MMC controllers for ultra low harmonic distortion

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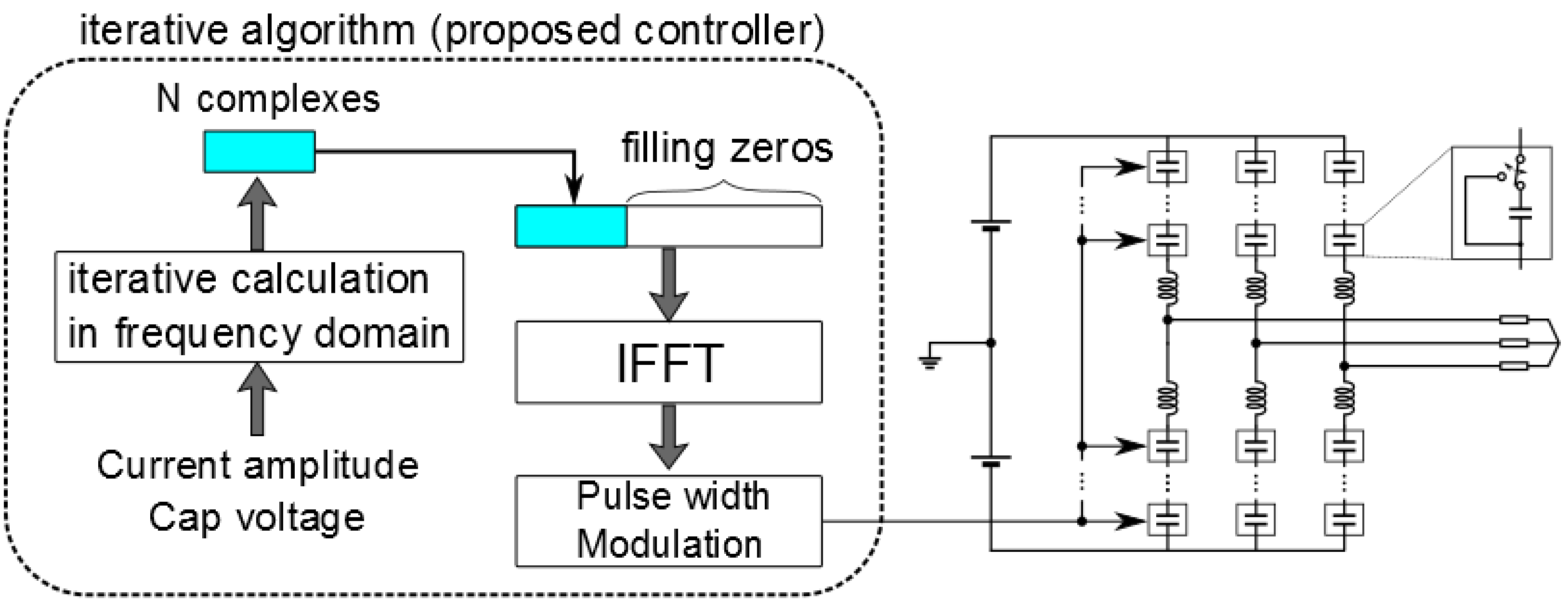
Basic approach

- Comprehensive study on the behavior of MMCs in Frequency domain.
- Iterative algorithm to obtain control signals as fast as possible.
- Controller based on FFT, that's readily available in digital domain.

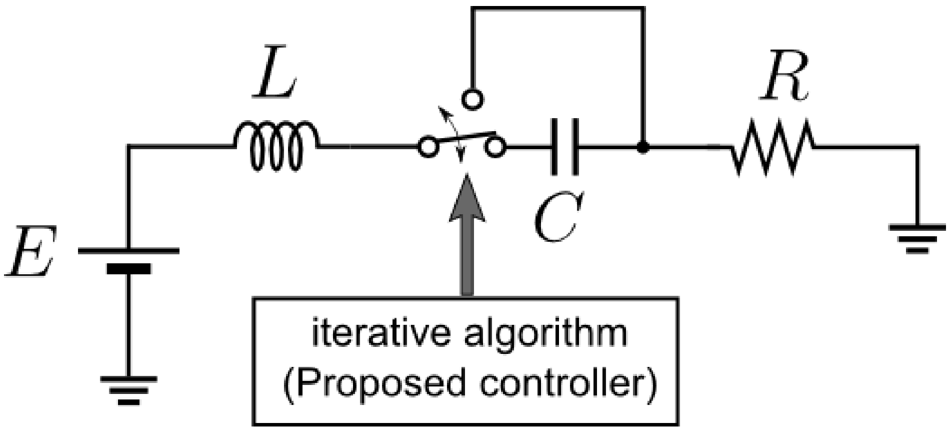
Proposed MMC controller



- The proposed system described above minimizes the harmonic distortion of the output current by adjusting the higher harmonics in control signals.
- It adopts an iterative algorithm in finding the optimum control signals.
- N<16 has been found to be enough for most of cases.

--- Test circuits ---

Test circuit I (LCR series circuit)



$E = 100$ [V]

$L = 0.5 / 1.0 / 2.0$ [mH]

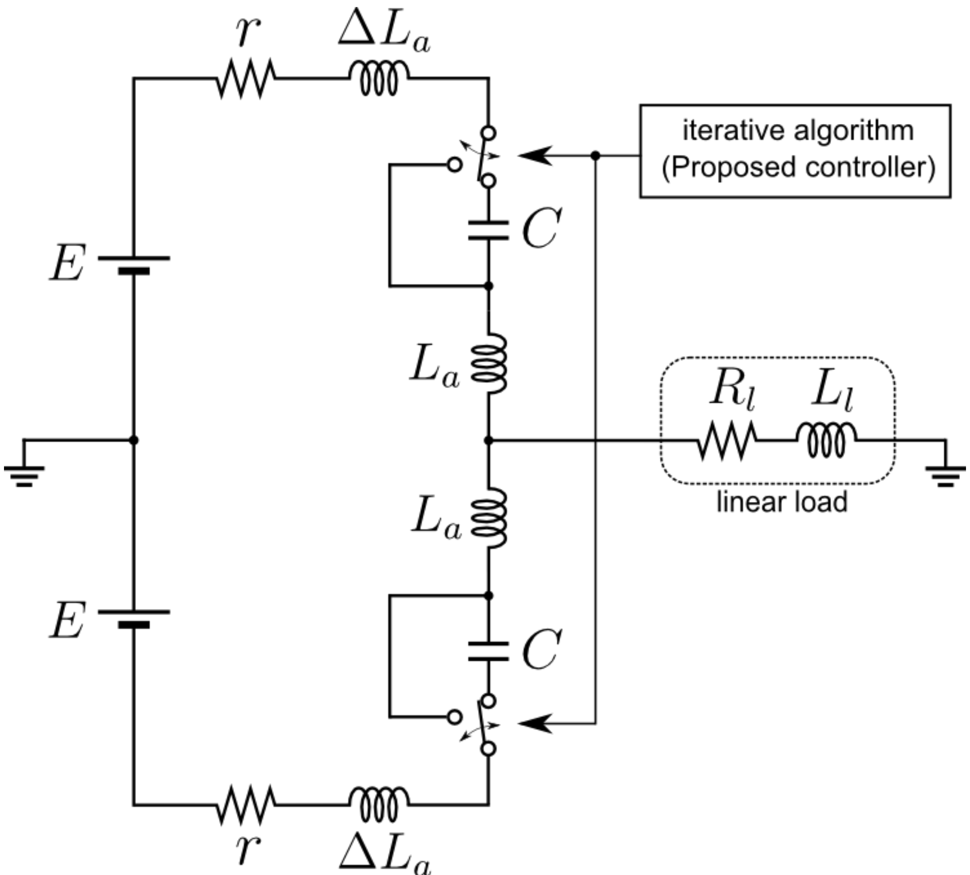
$C = 0.5 / 1.0 / 2.0$ [mF]

$R = 10$ [Ω]

$f = 50$ [Hz]

- The simplest conceivable circuit for the control
- continuous-time approximation to check THD
- This simple study is applicable to controls of other complicated MMC circuits.

