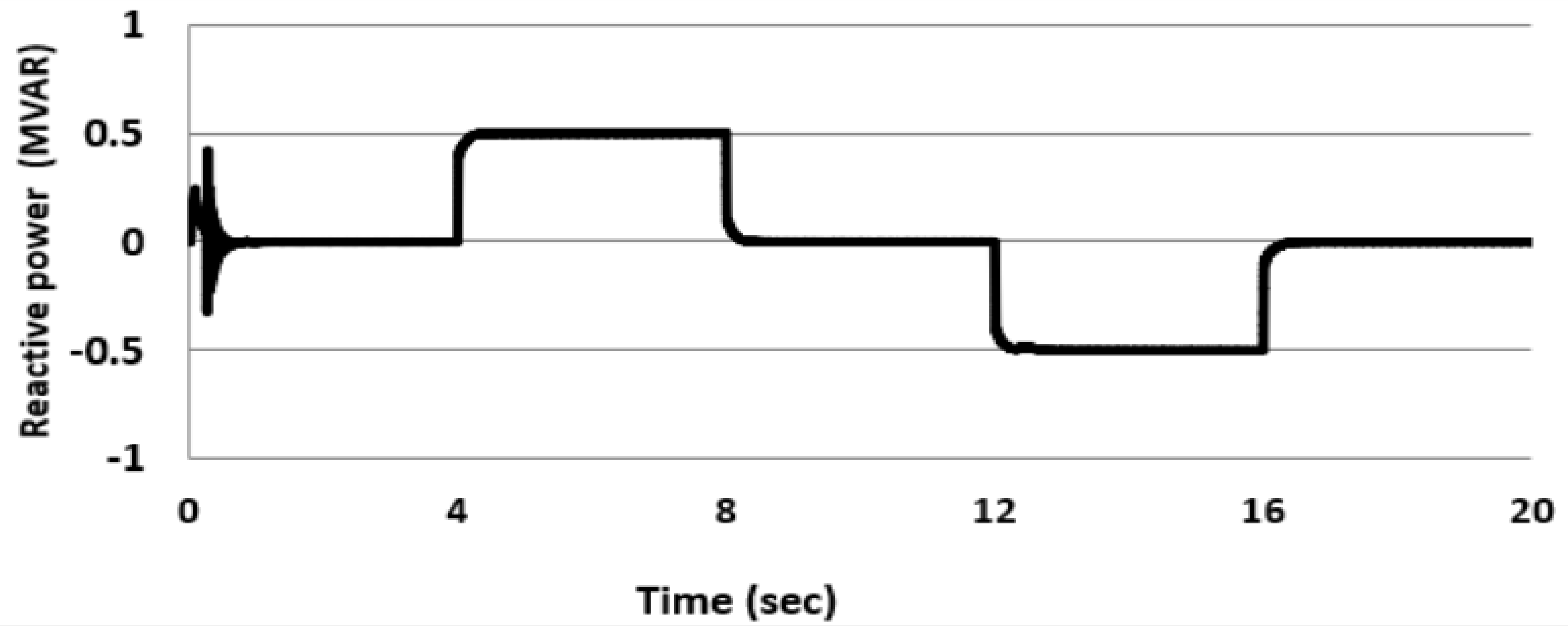

Wind speed variation profile




Generated active power in response to wind speed variation

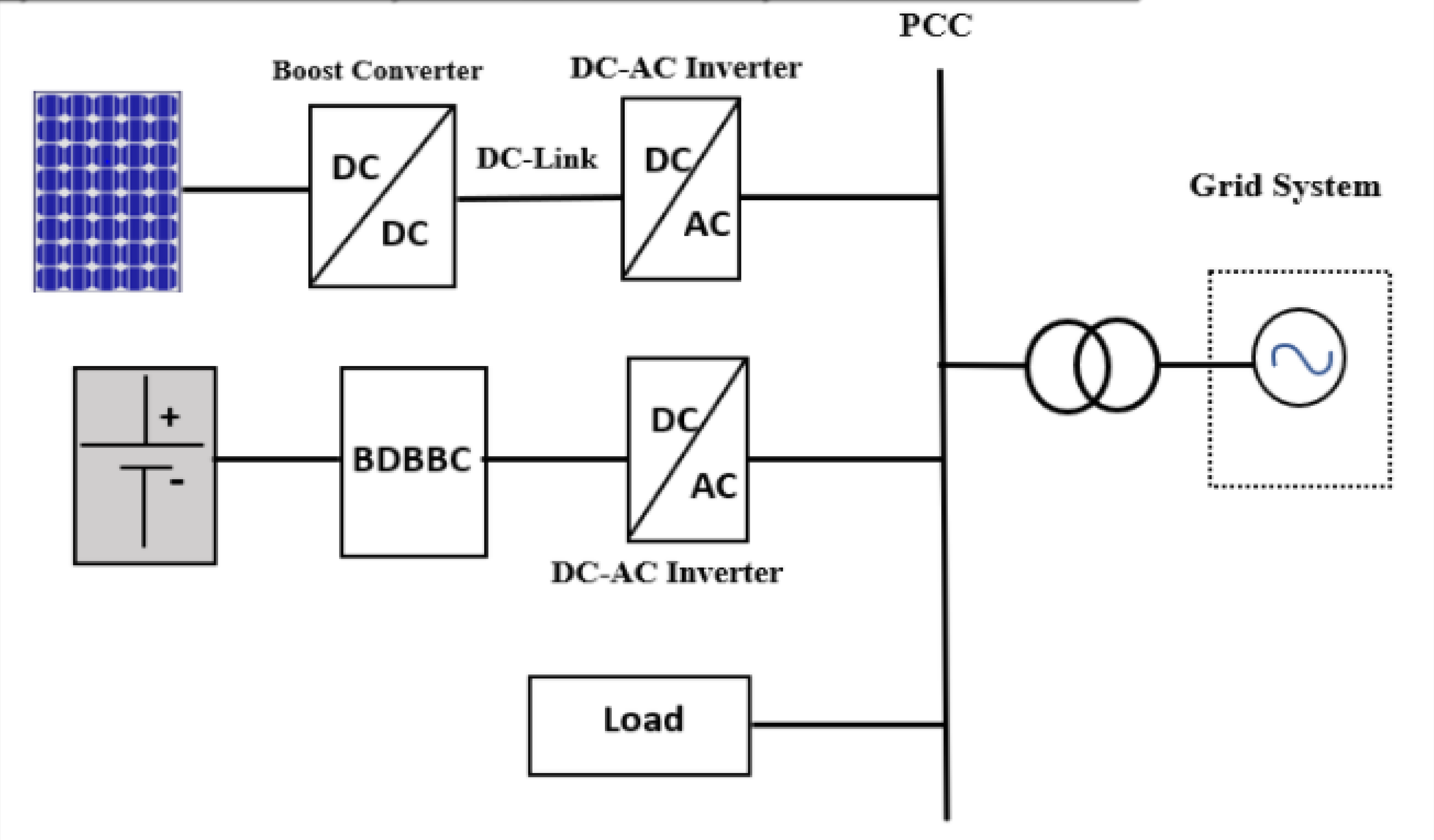



Generated reactive power profile




Reactive power variation profile

## Modeling and control of solar PV System combined with BESS




Layout of the proposed system

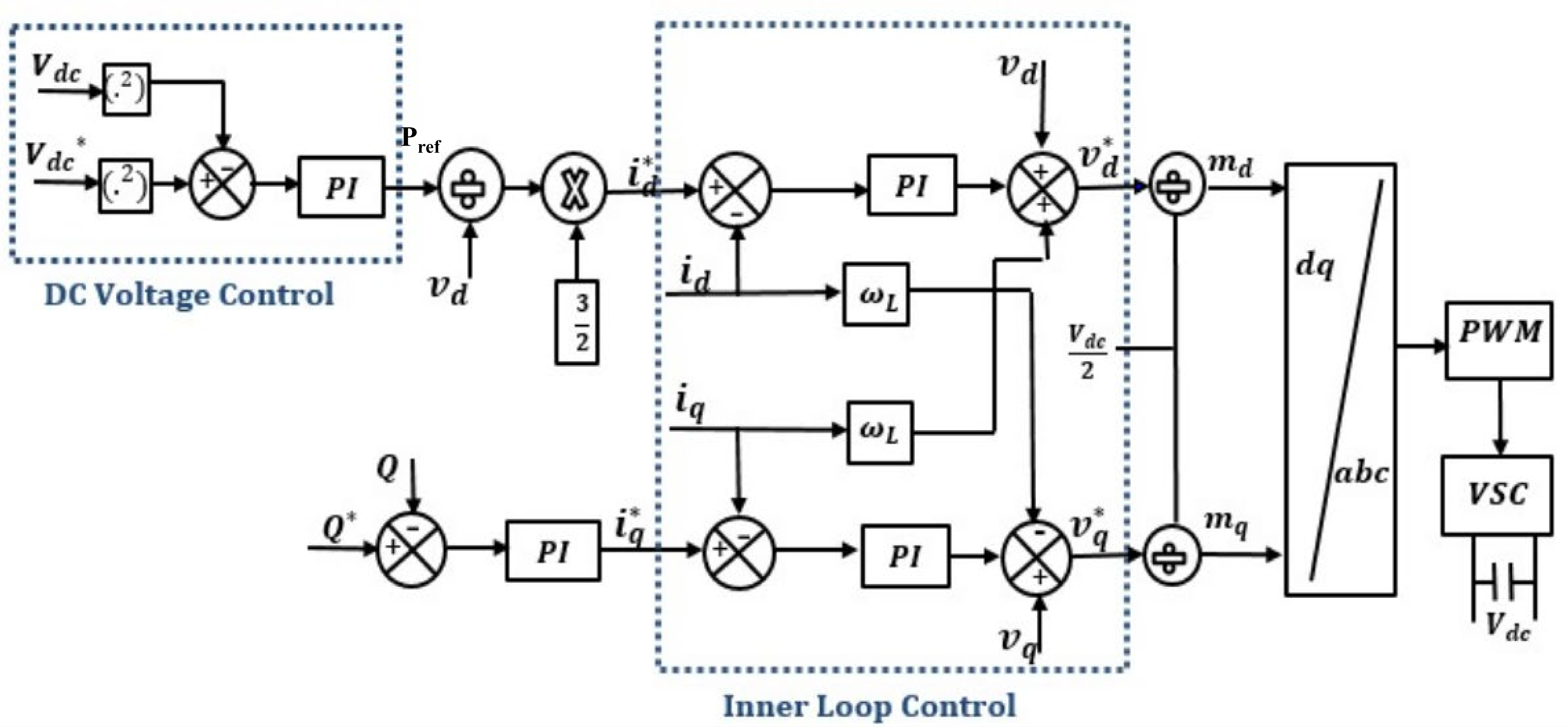
**Published in:**

**The annual IEEE Canadian Electrical Power and Energy Conference (EPEC 2021)**

# DC-AC converter controller

-Outer loops

-Inner loops

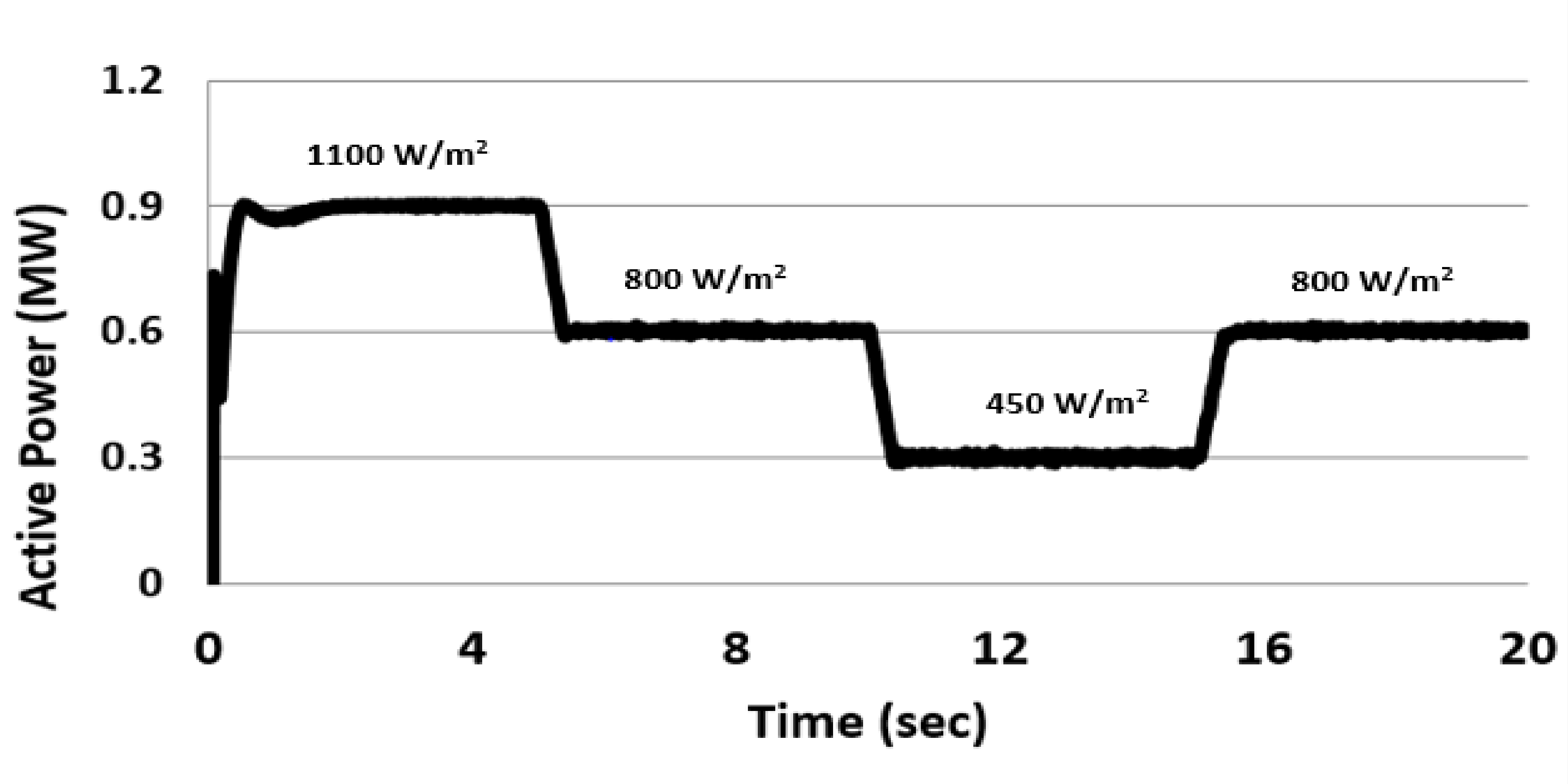



Dc-Ac converter control circuit

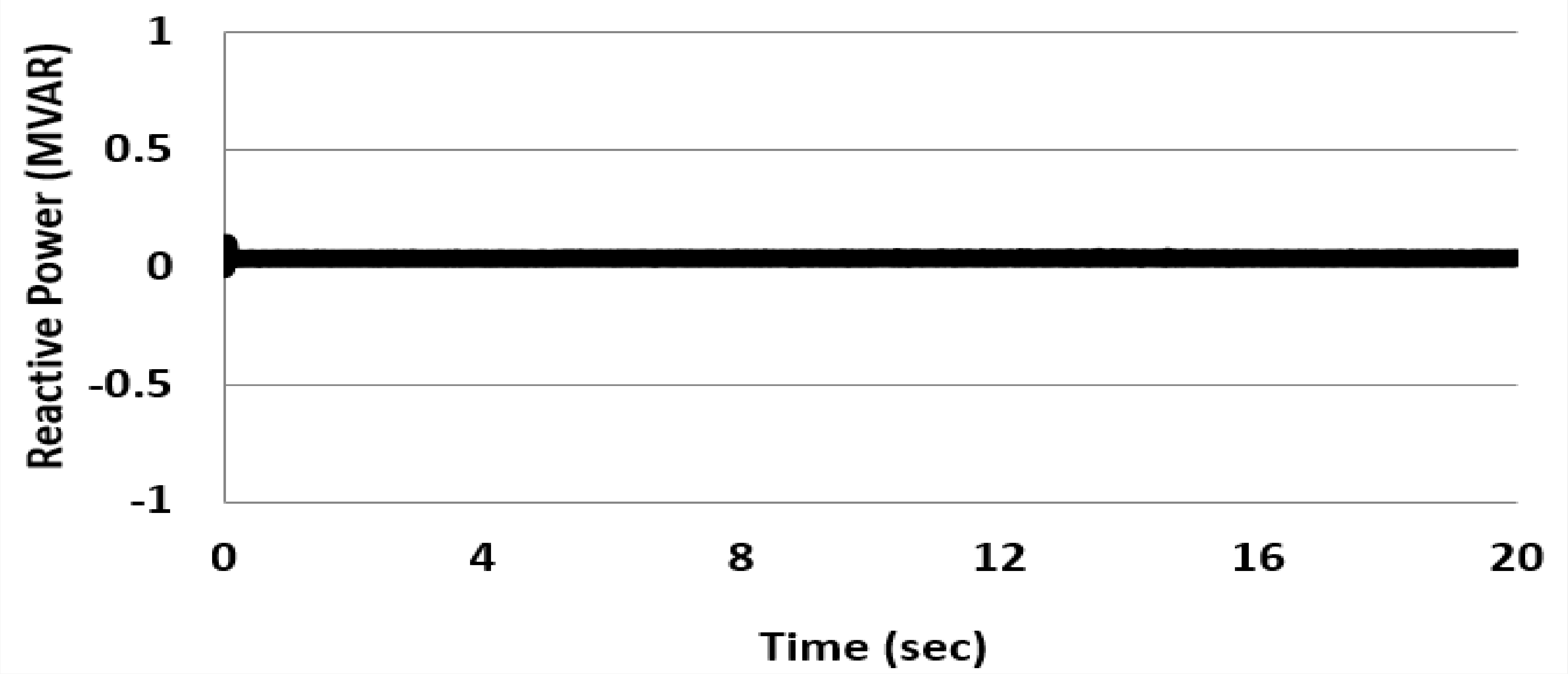
$$v_d^* = v_d + \omega.Li_q + (K_p + \frac{K_i}{S}(i_d^* - i_d))$$

$$v_q^* = v_q + \omega.Li_q + (K_p + \frac{K_i}{S}(i_q^* - i_q))$$

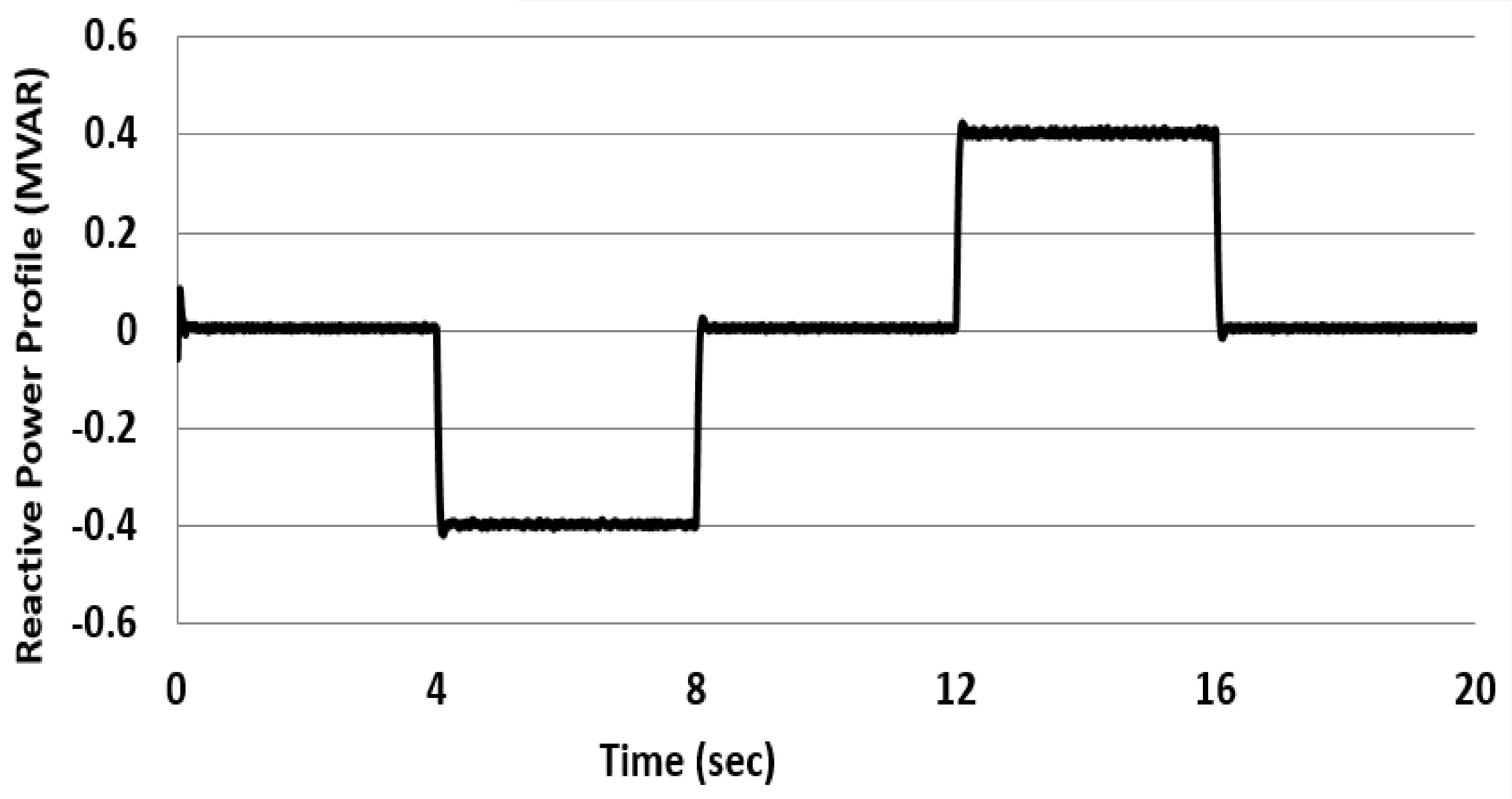
# Simulation of PV system with variable irradiation level



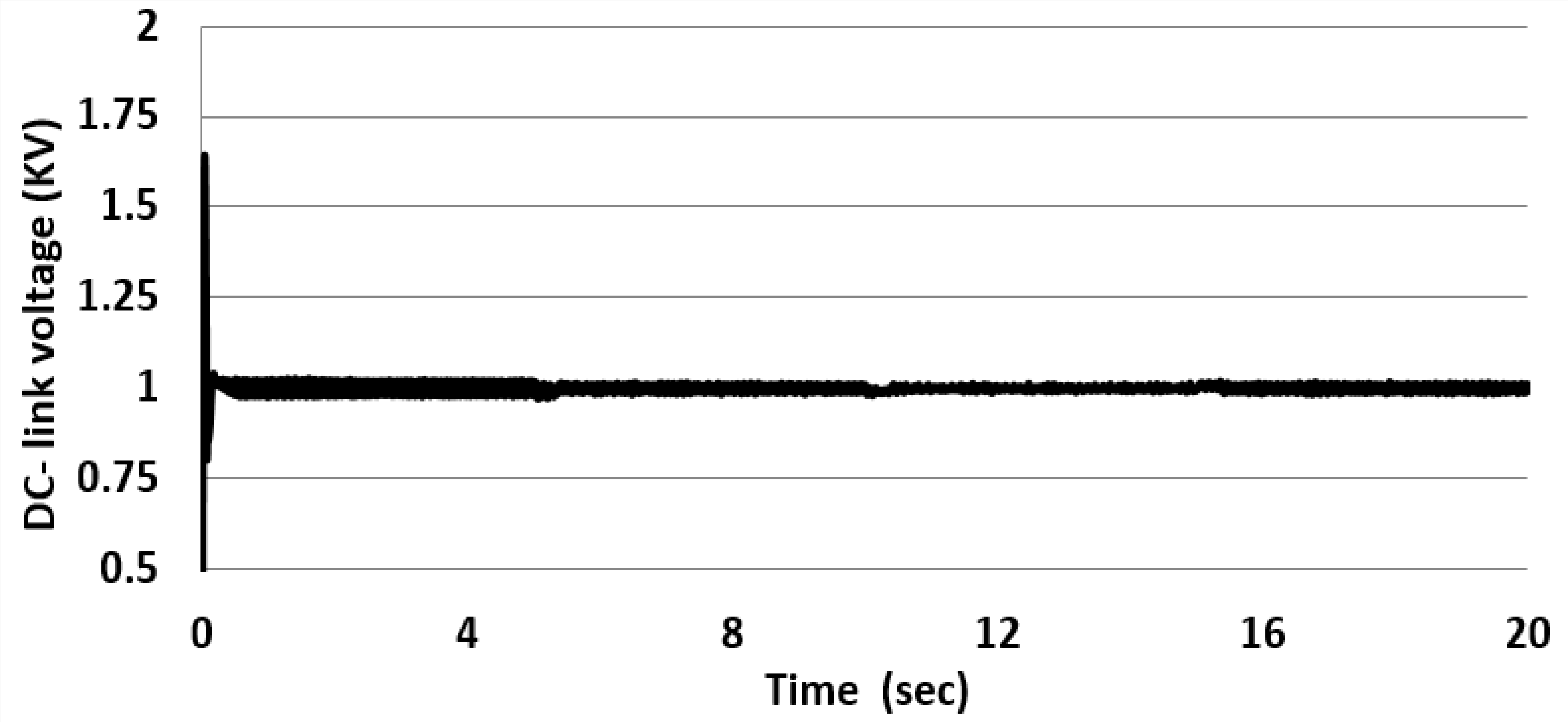

Generated active power in response to variations in irradiation




Generated reactive power as irradiation is varied

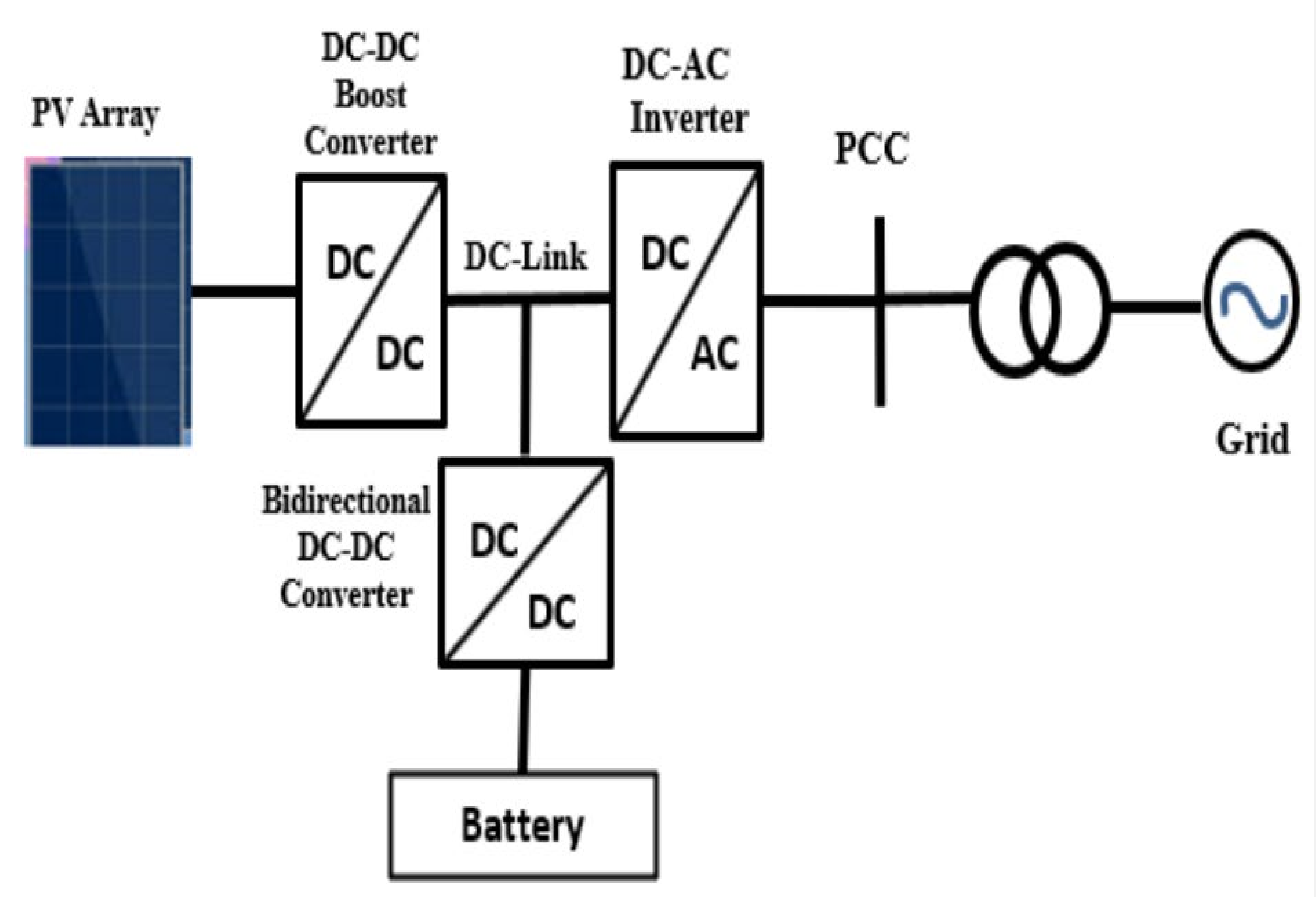



Reactive power variation profile




DC-link voltage profile in response to changes in irradiation

# Volt /Var Control of Solar Photovoltaic System

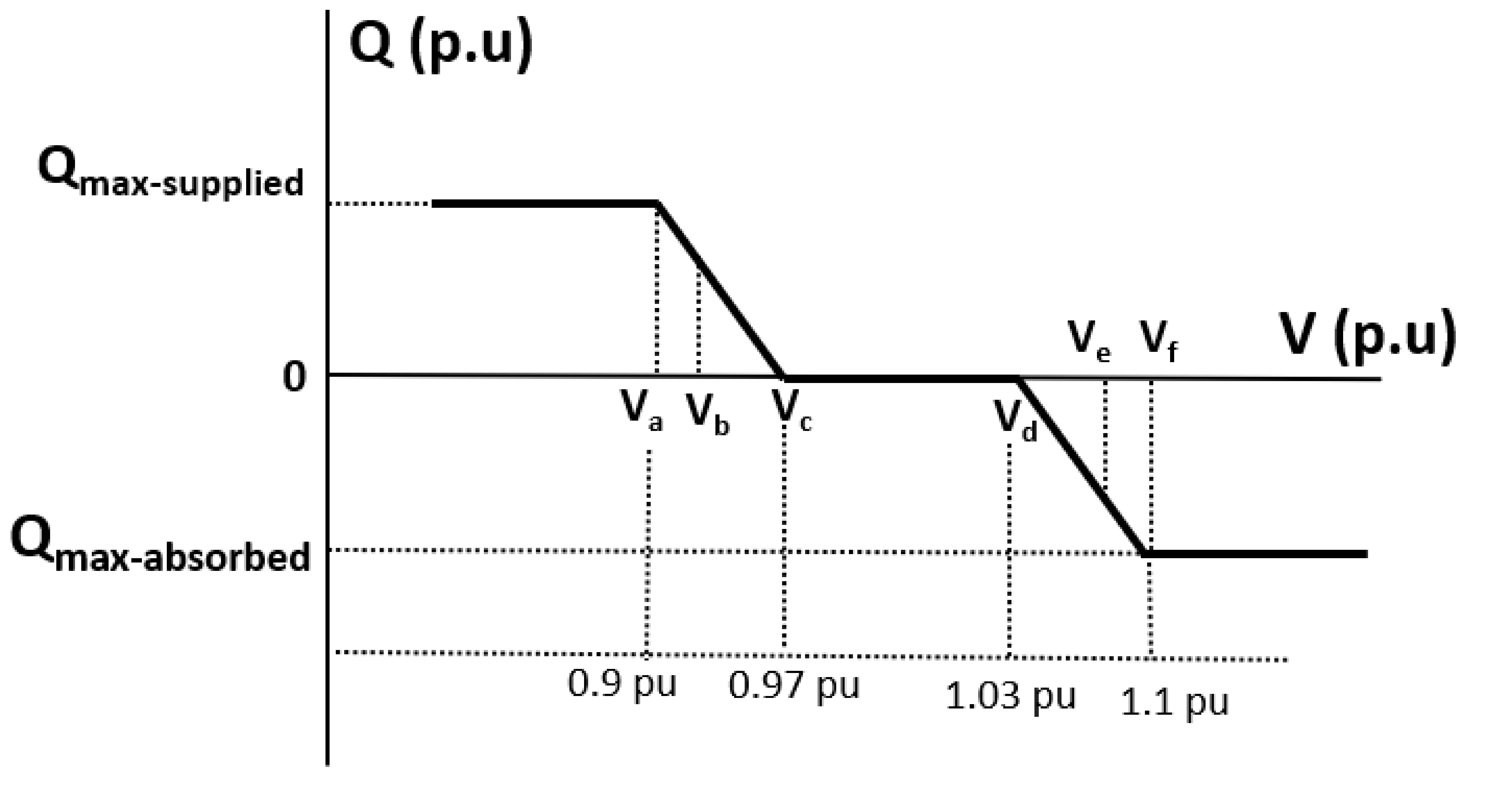



Layout of the proposed system

Published in:

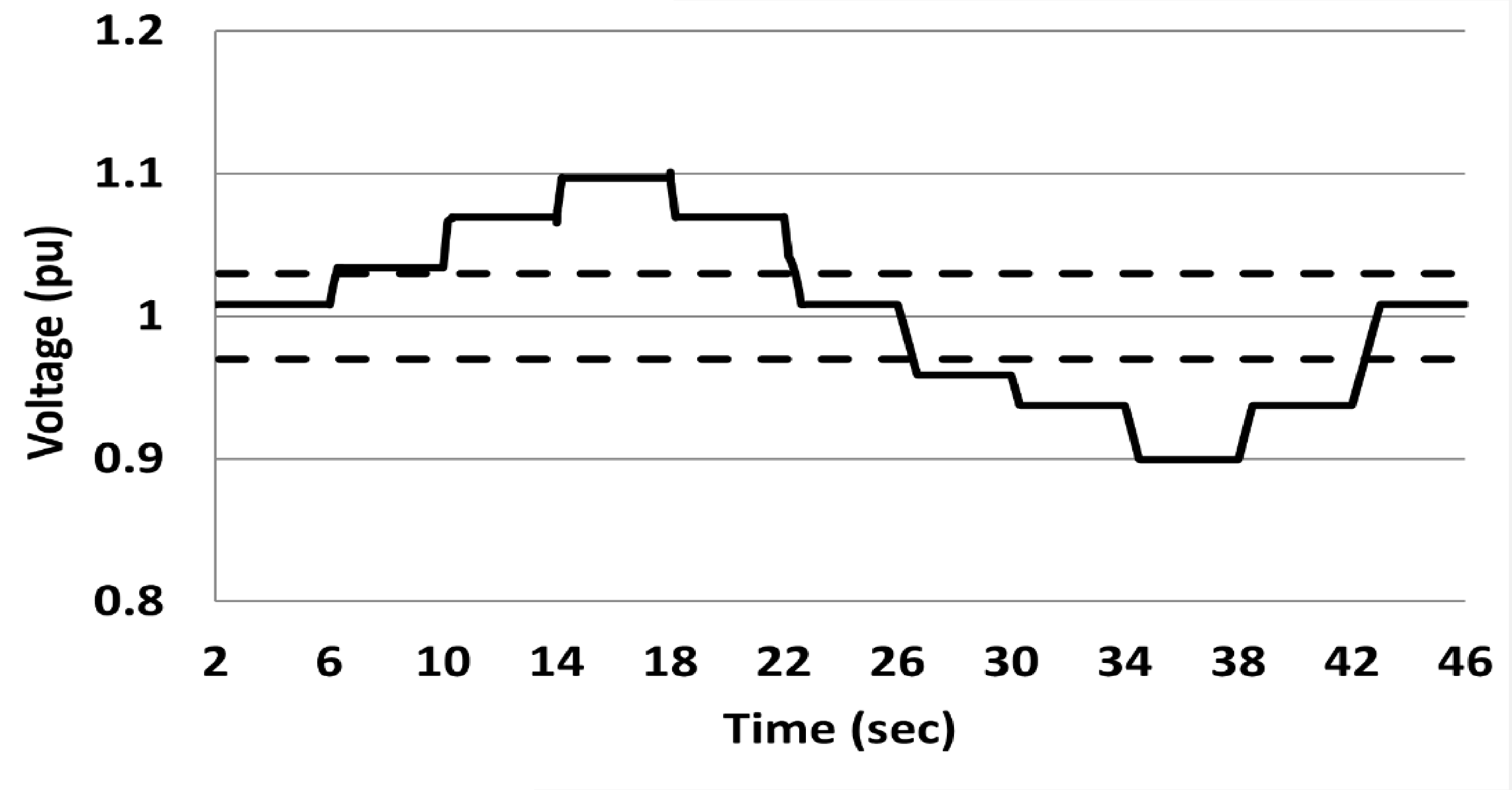
**The 53rd North American Power Symposium 2021/ IEEE**

# Volt/var control strategy

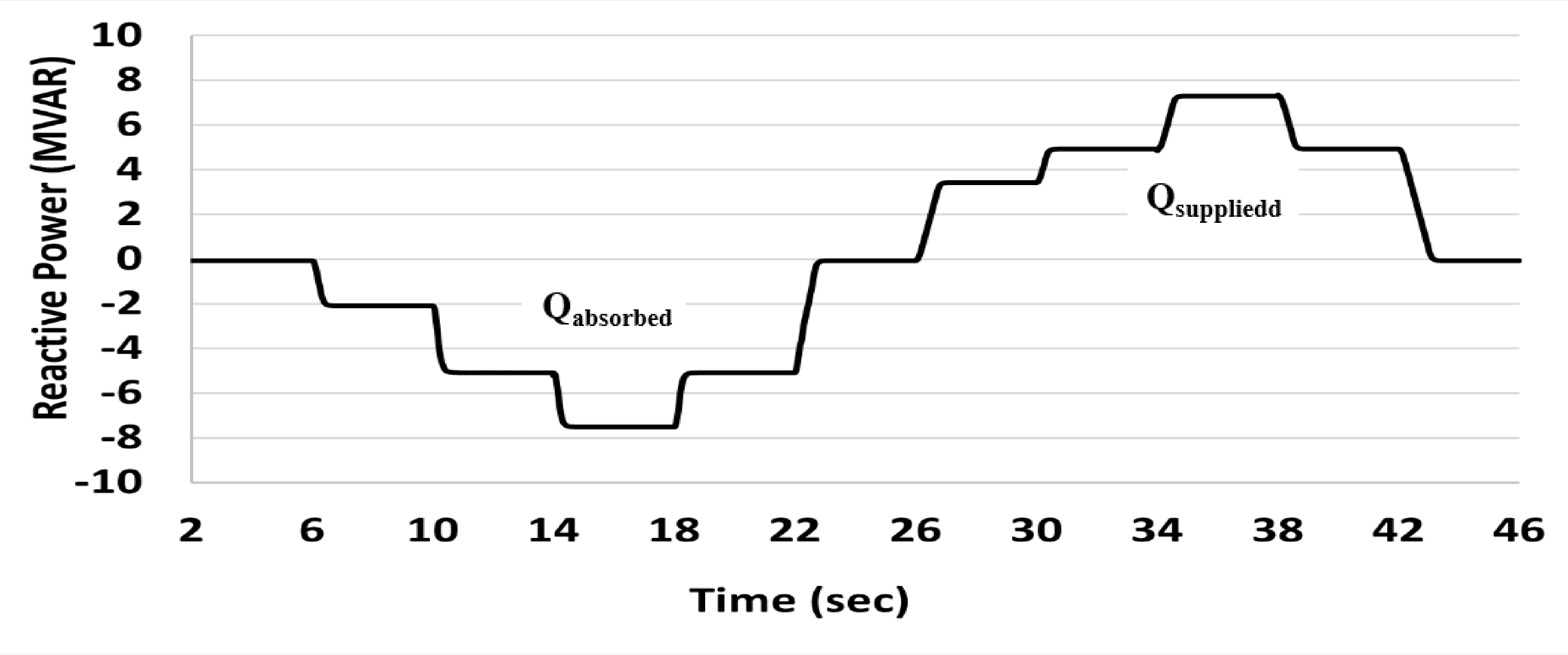



Volt/var control function

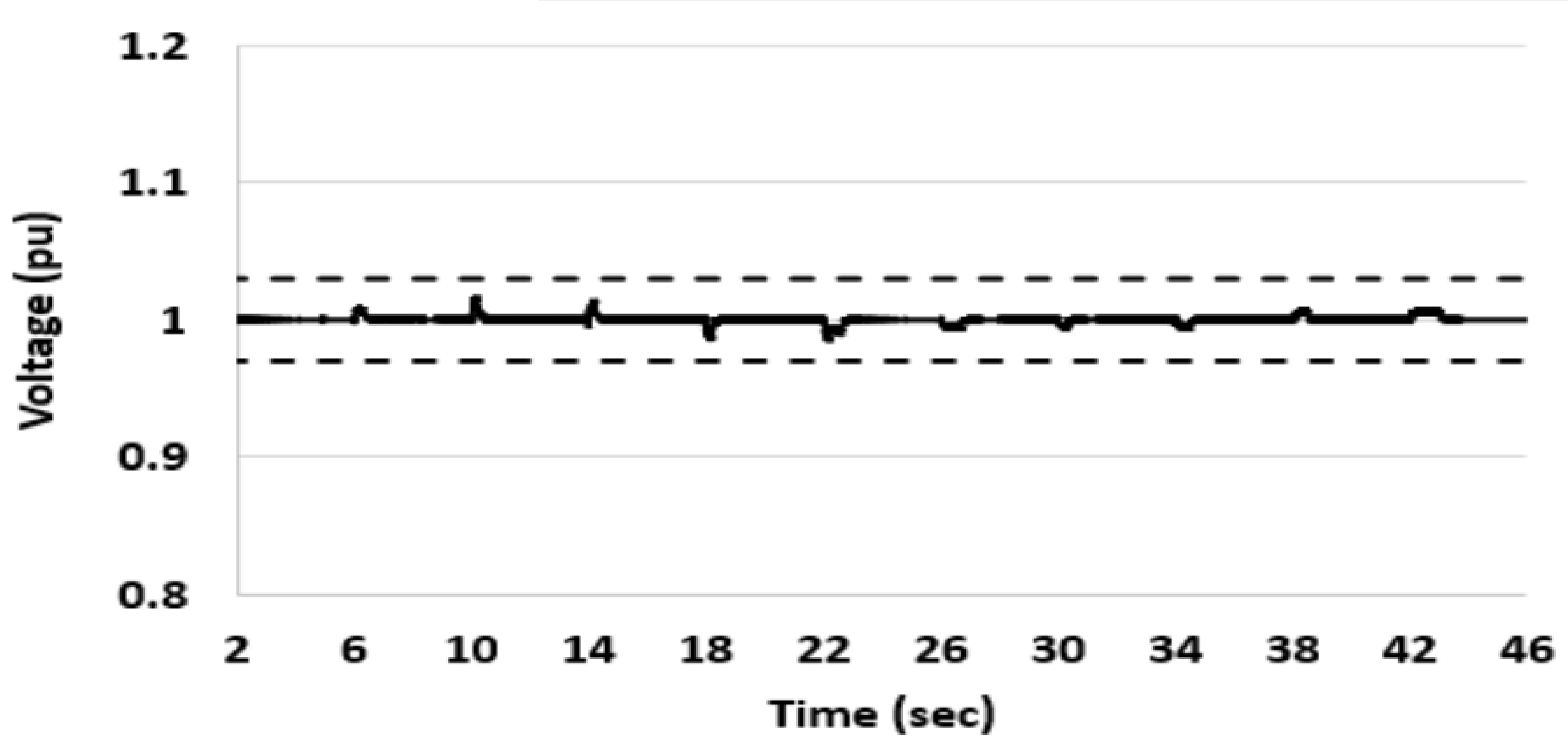
# Simulation results:



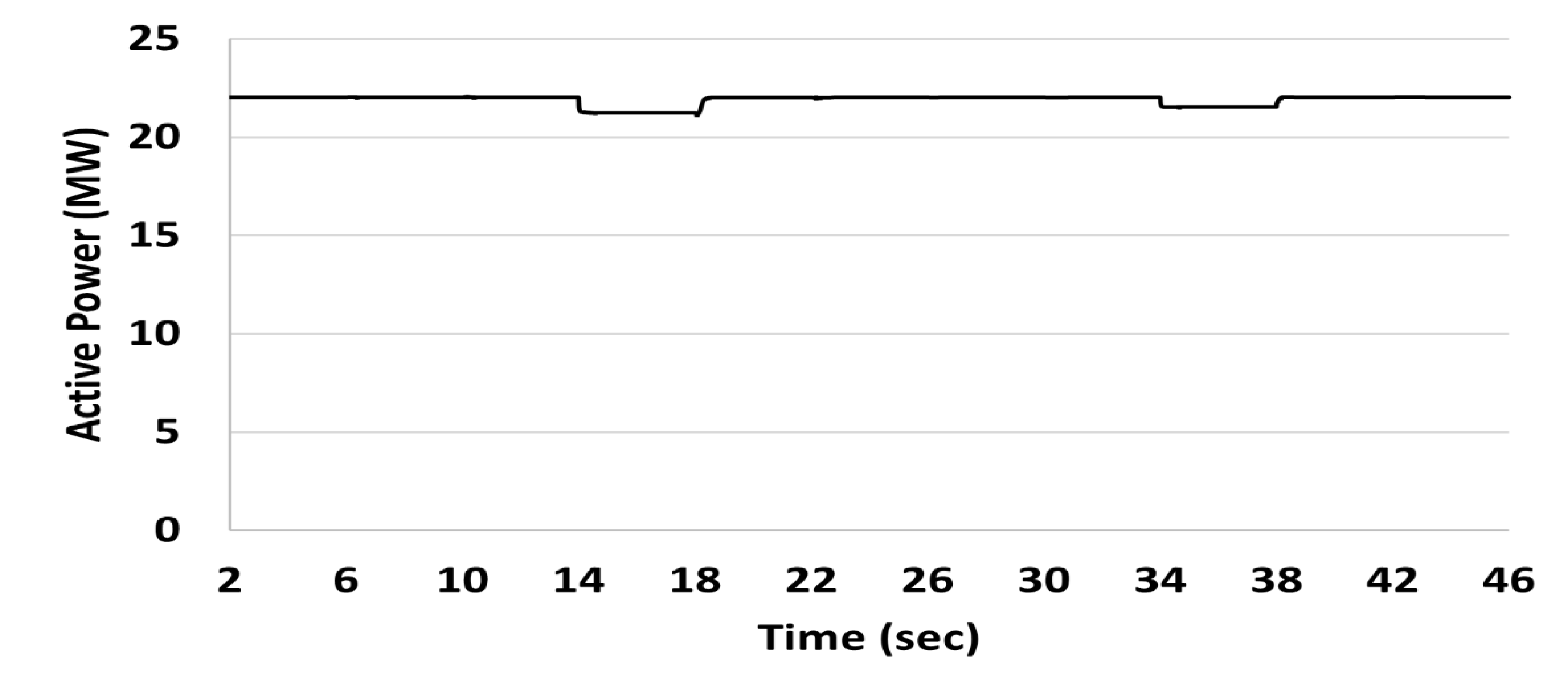

Voltage variation profile without reactive power support




Reactive power variation profile

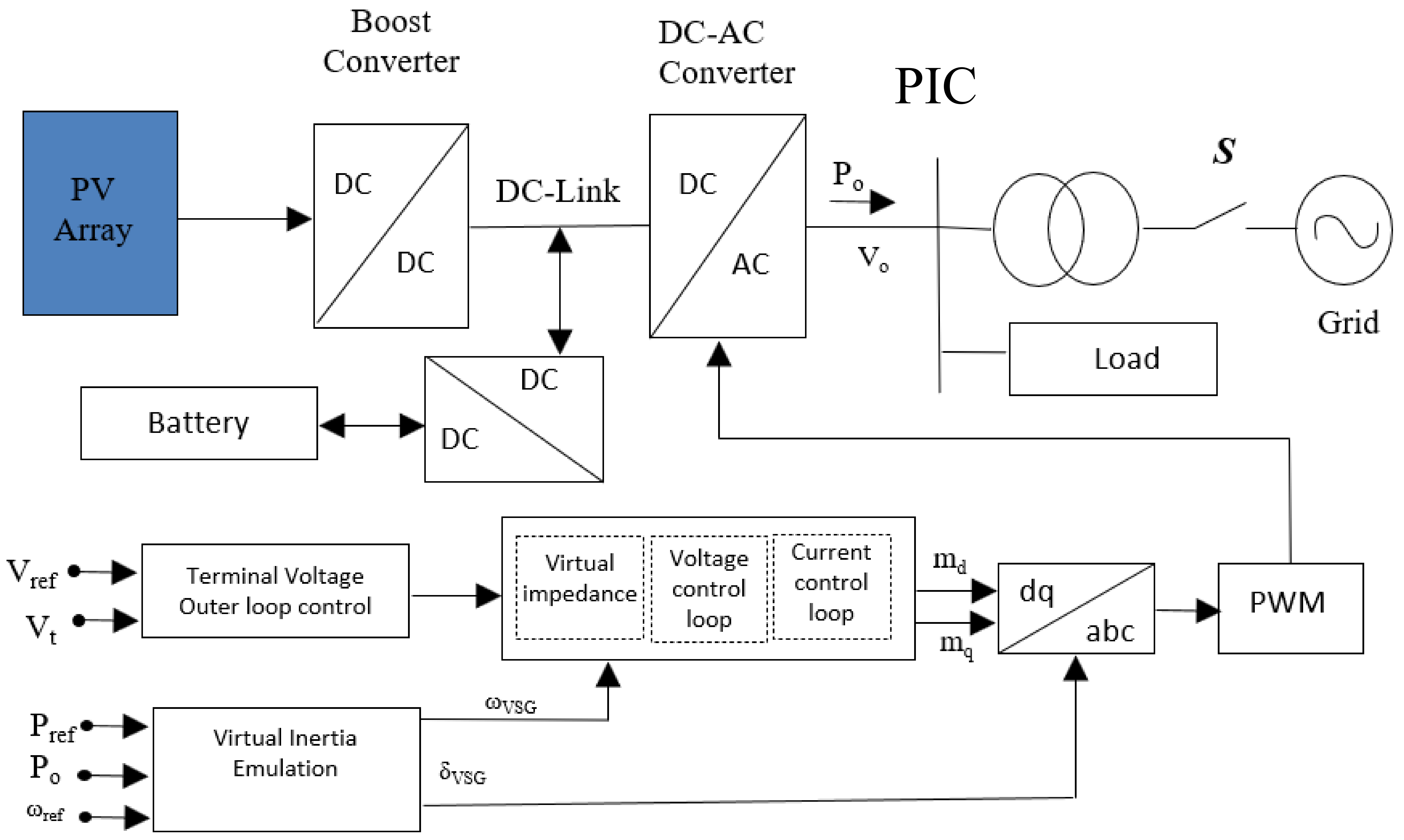



Voltage variation profile with reactive power support




Active power profile

# Virtual Synchronous Generator Controller Performance and Evaluation

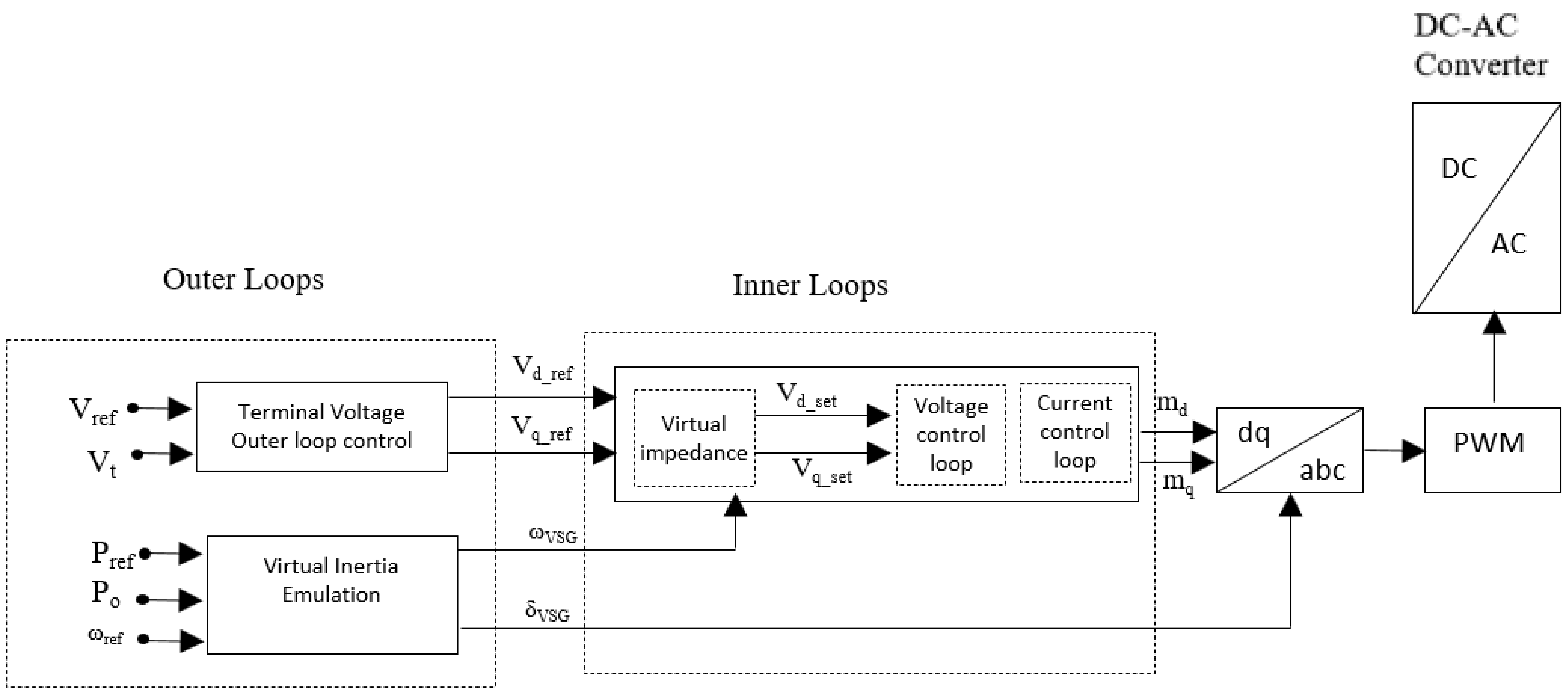



General layout of the proposed system

Accepted for:

