Current Improvement for a 3ϕ Bi-directional Inverter with Wide Inductance Variation

- *Predictive Current Control*
- *Current Improvement*
- *Experimental Results*

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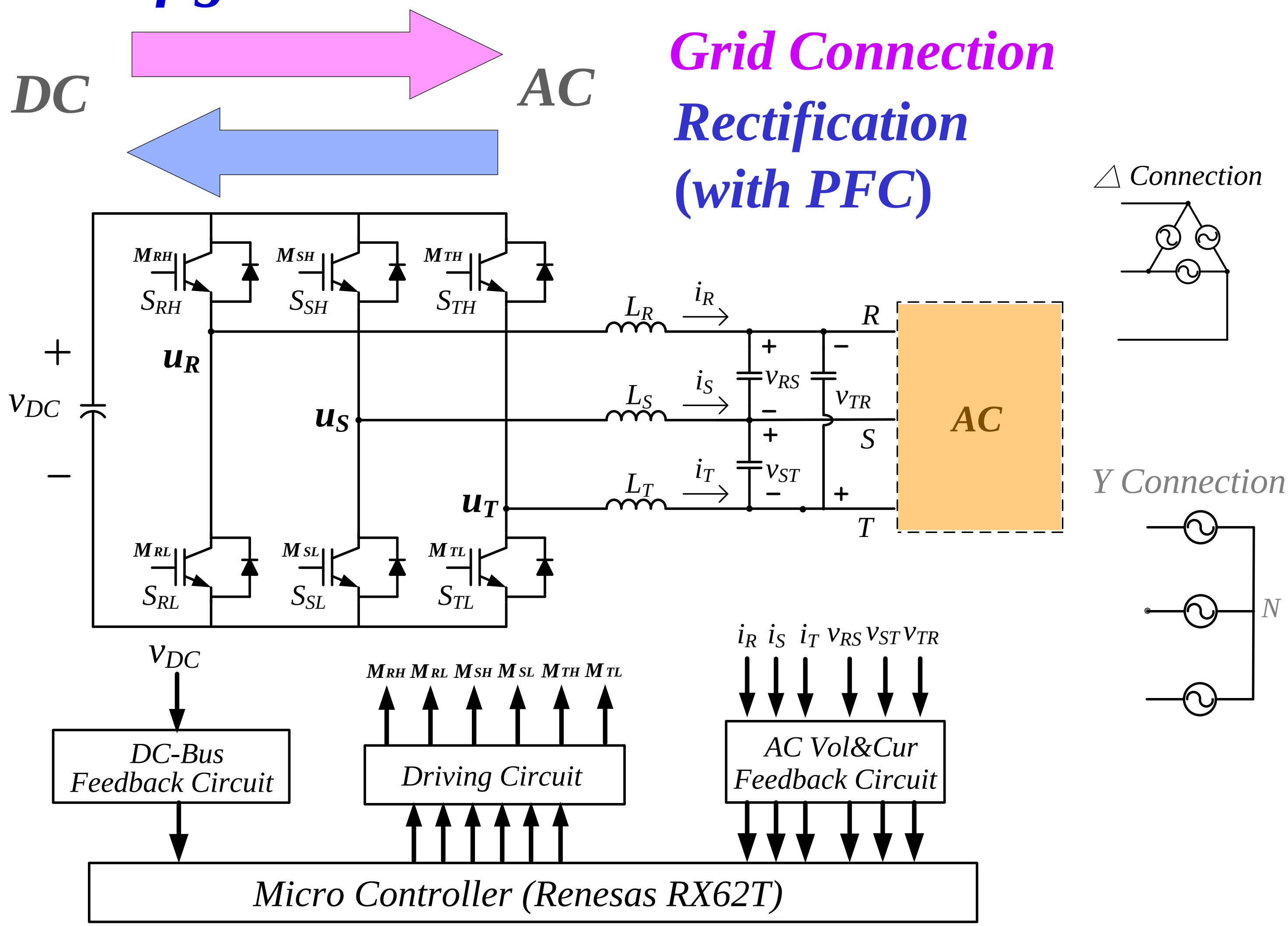
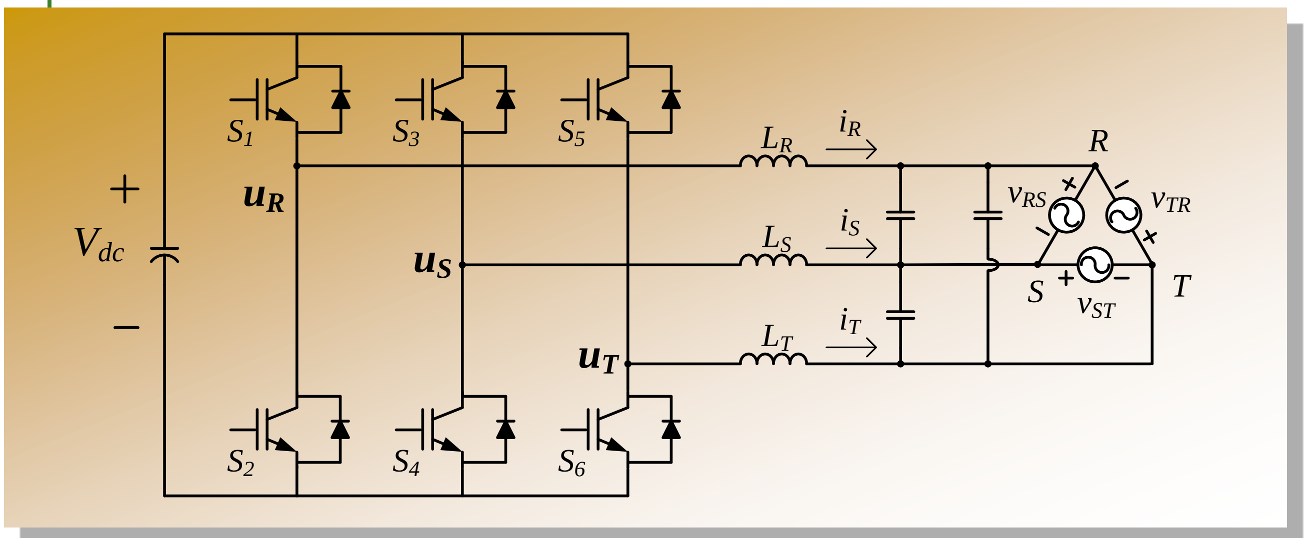
Predictive Current Control

