State-Space “Switching” Model of DC-DC Converters in SystemVerilog.

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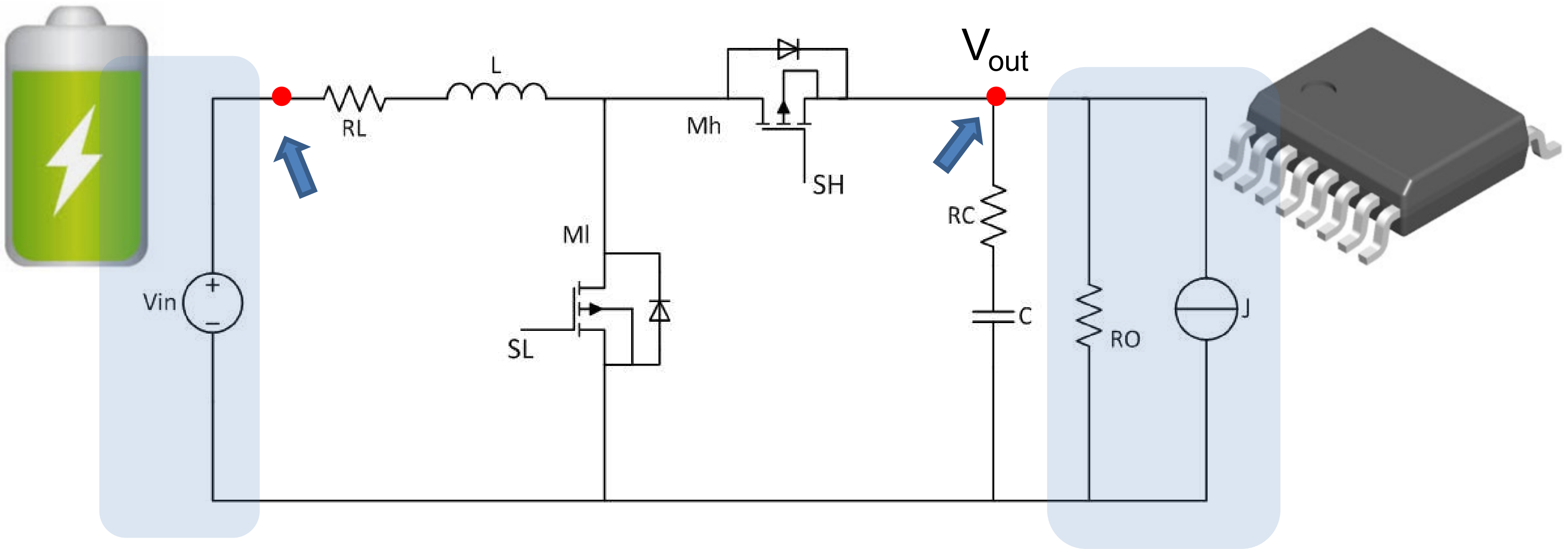
Use Case: Boost Converter

