Parallel Operation of Grid-forming Inverters with Synchronous Machines

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1. Introduction

- The inverter-tied resources require to co-exists with conventional SMs. But inverters have some drawbacks.

Drawback	Solution
Absence of Inherent Inertia	• Introduce Virtual Inertia
Low Current Carrying Capability	• Introduce a current controller
Harmonic Injection	• Use An *LCL* filter

- This work looks at the fault-ride-through (FRT) capability of grid-forming inverters (GFMI) and Synchronous machines (SM)

2. Test System

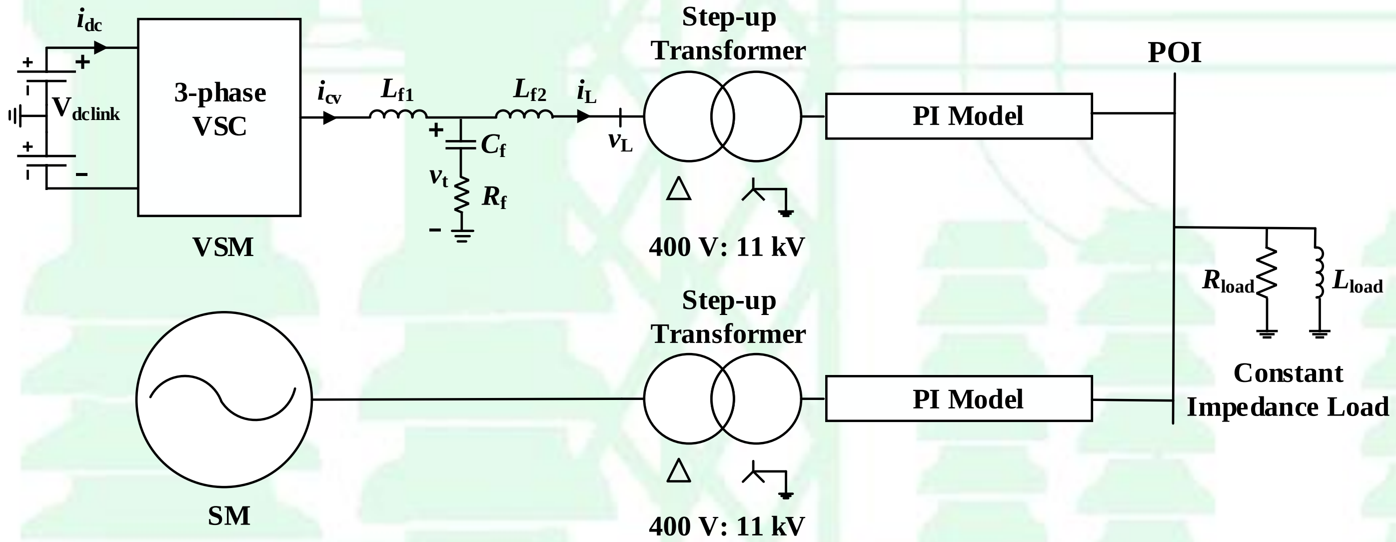


Figure 1 The single-line diagram of the test system

Table 1 The Parameters of the Test System

Parameter	Value	Parameter	Value
S_{rated}	500 kVA	R_f	0.09526 Ω
V_{dclink}	820 V	L_{tf}	0.1 pu
L_{f1}	150 μH	R_{tf}	0.01 pu
L_{f2}	30 μH	R_{load}	172.857 Ω
C_f	828.93 μF	L_{load}	0.917 H

Table 2 The Parameters of the Transmission Line Model

Positive-sequence parameters	Negative-sequence parameters
R=0.103 Ω/km, X_L=0.405 Ω/km, X_C=4.117 μs/km	R=0.279 Ω/km, X_L=1.802 Ω/km, X_C=2.414 μs/km

2.1. SM Model

Table 3 The SM Model Data

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
H	2 s	D (Mech. Fric. and Windage)	0.0 pu	$V_{L\text{-}N_}$rms	0.23094 kV	I_rms	0.7217 kA

2.1.1. SM Governor and Turbine Model

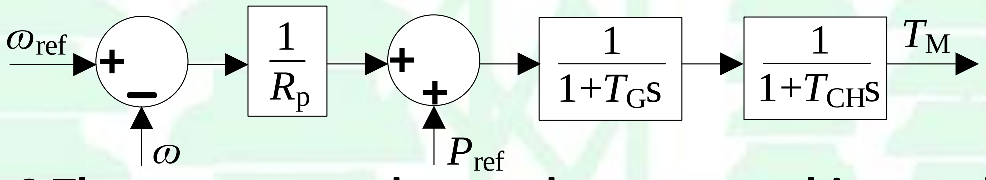


Figure 2 The governor and non-reheat type turbine model of SM

Table 4 The Governor and Turbine Model Data

Parameter	Value	Parameter	Value
T_G	0.2 s	T_{CH}	0.3 s
R_p	0.03 pu	P_{ref}	0.7 pu
		ω_{ref}	1.0 pu