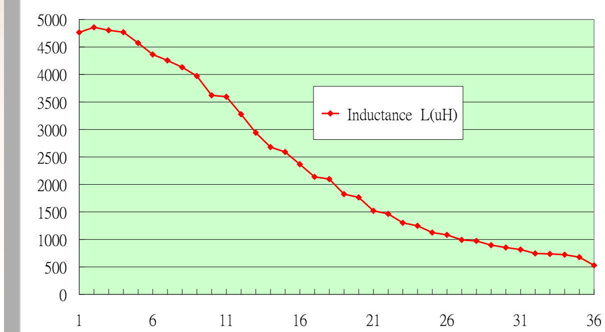
- ***System Configuration***



Predictive Current Control

- *Power Stage — 3 ϕ 3W*





- Circuit diagram of a three phase bi-directional inverter.

- **By KCL**

- **State Equations**

$$i_R + i_S + i_T = 0$$

$$\frac{di_R}{dt} + \frac{di_S}{dt} + \frac{di_T}{dt} = 0$$

$$\begin{bmatrix} u_{RS} \\ u_{ST} \end{bmatrix} = \begin{bmatrix} L_R & -L_S \\ L_T & L_S + L_T \end{bmatrix} \begin{bmatrix} \frac{di_R}{dt} \\ \frac{di_S}{dt} \end{bmatrix} + \begin{bmatrix} v_{RS} \\ v_{ST} \end{bmatrix}$$