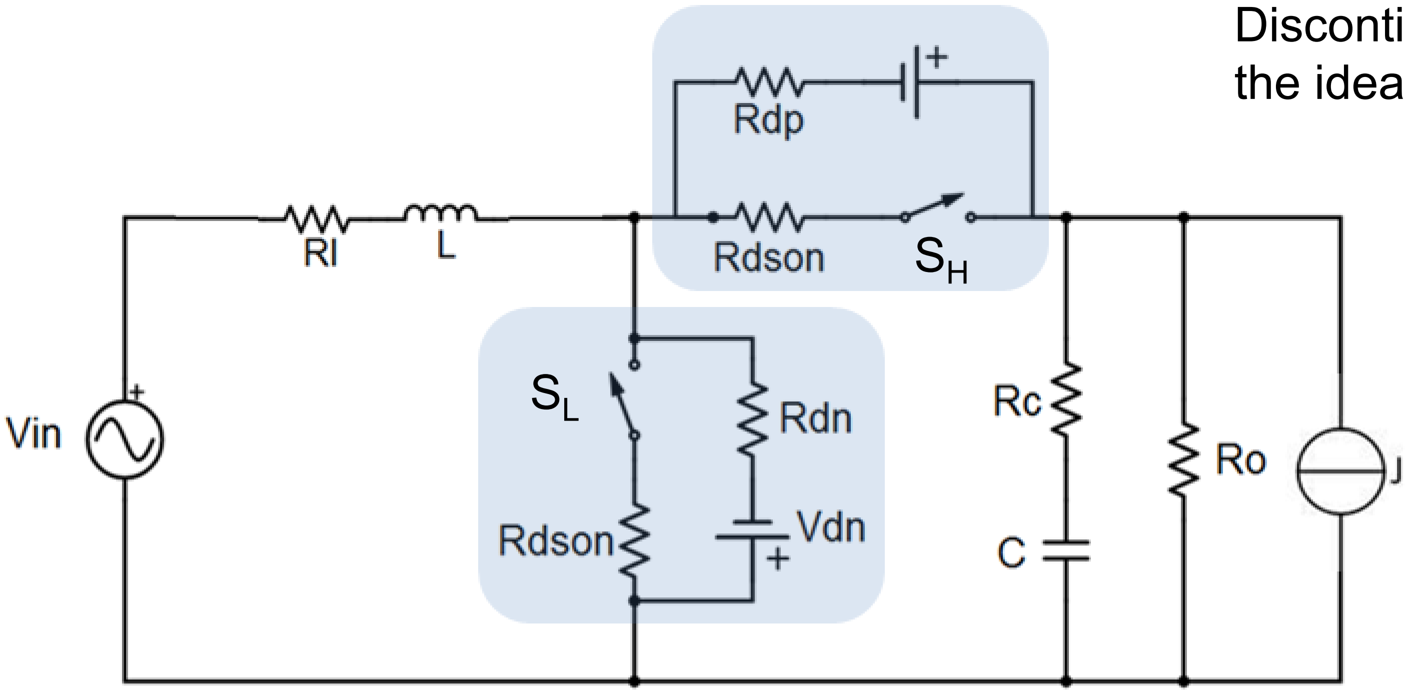
$V_{OUT} >= V_{IN}$



Secondary effects:

- Parasitic resistors (R_L, R_C).
- Body diodes for the switches.

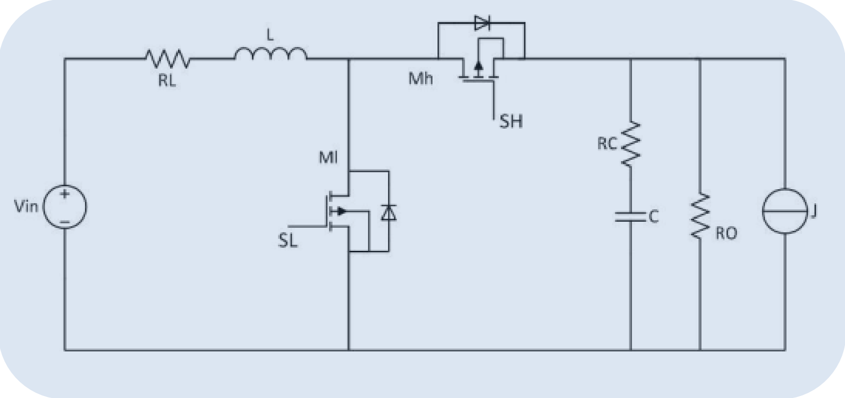
Step 1: Replace Mosfet with simpler model



Discontinuities are created due to the ideal switches !!!

More options are available for modeling transistors...

Step 2: Linearize the resulting circuit



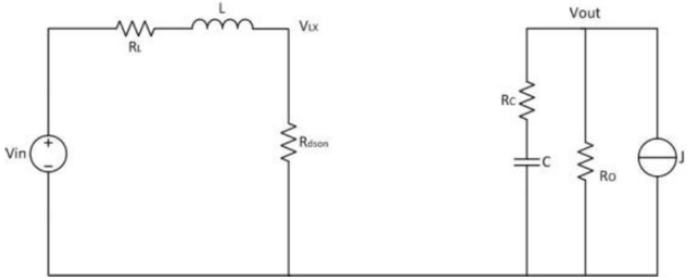


Figure 4a. Inductor charging phase

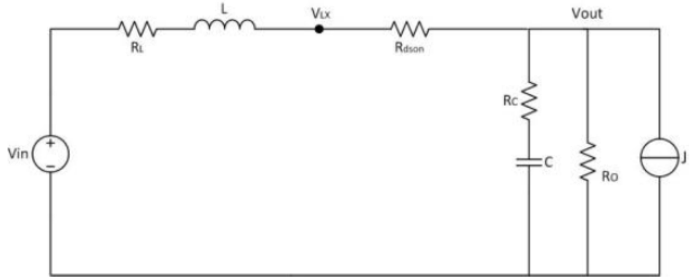


Figure 4b. Inductor discharge phase

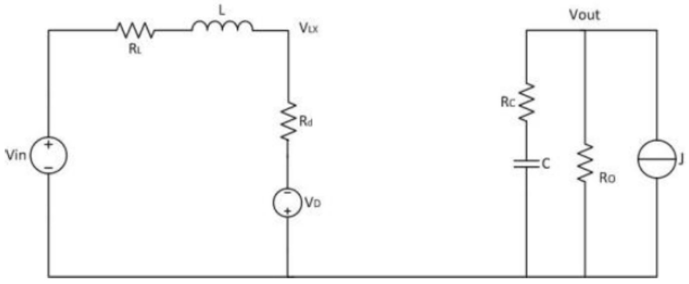


Figure 4c. Low side diode in conduction.