Test circuit II (The simplest MMC)



$E = 100$ [V]

$L_a = 0.5 / 1.0 / 2.0$ [mH]

$\Delta L_a = 0$ [mH]

$L_l = 10$ [mH]

$C = 0.25 / 0.5 / 1.0$ [mF]

$R = 10$ [Ω]

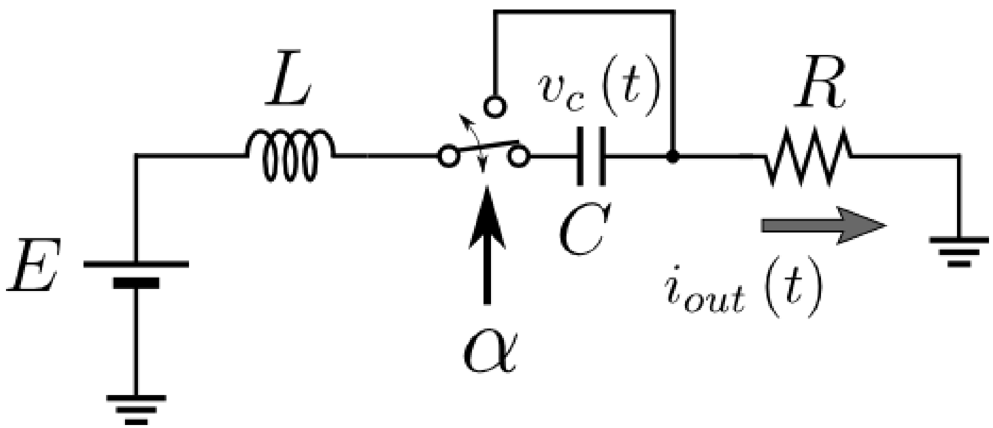
$r = 0.3$ [Ω]

$f = 50$ [Hz]

Performed a transient simulation (LTSpice IV) to check THD.

--- Construction of the models ---

Continuous-time model of test circuit I (1)

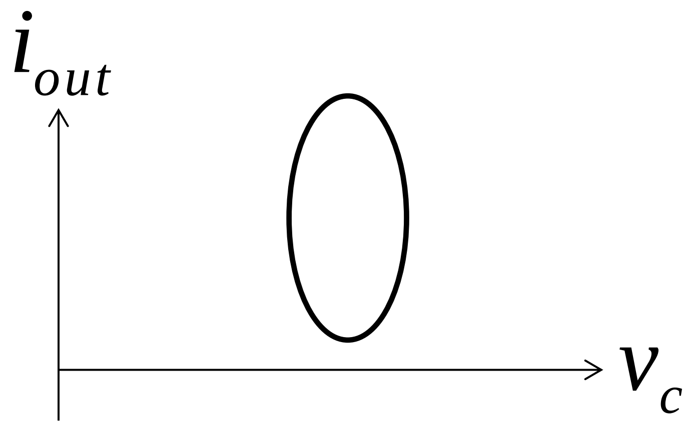


$$\frac{d}{dt}\begin{pmatrix} v_c(t) \\ i_{out}(t) \end{pmatrix} = \begin{pmatrix} \dfrac{\alpha(t) i_{out}(t)}{C} \\ \dfrac{1}{L}\left(E - \alpha(t) v_c(t) - R i_{out}(t)\right) \end{pmatrix} = \begin{pmatrix} 0 & \dfrac{\alpha(t)}{C} \\ -\dfrac{\alpha(t)}{L} & -\dfrac{R}{L} \end{pmatrix}\begin{pmatrix} v_c(t) \\ i_{out}(t) \end{pmatrix} + \frac{1}{L}\begin{pmatrix} 0 \\ E \end{pmatrix}$$

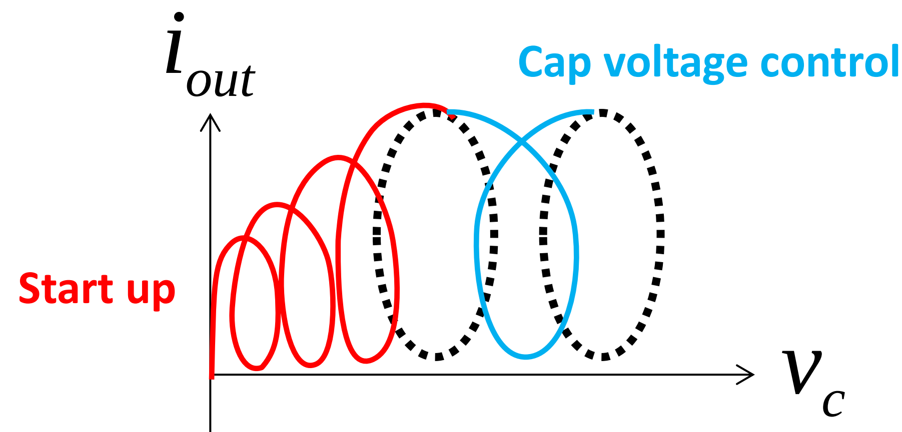
The derivatives of the cap voltage and the output current is expressed in a linear formation.

Continuous-time model of test circuit I (2)

$$\frac{d}{dt}\begin{pmatrix} v_c(t) \\ i_{out}(t) \end{pmatrix} = \begin{pmatrix} \dfrac{\alpha(t) i_{out}(t)}{C} \\ \dfrac{1}{L}\left(E - \alpha(t) v_c(t) - R i_{out}(t)\right) \end{pmatrix} = \begin{pmatrix} 0 & \dfrac{\alpha(t)}{C} \\ -\dfrac{\alpha(t)}{L} & -\dfrac{R}{L} \end{pmatrix} \begin{pmatrix} v_c(t) \\ i_{out}(t) \end{pmatrix} + \frac{1}{L}\begin{pmatrix} 0 \\ E \end{pmatrix}$$



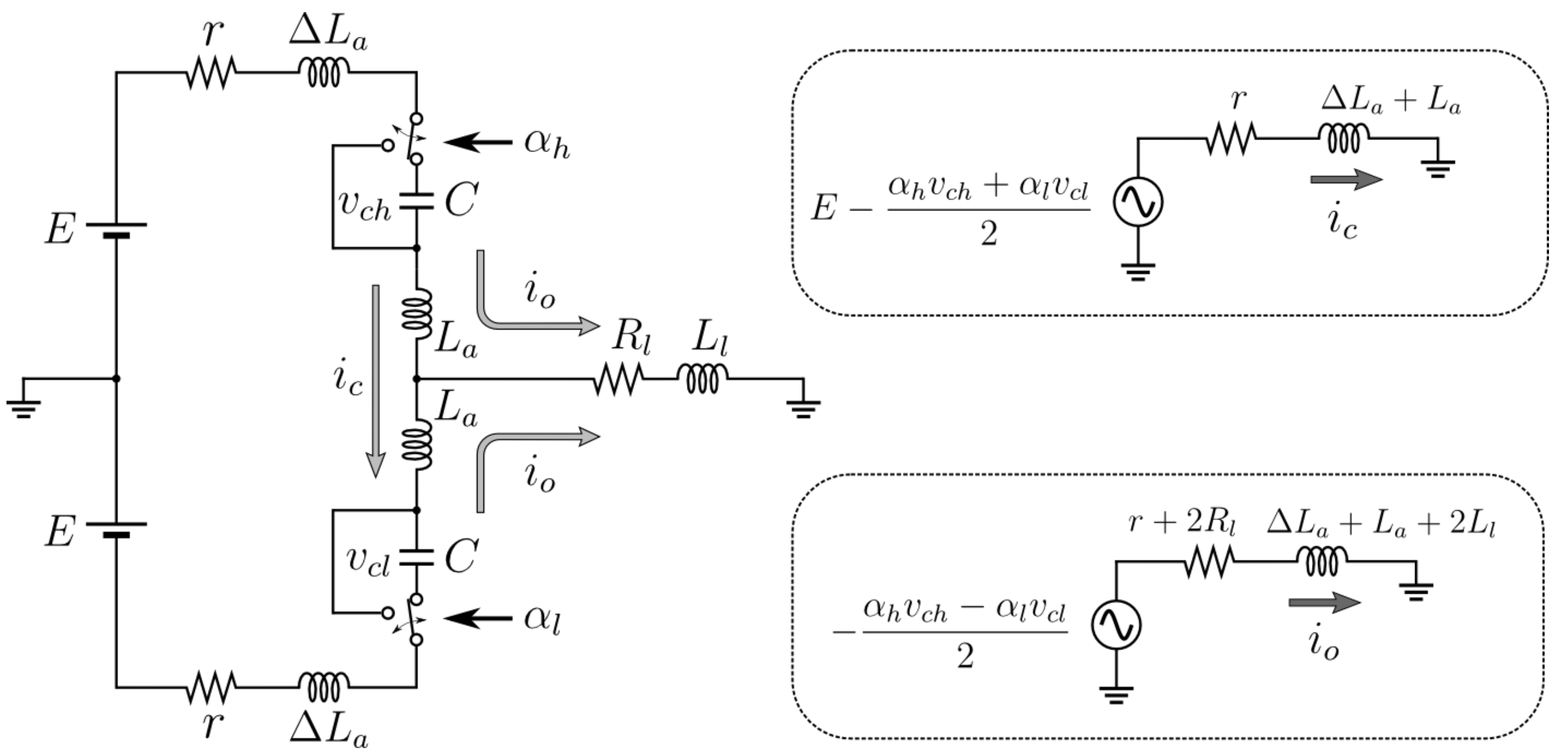
Periodic case



Transient case

Phase space is helpful for our intuitive understandings of MMC dynamics.

