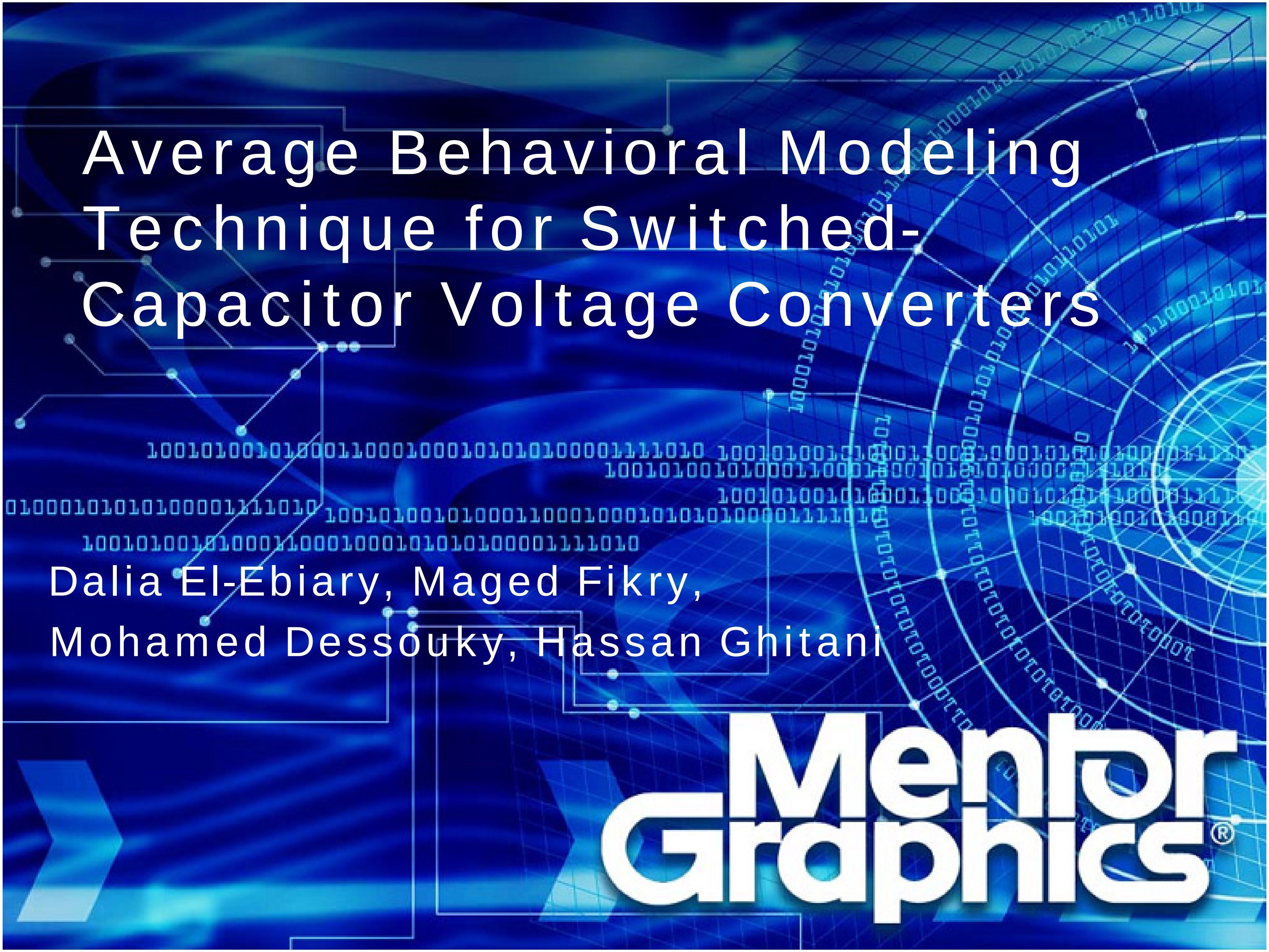

Average Behavioral Modeling Technique for Switched-Capacitor Voltage Converters

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Mohamed Dessouky, Hassan Ghitani

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Outline

- Introduction
- Average Modeling Approach
- Switched Capacitor DC-DC Converters
- Voltage Doubler
  - Basic principle of operation
  - Average model analysis
  - Experimental results
- Voltage Inverter
  - Basic principle of operation
  - Average model analysis
  - Experimental results
- Push-Pull Voltage Doubler
  - Basic principle of operation
  - Average model analysis
  - Experimental results
- Conclusion

Introduction

- Complex systems today are becoming more and more mixed-signal, with the analog part being the design and verification bottleneck
- Traditionally, the virtual verification for the analog part of the design was only available through transistor-level SPICE simulations.
- Provide accurate results BUT require extensive computations
- Very often, speed is more critical than accuracy

Introduction Cont.

- Recently, behavioral modeling has been proved to be the right methodology to cope with today's design and verification demands
- However, some behavioral models of complex systems still consume a lot of simulation time
- May be caused by high switching rates
  - Simulation time-step is bound by the switching period
- Actual information of interest is usually of a much lower frequency

Average Modeling Approach

- **Average models concentrate on the information bearing signal of lower frequency**
  - **Simulation time-step is greatly relaxed**

- **Detailed high frequency transients and ripples produced by the actual circuit are discarded**

- **Useful in:**
  - **Efficient system level simulations,**
  - **Design parameter exploration,**
  - **Obtaining engineering intuition into the operation of these switched circuits**

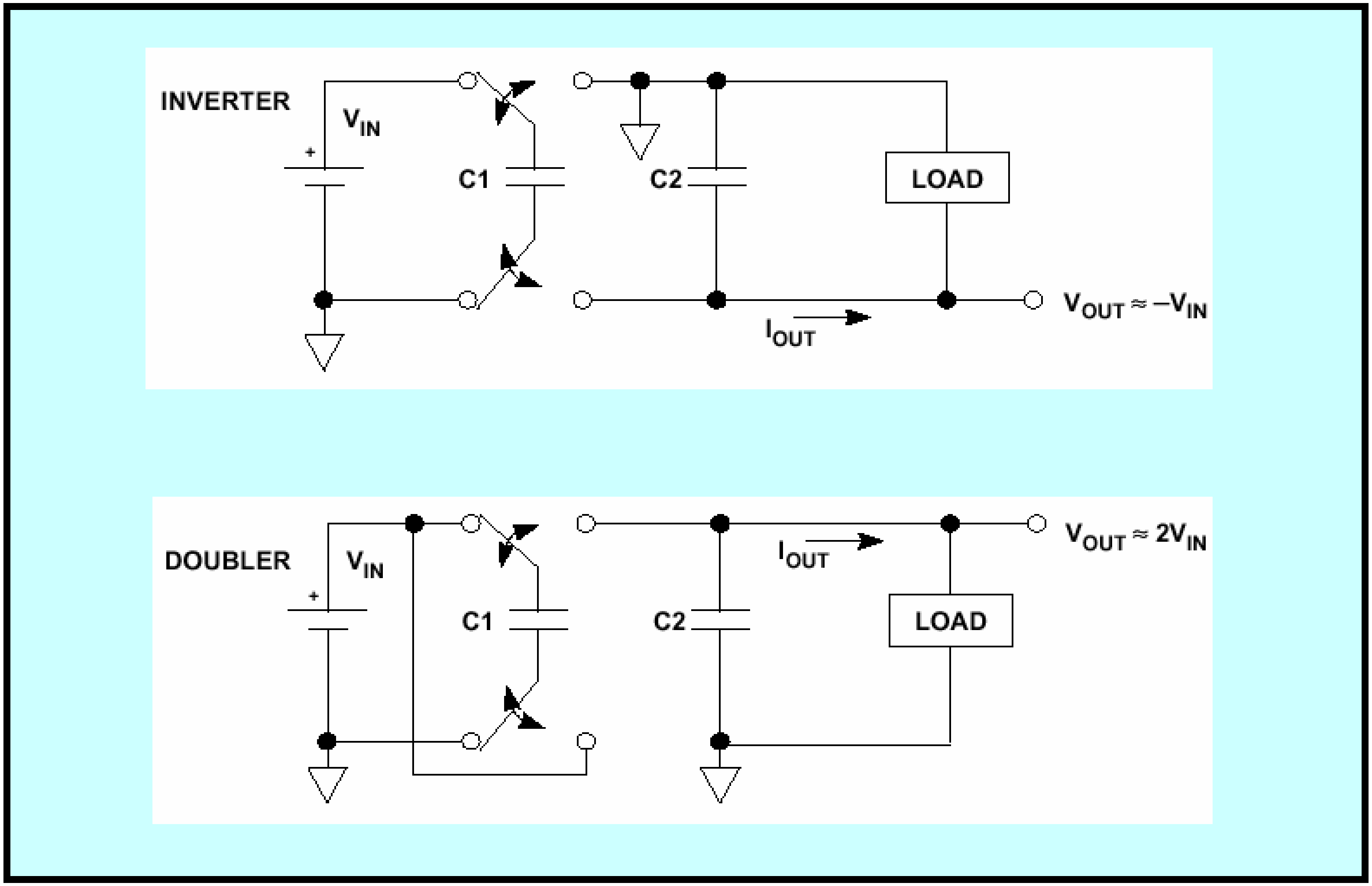
Switched Capacitor DC-DC Converters

- **Also known as charge pump DC-DC converters**
- **Used for:**
  - **Multiplying the voltage level available from a low-voltage battery**
  - **Generate invert voltages**
- **Accomplish energy transfer and voltage conversion using capacitors and semiconductor switches – *Inductorless***