Grid of the Future Symposium / CIGRE / Nov. 2022

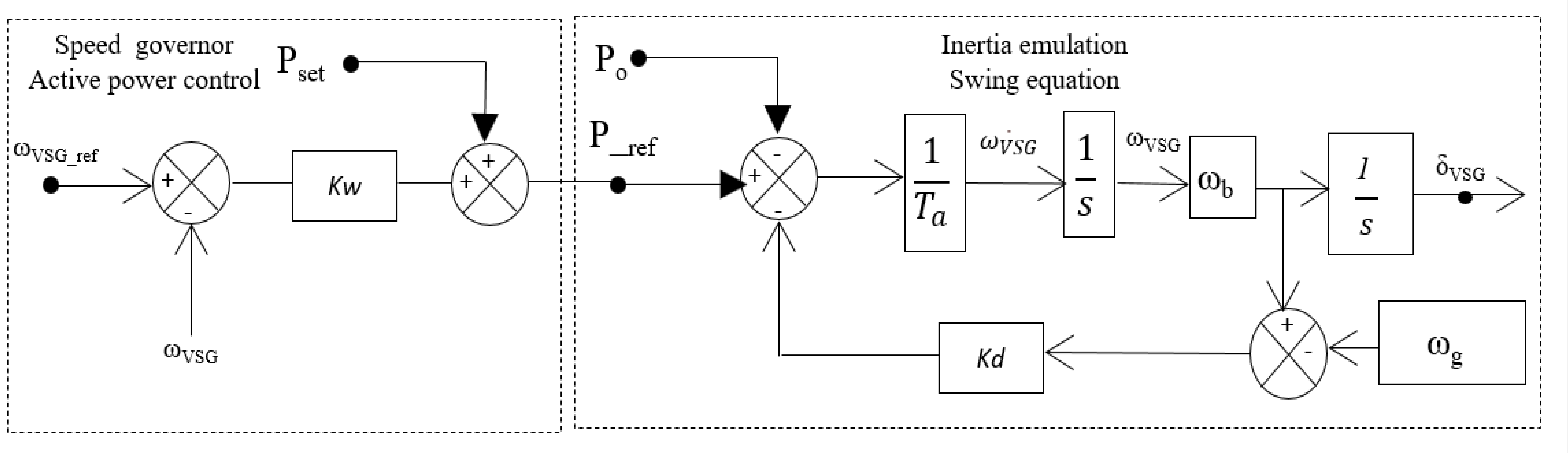
# DC-AC converter controller




DC-AC converter controller

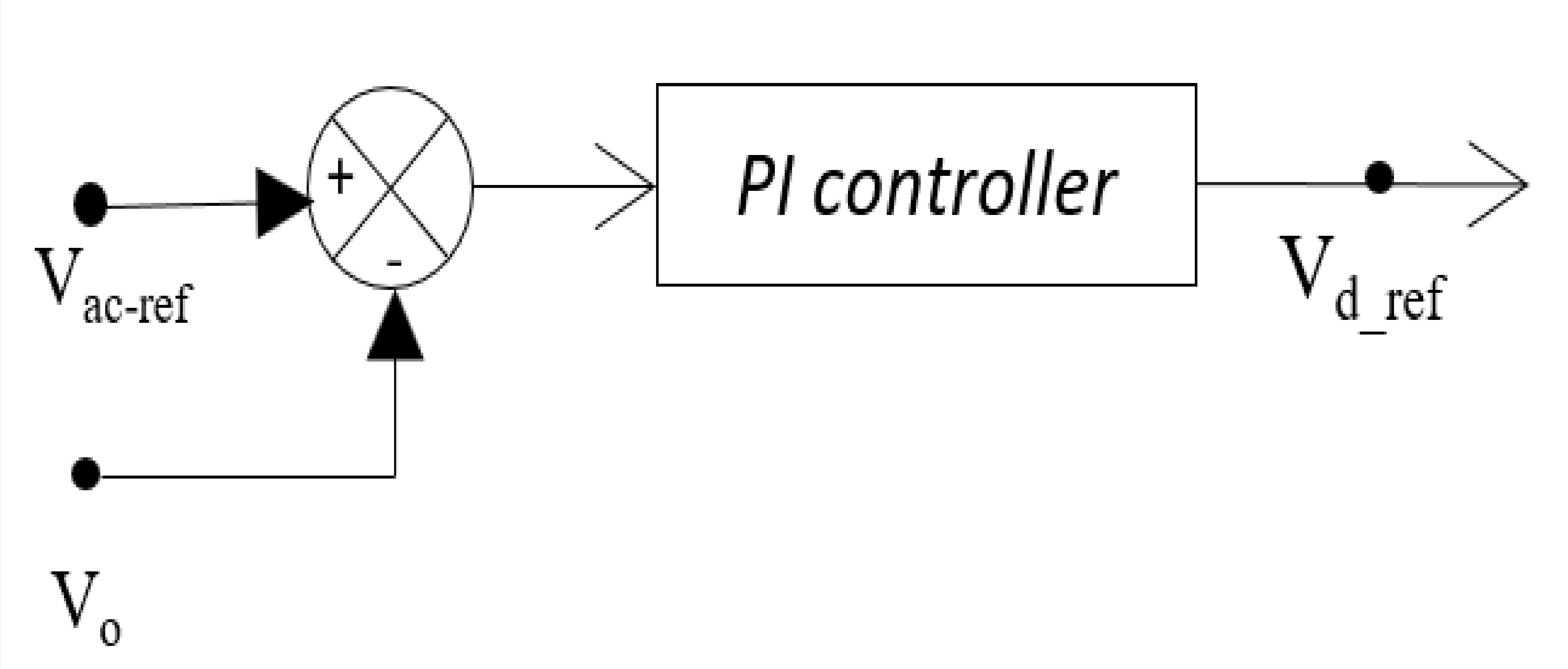
# DC-AC converter controller

Outer loops:
Virtual inertia emulation



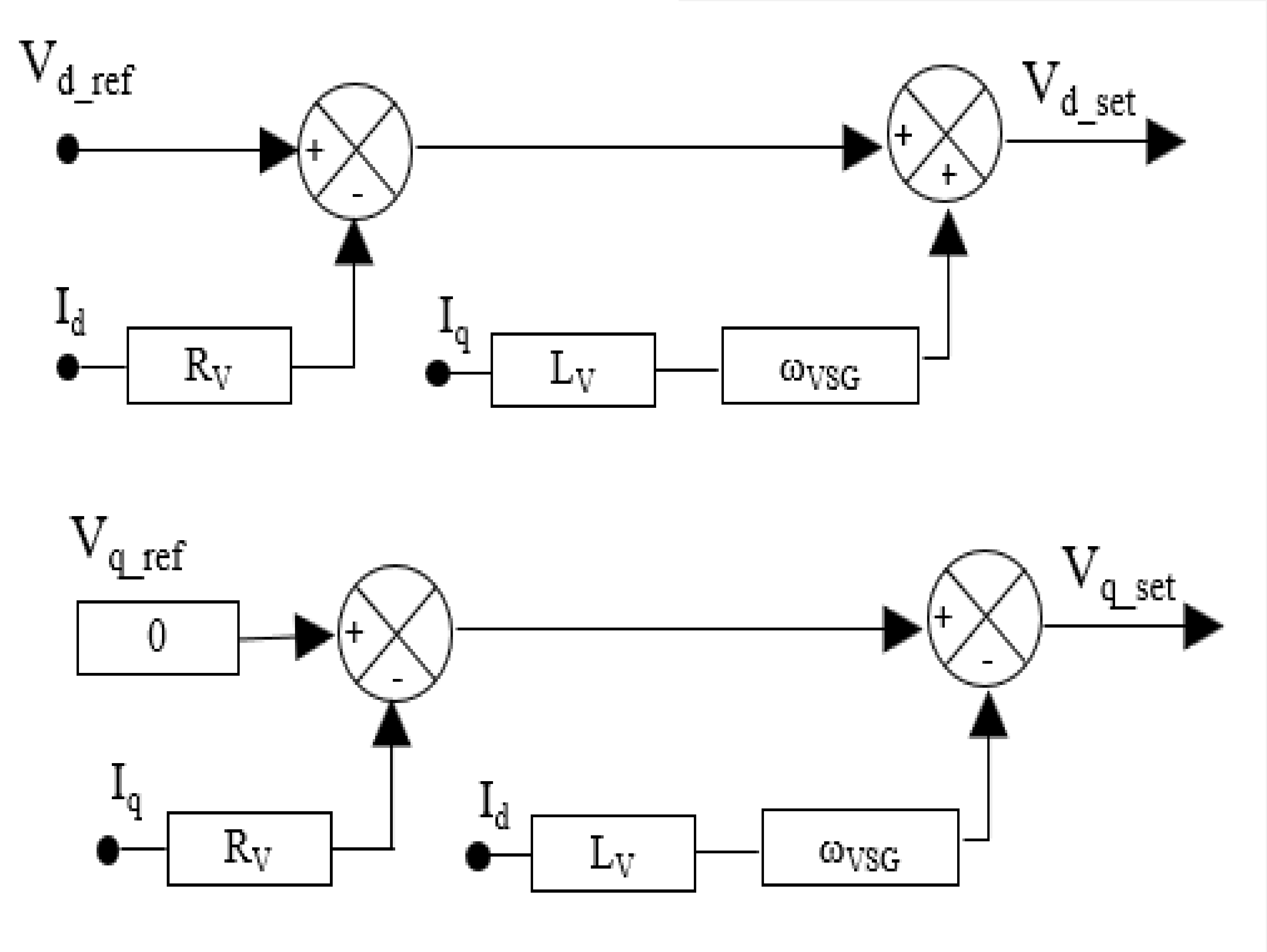

Ta ….Inertia time constant
Kd ….Damping constant
Kw….Frequency droop constant

Outer loop:
Terminal voltage Controller

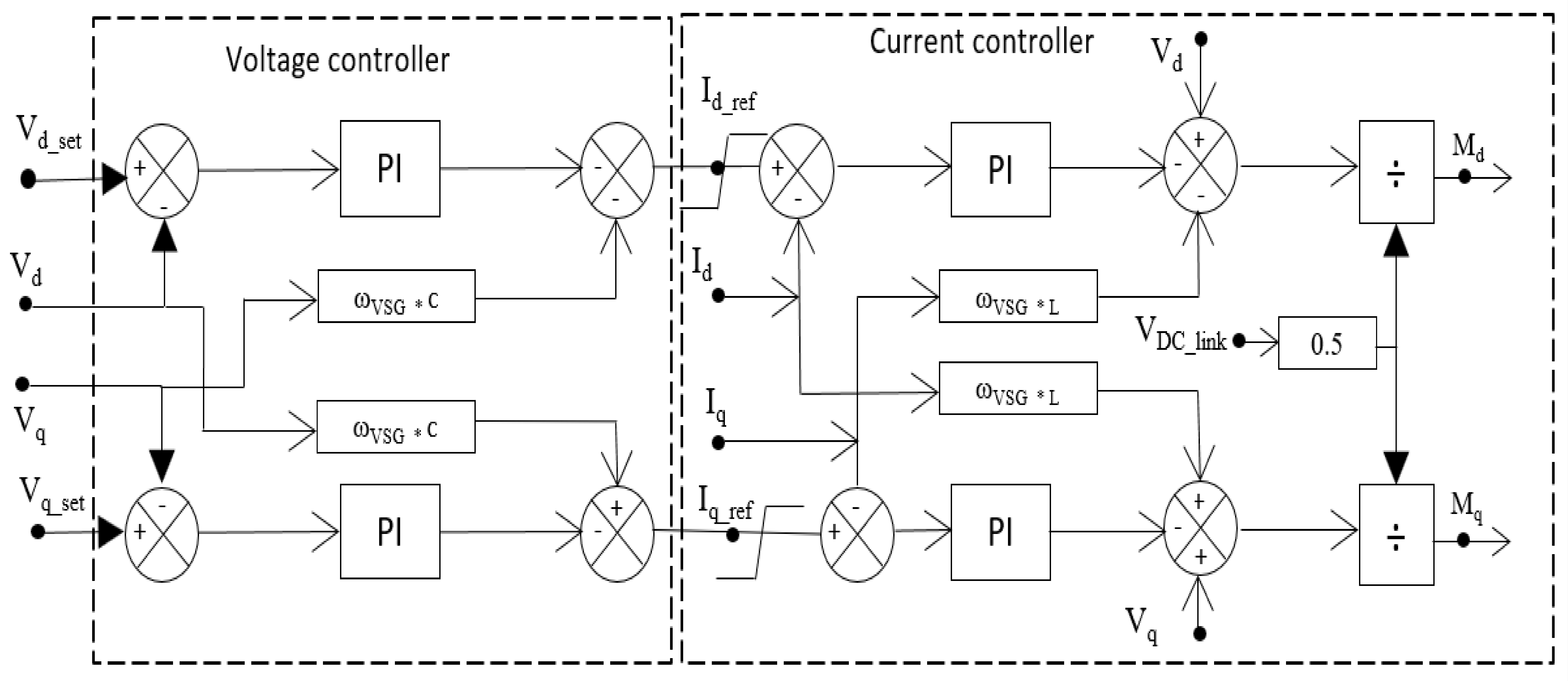


# DC-AC converter controller

## Inner loops

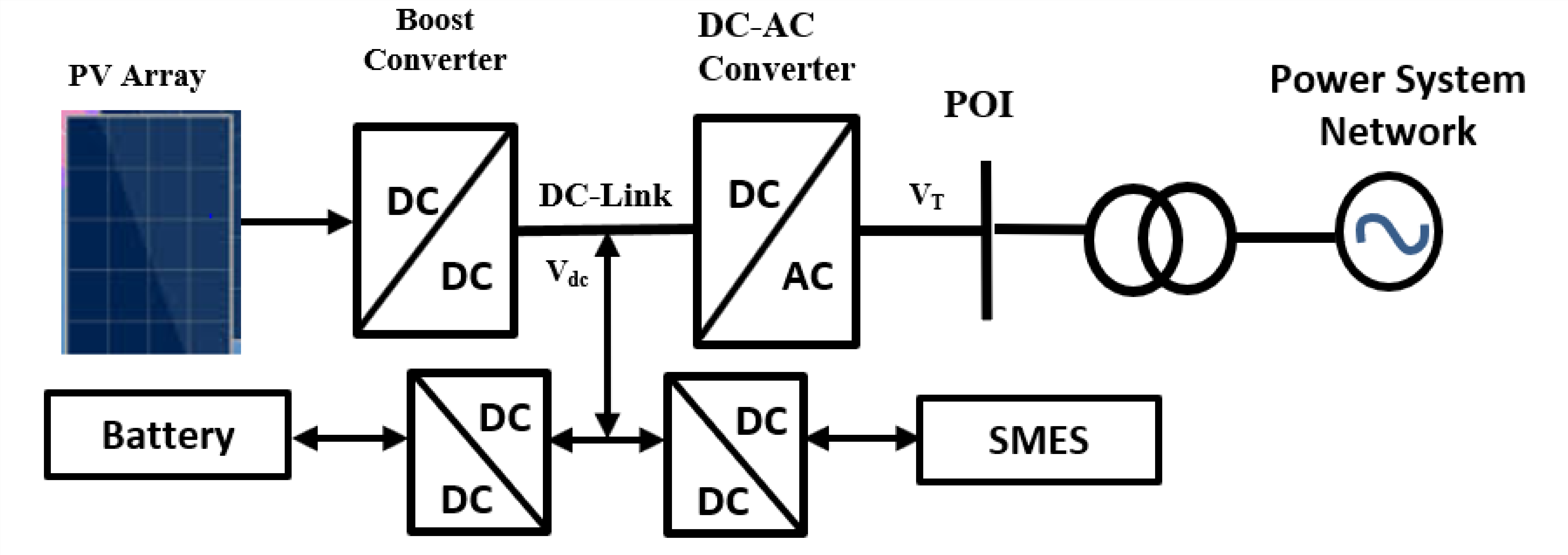



Virtual impedance




Cascaded voltage and current inner control loops

# VSG Controller Based SMES/Battery Energy Storage System




General layout of the proposed system

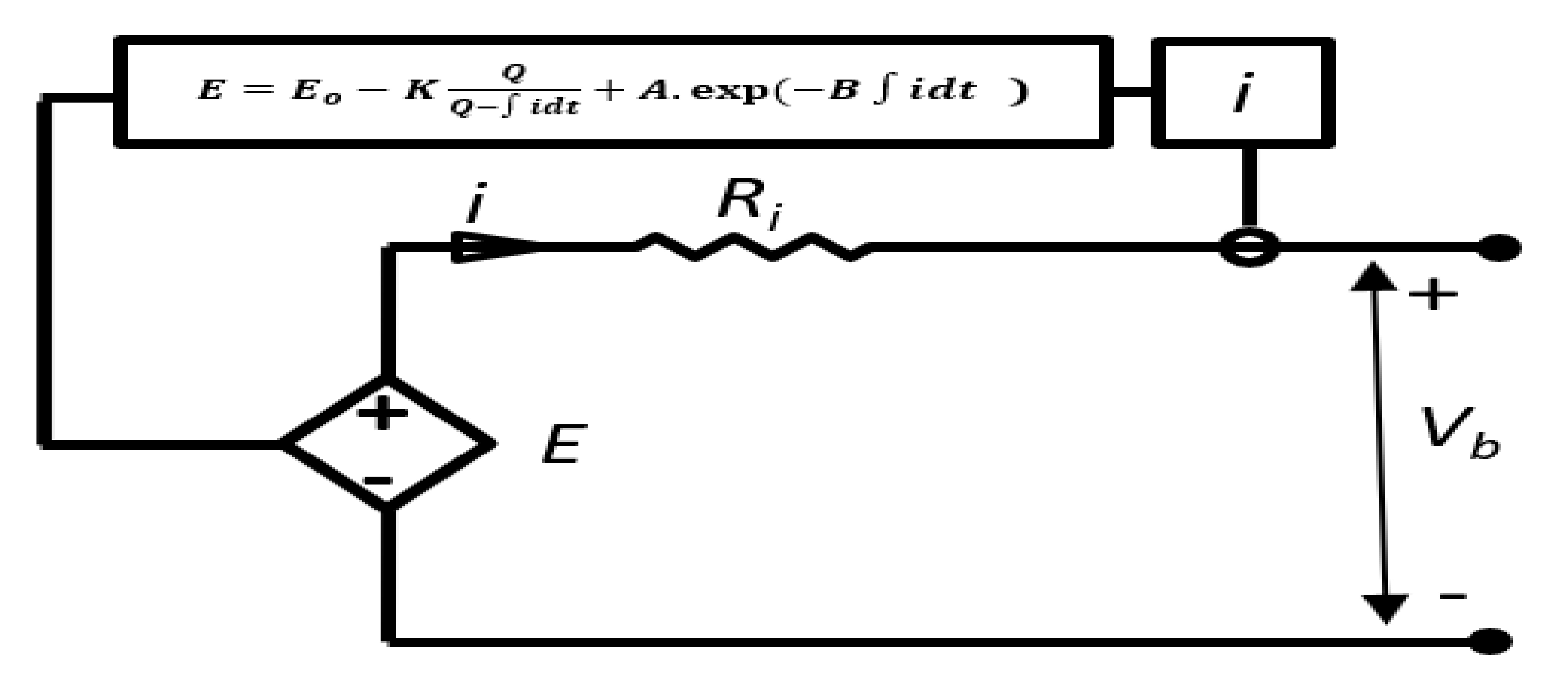
Accepted for:

Grid of the Future Symposium/ CIGRE /Nov. 2022

# Battery storage system and dc-dc converter

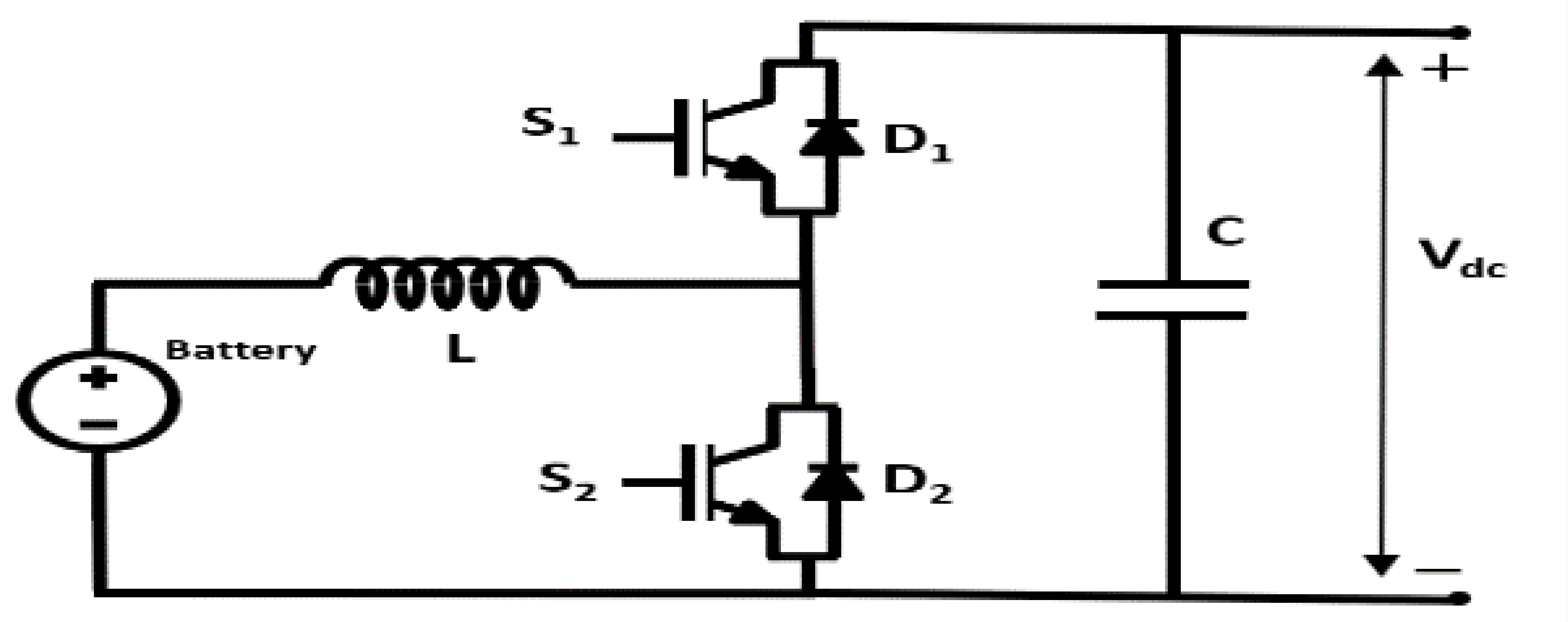
$$E = E_0 - K\left(\frac{Q}{Q - it}\right) + A * e^{-B \int idt}$$

$$V_b = E - R_i * i$$



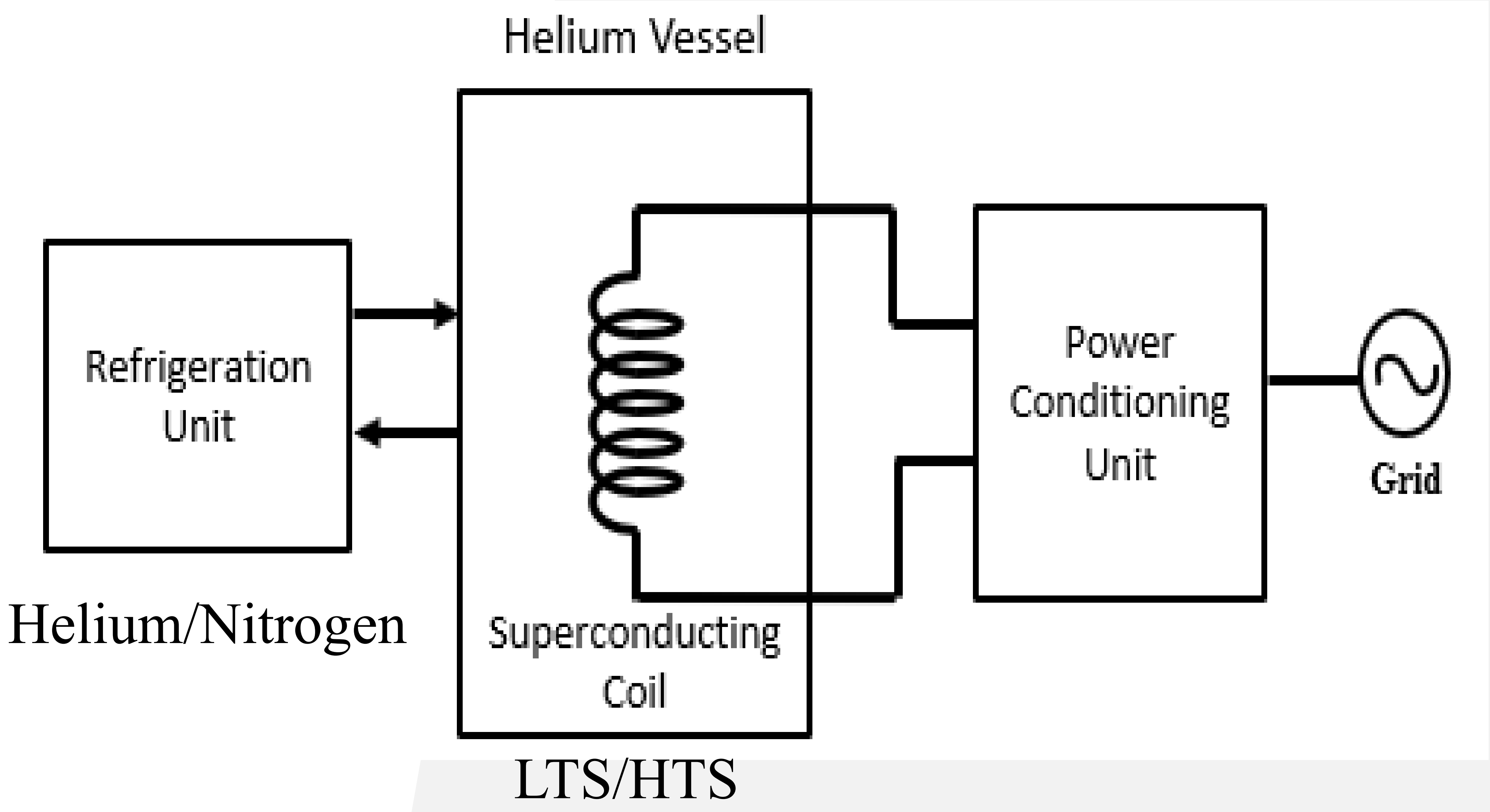

Battery equivalent electric circuit model

## Battery Buck–Boost Converter controller

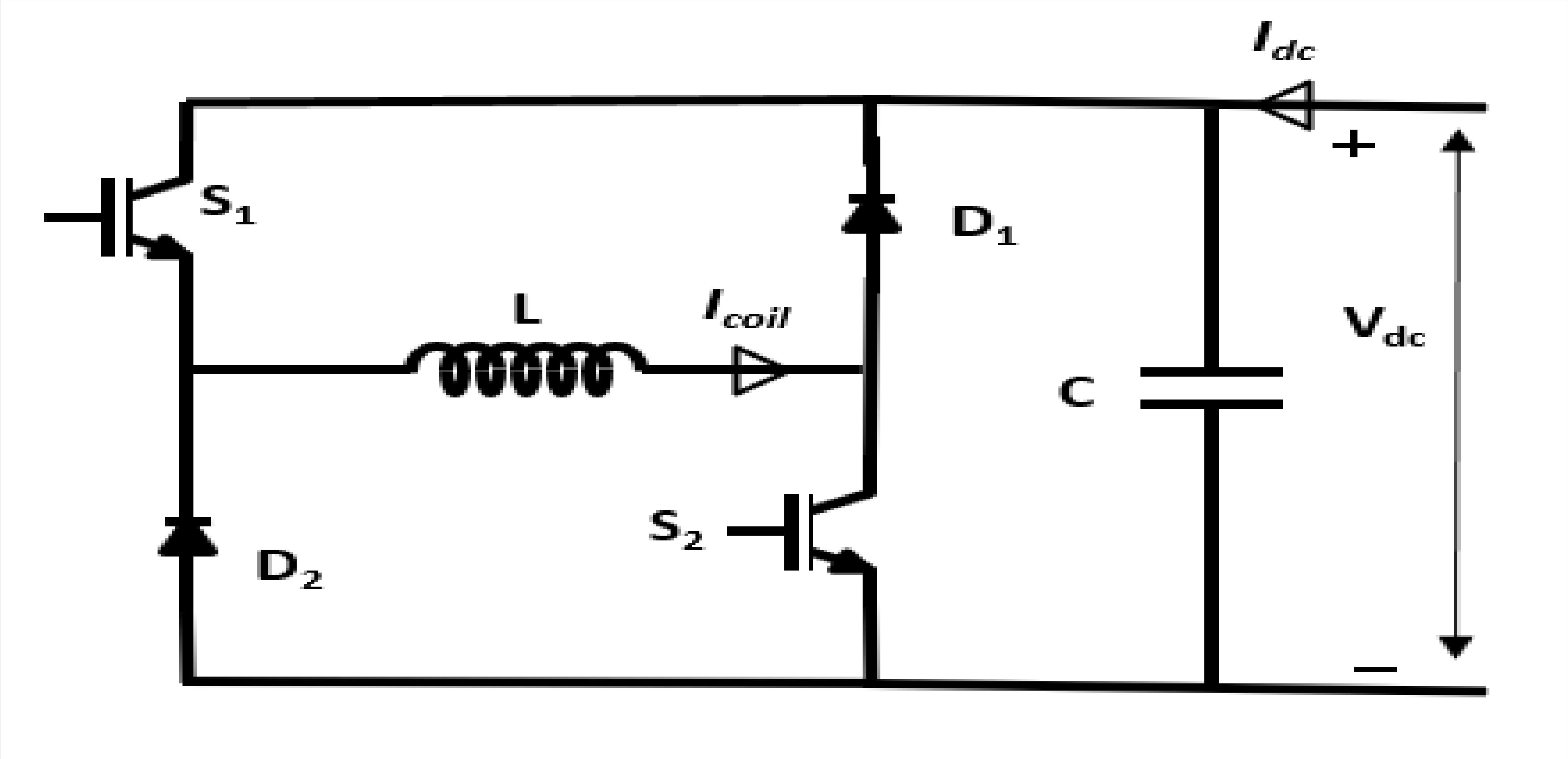



Battery Buck–Boost converter controller

# SMES system and converter controller

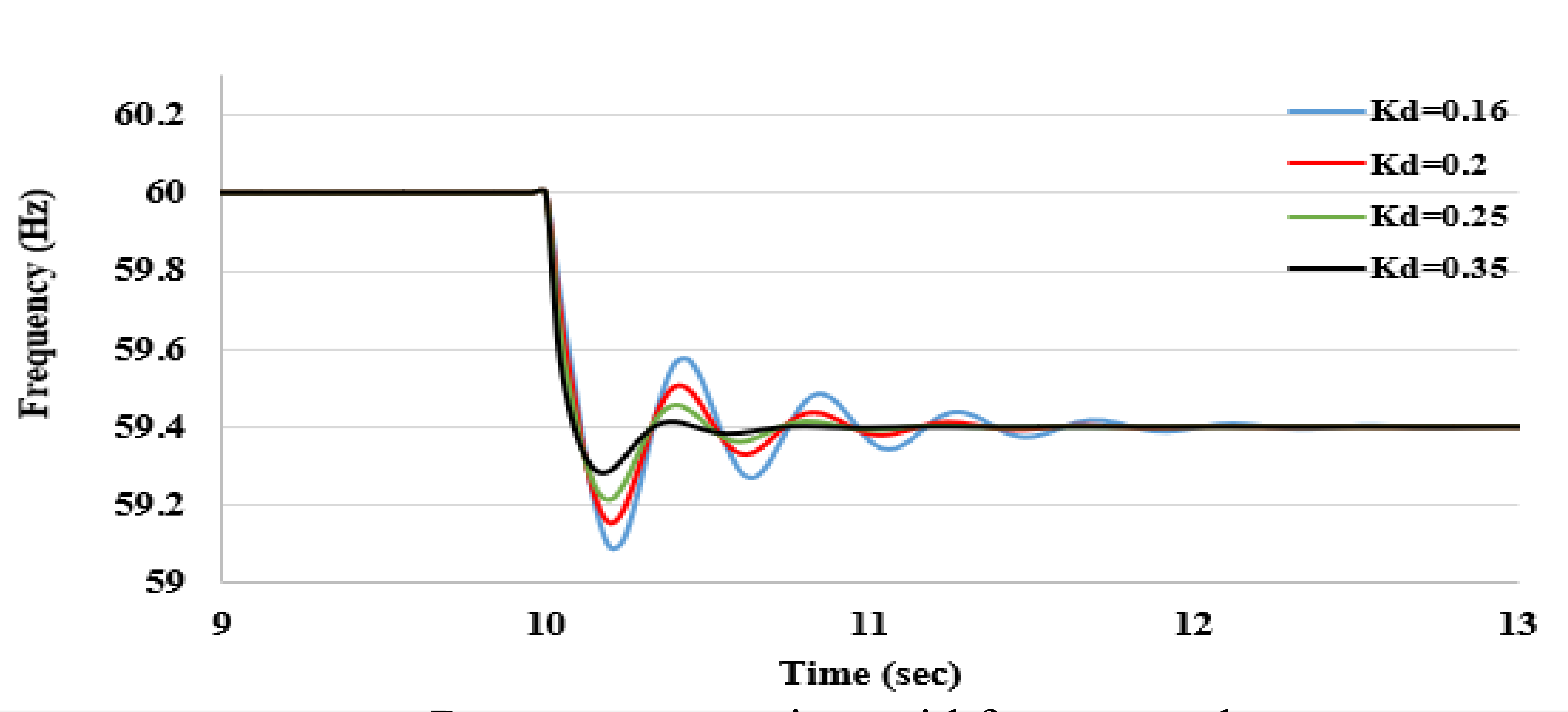



Schematic diagram of a SMES system



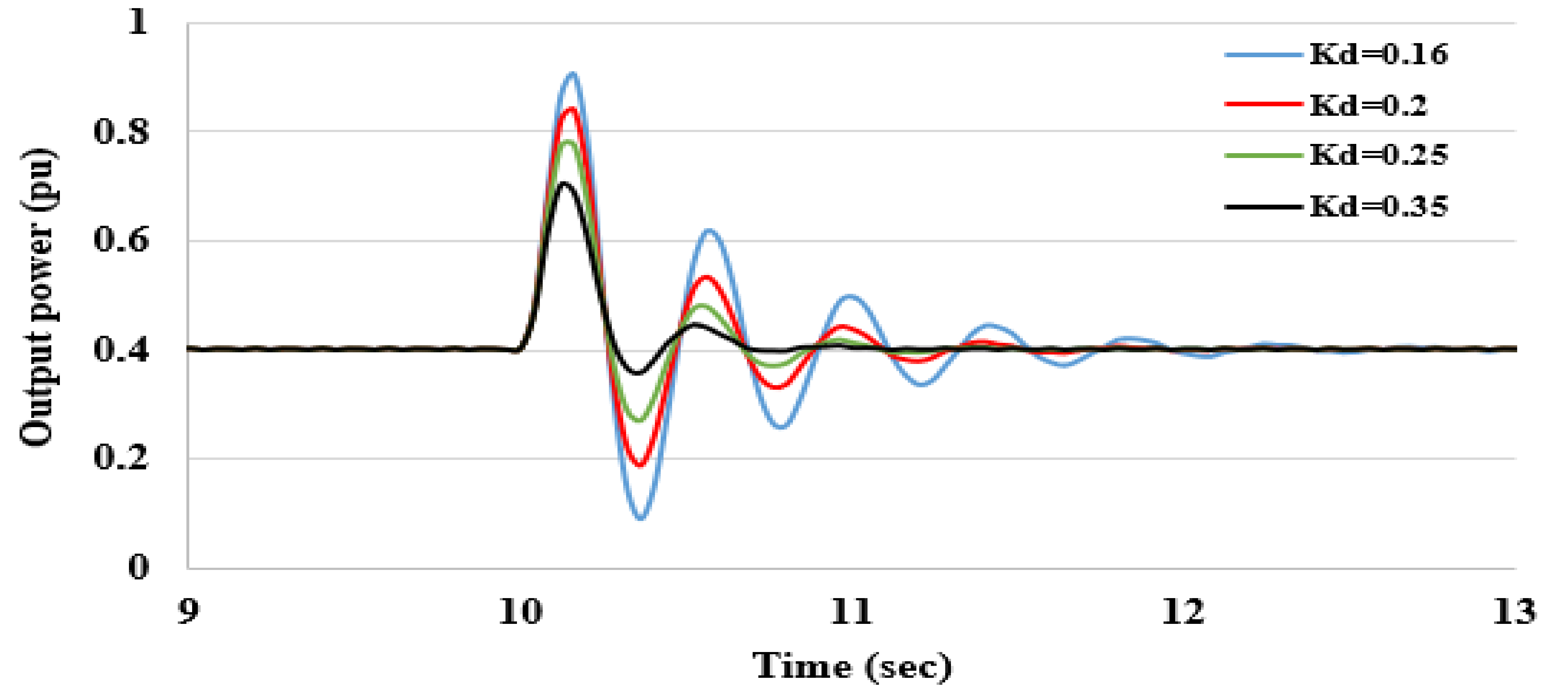

DC-DC chopper of the SMES coil

# Simulation results: microgrid frequency drop



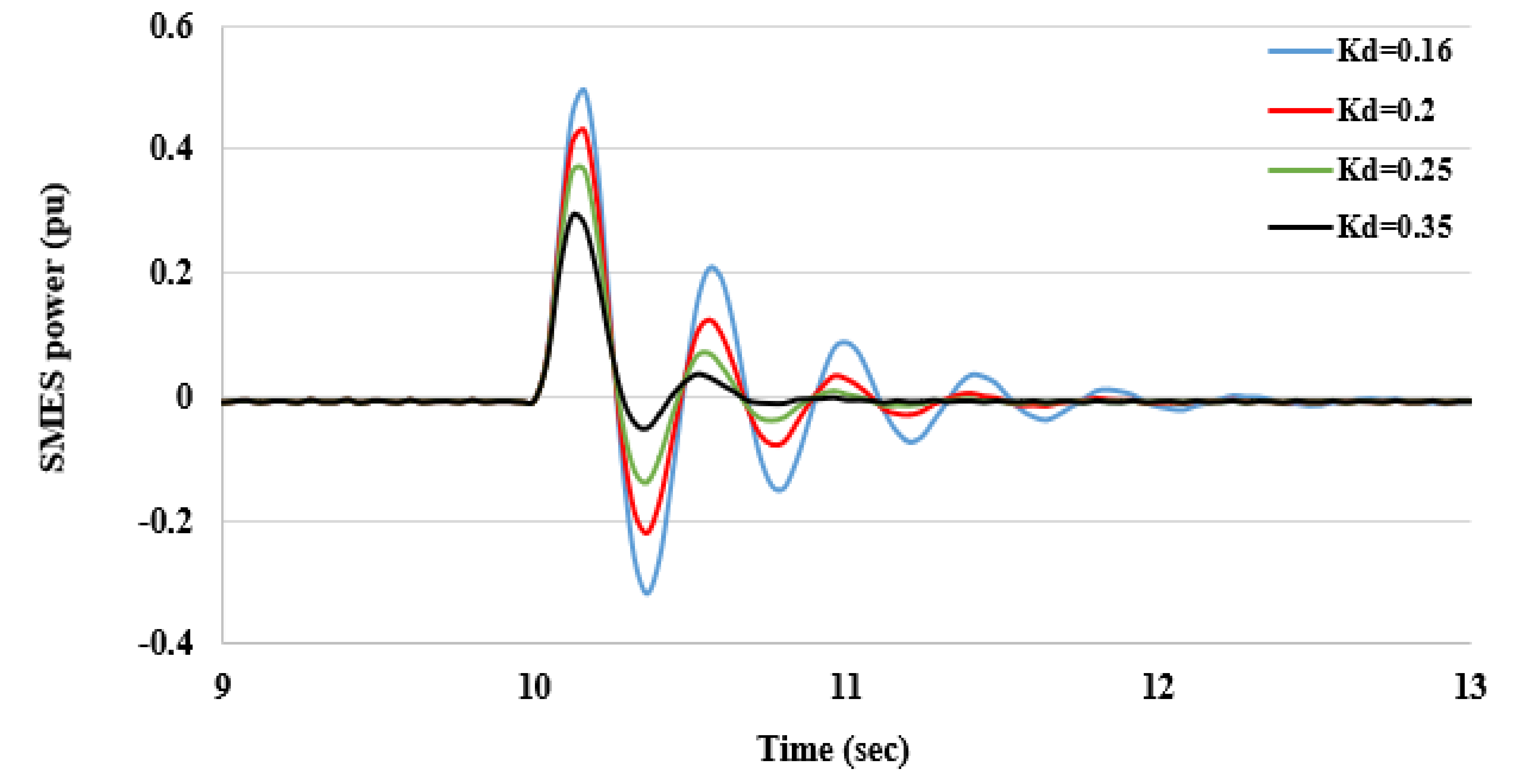

Response to a microgrid frequency drop
at different damping constants (Ta=5)

# Simulation results: microgrid frequency drop



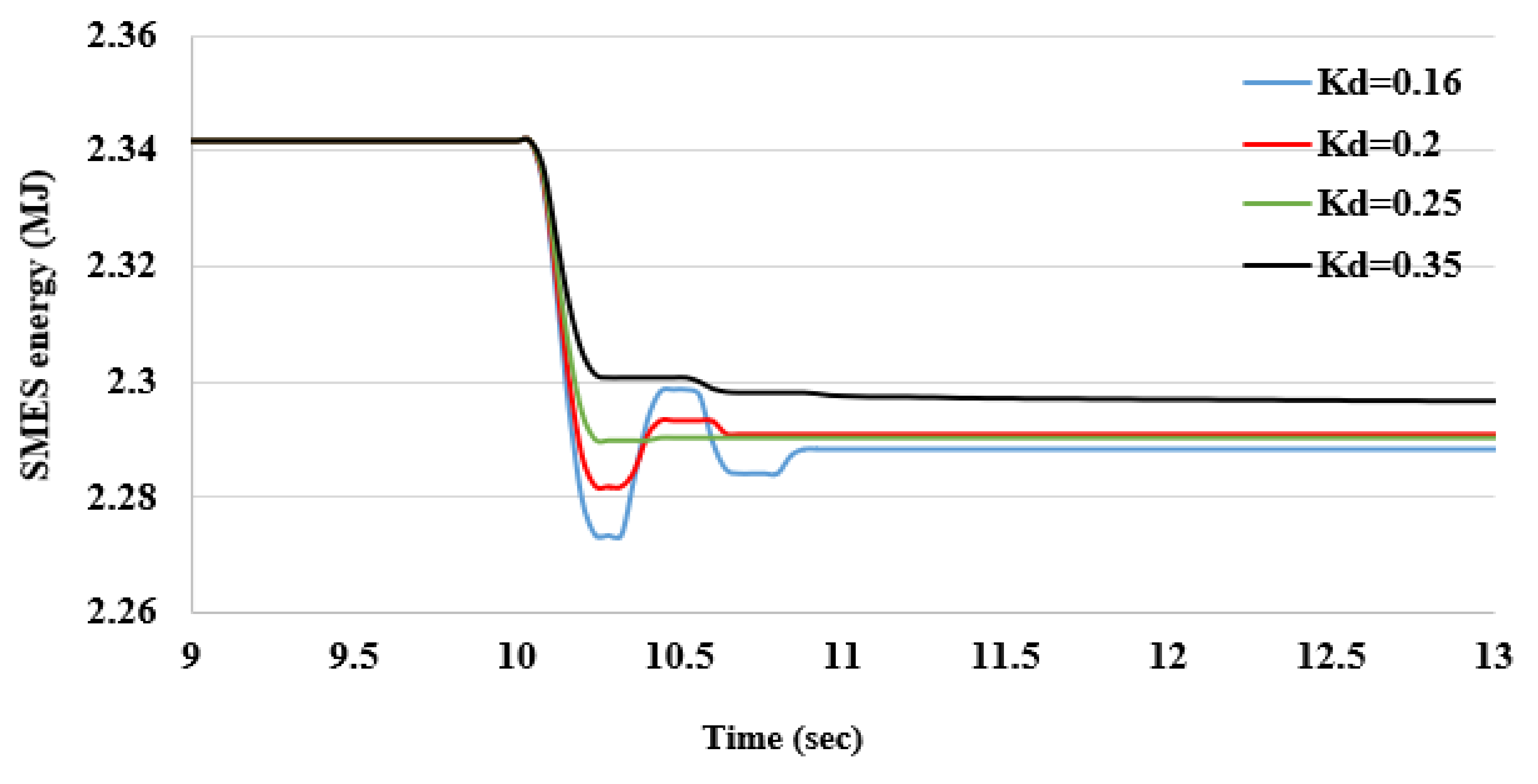

Converter output power at different damping constants in response to a microgrid frequency drop (Ta=5)