Continuous-time model of test circuit II (1)



However complicated the circuit would be, the dynamic system can be expressed in linear formation (matrices).

Continuous-time model of test circuit II (2)

$$\frac{d}{dt}\begin{pmatrix}\vec{v}_c(t)\\ \vec{i}(t)\end{pmatrix}=\begin{pmatrix}\dfrac{\boldsymbol{\alpha}(t)\vec{i}(t)}{C}\\ \mathbf{L}^{-1}\left(E-\boldsymbol{\alpha}(t)\vec{v}_c(t)-\mathbf{R}\vec{i}(t)\right)\end{pmatrix}=\begin{pmatrix}0 & \dfrac{\boldsymbol{\alpha}(t)}{C}\\ -\mathbf{L}^{-1}\boldsymbol{\alpha}(t) & -\mathbf{L}^{-1}\mathbf{R}\end{pmatrix}\begin{pmatrix}\vec{v}_c(t)\\ \vec{i}(t)\end{pmatrix}+\mathbf{L}^{-1}\begin{pmatrix}\vec{0}\\ \vec{E}\end{pmatrix}$$

$$\vec{v}_c(t)=\begin{pmatrix}v_{ch}(t)\\ v_{cl}(t)\end{pmatrix}\qquad \vec{i}(t)=\begin{pmatrix}i_h(t)\\ i_l(t)\end{pmatrix}\qquad \vec{E}=\begin{pmatrix}E\\ E\end{pmatrix}$$

$$\mathbf{R}=\begin{pmatrix}r+R & -R\\ -R & r+R\end{pmatrix}\qquad \mathbf{L}=\begin{pmatrix}L_a+L_l & -L_l\\ -L_l & L_a+L_l\end{pmatrix}\qquad \boldsymbol{\alpha}(t)=\begin{pmatrix}\alpha_h(t) & 0\\ 0 & \alpha_l(t)\end{pmatrix}$$

It’s very similar to the continuous-time model of test circuit I (simple LCR series circuit) !!

--- Details of the iterative algorithm ---

Iterative algorithm for test circuit I (1)

<Fundamental equation of test circuit I>

$$\frac{d}{dt}\begin{pmatrix} v_c(t) \\ i_{out}(t) \end{pmatrix} = \begin{pmatrix} \dfrac{\alpha(t) i_{out}(t)}{C} \\ \dfrac{1}{L}\left(E - \alpha(t) v_c(t) - R i_{out}(t)\right) \end{pmatrix} = \begin{pmatrix} 0 & \dfrac{\alpha(t)}{C} \\ -\dfrac{\alpha(t)}{L} & -\dfrac{R}{L} \end{pmatrix} \begin{pmatrix} v_c(t) \\ i_{out}(t) \end{pmatrix} + \frac{1}{L}\begin{pmatrix} 0 \\ E \end{pmatrix}$$

<Fourier transformation>

$$v_c(t) = \sum_{k=-\infty}^{\infty} \tilde{v}_c^{(k)} e^{jk\omega t} \qquad i_{out}(t) = \sum_{k=-\infty}^{\infty} \tilde{i}_{out}^{(k)} e^{jk\omega t} \qquad \alpha(t) = \sum_{k=-\infty}^{\infty} \tilde{\alpha}^{(k)} e^{jk\omega t}$$

Calculate the Fourier transform of the fundamental equation to find the optimum $\alpha(t)$ for non-distorted $i_{out}(t)$.

Iterative algorithm for test circuit I (2)

＜Fundamental equations for non-distorted $i_{out}(t)$ ＞

$$\tilde{v}_c^{(0)}\tilde{\alpha}^{(k)} + f\left(\left\{\tilde{\alpha}^{(n)}\right\},\infty,k\right) = \begin{cases} E - R\tilde{i}_{out}^{(0)} & (k=0) \\ -(j\omega L + R)\tilde{i}_{out}^{(1)} & (k=1) \\ -(-j\omega L + R)\tilde{i}_{out}^{(-1)} & (k=-1) \\ 0 & (|k| \geq 2) \end{cases}$$

Condition1

$$\tilde{\alpha}^{(0)}\frac{E}{R} = \tilde{v}_c^{(0)}\sum_{k=-\infty}^{\infty}\frac{\left|\tilde{\alpha}^{(k)}\right|^2}{jk\omega L + R} + \sum_{k=-\infty}^{\infty}\frac{\tilde{\alpha}^{(-k)}}{jk\omega L + R} f\left(\left\{\tilde{\alpha}^{(n)}\right\},\infty,k\right)$$

Condition2

where

$$f\left(\left\{\tilde{\alpha}^{(n)}\right\},N,p\right) = \sum_{m=-N/2}^{-1}\tilde{\alpha}^{(p-m)}\frac{\tilde{i}_{out}^{(0)}\tilde{\alpha}^{(m)} + \tilde{i}_{out}^{(-1)}\tilde{\alpha}^{(m+1)} + \tilde{i}_{out}^{(1)}\tilde{\alpha}^{(m-1)}}{jm\omega C} + \sum_{m=1}^{N/2}\tilde{\alpha}^{(p-m)}\frac{\tilde{i}_{out}^{(0)}\tilde{\alpha}^{(m)} + \tilde{i}_{out}^{(-1)}\tilde{\alpha}^{(m+1)} + \tilde{i}_{out}^{(1)}\tilde{\alpha}^{(m-1)}}{jm\omega C}$$

Iterative algorithm for test circuit I (3)

<Iterative algorithm for test circuit I>

$$\left(\tilde{v}_c^{(0)}, \tilde{i}_{out}^{(1)}\right) \Rightarrow \left(\tilde{\alpha}^{(0)}, \tilde{\alpha}^{(1)}, \tilde{i}_{out}^{(0)}\right)$$

Input parameters

Initial values

$$\tilde{v}_c^{(0)}\tilde{\alpha}_0^{(k)} = \begin{cases} E - R\tilde{i}_{out}^{(0)} & (k=0) \\ -(j\omega L + R)\tilde{i}_{out}^{(1)} & (k=1) \\ -(-j\omega L + R)\tilde{i}_{out}^{(-1)} & (k=-1) \\ 0 & (|k| \geq 2) \end{cases}$$

Equation for the iteration

$$\tilde{v}_c^{(0)}\tilde{\alpha}_{q+1}^{(k)} + f\left(\left\{\tilde{\alpha}_q^{(n)}\right\}, N, k\right) = \begin{cases} E - R\tilde{i}_{out}^{(0)} & (k=0) \\ -(j\omega L + R)\tilde{i}_{out}^{(1)} & (k=1) \\ -(-j\omega L + R)\tilde{i}_{out}^{(-1)} & (k=-1) \\ 0 & (|k| \geq 2) \end{cases}$$

(q+1)'th complex series $\left\{\tilde{\alpha}_{q+1}^{(n)}\right\}$ can be obtained by calculating $f\left(\left\{\tilde{\alpha}_q^{(n)}\right\}, N, k\right)$

Iterative algorithm for test circuit II (1)

＜Fundamental equation of test circuit II＞

$$\frac{d}{dt}\begin{pmatrix} \vec{v}_c(t) \\ \vec{i}(t) \end{pmatrix} = \begin{pmatrix} \dfrac{\boldsymbol{\alpha}(t)\vec{i}(t)}{C} \\ \mathbf{L}^{-1}\left(E - \boldsymbol{\alpha}(t)\vec{v}_c(t) - \mathbf{R}\vec{i}(t)\right) \end{pmatrix} = \begin{pmatrix} 0 & \dfrac{\boldsymbol{\alpha}(t)}{C} \\ -\mathbf{L}^{-1}\boldsymbol{\alpha}(t) & -\mathbf{L}^{-1}\mathbf{R} \end{pmatrix}\begin{pmatrix} \vec{v}_c(t) \\ \vec{i}(t) \end{pmatrix} + \mathbf{L}^{-1}\begin{pmatrix} \vec{0} \\ \vec{E} \end{pmatrix}$$

＜Fourier transformation＞

$$\vec{v}_c(t) = \sum_{k=-\infty}^{\infty} \vec{\tilde{v}}_c^{(k)} e^{jk\omega t} \qquad \vec{i}(t) = \sum_{k=-\infty}^{\infty} \vec{\tilde{i}}^{(k)} e^{jk\omega t} \qquad \boldsymbol{\alpha}(t) = \sum_{k=-\infty}^{\infty} \boldsymbol{\alpha}^{(k)} e^{jk\omega t}$$

Fourier transform to find the optimum $\boldsymbol{\alpha}(t)$ for non-distorted $\vec{i}_{out}(t)$.