where $L_R \neq L_S \neq L_T$

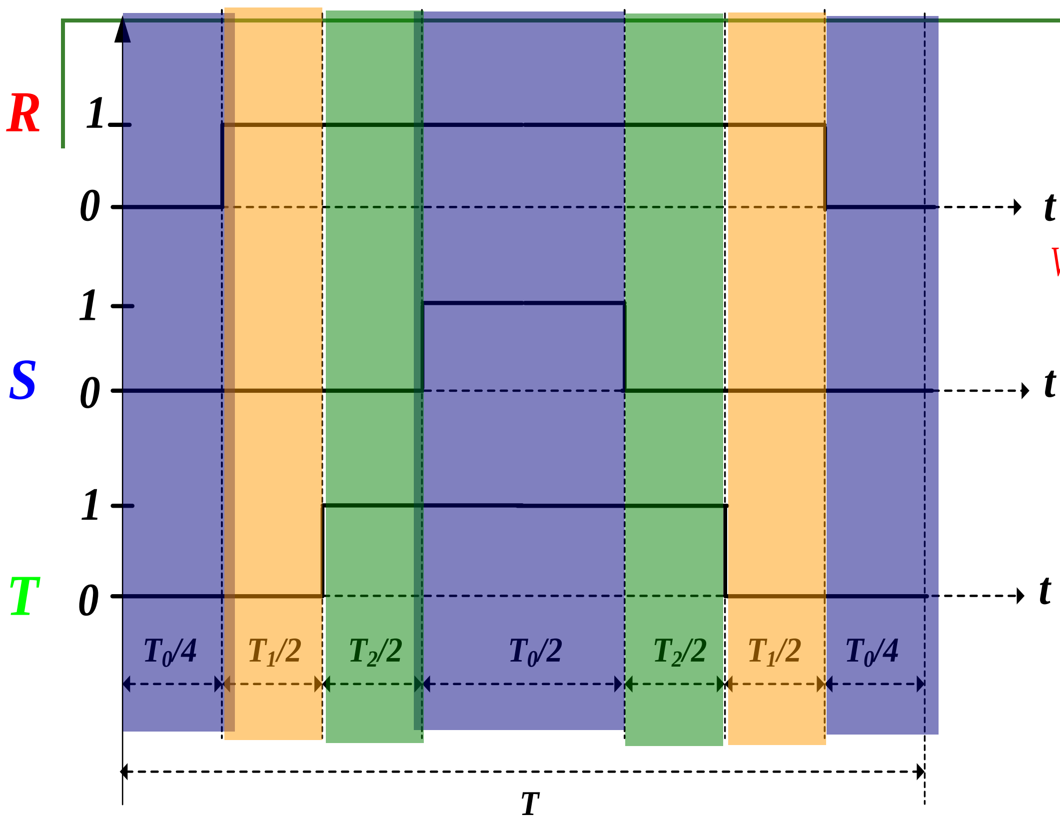
$$u_{RS} = u_R - u_S$$

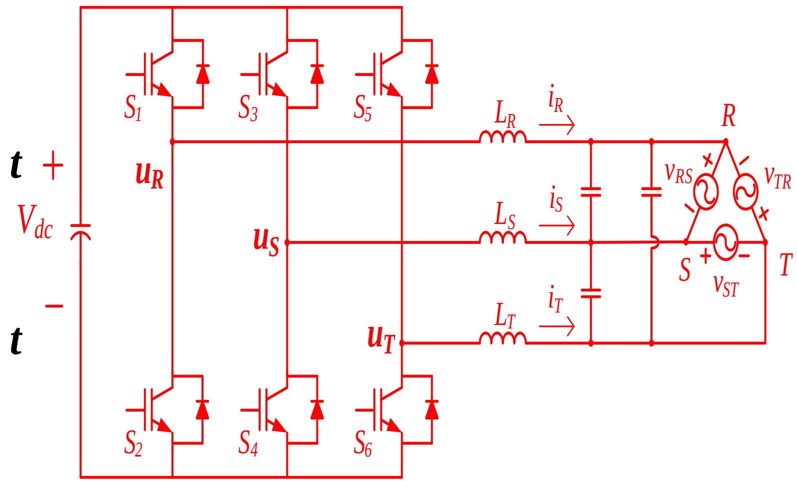
and

$$u_{ST} = u_S - u_T$$

$$L_R \frac{di_R}{dt} + L_S \frac{di_S}{dt} + L_T \frac{di_T}{dt} \neq 0$$

Predictive Current Control





•State Equations

$$\begin{bmatrix} u_{RS} \\ u_{ST} \end{bmatrix} = \begin{bmatrix} L_R & -L_S \\ L_T & L_S + L_T \end{bmatrix} \begin{bmatrix} \frac{di_R}{dt} \\ \frac{di_S}{dt} \end{bmatrix} + \begin{bmatrix} v_{RS} \\ v_{ST} \end{bmatrix}$$

Interval T_0:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} L_R & -L_S \\ L_T & L_S + L_T \end{bmatrix} \begin{bmatrix} \Delta i_{v(R),0} \\ \Delta i_{v(S),0} \end{bmatrix} \frac{1}{T_0} + \begin{bmatrix} v_{RS} \\ v_{ST} \end{bmatrix}$$

Interval T_1:

$$\begin{bmatrix} v_{DC} \\ 0 \end{bmatrix} = \begin{bmatrix} L_R & -L_S \\ L_T & L_S + L_T \end{bmatrix} \begin{bmatrix} \Delta i_{v(R),1} \\ \Delta i_{v(S),1} \end{bmatrix} \frac{1}{T_1} + \begin{bmatrix} v_{RS} \\ v_{ST} \end{bmatrix}$$

