Behavioral Modeling and Parameter Extraction of VRMs for Power Integrity Analysis

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Outline

- Background: VRM and PDN
- VRM behavioral model
- VRM model parameter extraction
- Validation
- Conclusion

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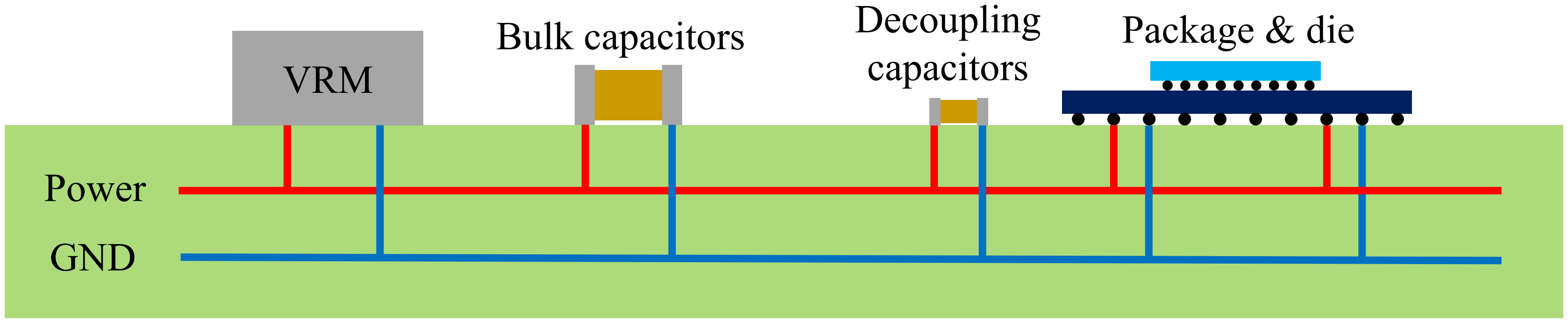
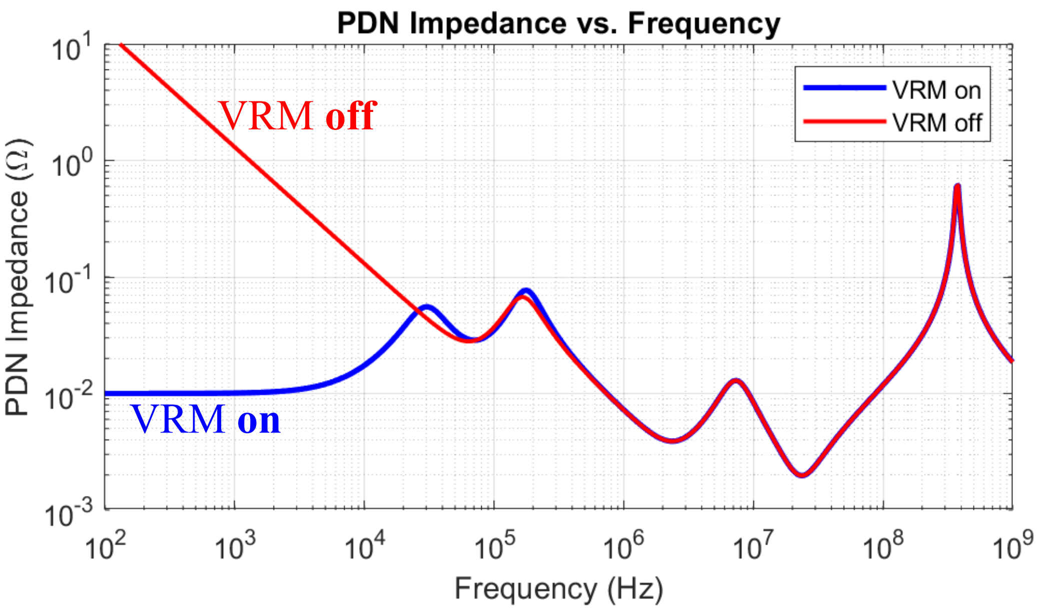
Introduction: VRM and PDN



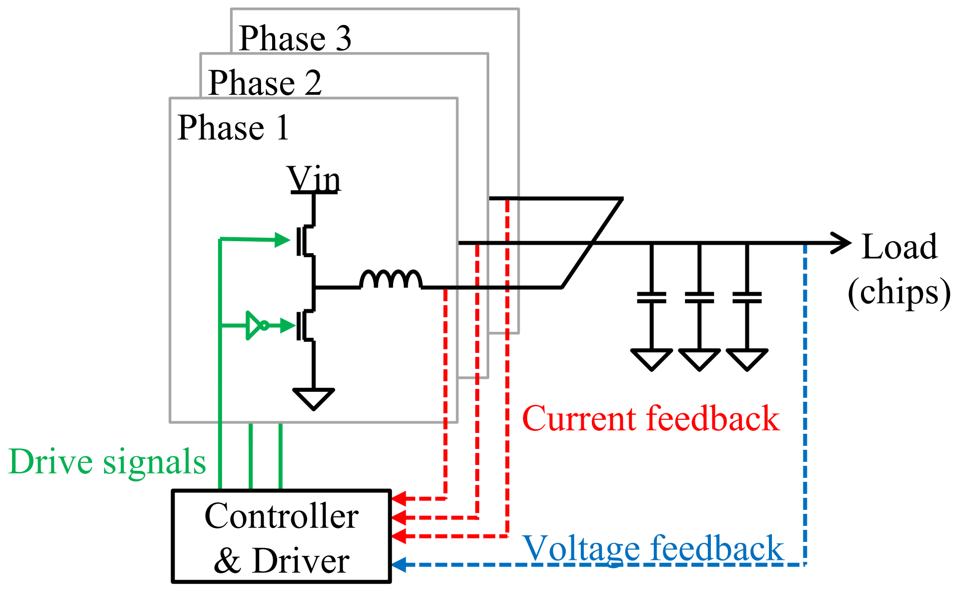
< Power delivery network >



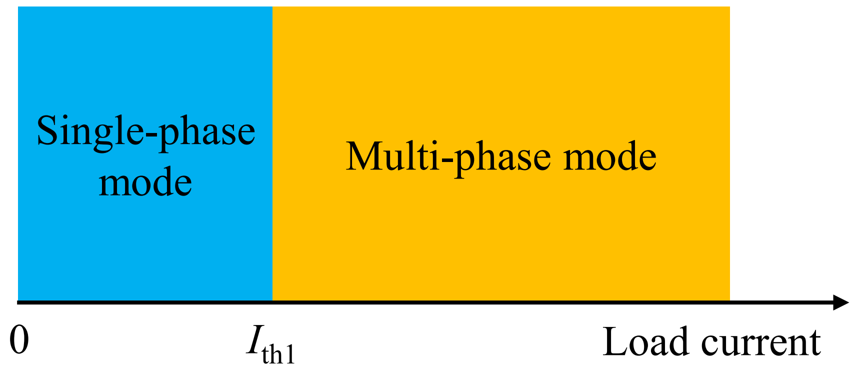
< PDN impedance: with vs. without VRM >

- VRM plays an import role in the PDN.
- Especially at the low frequencies.

Introduction: VRM and Power Integrity Simulation



< Typical multi-phase VRM>



< Operation mode vs. Load current >

- Multi-phase Buck converter is widely used nowadays.
  - It selects the best operation mode based on the load current.
  - Single-phase mode and multi-phase mode.
- The mode transition is **nonlinear** behavior.

- Goal: build a VRM behavioral model for power integrity simulation in the time-domain.