Iterative algorithm for test circuit II (2)

＜Iterative algorithm for test circuit II＞

$$\left(\tilde{\vec{v}}_c^{(0)}, \tilde{\vec{i}}_{out}^{(1)}\right) \Rightarrow \left(\tilde{\boldsymbol{\alpha}}^{(0)}, \tilde{\boldsymbol{\alpha}}^{(1)}, \tilde{\vec{i}}_{out}^{(0)}\right)$$

Input parameters

Initial values

$$\tilde{\vec{v}}_c^{(0)} \tilde{\boldsymbol{\alpha}}_0^{(k)} = \begin{cases} \vec{E} - \mathbf{R}\tilde{\vec{i}}^{(0)} & (k=0) \\ -(j\omega\mathbf{L} + \mathbf{R})\tilde{\vec{i}}^{(1)} & (k=1) \\ -(-j\omega\mathbf{L} + \mathbf{R})\tilde{\vec{i}}^{(-1)} & (k=-1) \\ 0 & (|k| \geq 2) \end{cases}$$

Equation for the iteration

$$\tilde{\vec{v}}_c^{(0)} \tilde{\boldsymbol{\alpha}}_{q+1}^{(k)} + f\left(\left\{\tilde{\boldsymbol{\alpha}}_q^{(n)}\right\}, N, k\right) = \begin{cases} \vec{E} - \mathbf{R}\tilde{\vec{i}}^{(0)} & (k=0) \\ -(j\omega\mathbf{L} + \mathbf{R})\tilde{\vec{i}}^{(1)} & (k=1) \\ -(-j\omega\mathbf{L} + \mathbf{R})\tilde{\vec{i}}^{(-1)} & (k=-1) \\ 0 & (|k| \geq 2) \end{cases}$$

where

$$f\left(\left\{\tilde{\boldsymbol{\alpha}}^{(n)}\right\}, N, p\right) = \sum_{m=-N/2}^{-1} \tilde{\boldsymbol{\alpha}}^{(p-m)} \frac{\tilde{\vec{i}}^{(0)}\tilde{\boldsymbol{\alpha}}^{(m)} + \tilde{\vec{i}}^{(-1)}\tilde{\boldsymbol{\alpha}}^{(m+1)} + \tilde{\vec{i}}^{(1)}\tilde{\boldsymbol{\alpha}}^{(m-1)}}{jm\omega C} + \sum_{m=1}^{N/2} \tilde{\boldsymbol{\alpha}}^{(p-m)} \frac{\tilde{\vec{i}}^{(0)}\tilde{\boldsymbol{\alpha}}^{(m)} + \tilde{\vec{i}}^{(-1)}\tilde{\boldsymbol{\alpha}}^{(m+1)} + \tilde{\vec{i}}^{(1)}\tilde{\boldsymbol{\alpha}}^{(m-1)}}{jm\omega C}$$

--- Simulation results ---

Simulation results of test circuit I (1)

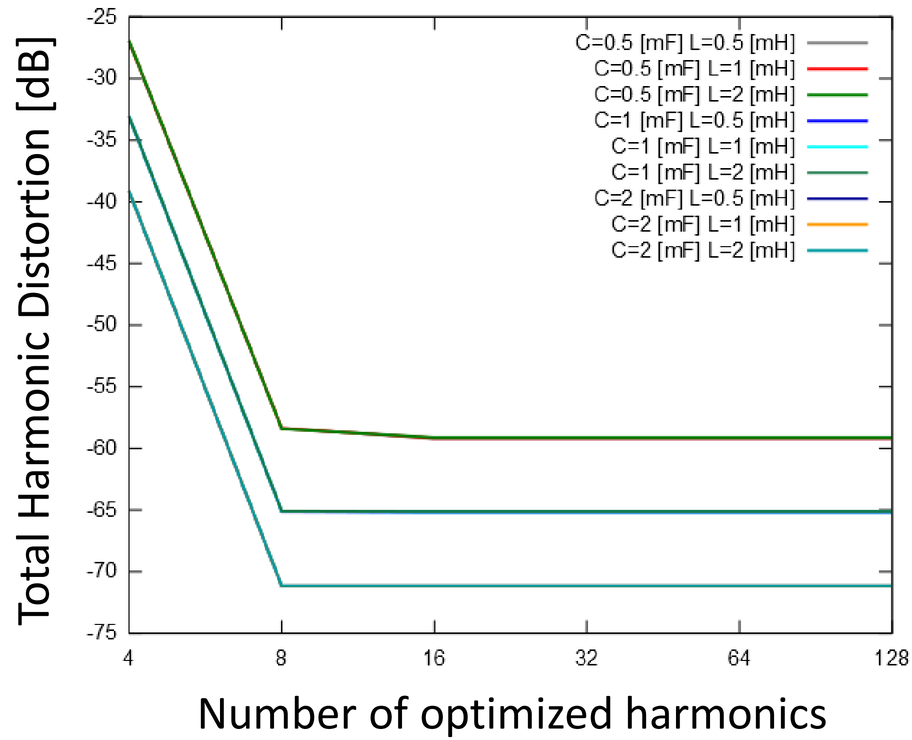
<THD vs # of harmonics>

$$L = 0.5 / 1.0 / 2.0 \quad [\mathrm{mH}]$$

$$C = 0.5 / 1.0 / 2.0 \quad [\mathrm{mF}]$$

$$\tilde{v}_c^{(0)} = 130 \quad [\mathrm{V}]$$

$$I^{(1)} = 2.5 \quad [\mathrm{A}]$$



We have only to optimize 8-16 harmonics in control signals to achieve sufficient THD performance.

Simulation results of test circuit I (2)

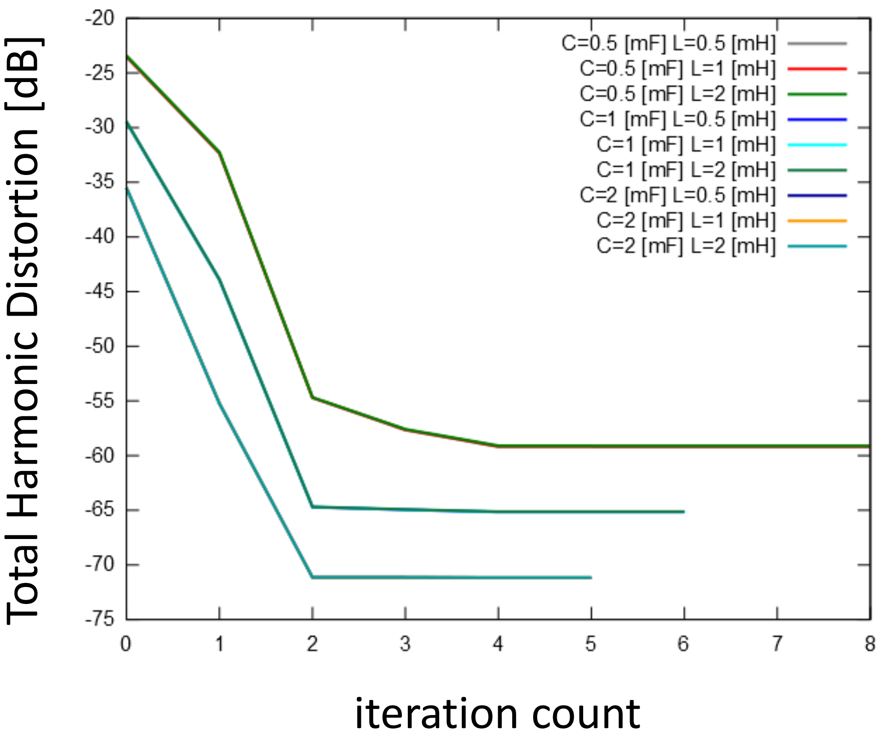
<THD vs iteration count>

$$L = 0.5/1.0/2.0 \quad [\mathrm{mH}]$$

$$C = 0.5/1.0/2.0 \quad [\mathrm{mF}]$$

$$\tilde{v}_c^{(0)} = 130 \quad [\mathrm{V}]$$

$$I^{(1)} = 2.5 \quad [\mathrm{A}]$$



- Required iteration count is less than 8 in typical design.
- Less capacitance tends to need more iteration counts.