2.1.1. SM Exciter Model (ACA4)

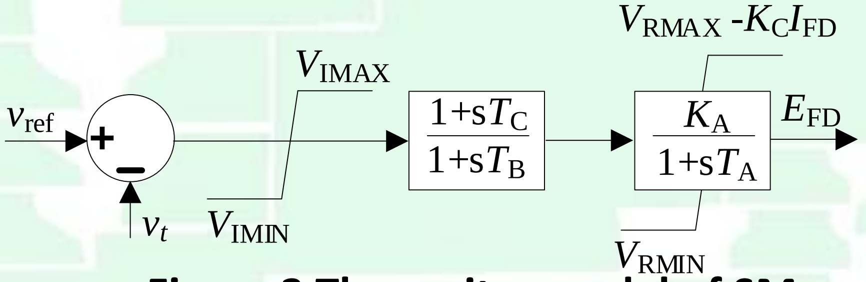


Figure 3 The exciter model of SM

Table 5 The Exciter Model Data

Parameter	Value	Parameter	Value
K_A	200.0	T_B	10.0 s
T_A	0.015 s	T_C	1.0 s
v_{ref}	1.05 pu	K_C	0.0
V_{RMAX}	5.64 pu	V_{RMIN}	-4.53 pu
V_{IMAX}	10.0 pu	V_{IMIN}	-10.0 pu

3. Controller Topology

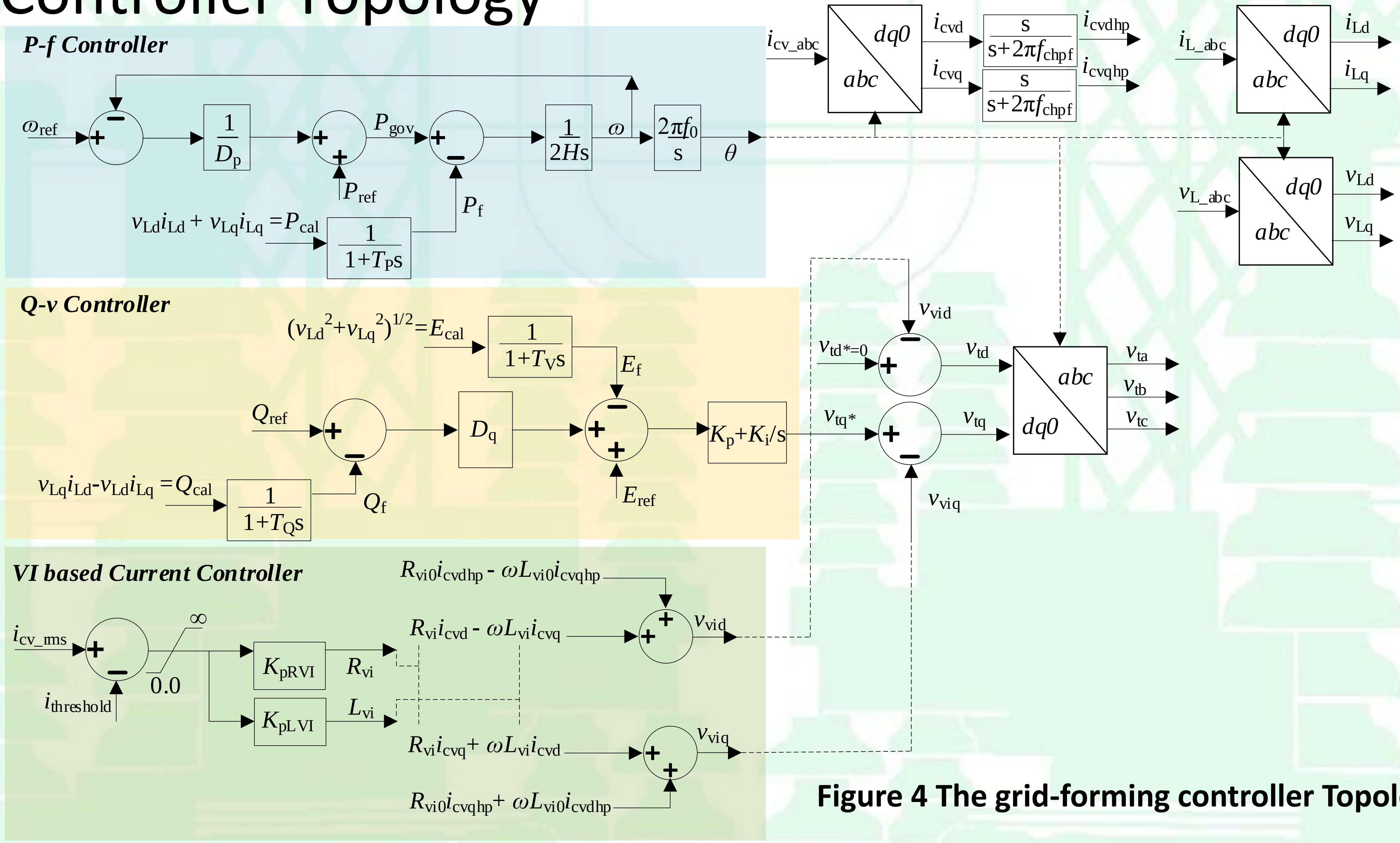


Figure 4 The grid-forming controller Topology

3.1. Controller Parameters

Table 6 The Controller Parameters

Parameter	Value	Parameter	Value
H	2 s	f_{sw}	4 kHz
D_{p}	0.03 pu	f_0	60 Hz
T_p	0.01 s	f_{chpf}	0.5 Hz
T_Q	0.01 s	D_{q}	0.03 pu
T_v	0.01 s	K_{p}	0.1
P_{ref}	0.7 pu	K_{i}	1 s^{-1}
ω_{ref}	1.0 pu	K_{pRVI}	5
Q_{ref}	0.35 pu	K_{pLVI}	0
E_{ref}	1.05 pu	R_{vi0}	0.0
$i_{threshold}$	1.1 pu	L_{vi0}	0.0

