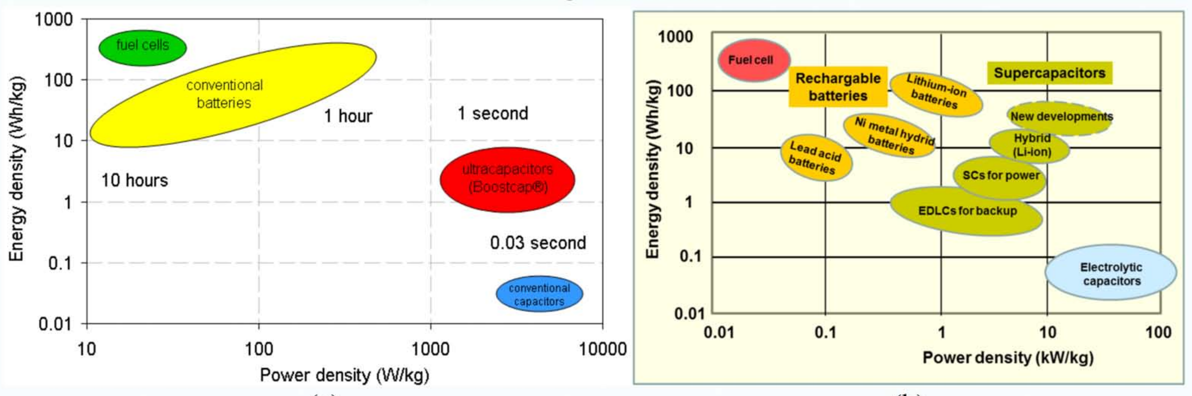
Modelling and Control of Ultracapacitor based Bidirectional DC-DC converter systems

PhD Scholar : Saichand K   Advisor: Prof. Vinod John

Department of Electrical Engineering, Indian Institute of Science, Bangalore

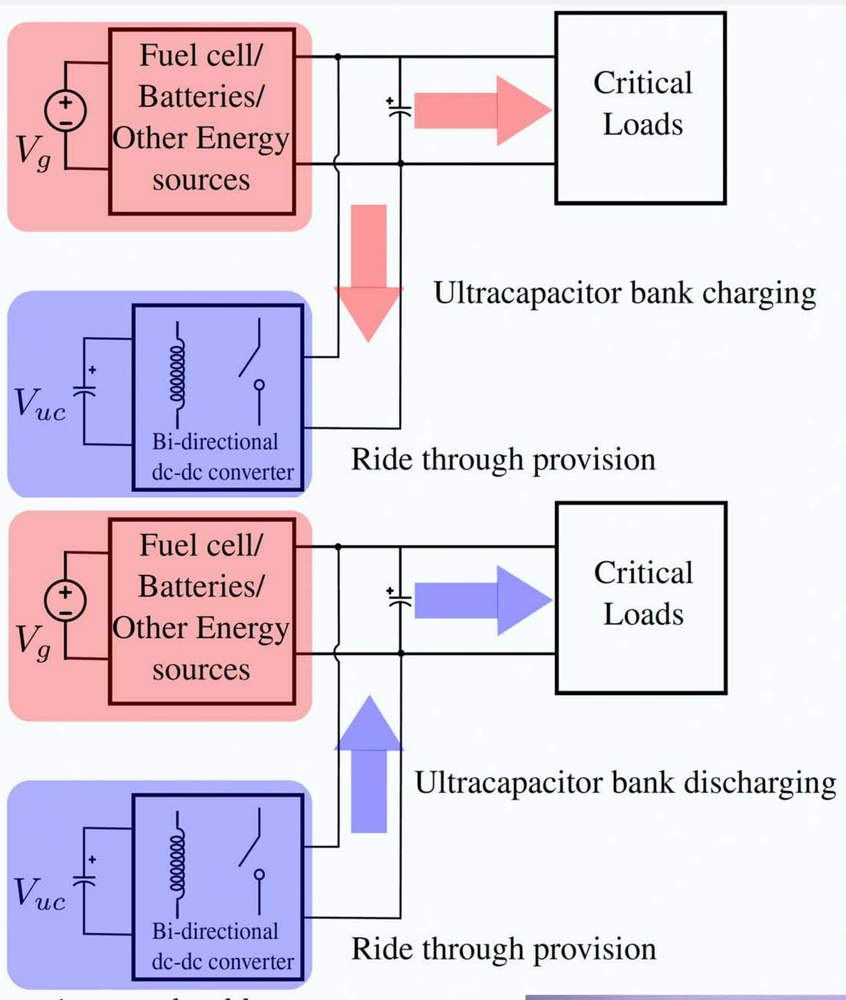
Comparison of energy storage elements

- **Advantages over batteries:**
  - Greater reliability
  - Uses non-corrosive electrolytes and low material toxicity
  - Has higher power density, Low cost per cycle
  - Low ESR => Fast charging and discharging
  - Low ESR => Low heating levels during charging and discharging
- **Disadvantages over batteries:**
  - Lower energy density
  - Greater self-discharge (Always needs a power conv. for regulating the voltage)
  - High voltage drop
  - Low ESR leads to rapid discharge when shorted



(a) (b)

Ultracapacitor based backup systems



- Ultracapacitor stack addresses:
  - Short duration black-outs
  - Peak power demands
  - Load leveling the battery packs in EV/HEV.
- Ultracapacitors used widely in power quality improvement, traction, EV/HEV etc;

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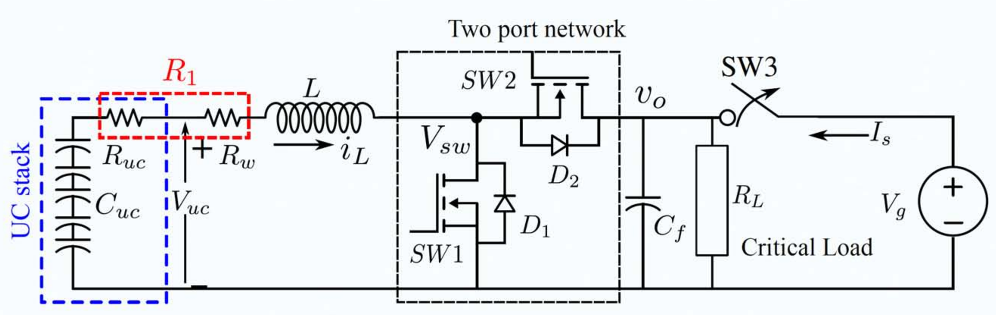
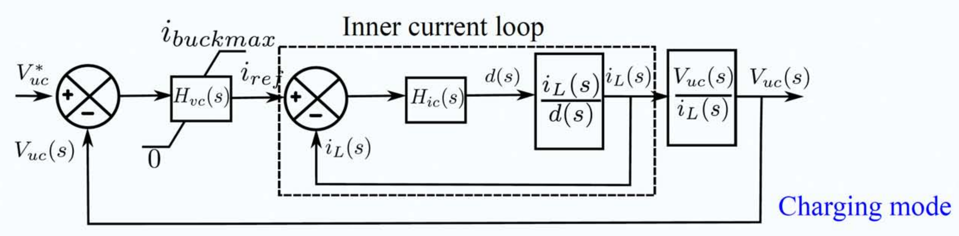
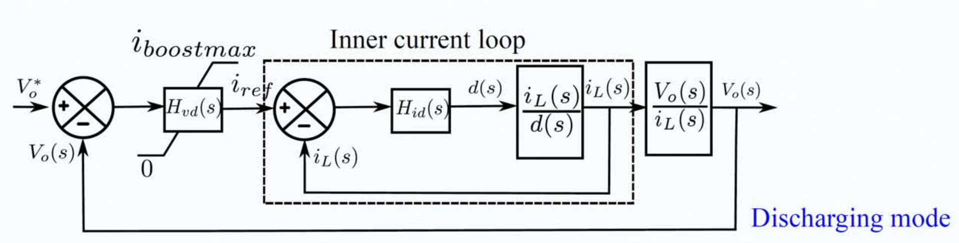