Simulation results of test circuit I (3)

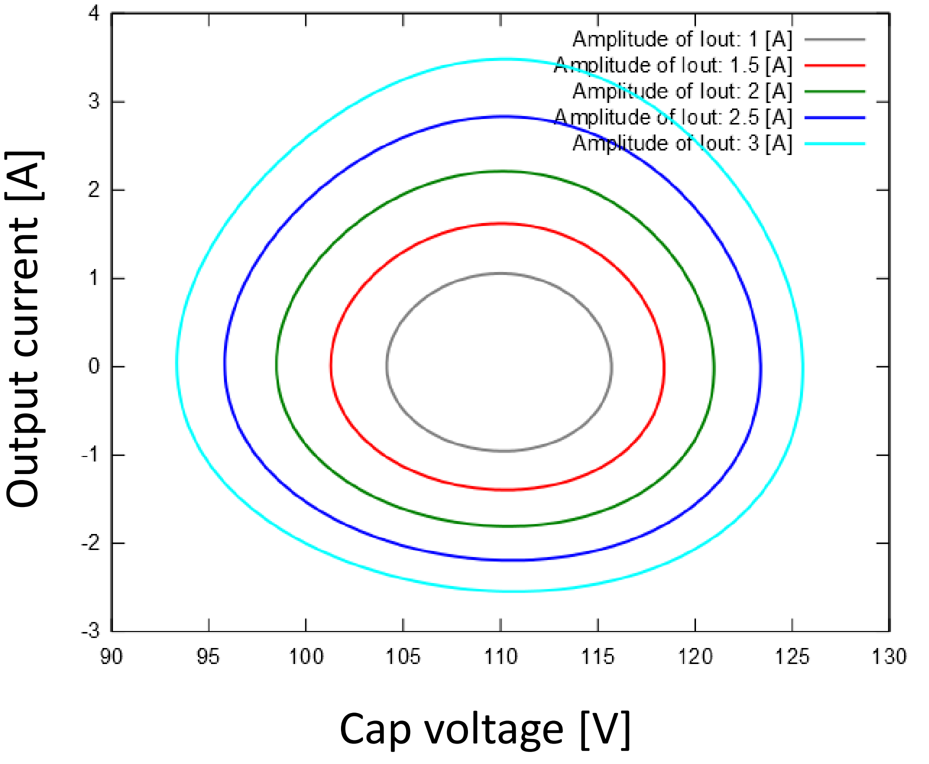
<dependence on $I^{(1)}$ >

$$L = 2.0 \quad [\mathrm{mH}]$$

$$C = 0.5 \quad [\mathrm{mF}]$$

$$\tilde{v}_c^{(0)} = 110 \quad [\mathrm{V}]$$

$$I^{(1)} = 1.0/1.5/2.0/2.5/3.0 \quad [\mathrm{A}]$$



- Trajectories for 5 different output currents.
- Applicable to power controls without any degradation of THD.

Simulation results of test circuit I (4)

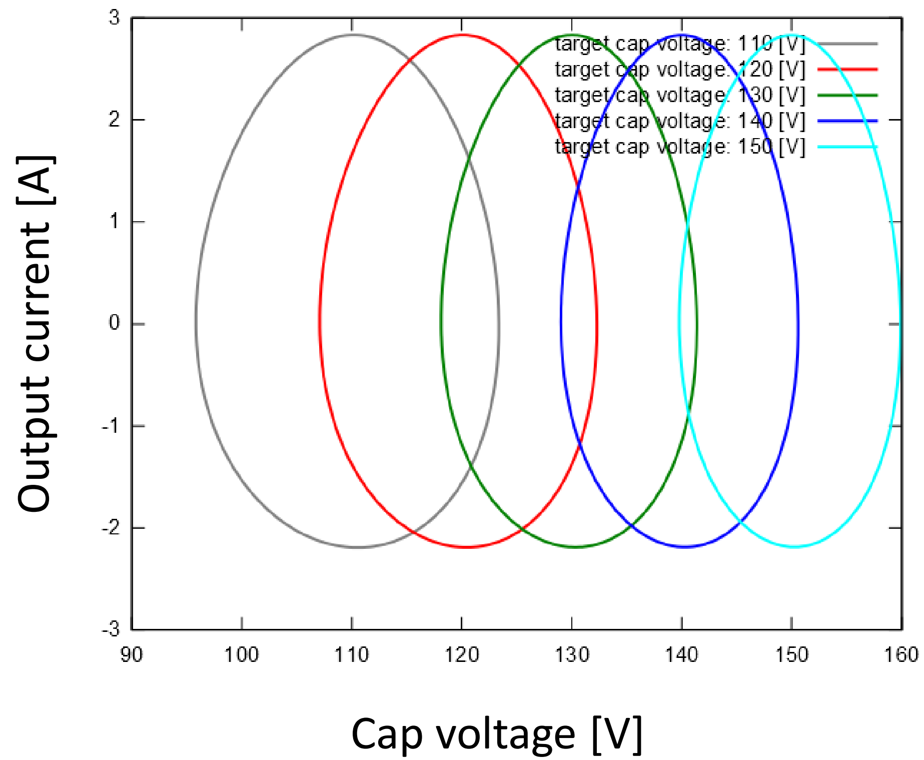
<dependence on $\tilde{v}_c^{(0)}$>

$$L = 2.0 \quad [\mathrm{mH}]$$

$$C = 0.5 \quad [\mathrm{mF}]$$

$$I^{(1)} = 2.5 \quad [\mathrm{A}]$$

$$\tilde{v}_c^{(0)} = 110/120/130/140/150 \quad [\mathrm{V}]$$



- Trajectories for 5 different cap voltages.
- Applicable to cap voltage recovery(restart/mode-switch) without any degradation of THD.

Simulation results of test circuit II (1)

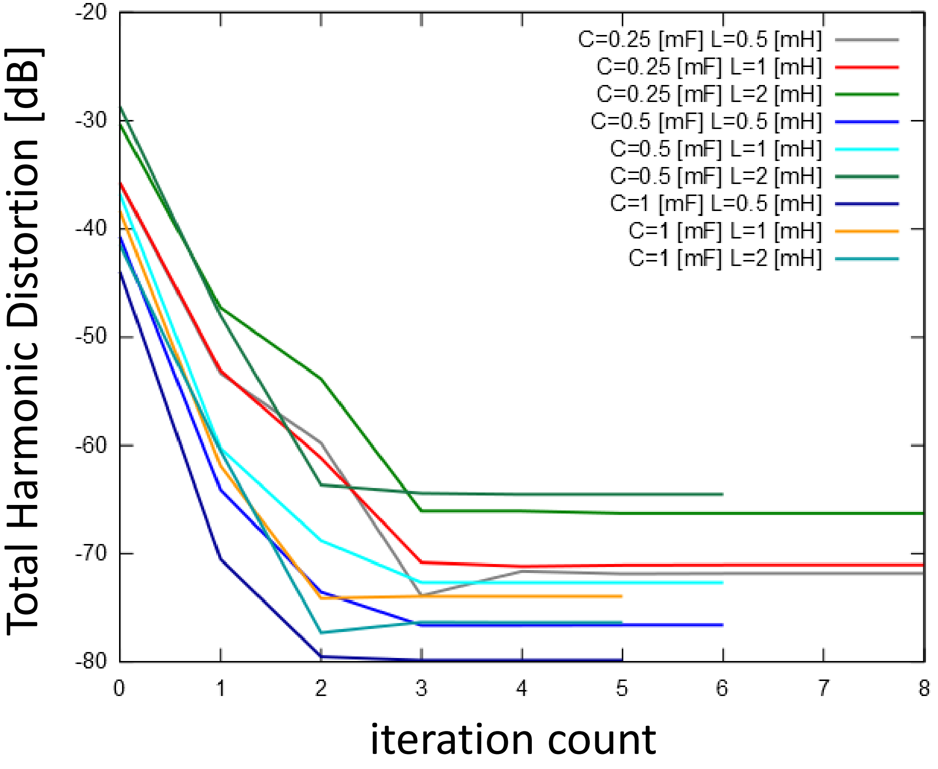
<THD vs iteration count>

$$L_a = 0.5/1.0/2.0 \quad [\mathrm{mH}]$$

$$C = 0.5/1.0/2.0 \quad [\mathrm{mF}]$$

$$\tilde{v}_{ch}^{(0)} = \tilde{v}_{cl}^{(0)} = 150 \quad [\mathrm{V}]$$

$$I^{(1)} = 4 \quad [\mathrm{A}]$$



- Required iteration count is less than 8 in typical design.
- Test circuit II exhibits better THD results compared to test circuit I with the same cap values.