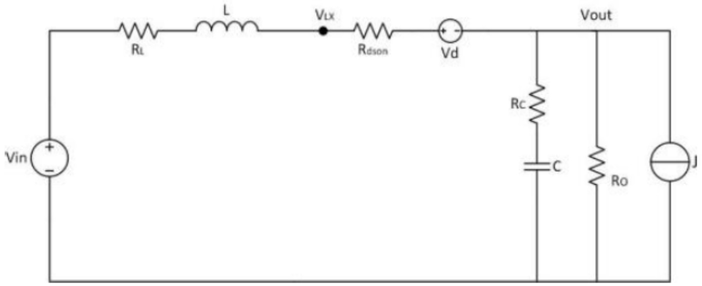


Figure 4d. High side diode in conduction.

Create possible circuit configurations:

- Ideal switch positions
- Diode polarity,

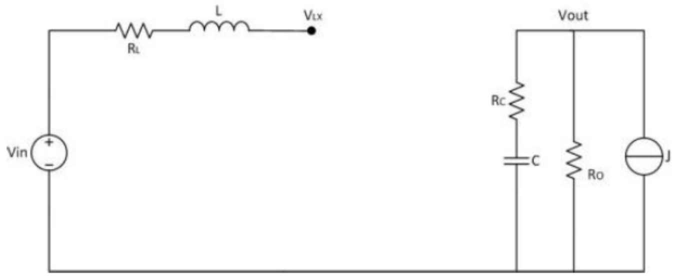


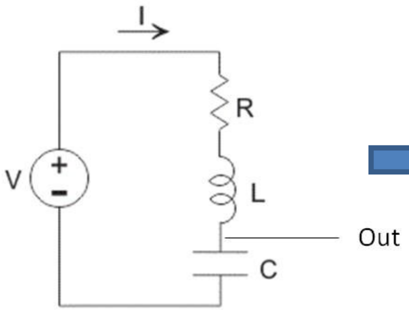
Figure 4e. Discontinuous mode of operation, no current in the coil.

Step 3: Write circuit equations

For each configuration:

1. Define its differential equations. $$m\frac{\mathrm{d}^2 x(t)}{\mathrm{d}t^2} = F(x(t))$$
2. Bring the equations in Vector notation via A,B,C,D matrices (SS Model)

$$\dot{\mathbf{x}}(t) = A\mathbf{x}(t) + B\mathbf{u}(t)$$
$$\mathbf{y}(t) = C\mathbf{x}(t) + D\mathbf{u}(t)$$



1

$$\dot{I}_L = \frac{dI_L}{dt} = \frac{1}{L}V - \frac{R}{L}I_L + \frac{1}{L}V_C$$

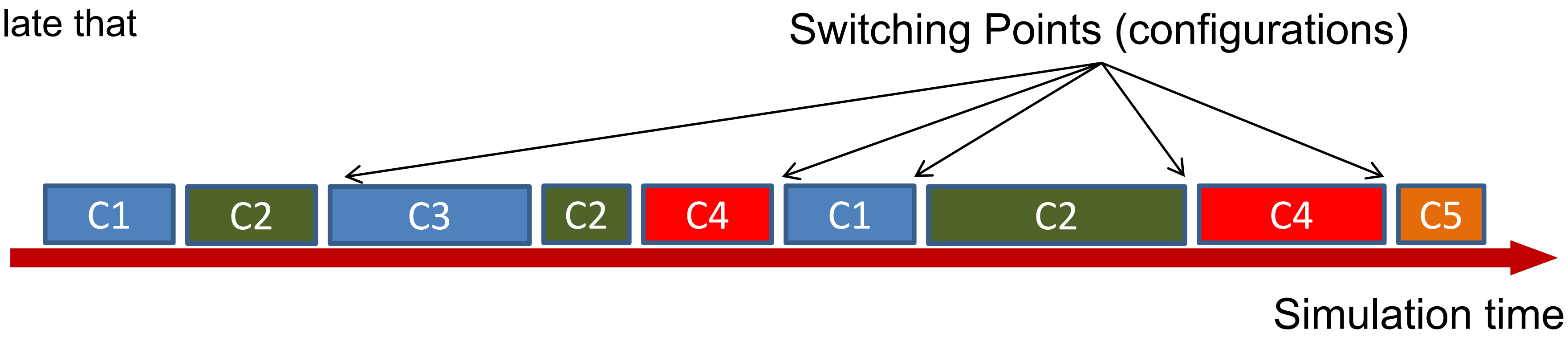
$$\dot{V}_C = \frac{dV_C}{dt} = \frac{1}{C}I_L$$