- Since, supply and UC stack side voltages are quite close, the topology chosen is a non-isolated bidirectional converter.
- UCs has a potential to replace batteries for light energy density applications.
- UC based backup systems can be used in both grid connected or stand alone applications.
- Buck converter during charging, boost converter during discharging.
- During charging, UC stack voltage V_{uc} is regulated. During discharging, output voltage V_o is regulated.

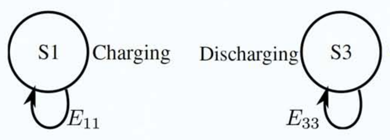
PWM blocking for seamless mode transition

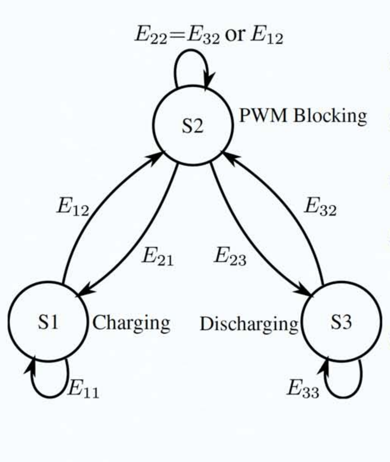
- UC based converters have two operating modes - a) charging mode, b) discharging mode.





- Both operating modes have different control structures.
- However, the two states share the same physical elements of converter.
- This necessitates a mode transition logic.
- Smooth, seamless and fast transition between control modes is crucial.





- PWM blocking acts as a mode transition logic.
- How long PWM blocking should be done?
- This is decided by mode identification algorithm.
- The proposed algorithm decides the control modes accurately.
- The algorithm is based on local parameters inductor current, i_L and output voltage, V_o.

Mode identification algorithm

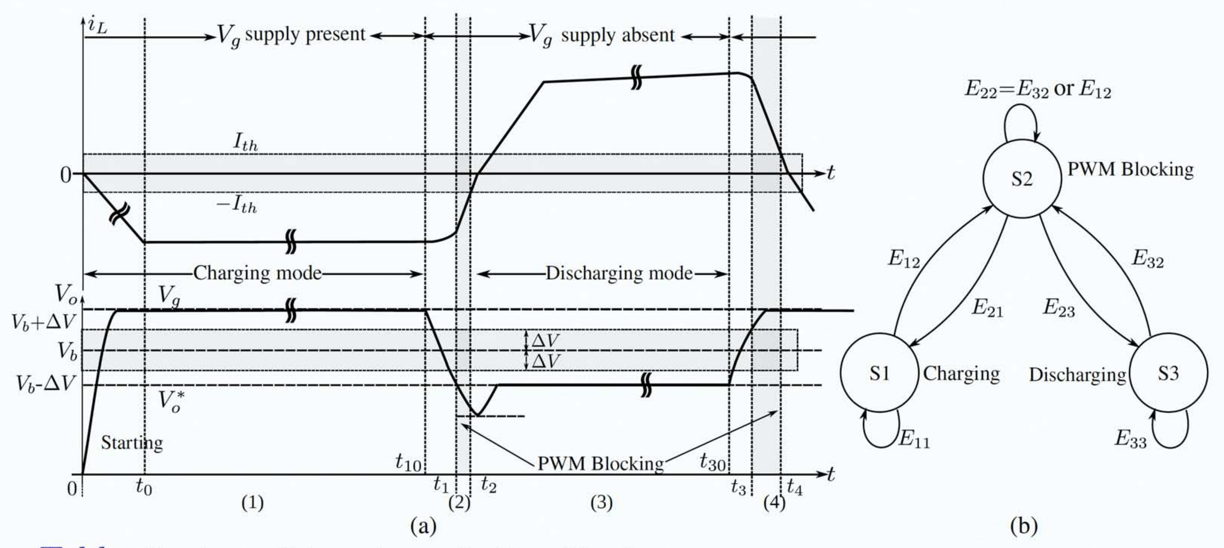


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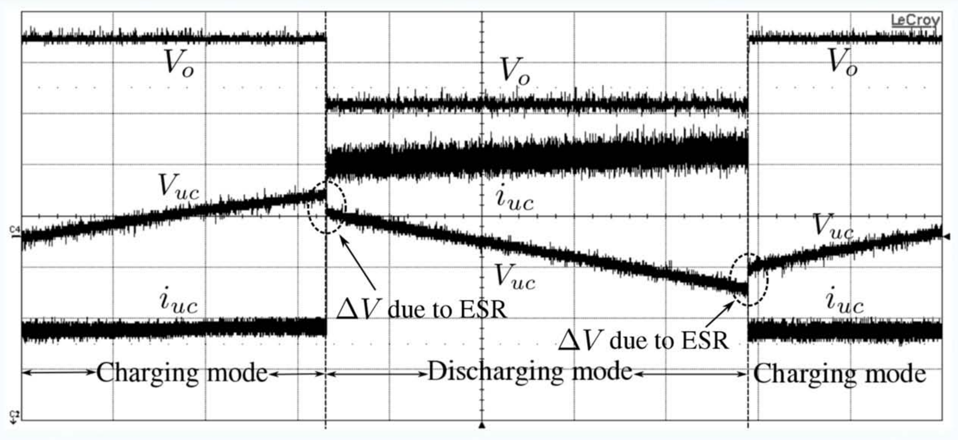
Table: Logic conditions for mode identification.

Time durations	i_L	V_o	State
$0<t<t_1$	$i_L<I_{TH}$	$V_o>V_b+\Delta V$	Charging mode (S1)
$t_1<t<t_2$	$i_L<I_{TH}$	$V_o<V_b-\Delta V$	Charging-Discharging tr. (S2)
$t_2<t<t_3$	$i_L>-I_{TH}$	$V_o<V_b-\Delta V$	Discharging mode (S3)
$t_3<t<t_4$	$i_L>I_{TH}$	$V_o>V_b+\Delta V$	Discharging-Charging tr. (S2)

- Voltage and current hysteresis included.
- This reduces error mode identification.
- Fastest mode transition using PWM blocking.