Simulation results of test circuit II (2)

<Spice simulation (1) – test bench – >

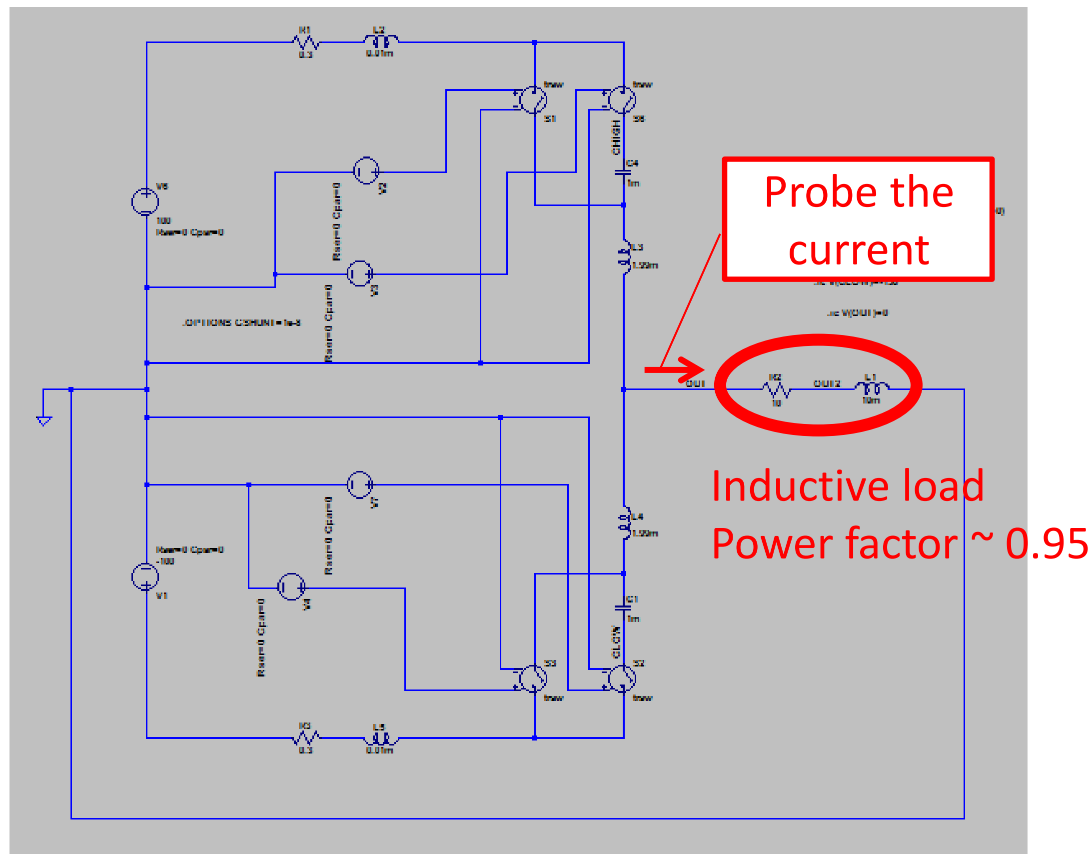
- Half bridge MMC inverter
- One cap for each arm
  for simplicity
- Switching freq: 12.8[kHz]
- PWM resolution: 100 [ns]
- Control signals @ 7'th iteration

$$L_a = 2.0 \quad [\mathrm{mH}]$$

$$C = 0.25 \quad [\mathrm{mF}]$$

$$\tilde{v}_{ch}^{(0)} = \tilde{v}_{cl}^{(0)} = 200 \quad [\mathrm{V}]$$

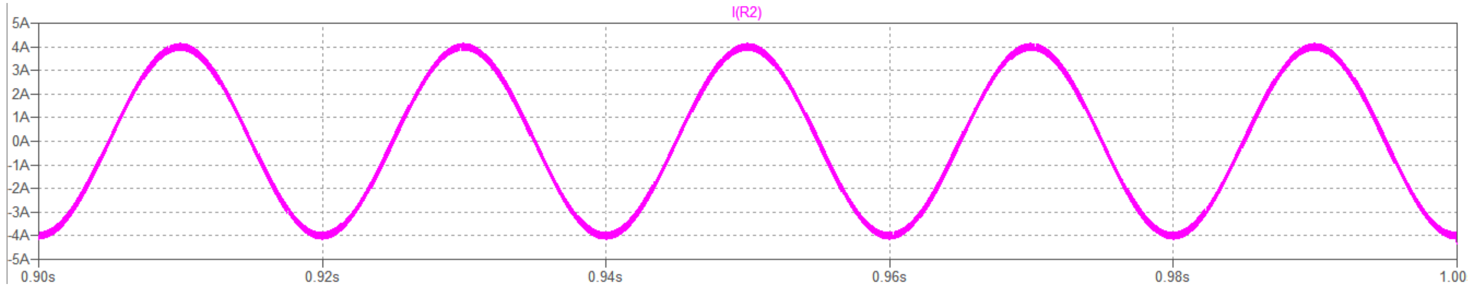
$$I^{(1)} = 4 \quad [\mathrm{A}]$$



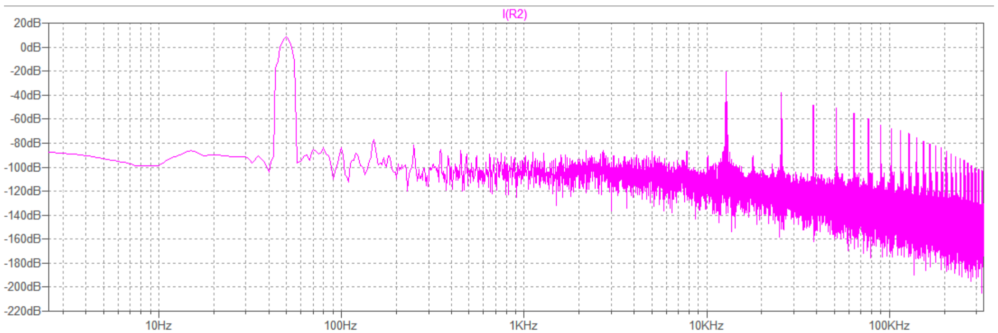
Simulation results of test circuit II (3)

<Spice simulation (2) – output current – >

[transient waveform of the output current]



[FFT result of the output current]

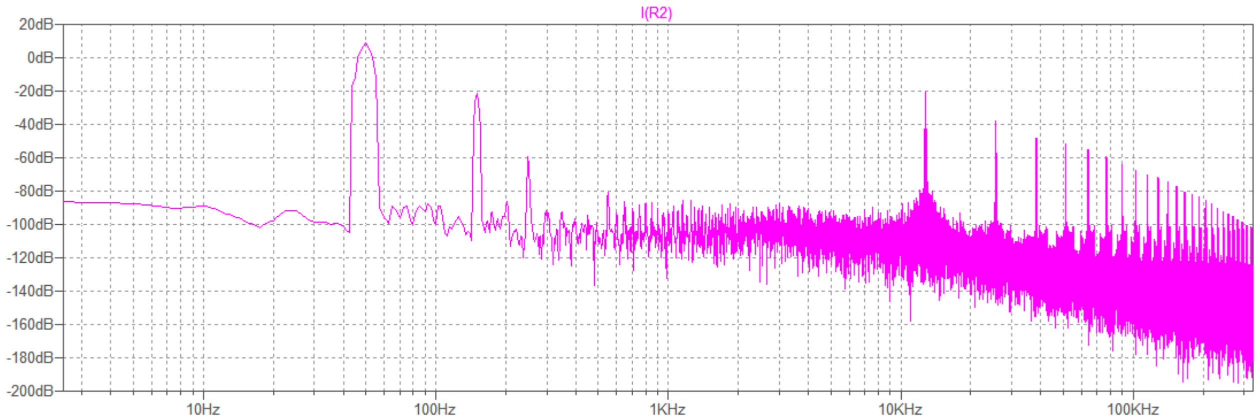


- No spurious @50*n [Hz]
- Carrier leakage @ 12.8*n [kHz]
- THD is less than -80 [dB]

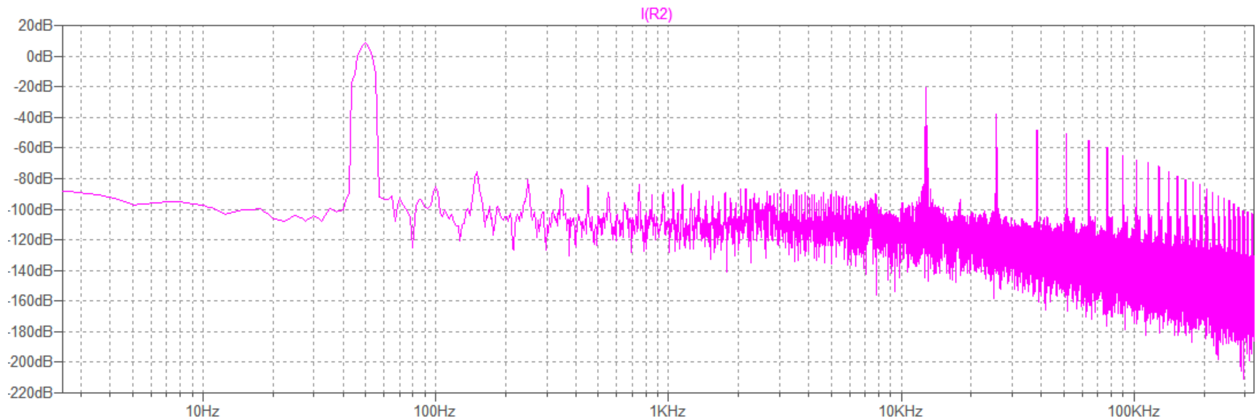
Simulation results of test circuit II (3)