2

$$\begin{bmatrix}\dot{I}_L\\ \dot{V}_C\end{bmatrix} = \begin{bmatrix}\frac{-R}{L} & \frac{1}{L}\\ \frac{1}{C} & 0\end{bmatrix}\begin{bmatrix}I_L\\ V_C\end{bmatrix} + \begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}V$$

Step 4: Identify conditions for which we need to switch to a certain configuration

At any given time, the circuit can only be in one of the configurations therefor simulate that



- All configurations have in common the same state variables and their derivatives.
- Each configurations has its own matrix coefiecients.
- @ each switching point, only the coefficient need to be replaced with those of the configuration we are going to as next. Replace the matrix at any switching point.

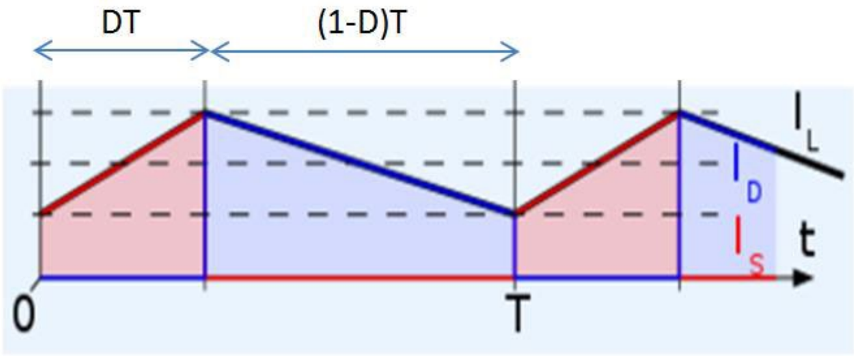
Step 5: Define the computation step

- The state variable and their derivatives must be recalculated at every time step T.
- The time step has to be decidede based on the system requirements.
- Since in discrete time domain, the State Space equations should be discretized before, but if the time step is quite small the two systems will be converging.

```
bit clk; initial forever #(T*1s) clk = !clk;
var real a00, a01, a10, a11;
var real b00, b01, b10, b11;

always @(clk) begin
        // calculate the first derivatives
        dx0 = a00*x0 + a01*x1 + b00*J + b01*Vin;
        dx1 = a10*x0 + a11*x1 + b10*J + b11*Vin;
        // calculate the next state variables
        x0 = x0 + dx0*T;
        x1 = x1 + dx1*T;
end
```