Switched Capacitor DC-DC Converters

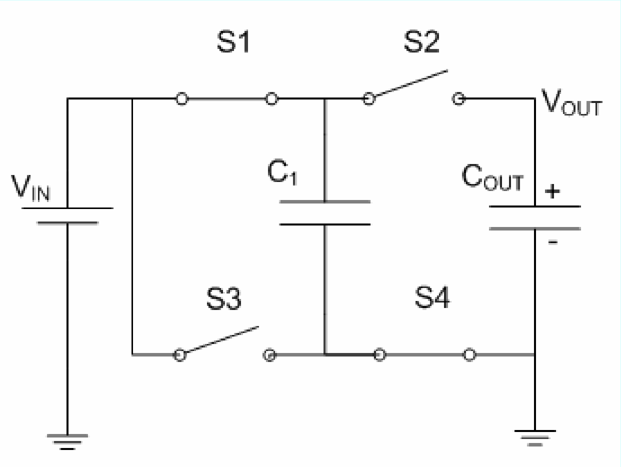
- **Advantages:**
  - **Do not require magnetic components**
  - **Simple, small, low cost**
- **Recent trend on low-power-low-voltage circuit design and applications of portable equipments leads to renewed interest on charge pump circuits**
- **Mandatory in power management ICs for battery powered portable applications**

Types of Switched-Capacitor DC-DC Converter Circuits



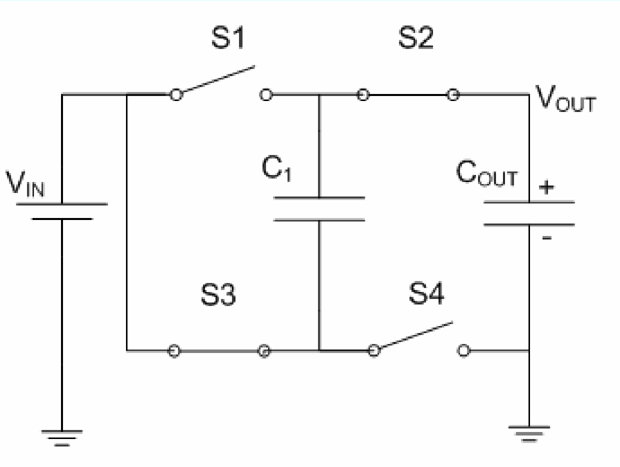
Voltage Doubler Basic Principle of Operation

ON State:



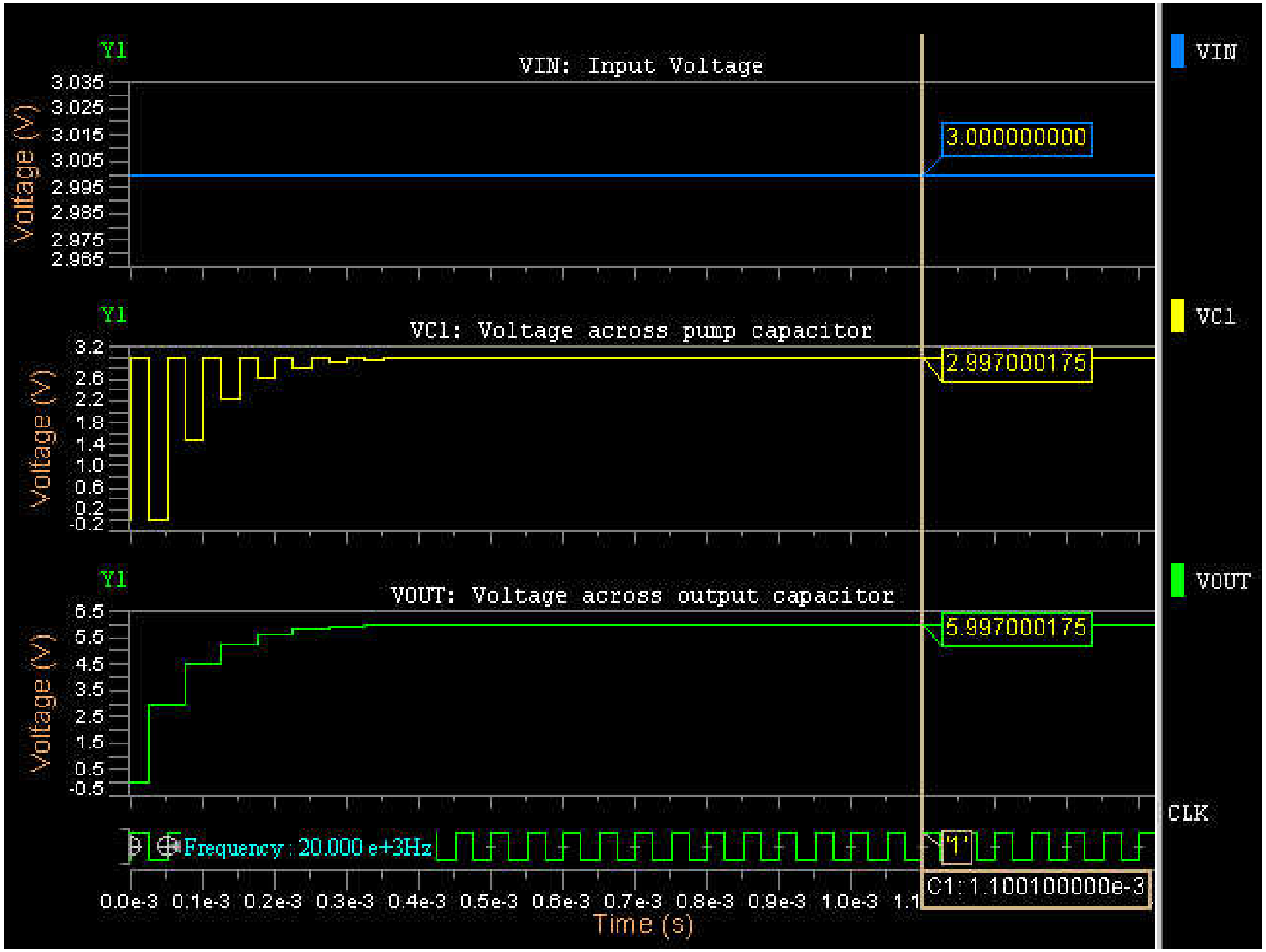
- Connect C_1 (pump capacitor) in parallel with V_{IN}
- Charge C_1 by V_{IN}
- C_{OUT} discharges through load

OFF State:



- Connect C_1 in series with V_{IN} and C_{OUT}
- Compensate voltage loss in C_{OUT} (charge sharing)
- Exponential growth targeting ($2V_{IN}$)