<Spice simulation (3) – Before/After the correction– >

Iteration count:0
THD: -30.5 [dB]



Iteration count:3
THD: -79.0 [dB]



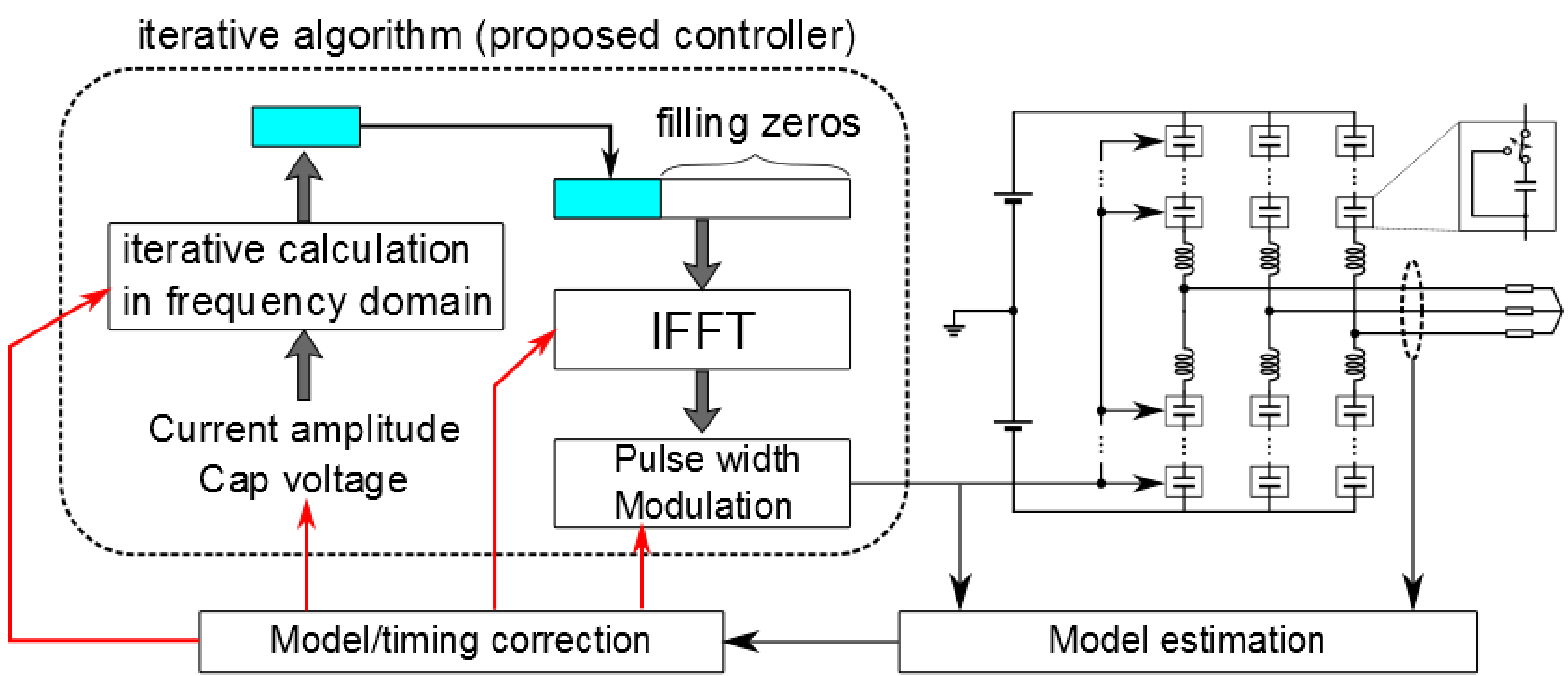
Summary

- THD has been drastically reduced by adjusting a few harmonics in control signals.
- An iterative method has been found to be an effective approach to get numerical solutions of our complicated equations as fast as possible.
- This approach is applicable to any optimization in periodic controls.

--- Future prospects ---

Future prospects (1)

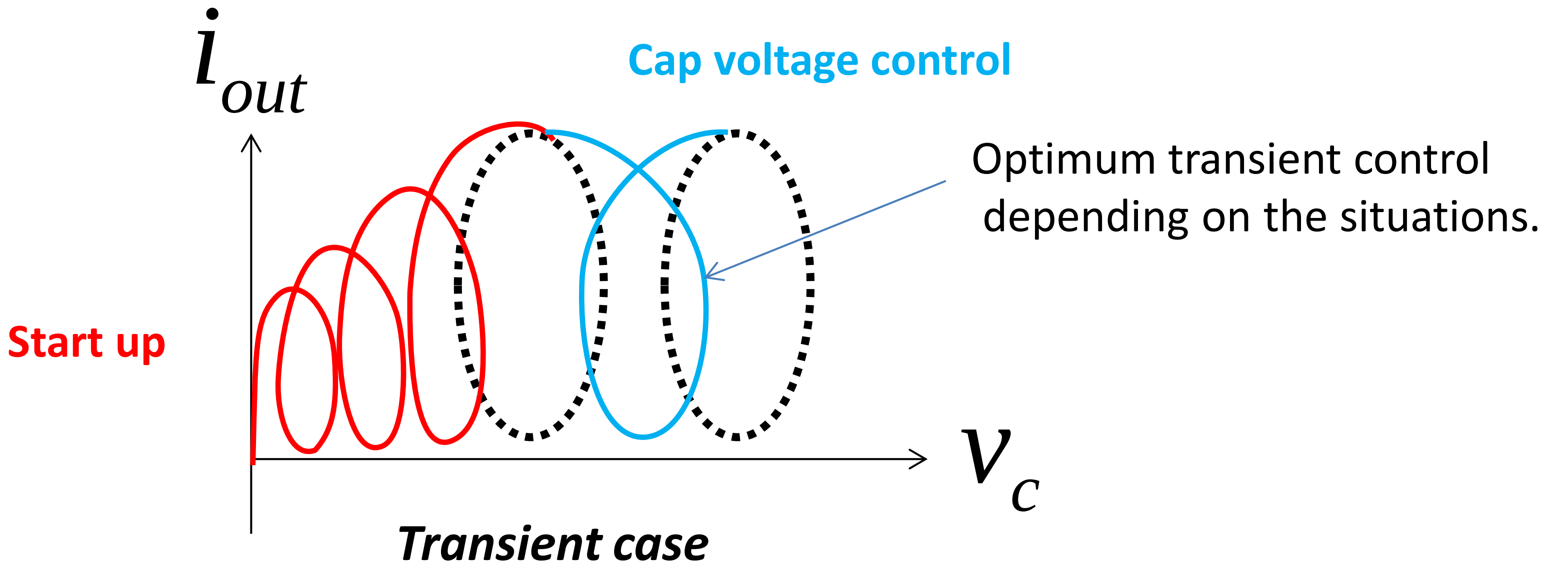
<Periodic control>



- Optimization of control signals including any non-ideal effects.
- For example, skew/device mismatch/dead time/clock feed through /non-linear load,,,etc

Future prospects (2)

<Transient control>



- Optimization of evaluation functions in transient controls.
- For example, quick start-up/mode-switch/silent recovery from accidents.

Future prospects (3)

- Optimization of other characteristics of MMCs in periodic/transient operations.

- Proposals of Digital controllers estimating and correcting any conceivable non-ideal factors in analog portions.