# Simulation results: microgrid frequency drop



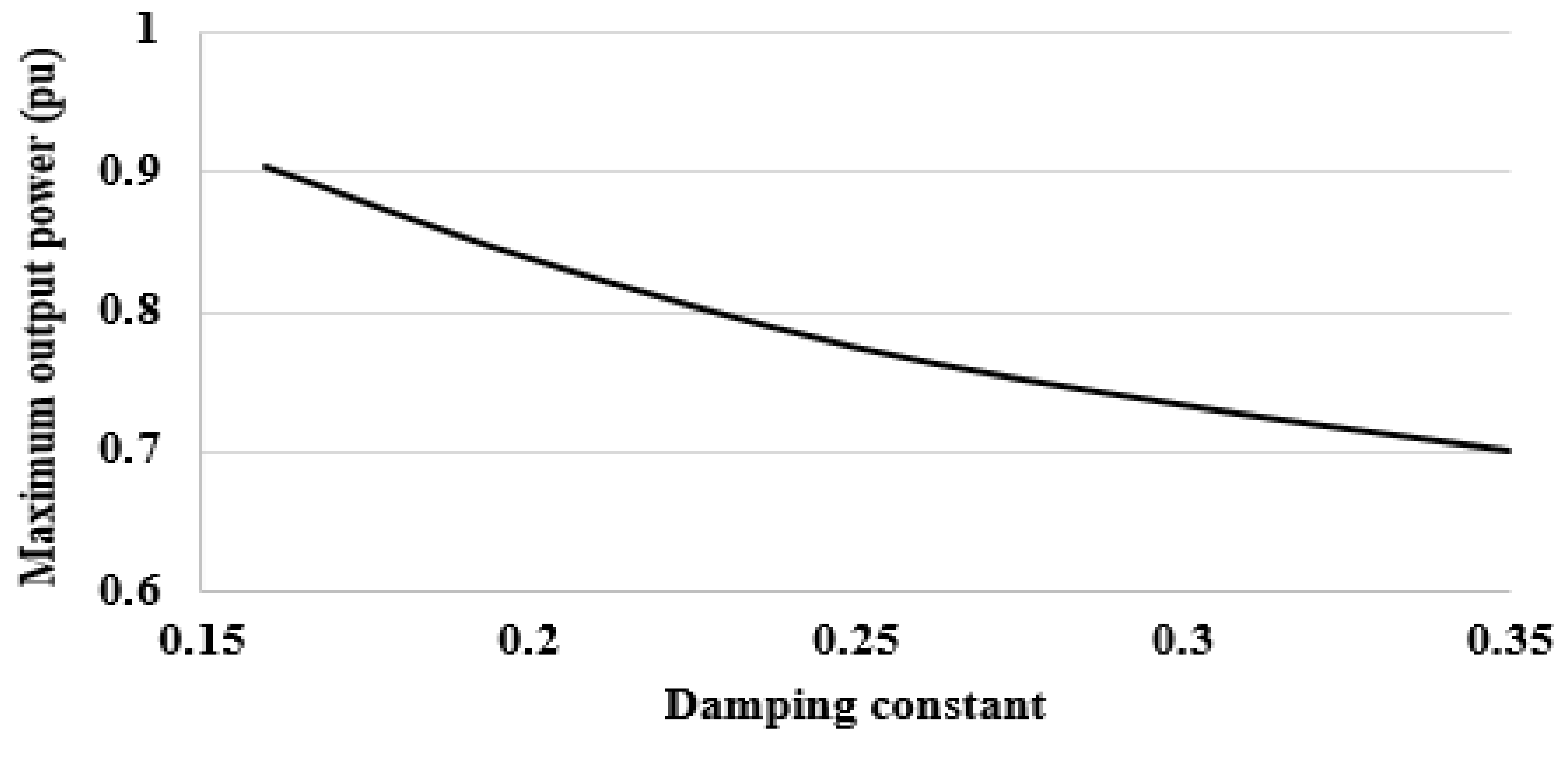

SMES instantaneous power in response to a microgrid frequency drop (Ta=5)

# Simulation results: microgrid frequency drop



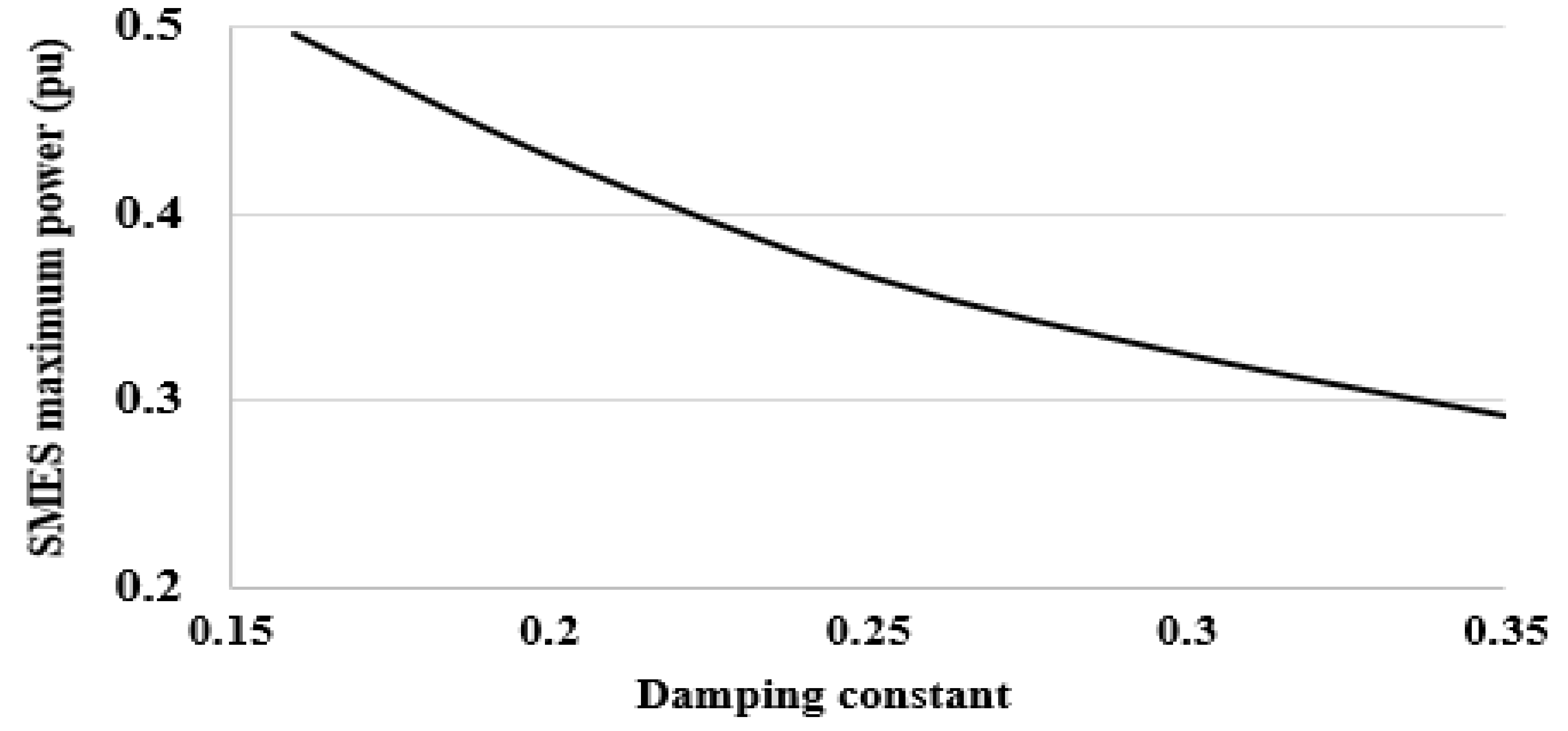

SMES energy at different damping constant in response to a microgrid frequency drop (Ta=5)

# Simulation results: microgrid frequency drop



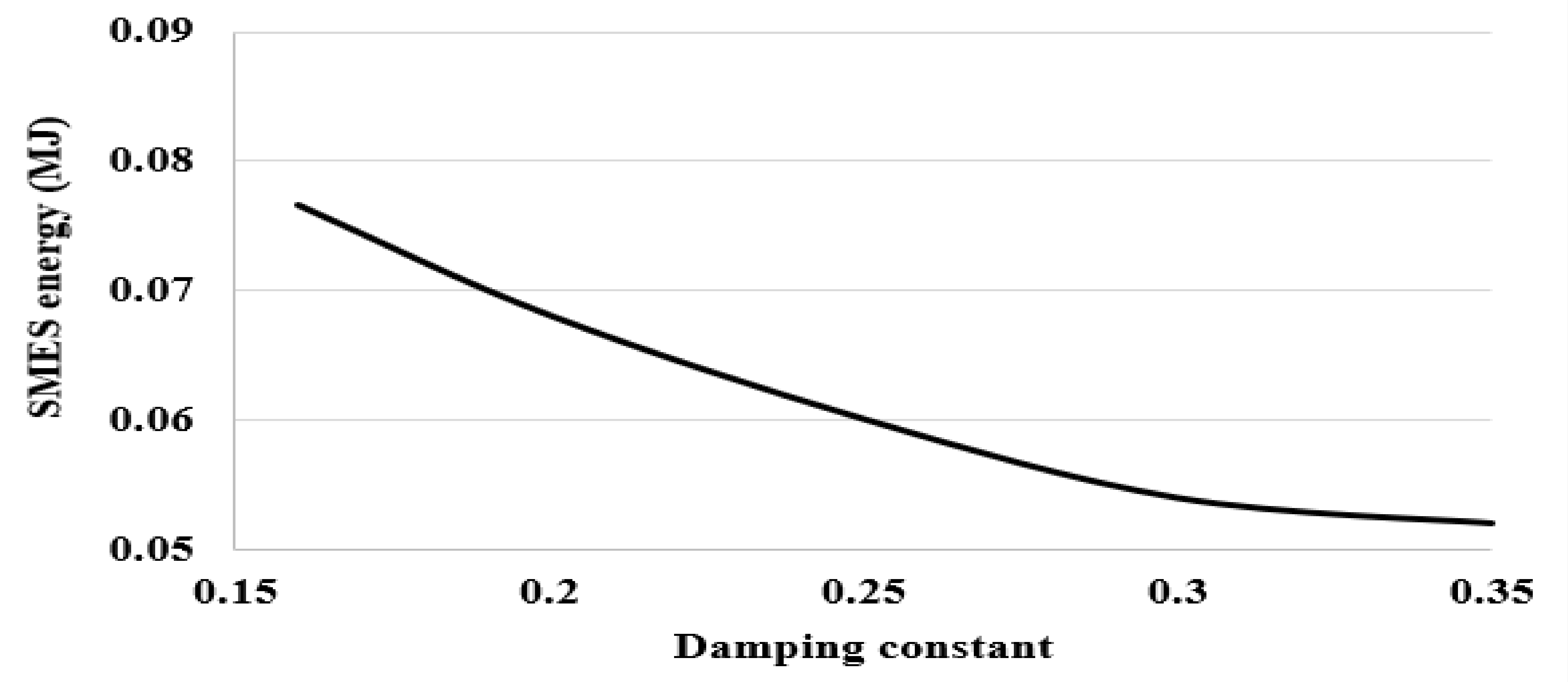

Maximum converter output power versus damping constant in response to a microgrid frequency drop

# Simulation results: microgrid frequency drop



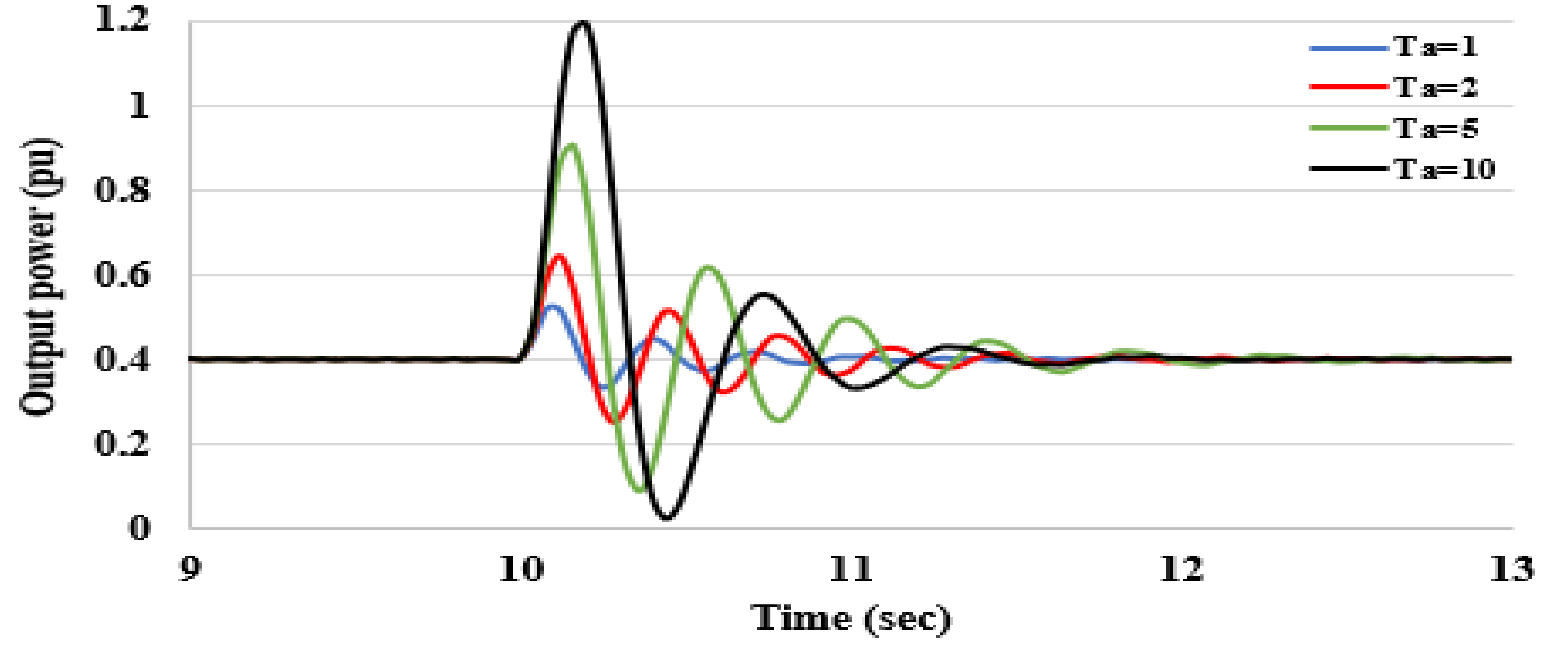

SMES maximum power versus damping constant in response to a microgrid frequency drop

# Simulation results: microgrid frequency drop



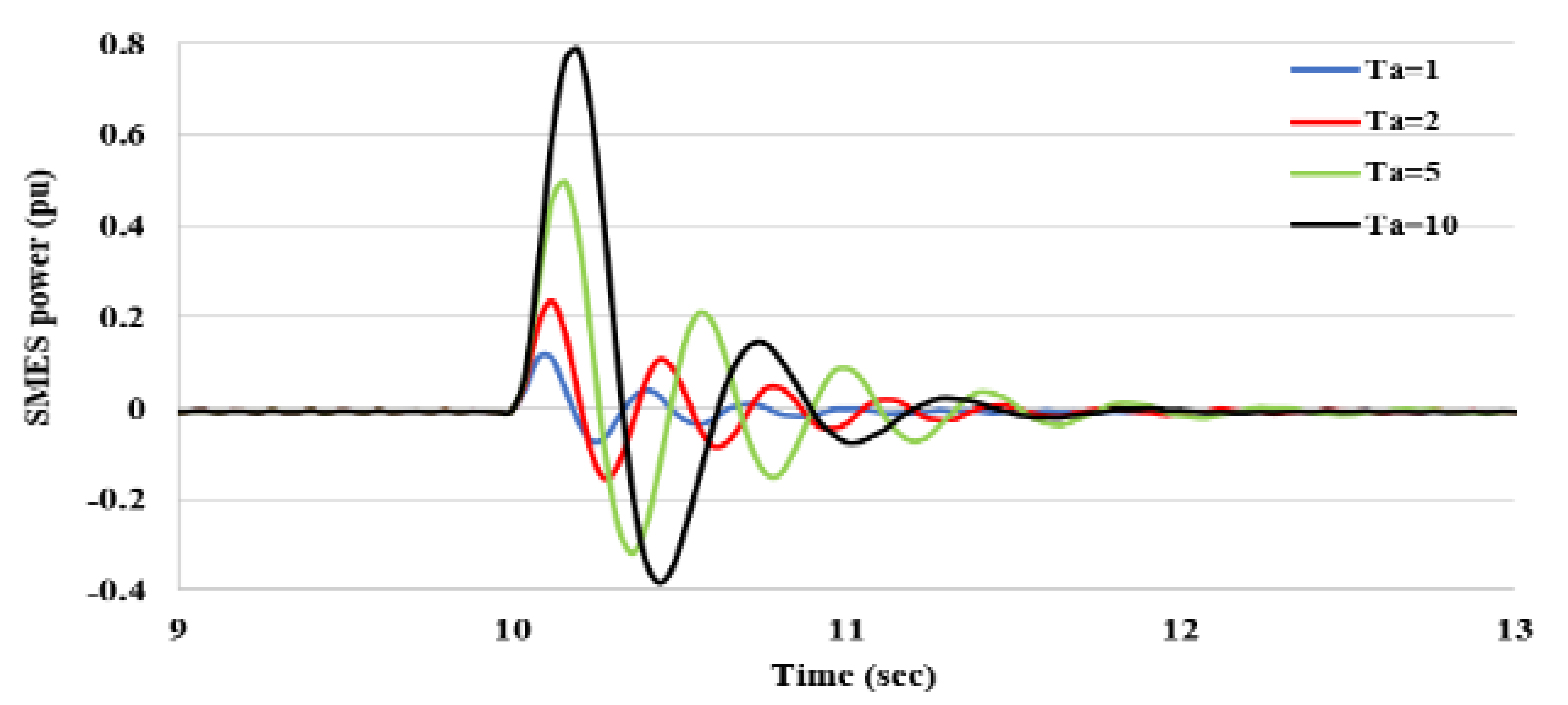

SMES generated energy versus damping constant in response to a microgrid frequency drop

# Simulation results: microgrid frequency drop at different inertia time constants



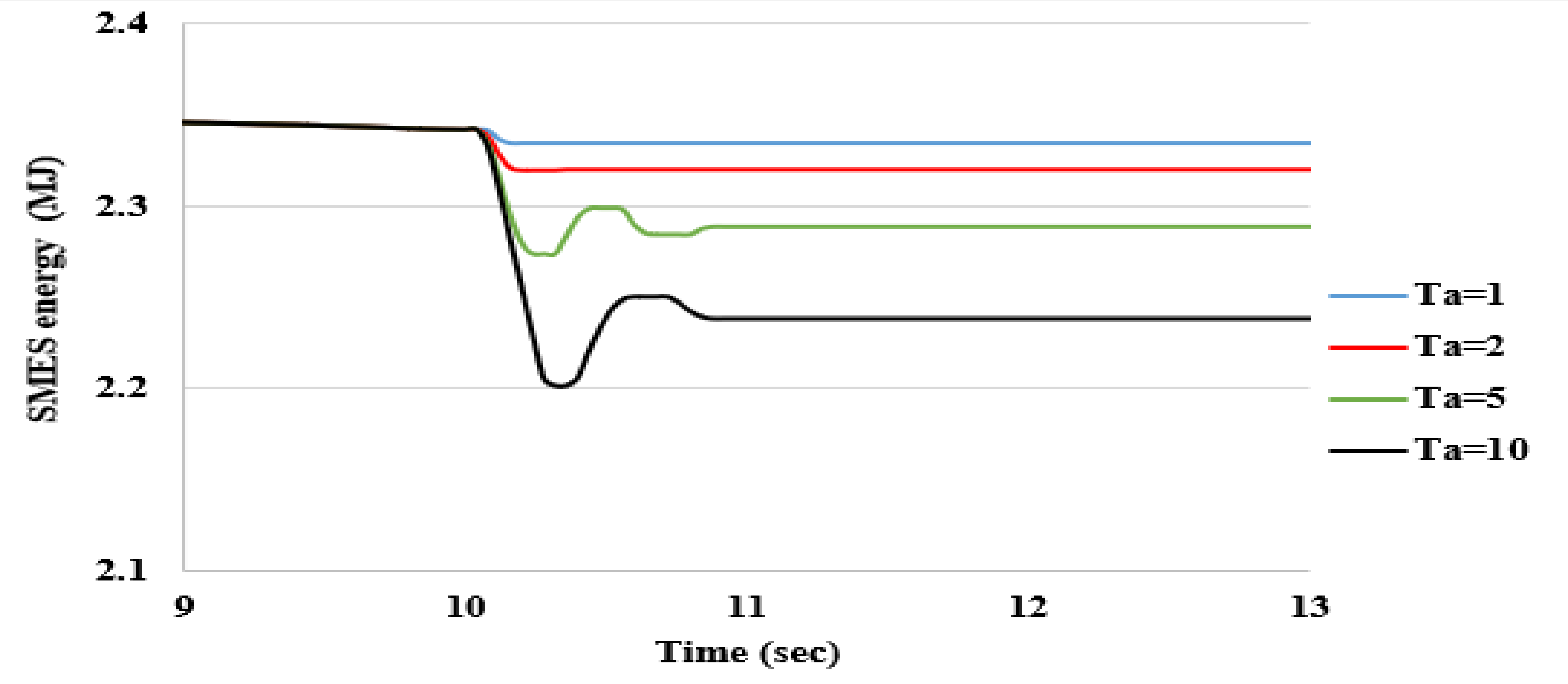

Converter output power at different inertia constants in response to a microgrid frequency drop (Kd=0.16)

# Simulation results: microgrid frequency drop



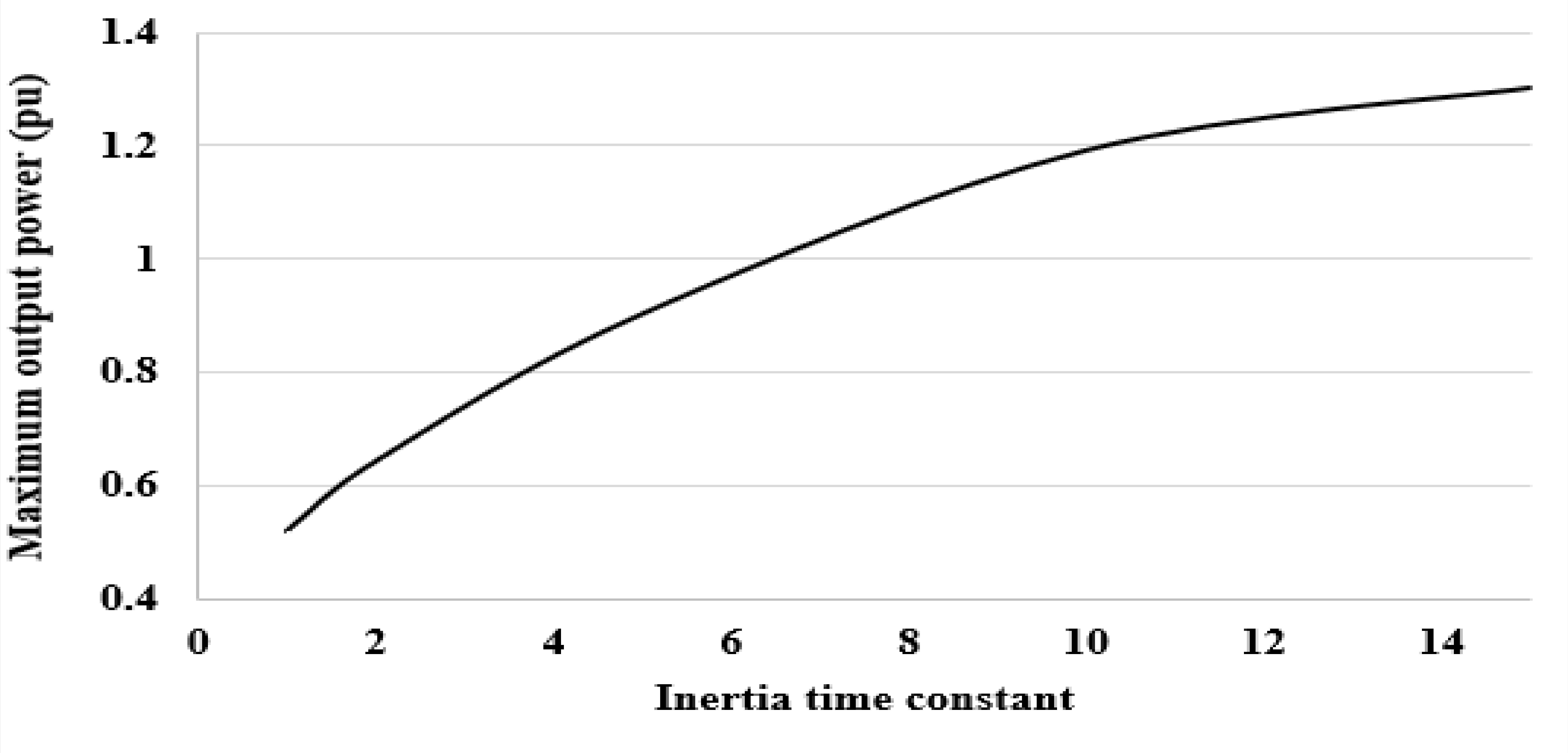

SMES output power at different inertia constants in response to a microgrid frequency drop (Kd=0.16)

# Simulation results: microgrid frequency drop



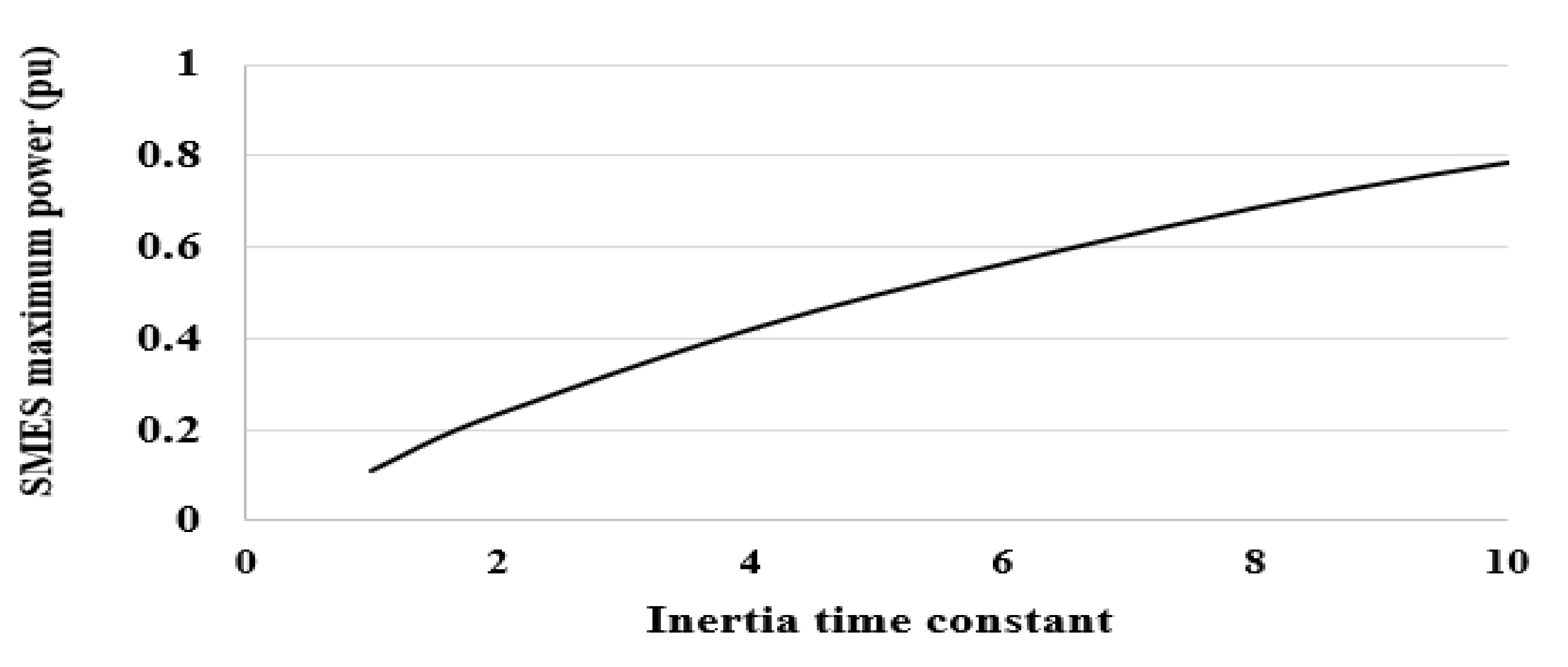

SMES energy at different inertia constants in response to a microgrid frequency drop (Kd=0.16)

# Simulation results: microgrid frequency drop



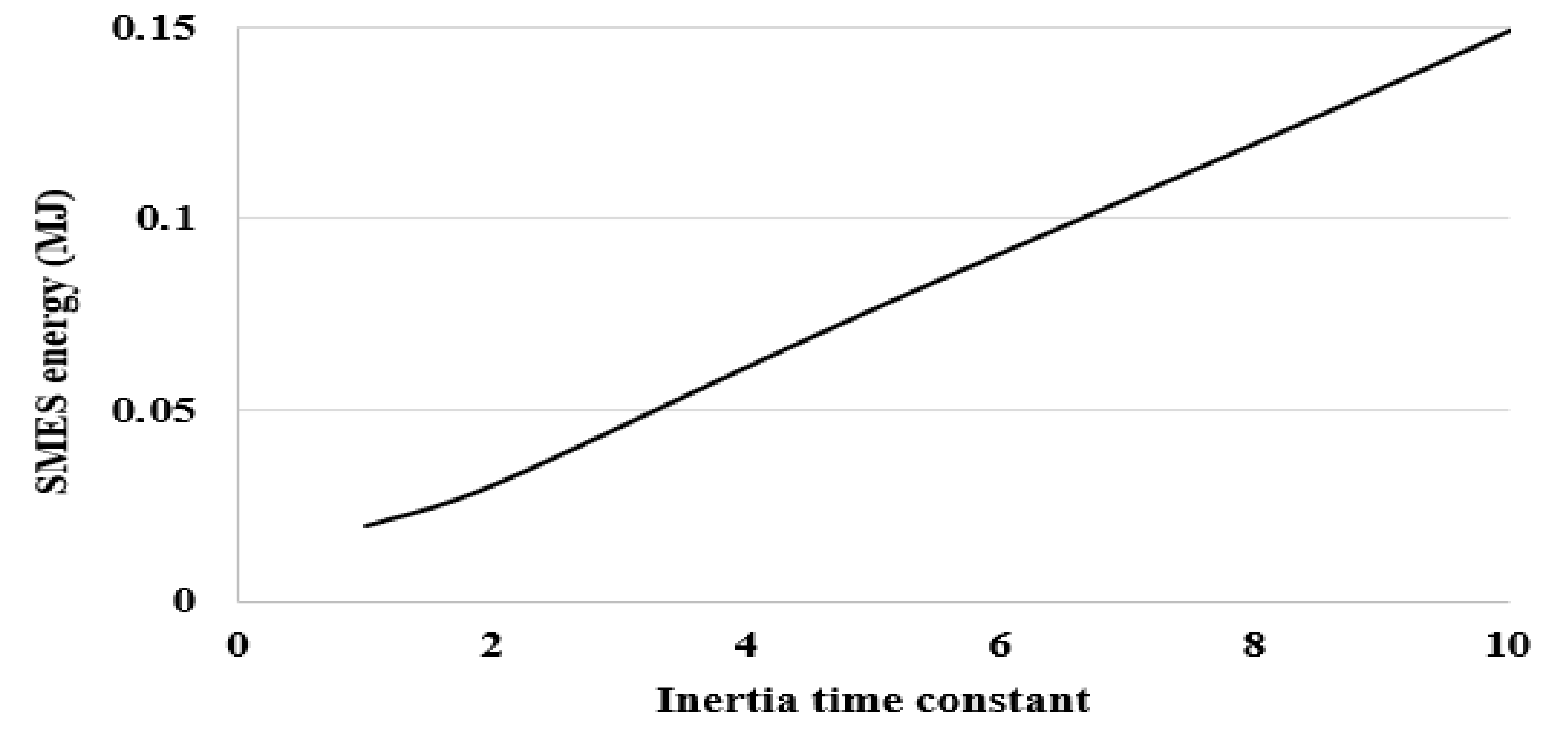

Maximum converter output power versus inertia constants in response to a microgrid frequency drop

# Simulation results: microgrid frequency drop




SMES maximum power versus inertia constants in response to a microgrid frequency drop

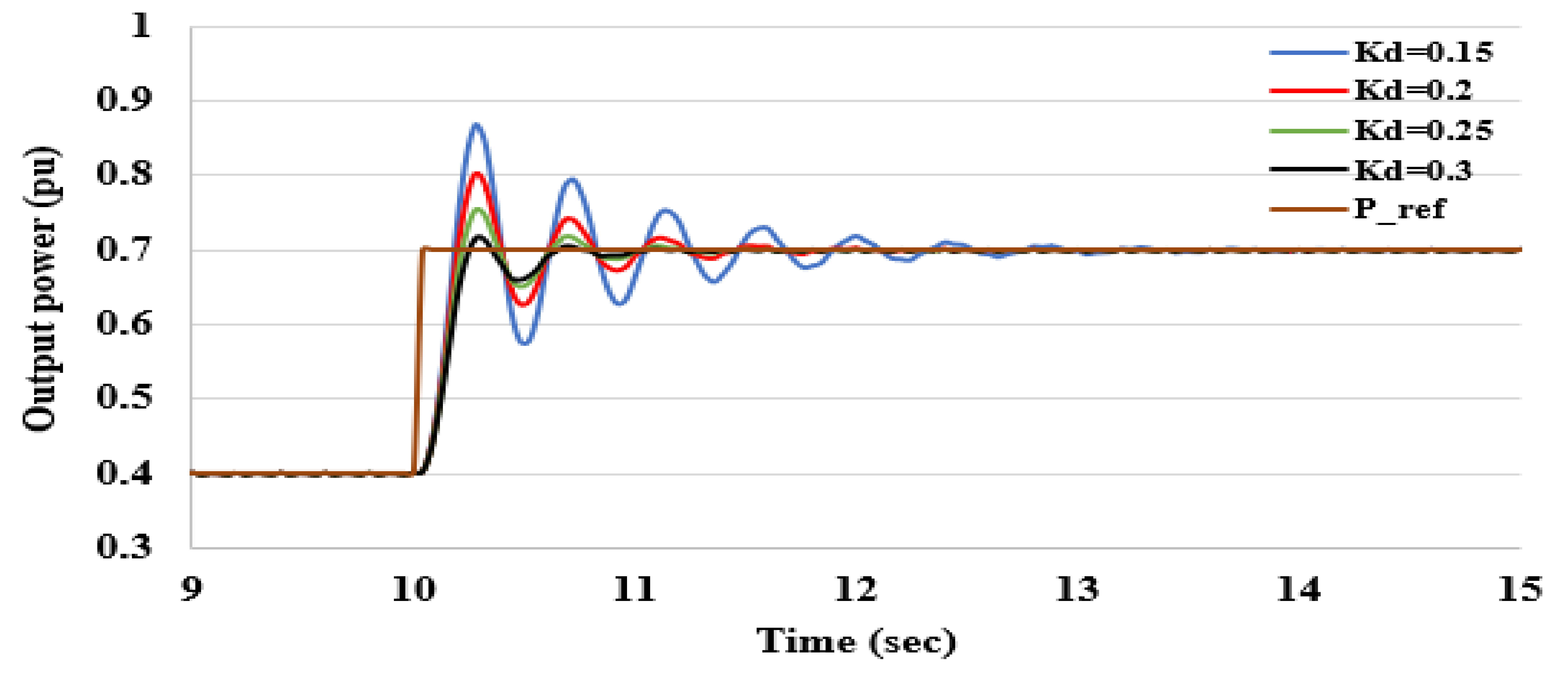
# Simulation results: microgrid frequency drop




