

シンクロトロン「内在リップル」について

study of the 'Intrinsic ripples' in synchrotron

白壁義久^{#, A)}, アレクサンダー・モロドゼンツェフ^{B)}, 森義治^{C)}, 武藤正文^{C)}, 堺高見^{D)}, 山崎長治^{D)}, 吉野輝雄^{D)}

Yoshihisa Shirakabe ^{#, A)}, Alexander Molodozhentsev ^{B)},

Yoshiharu Mori ^{C)}, Masayuki Muto ^{C)}, Takami Sakai ^{D)}, Choji Yamazaki ^{D)}, Teruo Yoshino ^{D)}

^{A)} KEK High Energy Accelerator Research Organization, ^{B)} Institute of Physics, Academy of Sciences of Czech Republic

^{C)} Research Reactor Institute, Kyoto University, ^{D)} TMEIC Toshiba Mitsubishi-Electric Industrial Systems

1. はじめに
2. 電磁石負荷回路系と電流パターン
3. 単一負荷回路、複数負荷回路
4. 配線系キャパシタンス、並列ダンピング抵抗
5. まとめ

1. はじめに (駆足の紹介となりますので、詳しくは以下の論文をご参照下さい)

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 61, NO. 5, OCTOBER 2014

2579

Study of Transient Ripple in Synchrotron

Yoshihisa Shirakabe, Yoshiharu Mori, Masayuki Muto, Takami Sakai, Choji Yamazaki, and Teruo Yoshino

Abstract—Beam ripples are one of the most important issues both in designs and operations of proton synchrotrons, and their magnitude should be suppressed in the order of $1e-6$ to achieve stable beam acceleration. In this paper, ripples in magnet circuits

difference between them is that the former employs shielded cables and the latter bus-bars for their magnet interconnections. The difference of their magnet circuit geometries, especially

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IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 61, NO. 5, OCTOBER 2014

Study of Transient Ripple in Synchrotron – Practical Applications

Yoshihisa Shirakabe, Yoshiharu Mori, Masayuki Muto, Takami Sakai, Choji Yamazaki, and Teruo Yoshino

Abstract—Characteristics of ripples generated as transient responses with idealized current patterns in synchrotrons are studied along with practical applications. The ripples intrinsically occur in synchrotron magnets when the magnets are operated with a ramp pattern.

occur as a forced harmonic oscillation driven by the external force of the current ramp. Thus the intrinsic ripples reside in any synchrotrons as long as they are operated with the ramp pattern.

TUPRO093

Proceedings of IPAC2014, Dresden, Germany

NUMERICAL STUDY OF INTRINSIC RIPPLES IN J-PARC MAIN-RING MAGNETS

Y. Shirakabe[#], A. Molodozhentsev, M. Muto*, KEK, Tsukuba, Ibaraki, Japan

Abstract

Numerical simulation results on intrinsic ripples in the J-PARC Main-ring synchrotron magnets are presented. Intrinsic ripples unavoidably arise in synchrotrons when the magnets are operated by acceleration pattern currents.

group in Fig. 1, the parallel resistance is $79 \times 8 = 632\Omega$.

The assumed ramp pattern of the QFN magnet current is shown in Figure 2. The pattern is generally based on the initially designed acceleration cycle of J-PARC MR in the 30 GeV operations. The repetition rate is 3 seconds per cycle. 日本加速器学会第12回年会, 2015, (8)16(本) to 2

1. はじめに (1)

加速器では : 「**ビームの安定な加速**」 = 最重要課題

↓ これを妨げる要因
(いろいろあるが・・・)

シンクロトロン: **偏向・収束電磁石等の磁場リップル**
: 最も基本的要因

安定な加速のためには: **磁場リップル $\leq 1e-6$**

↓ その一方で、

磁場リップルの発生・伝播機構

: シンクロトロン発明 70 年の今日でも十分解明されていない
⇒ 多数の電磁石回路 = 高階微分方程式系 ⇒ 解けない

磁場リップルの発生・伝播機構



解明の第1歩として 「無リップルの理想的電源を仮定」

理想的パターン電流 ⇒ 電磁石負荷系に流す



磁場にリップルが発生する = 世界初の発見

「内在リップル」 'Intrinsic ripples'

Y. Shirakabe, et al., “Study of Transient Ripple in Synchrotron,”

IEEE Transactions on Nuclear Science, vol. 61, Issue 5, Part 2, Oct. 2014, pp. 2579-2587

<http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6895313>

Y. Shirakabe, et al., “Study of Transient Ripple in Synchrotron - Practical Applications,”

ibid., pp. 2588-2594

<http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6895320>

以下、駆足で紹介...

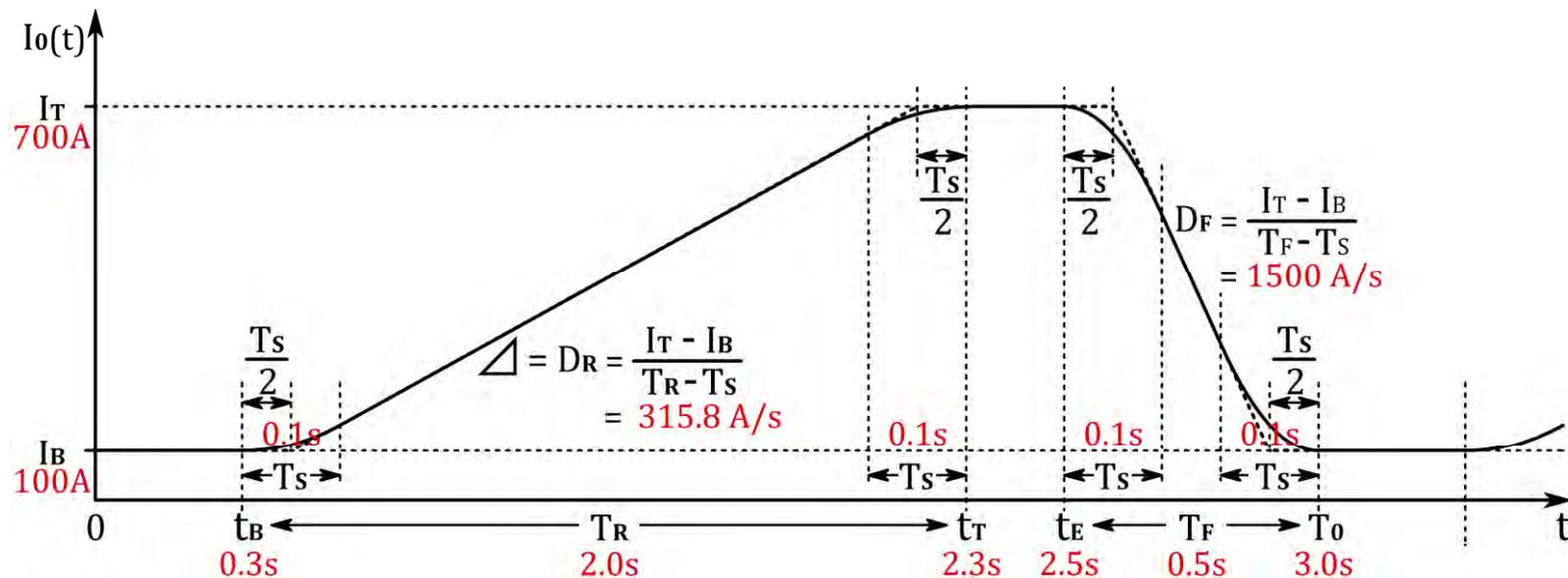
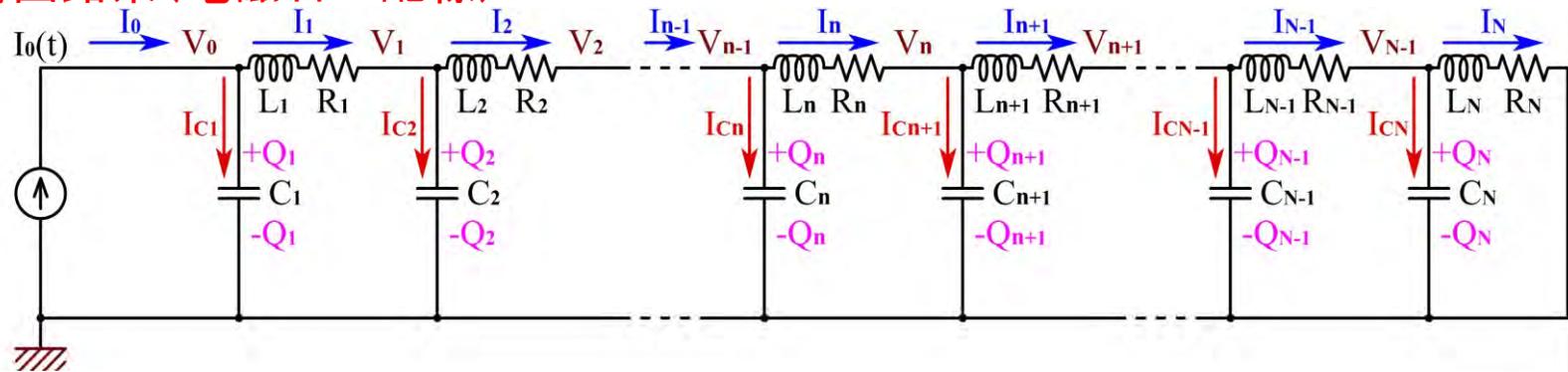
2. 電磁石負荷回路系と電流パターン (1)

シンクロトロン: 多数の電磁石 ⇒ グループ化 = ファミリー

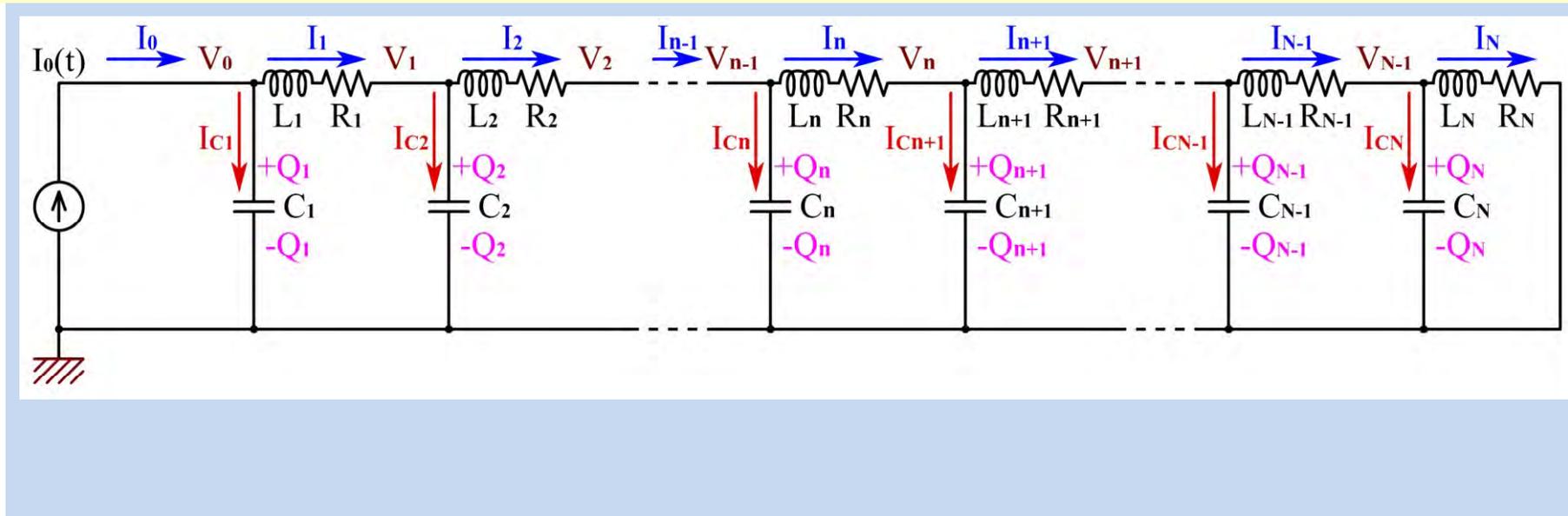
J-PARC MR の例:

	N	Length	L	R	C	Cable	Total
	units	[m]	[mH]	[mΩ]	[nF]	[nF]	[nF]
BM1	16	5.85	103.5	42.5	50.0	2920	3720
QFN	48	1.56	59.7	39.2	18.7	2710	3608
QDT	6	1.86	67.7	39.6	22.3	490	624

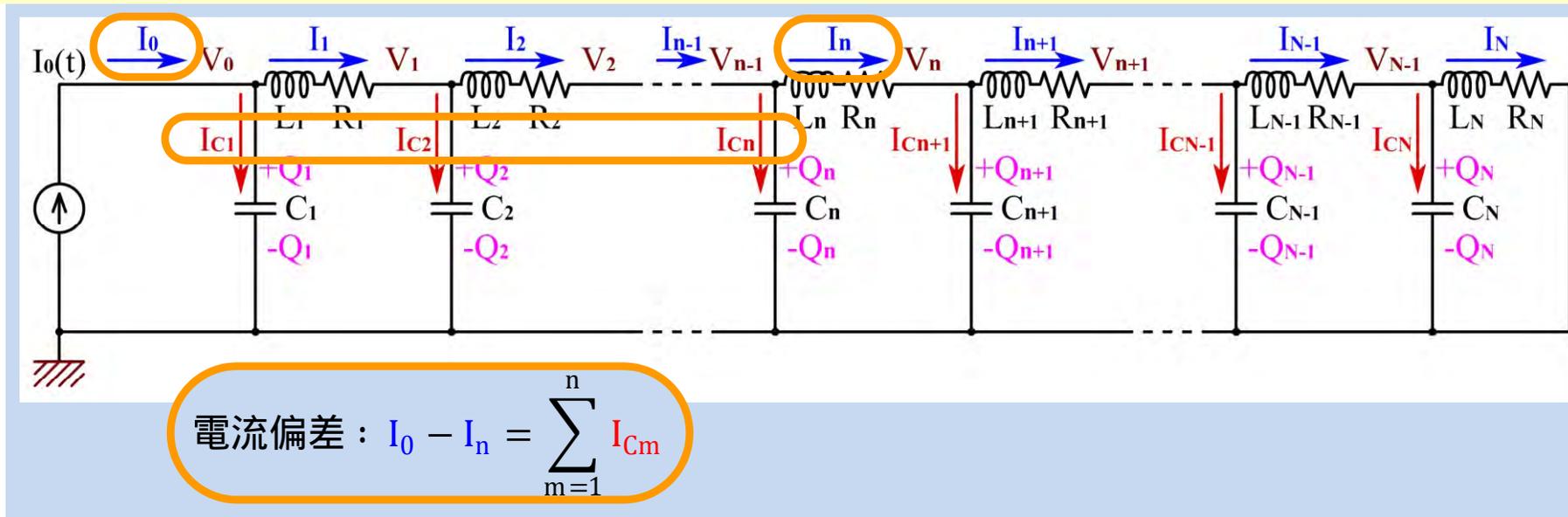
負荷回路系(電磁石+配線):