Interval T_2:

$$\begin{bmatrix} v_{DC} \\ -v_{DC} \end{bmatrix} = \begin{bmatrix} L_R & -L_S \\ L_T & L_S + L_T \end{bmatrix} \begin{bmatrix} \Delta i_{v(R),2} \\ \Delta i_{v(S),2} \end{bmatrix} \frac{1}{T_2} + \begin{bmatrix} v_{RS} \\ v_{ST} \end{bmatrix}$$

where

$T_0 = T - T_1 - T_2$

Predictive Current Control

- ***Derivation Steps***

Interval T_0:

$$\begin{bmatrix}\Delta i_{v(R),0}\\ \Delta i_{v(S),0}\end{bmatrix} = -\begin{bmatrix}\frac{L_S+L_T}{L_{total}^2} & \frac{L_S}{L_{total}^2}\\ \frac{-L_T}{L_{total}^2} & \frac{L_R}{L_{total}^2}\end{bmatrix}\begin{bmatrix}v_{RS}\\ v_{ST}\end{bmatrix}T_0$$

Interval T_1:

$$\begin{bmatrix}\Delta i_{v(R),1}\\ \Delta i_{v(S),1}\end{bmatrix} = -\begin{bmatrix}\frac{L_S+L_T}{L_{total}^2} & \frac{L_S}{L_{total}^2}\\ \frac{-L_T}{L_{total}^2} & \frac{L_R}{L_{total}^2}\end{bmatrix}\begin{bmatrix}v_{RS}\\ v_{ST}\end{bmatrix}T_1 - \begin{bmatrix}\frac{L_S+L_T}{L_{total}^2} & \frac{L_S}{L_{total}^2}\\ \frac{-L_T}{L_{total}^2} & \frac{L_R}{L_{total}^2}\end{bmatrix}\begin{bmatrix}-v_{DC}\\ 0\end{bmatrix}T_1$$

Interval T_2:

$$\begin{bmatrix}\Delta i_{v(R),2}\\ \Delta i_{v(S),2}\end{bmatrix} = -\begin{bmatrix}\frac{L_S+L_T}{L_{total}^2} & \frac{L_S}{L_{total}^2}\\ \frac{-L_T}{L_{total}^2} & \frac{L_R}{L_{total}^2}\end{bmatrix}\begin{bmatrix}v_{RS}\\ v_{ST}\end{bmatrix}T_2 - \begin{bmatrix}\frac{L_S+L_T}{L_{total}^2} & \frac{L_S}{L_{total}^2}\\ \frac{-L_T}{L_{total}^2} & \frac{L_R}{L_{total}^2}\end{bmatrix}\begin{bmatrix}-v_{DC}\\ v_{DC}\end{bmatrix}T_2$$

+

$$\begin{bmatrix}\Delta i_{v(R)}\\ \Delta i_{v(S)}\end{bmatrix} = -\begin{bmatrix}\frac{L_S+L_T}{L_{total}^2} & \frac{L_S}{L_{total}^2}\\ \frac{-L_T}{L_{total}^2} & \frac{L_R}{L_{total}^2}\end{bmatrix}\begin{bmatrix}v_{RS}\\ v_{ST}\end{bmatrix}T - \begin{bmatrix}\frac{L_S+L_T}{L_{total}^2} & \frac{L_S}{L_{total}^2}\\ \frac{-L_T}{L_{total}^2} & \frac{L_R}{L_{total}^2}\end{bmatrix}\begin{bmatrix}-v_{DC} & -v_{DC}\\ 0 & v_{DC}\end{bmatrix}\begin{bmatrix}T_1\\ T_2\end{bmatrix}$$

Predictive Current Control

- ***General Form of the Control Laws***

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{v_{DC}} & -\frac{1}{v_{DC}} \\ 0 & \frac{1}{v_{DC}} \end{bmatrix} \left\{ \begin{bmatrix} L_R & -L_S \\ L_T & L_S + L_T \end{bmatrix} \begin{bmatrix} -\Delta i_{v(R)} \\ -\Delta i_{v(S)} \end{bmatrix} - \begin{bmatrix} v_{RS} \\ v_{ST} \end{bmatrix} T \right\}$$