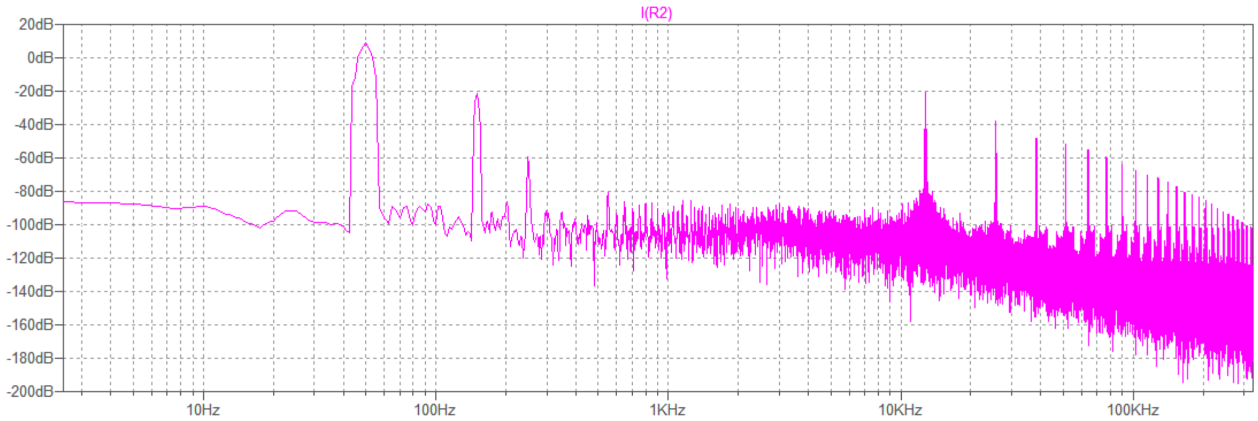
- Comprehensive studies on controls of various inverters/converters in periodic/transient operations.

--- Appendix ---

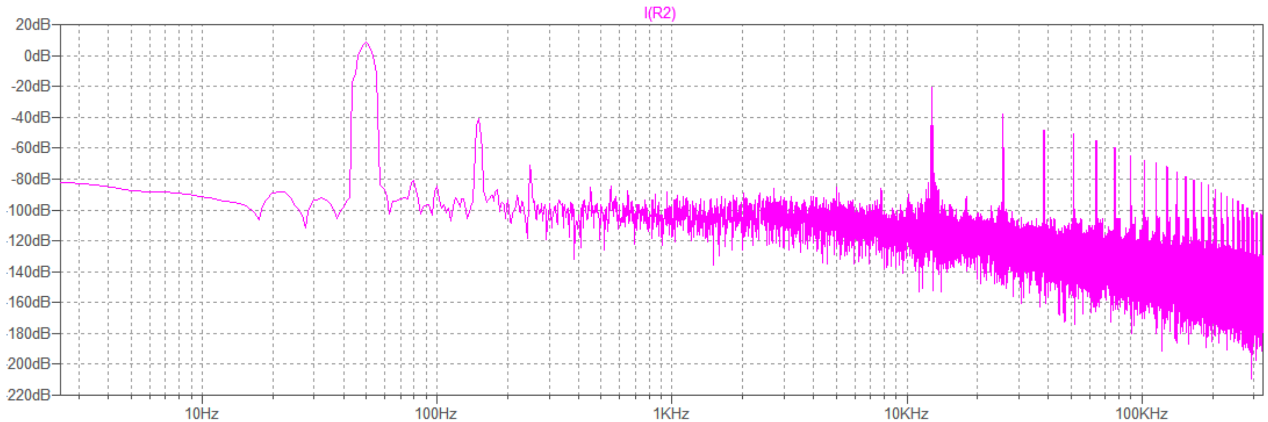
Simulation results of test circuit II

<Spice simulation of test circuit II – FFT results (1) – >

Iteration count:0
THD: -30.5 [dB]



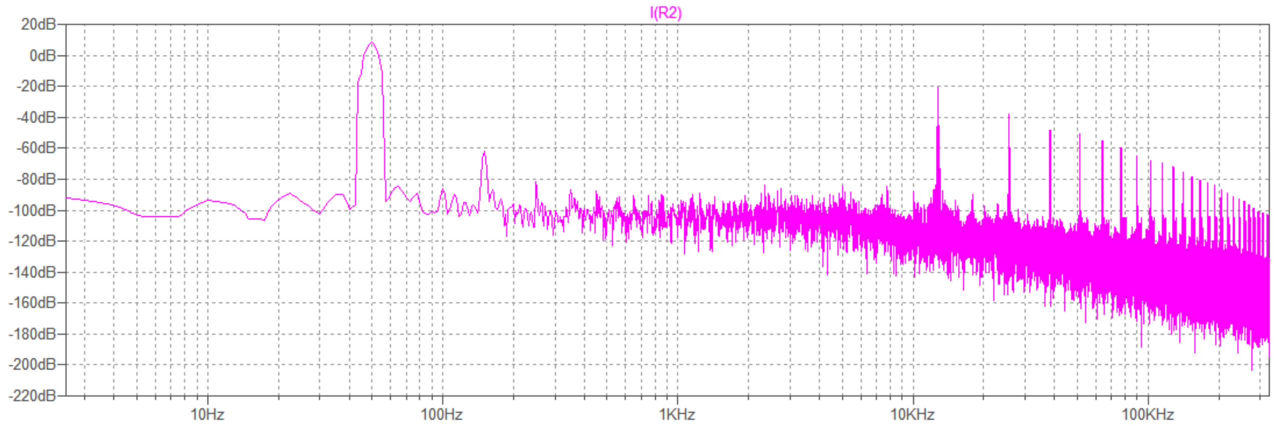
Iteration count:1
THD: -50.2 [dB]



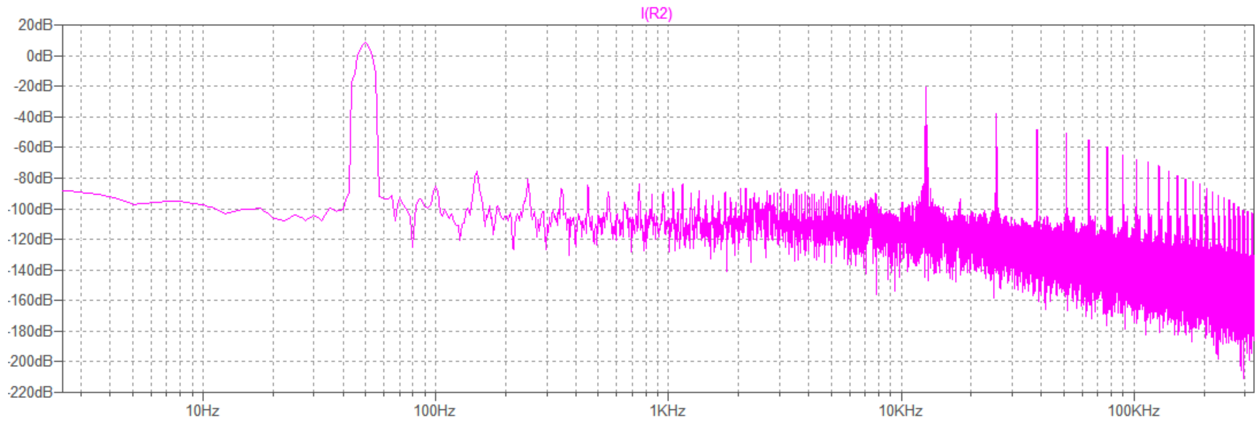
Simulation results of test circuit II

<Spice simulation of test circuit II – FFT results (2) – >

Iteration count:2
THD: -70.8 [dB]



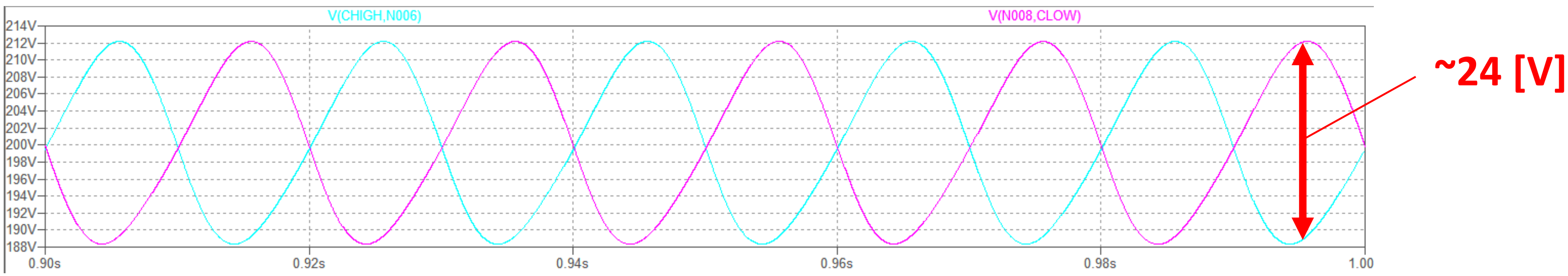
Iteration count:3
THD: -79.0 [dB]



Simulation results of test circuit II

<Spice simulation of test circuit II – Cap voltages – >

[Cap voltages]



[Current in upper arm]