4.1. Effect on FRT from: current controller parameters

A. Effect from K_{pRVI}

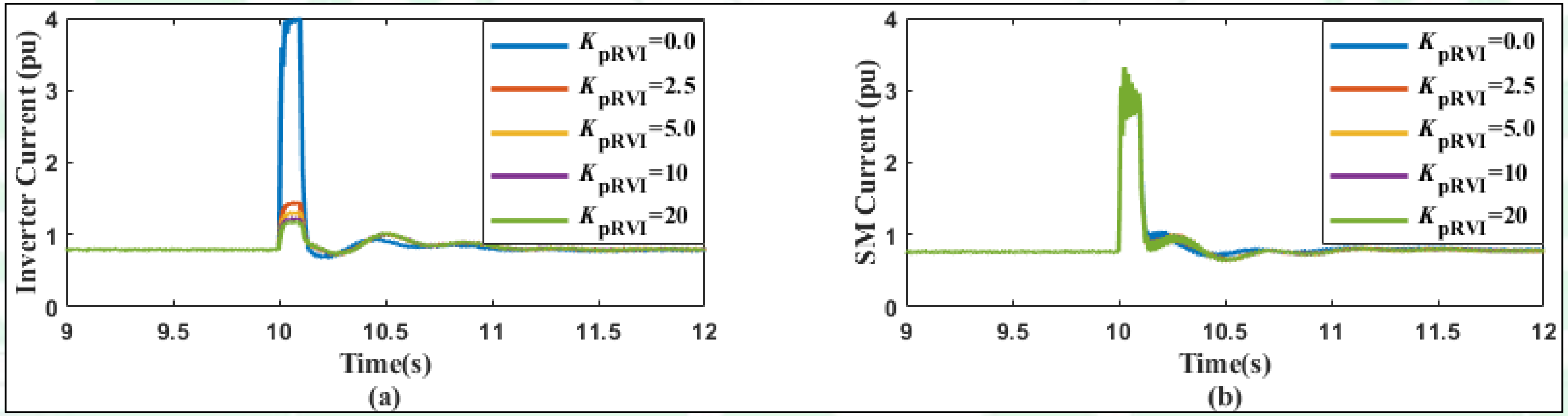


Figure 5 Current contributions from (a) inverter and (b) SM for different values of K_{pRVI} following a balanced fault.

Observations:

- K_{pRVI}=0 → No current limiting
- Higher K_{pRVI} → Better over current limiting and increases the post-fault oscillations

B. Effect from $I_{threshold}$

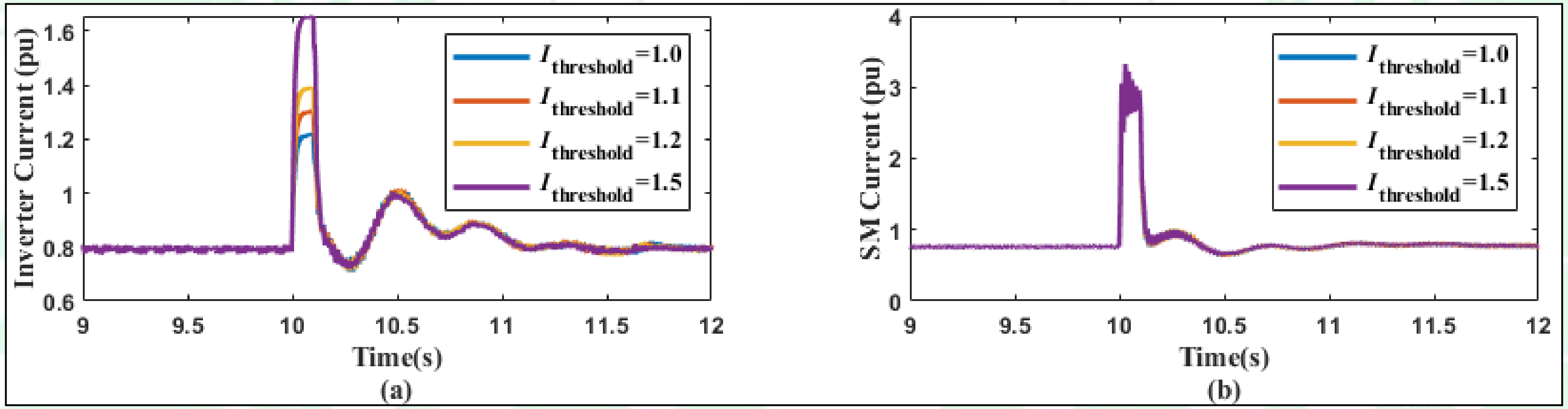


Figure 6 Current contributions from (a) inverter and (b) SM for different values of $I_{threshold}$ following a balanced fault.