$$= \begin{bmatrix} -\frac{1}{v_{DC}} & -\frac{1}{v_{DC}} \\ 0 & \frac{1}{v_{DC}} \end{bmatrix} \begin{bmatrix} -L_R \Delta i_{v(R)} + L_S \Delta i_{v(S)} - v_{RS} T \\ -L_T \Delta i_{v(R)} - (L_S + L_T) \Delta i_{v(S)} - v_{ST} T \end{bmatrix}$$

$$= \begin{bmatrix} \frac{(L_R + L_T)\Delta i_{v(R)} + L_T \Delta i_{v(S)}}{v_{DC}} - \frac{v_{TR}}{v_{DC}} T \\ \frac{-L_T \Delta i_{v(R)} - (L_S + L_T)\Delta i_{v(S)}}{v_{DC}} - \frac{v_{ST}}{v_{DC}} T \end{bmatrix}$$

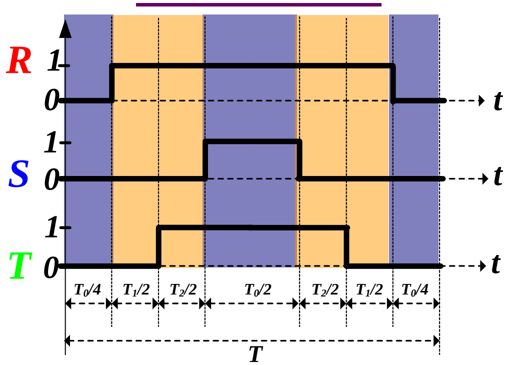
and

$T_0 = T - T_1 - T_2.$

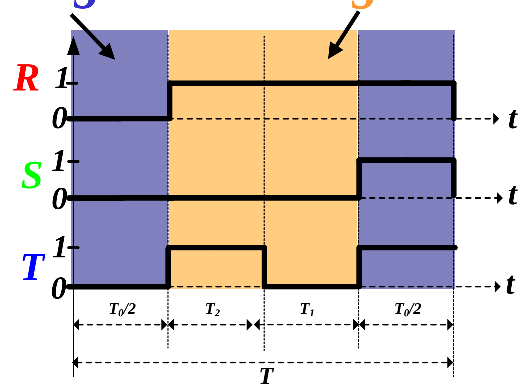
Predictive Current Control

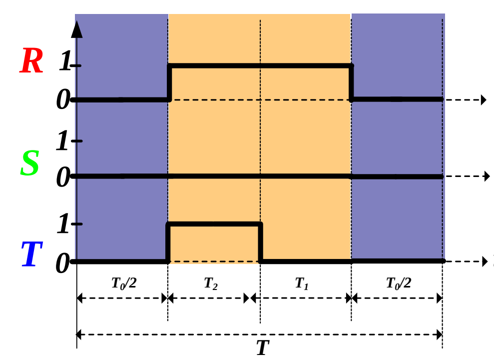
- *Equivalent Gate Signal*

SVPWM