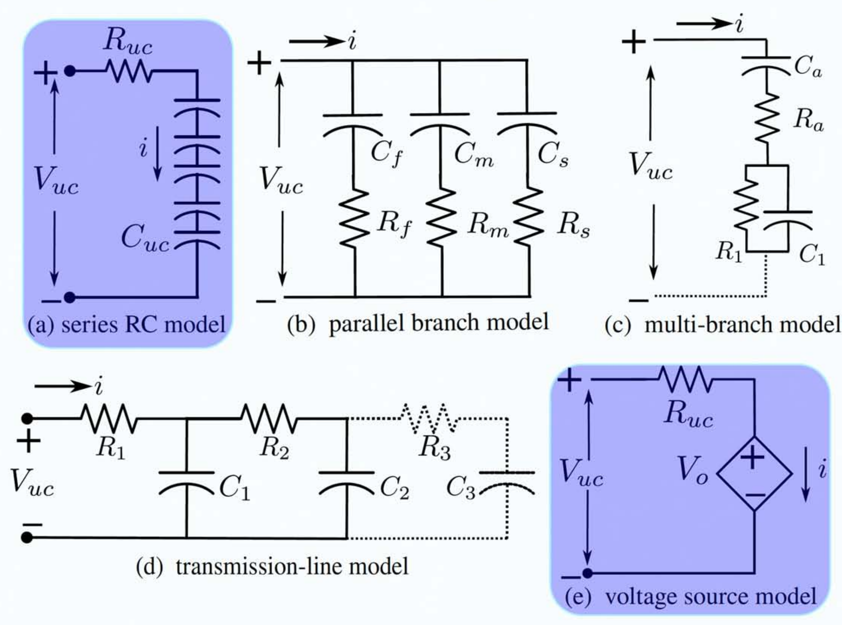
Experimental results for PWM blocking



- Smooth and seamless transition between control modes is achieved.
- Accurate mode identification is performed using mode identification algorithm.
- The proposed control allows decoupled controls for both operating modes.
- During PWM blocking, no control on dynamics of inductor current i_L.
  - An alternate **virtual resistance based control** allows complete control over time duration, inductor current i_L dynamics during mode transition.
  - Prevents undue stress on switches and inductor unlike PWM blocking control in case of error mode identification.

Simplified modelling of ultracapacitors

- UCs are usually modelled as series/parallel RC networks.
- Modelling of UC as a large capacitance in series with ESR is quite popular.
- Here, modelling of UC as a variable voltage source is studied.



Motivation for modelling of ultracapacitors

Ultracapacitors as variable voltage sources

Table: Experimental set-up for UC based bidirectional dc-dc converter.

Hardware details	
Filter inductor, L	$300\mu H$
Filter capacitor, C_f	$2000\mu F$
UC stack[†]capacitance C_{uc}, ESR R_{uc}	$12.5F$, 0.2Ω
Maximum Power, Supply Voltage V_g, f_{sw}	$200W$, $26V$, $100kHz$

† UC stack has 12 ***Maxwell BCAP0150*** ultracapacitors in series.

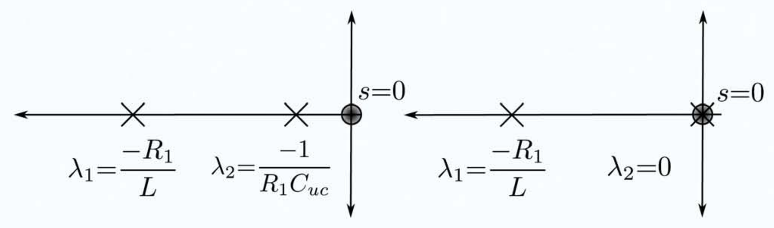
$$\frac{\hat{i_L}(s)}{\hat{d}(s)}=\frac{sV_gC_{uc}}{LC_{uc}s^2+R_1C_{uc}s+1}=\frac{\frac{V_g}{L}s}{s^2+\frac{R_1}{L}s+\frac{1}{LC}}=\frac{\frac{V_g}{L}s}{(s+\lambda_1)(s+\lambda_2)}$$

$$\lambda_1=-\frac{R_1}{2L}-\frac{1}{2L}\sqrt{\frac{C_{uc}R_1^2-4L}{C_{uc}}}\approx-666.268,\ \lambda_2=-\frac{R_1}{2L}+\frac{1}{2L}\sqrt{\frac{C_{uc}R_1^2-4L}{C_{uc}}}\approx-0.4$$

- Here, the approximation $C_{uc}R_1^2\gg L$ would be valid, allowing $\lambda_2=0$, and $\lambda_1=\frac{-R_1}{L}$.
- Also, the two eigen values are well separated. The quadratic systems with well separated eigen values are discussed in [2].

$$Q=\sqrt{\frac{L}{C_{uc}R_1^2}},\quad F=0.5+0.5\sqrt{1-4Q^2},\quad \lambda_1=\frac{-FR_1}{L},\quad \lambda_2=\frac{-1}{R_1C_{uc}F} \qquad (1)$$

- if $Q\approx0 \Rightarrow F\approx1$, then decoupling of eigen values, $\lambda_2=\frac{-1}{R_1C_{uc}}$, and $\lambda_1=\frac{-R_1}{L}$.



(a) (b)

- In this work, it is shown UCs can be modelled as a 1^{st} order system.

$$\frac{\hat{i_L}(s)}{\hat{d}(s)}=\frac{V_g}{L(s+\lambda_1)} \qquad (2)$$

Scope of this work

- Qualitative and quantitative comparison of the proposed variable voltage source model with series RC model.
- For this comparison, comparison metrics
  - F and Q parameters
  - the z-domain current loop plant transfer function, $\frac{\hat{i_L}(z)}{\hat{d}(z)}$ are used.
- Validation of comparison metrics over wide range of design voltage, power levels and sampling frequencies.
- Limiting operating voltage and power levels for different UC stack and converter designs for the proposed voltage source model.
- The corresponding controller design and experimental verification.

- The comparison metrics are dependent on circuit parameters.
- $P_o\in$ (100W,100kW), $V_g\in$ (30V,1000V)

Comparison using z-domain bode plots

Why analysis in z-domain??

- The transfer functions of a buck converter feeding a UC stack, $\frac{\hat{i_L}(z)}{\hat{d}(z)}$ for both the models are derived in z-domain.
- Usually, the control is implemented in digital platform.
- The non-idealities and other delays such as sampling and PWM delays can also be readily incorporated in the z-domain models.
- z-domain transfer functions obtained from continous time state space models.

Why use exact discretization?

- The comparison of $\frac{\hat{i_L}(z)}{\hat{d}(z)}$ for both the models is performed for wide range of design and operating conditions.
- Discretization methods such as Forward and Backward Euler, Tustin's method is not accurate for wide range of sampling frequencies, f_s[2].

[2] F.L. Lewis, Applied Optimal Control Estimation: Digital Design & Implementation, ser. Prentice Hall and Texas Instruments digital signal processing series. Prentice-Hall, 1992.