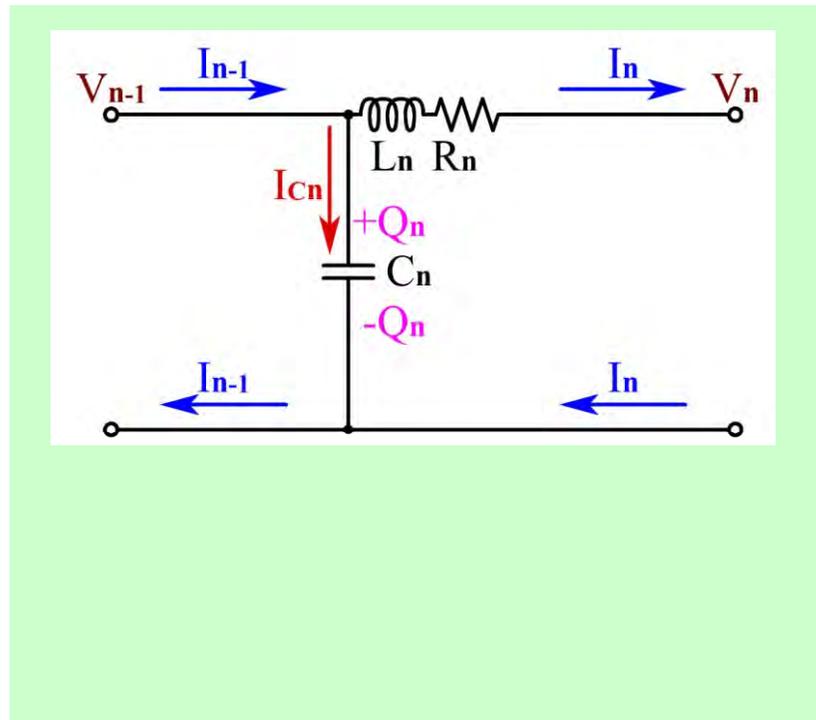
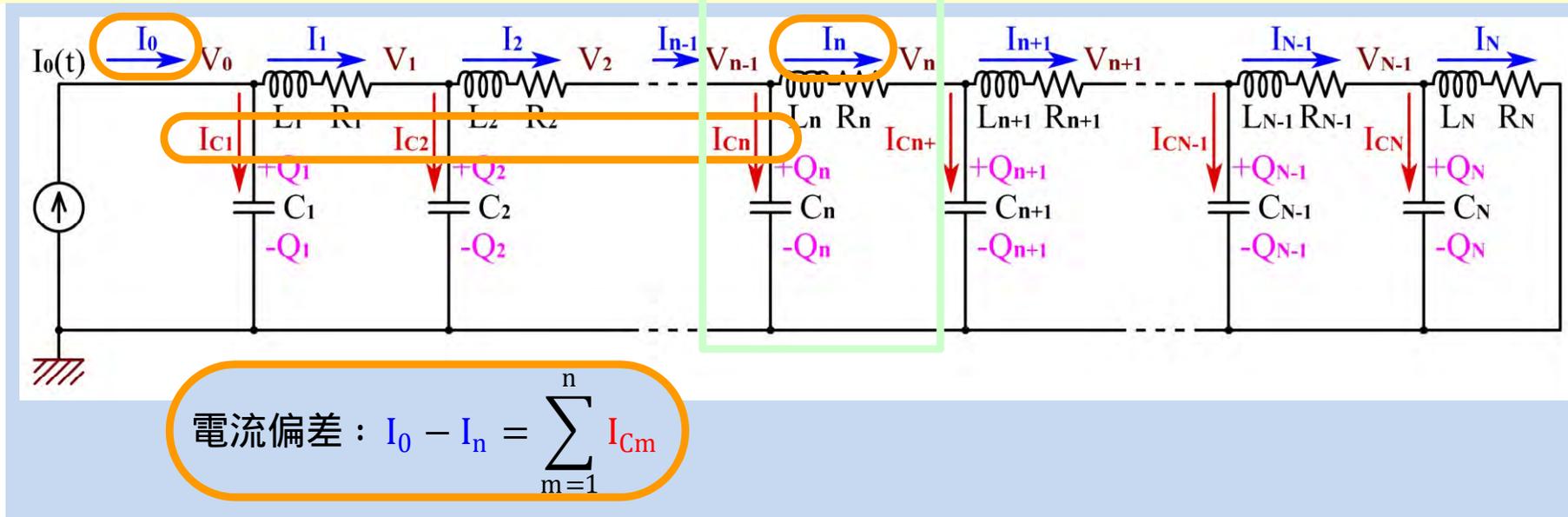
2. 電磁石負荷回路系と電流パターン (2)



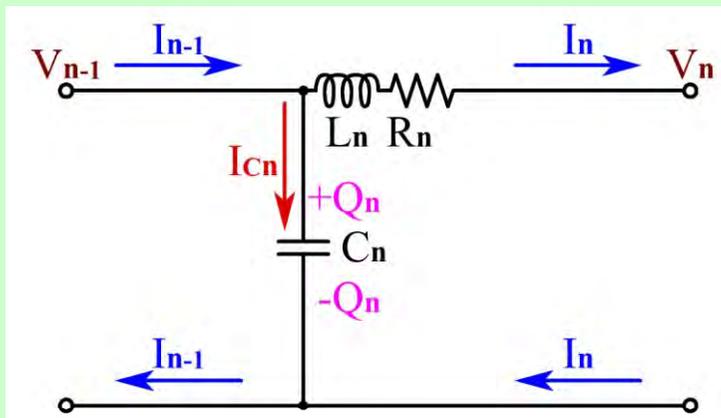
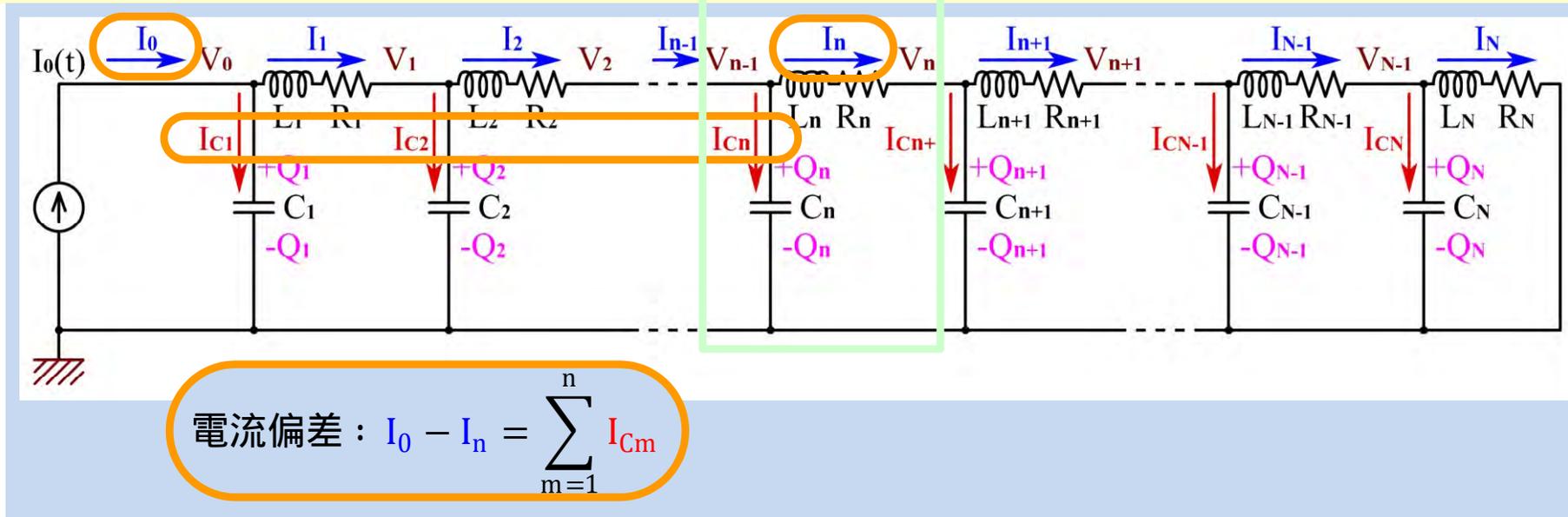
2. 電磁石負荷回路系と電流パターン (3)



2. 電磁石負荷回路系と電流パターン (4)



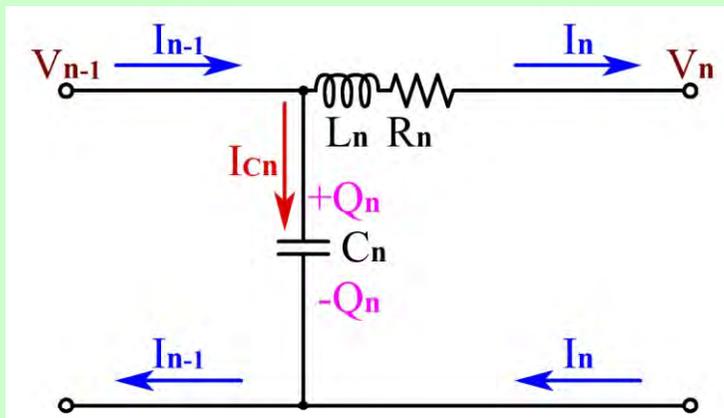
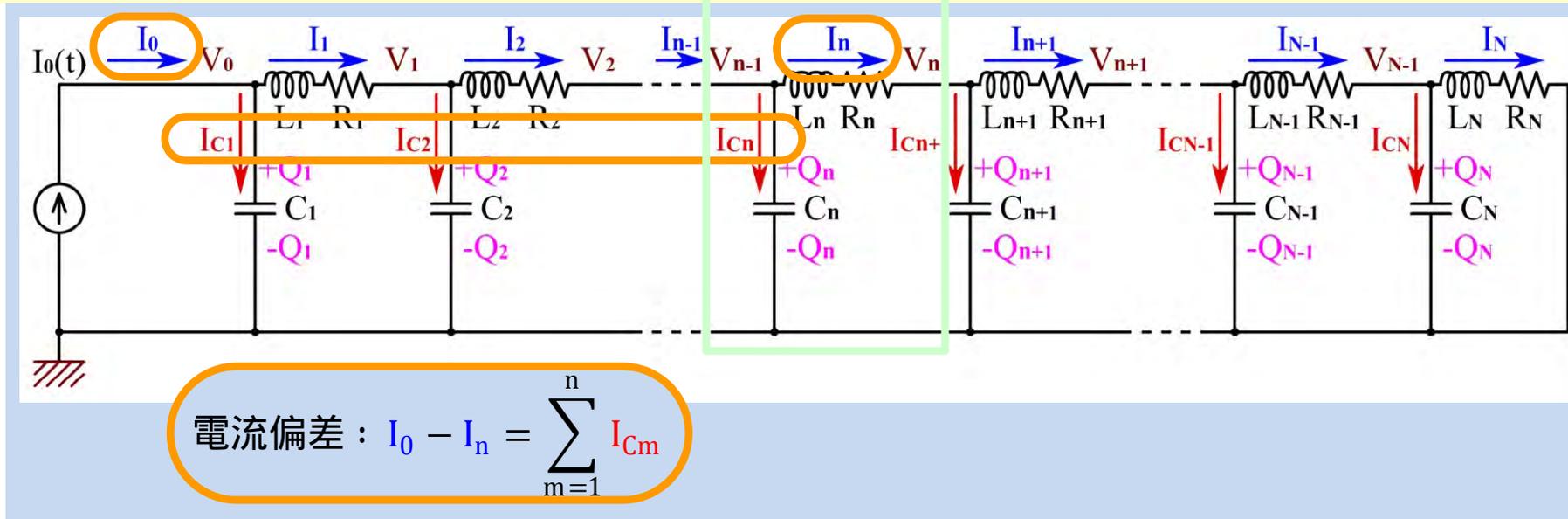
2. 電磁石負荷回路系と電流パターン (5)



$$\begin{cases} V_{n-1} - V_n = L_n \dot{I}_n + R_n I_n \\ I_{Cn} = \dot{Q}_n = C_n \dot{V}_{n-1} \end{cases}$$

$$\Rightarrow \frac{1}{L_n C_n} I_{Cn} - \frac{1}{L_n C_{n+1}} I_{Cn+1} = \ddot{I}_n + \frac{R_n}{L_n} \dot{I}_n$$

2. 電磁石負荷回路系と電流パターン (6)



$$\begin{cases} V_{n-1} - V_n = L_n \dot{I}_n + R_n I_n \\ I_{Cn} = \dot{Q}_n = C_n \dot{V}_{n-1} \end{cases}$$

$$\Rightarrow \frac{1}{L_n C_n} I_{Cn} - \frac{1}{L_n C_{n+1}} I_{Cn+1} = \ddot{I}_n + \frac{R_n}{L_n} \dot{I}_n$$

$n=1 \sim N$:

$$\sum_{m=1}^n \ddot{I}_{Cm} + 2\lambda_n \sum_{m=1}^n \dot{I}_{Cm} + \omega_n^2 I_{Cn} - \omega_n'^2 I_{Cn+1} = \ddot{I}_0 + 2\lambda_n \dot{I}_0$$

$$\omega_n = \frac{1}{\sqrt{L_n C_n}}, \quad \omega_n' = \frac{1}{\sqrt{L_n C_{n+1}}} \quad [\text{rad/s}]$$