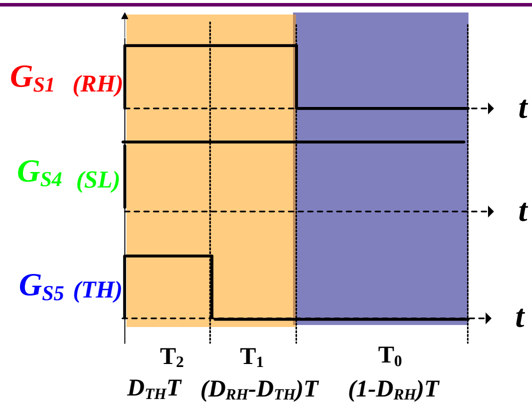


Demagnetizing Time *Magnetizing Time*



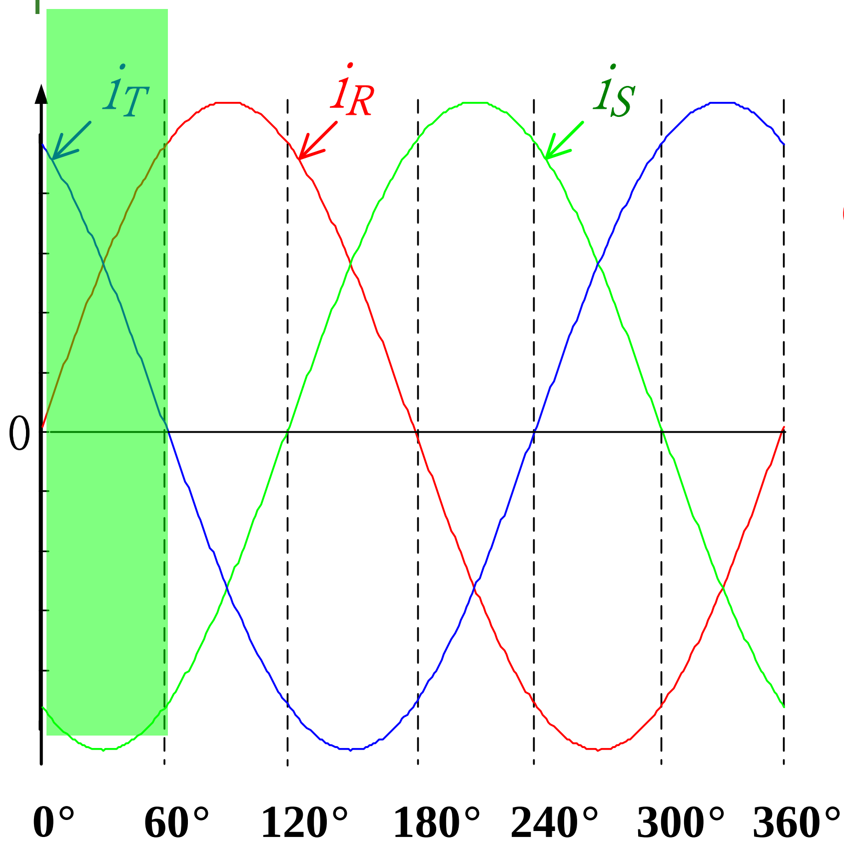


Two-Phase Modulation (TPM)

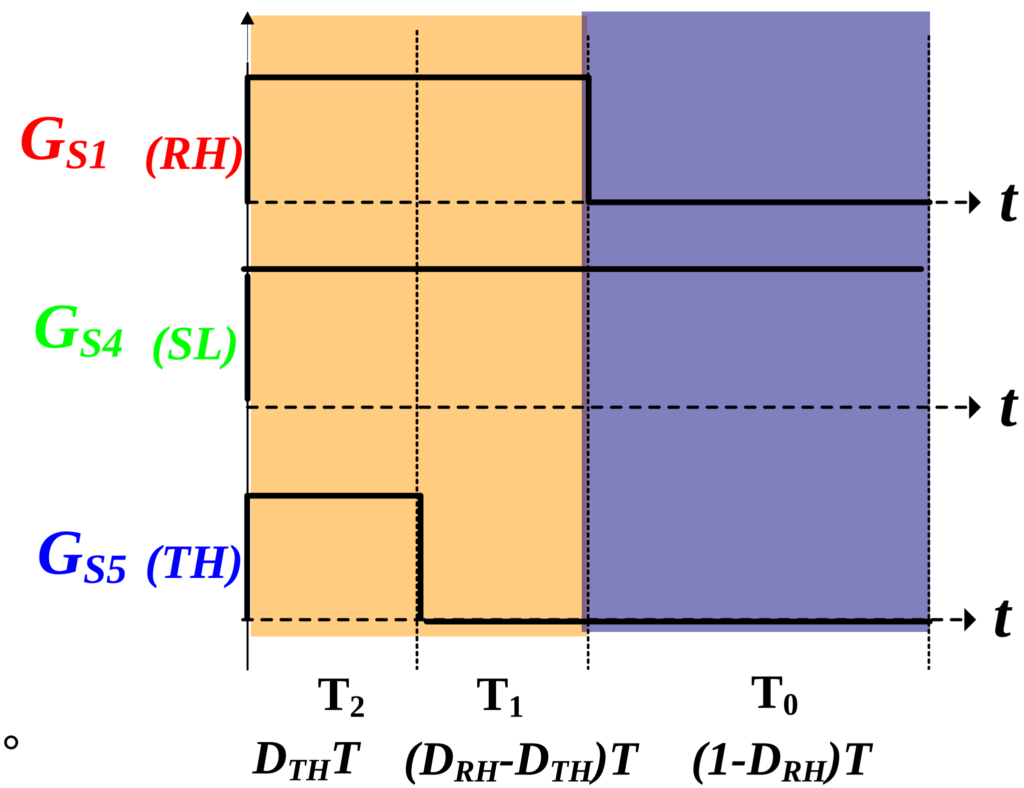


Predictive Current Control

- ***Six regions for three-phase line currents***



TPM



Region I : 0° ~ 60°

Predictive Current Control

Region I : 0°~ 60 °

- *Control laws for Grid-Connection Mode*

$$\begin{bmatrix} D_{RH} \\ D_{SL} \\ D_{TH} \end{bmatrix} = \begin{bmatrix} \dfrac{(L_R + L_S)\Delta i_{v(R)} + L_S \Delta i_{v(T)}}{v_{DC} T} \\ 0 \\ \dfrac{(L_T + L_S)\Delta i_{v(T)} + L_S \Delta i_{v(R)}}{v_{DC} T} \end{bmatrix} + \begin{bmatrix} \dfrac{v_{RS}}{v_{DC}} \\ 1 \\ -\dfrac{v_{ST}}{v_{DC}} \end{bmatrix}$$