Ideal Voltage Doubler Spice Simulation

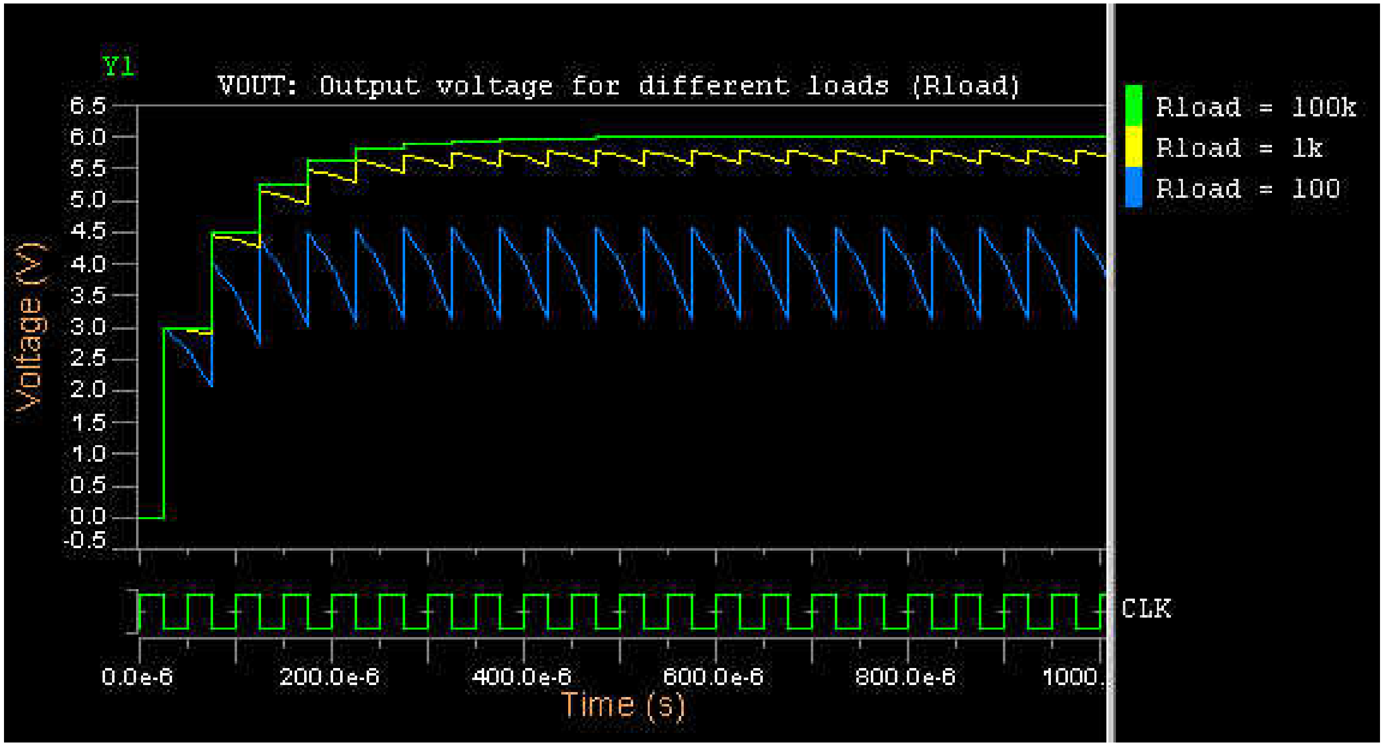


f = 20kHz,
C_1=1uF,
C_{OUT}=1uF,
R_{LOAD}=100k

Assume ideal switches and capacitors

Ideal Voltage Doubler Spice Simulation

with varying output load

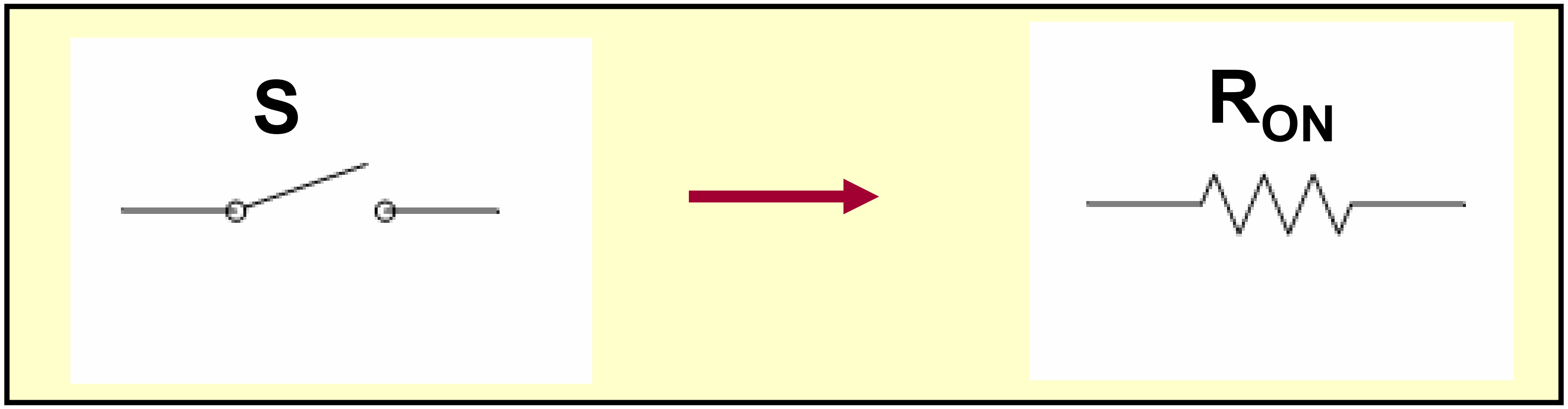


f = 20kHz,
C_1=1uF,
C_{OUT}=1uF,
R_{LOAD}=100, 1k, 100k

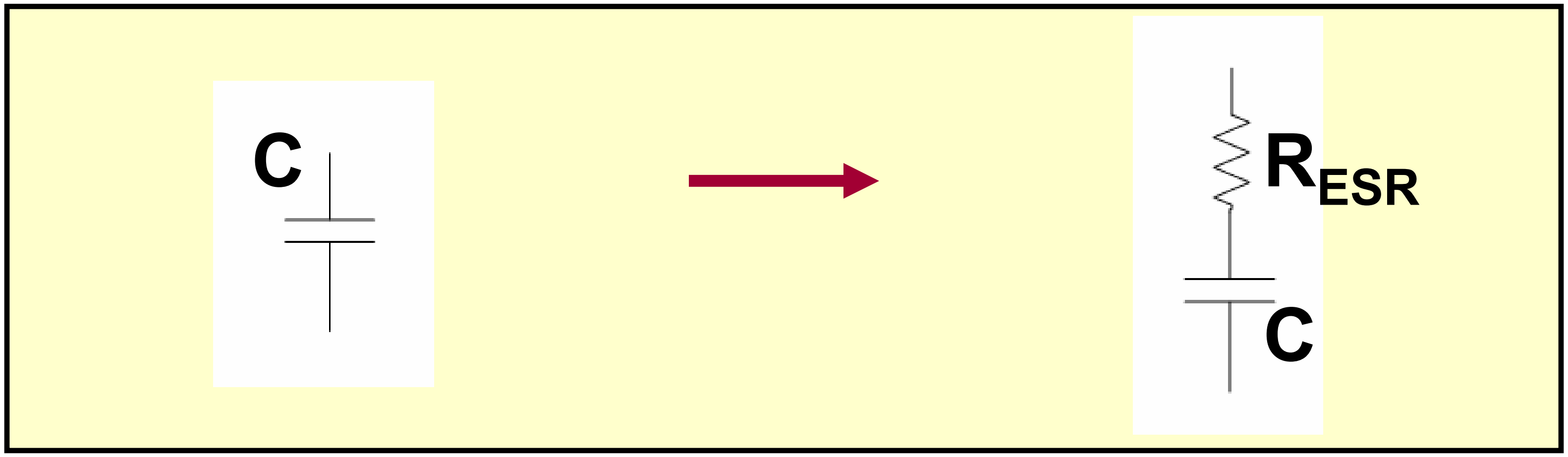
Assume ideal switches and capacitors

Non-Ideal Voltage Doubler

- Non-ideal switch



- Non-ideal capacitor

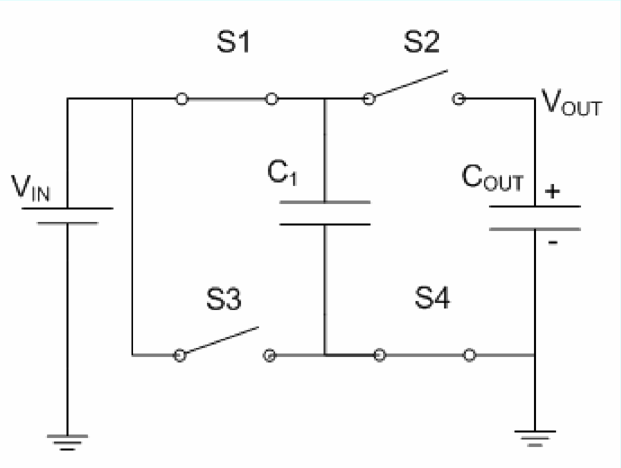


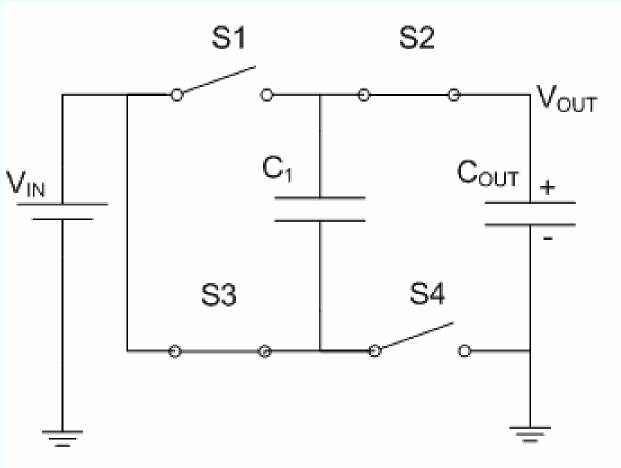
Non-Ideal Voltage Doubler

ON State:

OFF State:

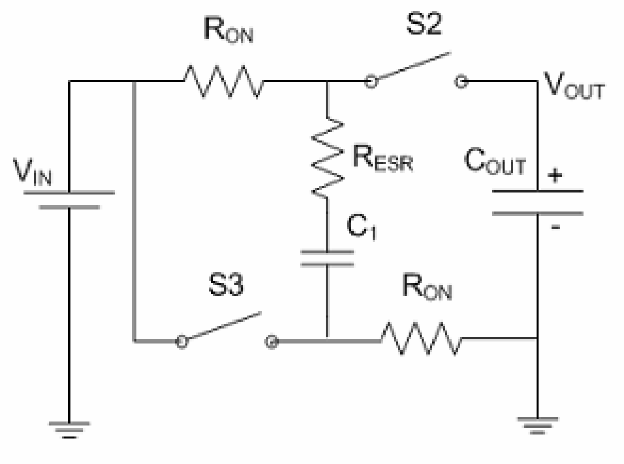
Ideal

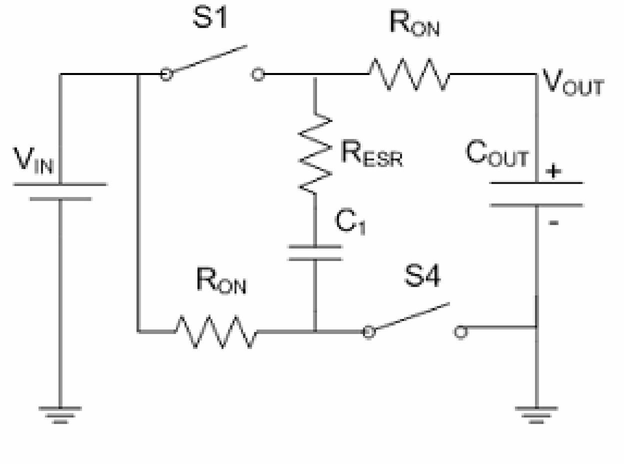




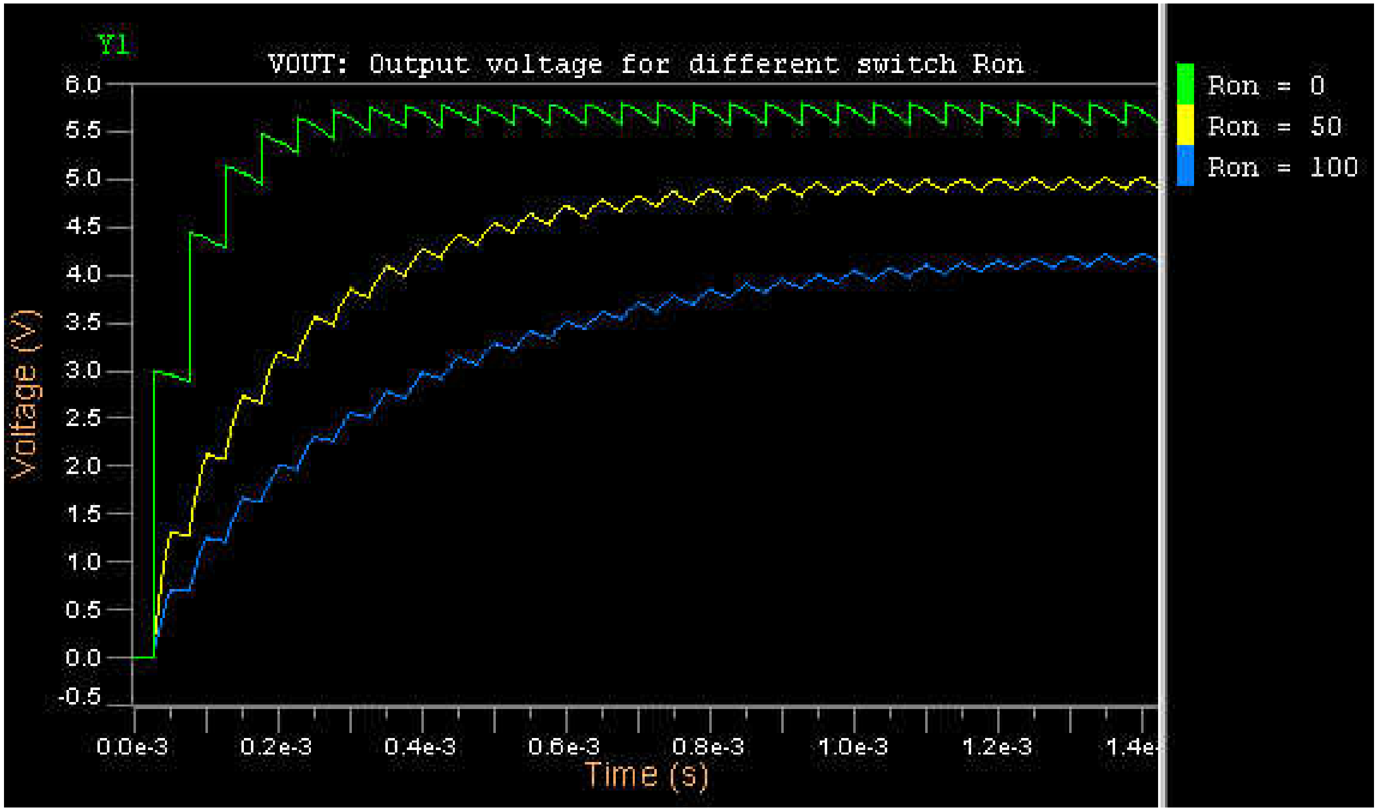
Non-Ideal

(R_{ON}, R_{ESR})





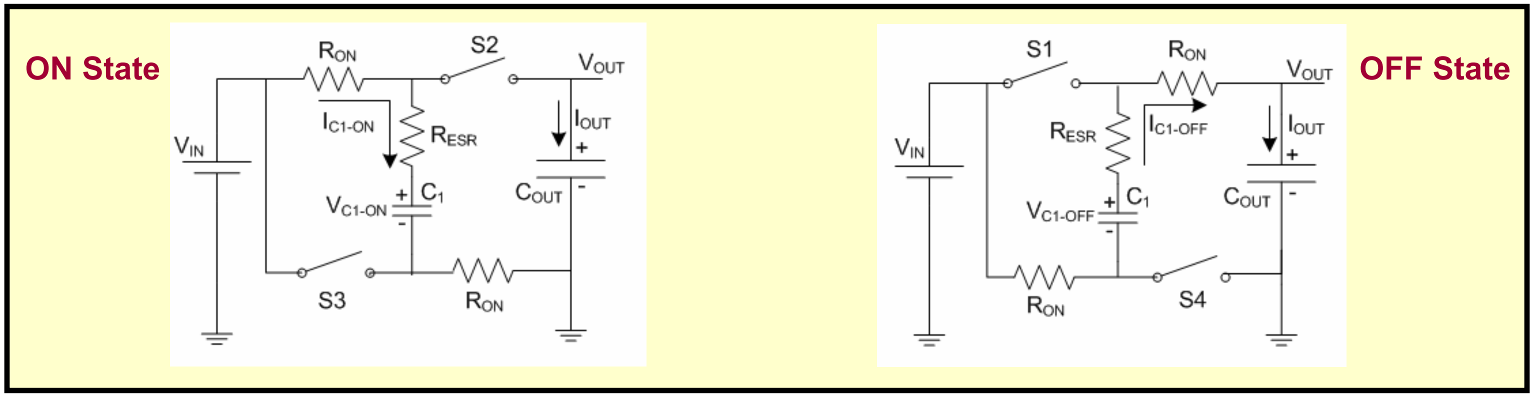
Non-Ideal Voltage Doubler Spice Simulation



f = 20kHz,
C_1=1uF,
C_{OUT}=1uF,
R_{LOAD}=100k
R_{ESR}=0
R_{ON}=0, 50, 100

Assume non-ideal switches (R_{ON})

Average Model: Analysis



ON STATE:

$$V_{C1\text{-}ON}(t) = V_{IN} - 2R_{ON}\, I_{C1\text{-}ON}(t) - R_{ESR}\, I_{C1\text{-}ON}(t)$$

Average voltage during ON state:

$$V_{C1\text{-}ON\text{-}AVE} = V_{IN} - 2R_{ON} \bullet I_{C1\text{-}ON\text{-}AVE} - R_{ESR}\, I_{C1\text{-}ON\text{-}AVE} \qquad \ldots (1)$$

OFF STATE:

$$V_{C1\text{-}OFF}(t) = V_{OUT}(t) - V_{IN} + 2R_{ON}\, I_{C1\text{-}OFF}(t) - R_{ESR}\, I_{C1\text{-}OFF}(t)$$

Average voltage during ON state:

$$V_{C1\text{-}OFF\text{-}AVE} = V_{OUT\text{-}AVE} - V_{IN} + 2R_{ON}\, I_{C1\text{-}OFF\text{-}AVE} - R_{ESR}\, I_{C1\text{-}OFF\text{-}AVE} \qquad \ldots (2)$$

Difference charge stored in C_1 between ON and OFF states

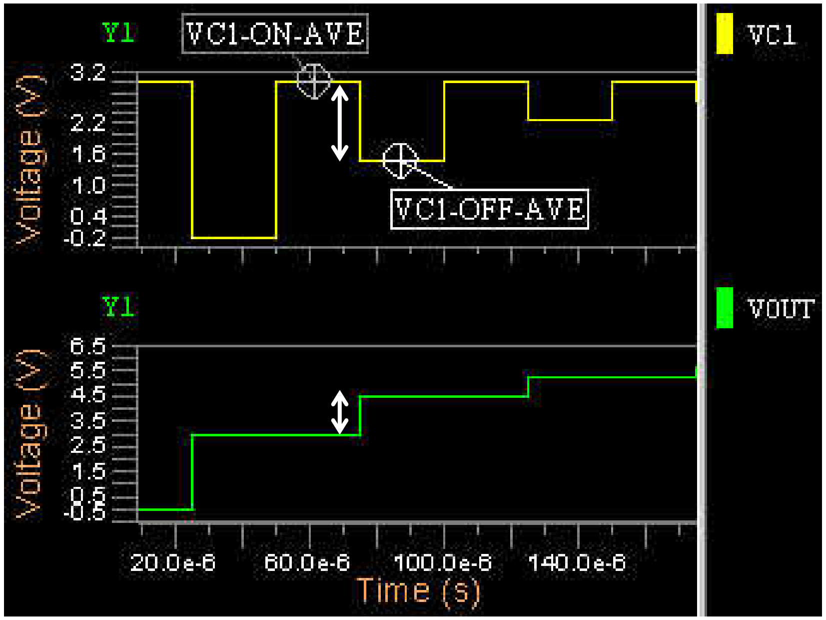
=

Net charge/current transferred to the output in one cycle:

$$I_{OUT\text{-}AVE} = f \bullet \Delta Q_{C1\text{-}AVE}$$

$$= f \bullet (Q_{CI\text{-}ON\text{-}AVE} - Q_{CI\text{-}OFF\text{-}AVE})$$

$$= f\, C_1(V_{C1\text{-}ON\text{-}AVE} - V_{C1\text{-}OFF\text{-}AVE})$$

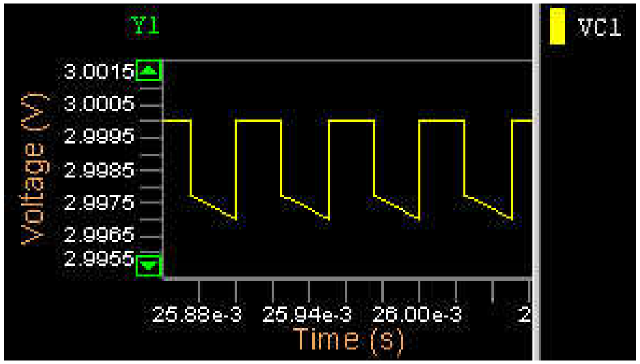


Using (1) and (2):

$$I_{OUT\text{-}AVE} = fC_1\{2V_{IN} - V_{OUT\text{-}AVE}$$

$$- (2R_{ON}+R_{ESR})I_{C1\text{-}ON\text{-}AVE} - (2R_{ON}+R_{ESR})I_{C1\text{-}OFF\text{-}AVE}\} \qquad \ldots (3)$$