Small signal analysis for plant model

- **Model 2:** $\frac{\hat{i_L}(z)}{\hat{d}(z)}=\frac{V_gT_s}{L}\frac{2e^{\lambda_2T_s(1-d)}-e^{\lambda_1T_s(1-d)}}{(z-e^{\lambda_2T_s})(z-e^{\lambda_1T_s})}\times(z-[\frac{2e^{\lambda_1T_s+\lambda_2T_s(1-d)}-e^{\lambda_1T_s(1-d)+\lambda_2T_s}}{2e^{\lambda_2T_s(1-d)}-e^{\lambda_1T_s(1-d)}}])$

Approximating $\lambda_2=0$

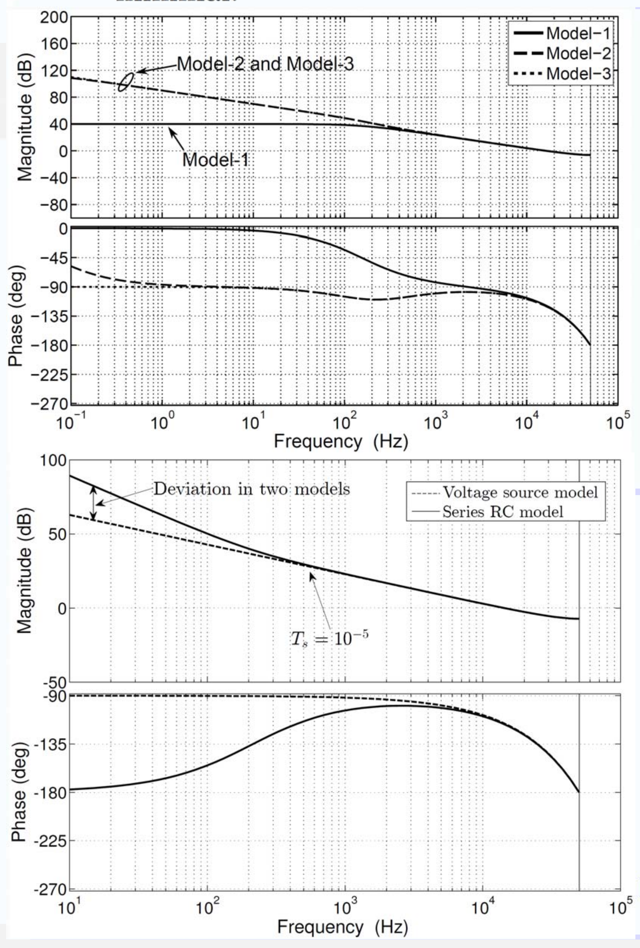
- **Model 3:** $\frac{\hat{i_L}(z)}{\hat{d}(z)}=\frac{V_gT_s}{L}\frac{2-e^{\lambda_1T_s(1-d)}}{(z-1)(z-e^{\lambda_1T_s})}(z-[\frac{2e^{\lambda_1T_s}-e^{\lambda_1T_s(1-d)}}{2-e^{\lambda_1T_s(1-d)}}])$

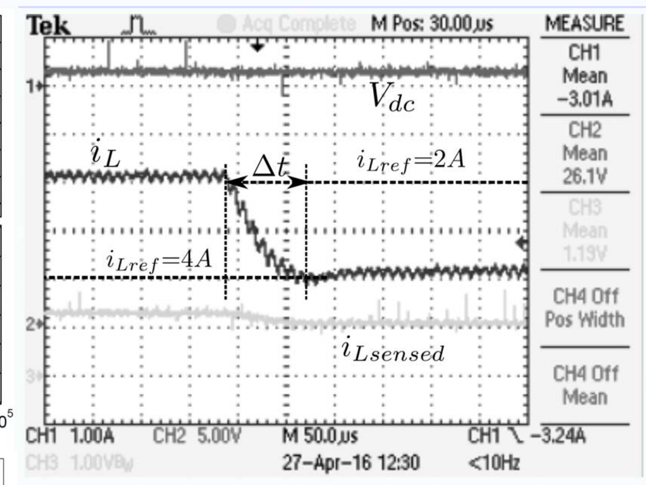
Model 1: $\frac{\hat{i_L}(z)}{\hat{d}(z)}=\frac{V_gT_s}{L}\left[\frac{1}{z-e^{\lambda_1T_s}}\right]e^{\lambda_1T_s(1-d)}$

if $\lambda_1T_s\approx0$

$\frac{\hat{i_L}(z)}{\hat{d}(z)}=\frac{V_gT_s}{L}\left[\frac{1}{z-1}\right]$ **This deviation not found in s-domain TFs, is analyzed in z- domain.**

- The effect of variation of duty ratio, d on the three models is found to be minimal.





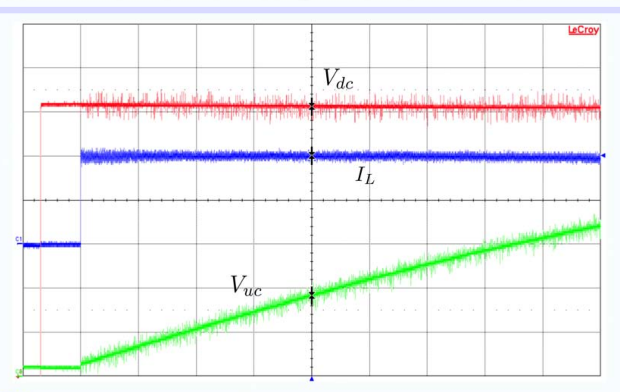
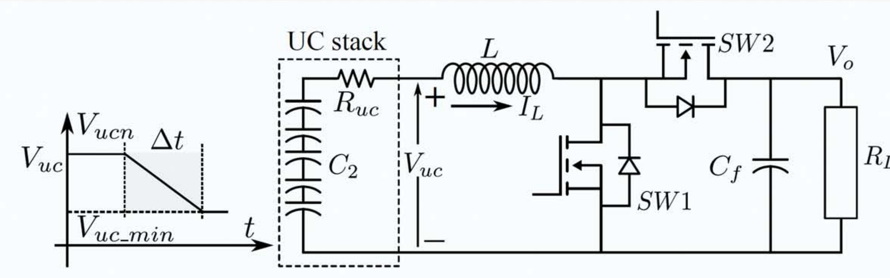


Figure: Charging of UC stack from 0-16V [Ch.1: i_L 1A/div., Ch.2: V_{uc} 5V/div., Ch.3: V_{dc} 5V/div., time scale: 20s/div.]

Adaptive control for discharging mode of operation



- The control structure should accommodate for variation in:
  - plant characteristics
  - RHP zero especially due to UC stack deep discharging.

Advantages of adaptive control

- The controller gains are estimated on-line.
- The proposed control ensures best performance criteria possible.
- Adaptive control incorporates the variation of RHP zero and varies the bandwidth accordingly[4].

Conclusions and Contributions

- Mode identification algorithm based on PWM blocking has been proposed which ensures:
  - Fastest mode transition.
  - Smooth, seamless mode transition.
  - Accurate identification of control modes.
- Alternately, virtual resistance control is proposed which allows control on current dynamics during mode transition as well.
- Simplified voltage source model for UCs similar to batteries have been proposed and verified which simplifies the controller design.
- The possibility of using this simplified model have been studied for wide range of design applications.
- For this, a generalized passives design is carried out where the variation of passives for various design applications is carried out.
- An adaptive control has been proposed which allows online variation of controller gains to accommodate system characteristics and RHZ variation.

Key Publications

[1] K. Saichand and V. John, "PWM block method for control of an ultracapacitor-based bidirectional DC/DC backup system," *IEEE Transactions on Industry Applications*, vol. 52, no. 5, pp. 4126–4134, Sept 2016.

[2] K. Saichand, A. Kumrawat, and V. John, "High performance AC-DC control power supply for low voltage ride through inverters," *Sadhana*, vol. 41, no. 2, pp. 147–159, 2016.

[3] K. Saichand and V. John, "Simplified modeling of ultracapacitors for bidirectional DC-DC converter applications," accepted for publication in *Applied Power Electronics Conference*. Tampa, Florida: APEC-2017, March 2017, pp. 1–6.