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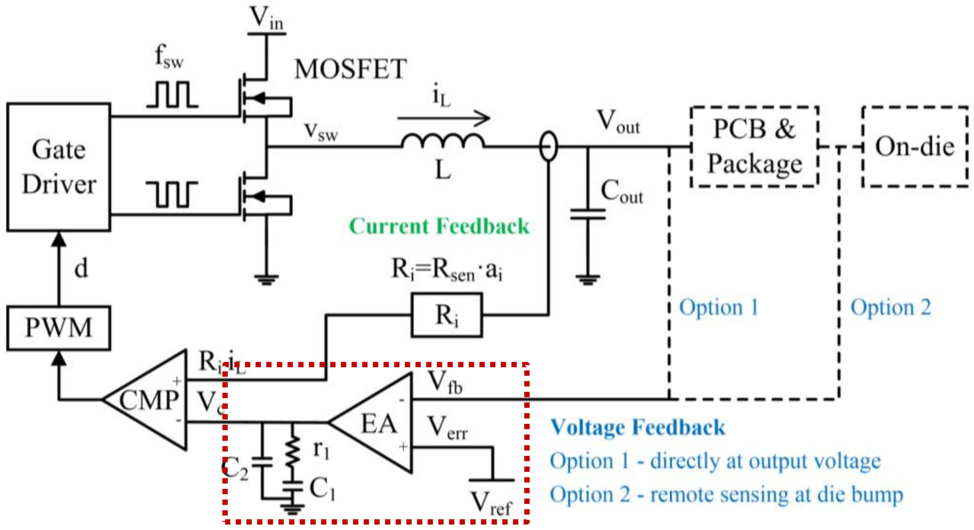
Modeling of Voltage Control Loop



< Single-phase VRM >

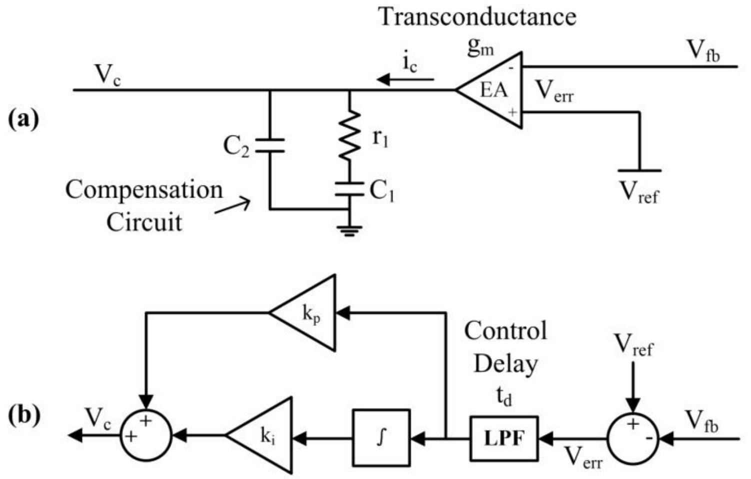


Fig. 4. Modeling of the voltage control loop: (a) actual design with the Type II compensation circuit; and (b) equivalent model with LPF and PI control.

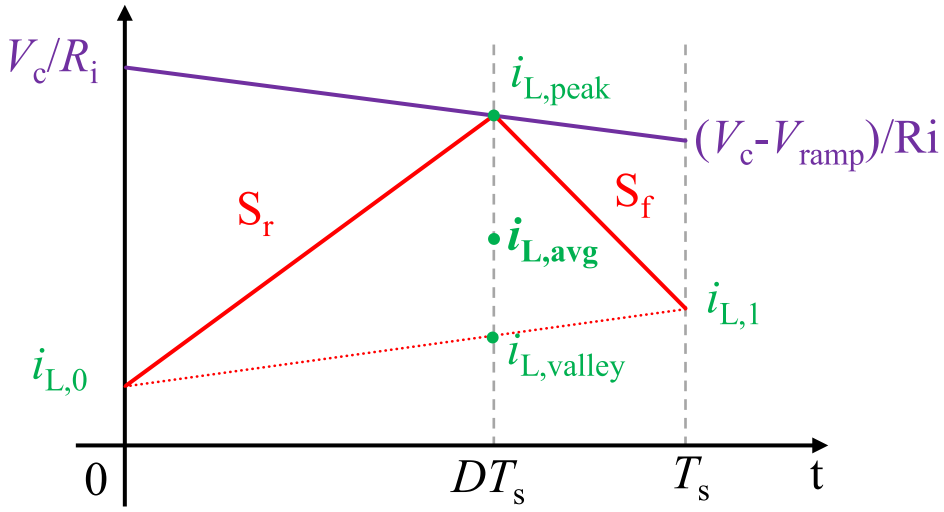
< Type-II Voltage Compensator >

- VRM:
  - Power stage
  - Controller: voltage loop, current loop
- Type-II voltage compensator
  - Equivalent to LPF + PI controller

$$\frac{V_c}{V_{err}} \approx \frac{g_m(sC_1 r_1 + 1)}{s^2 C_1 C_2 r_1 + sC_1} = \underbrace{\frac{1}{sC_2 r_1 + 1}}_{\text{LPF}} \underbrace{\left(g_m r_1 + \frac{g_m}{C_1} \cdot \frac{1}{s}\right)}_{\text{PI controller}}$$

Reference: J. Sun, Y. Yan, H. Wang, E. Chen, K. Wu and J. Fan, "Topology-Based Accurate Modeling of Current-Mode Voltage Regulator Modules for Power Distribution Network Design," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 64, no. 2, pp. 524-535, April 2022, doi: 10.1109/TEMC.2021.3123338.

Modeling of PWM Modulator (Current Control Loop)