SMES energy versus inertia constants in response to a microgrid frequency drop

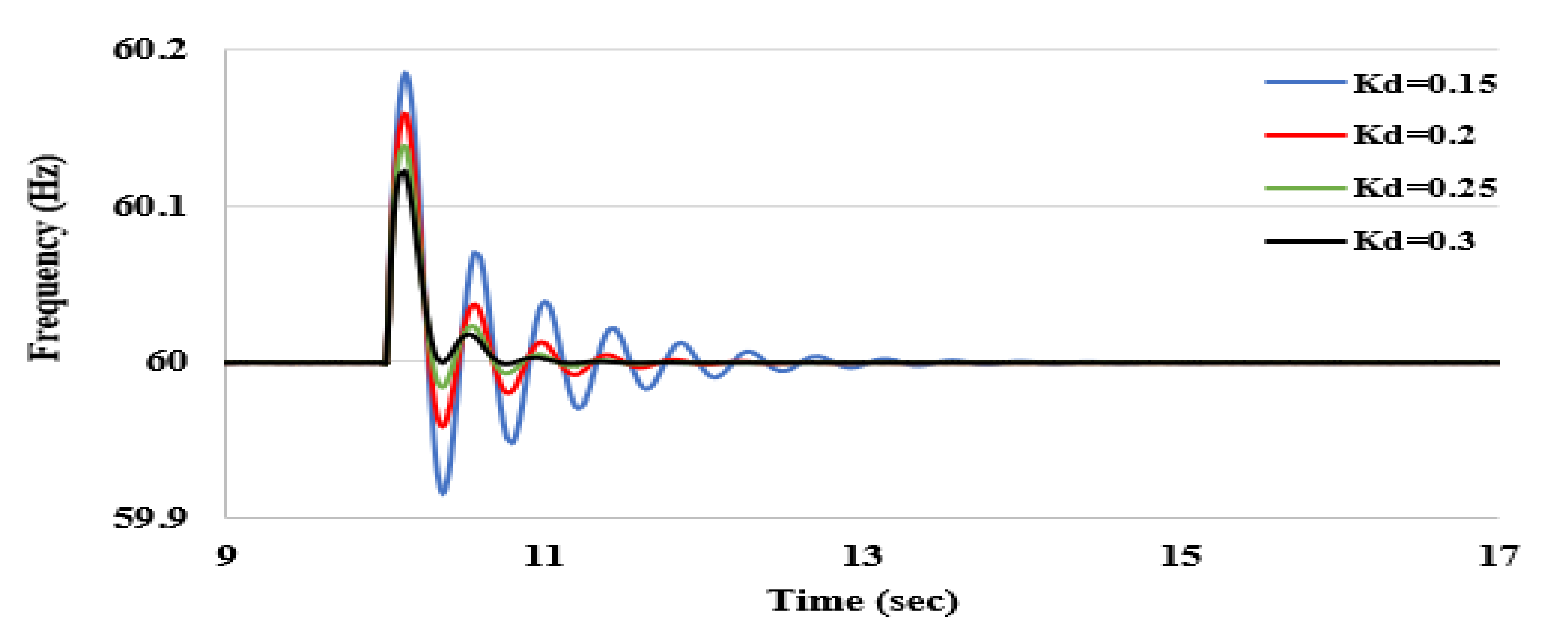
# Simulation results:

## **<u>step power setpoint increase</u>** at different damping constants



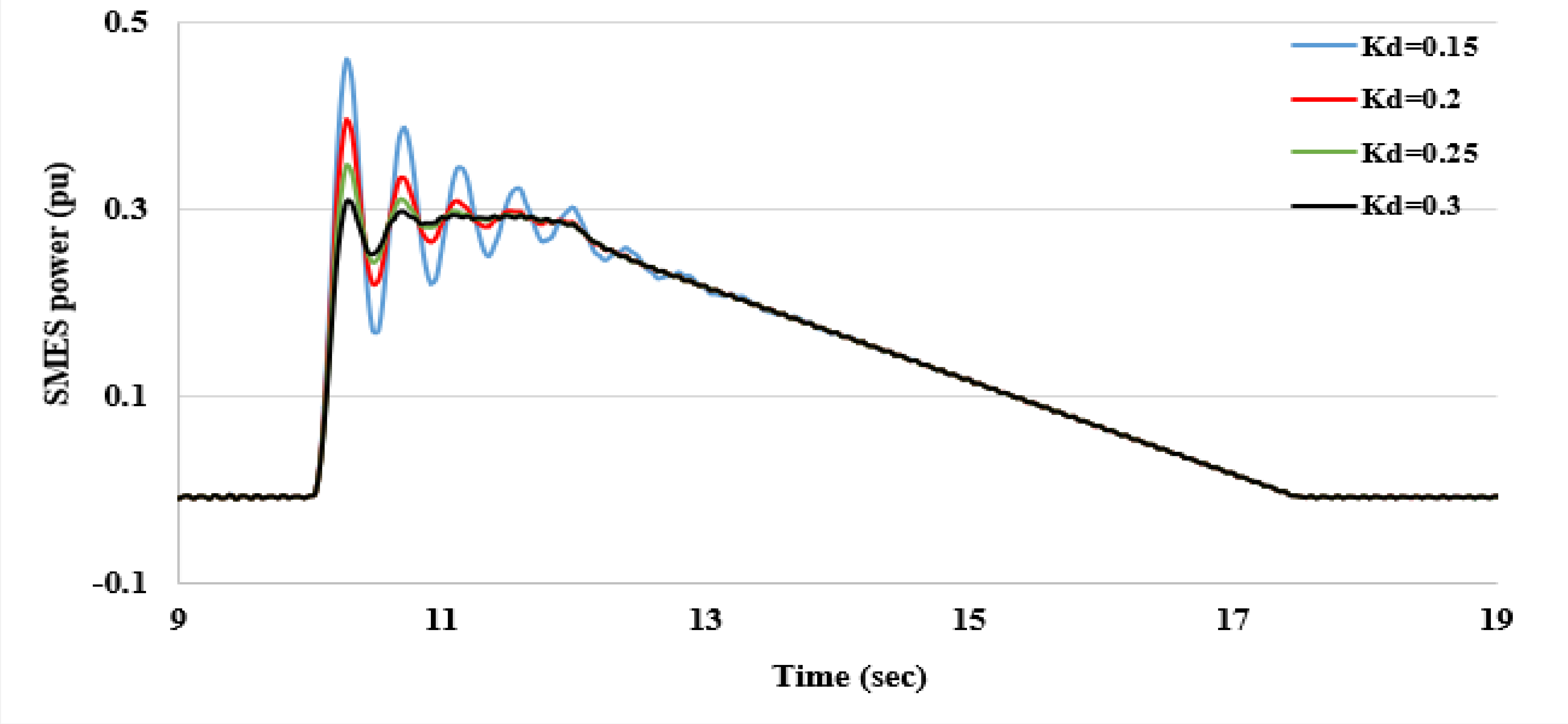

Converter power at different damping constants in response to step power setpoint increase (Ta=6)

# Simulation results: step power setpoint increase



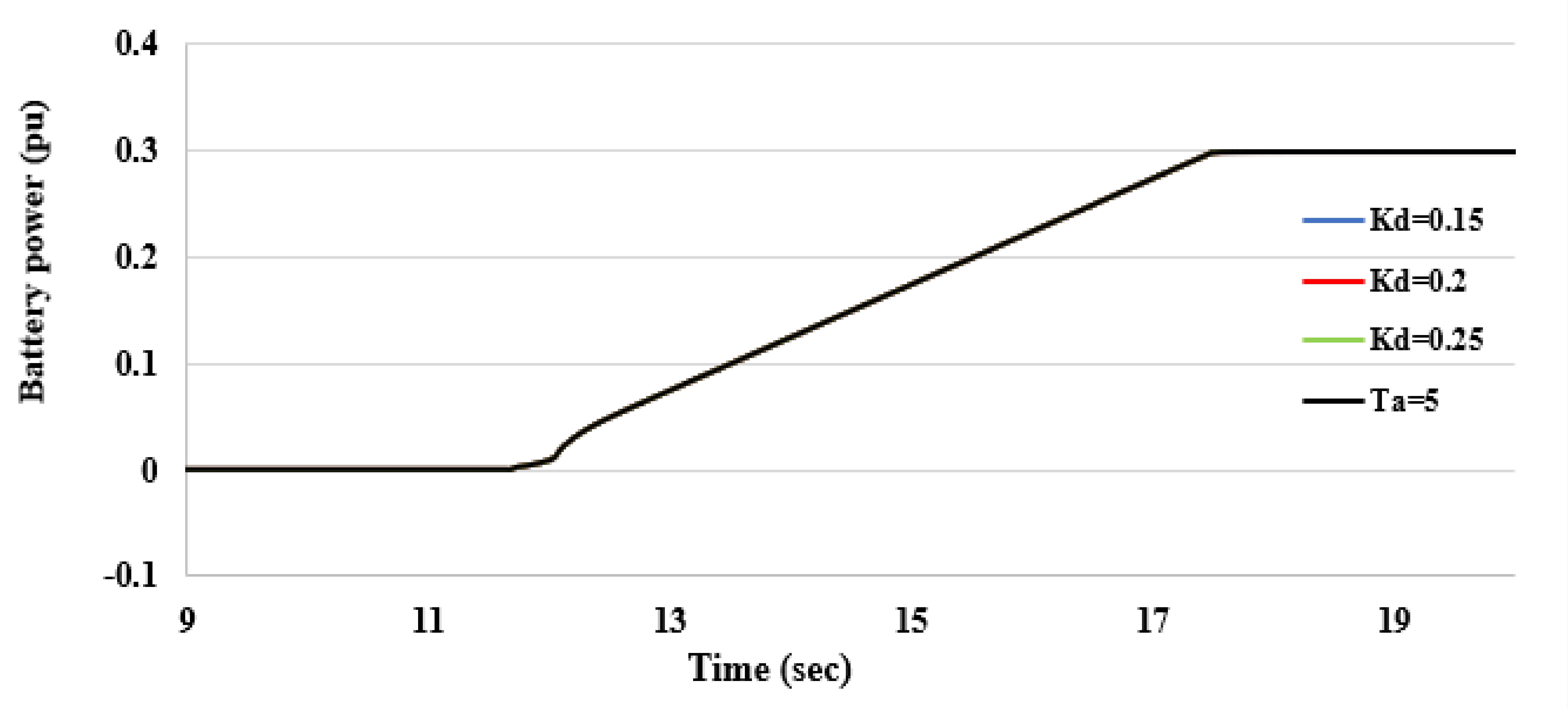

Frequency change at different damping constants in response to step power setpoint increase (Ta=6)

# Simulation results: step power setpoint increase



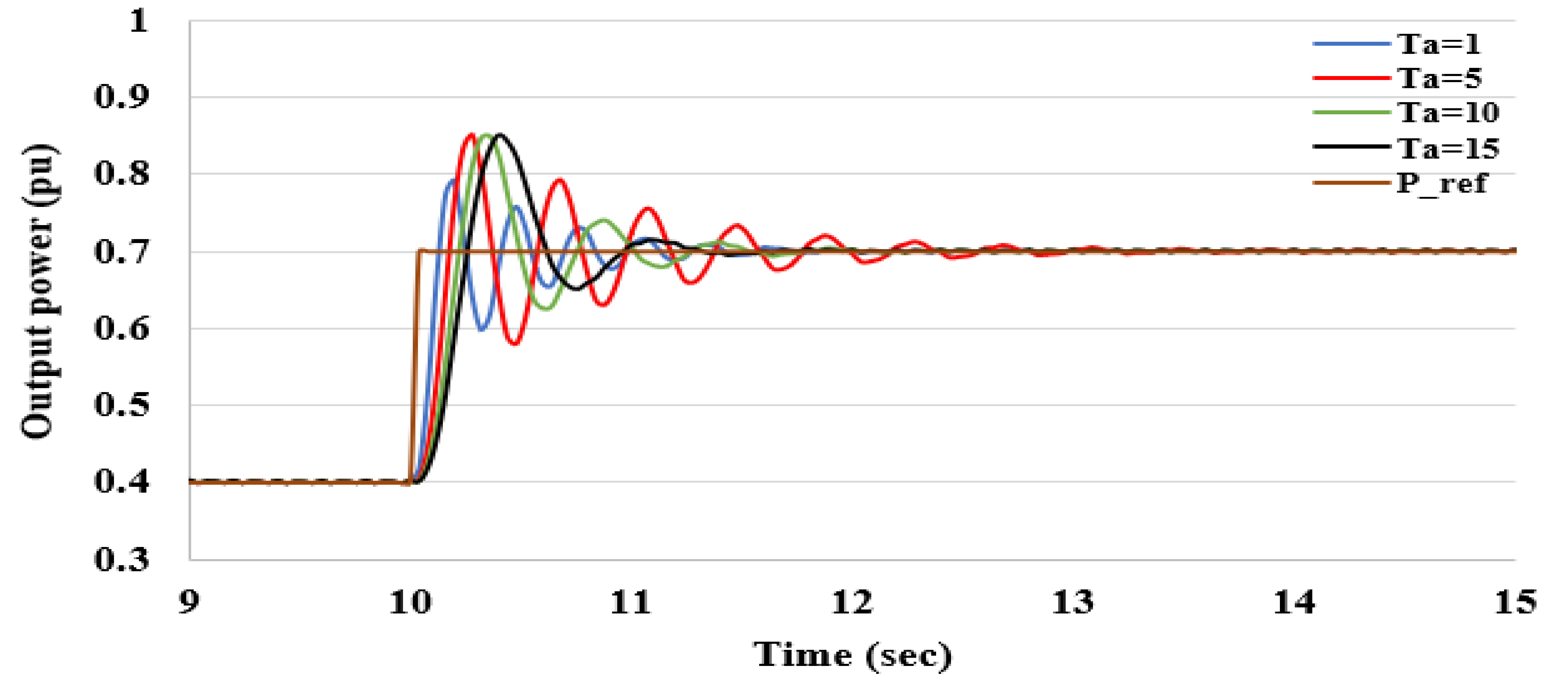

SMES power at different damping constant in response to step power setpoint increase (Ta=6)

# Simulation results: step power setpoint increase



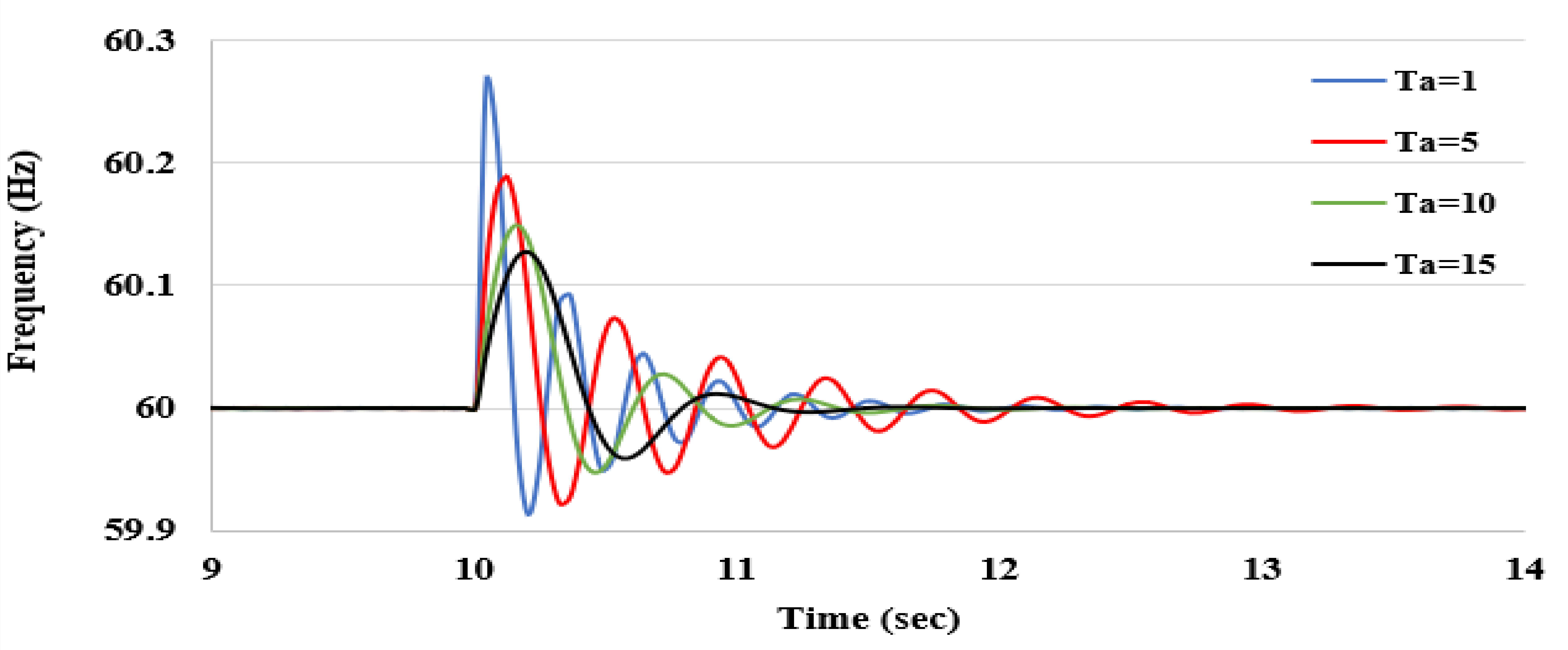

Battery power profile

# Simulation results: step power setpoint increase at different inertia time constants



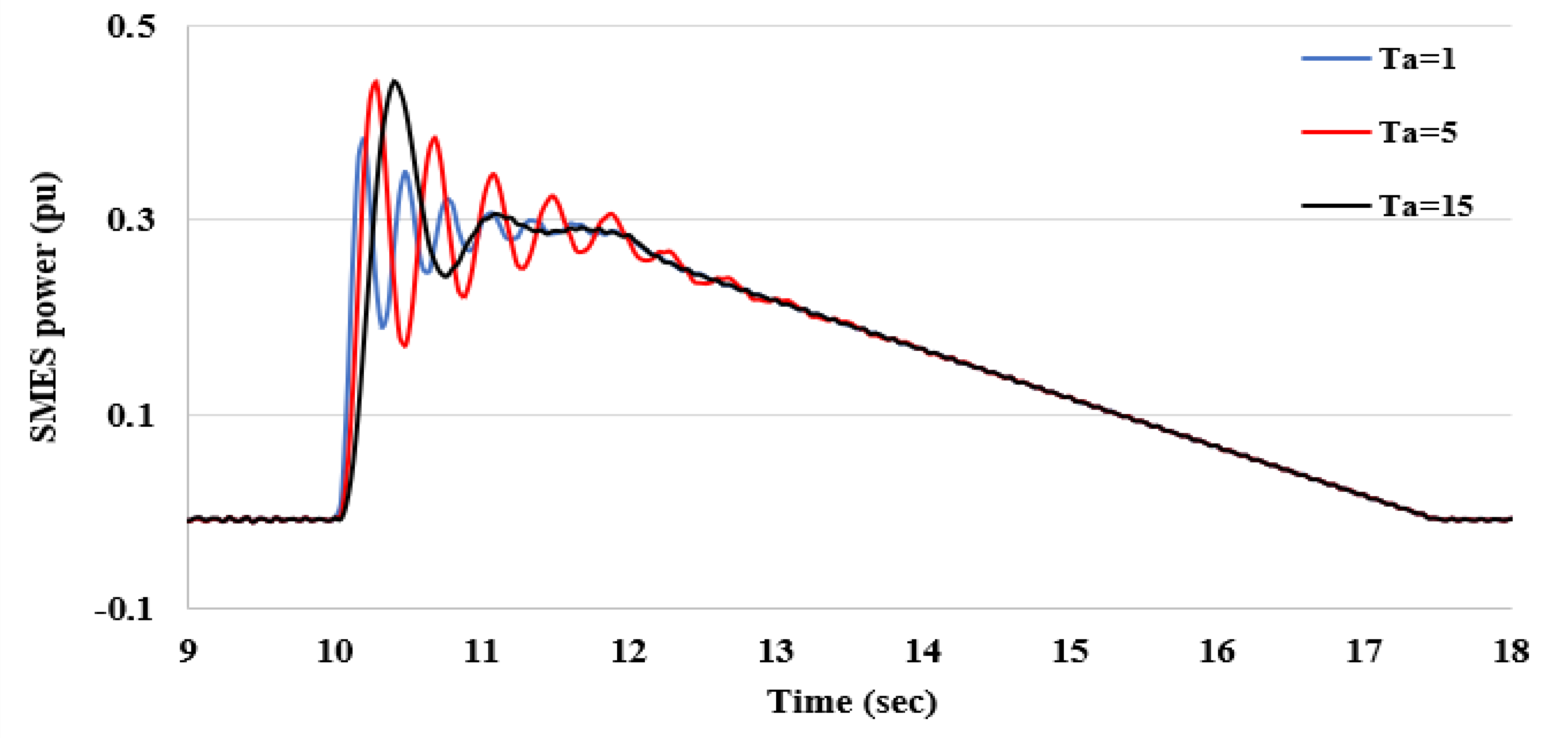

Converter power at different inertia constants in response to step power setpoint increase (Kd=0.16)

# Simulation results: step power setpoint increase



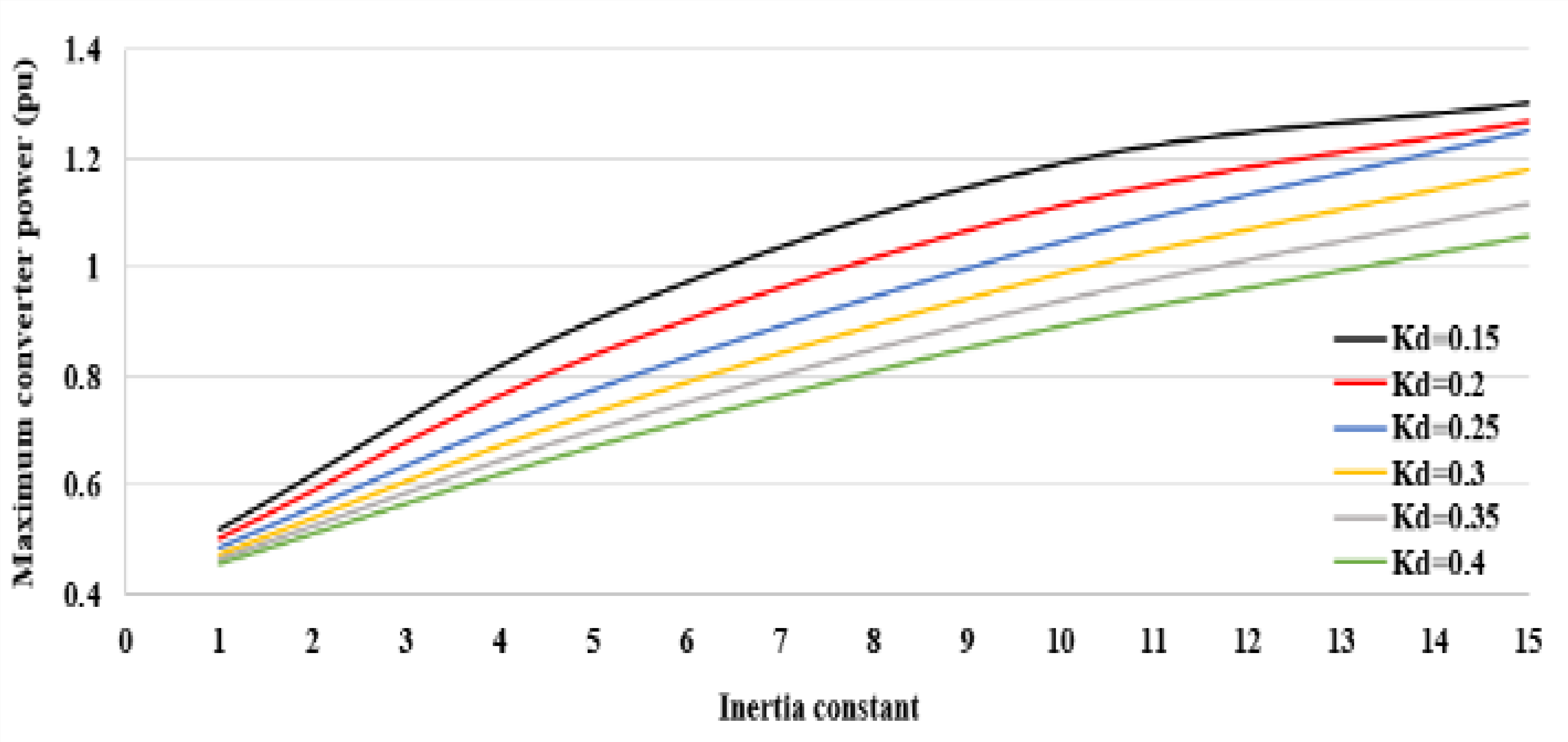

Frequency change at different inertia constants in response to step power setpoint increase (Kd=0.16)

# Simulation results: step power setpoint increase



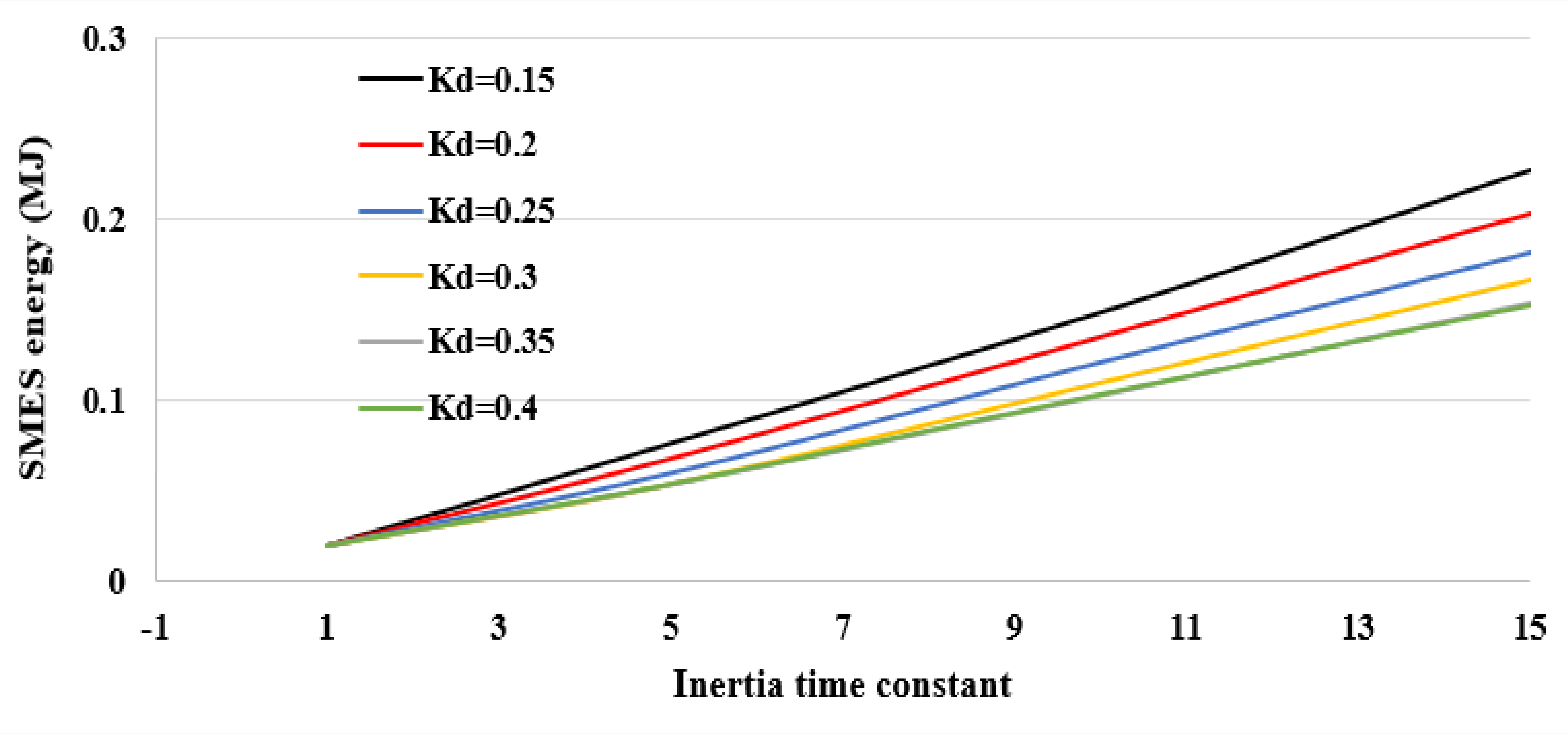

SMES power at different inertia constants in response to step power setpoint increase (Kd=0.16)