Differences with Average SS Model



Create one matrix from all the existing one

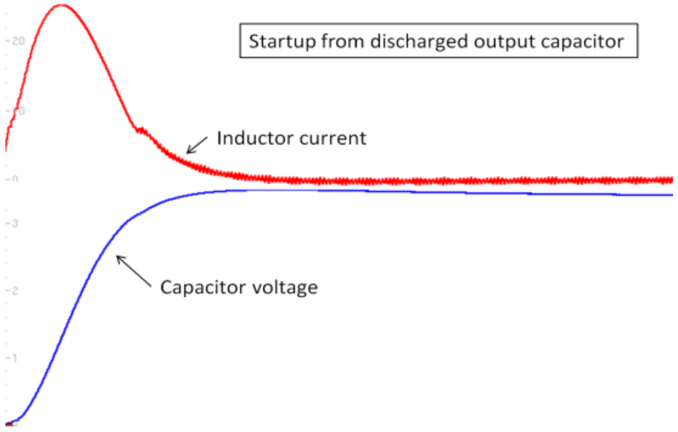
$$A_{avg} = DA_a + (1\text{-}D)A_b$$

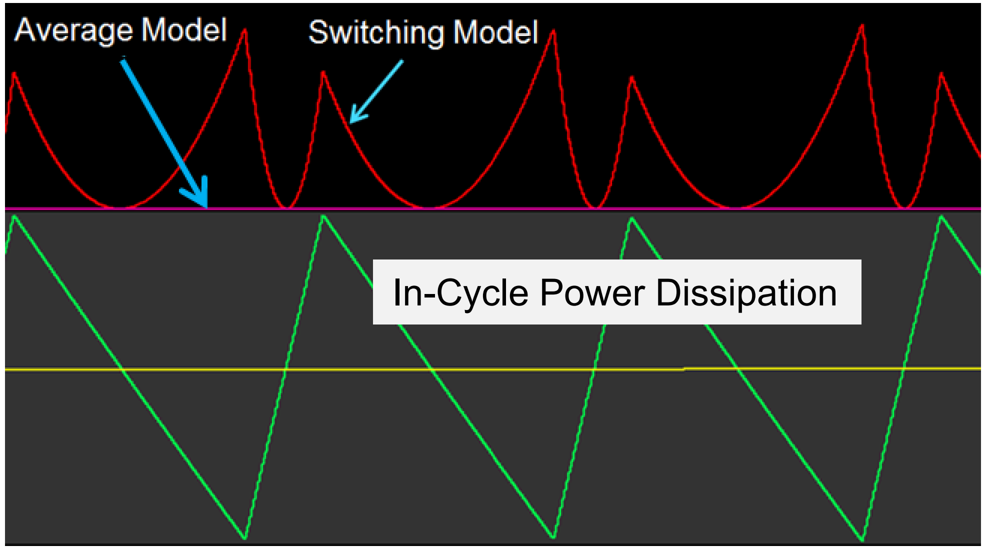
$$B_{avg} = DB_a + (1\text{-}D)B_b$$

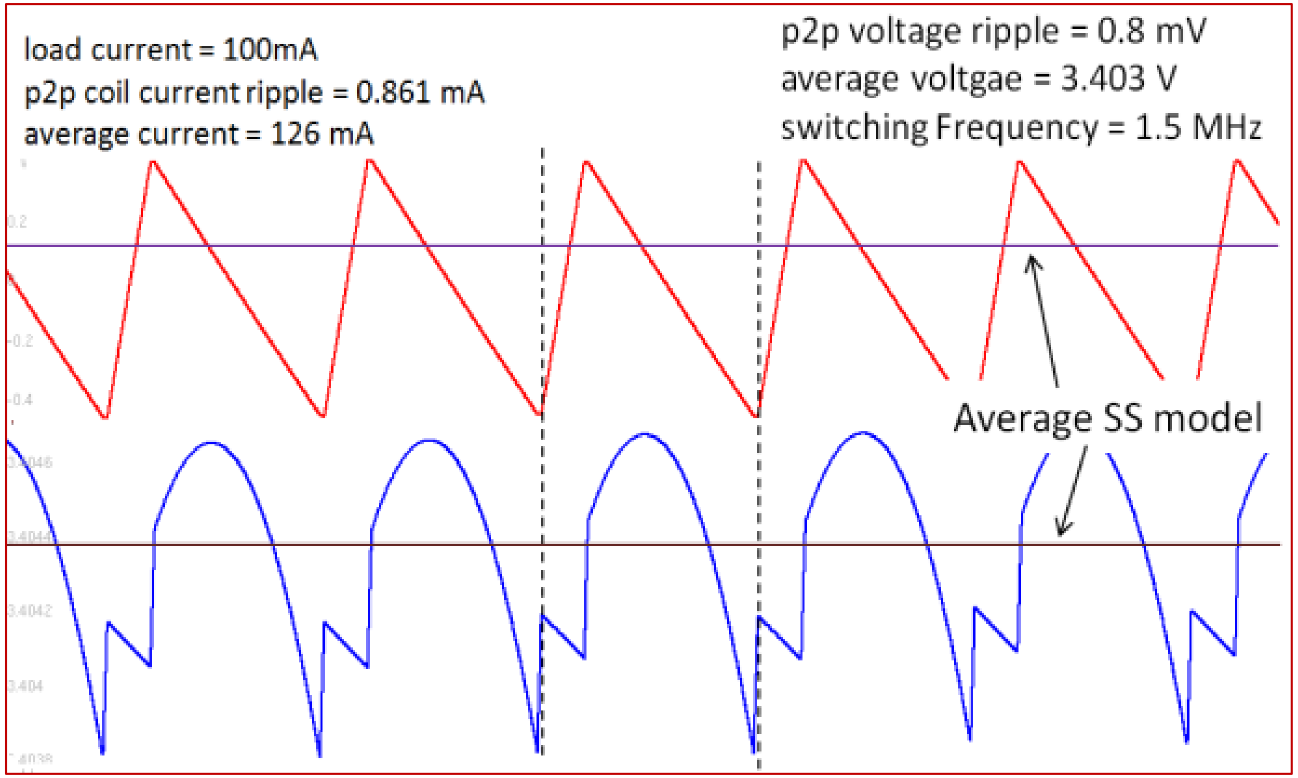
Current in a boost converter. Continuous conduction mode (CCM).