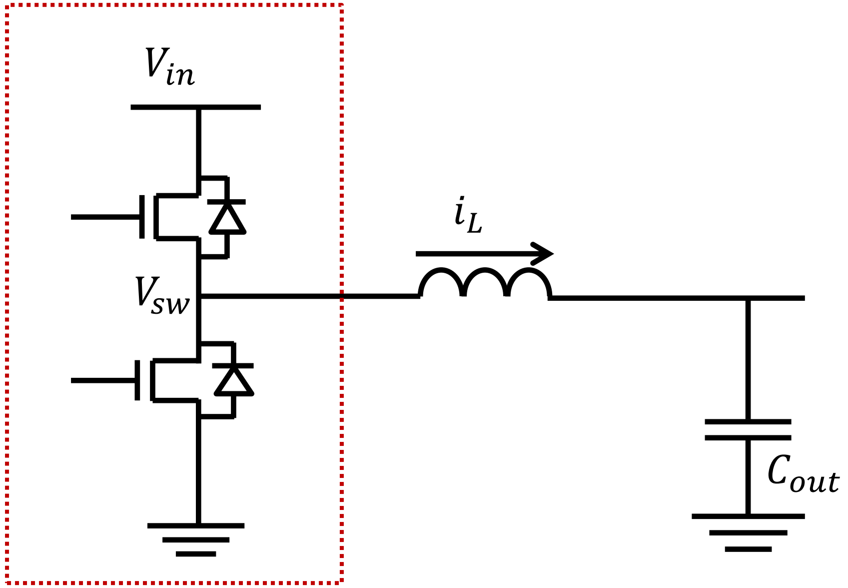


< PWM modulation >

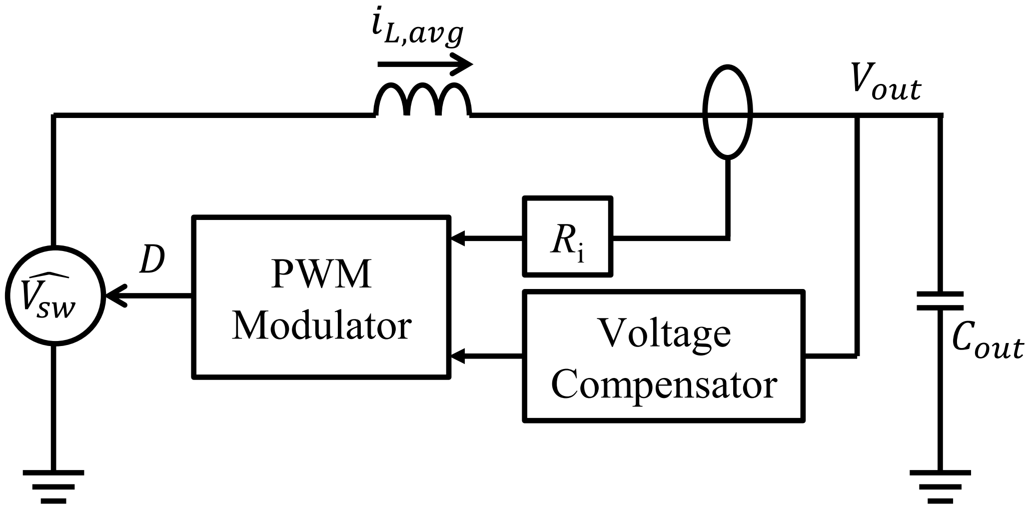
- Average inductor current definition:
  - $i_{L,avg} = \frac{1}{2}(i_{L,peak} + i_{L,valley})$
- Then, we have the follow derivation:
  - $i_{L,avg} = \left(\frac{V_c}{R_i} - \frac{V_{ramp}}{R_i} D\right) + \frac{1}{2}\left[\left(S_r - S_f\right)T_s D^2 - \left(S_r - S_f\right)T_s D\right]$
- Eventually, the duty cycle D can be found:
  - $D = \frac{1}{2} - \frac{V_{ramp}}{T_s \Delta S R_i} + \sqrt{\left(\frac{1}{2} - \frac{V_{ramp}}{T_s \Delta S R_i}\right)^2 + \frac{2}{T_s \Delta S}\left(\frac{V_c - V_{ramp}}{R_i} - \widehat{i_L}\right)}$

Reference: J. Sun, Y. Yan, H. Wang, E. Chen, K. Wu and J. Fan, "Topology-Based Accurate Modeling of Current-Mode Voltage Regulator Modules for Power Distribution Network Design," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 64, no. 2, pp. 524-535, April 2022, doi: 10.1109/TEMC.2021.3123338.

Modeling of Power Stage



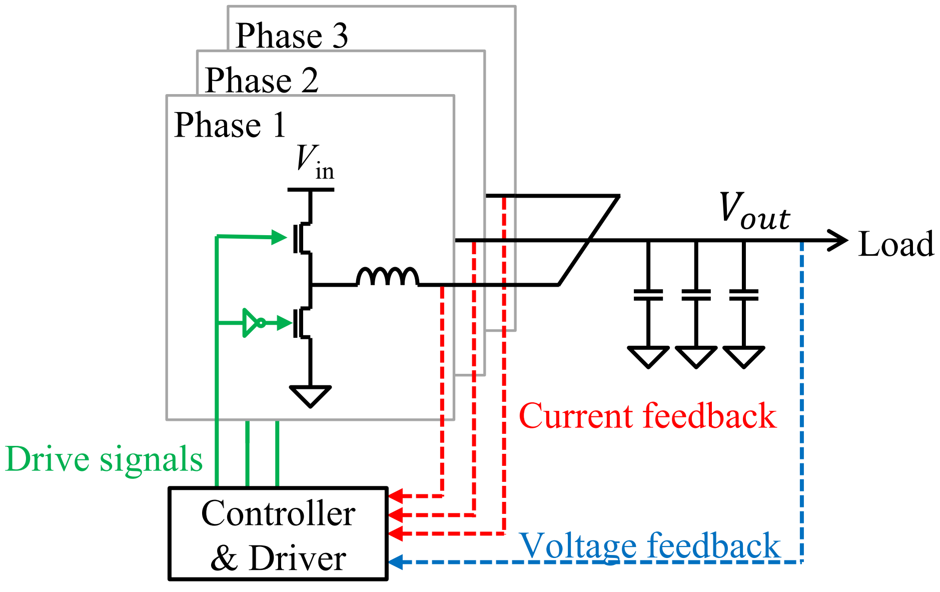
< VRM power stage >



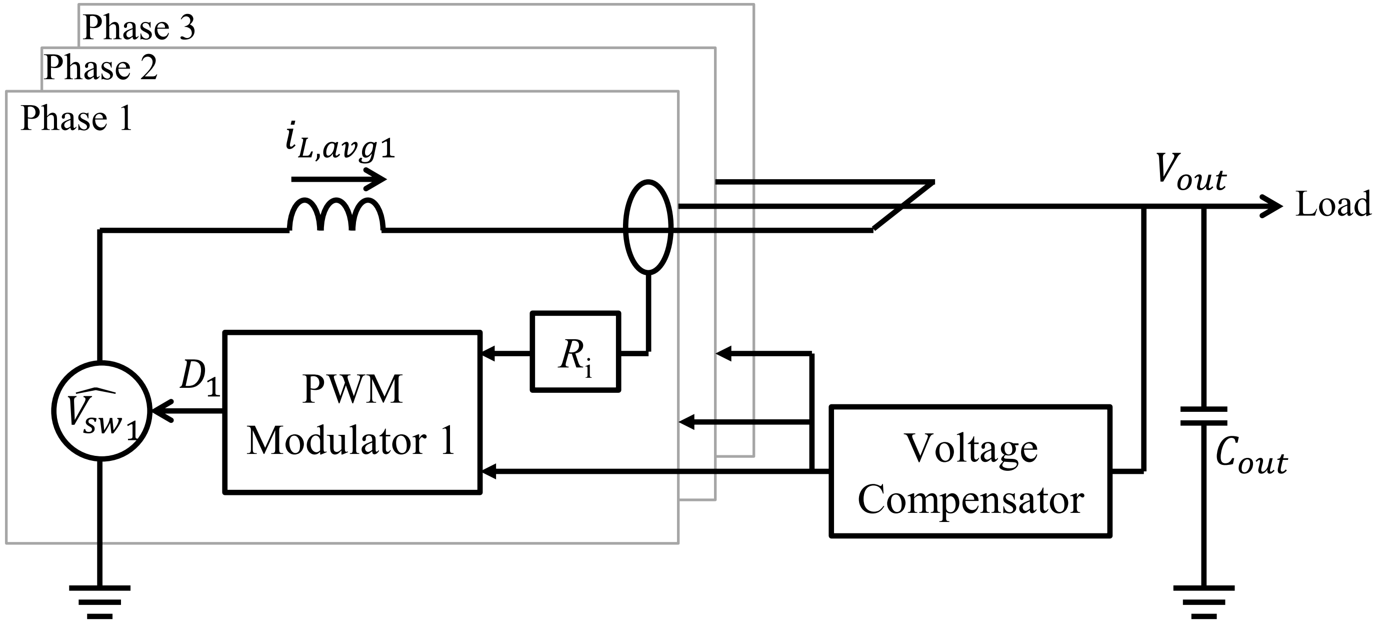
< Averaged behavioral VRM model >

- The high-side and low-side MOSFETs are replaced with a voltage source $\widehat{V_{sw}}$:
  - $\widehat{V_{sw}} = D \cdot V_{\mathrm{in}}$
- Everything can be easily built in a SPICE model.