where

$$D_{TH} = \frac{T_2}{T}$$

$$D_{RH} = \frac{T_1}{T} + \frac{T_2}{T}$$

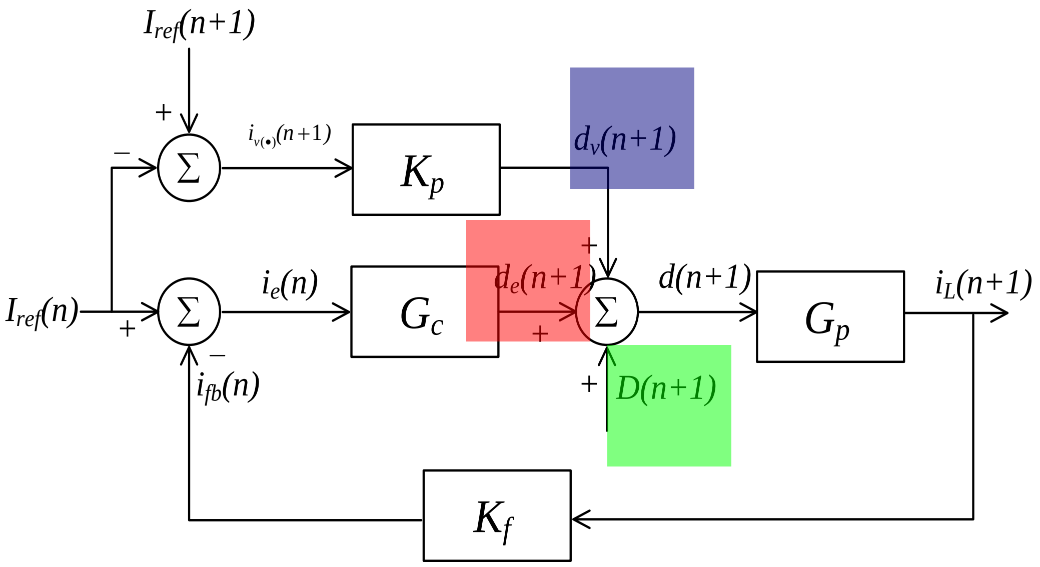
- *Complementary control laws for rectification mode*

$$\begin{bmatrix} D_{RL} \\ D_{SH} \\ D_{TL} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \left\{ \begin{bmatrix} \dfrac{(L_R + L_S)\Delta i_{v(R)} + L_S \Delta i_{v(T)}}{v_{DC} T} \\ 0 \\ \dfrac{(L_T + L_S)\Delta i_{v(T)} + L_S \Delta i_{v(R)}}{v_{DC} T} \end{bmatrix} + \begin{bmatrix} \dfrac{v_{RS}}{v_{DC}} \\ 1 \\ -\dfrac{v_{ST}}{v_{DC}} \end{bmatrix} \right\}$$

Predictive Current Control

- ***Control Configuration***

$$d(n+1) = d_v(n+1) + d_e(n+1) + D(n+1)$$



where $d_e(n+1) = G_c \cdot i_e(n)$

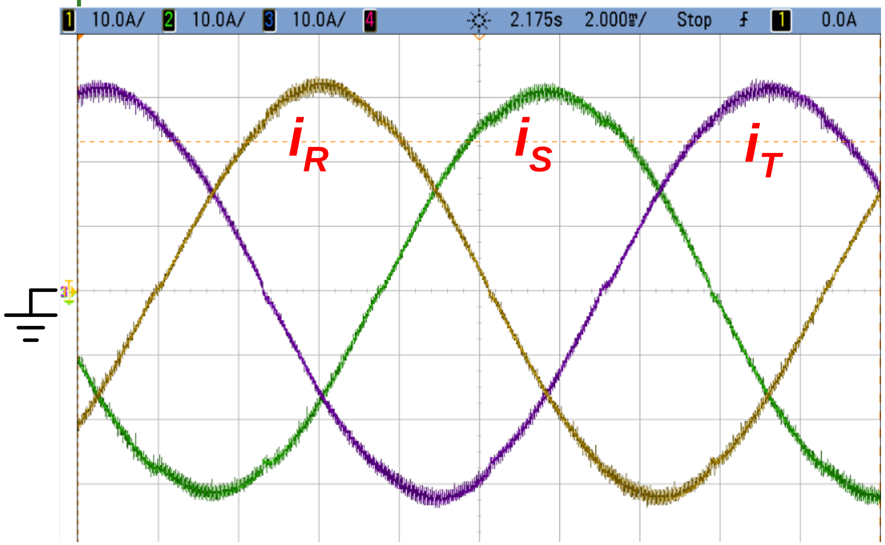
$$d_v(n+1) = K_p \cdot i_{v(\bullet)}(n+1)$$