Observations:

- Large $I_{threshold}$ → Large fault-current contribution
- Small $I_{threshold}$ → Small fault-current contribution. But very low thresholds can affect the normal operation

C. Effect from R_{vi0}

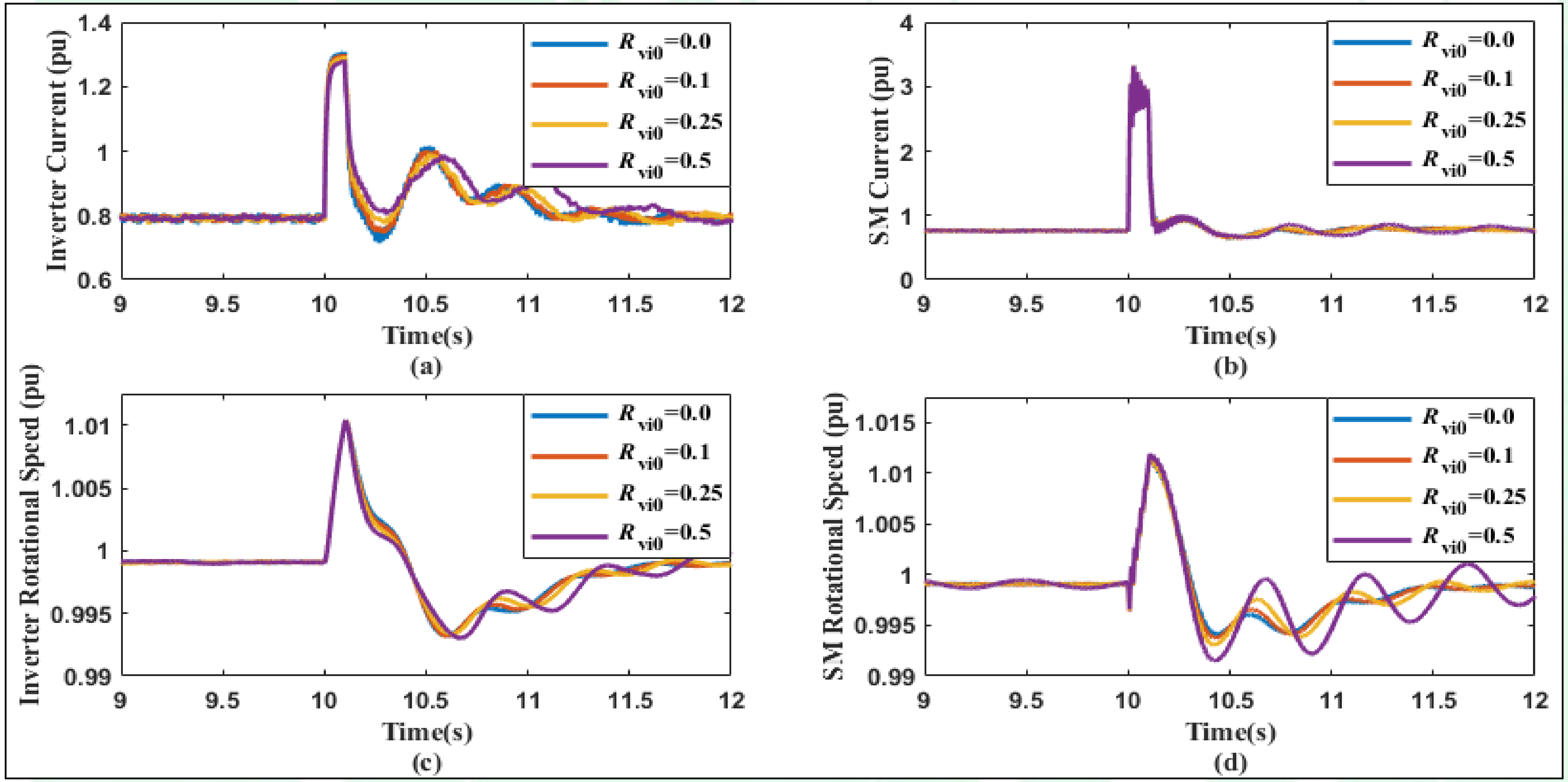


Figure 7 Current contributions from (a) inverter, (b) SM and the rotational speed of (c) inverter, (d) SM for different values of R_{vi0} following a balanced fault.

Observations:

- *Large R_{vi0}* → Damp the current oscillations but increases the oscillations in other variables.