- Averaging is ok as long as we know all the times and have fixed switching frequencies.
- Other mode of operation like pulse-skip or discontinuous mode of operation are difficult as we do not have a fixed T anymore.
- Behaviours happening within the switching cycle are not possible to observe due to the averaging effect. Example is power dissipation.
- Switching model does not relay on any Period or Duty Cycle information.

Simulation Results

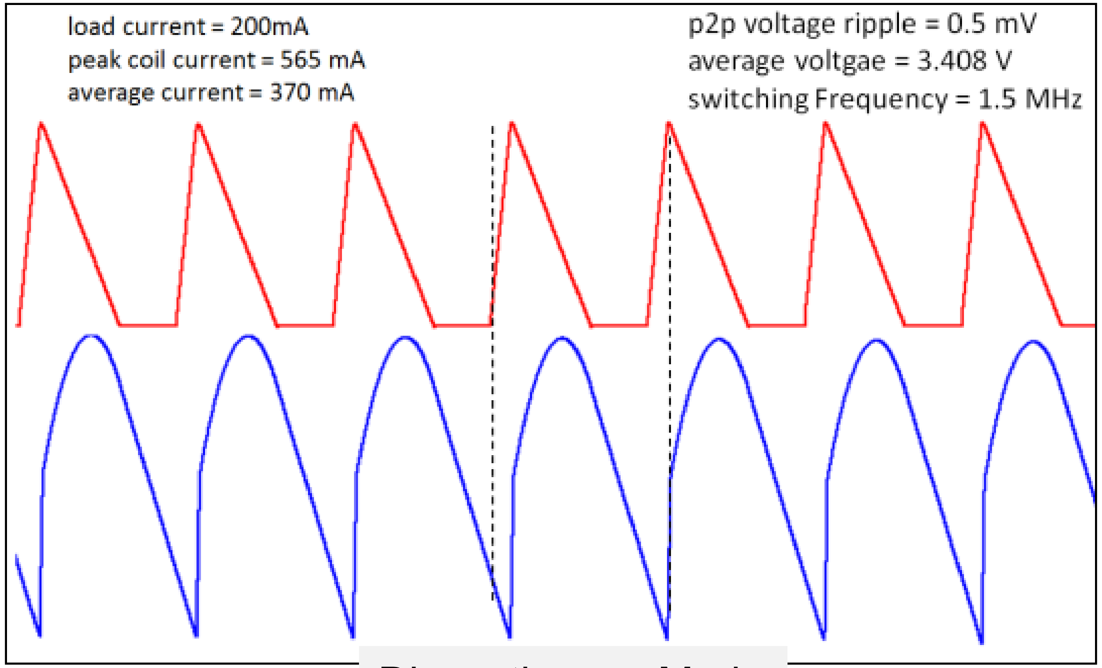




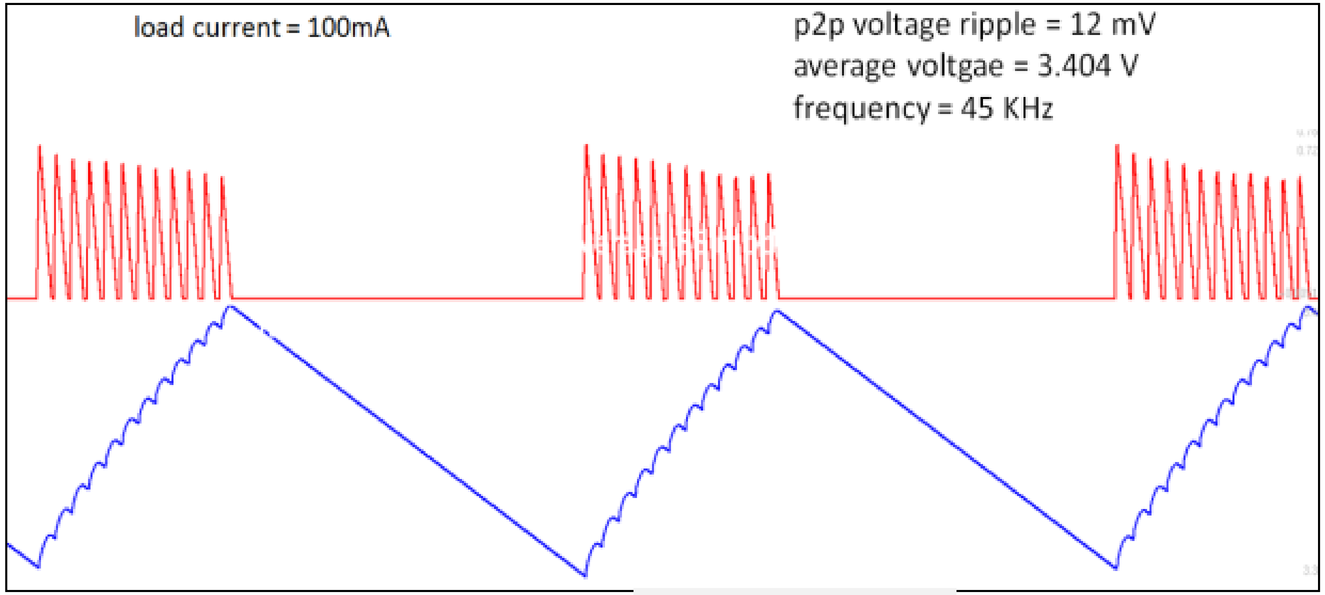