Due to law of conservation of charge in C_1:



amount of charge flowing into C_1 during ON state at S.S. (ΔQ_{ON})

=

amount of charge flowing out of C_1 at OFF state at S.S.(ΔQ_{OFF})

$$\Delta Q_{C1\text{-}ON\text{-}AVE} = \Delta Q_{C1\text{-}OFF\text{-}AVE}$$
$$I_{C1\text{-}ON\text{-}AVE} \bullet DT = I_{C1\text{-}OFF\text{-}AVE} \bullet (1-D)T$$
$$I_{C1\text{-}ON\text{-}AVE} \bullet D = I_{C1\text{-}OFF\text{-}AVE} \bullet (1-D) \qquad \ldots (4)$$

Also, the average output current:

$$I_{OUT\text{-}AVE} = I_{C1\text{-}OFF\text{-}AVE} \bullet (1-D)$$

Therefore,

$$I_{C1\text{-}OFF\text{-}AVE} = I_{OUT\text{-}AVE} / (1-D) \qquad \ldots (5)$$
$$I_{C1\text{-}ON\text{-}AVE} = I_{OUT\text{-}AVE} / D \qquad \ldots (6)$$

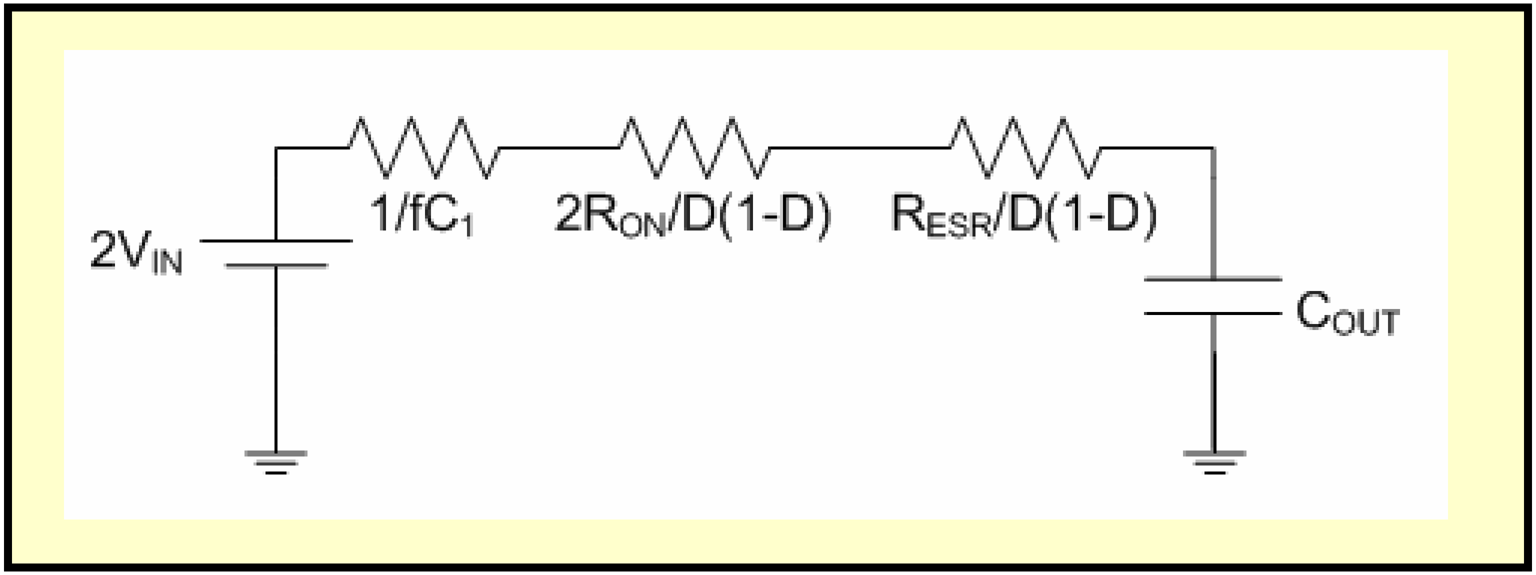
Substitute (5) & (6) in (3):

$$I_{OUT\text{-}AVE} = fC_1 \bullet \{ 2V_{IN} - V_{OUT\text{-}AVE} - (2R_{ON} + R_{ESR}) \bullet (I_{OUT\text{-}AVE} / (D(1\text{-}D))) \}$$

Which can be re-written as,

$$\boxed{2V_{IN} - V_{OUT\text{-}AVE} = \{ \frac{1}{fC_1} + \frac{2R_{ON}+R_{ESR}}{D(1\text{-}D)} \} \bullet I_{OUT\text{-}AVE}}$$

Average Equivalent Circuit



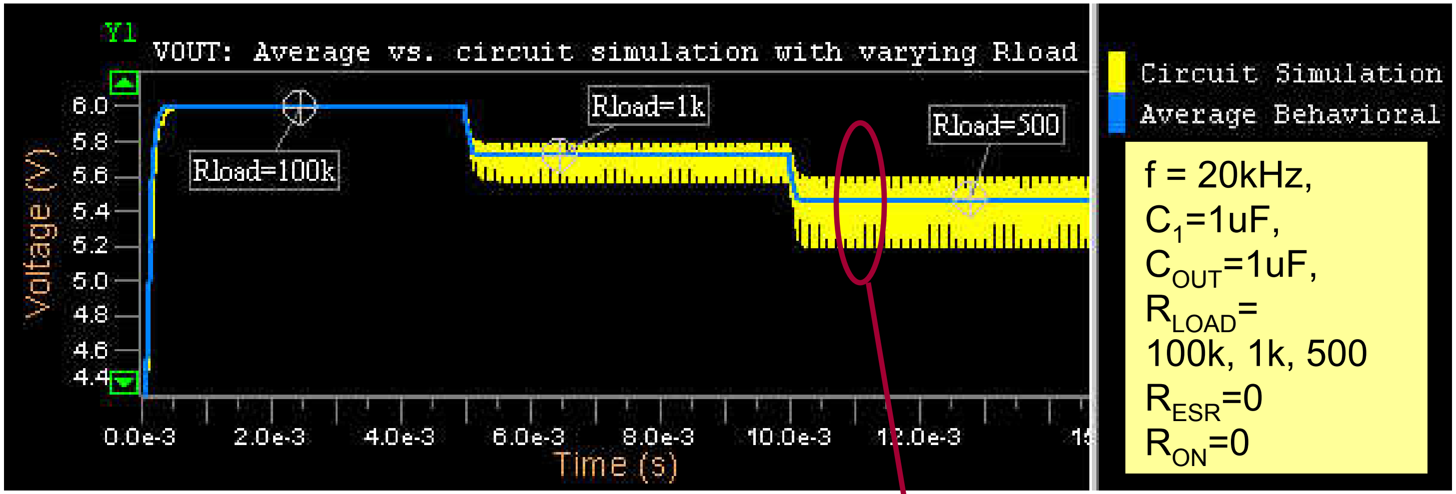
Required model parameters (given by user) :

C_1	:	*Pump Capacitance*
R_{ESR}	:	*Pump Capacitor Equivalent Series Resistance*
R_{ON}	:	*Switch ON Resistance*
F	:	*Switching Frequency*
D	:	*Switching Duty Cycle*

Experimental Setup

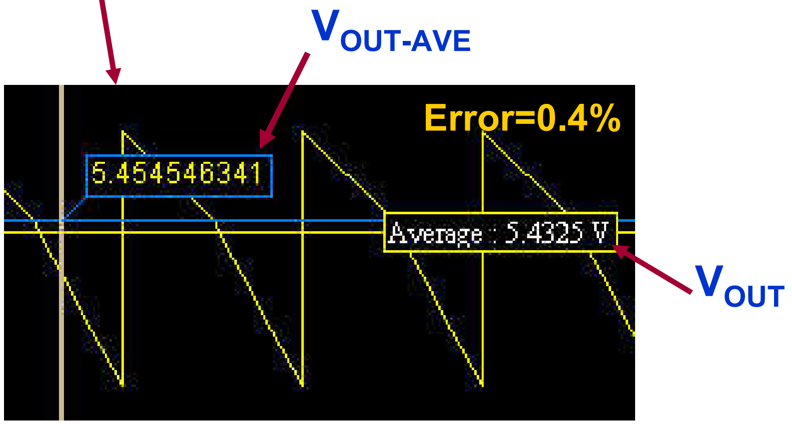
- Circuit level simulation:
  - Constructed using Eldo^{TM} primitives (voltage sources, resistors, capacitors, switch macromodels)
  - Transient analysis
  - Varying output resistive load (R_{load}) parallel to C_{OUT}
  - Simulated using ADVance MS^{TM}
- Behavioral Level Simulation (VHDL-AMS)
  - Instanciated within Eldo^{TM} netlist and connected to Eldo^{TM} voltage source for input
  - Transient analysis
  - Varying output resistive load (R_{load}) parallel to C_{OUT}
  - Simulated using ADVance MS^{TM}