4.2. Effect on FRT from: VSM Dynamics

A. Effect from *H*

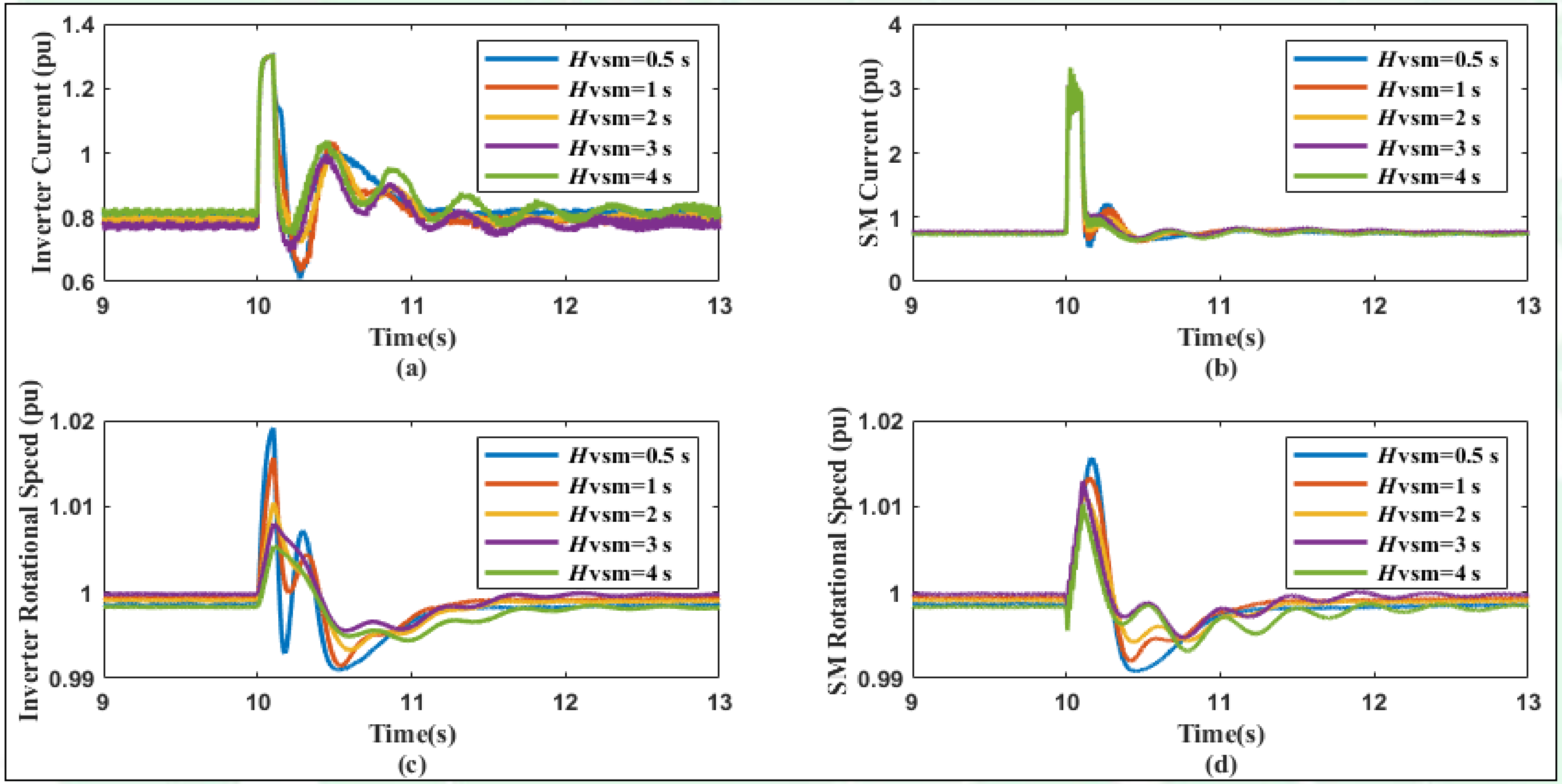


Figure 8 Current contributions from (a) inverter, (b) SM and the rotational speed of (c) inverter, (d) SM for different values of *H*.

Observations:

- H does not have an impact on the maximum fault current
- Effect of H comes at the post-fault recovery
- Large *H* → Large post-fault oscillations