[4] K. Saichand and V. John, "Adaptive control strategy for ultracapacitor based bidirectional DC-DC converters," accepted for publication in *Applied Power Electronics Conference*. Tampa, Florida: APEC-2017, March 2017, pp. 1–6.

[5] K. Saichand and V. John, "A generalized design procedure for passives in a ultracapacitor based bidirectional DC-DC system for backup power applications," accepted for publication in *Thirteenth Annual IEEE INDICON, 2016*. IISc Bangalore: IEEE Bangalore Section, December 2016, pp. 1–6.

[6] K. Saichand and V. John, "PWM block method for control of an ultracapacitor based bidirectional dc/dc backup system," in *2014 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, IISc bangalore, December 2014, pp. 1–6.

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Power electronics group,
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April 7-8, 2017

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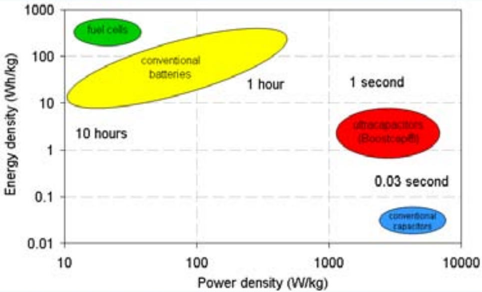

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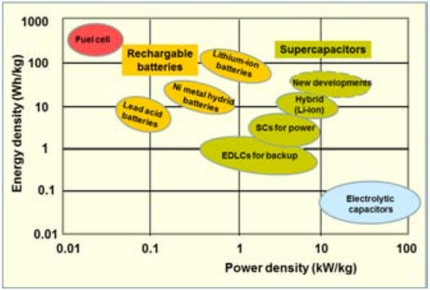
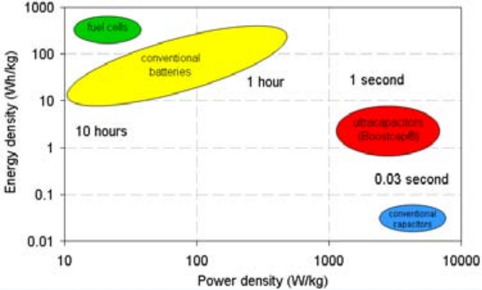


(b)

Source: https://upload.wikimedia.org/wikipedia/commons/6/6b/Supercapacitors_chart.svg



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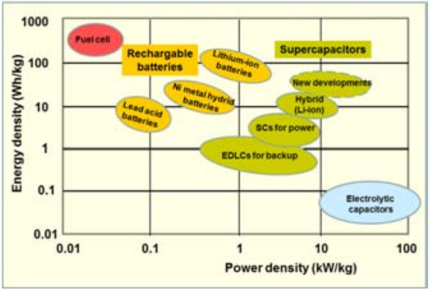

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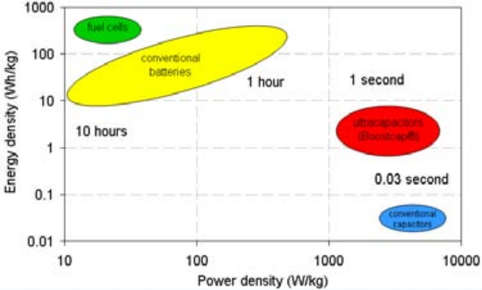

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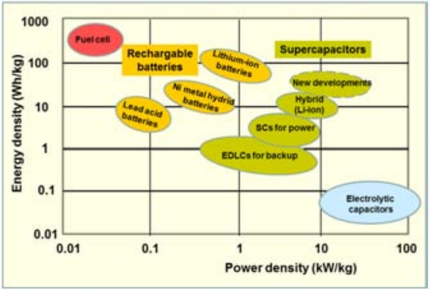

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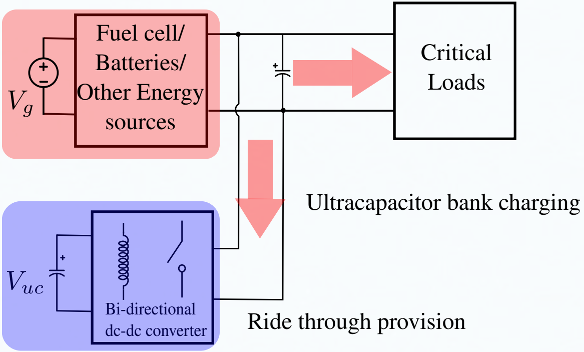

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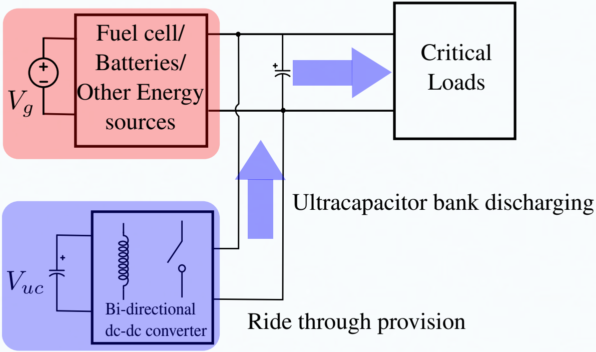

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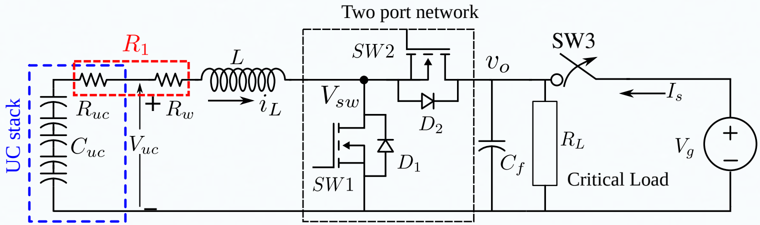

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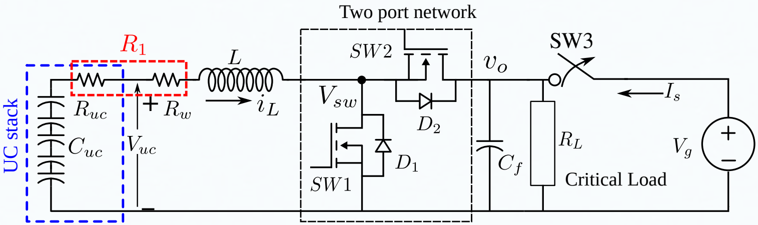

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List of contributions

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2. Virtual resistance control for seamless mode transition
3. Reduced order modelling of ultracapacitors
4. Generalized passives design for UC based backup system
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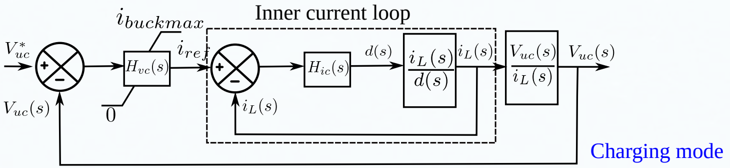

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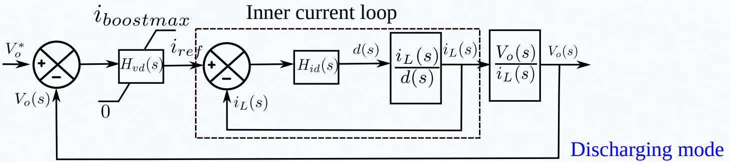