Contiuous Conduction Mode

Simulation Results – Modes of Operation

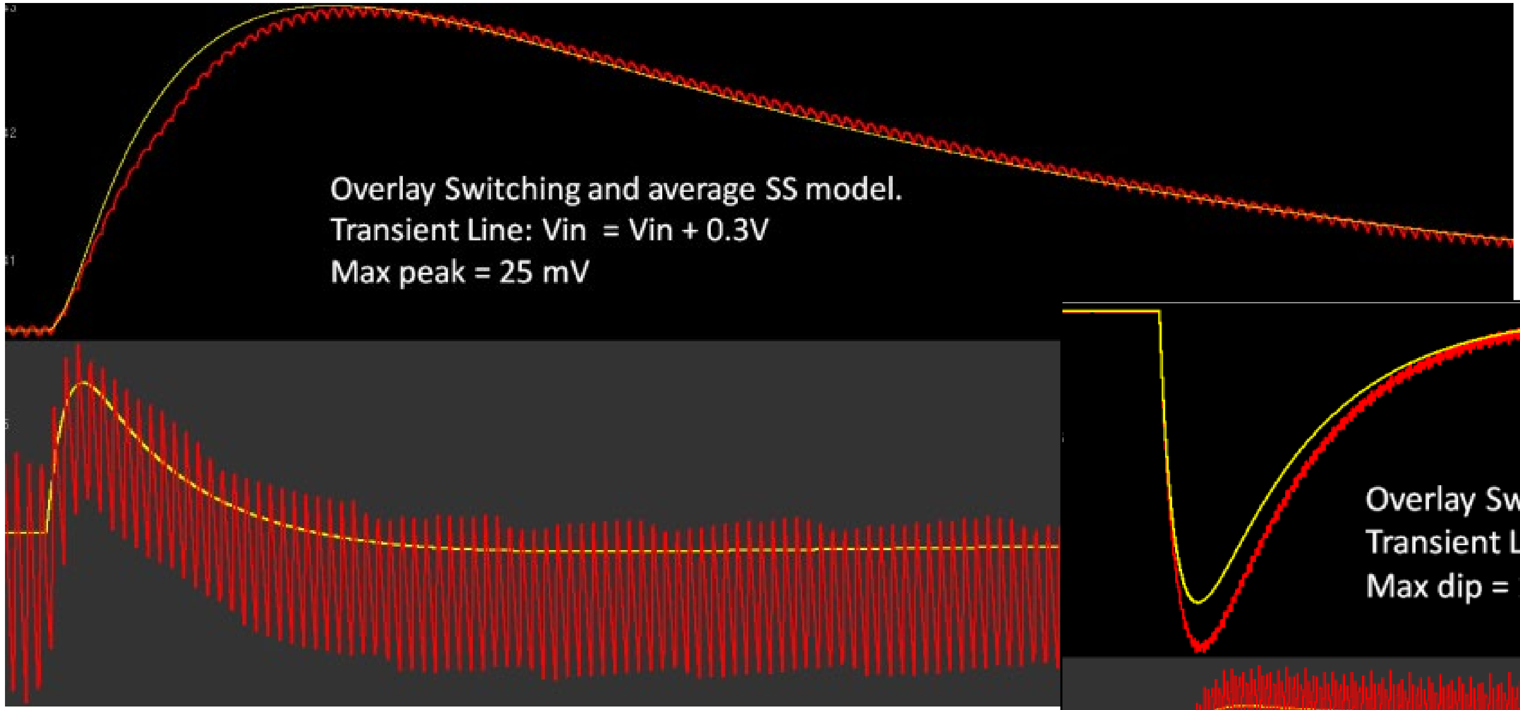


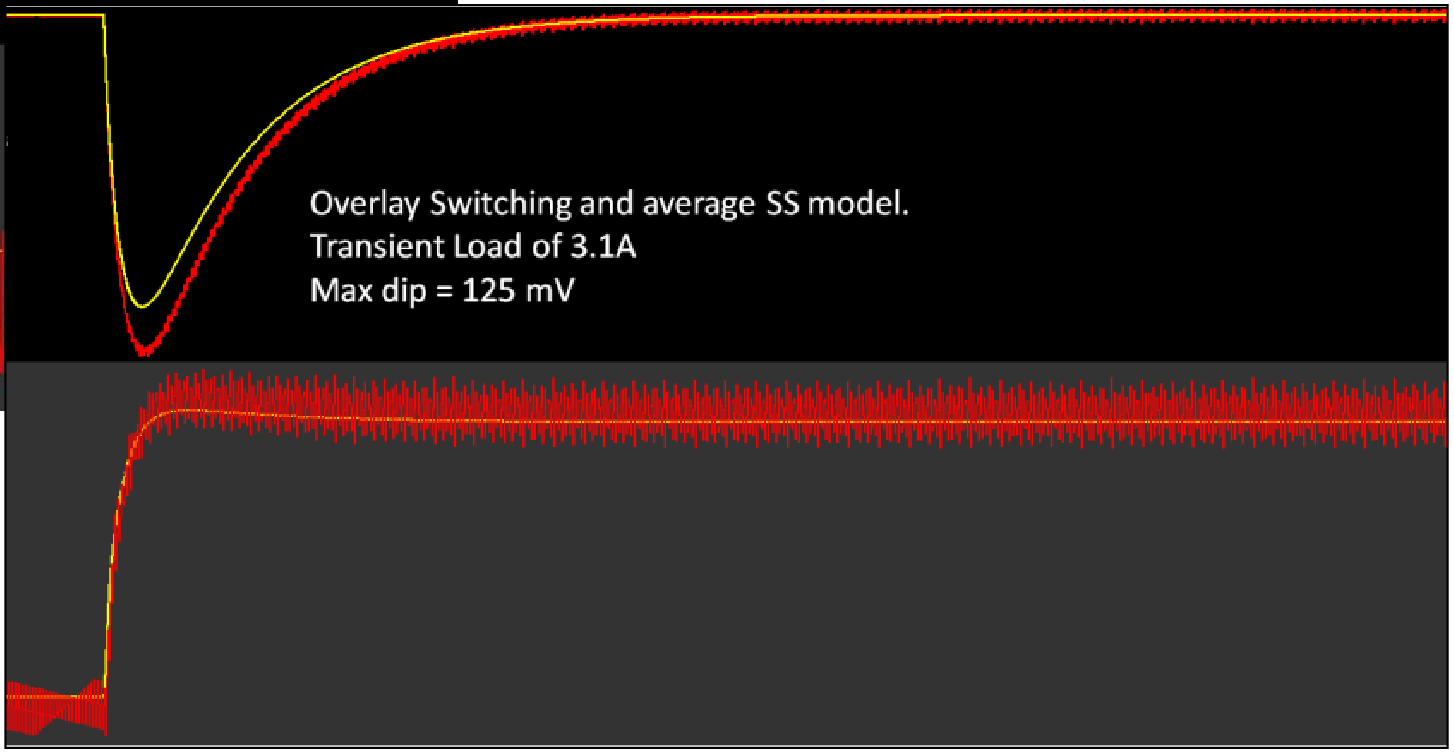
Discontinuous Mode



Pulse Skipping

Simulation Results - Transients





Caveats

- If the topology changes, we need to rewrite the equations.
- Complex circuits can have many configurations, each requiring to write its own equation.

Conclusions

- Switching SS model has been presented.

- Advantages over the commonly used “average” model have been shown.
  - extending the modelling capabilities to architectures and modes of operation which are difficult/not possible with the typical average model.
  - Observation of high order effects like efficiency, power dissipation, etc...
  - Possibility of simulating all together with the digital controller, within one environment.

- Switching model is not slower than an “average” model as the switching is at much higher time step with respect to the computation step (> 2° orders)

Questions

Finalize slide set with questions slide