# Simulation results:



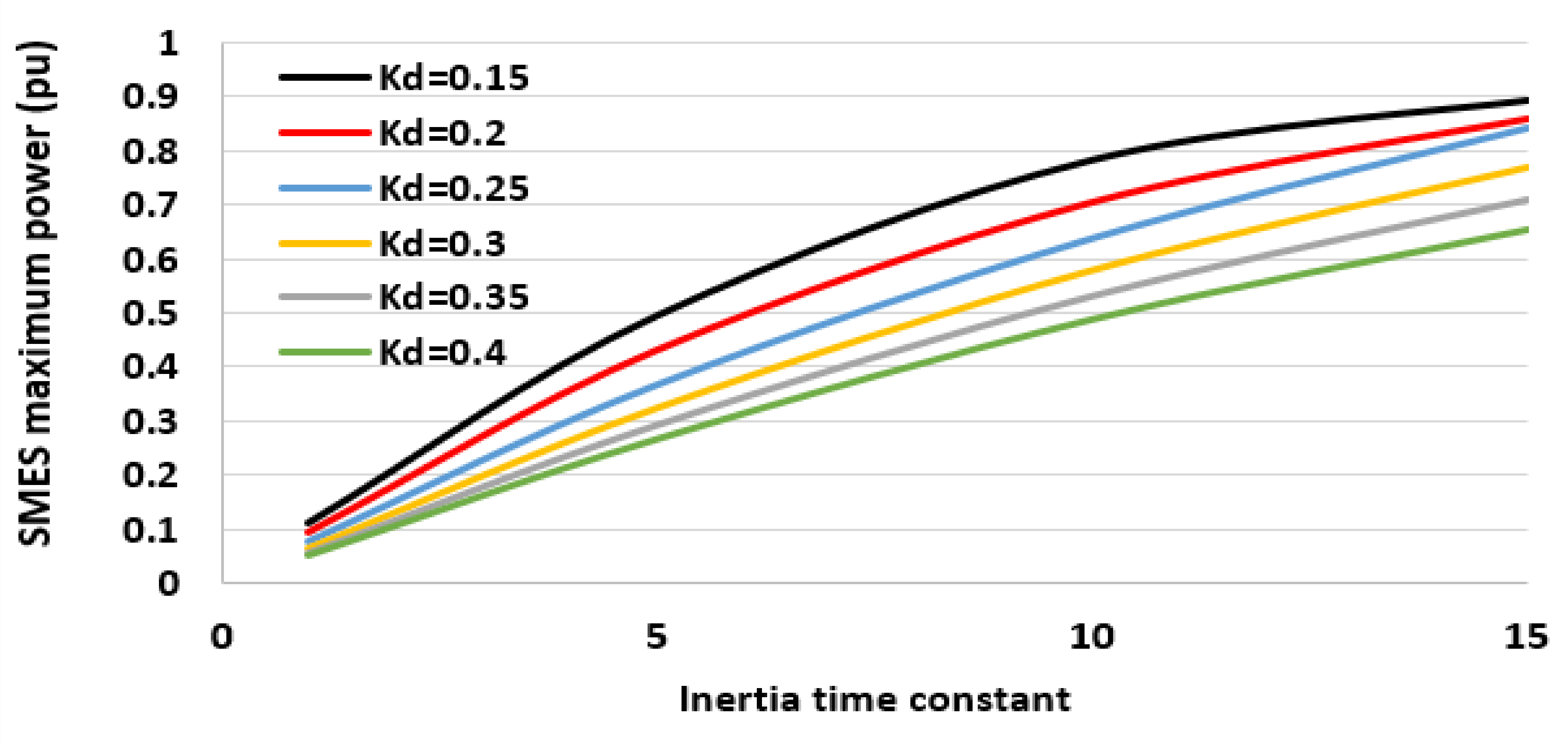

Converter output power at different inertia and damping constants

# Simulation results:



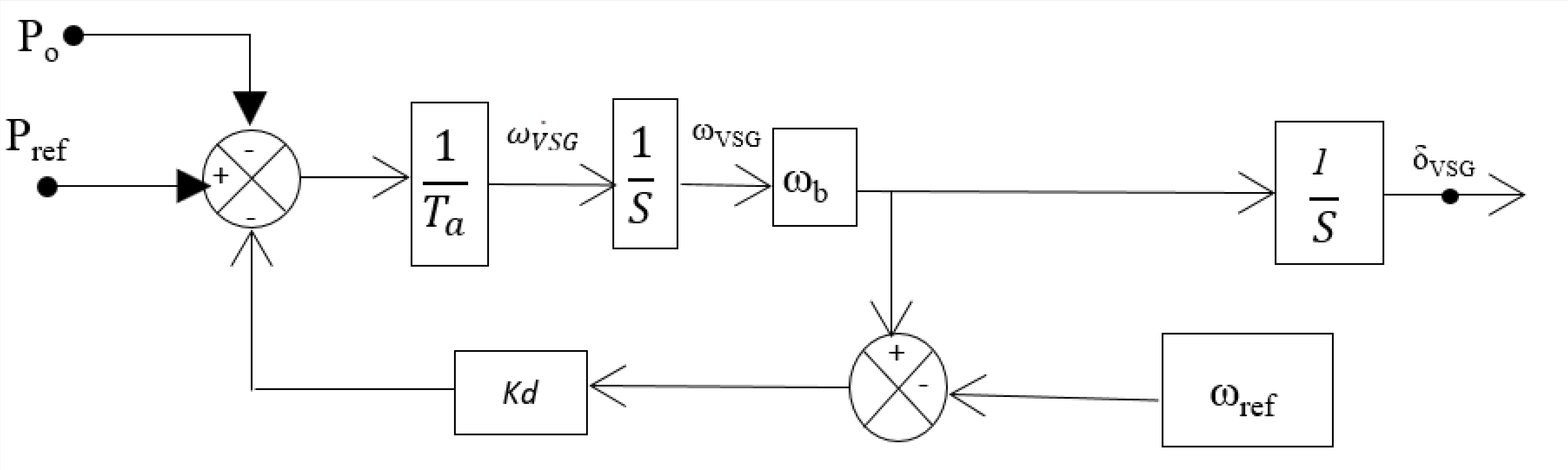

SMES energy at different inertia and damping constants

# Simulation results:



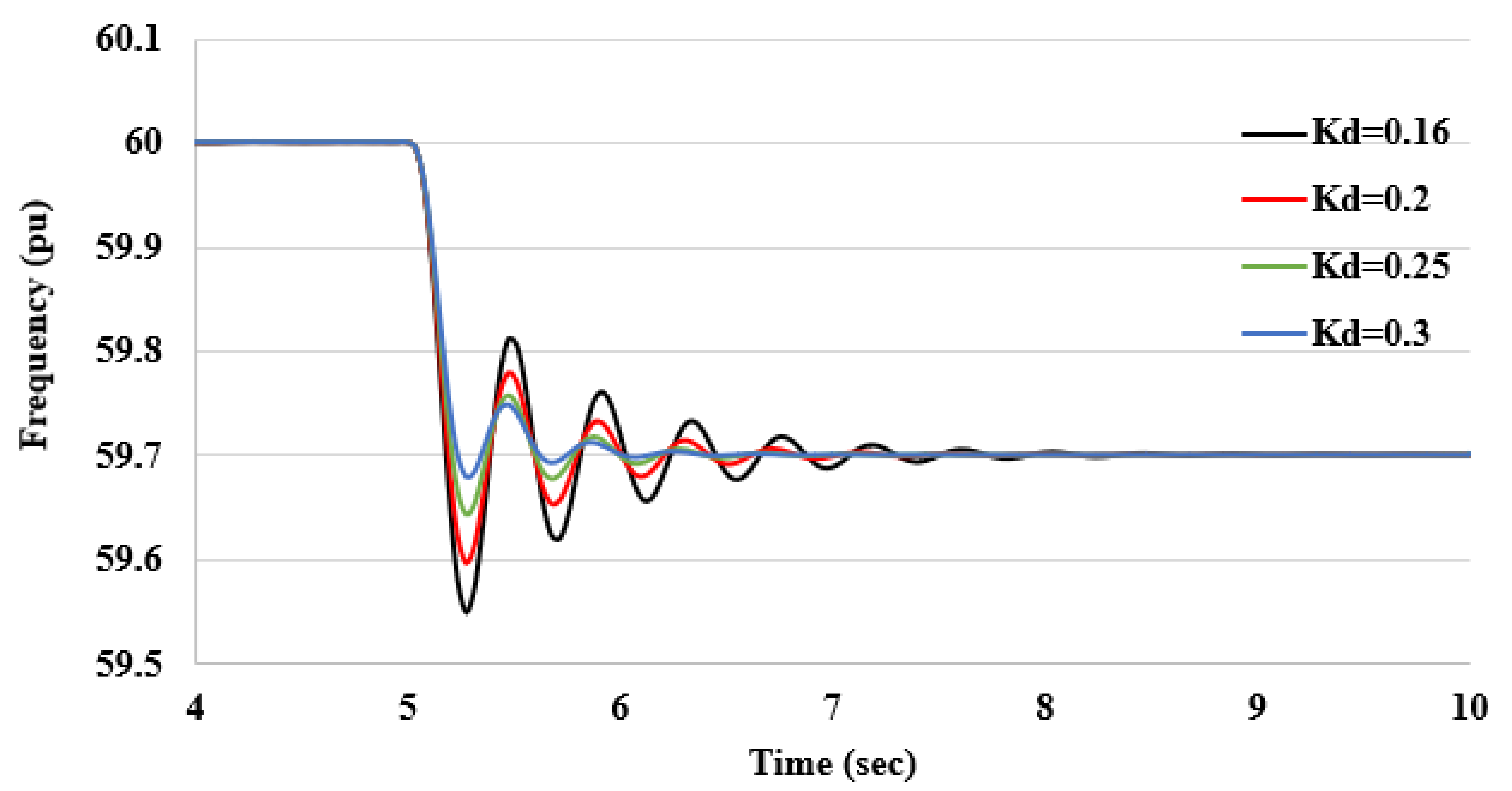

SMES maximum power at different inertia and damping constants

Outer loops: virtual inertia emulation



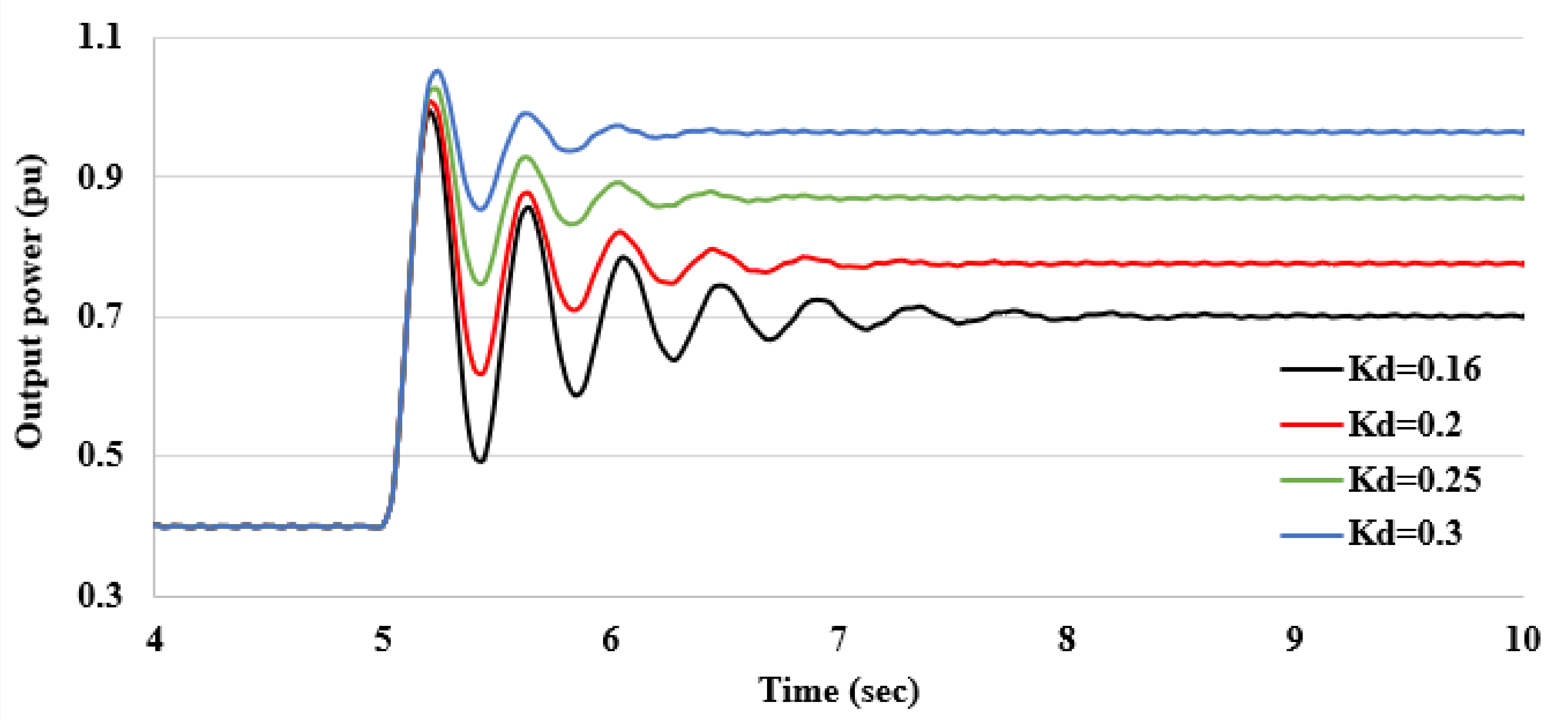

Virtual inertia emulation outer loops

# Simulation results: microgrid frequency drop at different damping constants



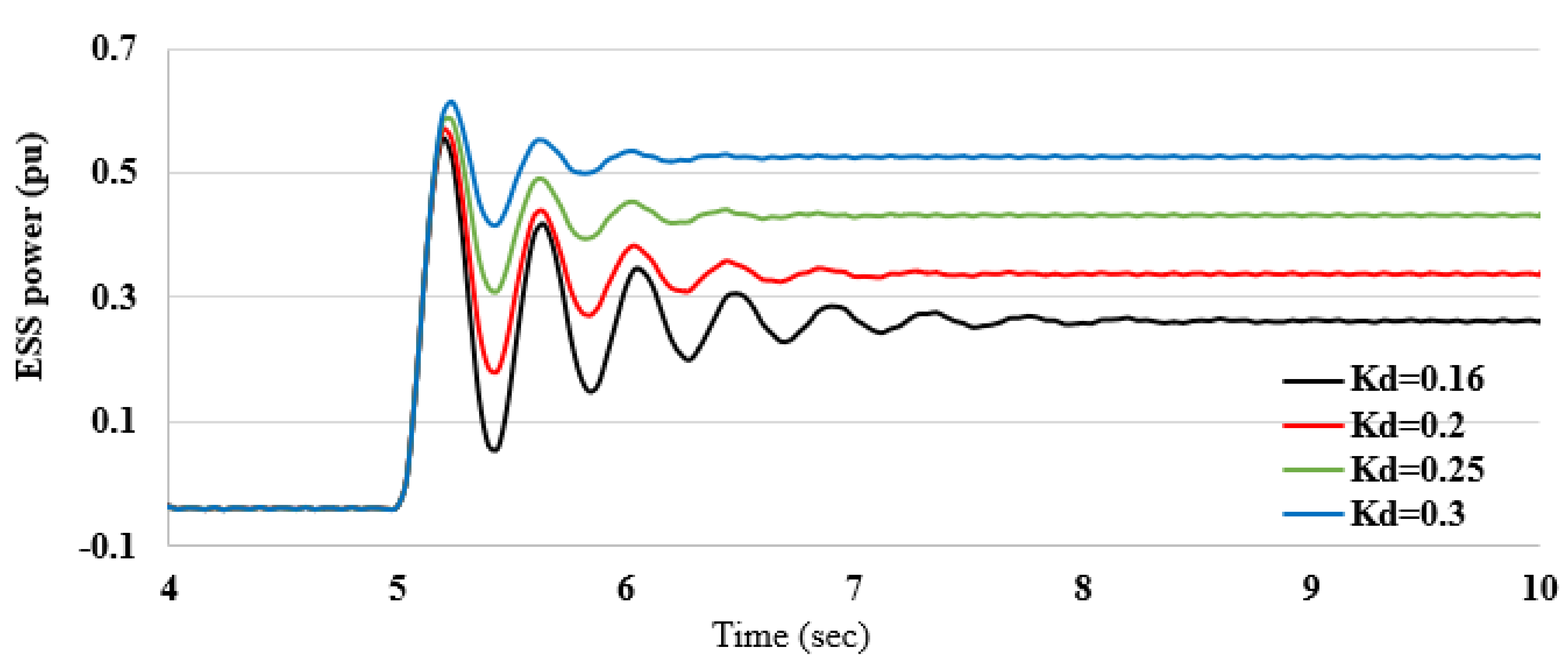

VSM frequency response to a microgrid frequency drop at different damping constants (Ta=6)

# Simulation results: microgrid frequency drop at different damping constants



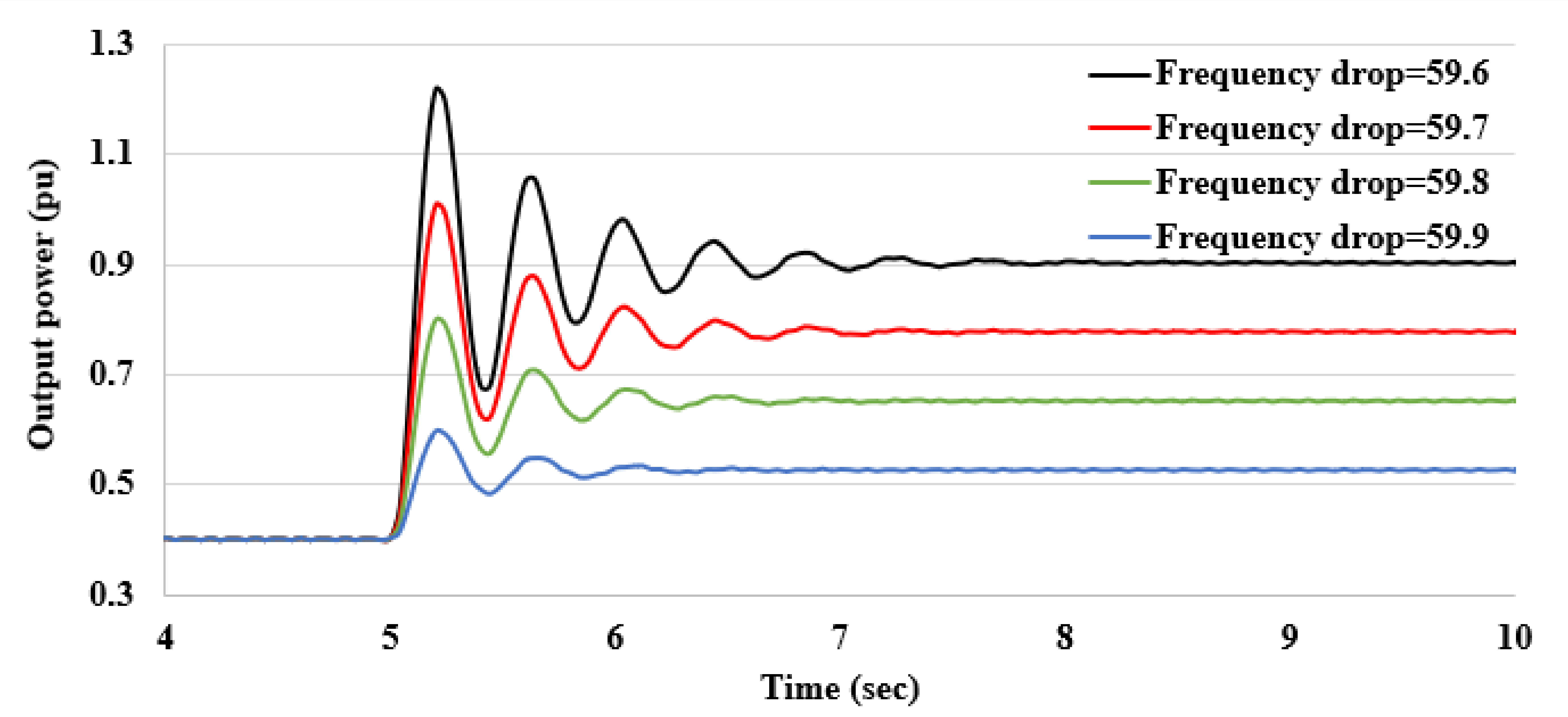

Converter output power at different damping constants in response to microgrid frequency drop (Ta=6)

# Simulation results: microgrid frequency drop at different damping constants



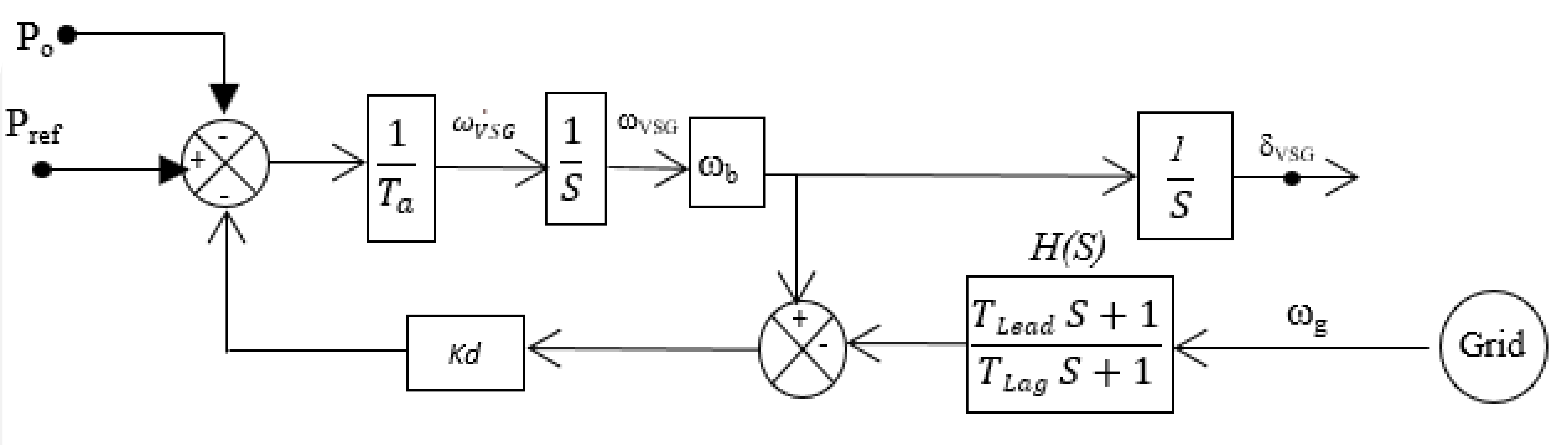

ESS power at different damping constants in response to microgrid frequency drop (Ta=6)

# Simulation results: microgrid frequency drop at different damping constants



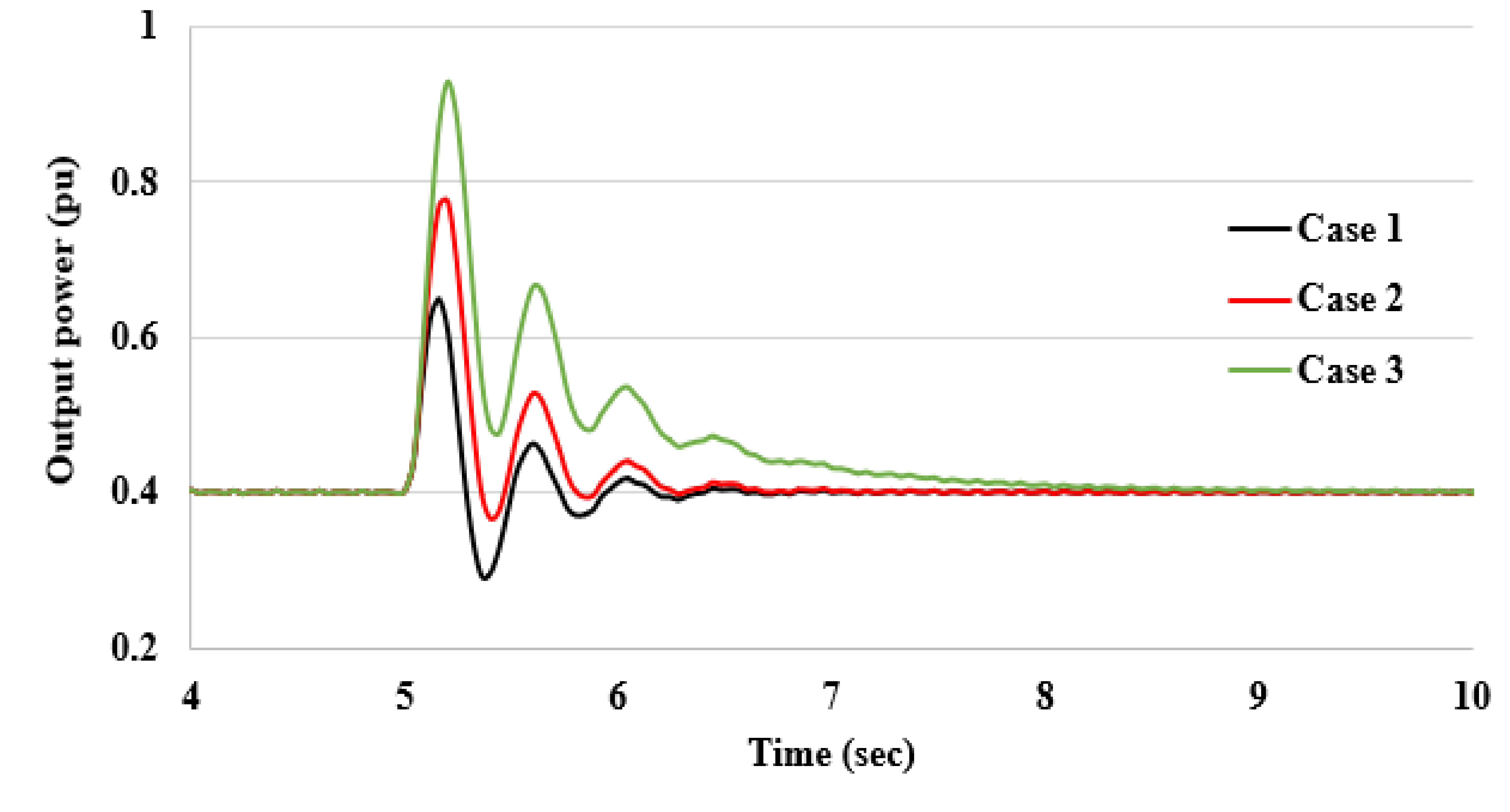

Converter output power in response to microgrid different frequency drop values (Kd=0.2)

# Phase compensation method




Lead-lag compensator cascaded with the grid frequency

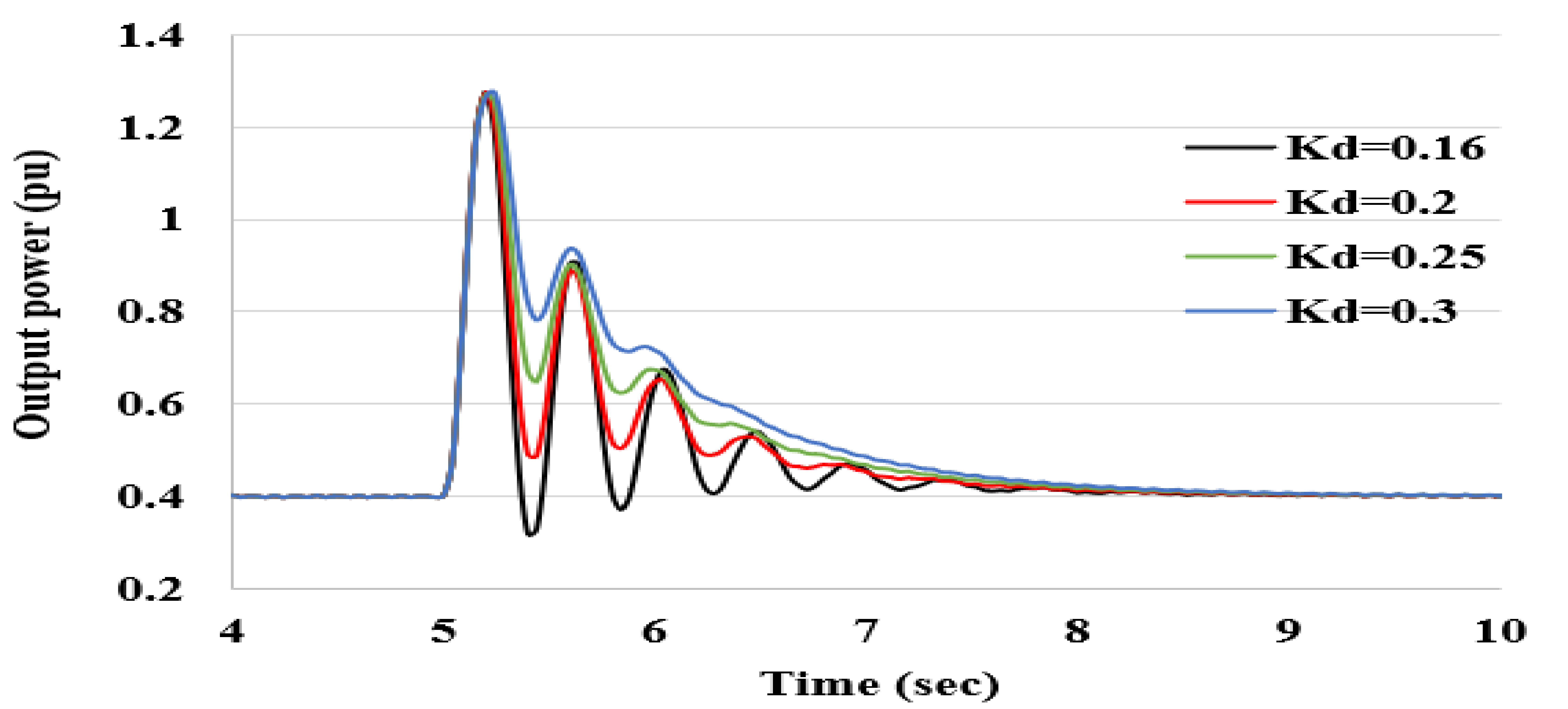
# Simulation results: microgrid frequency drop at different damping constants




|  | $T_{lead}$ | $T_{lag}$ |
|---|---|---|
| Case1 | 0 | 0 |
| Case2 | 0.2 | 0.4 |
| Case3 | 0.1 | 0.8 |

Converter output power at different cases (Ta=6, Kd=0.2)

# Simulation results: microgrid frequency drop at different damping constants

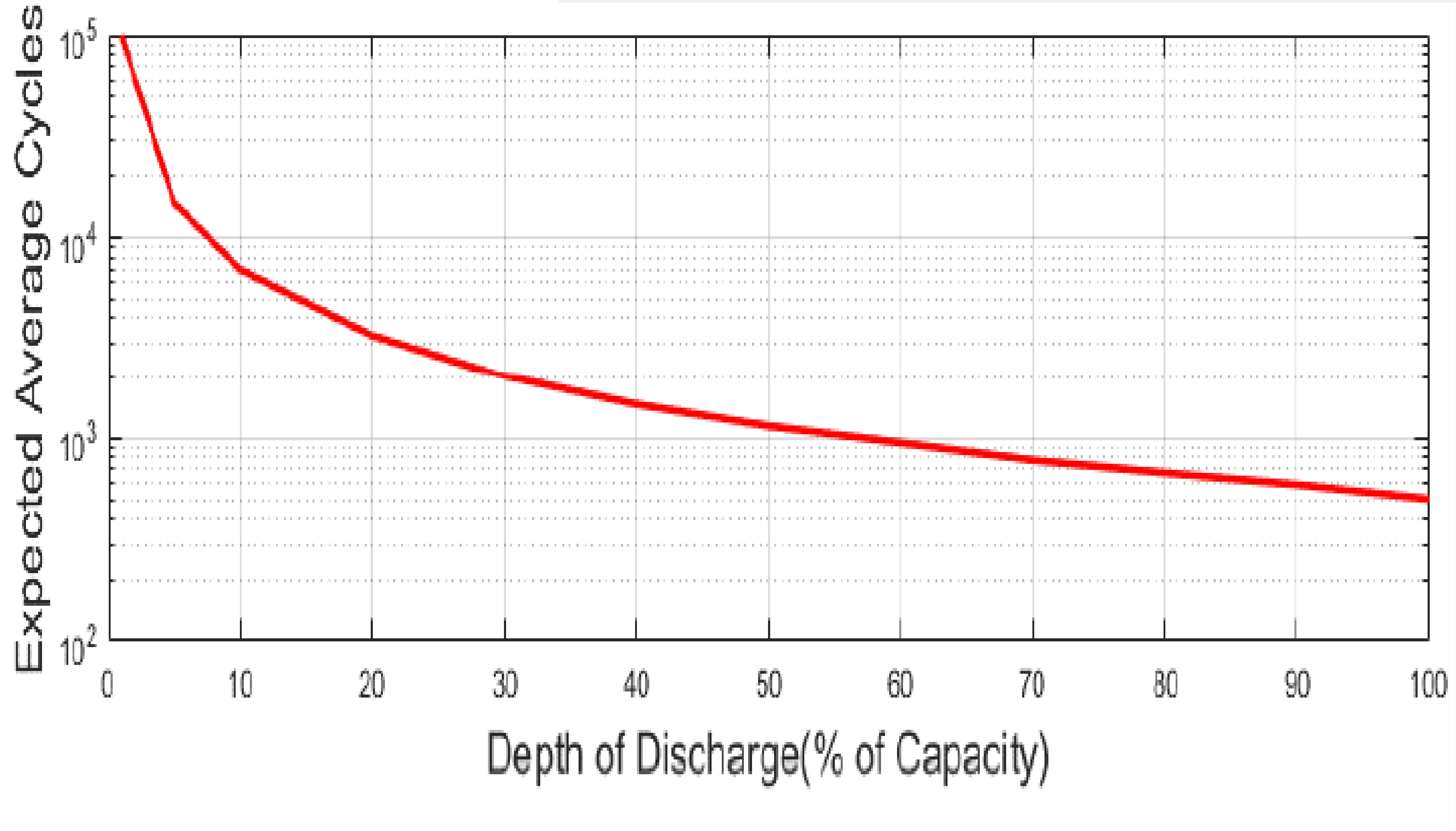



Converter output power at different damping constants for the parameters at cases2 ($T_{lead}$=0.2, $T_{lag}$=0.4)

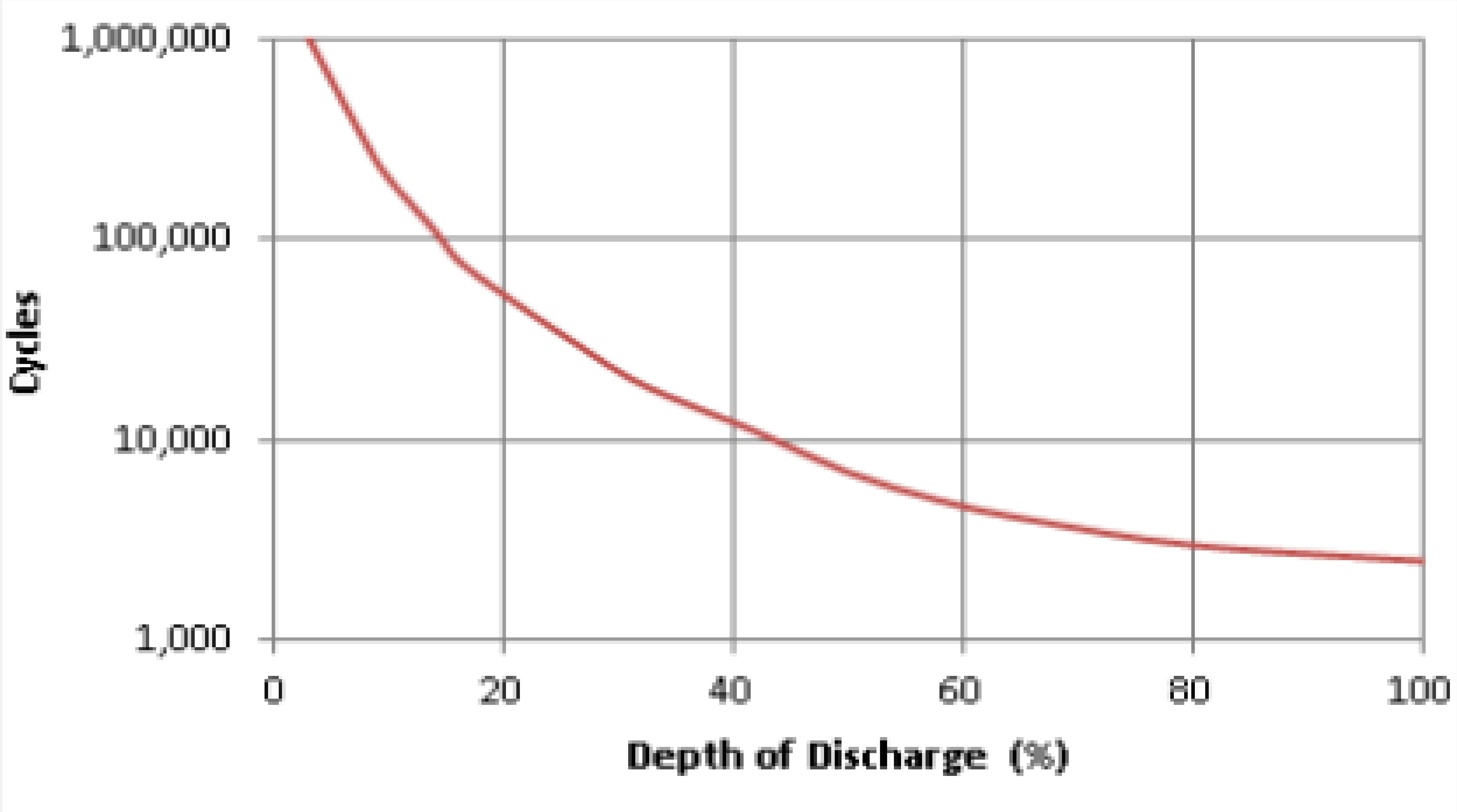
# Comparison between different types of ESSs:

| Characteristics of ESS | SMES | Li-ion | Lead-acid | Supercapacitor |
|---|---|---|---|---|
| Energy density (Wh/Kg) | 1-10 | 70 - 200 | 30 - 50 | 0.5 - 5 |
| Power density (W/Kg) | 500-2000 | 150-500 | 75-300 | 1000-10000 |
| Capital cost($/kWh) | 1000-10000 | 600-2500 | 200-400 | 500-15000 |
| Capital cost($/kW) | 200-500 | 1200-4000 | 300-600 | 100-400 |
| Life (cycles) | 100000+ | 1000-10000 | 500-1000 | - |
| Discharge time | m sec-hrs | mins-hrs | sec-hrs | m sec-60 min |