Modeling of Multiphase VRM



< Typical multi-phase VRM>



< Averaged behavioral VRM model >

- Each phase have its own power stage, and PWM modulator
- All phases share a common voltage compensator
- Some phases can be disabled dynamically based on load current.
  - A Verilog-A module is used to determine the state of each phase (enabled or disabled).
  - Many commercial simulation tools support Verilog-A.

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Parameters in the VRM Behavioral Model

Type	Parameters	Description
Power stage	V_{in}	Input voltage
	L	Inductor
	R_{ind}	Inductor ESR
	R_{on-h}	High-side MOSFET turn-on resistance
	R_{on-l}	Low-side MOSFET turn-on resistance
	f_s	Switching frequency
	C_{out}	Output capacitor
Mode transition	I_{th-add}	Phase add threshold
	t_{d-add}	Phase add delay
	$I_{th-drop}$	Phase drop threshold
	t_{d-drop}	Phase drop delay
	$I_{th-PFM2PWM}$	PFM to PWM threshold
	$t_{d-PFM2PWM}$	PFM to PWM delay
	$I_{th-PWM2PFM}$	PWM to PFM threshold
	$t_{d-PWM2PFM}$	PWM to PFM delay

Known parameters: easy to get

Datasheets / simple measurement

Type	Parameters	Description
Control loop	V_{ref}	Reference voltage
	K_{DC}	Single-phase DC gain
	K_P	Single-phase proportional gain
	K_I	Single-phase integral gain
	V_{rp}	Ramp compensation
	R_i	Current sensing gain
	K_{P2}	Multi-phase proportional gain
	K_{I2}	Multi-phase integral gain
	K_{DC2}	Multi-phase DC gain

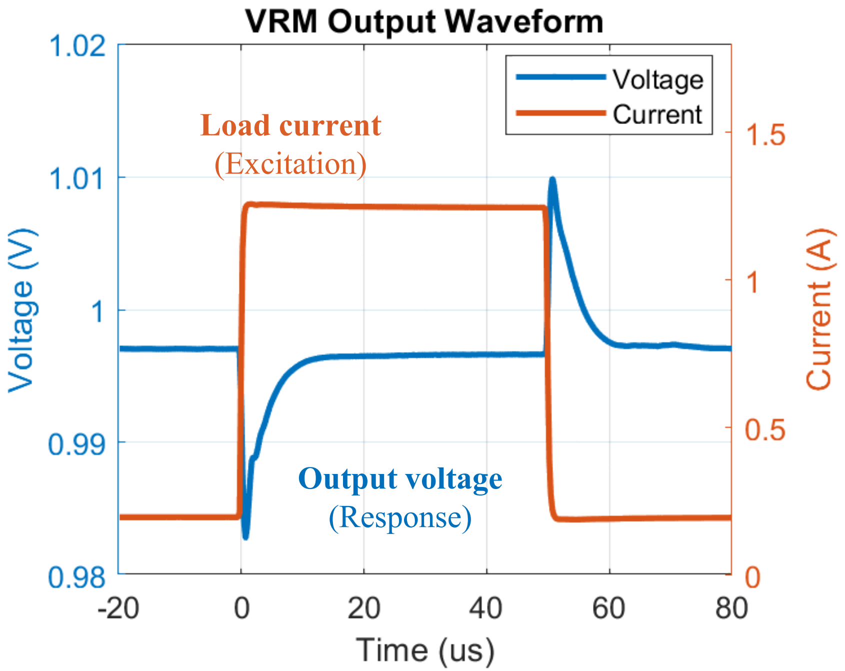
Unknown parameters: hard to obtain!

- Typically, not listed in datasheet.
- Cannot be directly measured.

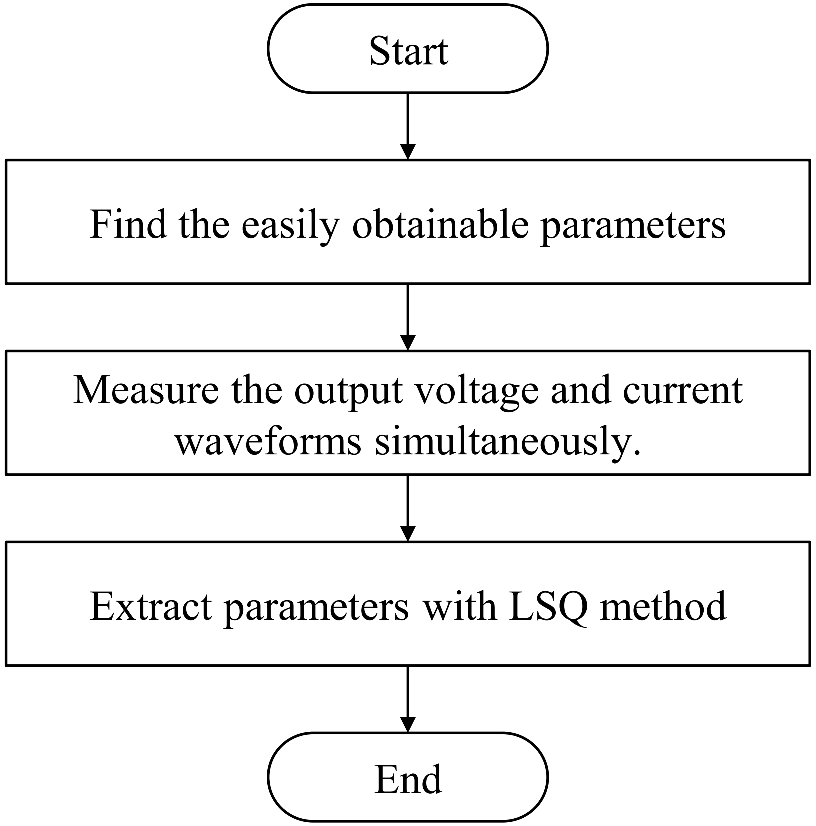
Automatic Parameter Extraction

We proposed a VRM parameter extraction method.

- Employ nonlinear least-square (LSQ) method.
- Take **output voltage and output current** waveforms as reference input.
- From oscilloscope measurement.