: angular frequency of LC oscillation

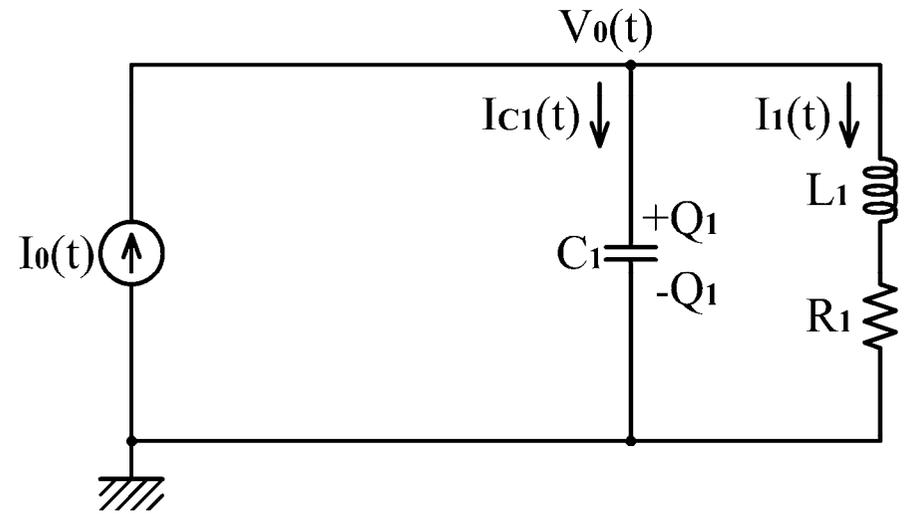
$$\lambda_n = \frac{R_n}{2L_n} \quad [1/\text{s}] \quad \text{: damping constant}$$

$$\omega_N' = 0, \quad I_{CN+1} = 0$$

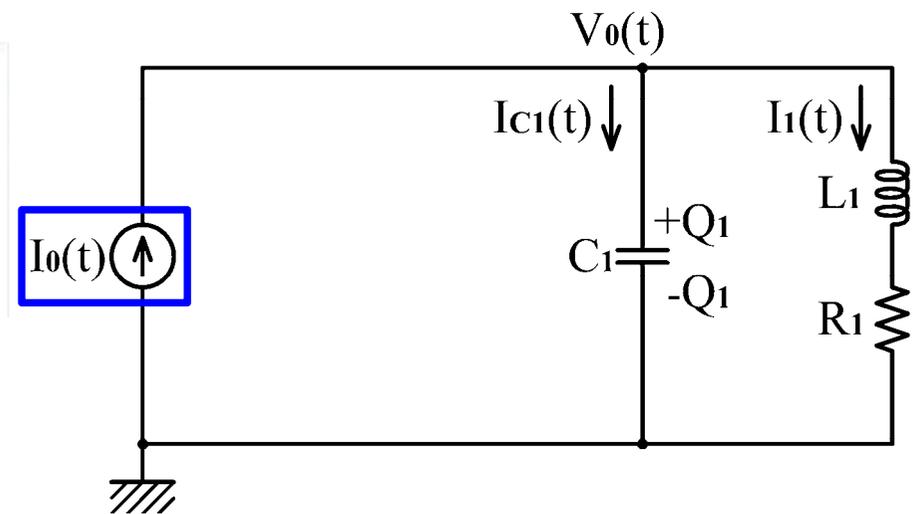
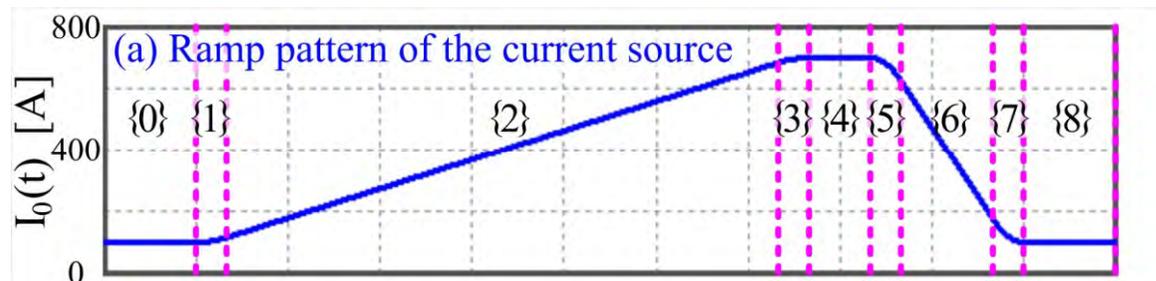
$N \geq 2$: 解析的には解けない (数値シミュレーションのみ)

$N = 1$: $\ddot{I}_{C1} + 2\lambda_1 \dot{I}_{C1} + \omega_1^2 I_{C1} = \ddot{I}_0 + 2\lambda_1 \dot{I}_0$ 単一負荷回路

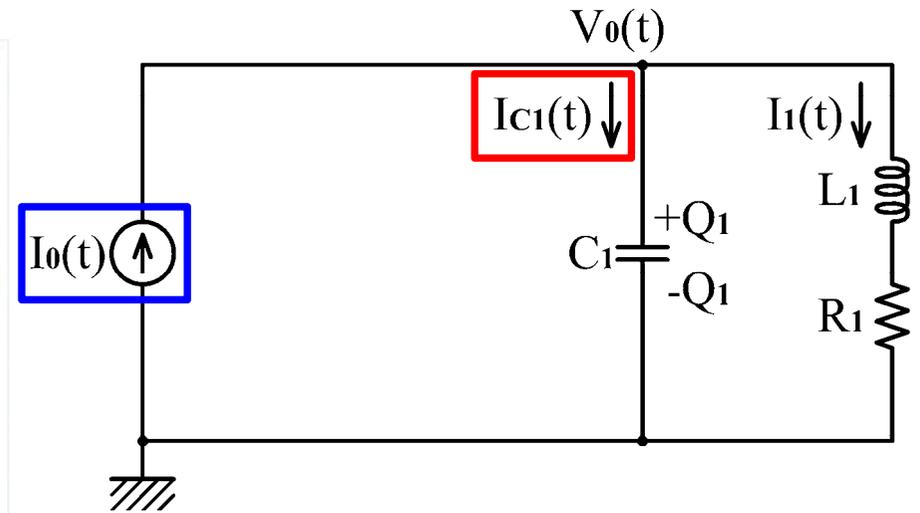
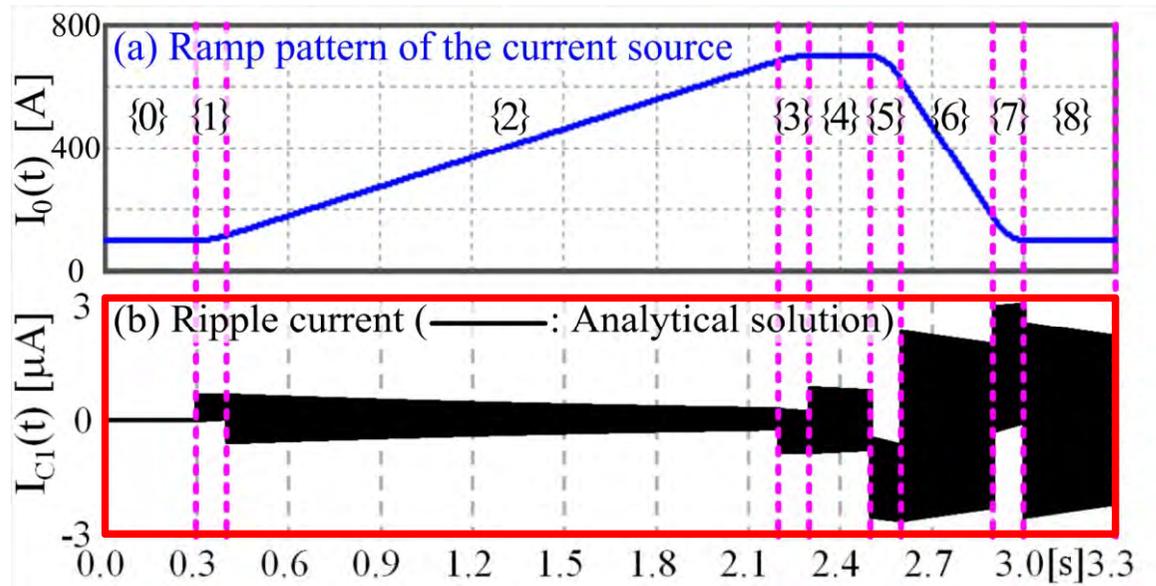
3. 单一负荷回路、複数负荷回路 / 3.1 单一负荷回路 (1)



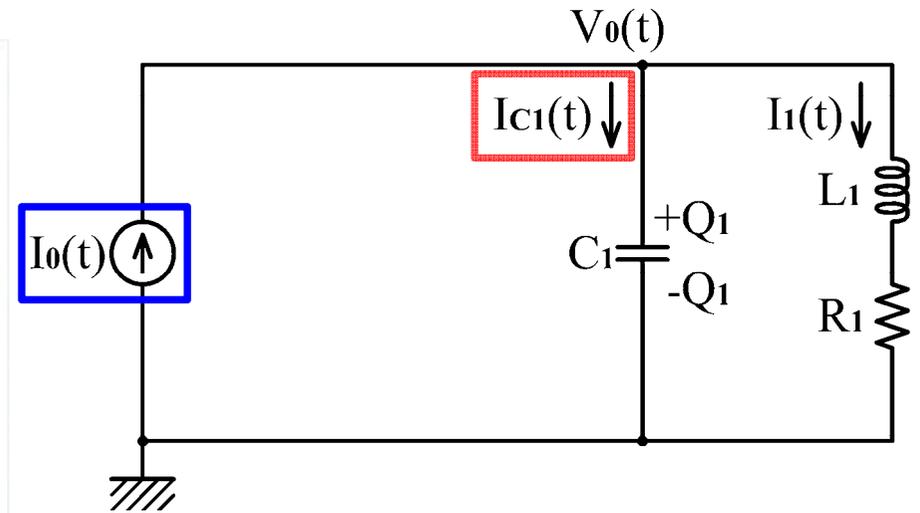
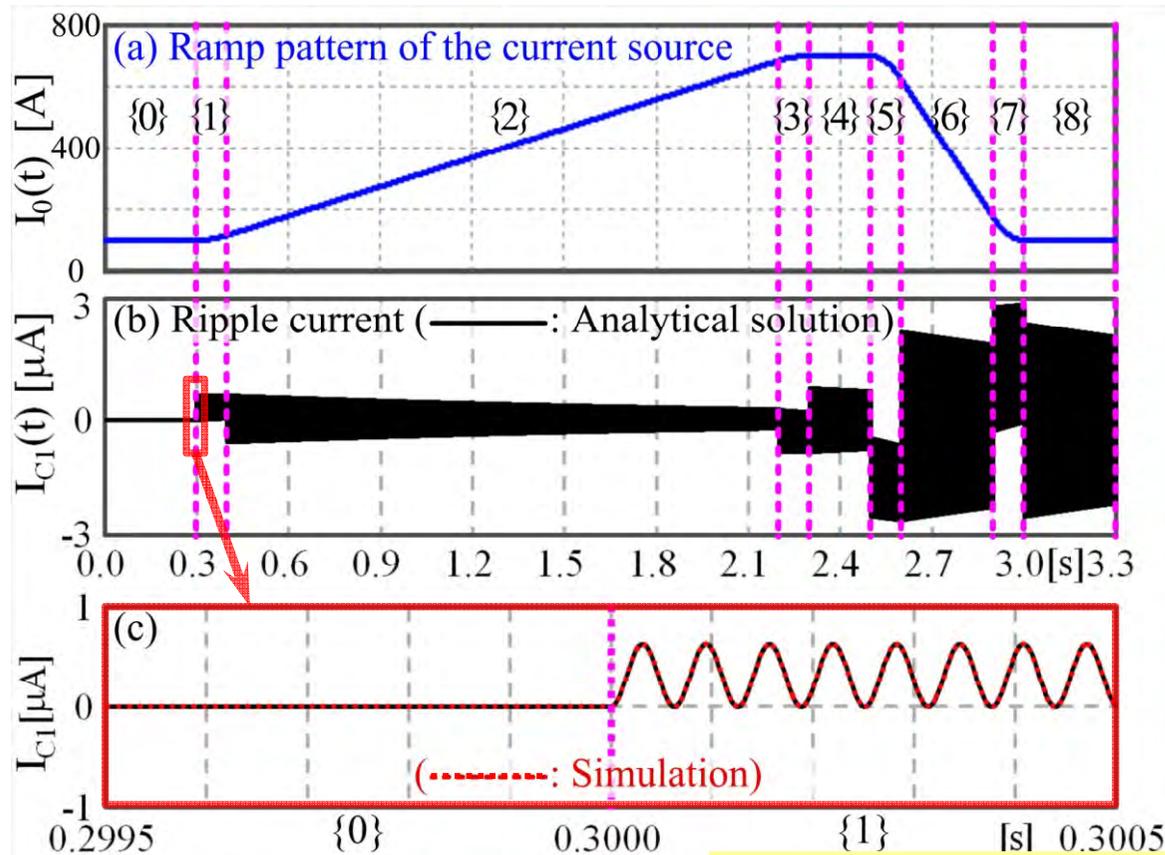
3. 单一负荷回路、複数负荷回路 / 3.1 单一负荷回路 (2)



3. 單一負荷回路、複數負荷回路 / 3.1 單一負荷回路 (3)



3. 單一負荷回路、複數負荷回路 / 3.1 單一負荷回路 (4)