B. Effect from D_P

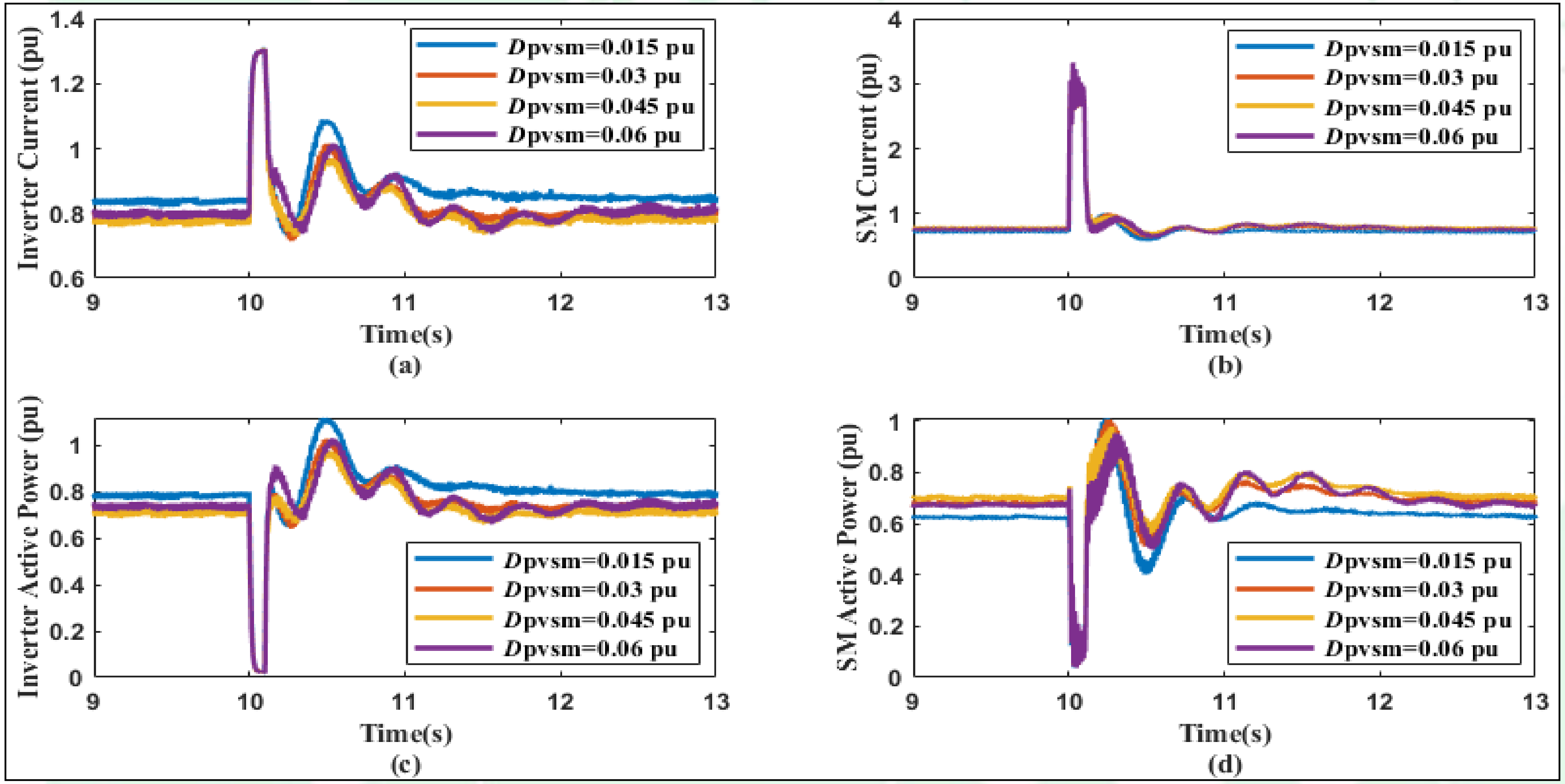


Figure 9 Current contributions from (a) inverter, (b) SM and the active power generation from (c) inverter, (d) SM for different values of *D*p

Observations:

- Similar to *H,* the effect of D_P can be found in the post-fault recovery
- *Large* D_P → Large post-fault oscillations