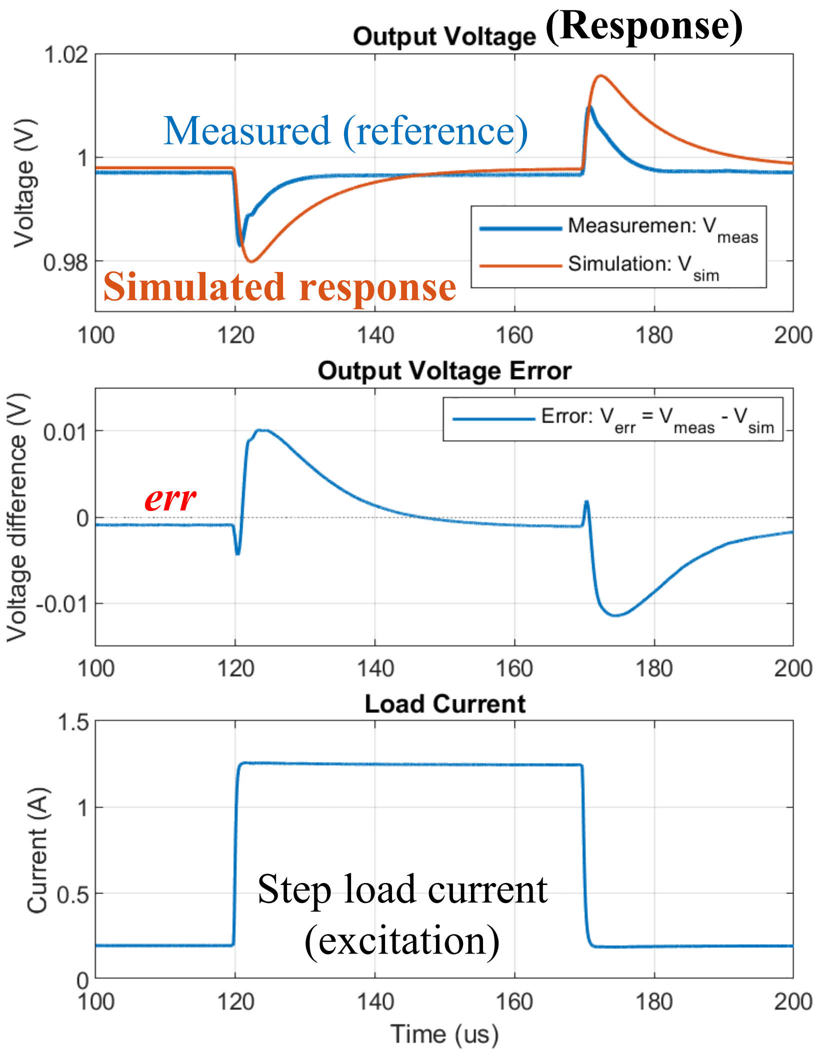


< VRM output waveform >



< Parameter extraction workflow >

Extract PWM-related Parameters



< Example waveform>

- Reference input waveform
  - Step load current excitation.
- Use nonlinear LSQ method to find the best estimation of the unknown parameters.
  - By minimizing the cost function.
  - SPICE simulations will be conducted in every iteration to update the cost function.

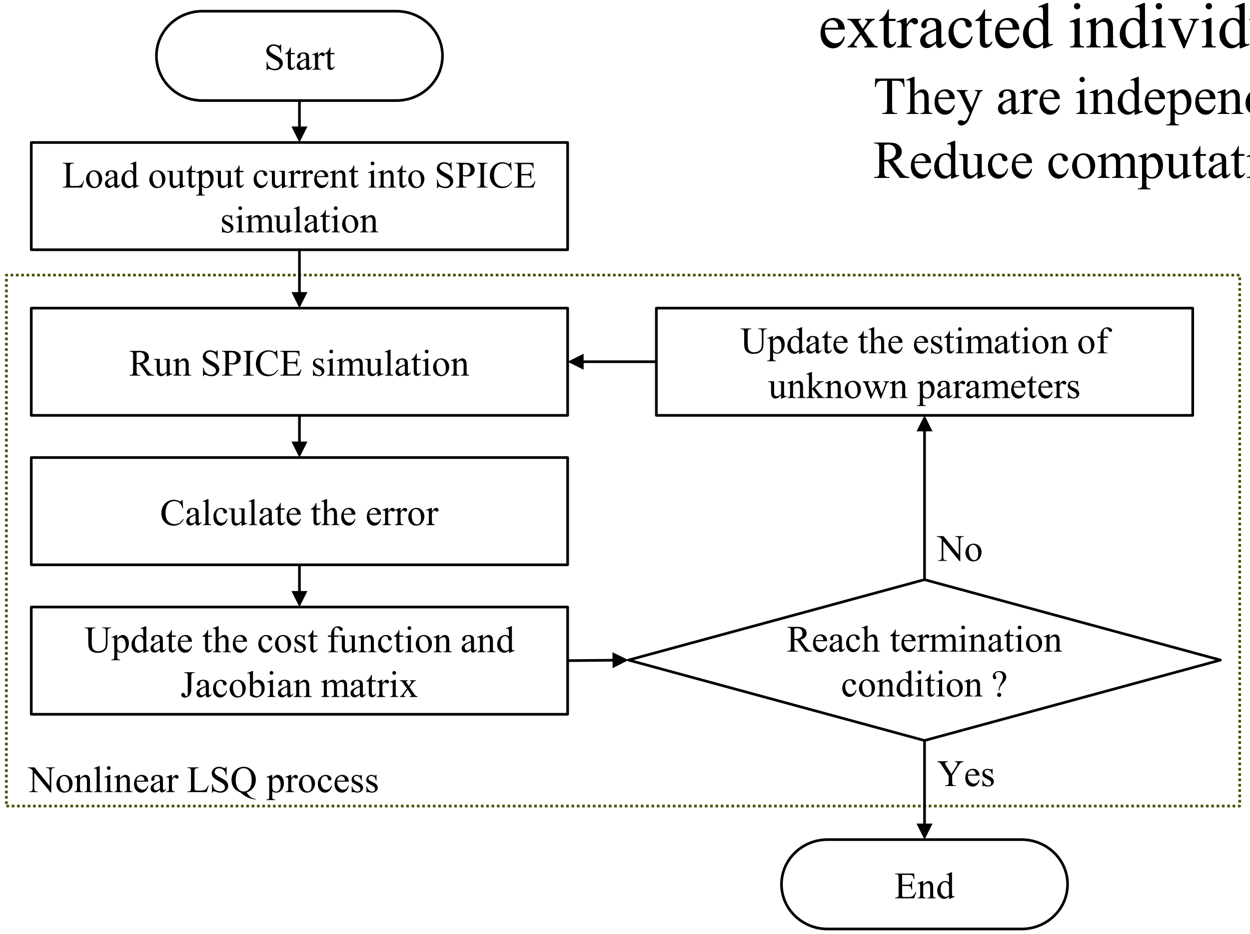
$$err[x] = V_{Meas.}[x] - V_{Sim.}[x]$$

$$Cost(parameters) = \sum_{x=1}^{n} err[x]^2$$

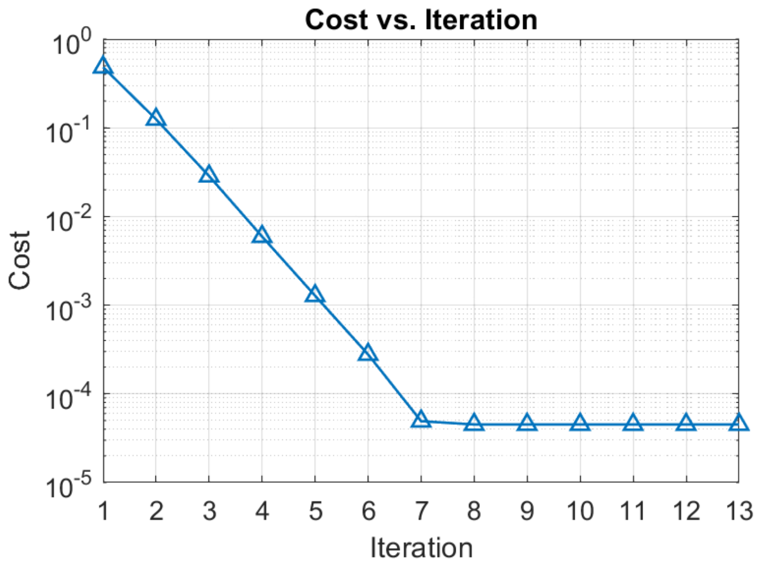
Minimize **Tune**

Extract Parameters (cont.)

- **Single-phase parameters** and **multi-phase parameters** are extracted individually.
  - They are independent.
  - Reduce computation time and improve convergence.