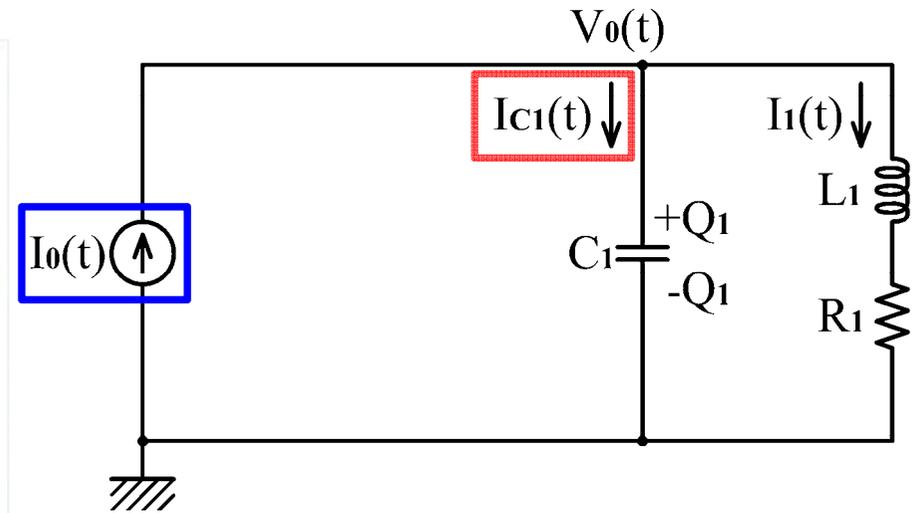
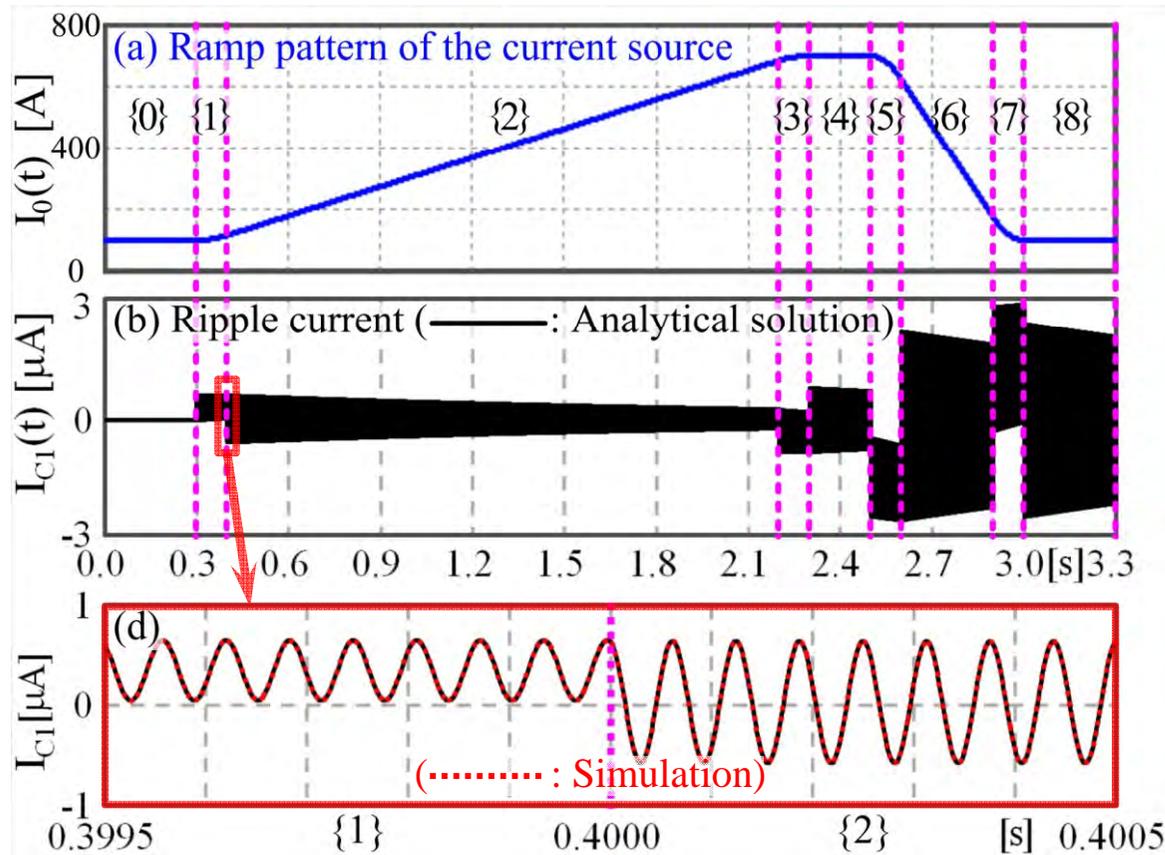
{1} $t_B \leq t < t_B + T_S$:

$$I_0(t) = I_B + \frac{D_R}{T_S} \frac{(t - t_B)^2}{2}$$

$$I_{C1}(t) = \frac{D_R}{\omega_1^2 T_S} \left\{ (1 - 4\zeta^2) + 2\lambda_1(t - t_B) - \frac{1}{\sqrt{1 - \zeta^2}} \cdot \cos(\sqrt{1 - \zeta^2} \cdot \omega_1(t - t_B) - \varphi_1) e^{-\lambda_1(t - t_B)} \right\}$$

$$\varphi_1 = \text{Tan}^{-1} \left(\frac{3 - 4\zeta^2}{1 - 4\zeta^2} \frac{\zeta}{\sqrt{1 - \zeta^2}} \right)$$

3. 単一負荷回路、複数負荷回路 / 3.1 単一負荷回路 (5)



{2} $t_B + T_S \leq t < t_T - T_S$:

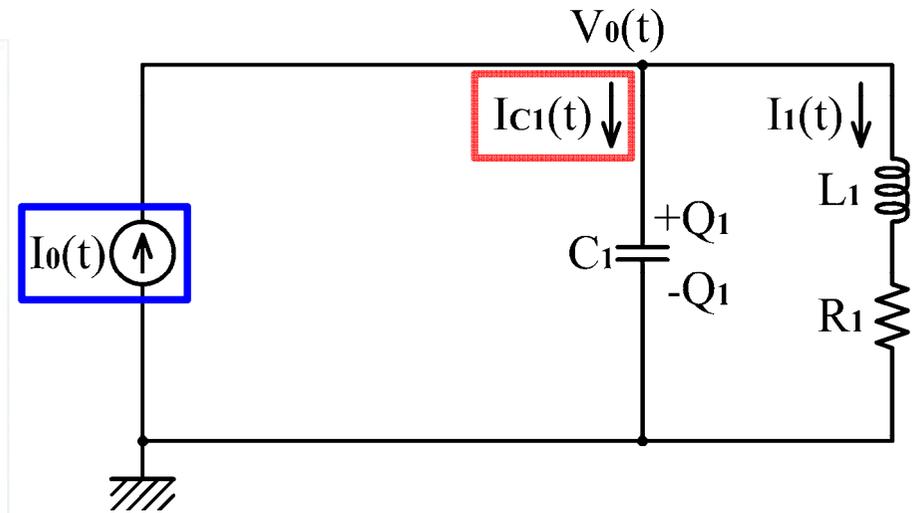
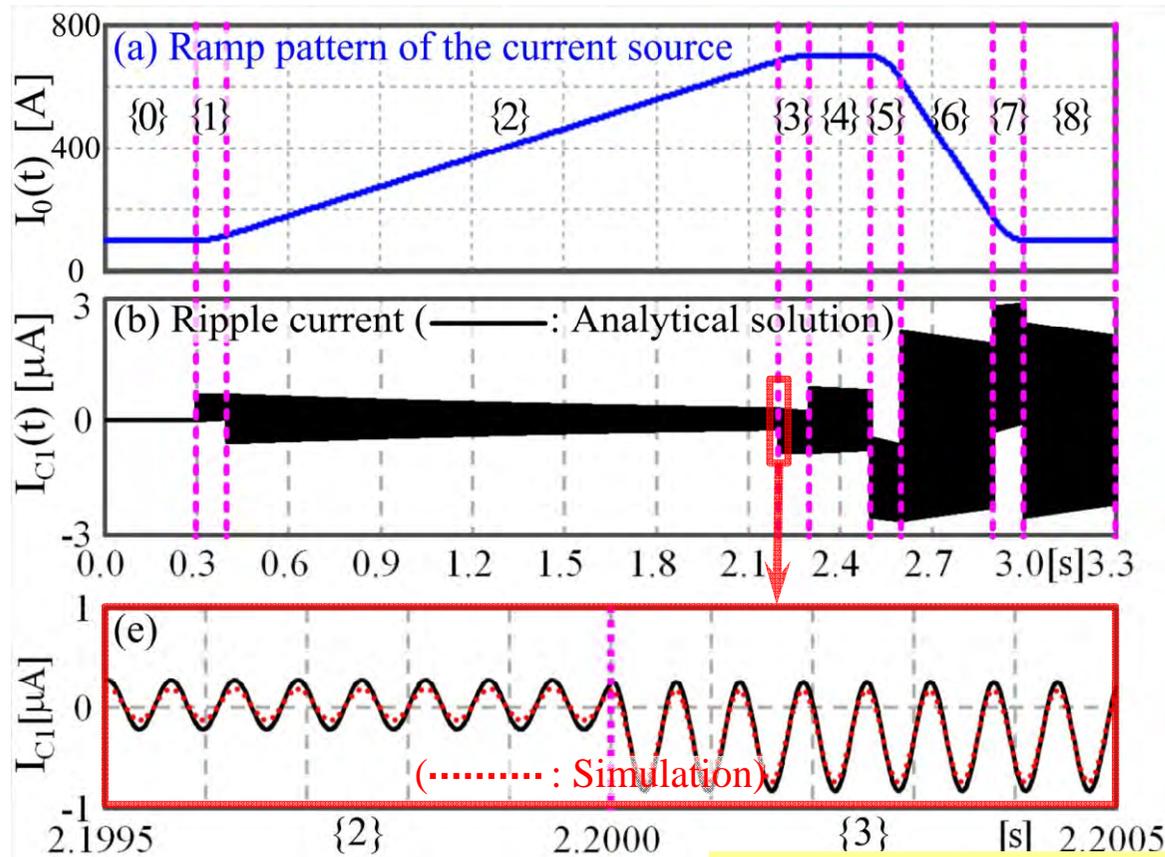
$$I_0(t) = I_B + D_R \left\{ t - \left(t_B + \frac{T_S}{2} \right) \right\}$$

$$I_{C1}(t) = \frac{D_R}{\omega_1^2 T_S} \left\{ 2\lambda_1 T_S + \frac{S_2}{\sqrt{1-\zeta^2}} \cdot \cos \left(\sqrt{1-\zeta^2} \omega_1 (t - (t_B + T_S)) - \varphi_2 \right) e^{-\lambda_1 (t - (t_B + T_S))} \right\}$$

$$S_2 = \sqrt{1 - 2 \cos \left(\sqrt{1-\zeta^2} \omega_1 T_S \right) e^{-\lambda_1 T_S} + e^{-2\lambda_1 T_S}}$$

$$\varphi_2 = \text{Tan}^{-1} \left(\frac{\sin \varphi_1 + \sin \left(\sqrt{1-\zeta^2} \omega_1 T_S - \varphi_1 \right) e^{-\lambda_1 T_S}}{\cos \varphi_1 - \cos \left(\sqrt{1-\zeta^2} \omega_1 T_S - \varphi_1 \right) e^{-\lambda_1 T_S}} \right)$$

3. 單一負荷回路、複數負荷回路 / 3.1 單一負荷回路 (6)



{3} $t_T - T_S \leq t < t_T$:

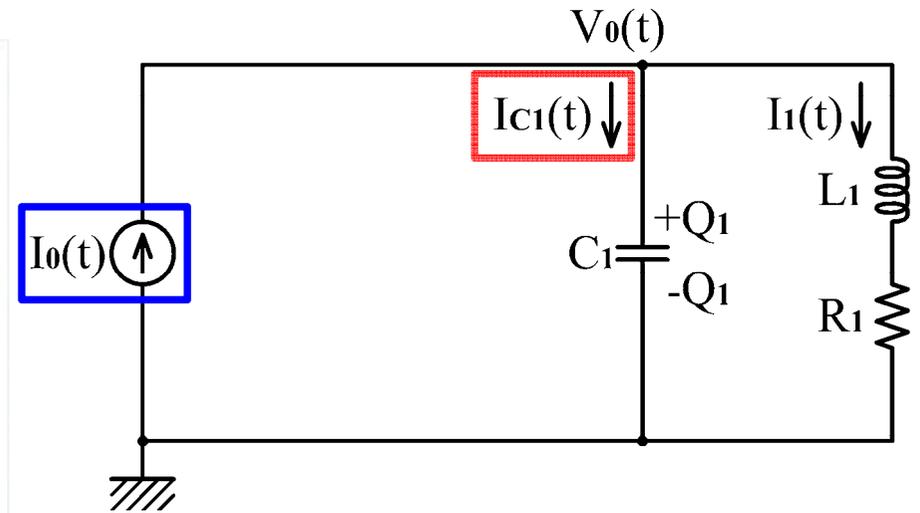
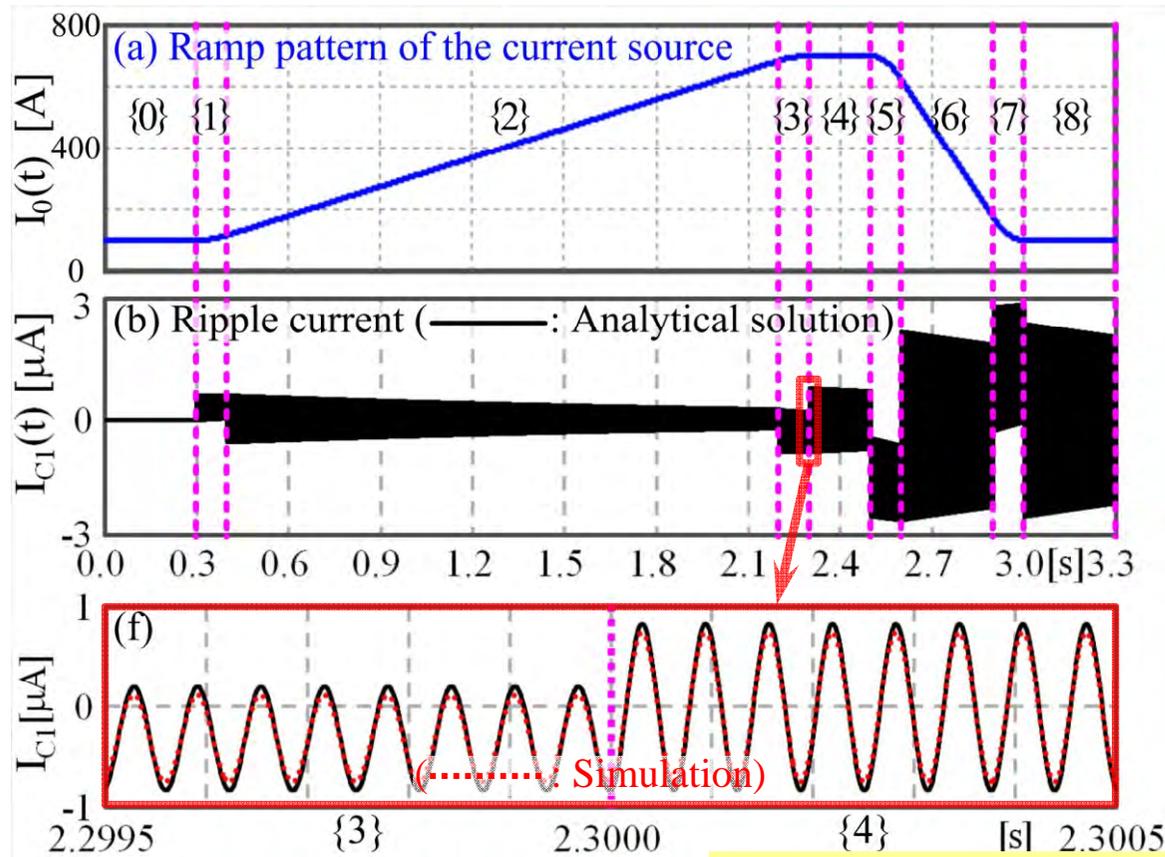
$$I_0(t) = I_T - \frac{D_R}{T_S} \frac{(t_T - t)^2}{2}$$

$$I_{C1}(t) = \frac{D_R}{\omega_1^2 T_S} \left\{ -(1 - 4\zeta^2) + 2\lambda_1(t_T - t) + \frac{S_3}{\sqrt{1 - \zeta^2}} \cdot \cos(\sqrt{1 - \zeta^2} \omega_1(t - (t_T - T_S)) - \varphi_3) e^{-\lambda_1(t - (t_T - T_S))} \right\}$$

$$S_3 = \sqrt{1 + 2 S_2 \cos(\sqrt{1 - \zeta^2} \omega_1(T_R - 2T_S) - \varphi_2 + \varphi_1) \cdot e^{-\lambda_1(T_R - 2T_S)} + S_2^2 e^{-2\lambda_1(T_R - 2T_S)}}$$

$$\varphi_3 = \text{Tan}^{-1} \left(\frac{\sin \varphi_1 - S_2 \cdot \sin(\sqrt{1 - \zeta^2} \cdot \omega_1(T_R - 2T_S) - \varphi_2) \cdot e^{-\lambda_1(T_R - 2T_S)}}{\cos \varphi_1 + S_2 \cdot \cos(\sqrt{1 - \zeta^2} \cdot \omega_1(T_R - 2T_S) - \varphi_2) \cdot e^{-\lambda_1(T_R - 2T_S)}} \right)$$