B. Effect from K_i

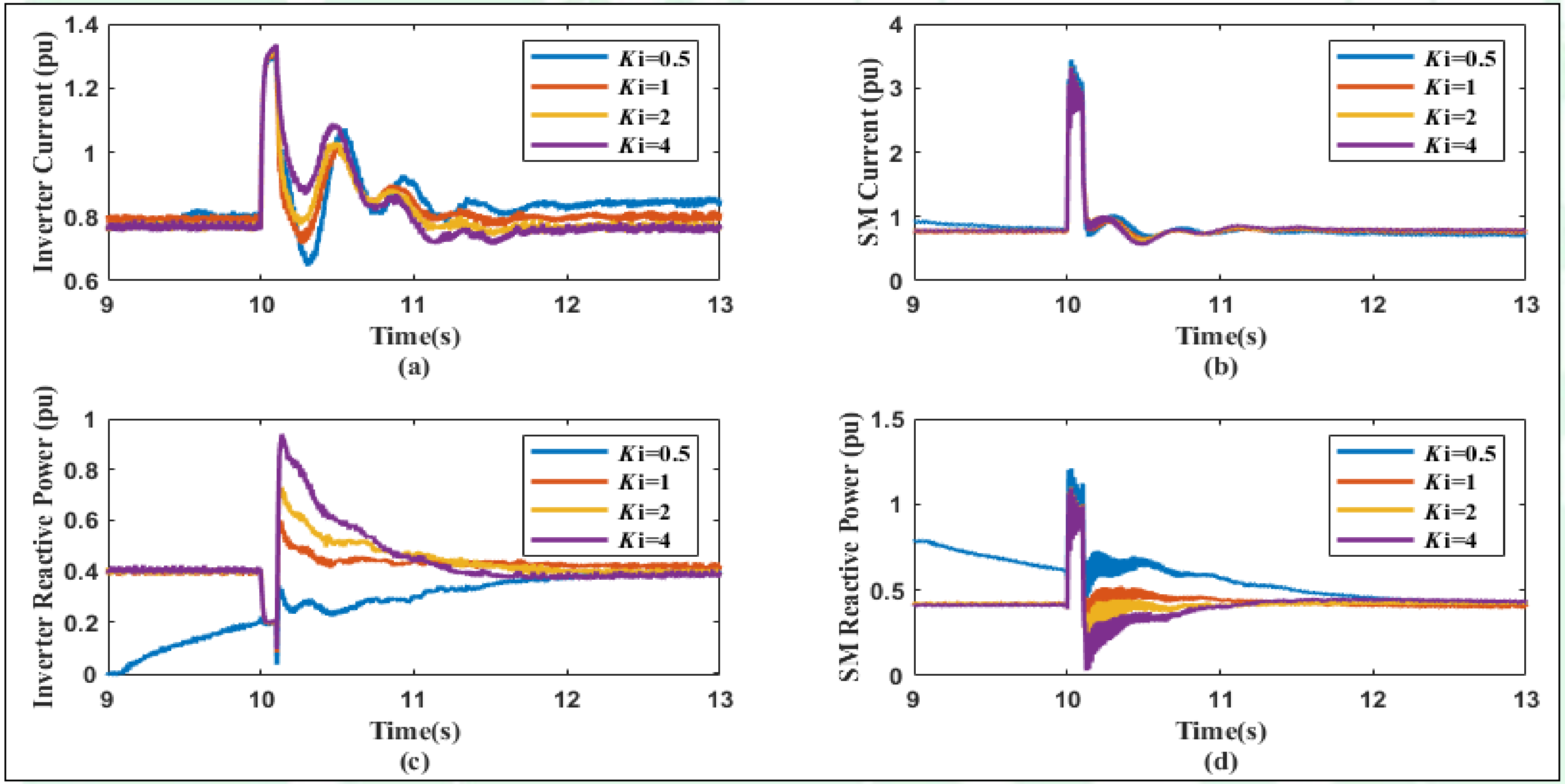


Figure 10 Current contributions from (a) inverter, (b) SM and the reactive power generation from (c) inverter, (d) SM for different values of K_i

Observations:

- $1/K_i$ gives the time constant of the PI controller used in the *Q-v* controller path.
- Effect on the maximum fault current is negligible.
- Large K_i → huge reactive power injections during the fault recovery
- Small K_i → Sluggish Response

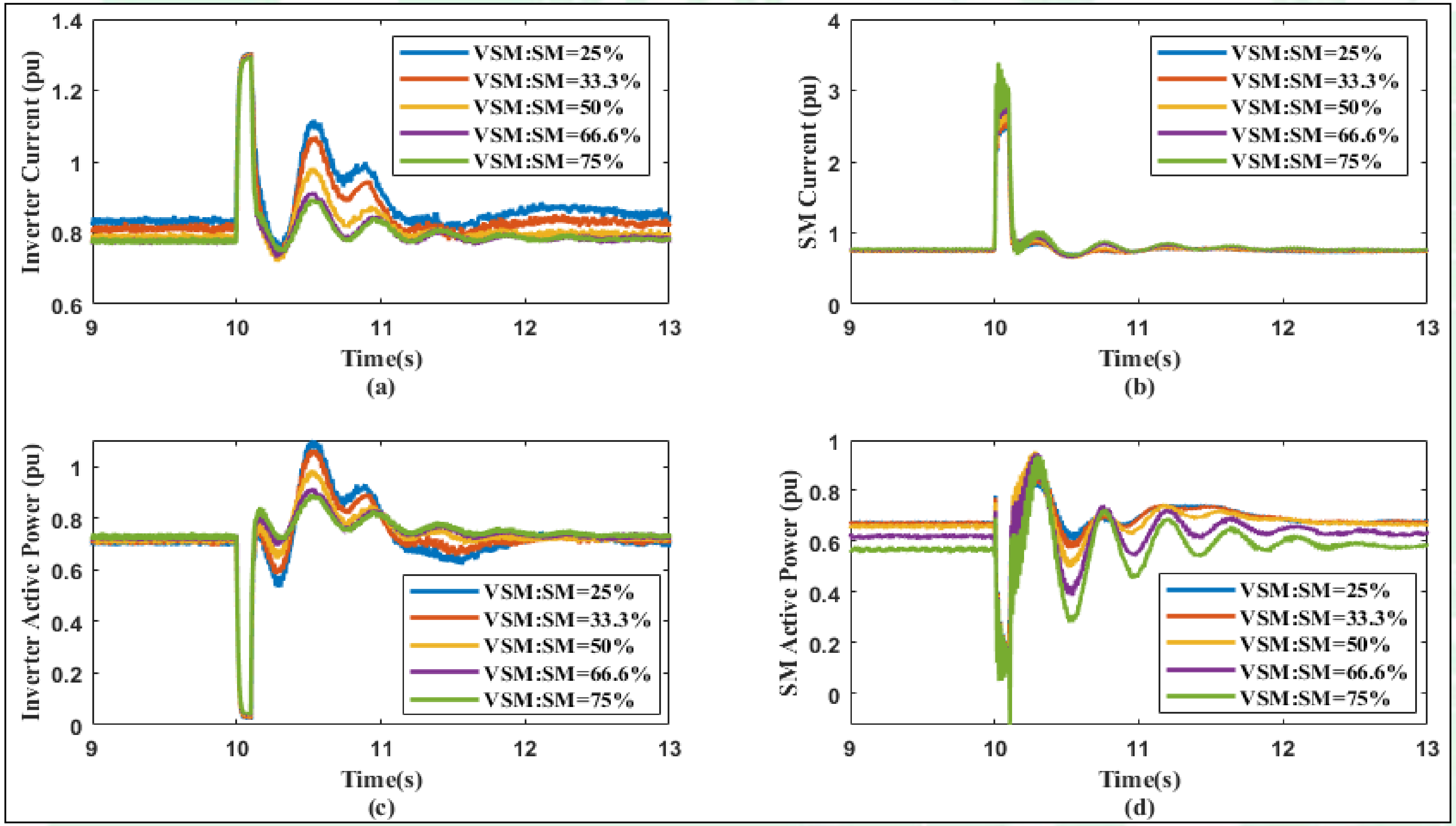
4.2. Effect on FRT from: GFMI Penetration Level