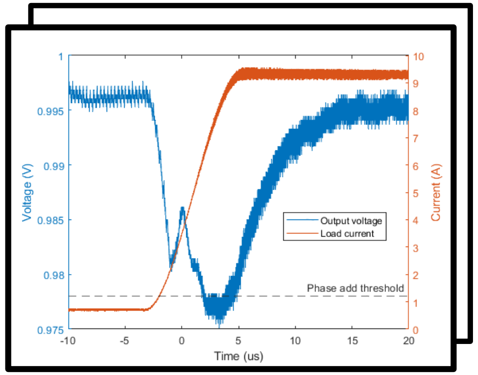


< Parameter extraction algorithm >



< Nonlinear LSQ cost vs. iteration>

Implementation: Automatic Parameter Extraction



Measurement waveforms

- Single-phase PWM waveform
- Multi-phase PWM waveform

Type	Parameters	Description
Power stage	V_{in}	Input voltage
	L	Inductor
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Known parameters

Input

Python script:
Parameter extraction

Output

Type	Parameters	Description
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	K_P	Single-phase proportional gain
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Unknown parameters

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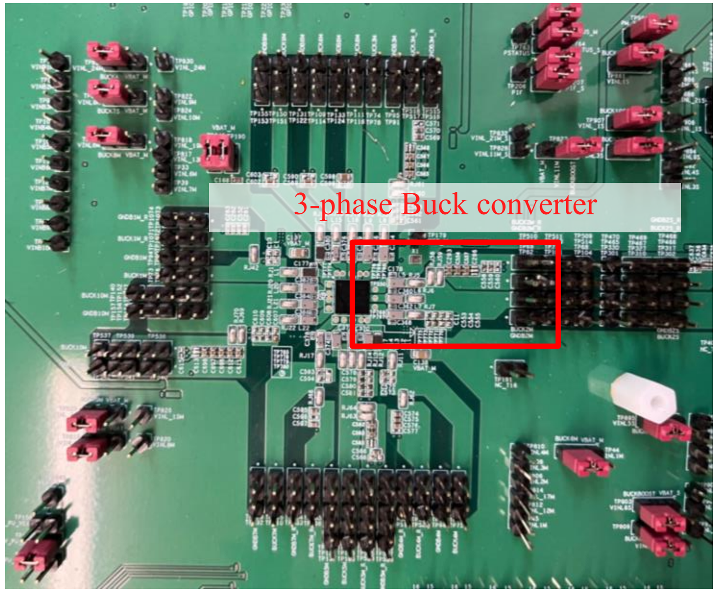
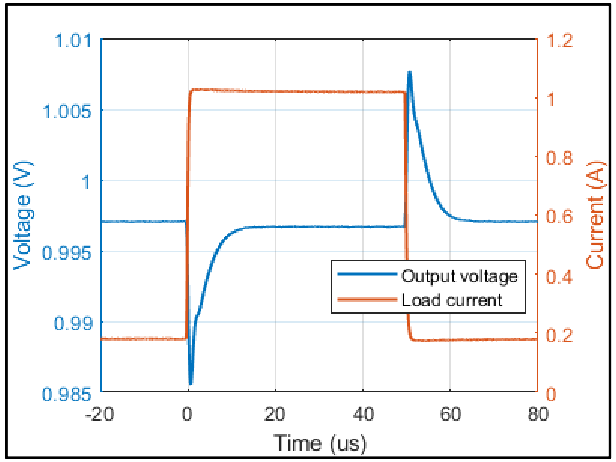
Validation Case 1: VRM EVB

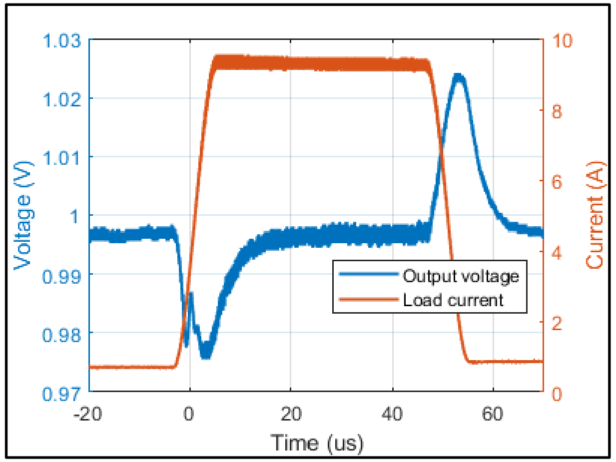


< VRM evaluation board for mobile applications >

< Measured output waveform of the EVB >



< Single-phase PWM waveform >



< Multi-phase PWM waveform >

- A 3-phase Buck converter
  - With single-phase mode and 3-phase mode.
- With the given input, the Python script found the unknown parameters in 20 mins.

Parameter Extraction Result

Known parameters

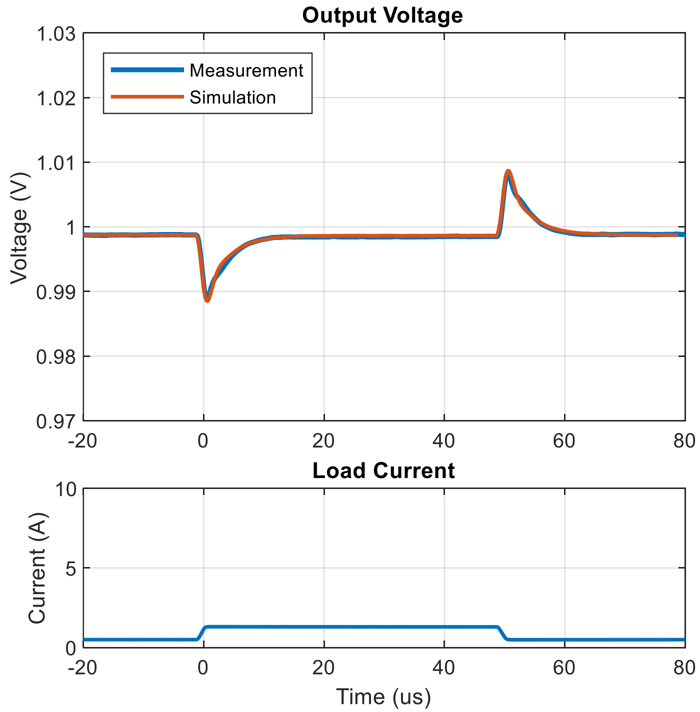
Category	Parameters	Value
Power stage	V_{in}	4
	L	240e-9
	R_{ind}	24e-3
	R_{on-h}	34e-3
	R_{on-l}	13e-3
	f_s	3.25e6
	C_{out}	1.5
Mode transition	I_{th-add}	1e-6
	t_{d-add}	1.2
	$I_{th-drop}$	20e-6
	t_{d-drop}	0.57
	$I_{th-PFM2PWM}$	0.33
	$t_{d-PFM2PWM}$	0
	$I_{th-PWM2PFM}$	40e-6
	$t_{d-PWM2PFM}$	14e-6