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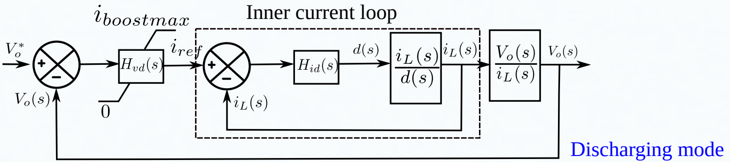

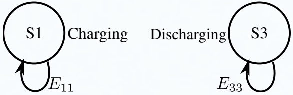

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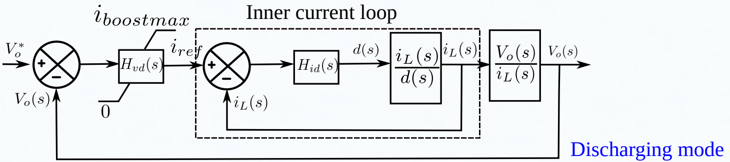

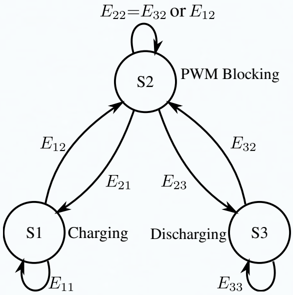

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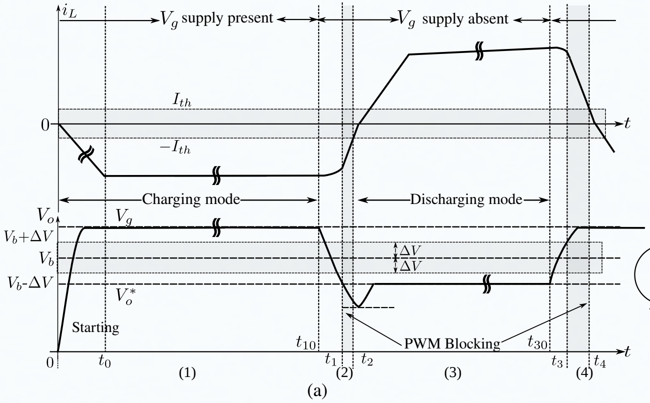

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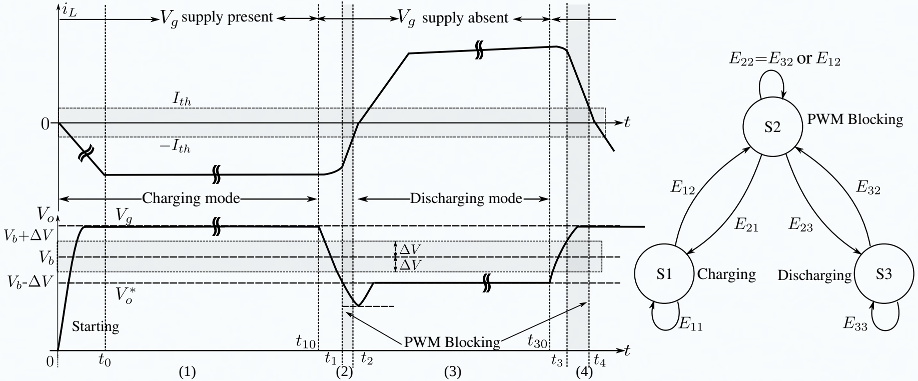

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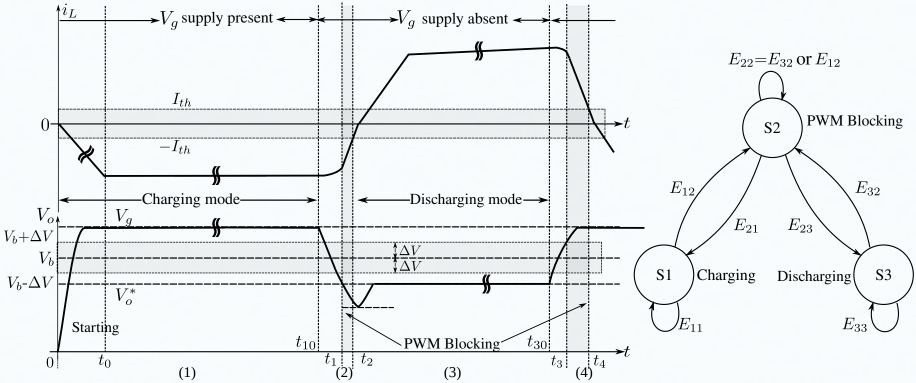
Mode identification algorithm



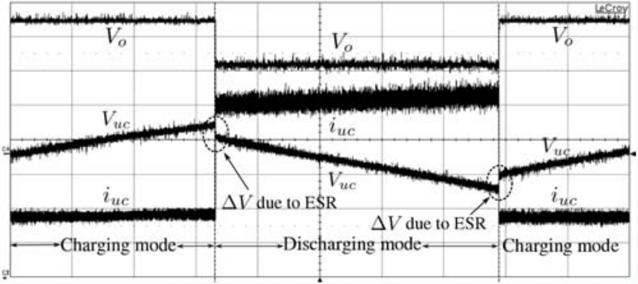
(a) (b)

Table: Logic conditions for mode identification.

Time durations	i_L	V_o	**State**
$0<t<t_1$	$i_L<I_{TH}$	$V_o>V_b+\Delta V$	Charging mode (S1)
$t_1<t<t_2$	$i_L<I_{TH}$	$V_o<V_b-\Delta V$	Charging-Discharging tr. (S2)
$t_2<t<t_3$	$i_L>-I_{TH}$	$V_o<V_b-\Delta V$	Discharging mode (S3)
$t_3<t<t_4$	$i_L>I_{TH}$	$V_o>V_b+\Delta V$	Discharging-Charging tr. (S2)

- Voltage and current hysteresis included.
- This reduces error mode identification.
- Fastest mode transition using PWM blocking.

Experimental results for PWM blocking



[1] K. Saichand and V. John,"PWM block method for control of an ultracapacitor-based bidirectional DC/DC backup system," IEEE Transactions on Industry Applications, vol. 52, no. 5, pp. 4126-4134, Sept 2016.

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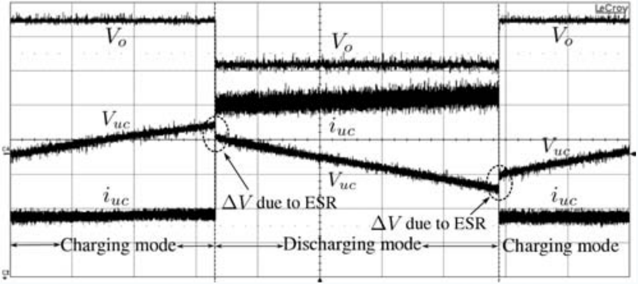

- Smooth and seamless transition between control modes is achieved.
- Accurate mode identification is performed using mode identification algorithm.
- The proposed control allows decoupled controls for both operating modes.
- During PWM blocking, no control on dynamics of inductor current i_L.
    - A **virtual resistance based control** allows complete control over time duration, inductor current i_L dynamics during mode transition[1].