Experimental Results: Waveforms



f = 20kHz,
C_1=1uF,
C_{OUT}=1uF,
R_{LOAD}=
100k, 1k, 500
R_{ESR}=0
R_{ON}=0

$$\text{Error}(\%) = \frac{V_{OUT} - V_{OUT\text{-}AVE}}{V_{OUT}} \bullet 100\%$$



Where,

$V_{OUT\text{-}AVE}$: average behavioral model output
V_{OUT}: calculated average of the circuit simulation output during one period

Experimental Results: Statistics

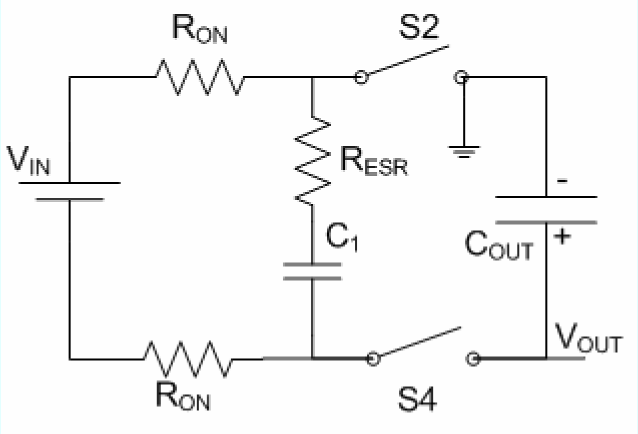
- Accuracy:
  - R_{LOAD} =100k : (5.9968-5.9970)/5.9968 x 100 = 0% Error
  - R_{LOAD} =1k : (5.6976-5.7143)/5.6976 x 100 = 0.3% Error
  - R_{LOAD} =500 : (5.4325-5.4545)/5.4325 x 100 = 0.4% Error

- Simulation Timepoints:
  - Switching Circuit: 560066 points
  - Average Model: 164 points
  - Saving: > 99 %

- Speed:
  - Switching Circuit: 1mn 34s 970ms
  - Average Model: 0s 020ms
  - Speed Gain: 4750 X

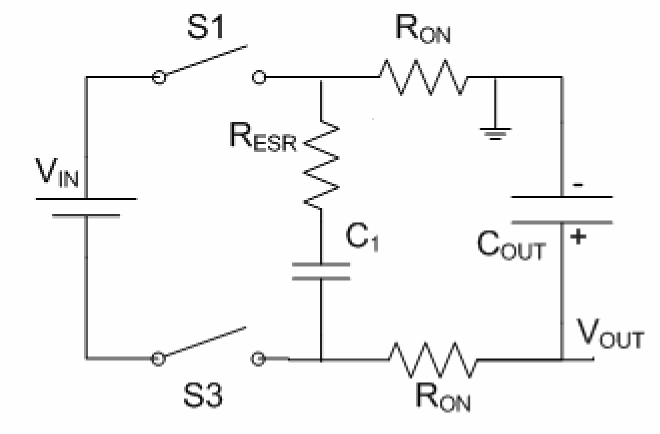
Voltage Inverter Basic Principle of Operation

ON State:



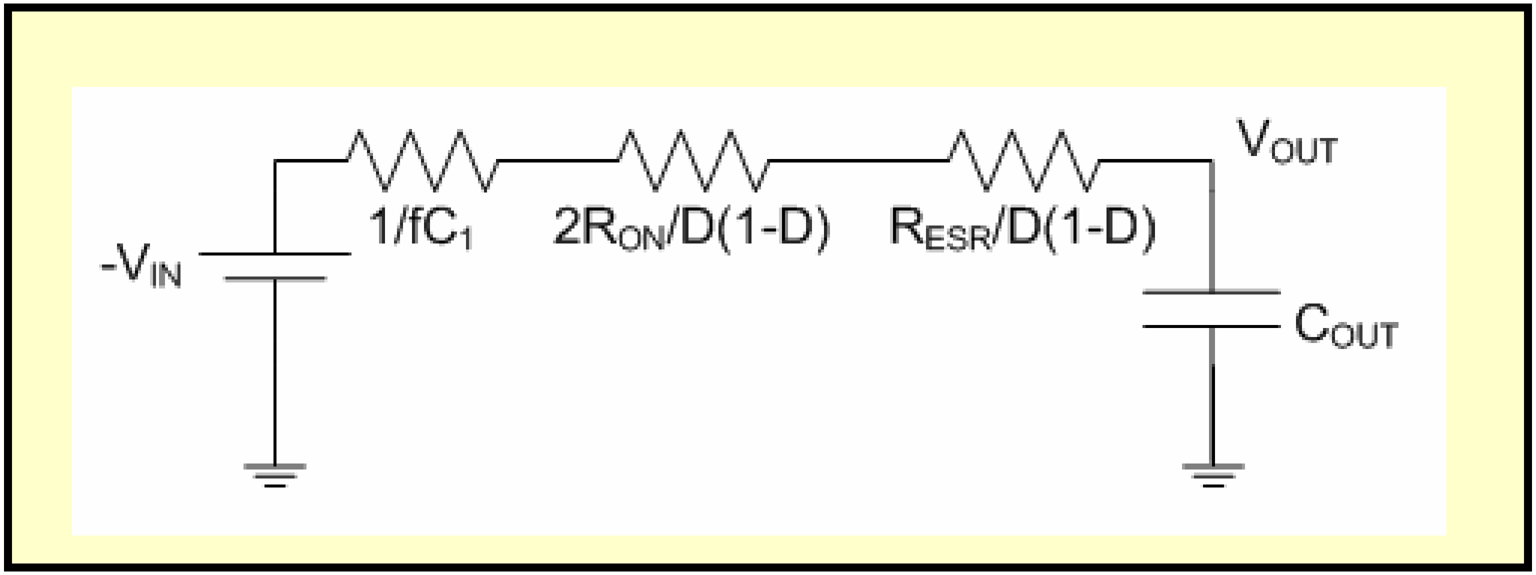
- Connect C_1 (pump capacitor) in parallel with V_{IN}
- Charge C_1 by V_{IN}
- C_{OUT} discharges through load.

OFF State:



- Connect C_1 in parallel with C_{OUT}
- Compensate voltage loss in C_{OUT} (charge sharing)
- Exponential growth targeting ($-V_{IN}$)

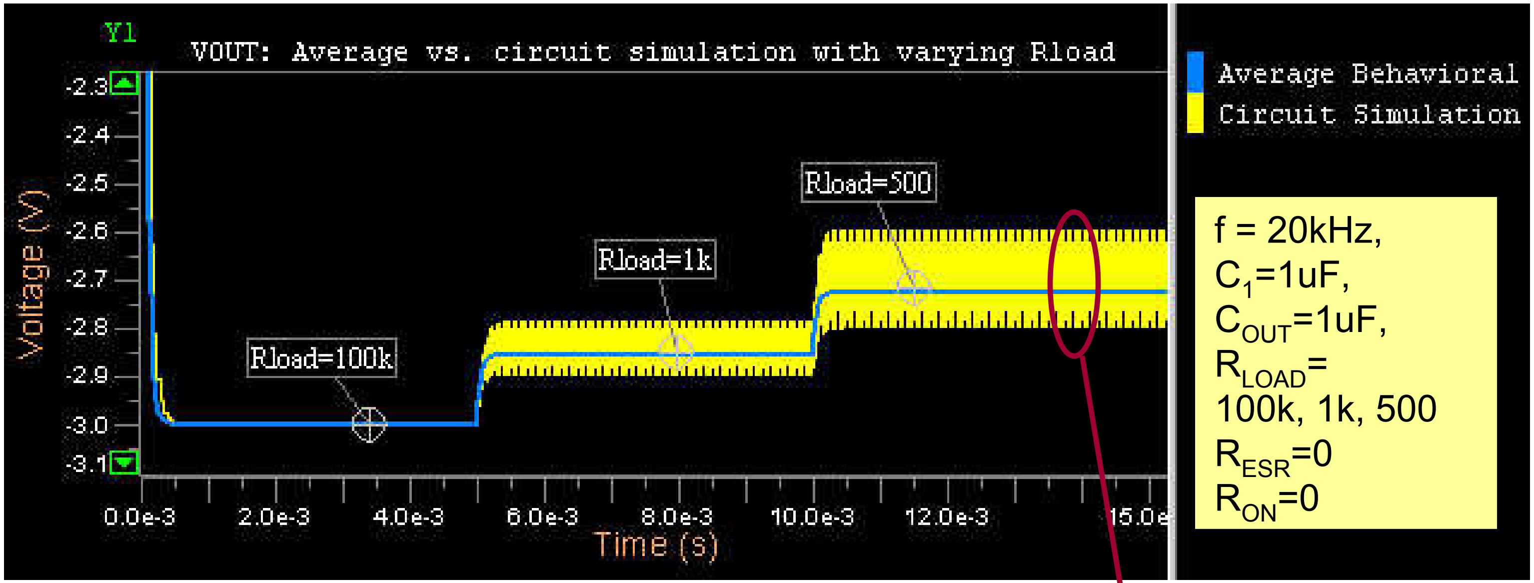
Average Equivalent Circuit



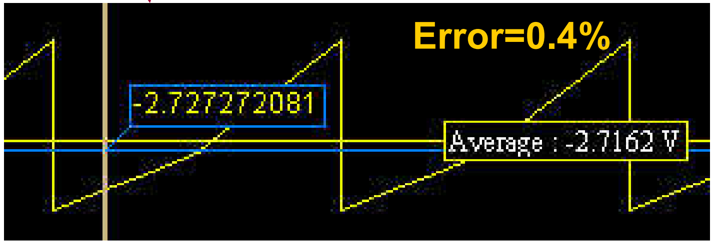
Required model parameters (given by user) :