Extracted parameters

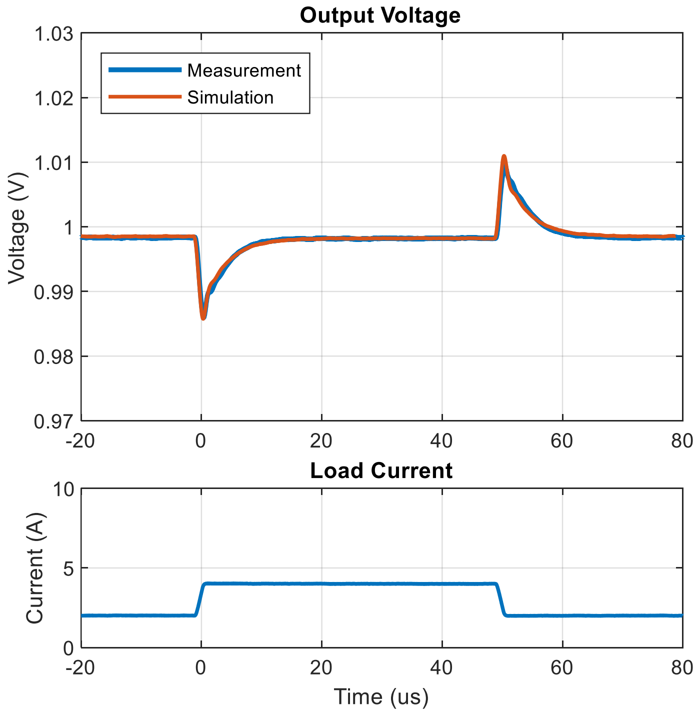
Category	Parameters	Initial value	Extracted value
PWM-related parameters	V_{ref}	1	0.99757
	K_{DC}	10	242.7
	K_P	1	5.693
	K_I	1e6	1441845
	V_{rp}	0.1	0.2793
	R_i	0.1	0.07246
	K_{P2}	1	3.836
	K_{I2}	1e6	1092029
	K_{DC2}	100	200.2

- The initial value is the start point for parameter extraction.
  - A very rough estimation of the unknown parameter.
  - The initial value listed here is a good start point for unknow VRM.

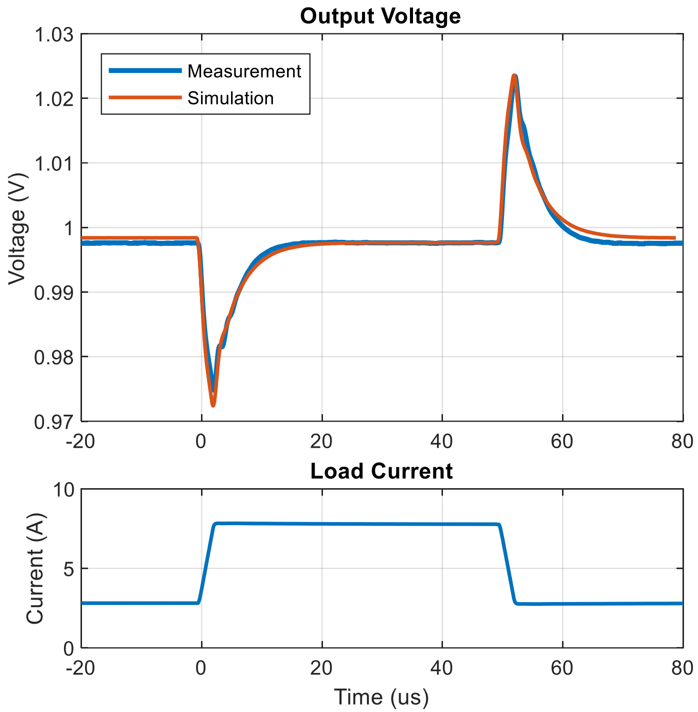
VRM EVB Validation Result



V_{in} = **3V**, I_{out} = **0.5A↔1.3A**, $t_{r/f}$ = **1us**, single-phase mode



V_{in} = **4.5V**, I_{out} = **2A↔4A**, $t_{r/f}$ = **1us**, 3-phase mode

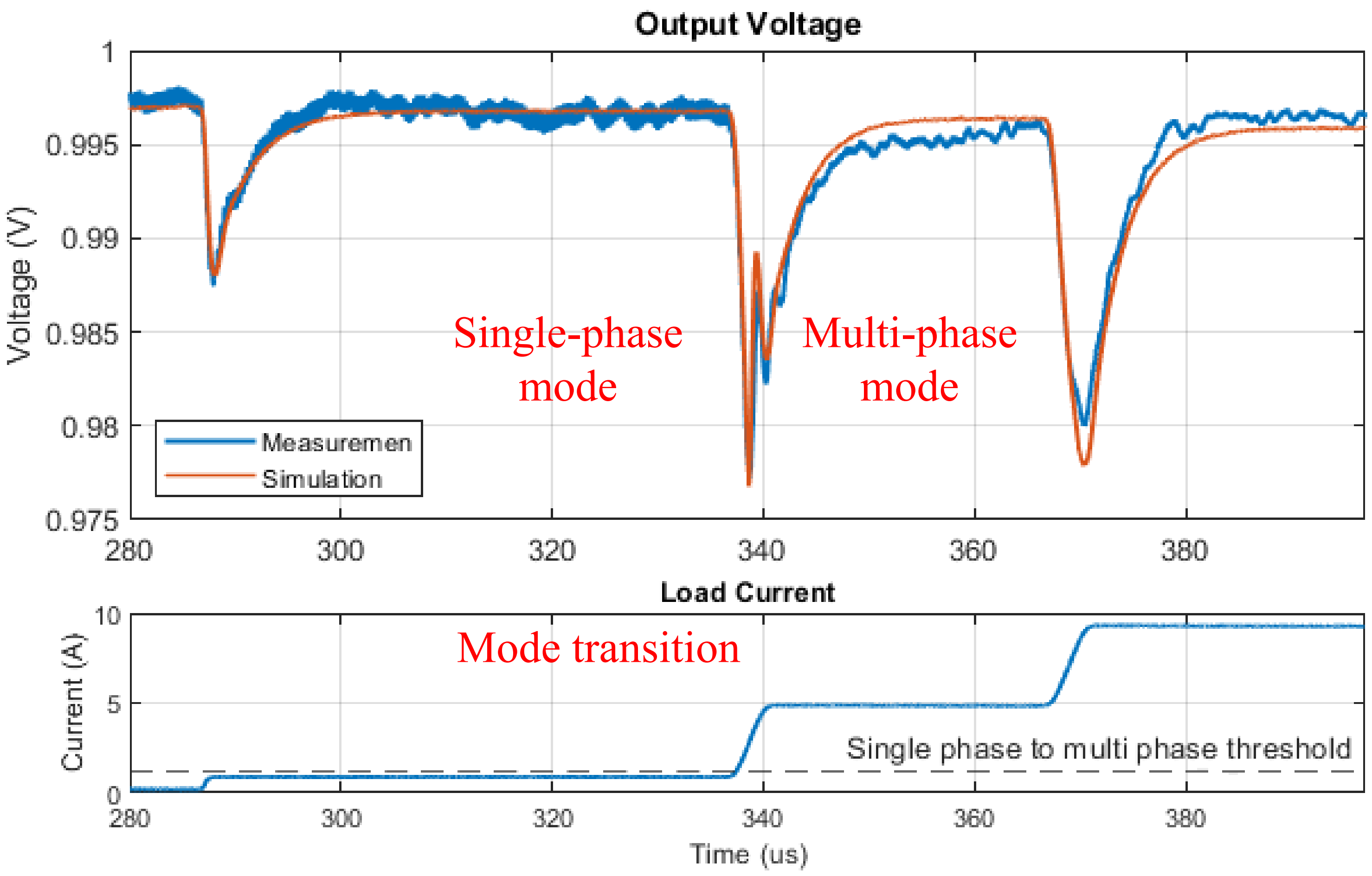


V_{in} = **4.0V**, I_{out} = **3A↔8A**, $t_{r/f}$ = **2us**, 3-phase mode

- Different test conditions.
  - Input voltage, current level, rising/falling time.