[1] K. Saichand and V. John,"PWM block method for control of an ultracapacitor-based bidirectional DC/DC backup system," IEEE Transactions on Industry Applications, vol. 52, no. 5, pp. 4126-4134, Sept 2016.

List of works

1. PWM Blocking control for seamless mode transition
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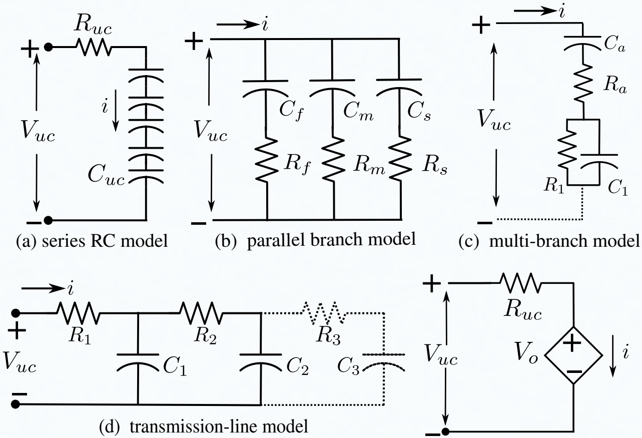
Reduced order modelling of ultracapacitors

- UCs are usually modelled as series/parallel RC networks.
- Modelling of UC as a large capacitance in series with ESR is quite popular.
- Here, modelling of UC as a variable voltage source is studied.



(a) series RC model

(b) parallel branch model

(c) multi-branch model

(d) transmission-line model

(e) voltage source model

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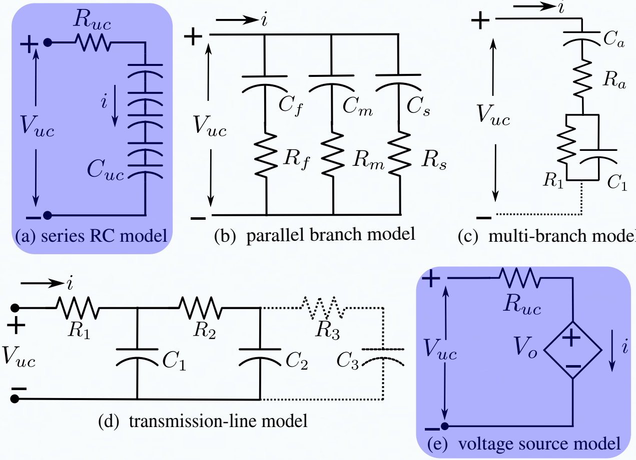

(a) series RC model (b) parallel branch model (c) multi-branch model

(d) transmission-line model (e) voltage source model

Table: Experimental set-up for UC based bidirectional dc-dc converter.

Hardware details	
Filter inductor, L	$300\mu H$
Filter capacitor, C_f	$2000\mu F$
UC stack[†]capacitance C_{uc}, ESR R_{uc}	$12.5F$, 0.2Ω
Maximum Power, Supply Voltage V_g, f_{sw}	$200W$, $26V$, $100kHz$

[†] UC stack has 12 ***Maxwell BCAP0150*** ultracapacitors in series.

$$\frac{\hat{i_L(s)}}{\hat{d(s)}} = \frac{sV_gC_{uc}}{LC_{uc}s^2 + R_1C_{uc}s + 1} = \frac{\frac{V_g}{L}s}{s^2 + \frac{R_1}{L}s + \frac{1}{LC}} = \frac{\frac{V_g}{L}s}{(s+\lambda_1)(s+\lambda_2)}^2$$

Motivation for modelling of ultracapacitors

Ultracapacitors as variable voltage sources

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$$\lambda_1 = -\frac{R_1}{2L} - \frac{1}{2L}\sqrt{\frac{C_{uc}R_1^2 - 4L}{C_{uc}}} \approx -666.268, \;\; \lambda_2 = -\frac{R_1}{2L} + \frac{1}{2L}\sqrt{\frac{C_{uc}R_1^2 - 4L}{C_{uc}}} \approx -0.4$$

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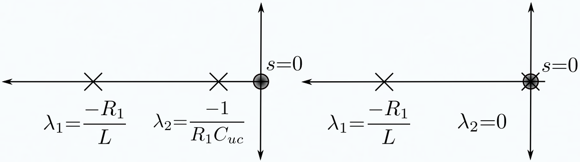
- Here, the approximation $C_{uc}R_1^2 \gg L$ would be valid, allowing $\lambda_2 = 0$, and $\lambda_1 = \frac{-R_1}{L}$.



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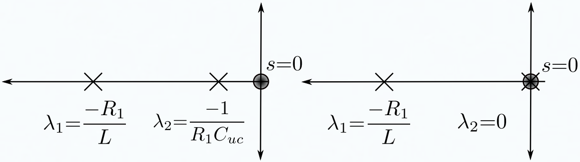

Comparison using z-domain bode plots

Why analysis in z-domain??

- The transfer functions of a buck converter feeding a UC stack, $\frac{\hat{i_L}(z)}{\hat{d}(z)}$ for both the models are derived in z-domain.
- Usually, the control is implemented in digital platform.
- The non-idealities and other delays such as sampling and PWM delays can also be readily incorporated in the z-domain models.
- z-domain transfer functions obtained from continous time state space models.

[3] F.L. Lewis, Applied Optimal Control Estimation: Digital Design & Implementation, ser. Prentice Hall and Texas Instruments digital signal processing series. Prentice-Hall, 1992.

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Why use exact discretization?

- The comparison of $\frac{i_L\hat{(z)}}{d\hat{(z)}}$ for both the models is performed for wide range of design and operating conditions.
- Discretization methods such as Forward and Backward Euler, Tustin's method are not accurate for wide range of sampling frequencies, f_s[3].

- The comparison metrics are dependent on circuit parameters.
- $P_o \in (100W, 100kW)$, $V_g \in (30V, 1000V)$

[3] F.L. Lewis, Applied Optimal Control Estimation: Digital Design & Implementation, ser. Prentice Hall and Texas Instruments digital signal processing series. Prentice-Hall, 1992.

Comparison of $\frac{\hat{i_L(z)}}{\hat{d(z)}}$ for the two UC models

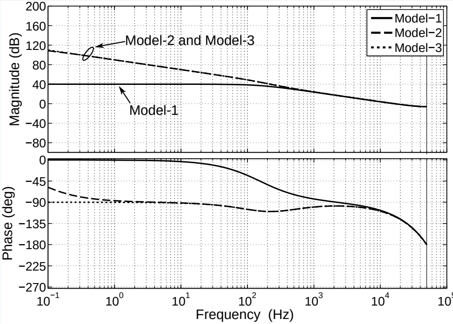


Figure: Bode plots comparing the three models for P_o=200W, V_g=30V.