3. 單一負荷回路、複數負荷回路 / 3.1 單一負荷回路 (7)



{4} $t_T \leq t < t_E$:

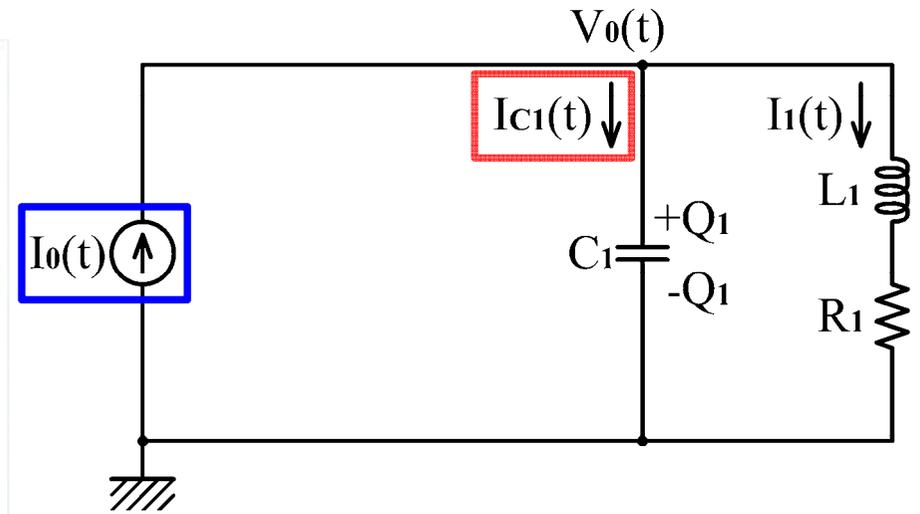
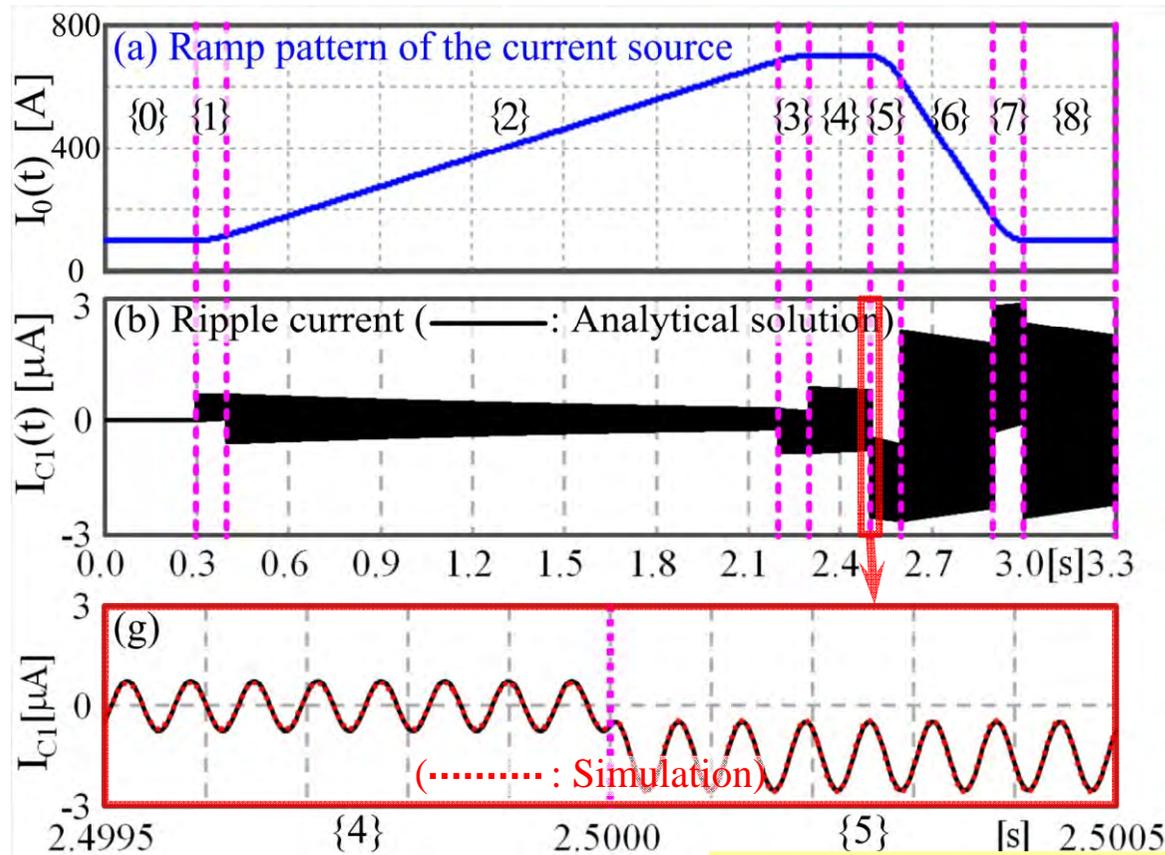
$$I_0(t) = I_T$$

$$I_{C1}(t) = \frac{D_R}{\omega_1^2 T_s} \frac{S_4}{\sqrt{1-\zeta^2}} \cdot \cos(\sqrt{1-\zeta^2} \cdot \omega_1(t-t_T) - \varphi_4) e^{-\lambda_1(t-t_T)}$$

$$S_4 = \sqrt{1 - 2S_3 \cos(\sqrt{1-\zeta^2} \omega_1 T_s - \varphi_3 + \varphi_1) e^{-\lambda_1 T_s} + S_3^2 e^{-2\lambda_1 T_s}}$$

$$\varphi_4 = \text{Tan}^{-1} \left(\frac{\sin \varphi_1 + S_3 \sin(\sqrt{1-\zeta^2} \omega_1 T_s - \varphi_3) e^{-\lambda_1 T_s}}{\cos \varphi_1 - S_3 \cos(\sqrt{1-\zeta^2} \omega_1 T_s - \varphi_3) e^{-\lambda_1 T_s}} \right)$$

3. 單一負荷回路、複數負荷回路 / 3.1 單一負荷回路 (8)



{5} $t_E \leq t < t_E + T_S$:

$$I_0(t) = I_0(t) = I_T - \frac{D_F}{T_S} \frac{(t - t_E)^2}{2}$$

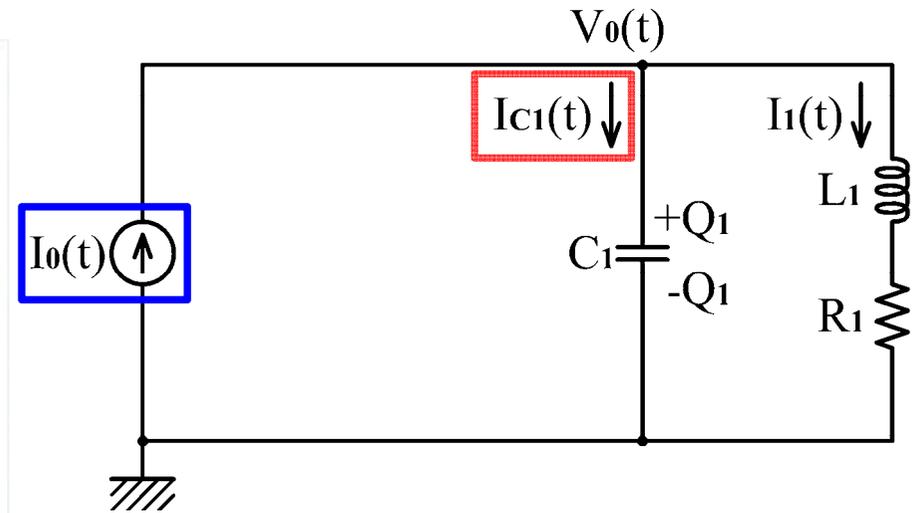
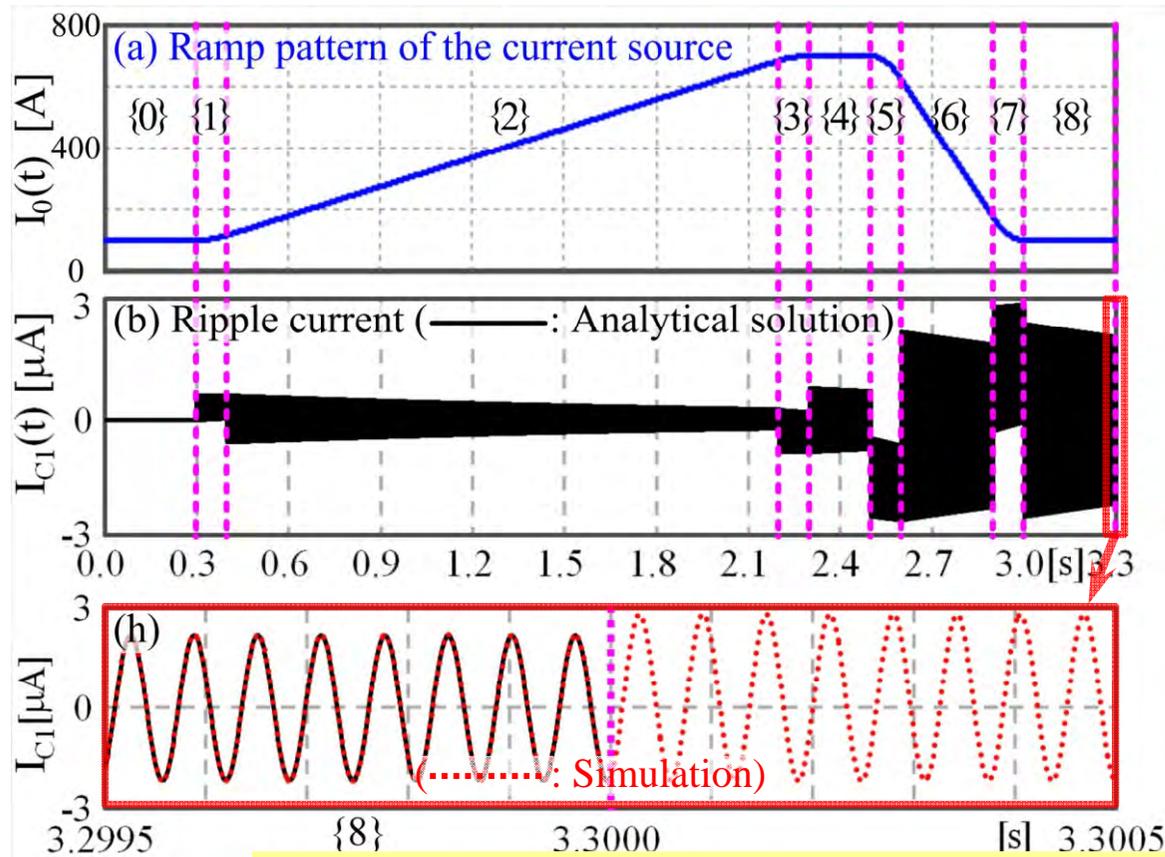
$$I_{C1}(t) = \frac{D_F}{\omega_1^2 T_S} \left\{ -(1 - 4\zeta^2) - 2\lambda_1(t - t_E) + \frac{S_5}{\sqrt{1 - \zeta^2}} \cdot \cos(\sqrt{1 - \zeta^2} \omega_1(t - t_E) - \varphi_5) e^{-\lambda_1(t - t_E)} \right\}$$

$$\rho_D = \frac{D_R}{D_F}$$

$$S_5 = \sqrt{1 + 2\rho_D S_4 \cos(\sqrt{1 - \zeta^2} \omega_1(t_E - t_T) - \varphi_4 + \varphi_1) \cdot e^{-\lambda_1(t_E - t_T)} + \rho_D^2 S_4^2 e^{-2\lambda_1(t_E - t_T)}}$$

$$\varphi_5 = \text{Tan}^{-1} \left(\frac{\sin \varphi_1 - \rho_D S_4 \sin(\sqrt{1 - \zeta^2} \omega_1(t_E - t_T) - \varphi_4) \cdot e^{-\lambda_1(t_E - t_T)}}{\cos \varphi_1 + \rho_D S_4 \cos(\sqrt{1 - \zeta^2} \omega_1(t_E - t_T) - \varphi_4) \cdot e^{-\lambda_1(t_E - t_T)}} \right)$$

3. 單一負荷回路、複數負荷回路 / 3.1 單一負荷回路 (9)



{8} $T_0 \leq t$:

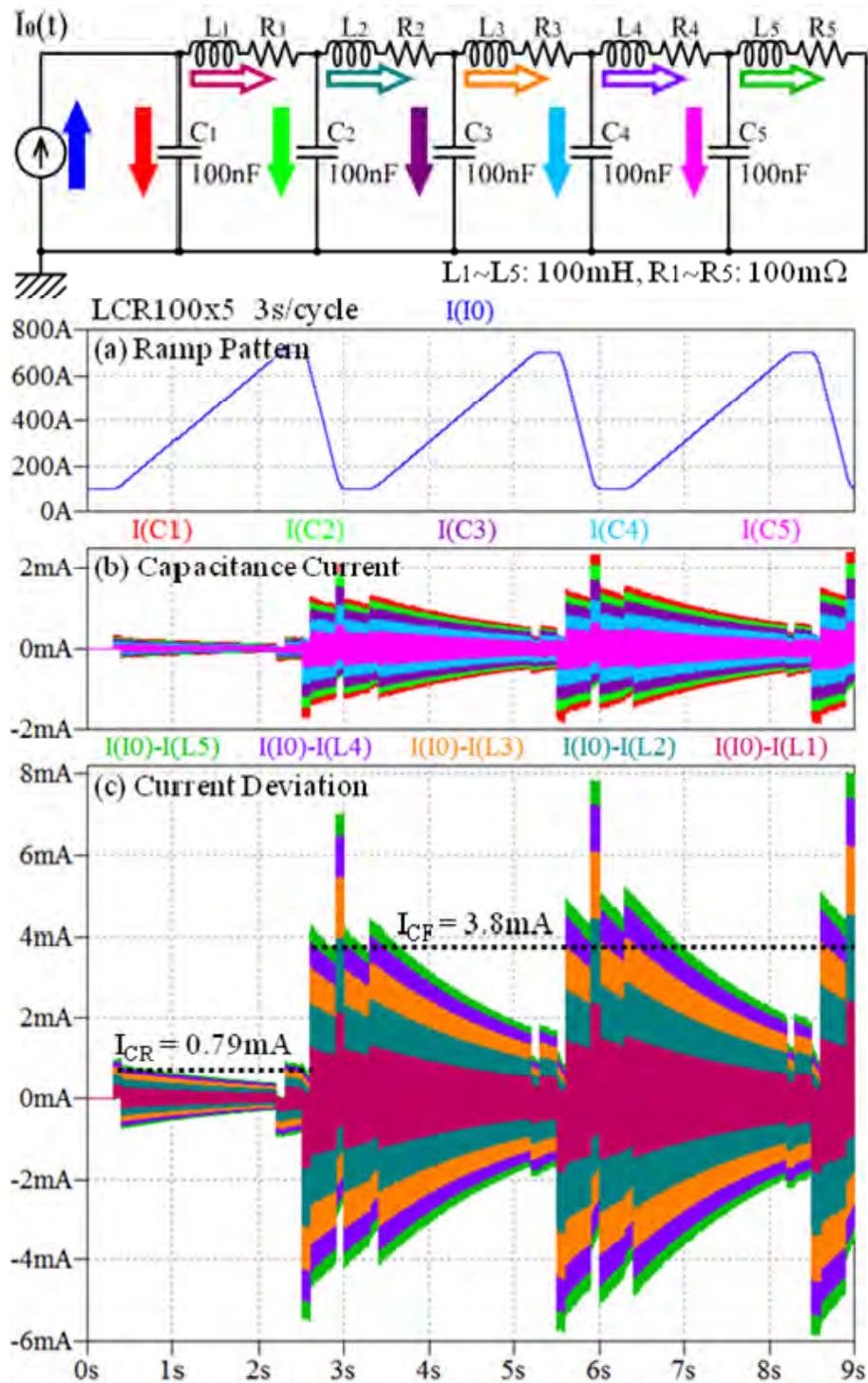
$$I_0(t) = I_B$$

$$I_{C1}(t) = \frac{D_F}{\omega_1^2 T_S} \frac{S_8}{\sqrt{1 - \zeta^2}} \cdot \cos(\sqrt{1 - \zeta^2} \omega_1(t - T_0) - \varphi_8) e^{-\lambda_1(t - T_0)}$$

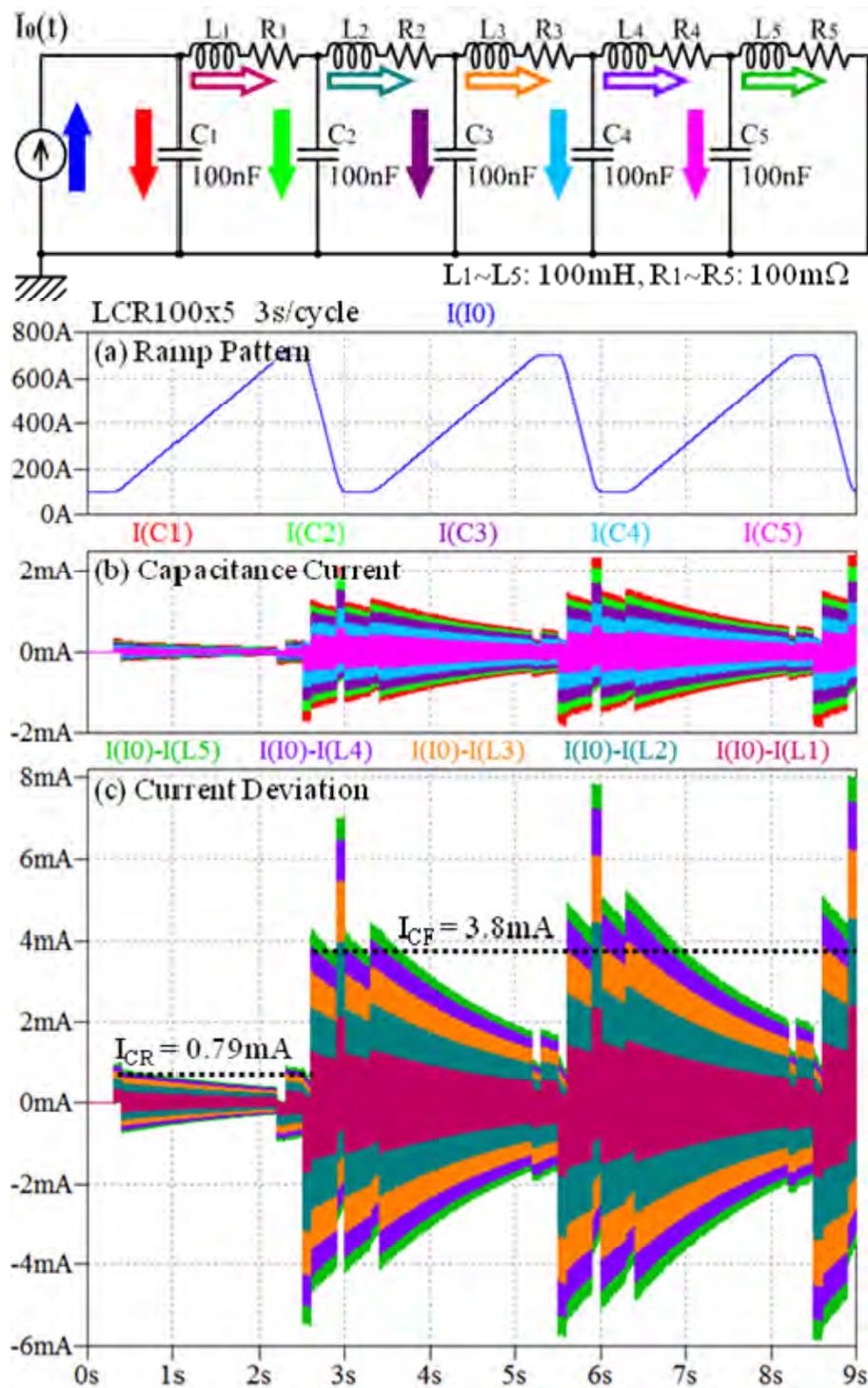
$$S_8 = \sqrt{1 + 2S_7 \cos(\sqrt{1 - \zeta^2} \omega_1 T_S - \varphi_7 + \varphi_1) e^{-\lambda_1 T_S} + S_7^2 e^{-2\lambda_1 T_S}}$$

$$\varphi_8 = \text{Tan}^{-1} \left(\frac{\sin \varphi_1 - S_7 \sin(\sqrt{1 - \zeta^2} \omega_1 T_S - \varphi_7) e^{-\lambda_1 T_S}}{\cos \varphi_1 + S_7 \cos(\sqrt{1 - \zeta^2} \omega_1 T_S - \varphi_7) e^{-\lambda_1 T_S}} \right)$$

3. 單一負荷回路、複數負荷回路 / 3.2 複數負荷回路 (1)



3. 単一負荷回路、複数負荷回路 / 3.2 複数負荷回路 (2)



電流上昇時: $I_{CR} \equiv \frac{D_R}{\omega_1^2 T_S} = L_1 C_1 \frac{D_R}{T_S}$

電流下降時: $I_{CF} \equiv \frac{D_F}{\omega_1^2 T_S} = L_1 C_1 \frac{D_F}{T_S}$

内在リップル振幅:

$L = 500\text{mH}, C = 500\text{nF}$

$I_{CR} = 0.79\text{mA}$

$I_{CF} = 3.8\text{mA}$

⇒負荷 L, C の影響大

4. 配線系キャパシタンス、並列ダンピング抵抗 / 4.1 配線系キャパシタンス (1)

配線系キャパシタンス

	r_0	r_i	\mathcal{L}	\mathcal{C}	\mathcal{R}
	[mm]		[$\mu\text{H}/\text{m}$]	[nF/m]	[m Ω /m]
Cable	15.9	13.5	0.034	0.74	0.0296
Bus-bar	500	20	0.64	0.017	0.013

4. 配線系キャパシタンス、並列ダンピング抵抗 / 4.1 配線系キャパシタンス (2)

配線系キャパシタンス

	r_0	r_i	\mathcal{L}	\mathcal{C}	\mathcal{R}
	[mm]		[$\mu\text{H}/\text{m}$]	[nF/m]	[m Ω /m]
Cable	15.9	13.5	0.034	0.74	0.0296
Bus-bar	500	20	0.64	0.017	0.013

ケーブル(断面 500mm^2)のキャパシタンスは
バスバーの 44 倍、 $0.74\text{nF}/\text{m}$ という巨大な値

4. 配線系キャパシタンス、並列ダンピング抵抗 / 4.1 配線系キャパシタンス (3)

配線系キャパシタンス

	r_0	r_i	\mathcal{L}	\mathcal{C}	\mathcal{R}
	[mm]		[$\mu\text{H}/\text{m}$]	[nF/m]	[m Ω /m]
Cable	15.9	13.5	0.034	0.74	0.0296
Bus-bar	500	20	0.64	0.017	0.013

ケーブル(断面 500mm²)のキャパシタンスは
バスバーの 44 倍、0.74nF/m という巨大な値

QFN ファミリーの例:

ケーブル(現状)

QFN Family	Amount	L	C	R
magnet	1/2 unit	29.9 mH	9.4 nF	19.6 m Ω
magAn, Bn	1/2 x 8	239 mH	74.8 nF	157 m Ω
Magnet Total	48 unit	2868 mH	898 nF	1884 m Ω
cabA1, B1	191.6 m	6.52 μH	142 nF	5.68 m Ω
cabA2, B2	203.2 m	6.90 μH	151 nF	6.02 m Ω
cabA3, B3	319.3 m	10.86 μH	237 nF	9.46 m Ω
cabA4, B4	203.2 m	6.90 μH	151 nF	6.02 m Ω
cabA5, B5	319.3 m	10.86 μH	237 nF	9.46 m Ω
cabA6, B6	203.2 m	6.90 μH	151 nF	6.02 m Ω
Cable Total	2880 m	97.88 μH	2138 nF	85.32 m Ω
Family Total		2868 mH	3036 nF	1969 m Ω

バスバー

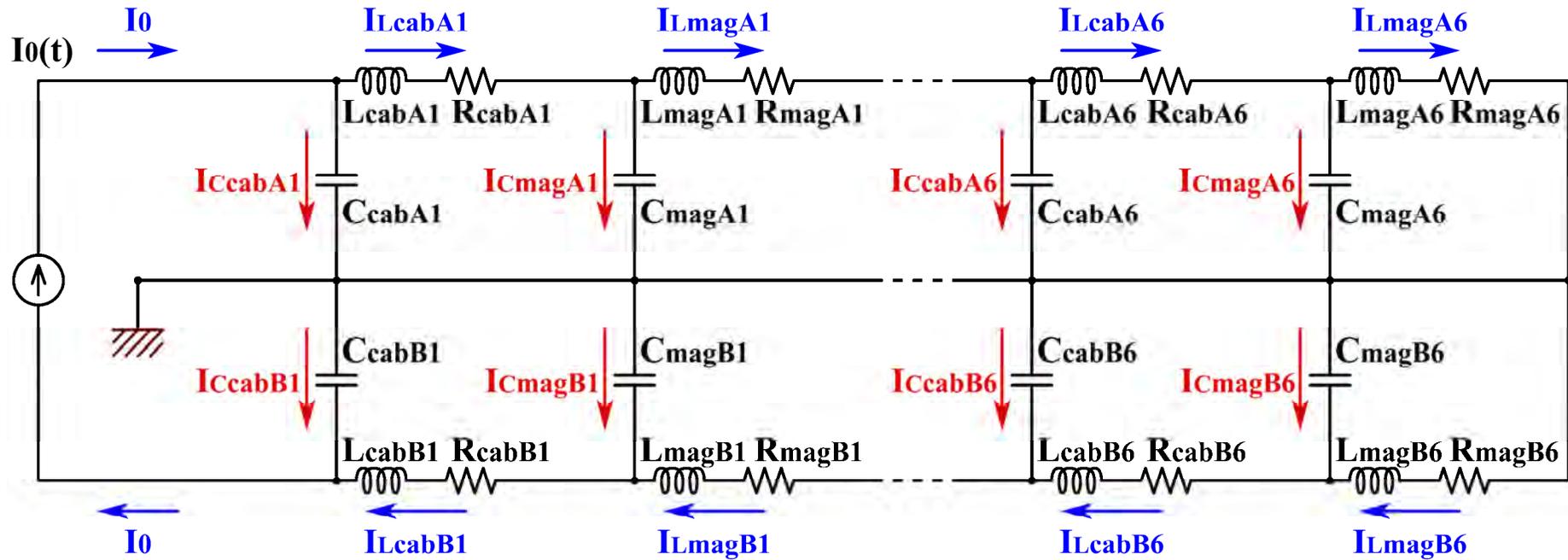
QFN Family	Amount	L	C	R
magnet	1/2 unit	29.9 mH	9.4 nF	19.6 m Ω
magAn, Bn	1/2 x 8	239 mH	74.8 nF	157 m Ω
Magnet Total	48 unit	2868 mH	898 nF	1884 m Ω
busA1, B1	191.6 m	127 μH	3.26 nF	2.49 m Ω
busA2, B2	203.2 m	130 μH	3.45 nF	2.64 m Ω
busA3, B3	319.3 m	204 μH	5.43 nF	4.15 m Ω
busA4, B4	203.2 m	130 μH	3.45 nF	2.64 m Ω
busA5, B5	319.3 m	204 μH	5.43 nF	4.15 m Ω
busA6, B6	203.2 m	130 μH	3.45 nF	2.64 m Ω
Busbar Total	2880 m	1850 μH	48.9 nF	37.42 m Ω
Family Total		2870 mH	947 nF	1921 m Ω