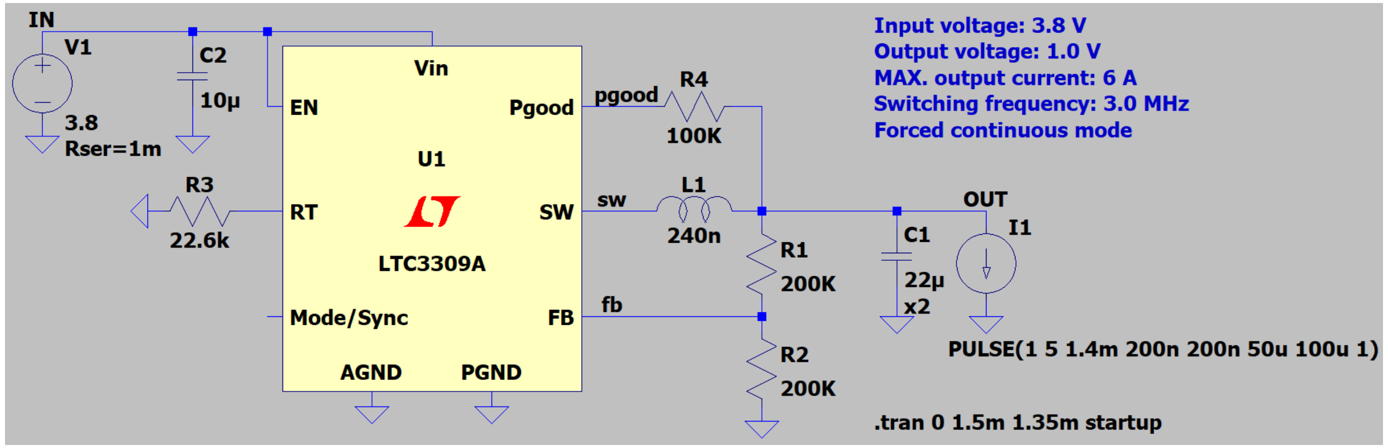
VRM EVB Validation Result (cont.)

- Nonlinear mode transition:
  - Single-phase mode to multi-phase mode.



Validation Case 2: LTC3309A

- Sometimes, we have the simulation model from the vender.
- But it is not suitable for PI simulation.
  - Encrypted, slow, not compatible with common PI simulation tools, …
- So, it need to be converted to the behavioral model.



LTC3309A simulation model

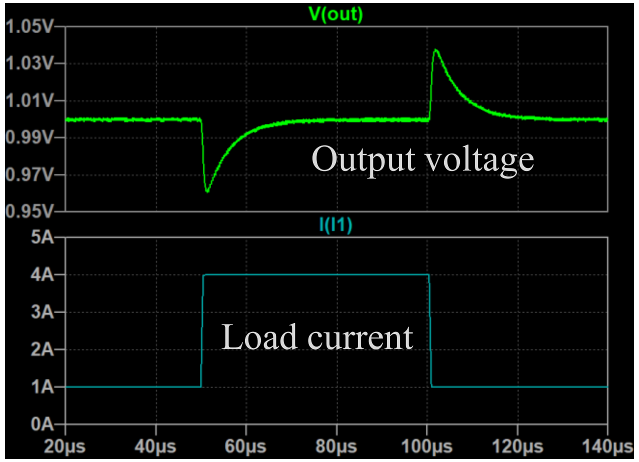
- Analog Device LTC3309A
  - Single-phase Buck converter
  - VRM model (encrypted) from vender
  - Input / output voltage: 3.8 V / 1.0 V
  - VRM: force continuous mode (FPWM)

Parameters of LTC3309A Model

- The unknown parameters were extracted based on the simulation result from the vender's model.

Parameters	Value
V_{in}	3.8
L	240e-9
R_{ind}	19.5e-3
R_{on-h}	31e-3
R_{on-l}	8e-3
f_s	3e6
C_{out}	44e-6

Known parameters



Input

Simulated waveform from vender's VRM model

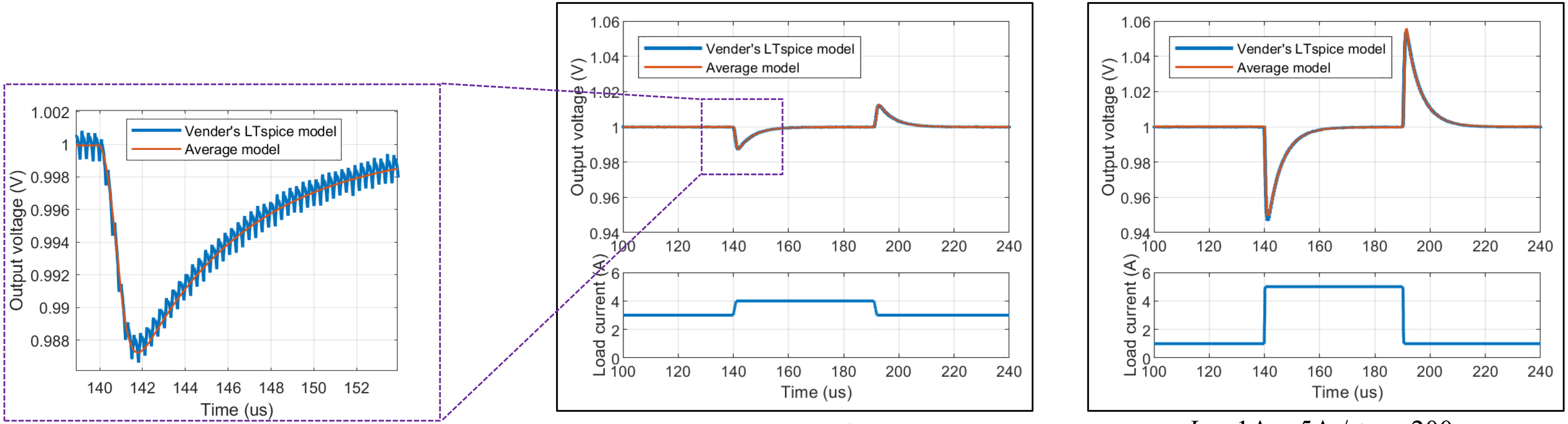
Python script: Parameter extraction

Output

Extracted parameters

Parameters	Initial value	Extracted value
V_{ref}	1	1.00023
K_P	1	6.948848
K_I	1e6	1183846.49
V_{rp}	0.1	0.13695
R_i	0.1	0.09399

LTC3309A Validation Result



I_{out}: 3A – 4A / $t_{r/f}$ = 1 us

I_{out}: 1A – 5A / $t_{r/f}$ = 200 ns

- Behavioral model.
  - Good correlation with the Vender's model.
  - Neglect the output ripple; smooth output.
  - Compatible with PI simulation tools.
  - Took 2.01 seconds.
- Vender's model
  - Includes the output ripple.
  - Took 19.21 seconds.

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Conclusion

- An averaged behavioral VRM model was introduced.
  - It can be used for time-domain simulation.
  - This model works for both single-phase and multi-phase VRMs.
  - It captures the nonlinear mode transition.
  - Compatible with common PI simulation tools.

- A parameter extraction method for VRM was introduced.
  - It uses the reference waveform as input.
  - Use nonlinear LSQ method to extract the unknown parameters automatically.

- An encrypted VRM model can be converted to the behavioral model for PI analysis.

- This method simplifies the VRM modeling process.