# Comparison between different types of ESSs' Cost:

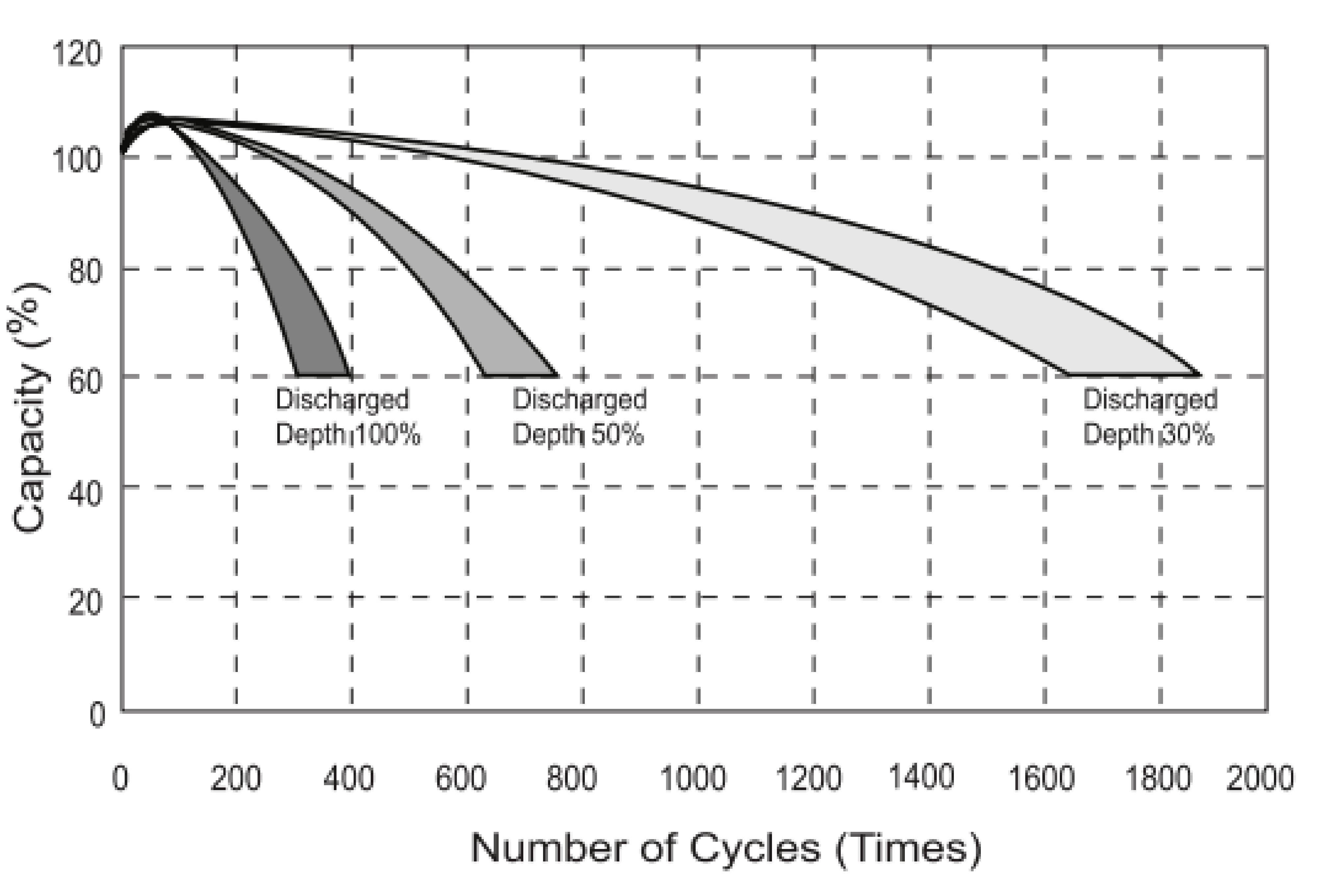



Cycle life versus DOD curve for a lead-acid battery

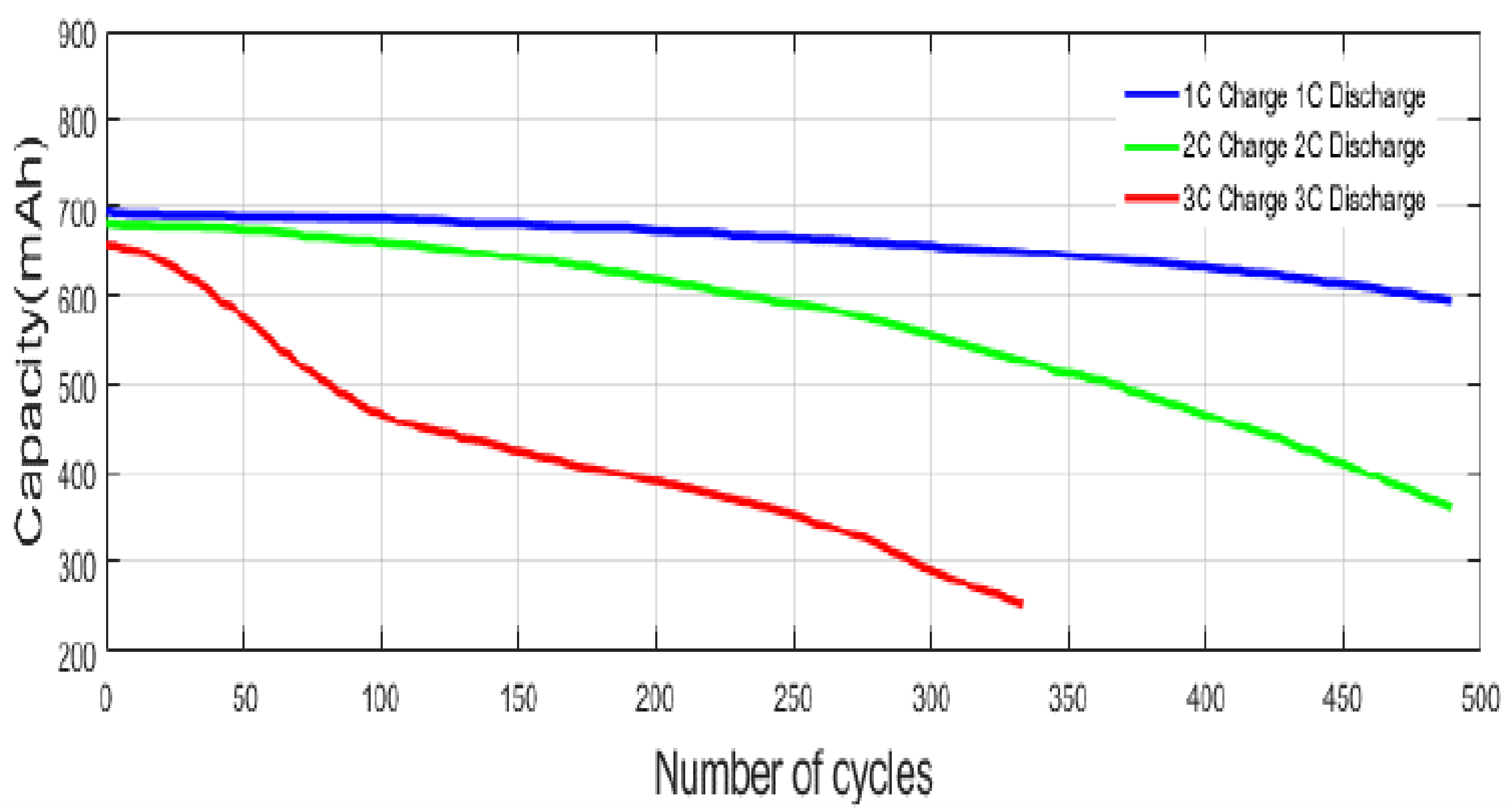



Cycle life versus DOD curve for a li-ion battery

# Comparison between different types of ESSs:




Battery capacity versus number of cycles for lead-acid battery




Battery capacity versus number of cycles under different rates for Li-ion battery

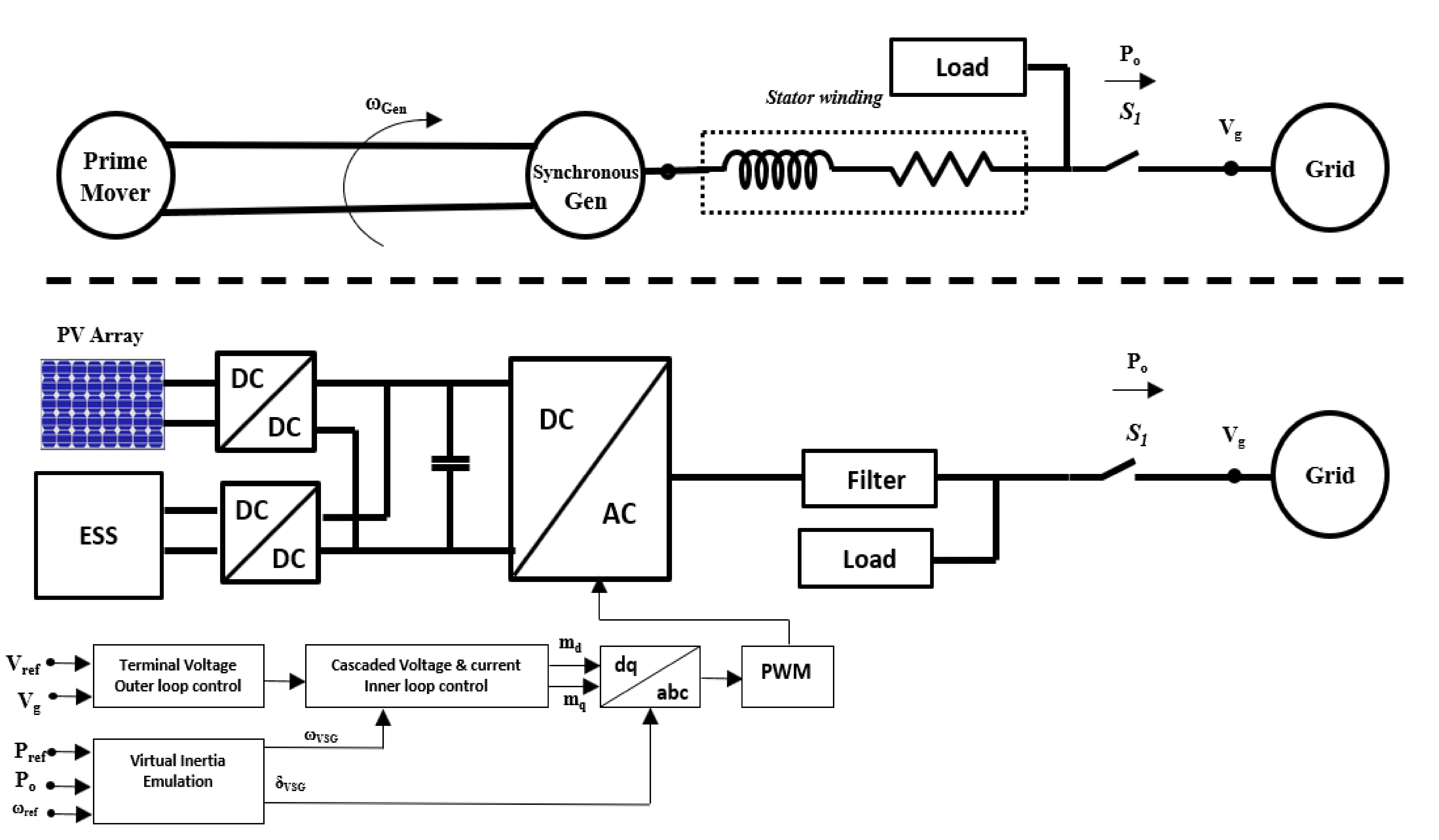
**1 kW, 1 kWh System Cost is:**

SMES cost is $ 6000

Lithium-ion battery cost = $ 4000

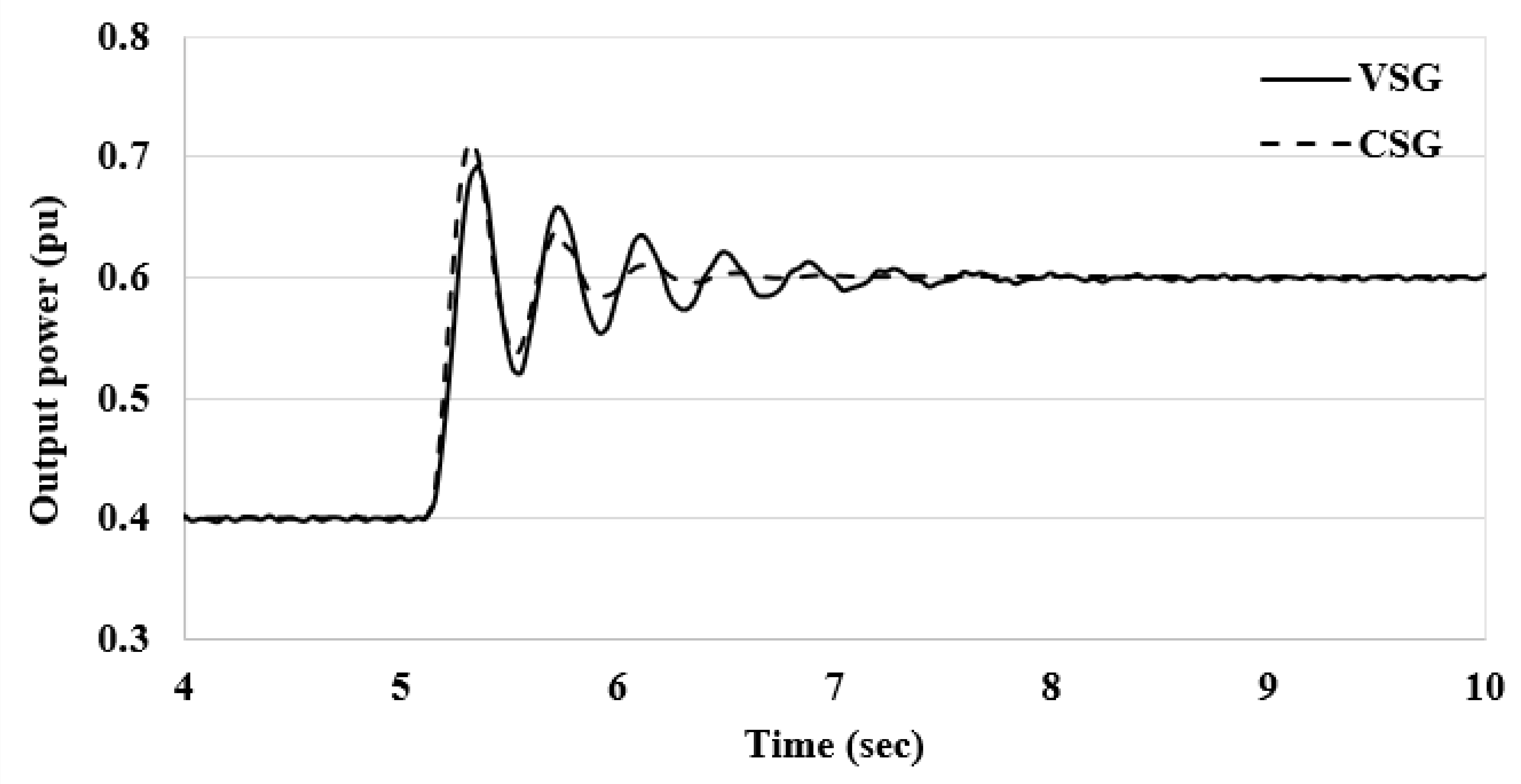
Lead-acid battery cost = $ 750

## Verification of VSG Compared to CSG



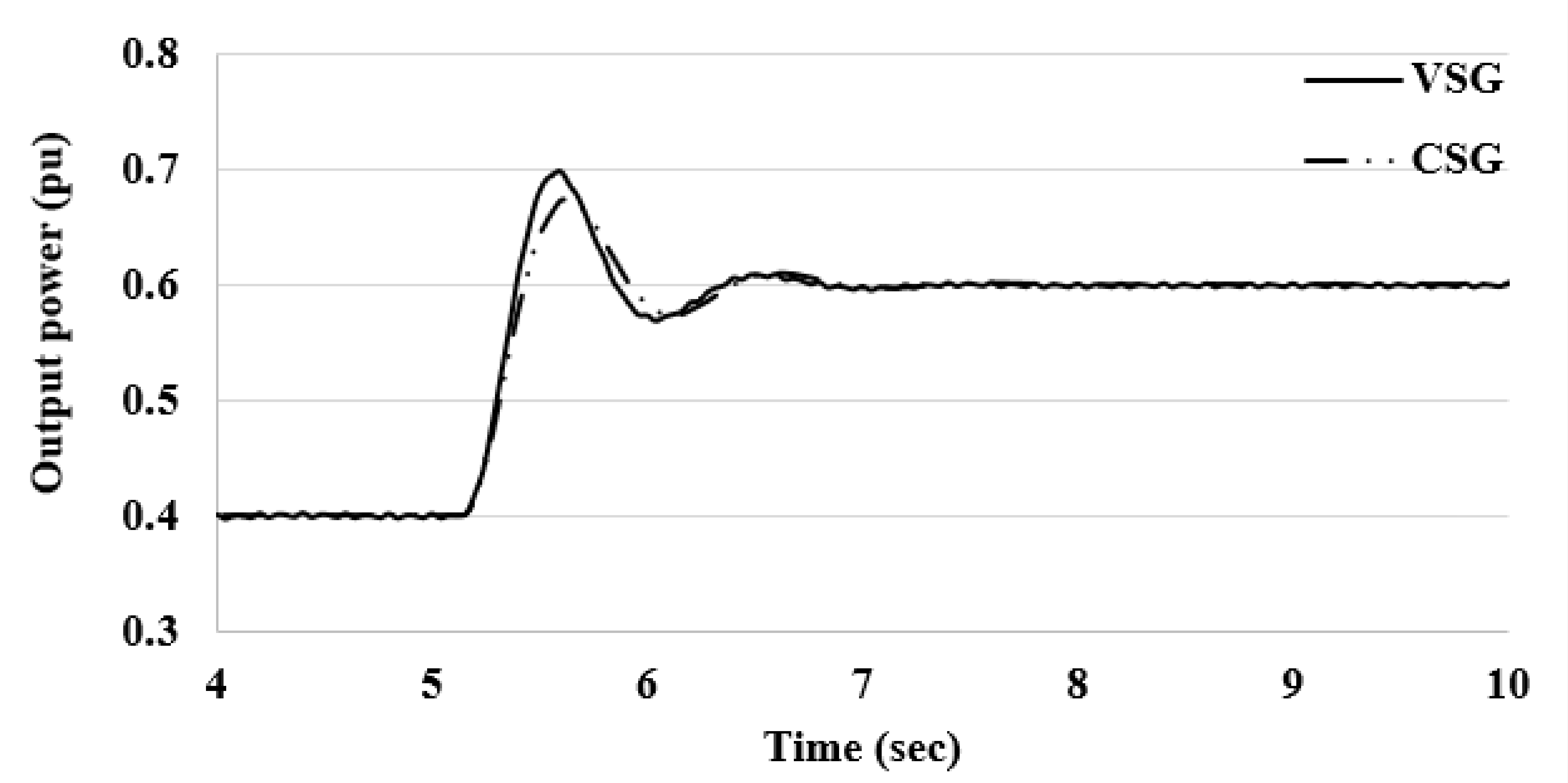

General layout of VSG and CSG systems

# Simulation results: step power setpoint increase at different inertia time constants



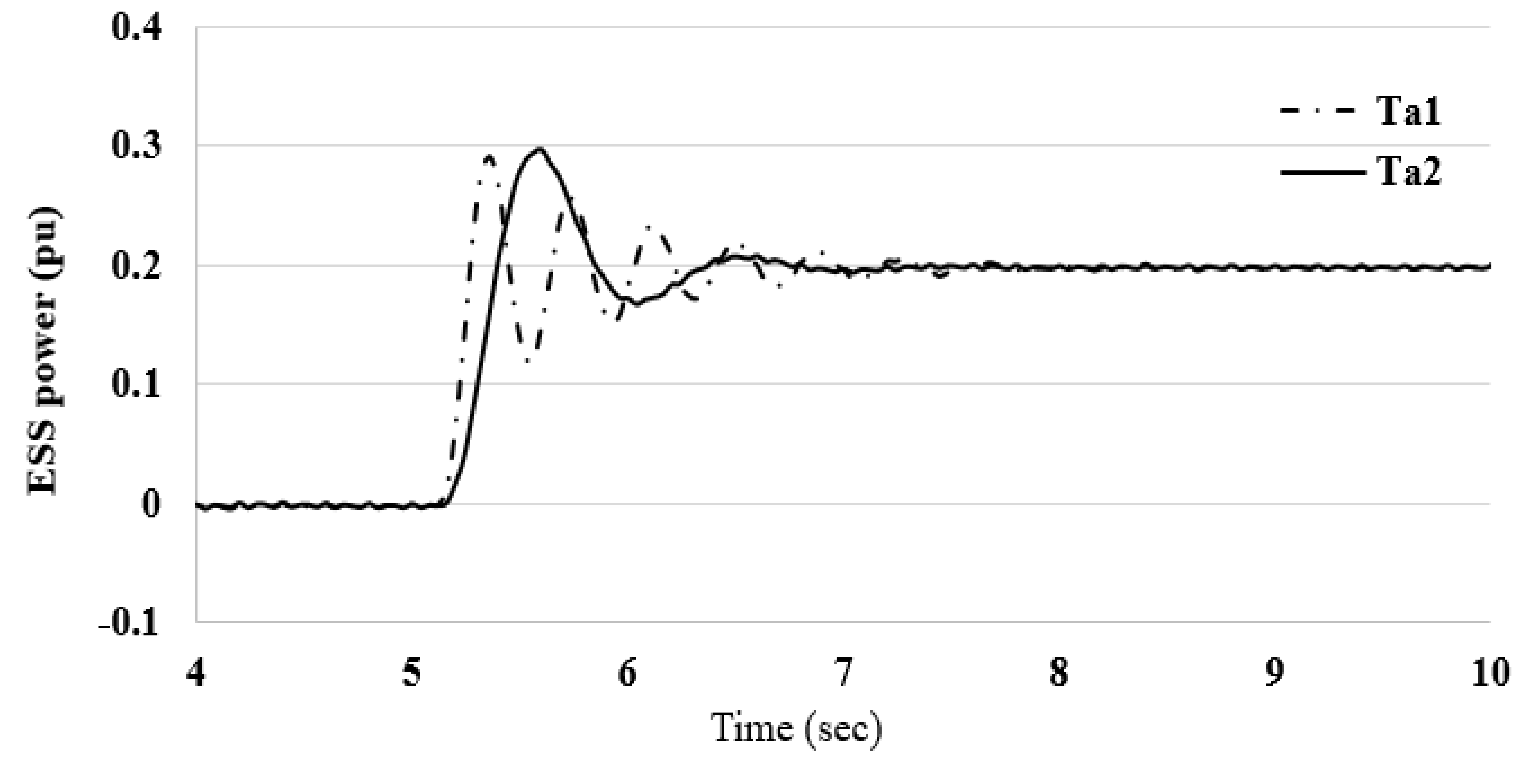

VSG and CSG active power step change at inertia time constant = 2

# Simulation results: step power setpoint increase at different inertia time constants



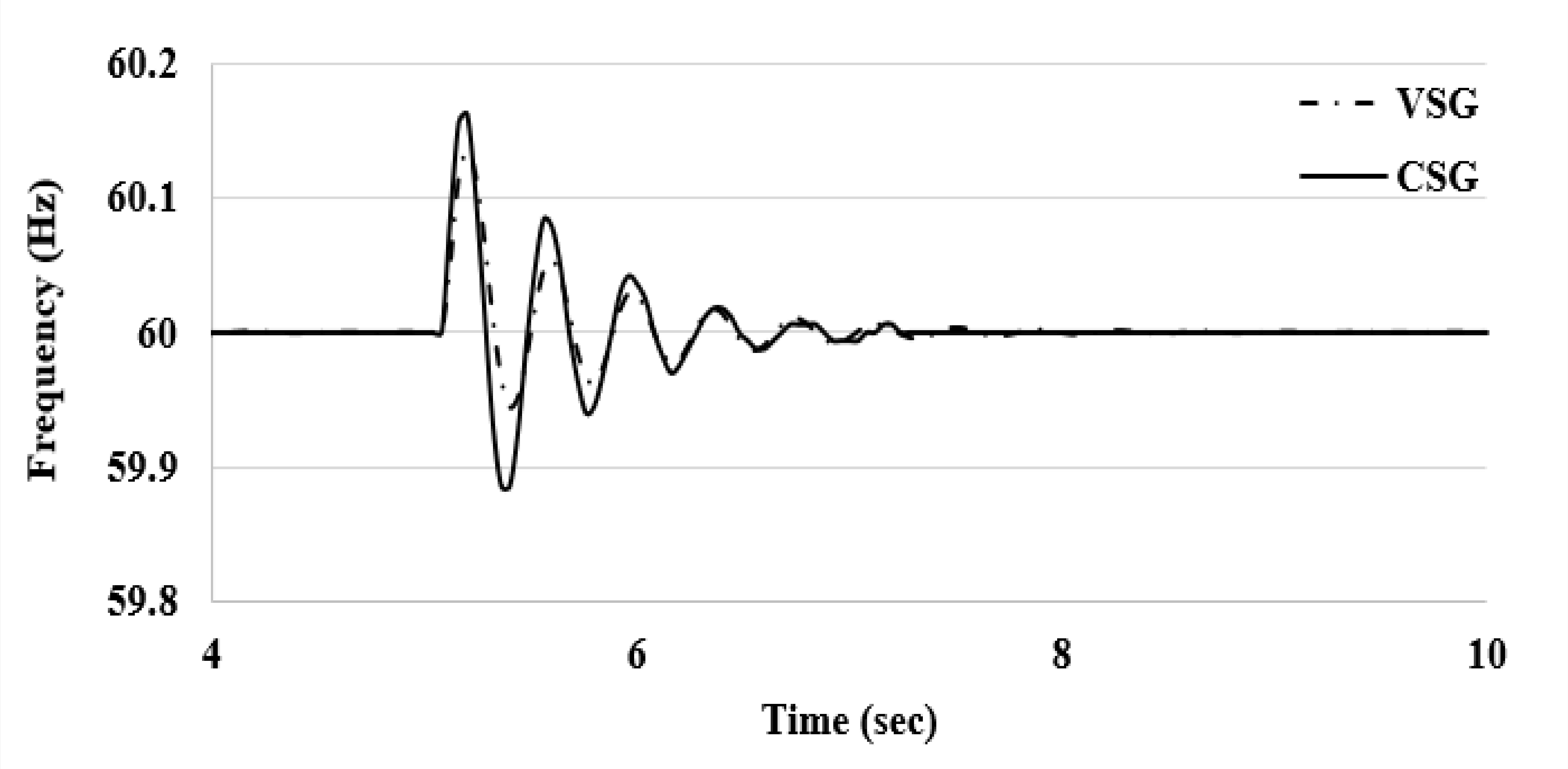

VSG and CSG active power step change at inertia time constant = 8

# Simulation results: step power setpoint increase at different inertia time constants



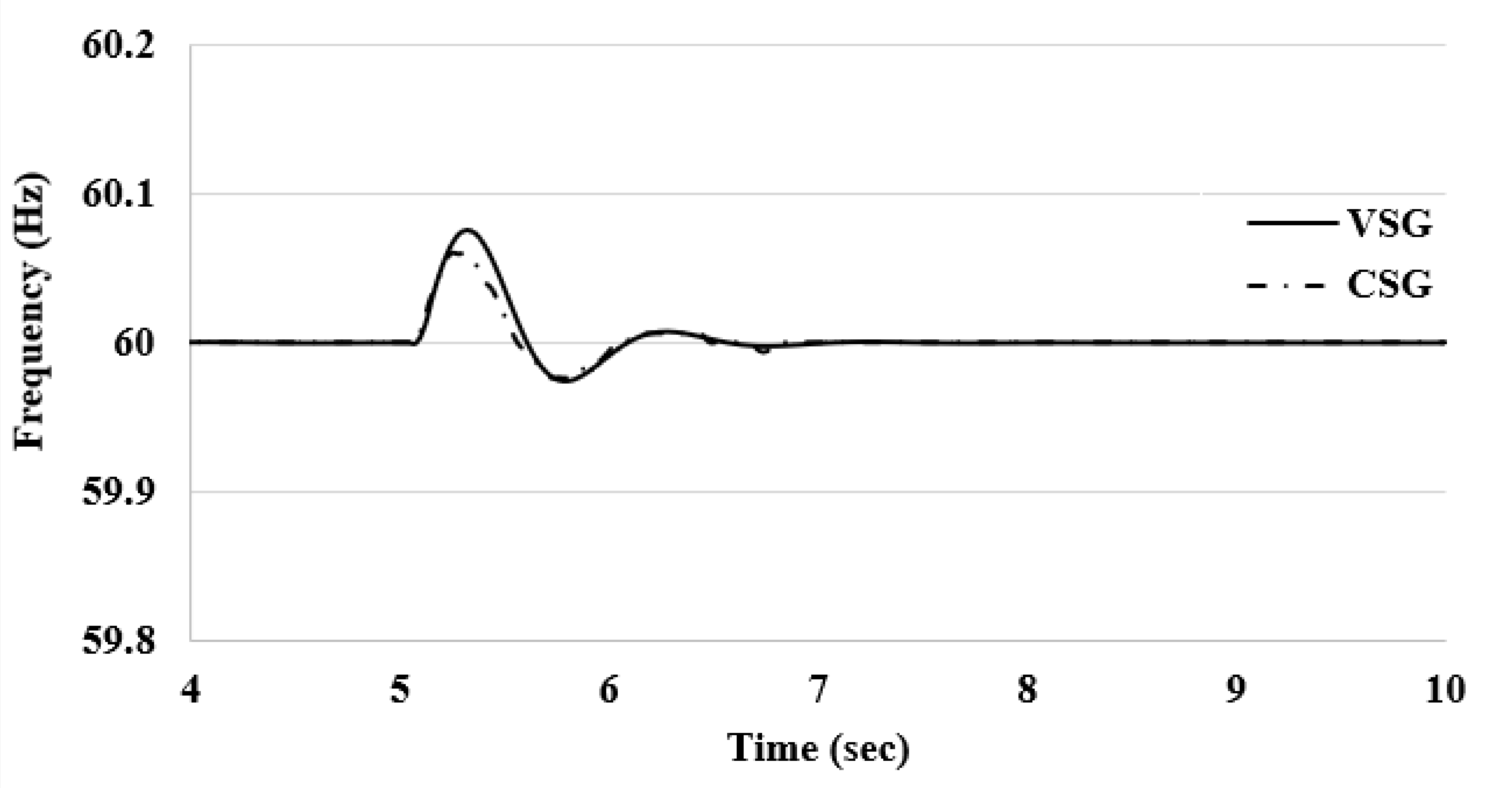

ESS power at different inertia time constants

# Simulation results: step power setpoint increase at different inertia time constants




Frequency profile at inertia time constant = 2

# Simulation results: step power setpoint increase at different inertia time constants




Frequency profile at inertia time constant = 8

# Conclusion

- WECS and PV systems can control the output active and reactive power independently.
- Frequency fluctuation depend on the system inertia and damping constants.
- VSG controller based grid forming converters combined with ESS can emulate the behavior of CSG.
- VSG parameters can be changed to mimic the features of many CSG.
- VSG controller supports the system's frequency and performance  (RoCoF and the frequency nadir).
- Increasing inertia and damping constants reduces the frequency oscillation and stabilizes the system.
- Damping and inertia time constants emulation affect the ratings of the converter and the ESS.
- Increasing the inertia time constant increases the converter and the ESS ratings.
- Increasing the damping constant decreases the converter and the ESS ratings.