4. 配線系キャパシタンス、並列ダンピング抵抗 / 4.2 J-PARC MR QFN ファミリーの例 (1)

ケーブル(現状)

QFN Family	Amount	L	C	R
magnet	1/2 unit	29.9 mH	9.4 nF	19.6 mΩ
magAn, Bn	1/2 x 8	239 mH	74.8 nF	157 mΩ
Magnet Total	48 unit	2868 mH	898 nF	1884 mΩ
cabA1, B1	191.6 m	6.52 μH	142 nF	5.68 mΩ
cabA2, B2	203.2 m	6.90 μH	151 nF	6.02 mΩ
cabA3, B3	319.3 m	10.86 μH	237 nF	9.46 mΩ
cabA4, B4	203.2 m	6.90 μH	151 nF	6.02 mΩ
cabA5, B5	319.3 m	10.86 μH	237 nF	9.46 mΩ
cabA6, B6	203.2 m	6.90 μH	151 nF	6.02 mΩ
Cable Total	2880 m	97.88 μH	2138 nF	85.32 mΩ
Family Total		2868 mH	3036 nF	1969 mΩ

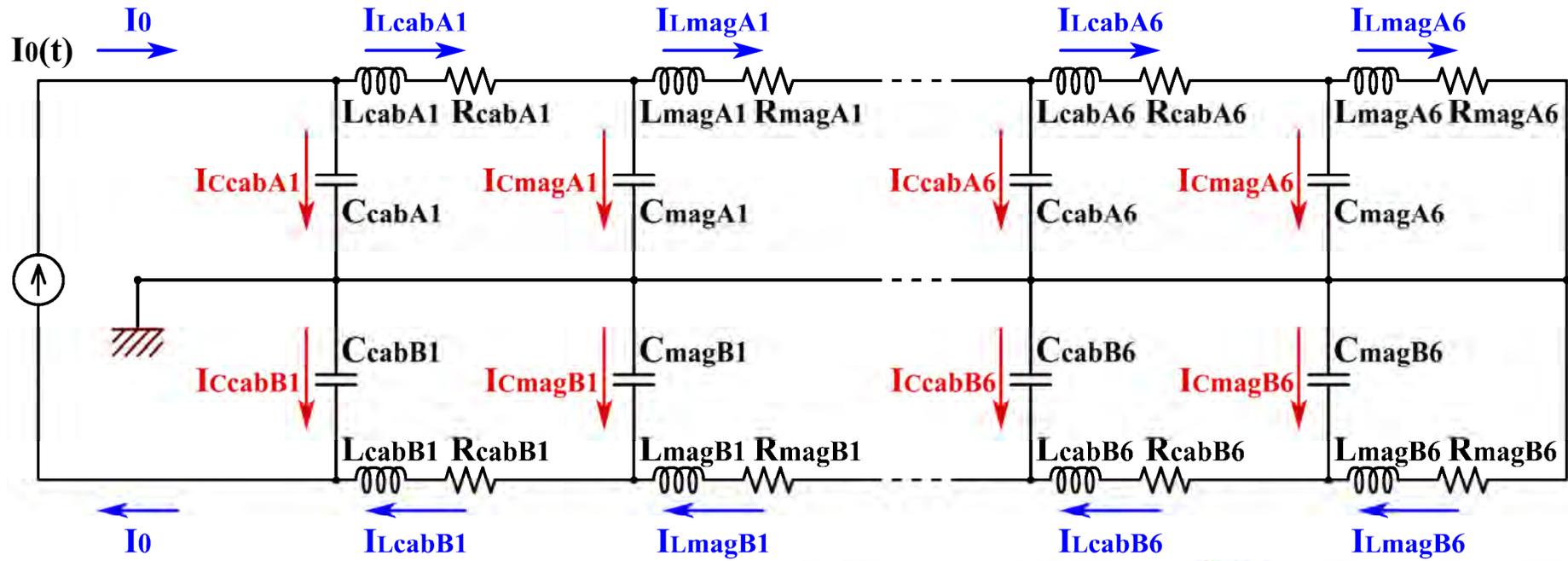
4. 配線系キャパシタンス、並列ダンピング抵抗 / 4.2 J-PARC MR QFN ファミリーの例 (2)



ケーブル(現状)

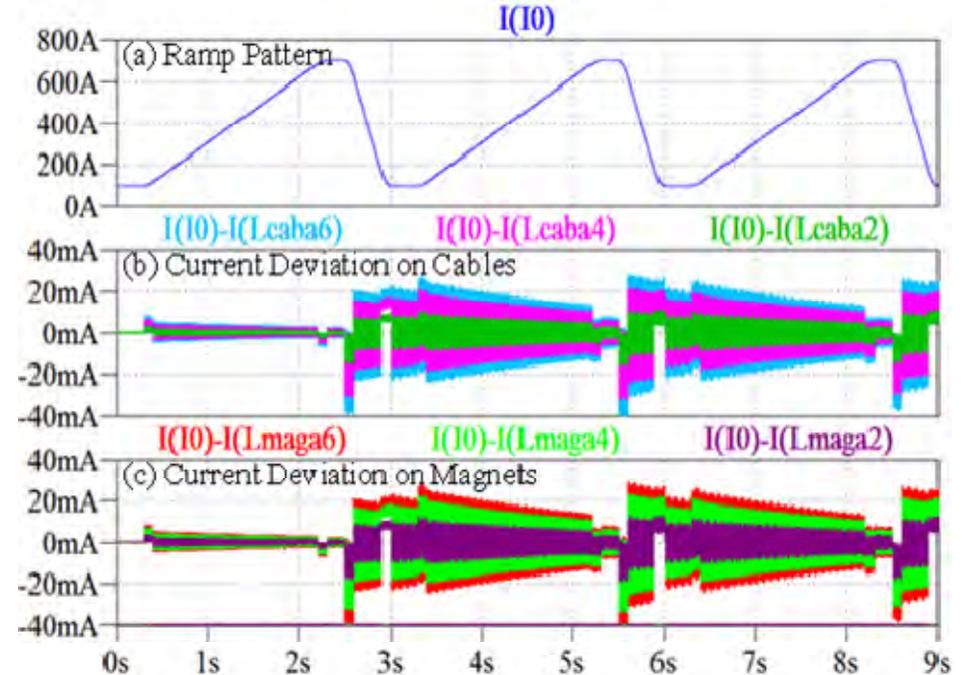
QFN Family	Amount	L	C	R
magnet	1/2 unit	29.9 mH	9.4 nF	19.6 mΩ
magAn, Bn	1/2 x 8	239 mH	74.8 nF	157 mΩ
Magnet Total	48 unit	2868 mH	898 nF	1884 mΩ
cabA1, B1	191.6 m	6.52 μH	142 nF	5.68 mΩ
cabA2, B2	203.2 m	6.90 μH	151 nF	6.02 mΩ
cabA3, B3	319.3 m	10.86 μH	237 nF	9.46 mΩ
cabA4, B4	203.2 m	6.90 μH	151 nF	6.02 mΩ
cabA5, B5	319.3 m	10.86 μH	237 nF	9.46 mΩ
cabA6, B6	203.2 m	6.90 μH	151 nF	6.02 mΩ
Cable Total	2880 m	97.88 μH	2138 nF	85.32 mΩ
Family Total		2868 mH	3036 nF	1969 mΩ

4. 配線系キャパシタンス、並列ダンピング抵抗 / 4.2 J-PARC MR QFN ファミリーの例 (3)

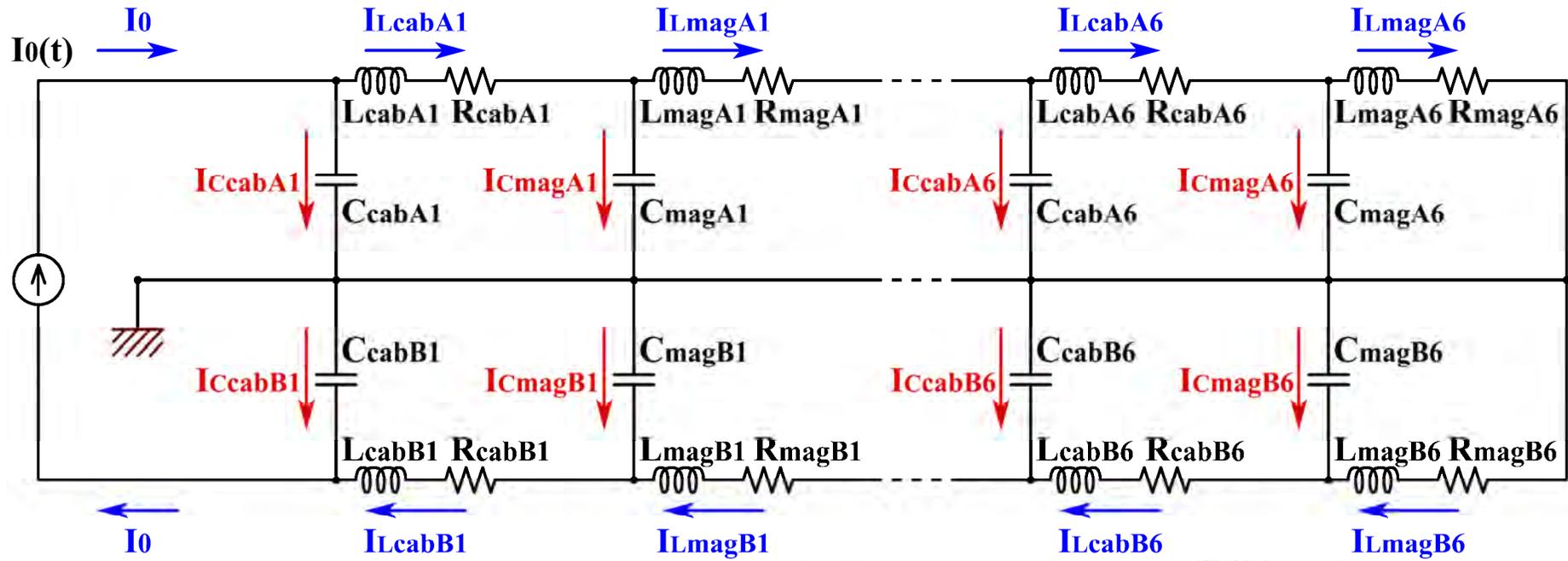


ケーブル(現状)

QFN Family	Amount	L	C	R
magnet	1/2 unit	29.9 mH	9.4 nF	19.6 mΩ
magAn, Bn	1/2 x 8	239 mH	74.8 nF	157 mΩ
Magnet Total	48 unit	2868 mH	898 nF	1884 mΩ
cabA1, B1	191.6 m	6.52 μH	142 nF	5.68 mΩ
cabA2, B2	203.2 m	6.90 μH	151 nF	6.02 mΩ
cabA3, B3	319.3 m	10.86 μH	237 nF	9.46 mΩ
cabA4, B4	203.2 m	6.90 μH	151 nF	6.02 mΩ
cabA5, B5	319.3 m	10.86 μH	237 nF	9.46 mΩ
cabA6, B6	203.2 m	6.90 μH	151 nF	6.02 mΩ
Cable Total	2880 m	97.88 μH	2138 nF	85.32 mΩ
Family Total		2868 mH	3036 nF	1969 mΩ

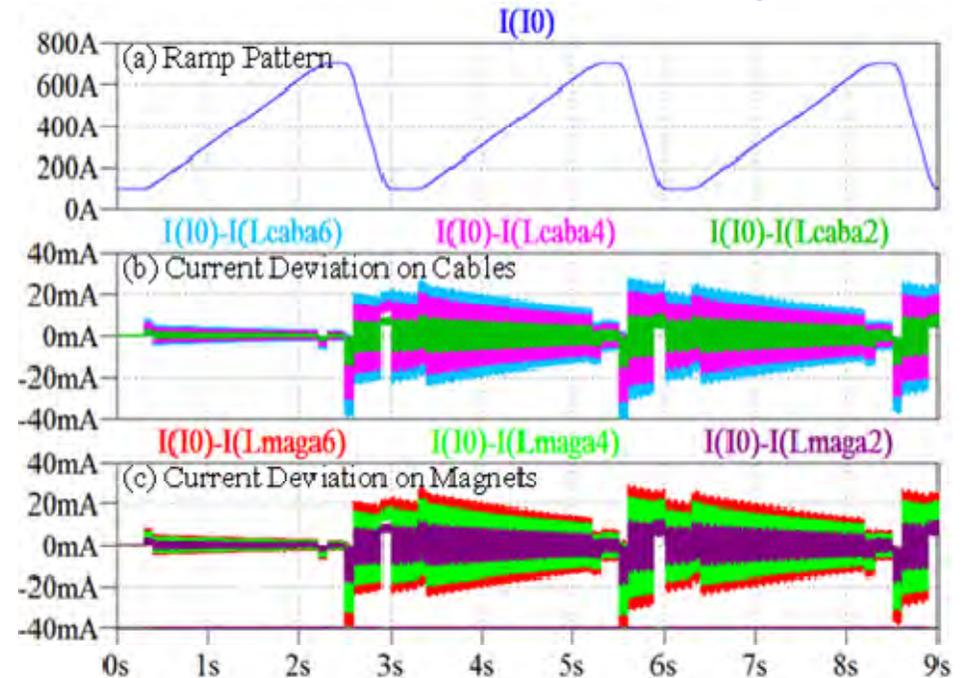


4. 配線系キャパシタンス、並列ダンピング抵抗 / 4.2 J-PARC MR QFN ファミリーの例 (4)



