Reachability Analysis of Closed-Loop Switching Power Converters

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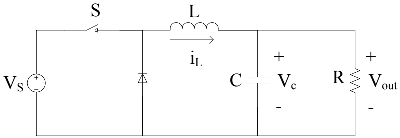
Switching Power Converters

1. DC-DC Converters
   - Buck converter
   - Boost converter
   - Buck-Boost converter
2. Rectifiers (AC-DC)
3. Inverters (DC-AC)
4. Transformers

Buck Converter

Circuit Diagram

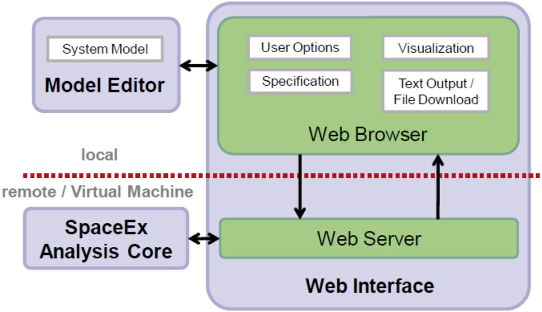


Design Verification of Switching Power Converters

1. Traditional simulation methods
   - Simulink/Stateflow
   - PSpice
   - Monte Carlo
2. Hybrid system verification tools
   - SpaceEx

SpaceEx

Software Architecture

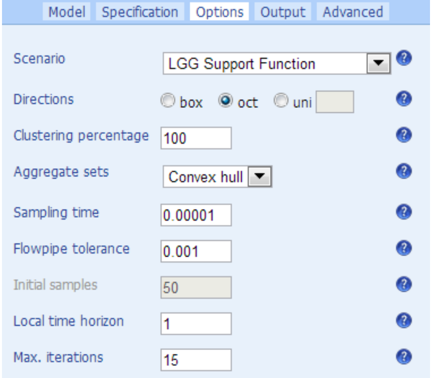


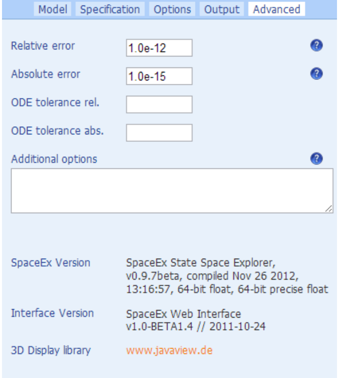
SpaceEx Reachability Algorithm

- Symbolic States
- Control:
  1. Maximum iterations
  2. Relative and absolute error

SpaceEx Interface

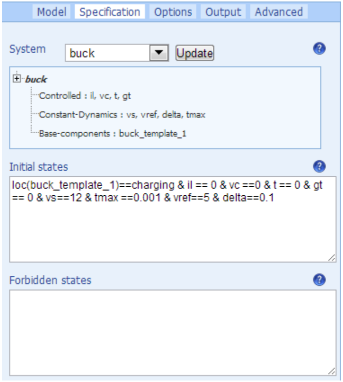
Setting Maximum Iterations and Relative and Absolute Errors

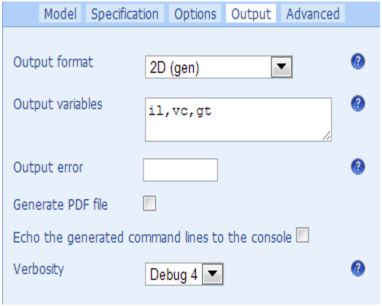




SpaceEx Interface

Initial States and Output Specification





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Model of Open-Loop Configuration

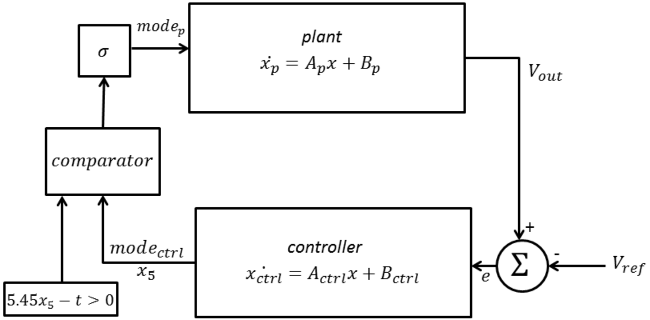
$$x = \begin{bmatrix} i_L \\ V_c \end{bmatrix}$$

$$A_o = A_c = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}$$

$$B_c = \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_s \;\; or \;\; B_o = \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_s$$

Linear Controller

Block Diagram



Linear Controller

System Model

$$A_{ctrl} = \begin{bmatrix} -\frac{1}{p_1} & 0 & 0 \\ -\frac{p_2}{p_1 p_3} + \frac{1}{p_3} & -\frac{1}{p_3} & 0 \\ -\frac{p_2 p_4}{p_1 p_3 p_5} + \frac{p4}{p3p5} & \frac{-p4}{p_3 p_5} + \frac{1}{p_5} & 0 \end{bmatrix}$$

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad B_{ctrl} = \begin{bmatrix} \frac{1}{p_1} \\ \frac{p_2}{p_1 p_3} \\ \frac{p_4 p_2}{p_1 p_3 p_5} \end{bmatrix}$$