C_1	**:**	***Pump Capacitance***
R_{ESR}	**:**	***Pump Capacitor Equivalent Series Resistance***
R_{ON}	**:**	***Switch ON Resistance***
F	**:**	***Switching Frequency***
D	**:**	***Switching Duty Cycle***

Experimental Results



f = 20kHz,
C_1=1uF,
C_{OUT}=1uF,
R_{LOAD}=
100k, 1k, 500
R_{ESR}=0
R_{ON}=0



Error=0.4%

Accuracy: 0 - 0.4% Error

Timepoints: 560066 vs. 163 point (>99% saving)

Speed:1mn 37s 930ms vs. 20ms (4900 X faster)

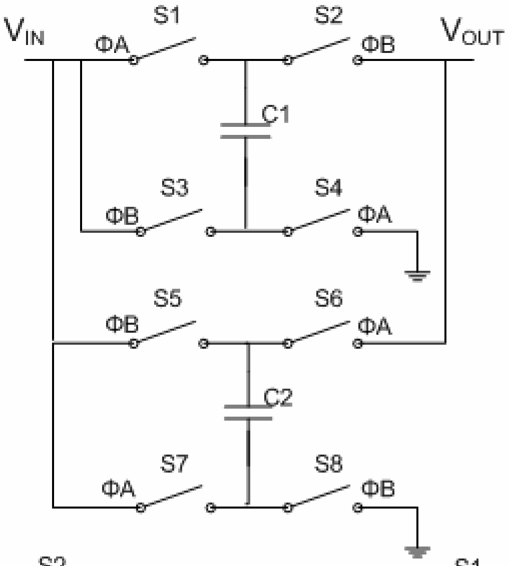
Voltage Doubler Push-Pull Configuration

- Two voltage doublers run in parallel and in opposite phases
  - When one pump is being charged, the other is charging the output

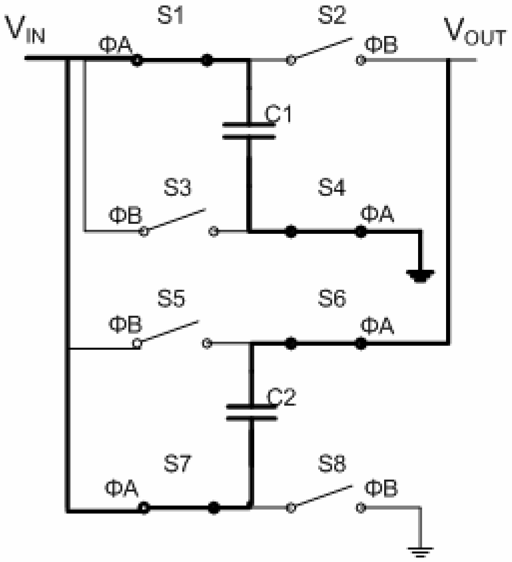
- In this architecture, one of the pump capacitors is always delivering charge to the output

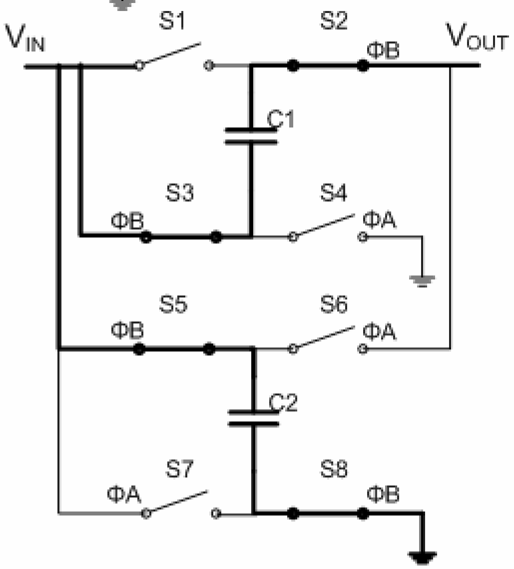
- Advantages:
  - Minimize voltage loss and output voltage ripple
  - Allows the use of smaller output capacitor compared to a conventional voltage doubler