Set;

- R_{load}=72.04Ω , L_{load}=0.3821 H
- Size the transformers and retune the LCL filter according to the size of the machine

Table 7 The Sizes of VSM and SM to Create Different Inverter Penetration Levels

VSM:SM ratio	25%	33.3%	50%	66.6%	75%
VSM size (kW)	600	800	1200	1600	1800
SM size (kW)	1800	1600	1200	800	600



Observations:

- Promising FRT capability even under large penetration level of inverters

Figure 11 Current contributions from (a) inverter, (b) SM and the active power generation from (c) inverter, (d) SM for different VSM penetration levels

4.2. Effect on FRT from: Distance between VSM and SM

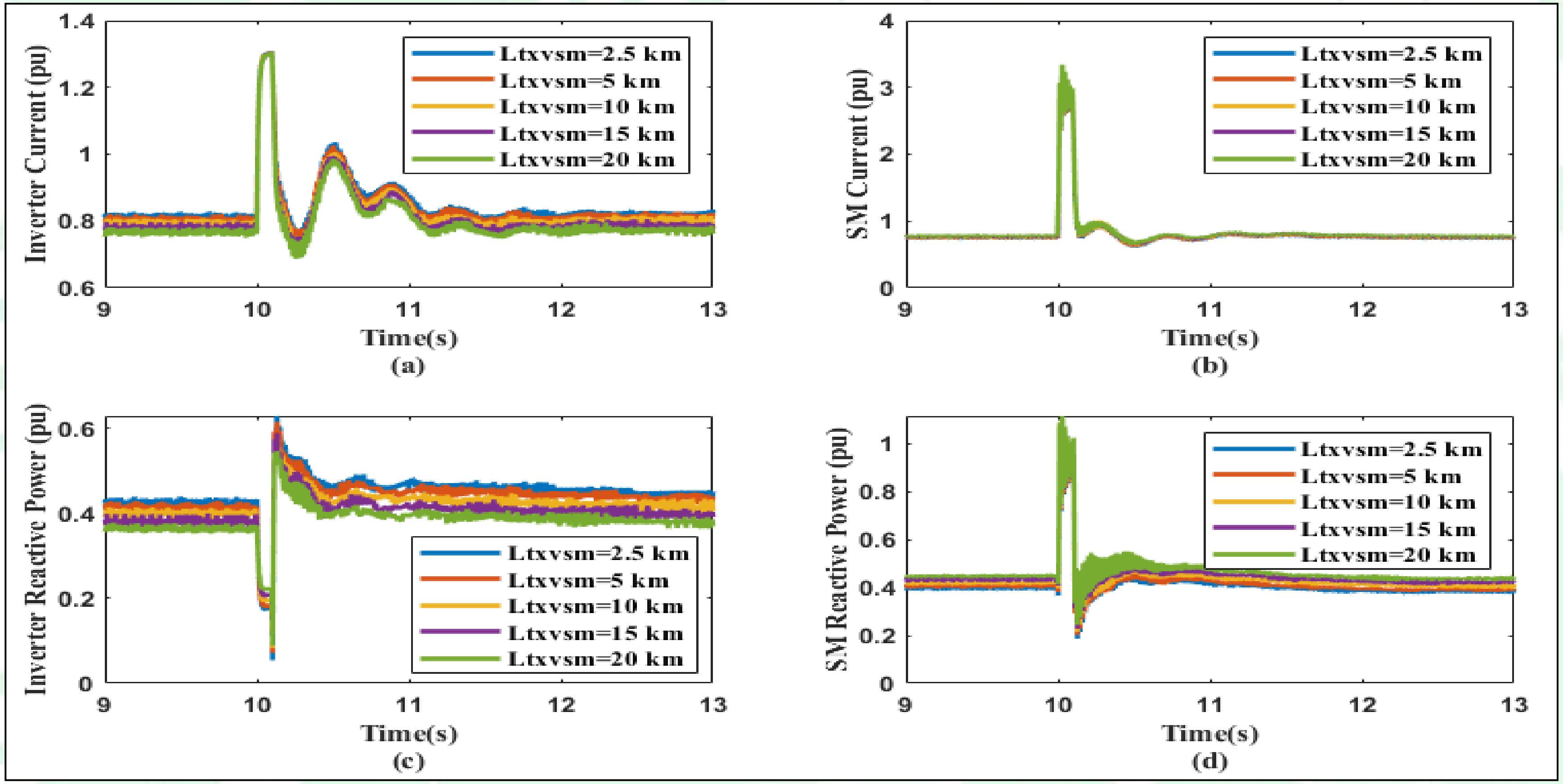


Figure 12 Current contributions from (a) inverter, (b) SM and the reactive power generation from (c) inverter, (d) SM for different transmission line lengths for VSM.

Observations:

- With different electrical distances, system can FRT without adverse interactions.
- The change in transmission line length has created different *v-i* droop characteristics.

5. Conclusions

- Large K_{pRVI} and low $i_{threshold}$ values create tight current limiting actions.
- But this comes at the expense of large post-fault oscillations.
- The current dependent VR path determines the maximum fault current.
- All the other VSM dynamics and network conditions come into action only during the post-fault transient duration.

Thank You!