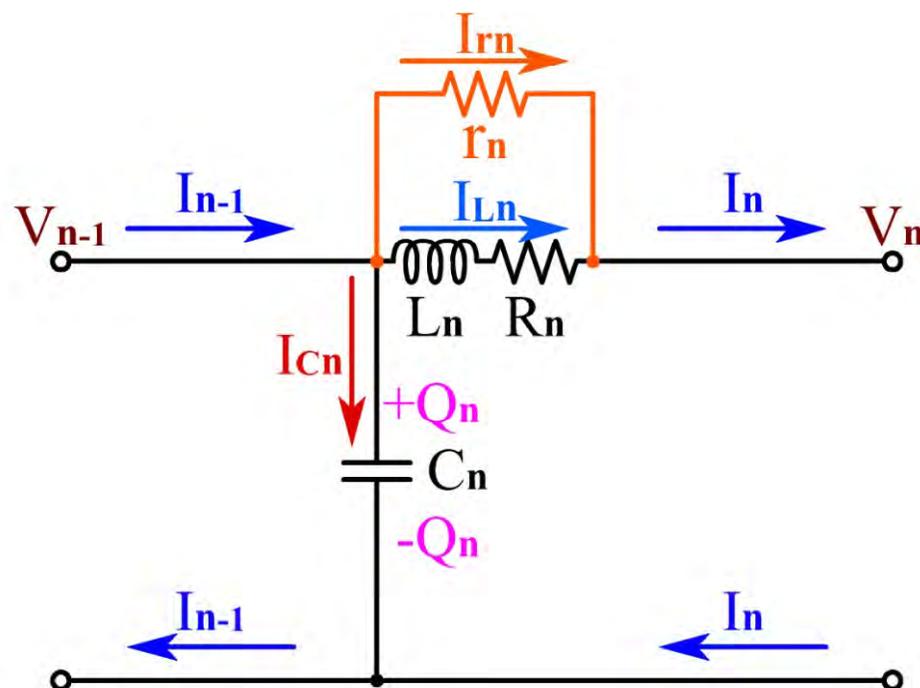
ケーブル(現状)

QFN Family	Amount	L	C	R
magnet	1/2 unit	29.9 mH	9.4 nF	19.6 mΩ
magAn, Bn	1/2 x 8	239 mH	74.8 nF	157 mΩ
Magnet Total	48 unit	2868 mH	898 nF	1884 mΩ
cabA1, B1	191.6 m	6.52 μH	142 nF	5.68 mΩ
cabA2, B2	203.2 m	6.90 μH	151 nF	6.02 mΩ
cabA3, B3	319.3 m	10.86 μH	237 nF	9.46 mΩ
cabA4, B4	203.2 m	6.90 μH	151 nF	6.02 mΩ
cabA5, B5	319.3 m	10.86 μH	237 nF	9.46 mΩ
cabA6, B6	203.2 m	6.90 μH	151 nF	6.02 mΩ
Cable Total	2880 m	97.88 μH	2138 nF	85.32 mΩ
Family Total		2868 mH	3036 nF	1969 mΩ



100~700A のパターン電流に対し
20mA 程の内在リップル: 1e-4 台

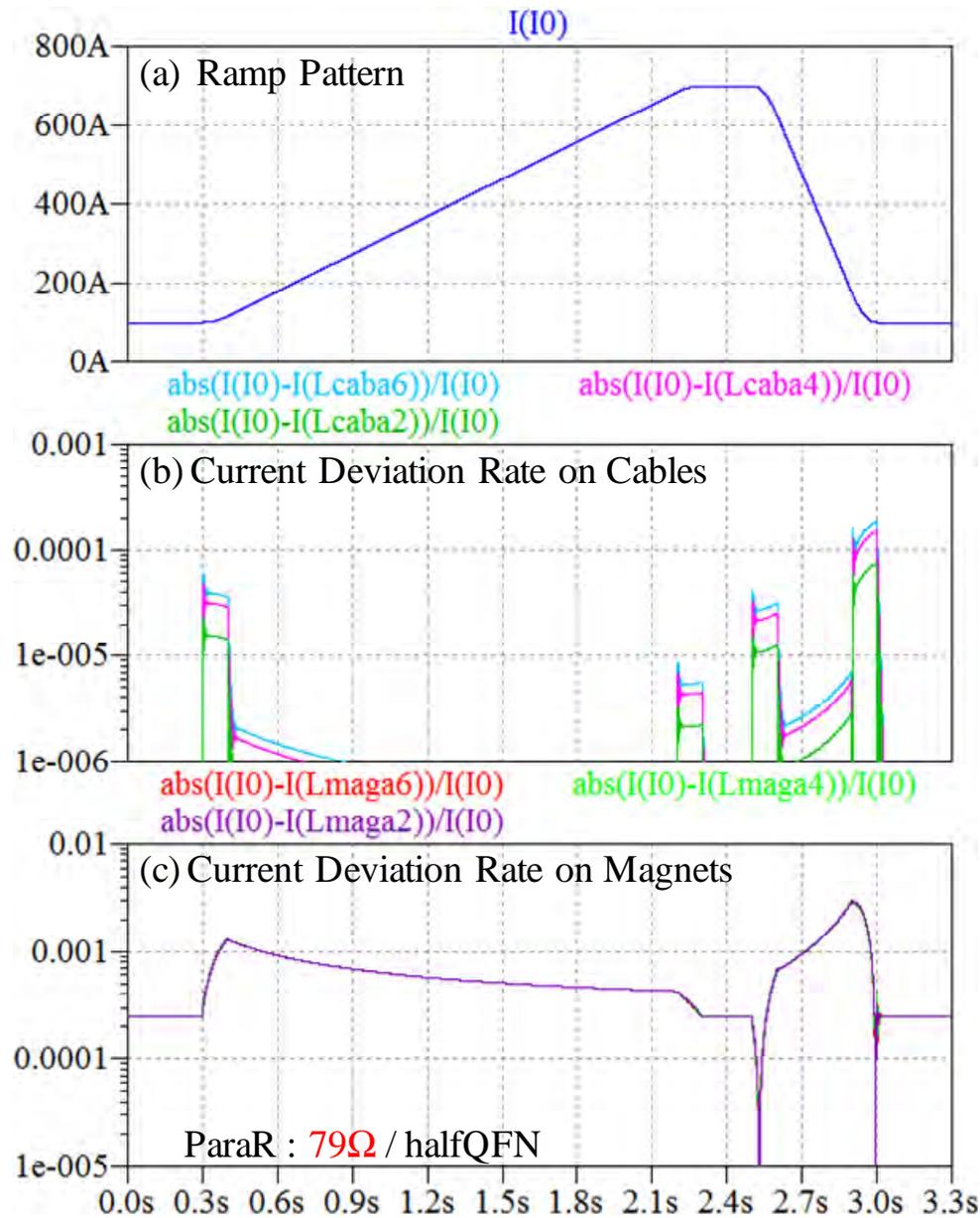
リップルの減衰を速める ⇒ 並列ダンピング抵抗の使用



$$\lambda'_n = \lambda_n + \frac{1}{2r_n C_n}$$

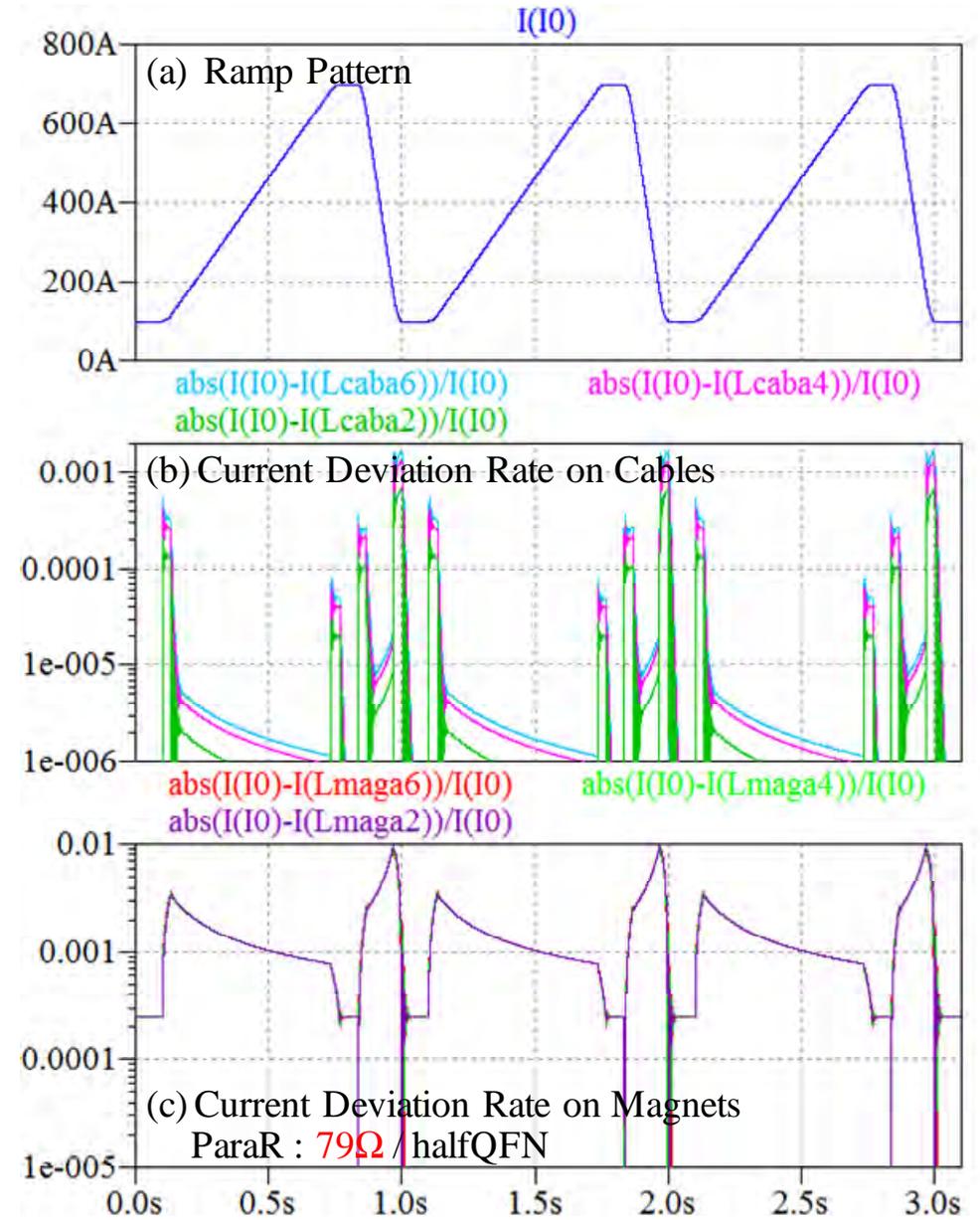
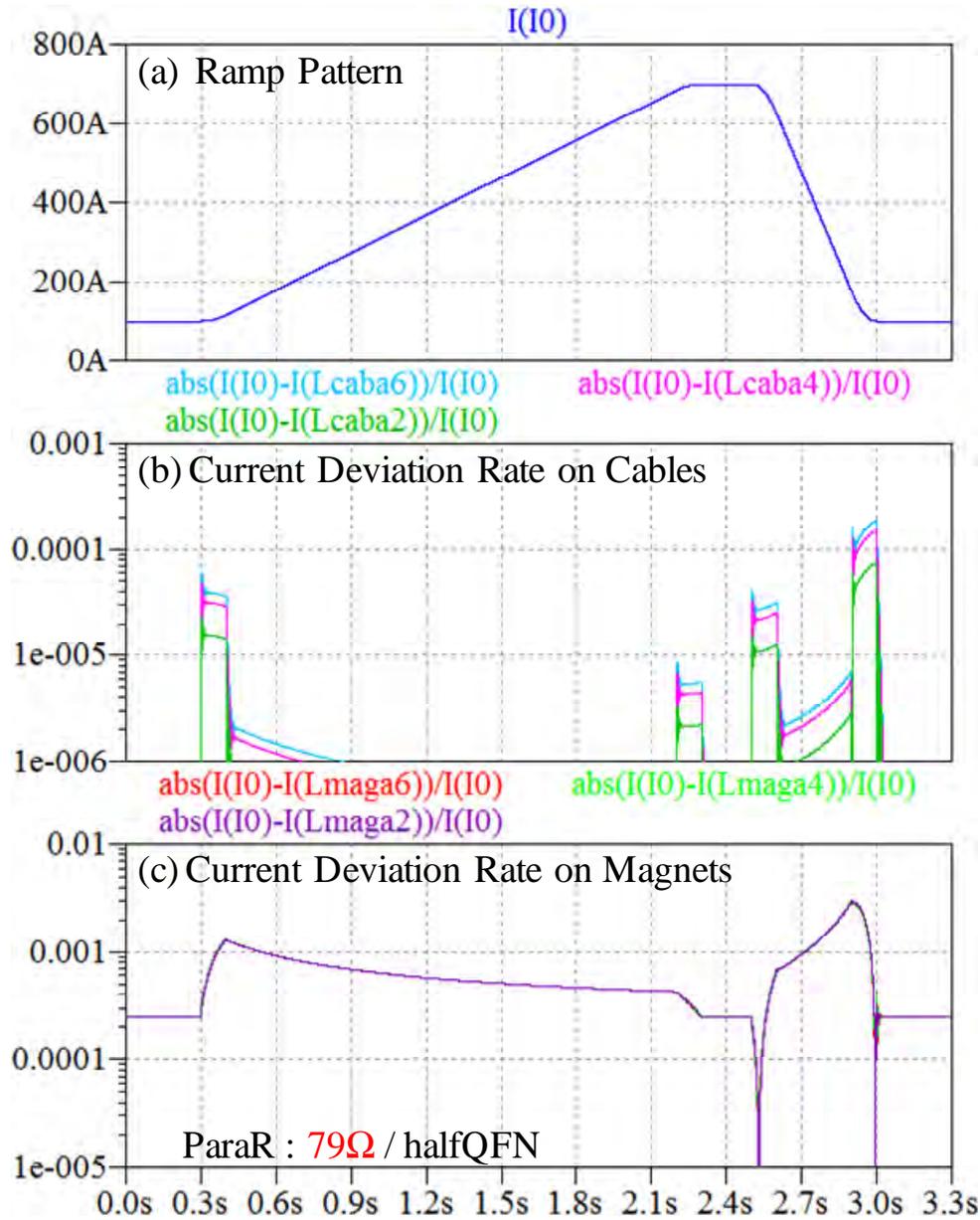
$\lambda'_n \gg \lambda_n \Rightarrow$ 減衰が格段に速くなる

4. 配線系キャパシタンス、並列ダンピング抵抗 / 4.3 並列ダンピング抵抗 (2)



現状 QFN: ケーブル配線
 ダンピング抵抗 = 79 Ω
 繰返しは 3s

4. 配線系キャパシタンス、並列ダンピング抵抗 / 4.3 並列ダンピング抵抗 (3)



現状 QFN: ケーブル配線
 ダンピング抵抗 = 79Ω
 繰返しは3s

繰返し ⇒ 1s

5. まとめ

- 1) シンクロトロンで「**内在リップル**」の存在が見出された。
- 2) 内在リップルの振幅は $L \cdot C \cdot D / T_S$ で得られる。
- 3) ダンピング抵抗を用いると内在リップルは軽減できるが、電流偏差を増大させる悪影響を及ぼす。
- 4) 繰返しを速めると、内在リップルに依る電流偏差は更に悪化する。
- 5) 高繰返し化の有効性は厳格な証明を要する。