Push-Pull Configuration



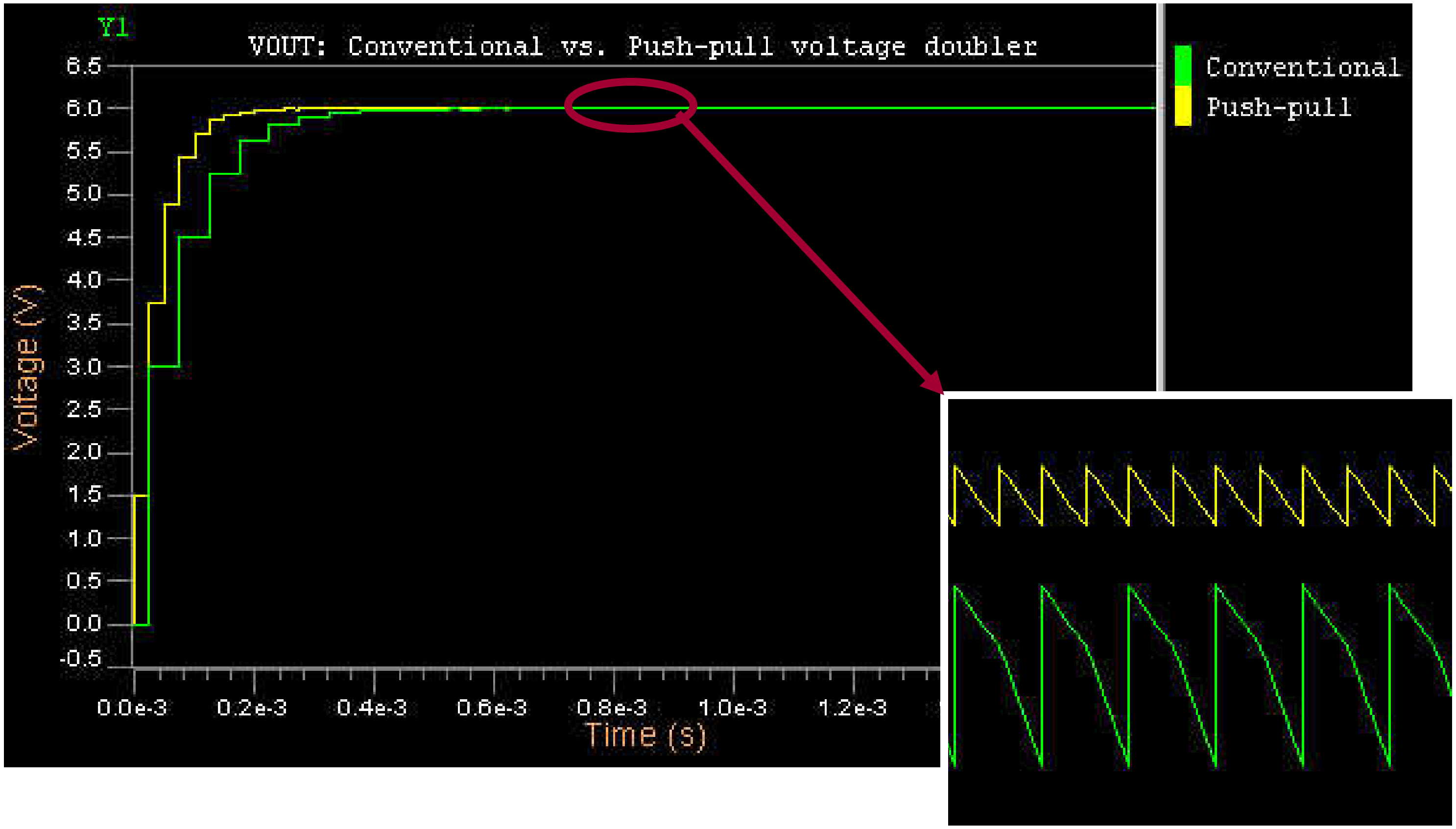
Phase I





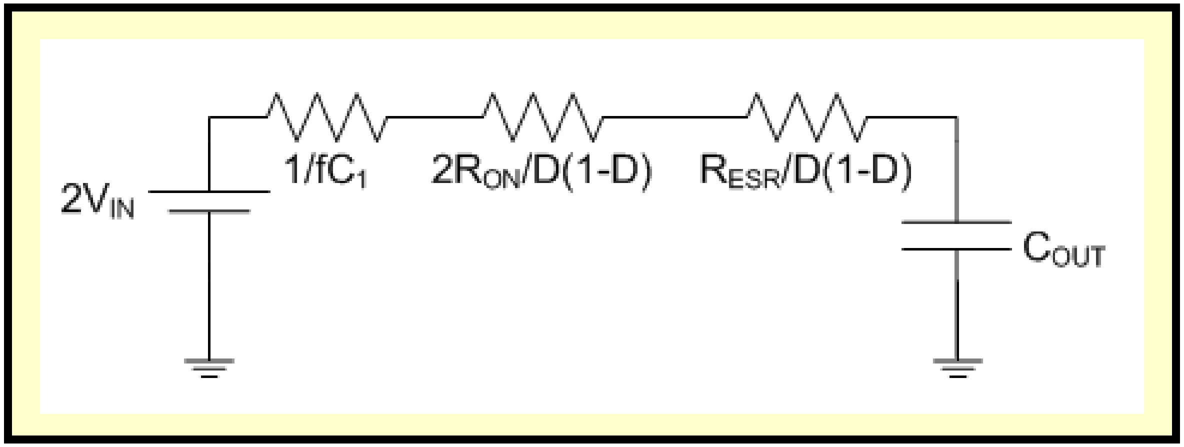
Phase II

Conventional Voltage Doubler
vs.
Push-Pull Voltage Doubler

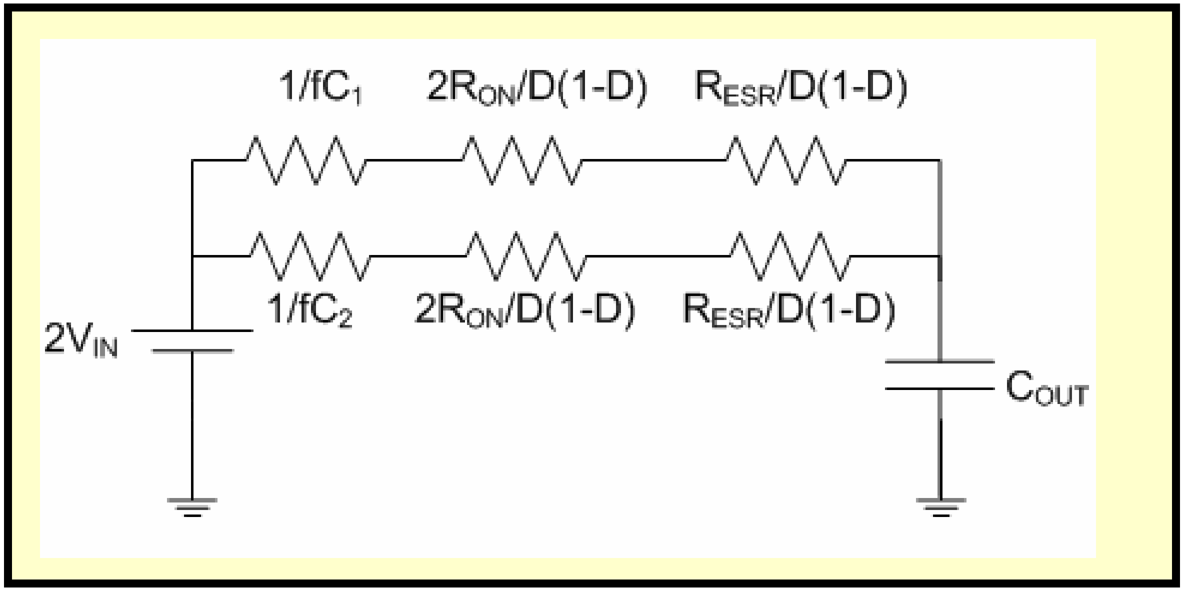


Modified Equivalent Average Circuit

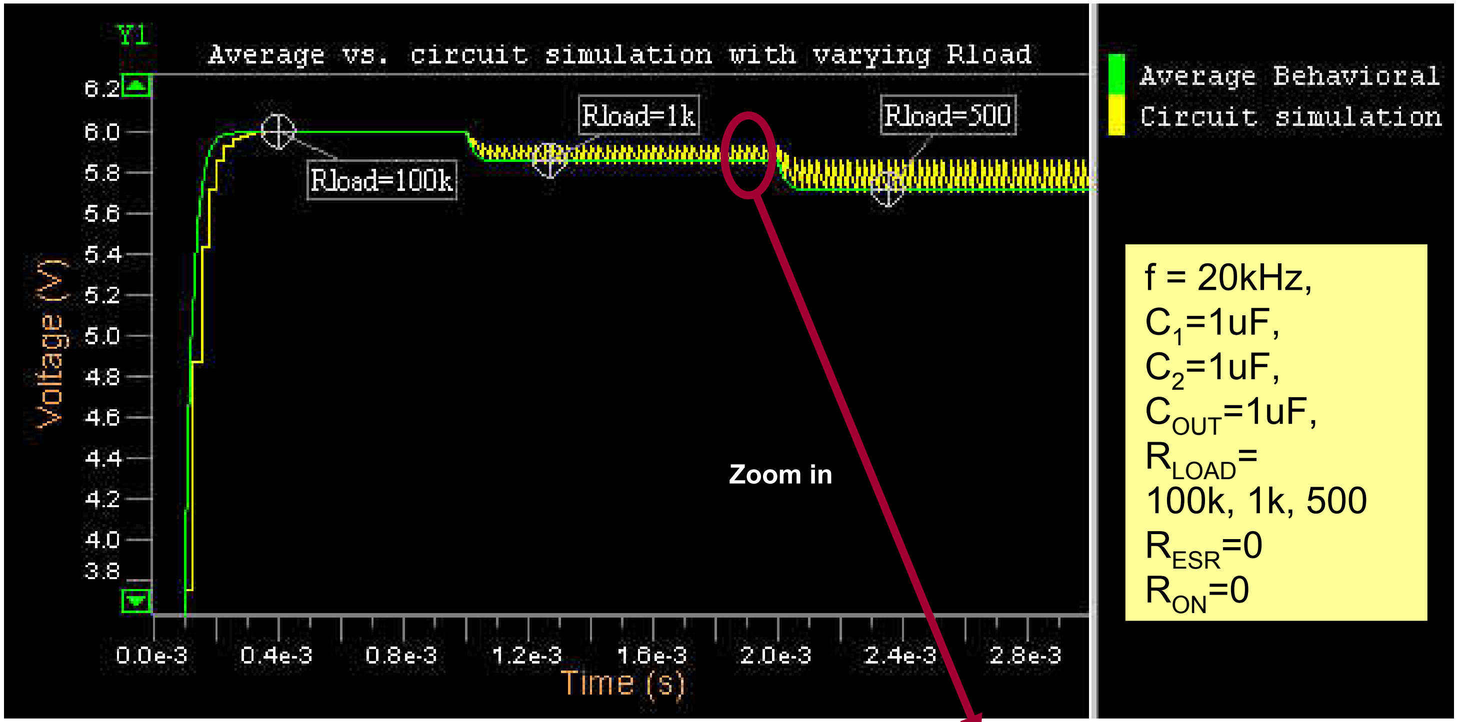
Conventional



Push Pull

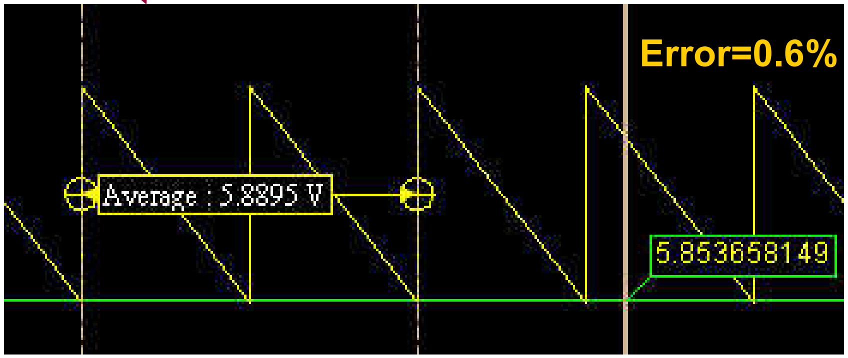


Experimental Results



f = 20kHz,
C_1=1uF,
C_2=1uF,
C_{OUT}=1uF,
R_{LOAD}=
100k, 1k, 500
R_{ESR}=0
R_{ON}=0

Zoom in



Error=0.6%

Accuracy: 0.007 - 1.2% Error

Timepoints: 460066 vs. 156 point (>99% saving)

Speed:1mn 43s 980ms vs. 20ms (5200 X faster)

Experimental Results (Error%)

f=20kHz

Rload	R_{ON}=0	R_{ON}=10	R_{ON}=50	R_{ON}=100
100k	0.007	0.0167	0.023	0.025
1k	0.6	1.6	1.9	1.9
500	1.2	2.3	3.7	3.3

f=250kHz

Rload	R_{ON}=0	R_{ON}=10	R_{ON}=50	R_{ON}=100
100k	0	0.0017	0.0017	0.0017
1k	0.05	0.19	0.18	0.17
500	0.1	0.37	0.31	0.28

Conclusion

- Average modeling is beneficial when the nature of the circuit includes 2 frequencies
  - High frequency → switching frequency
  - Lower frequency → information of interest
- Average modeling focuses on the lower frequency
- Discard the detailed analysis of high frequency component leading to large simulation speed gain
- Re-visited an average modeling technique for switched capacitor voltage converters
  - Voltage doubler, voltage inverter & push-pull doubler
- Average models capture circuit non-idealities (R_{ON}, R_{ESR})
- Average models may be implemented in any analog/mixed-signal HDL
- Results match circuit-level simulations faithfully
- Resulting speed gain is several thousand times

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