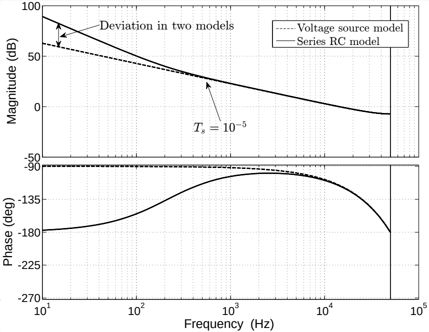
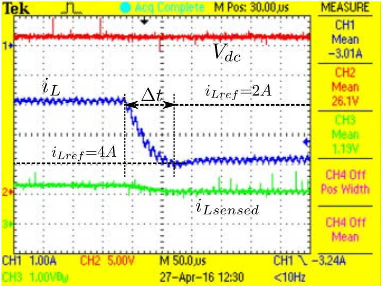
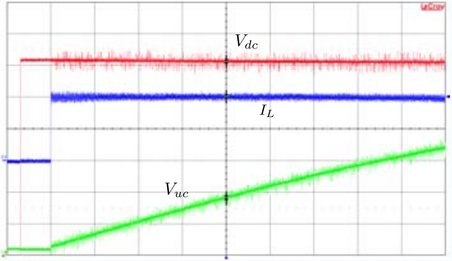


Figure: Bode plots for current loop plant transfer functions with PI control for Model 1 and Model 3.

- Model 2 and Model 3 match closely which shows that $\lambda_2 \approx 0$ is a valid approximation.
- For a given design application, Model 1 and Model 3 diverge especially at low frequency regions.
- The deviation between the two models reduces due to high gain of PI controller at low frequencies.
- The high frequency characteristics determines the stability and bandwidth.
- Phase margin of 70° and bandwidth of 10kHz is achieved.

Comparison of $\frac{\hat{i_L(z)}}{\hat{d(z)}}$ for the two UC models





- Charging mode inner current loop bandwidth, $f_b = \dfrac{4}{2\pi\Delta t}$
- Settling time, Δt of $70\mu s$ is observed based on which bandwidth of $9kHz$ is achieved.
- This verifies the dynamic performance of the designed inner loop current control.
- UC stack is charged in CC mode. The charging profile shows the stability of the designed current control.
- The charging duration can be verified by $C_{uc}\dfrac{\Delta V_{uc}}{\Delta t_c} = i_L$.
- The UC stack voltage, V_{uc} and charging current, i_L is chosen to be low, so that charging duration, Δt_c would be sufficiently high.

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Generalized passives design

- Why particularly necessary in UC based storage systems??
  - Batteries treated as fixed voltage sources.
  - UC stack undergo greater depth of discharge.
  - Converter design should accommodate wide range of operating conditions.

[4] K. Saichand and V. John, "A generalized design procedure for passives in a ultracapacitor based bidirectional DC-DC system for backup power applications," in Thirteenth Annual IEEE INDICON, 2016. IEEE Bangalore Section, 2016.

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- Converter design should accommodate wide variation in UC stack voltage, V_{uc}.
- The converter and passives' design should also accommodate for both the charging and discharging operating modes.

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- Converter design should accommodate wide variation in UC stack voltage, V_{uc}.
- The converter and passives' design should also accommodate for both the charging and discharging operating modes.
- Generalized design of passives is necessary:
  - To validate any proposed ultracapacitor model,
  - For performance studies on a UC based dc/dc systems for wide range of design applications.[4].
- Crucial in modeling of ultracapacitors and in design of adaptive control.

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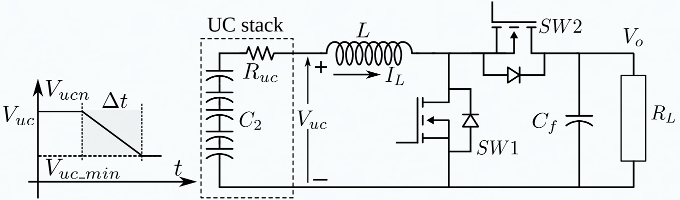
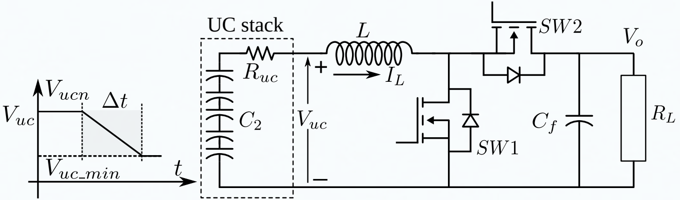
Adaptive control for discharging mode of operation



[5] K. Saichand and V. John, "Adaptive control strategy for ultracapacitor based bidirectional DC-DC converters," accepted for publication in Applied Power Electronics Conference. Tampa, Florida: APEC-2017, March 2017, pp. 1-6.

Adaptive control for discharging mode of operation



- The control structure should accommodate for variation in:
  - plant characteristics
  - RHP zero especially due to UC stack deep discharging.

Advantages of adaptive control

- The controller gains are estimated on-line.
- The proposed control ensures best performance criteria possible.
- Adaptive control incorporates the variation of RHP zero and varies the bandwidth accordingly[5].

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Conclusions and Contributions

- Mode identification algorithm based on PWM blocking has been proposed which ensures:
  - Fastest mode transition.
  - Smooth, seamless mode transition.
  - Accurate identification of control modes.
- Alternately, virtual resistance control is proposed which allows control on current dynamics during mode transition as well.
- Simplified voltage source model for UCs similar to batteries have been proposed and verified which simplifies the controller design.
- The possibility of using this simplified model have been studied for wide range of design applications.
- For this, a generalized passives design is carried out where the variation of passives for various design applications is carried out.
- An adaptive control has been proposed which allows online variation of controller gains to accommodate system characteristics and RHP zero variation.

List of Key Publications

[1] K. Saichand and V. John, "PWM block method for control of an ultracapacitor-based bidirectional DC/DC backup system," *IEEE Transactions on Industry Applications*, vol. 52, no. 5, pp. 4126–4134, Sept 2016.

[2] K. Saichand, A. Kumrawat, and V. John, "High performance AC-DC control power supply for low voltage ride through inverters," *Sadhana*, vol. 41, no. 2, pp. 147–159, 2016.

[3] K. Saichand and V. John, "Simplified modeling of ultracapacitors for bidirectional DC-DC converter applications," accepted for publication in *Applied Power Electronics Conference*. Tampa, Florida: APEC-2017, March 2017, pp. 1–6.

[4] K. Saichand and V. John, "Adaptive control strategy for ultracapacitor based bidirectional DC-DC converters," accepted for publication in *Applied Power Electronics Conference*. Tampa, Florida: APEC-2017, March 2017, pp. 1–6.

[5] K. Saichand and V. John, "A generalized design procedure for passives in a ultracapacitor based bidirectional DC-DC system for backup power applications," accepted for publication in *Thirteenth Annual IEEE INDICON, 2016*. IISc Bangalore: IEEE Bangalore Section, December 2016, pp. 1–6.

[6] K. Saichand and V. John, "PWM block method for control of ultracapacitor based bidirectional dc/dc backup system," in *2014 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, IISc bangalore, December 2014, pp. 1–6.

[7] A. Kumrawat, K. Saichand, and V. John, "Design of AC-DC control power supply with wide input voltage variation," in *2013 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, Nov 2013, pp. 1–6.

[8] K. Saichand, A. Kumrawat, and V. John, "Design of start-up power circuit for control power supplies with wide input voltage variation," in *National power electronics conference*. IIT Kanpur: NPEC, December 2013, pp. 1–6.

[9] K. Saichand and V. John, "Virtual resistance based control for ultracapacitor based bidirectional DC/DC backup system," in *National power electronics conference*. IIT Bombay: NPEC, December 2015, pp. 1–6.

Thank You....