# Conclusion

- Supplementing the battery with the SMES:
  - Provide both high power and energy capabilities.
  - High and low rate of change of power fluctuations response.
  - Reduces the number of charging and discharging cycles of the battery.
  - Reduces the stress on the battery system.
  - Increases its lifetime .
- VSG controllers based grid forming converters can promote expanding RERs in microgrids.

# Future work

- Considering different types of ESSs and studying the coordination between them.
- Studying the effect of climate change algorithms on ESSs w.r.t. the emulated constants changes.
- Connecting different RERs to the system.
- Studying multi VSG-based based grid forming converter controller system.
- Updating microgrids standards and indices to include VSG based grid forming converter controller.
- Evaluation standard and indices for VSG based grid forming converter controller.

# Publications

1. Virtual Synchronous Generator Controller Performance and Evaluation
2. Virtual Synchronous Controller Based SMES/Battery Energy Storage System
   - **Grid of the Future Symposium/ CIGRE / Nov. 2022**
3. Modelling and Control of Wind Energy Conversion System with BESS
4. Volt /Var Control of Solar Photovoltaic System
   - **The 53rd North American Power System Symposium 2021/ IEEE.**
5. Modeling and control of solar PV System combined with battery energy storage system
6. Virtual Synchronous Generator controller for Solar Photovoltaic System
   - **The annual IEEE Canadian Electrical Power and Energy Conference 2021**

# THANK YOU FOR ATTENTION

# Comparison between SMES & supercapacitors

**Advantages**

- high power density
- long lifetime
- high speed response
- high efficiency
- good cycle life

# Comparison between SMES & supercapacitors

**Disdvantages of supercapacitors**

- A supercapacitor is a series of capacitor cells with a voltage range limited to 2.5-3 volts.
- This series connection is inevitable, but it reduces the total capacitance.
- A protection circuit should be integrated with the system to protect the cells from overvoltage and non-uniform cells problems.
- A step-up and step-down converters are required to match supercapacitor voltage with the power system voltage.
- The converters have a complicated design, since the stored energy varies with square of the stored voltage complicating the converter control of the charging and discharging processes.

# Flywheel system

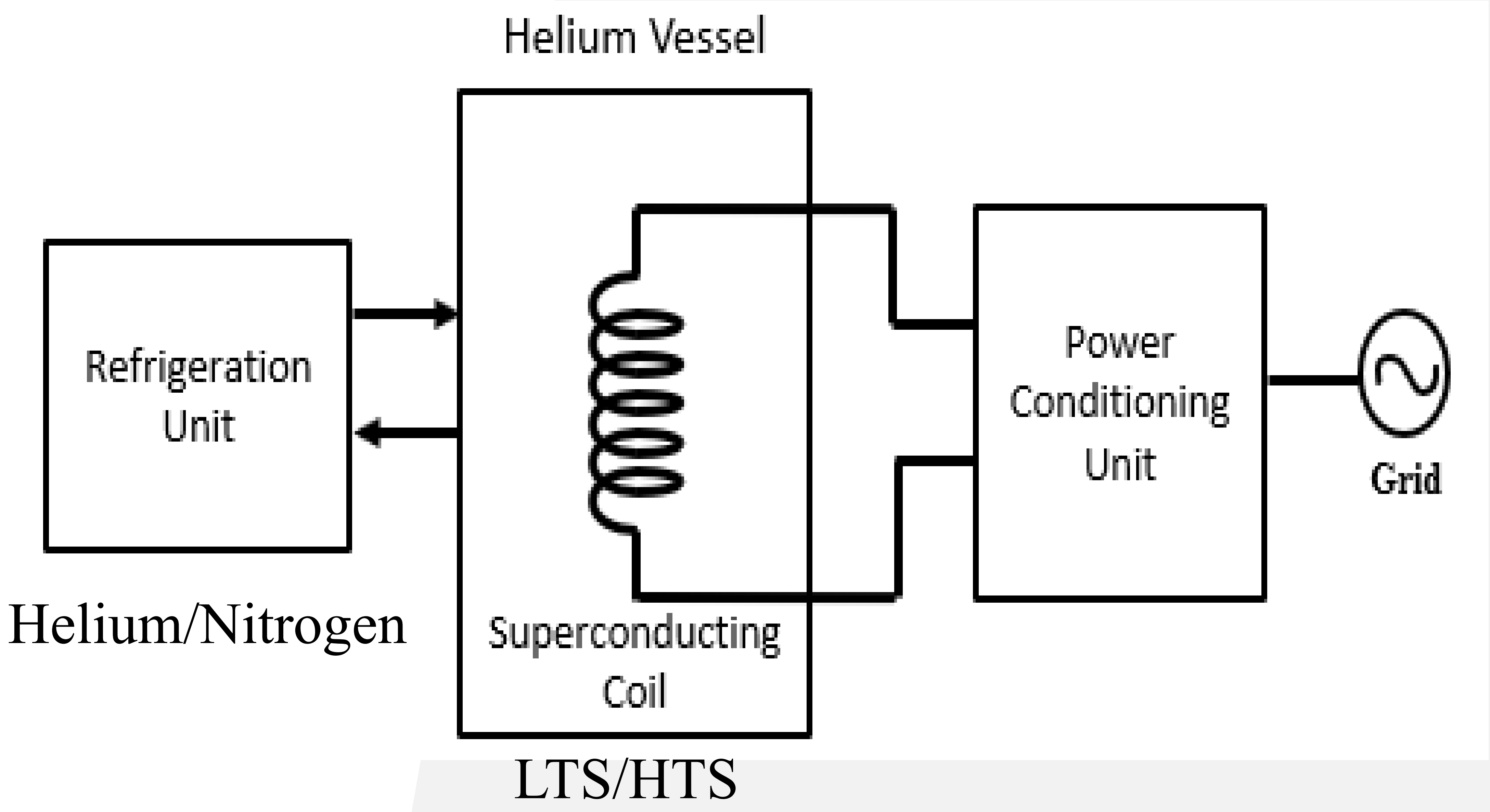
**Avantages**

- Low maintenance costs
- Long expected lifetime
- Fast response
- Roundtrip efficiency of about 90%

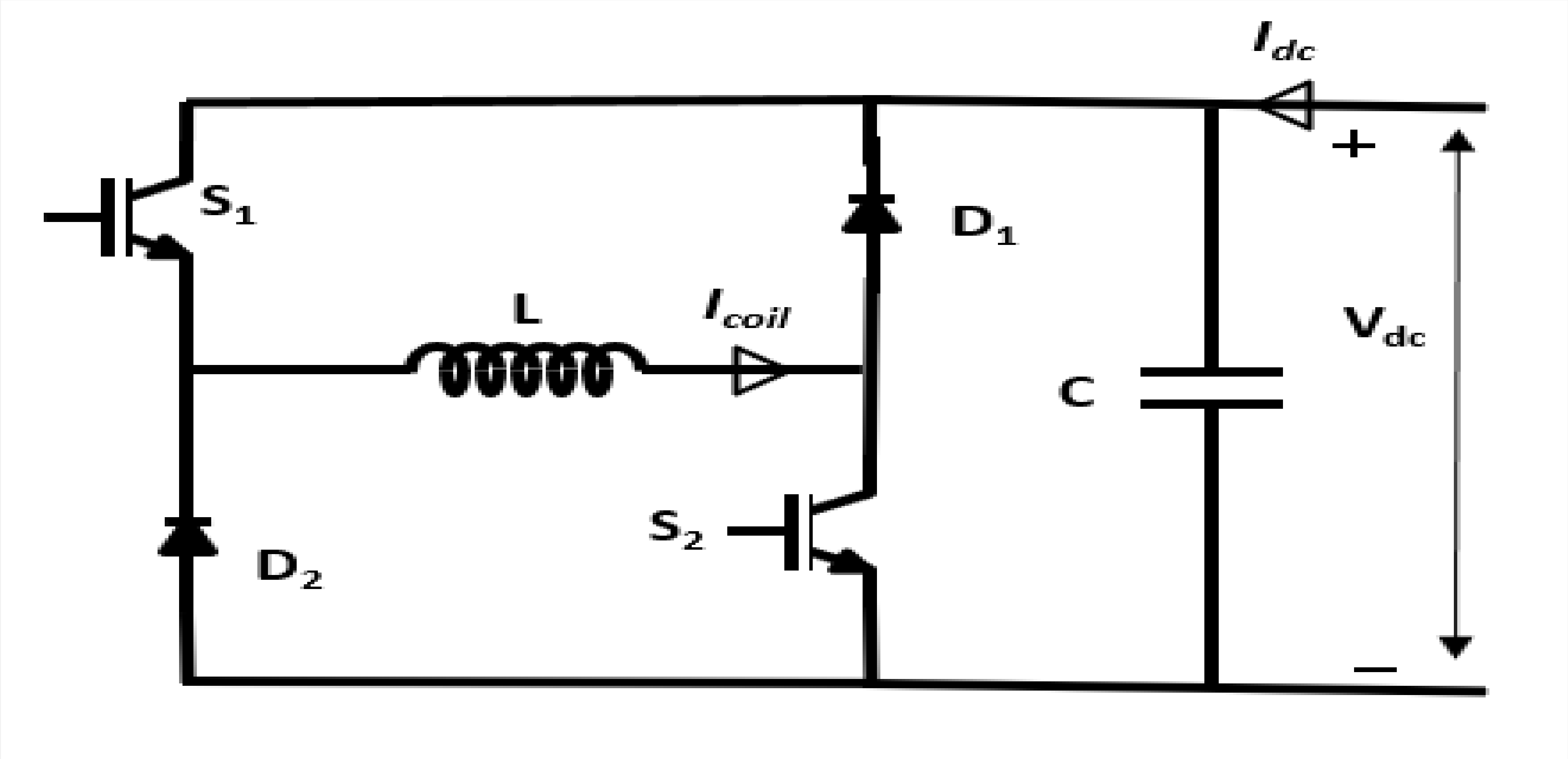
**Disavantages**

- High cost
- Appropriateness for smaller capacities only
- Mechanical stress and fatigue limits
- Relatively high intrinsic losses
- Potentially hazardous failure modes
- Short discharge times
- Self-discharge risk
- Noise

# SMES system and converter controller




Schematic diagram of a SMES system




DC-DC chopper of the SMES coil

# DC-DC chopper of the SMES coil

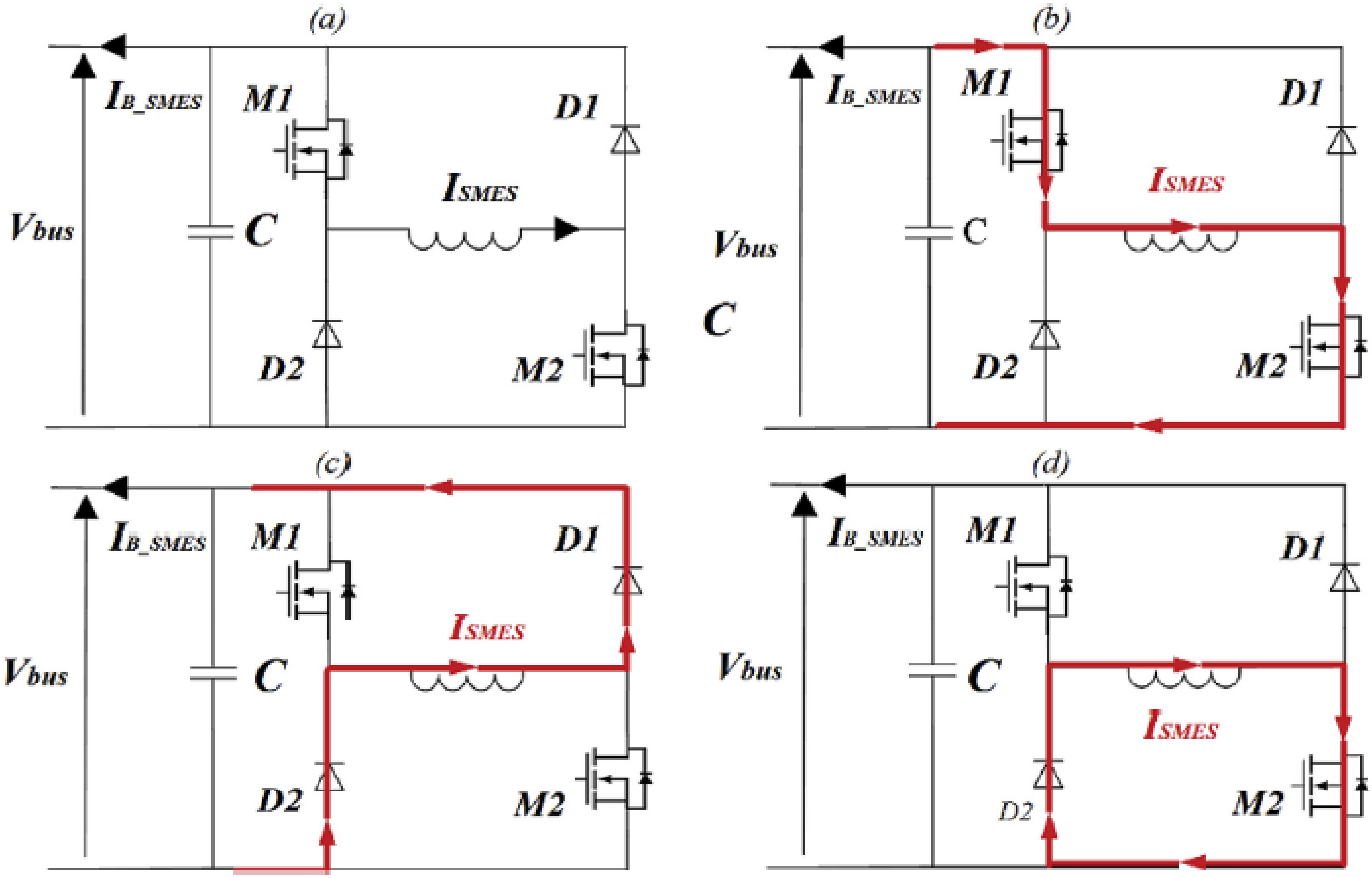
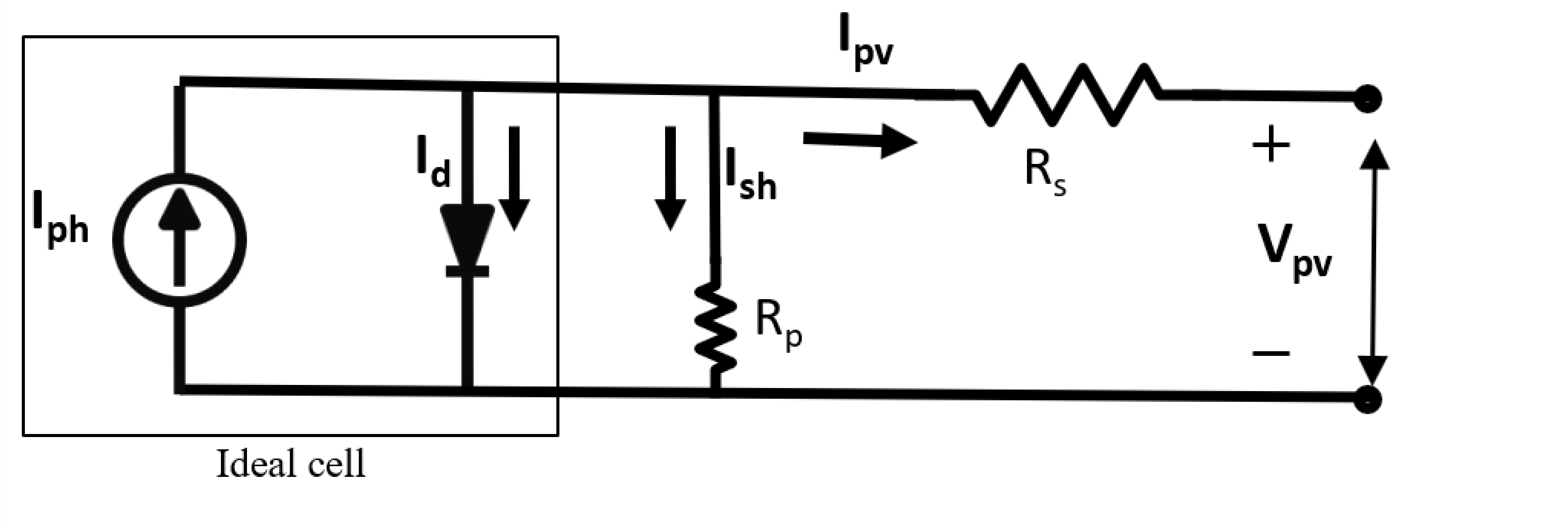



Fig. 4. SMES DC/DC converter showing current paths in different modes: (a) circuit topology; (b) charge mode; (c) discharge mode; (d) standby mode.

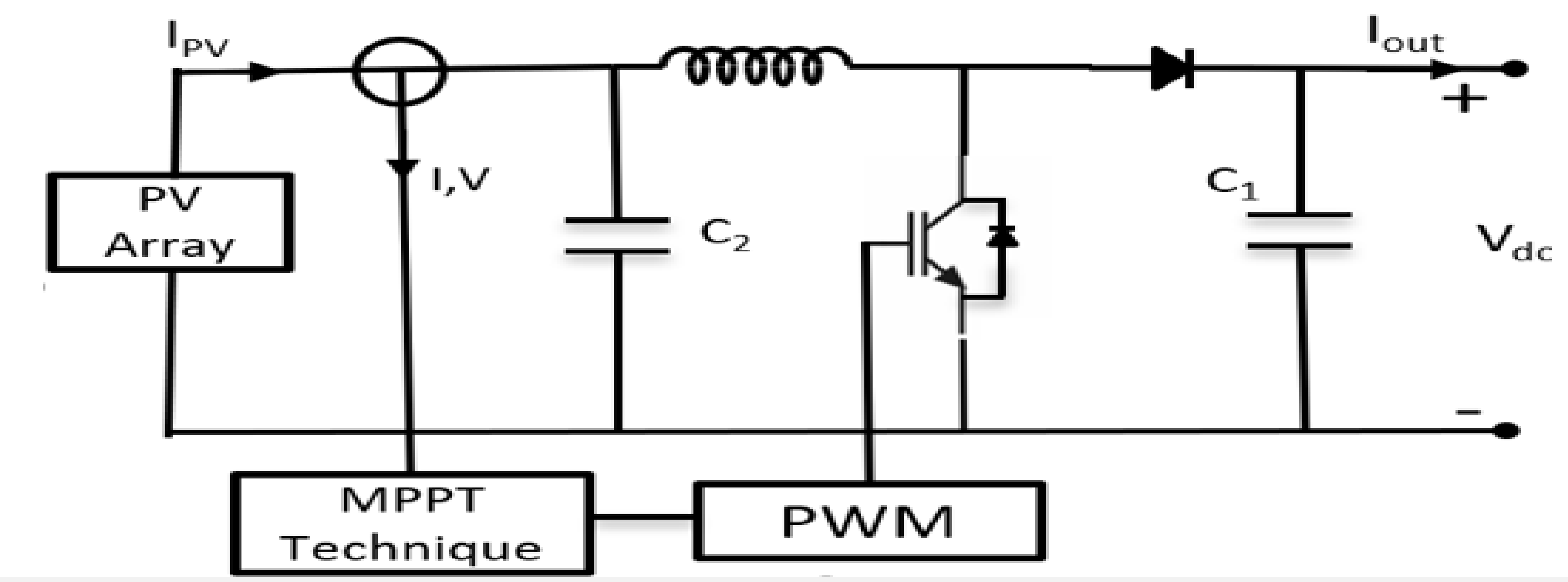
J. Li, Q. Yang, F. Robinson, F. Liang, M. Zhang, and W. Yuan, "Design and test of a new droop control algorithm for a smes/battery hybrid energy storage system," Energy, vol. 118, pp. 1110–1122, 2017.

PV Array_P235




Ideal single diode PV model

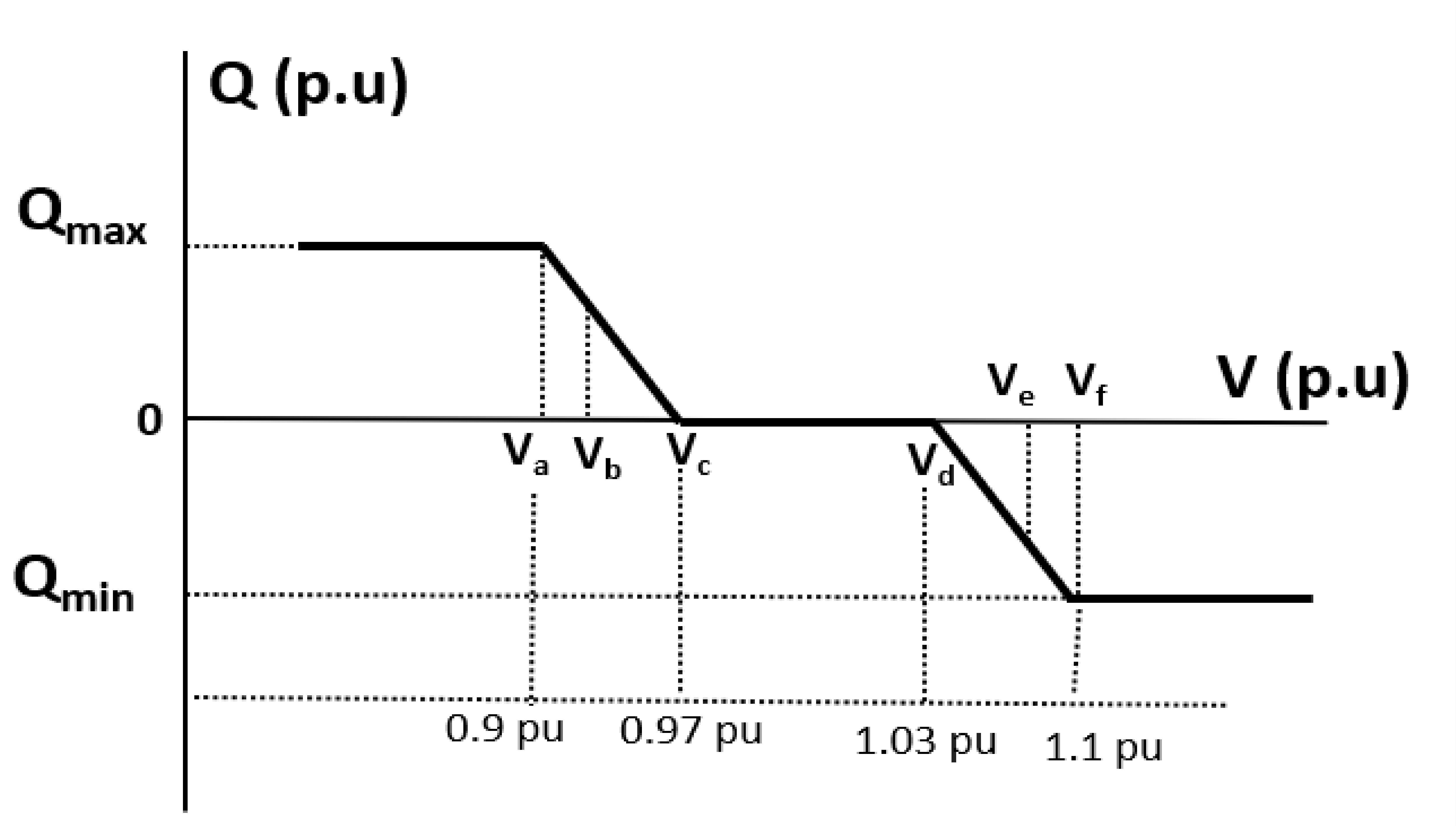
DC-DC boost converter




DC-DC boost converter

# Volt/var control strategy

Volt/var control function




**- Determination of the voltage points are set at the design and implementation of the system according to the recommendation of the utility that will be responsible for operating the system and to its following codes.**

**- In the future grids, these values should be able to be modified by the network operators to enhance the system performance optimization when the load pattern or the network topology are modified.**

# Grid forming inverter vs grid following inverter

- Inverter-based resources can be modeled with a grid-forming or –following  inverter.

**Grid-forming control**

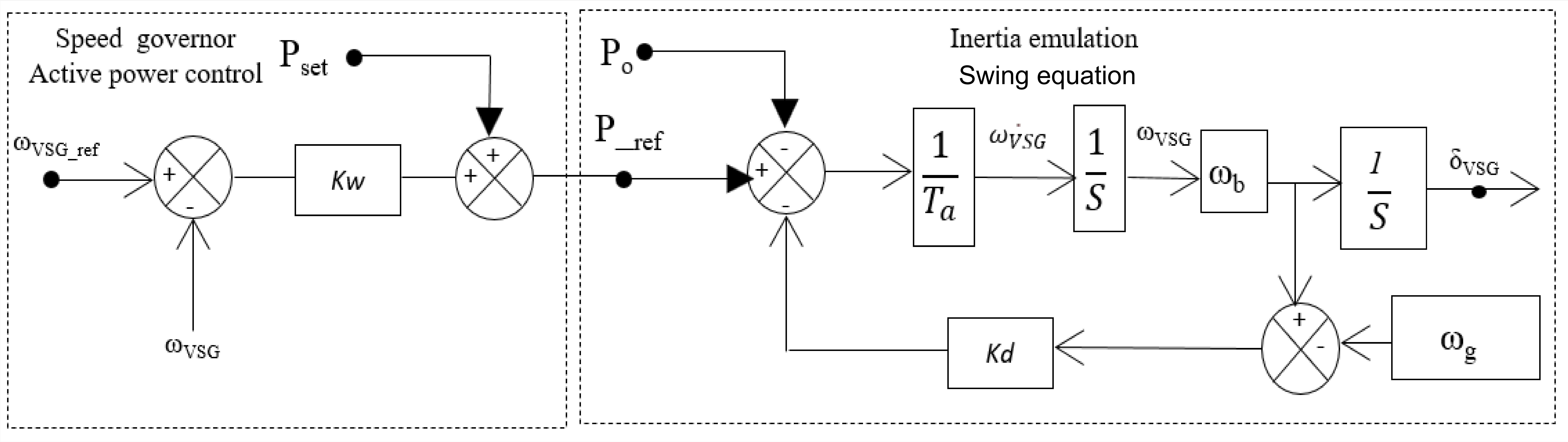
- converters act as voltage sources, where the inverter can respond instantaneously to system changes .
- Adjust the voltage magnitude
- Adjust the frequency of the system, supply fault current, and contribute to the system inertia .

**Grid-following inverters**

- Rely on the measurements of the phase-locked loop (PLL) and the proportional and integral control.
- Limited to tracking the voltage and frequency during disturbances.

# DC-AC converter controller

Outer loops:
Virtual inertia emulation



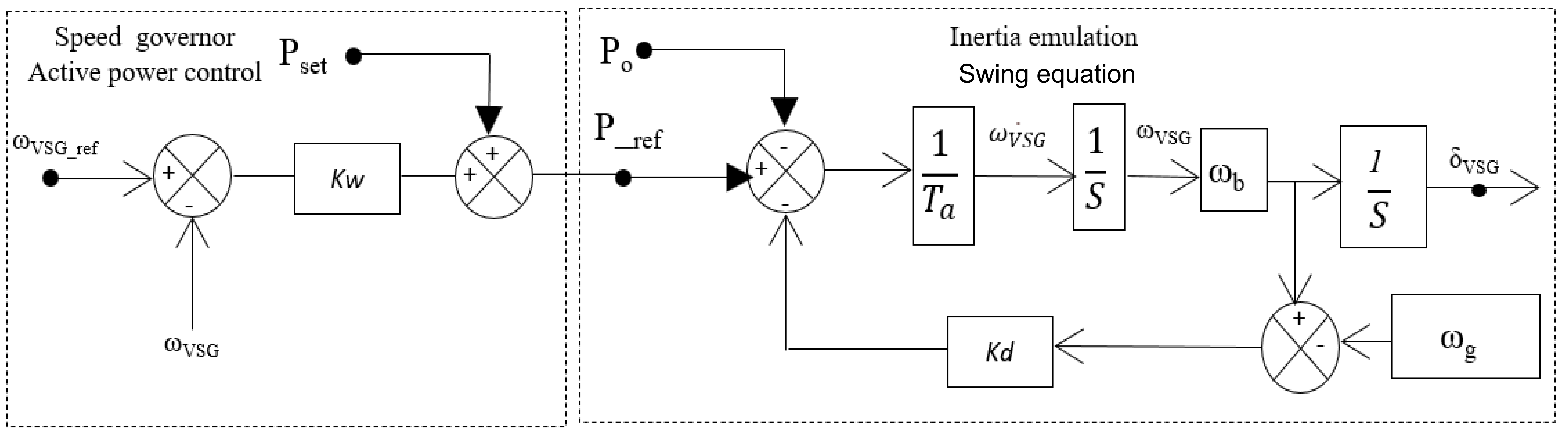

Ta ….Inertia time constant
Kd ….Damping constant
Kw….Frequency droop constant

$$T_m - T_e - D\Delta\omega = 2H\Delta\dot{\omega} \quad (5.1)$$

where $T_m$ is the mechanical torque driving the generator, $T_e$ is the electromagnetic torque due to electric load on the generator, D is the damping coefficient associated with the damper windings, $H$ is the per unit inertia constant for the stored kinetic energy in the rotor at rated speed divided by the chosen MVA base, and $\Delta\omega$ is the deviation from synchronous speed

# DC-AC converter controller

Outer loops:
Virtual inertia emulation



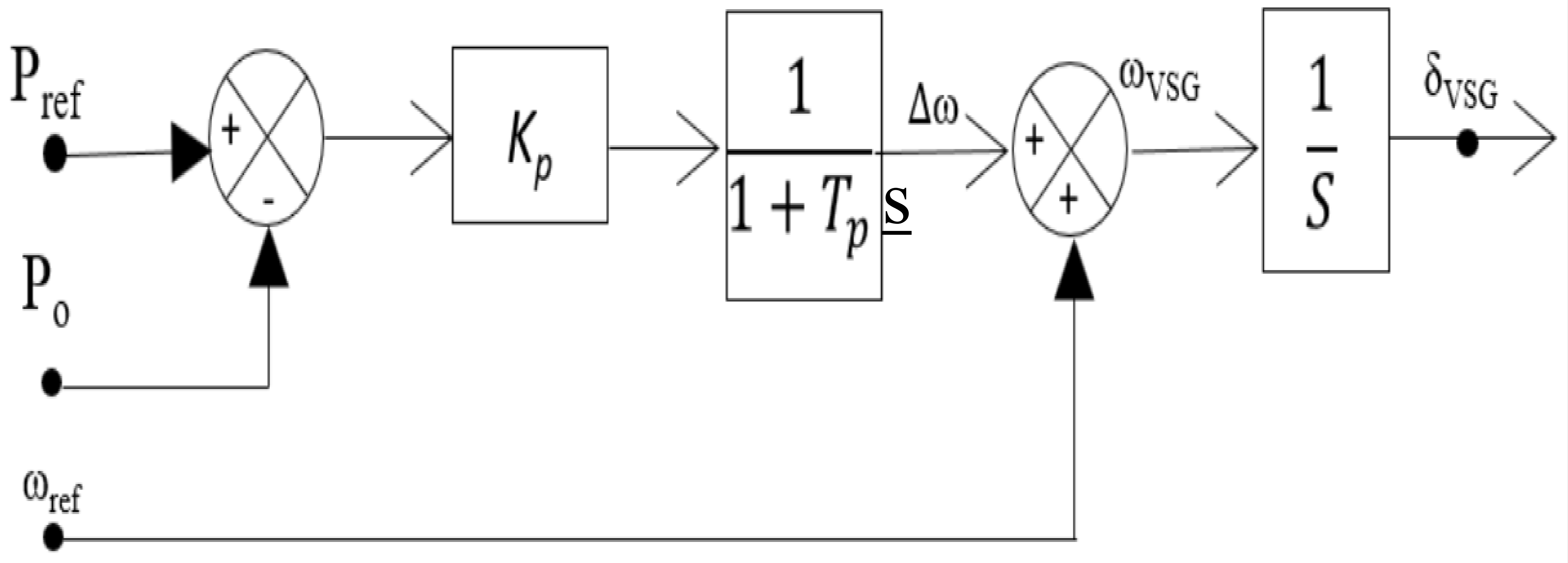

Ta ….Inertia time constant
Kd ….Damping constant
Kw….Frequency droop constant

$$T_m - T_e - D(\omega - \omega_g) = J\frac{d\omega}{dt}$$

Tm is the mechanical torque driving the generator,
Te is the electromagnetic torque due to electric load on the generator,
D is the coecient accounting for the damping torque associated with the damper winding,
w is the rotational speed of the
J is the rotor inertia kg .m2.

# DC-AC converter controller

Outer loop virtual inertia emulation controller




Virtual inertia emulation

The active power is associated with:
VSG emulated torque and angular speed of the rotor (ω)

(KP = 1 /Kd) Inverse of the damping.

(TP = Ta/ Kd) Time taken by the rotor to reach its rated speed.

$$T_m - T_e - D\Delta\omega = 2H\Delta\dot{\omega}$$

$$T_a.s.(\Delta\omega) = P_m - P_e - k_d(\Delta\omega)$$

$$\frac{\Delta\omega}{\Delta P} = -\frac{1}{T_a s + K_d} = \frac{K_p}{1 + sT_p}$$

$$T_m - T_e - D\Delta\omega = 2H\Delta\dot{\omega} \quad (5.1)$$

where $T_m$ is the mechanical torque driving the generator, $T_e$ is the electromagnetic torque due to electric load on the generator, D is the damping coefficient associated with the damper windings, $H$ is the per unit inertia constant for the stored kinetic energy in the rotor at rated speed divided by the chosen MVA base, and $\Delta\omega$ is the deviation from synchronous speed