Linear Controller

Composed System

$$\dot{x} = A_c \cdot x_c + B_{comp}\,(V_{ref} - V_{out})$$

Linear Controller

Composed System

$$A_c = \begin{bmatrix} 0 & \frac{-1}{L} & 0 & 0 & 0 & 0 \\ \frac{1}{C} & \frac{-1}{RC} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{p_1} & -\frac{1}{p_1} & 0 & 0 \\ 0 & 0 & -\frac{p_2}{p_1 p_3} & -\frac{p_2}{p_1 p_3} + \frac{1}{p_3} & -\frac{1}{p_3} & 0 \\ 0 & 0 & -\frac{p_4 p_2}{p_1 p_3 p_5} & -\frac{p_2 p_4}{p_1 p_3 p_5} + \frac{p_4}{p_3 p_5} & -\frac{p_4}{p_3 p_5} + \frac{1}{p_5} & 0 \end{bmatrix}$$

$$\dot{x_c} = \begin{bmatrix} \dot{i_L} \\ \dot{V_c} \\ \dot{x1} \\ \dot{x2} \\ \dot{x3} \end{bmatrix} \quad B_c = \begin{bmatrix} \frac{V_s}{L} \\ 0 \\ \frac{1}{p_1} \cdot V_{ref} \\ \frac{p_2}{p_1 p_3} \cdot V_{ref} \\ \frac{p_4 p_2}{p_1 p_3 p_5} \cdot V_{ref} \end{bmatrix} \quad B_o = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{p_1} \cdot V_{ref} \\ \frac{p_2}{p_1 p_3} \cdot V_{ref} \\ \frac{p_4 p_2}{p_1 p_3 p_5} \cdot V_{ref} \end{bmatrix}$$

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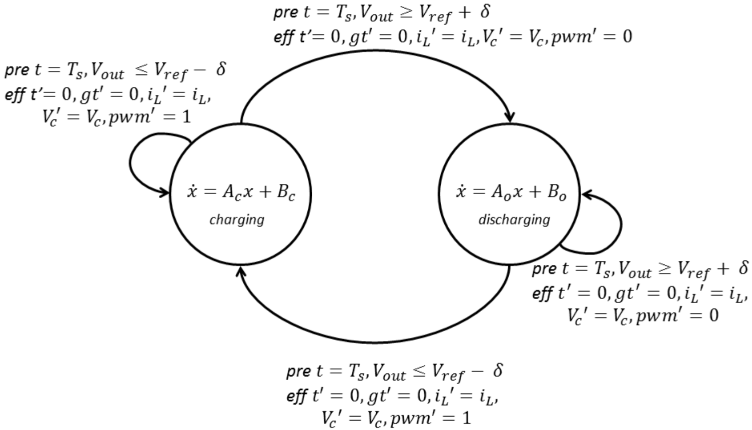
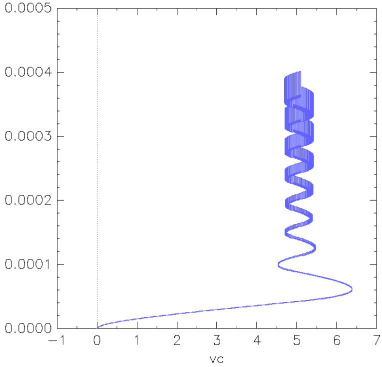
Hysteresis Controller

Hybrid Model of Buck Converter and Hysteresis Controller



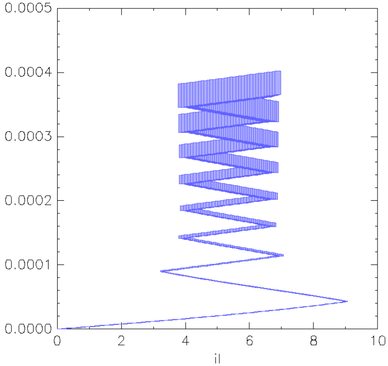
Results of Hysteresis Controller

Capacitor Voltage vs. Global Time



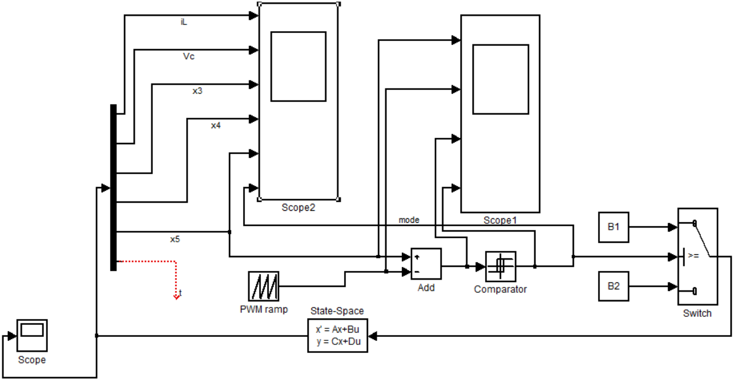
Results of Hysteresis Controller

Inductor Current vs. Global Time



Simulink Results for Composed System

Simulink Model

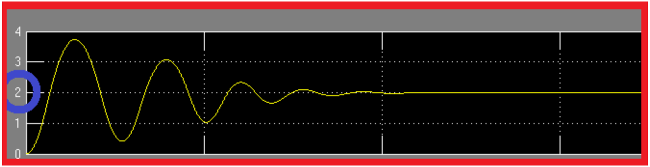


Simulink Results for Composed System

Simulink Output

Simulink Results for Composed System

Capacitor Voltage vs. Global Time



Conclusion and Future Work

- Open-loop and hysteresis controller configurations
- Modeling flexibility
- Overapproximation issues

References

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- Questions?