$$K_p = \frac{L(i)}{v_{DC} \cdot T_s}$$

$$D(n+1) = \frac{v_{RS}}{v_{DC}} \; or \; \frac{v_{ST}}{v_{DC}} \; or \; \frac{v_{TR}}{v_{DC}}$$

Experimental Results

- ***Wide Inductance Variation Test***



(i_R, i_S and i_T: 10A/div; time: 2ms/div)

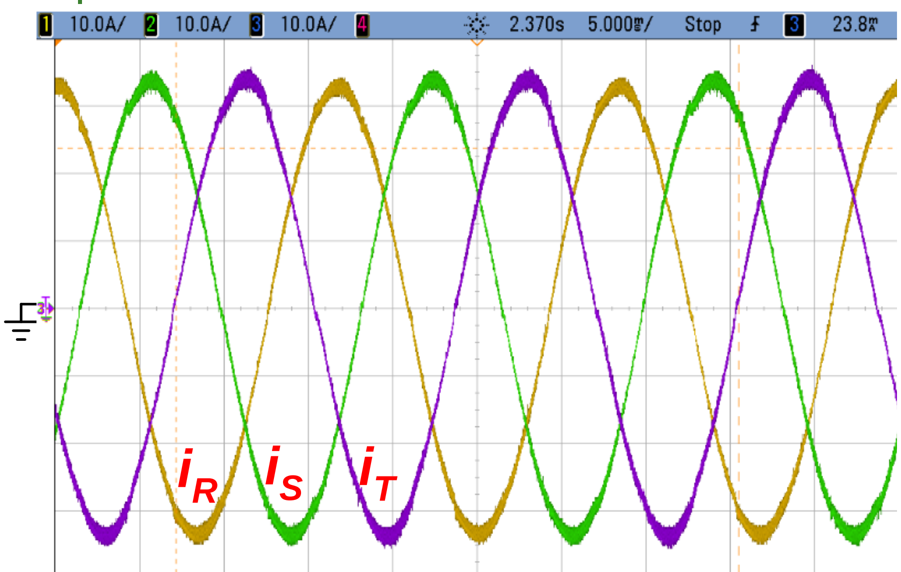
(a) with (9 kW) **(b) without (9 kW)**

considering wide inductance variation

(Grid-Connection Mode)

Experimental Results

- ***Wide Inductance Variation Test***



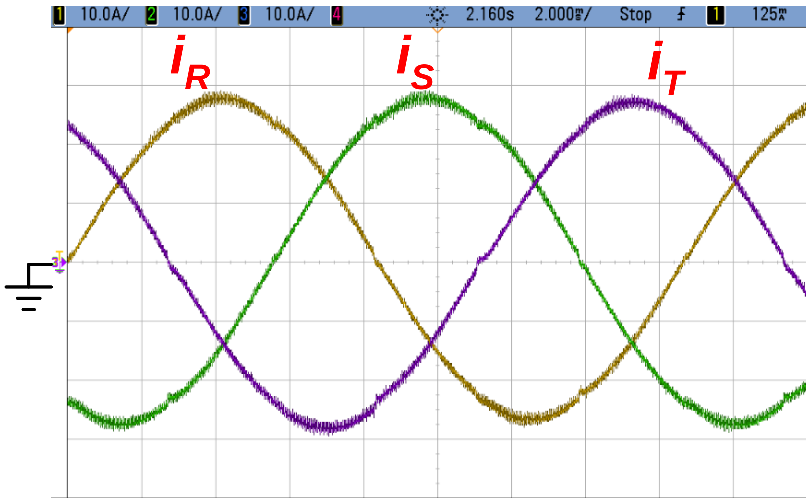
(i_R, i_S and i_T: 10A/div; time: 2ms/div)

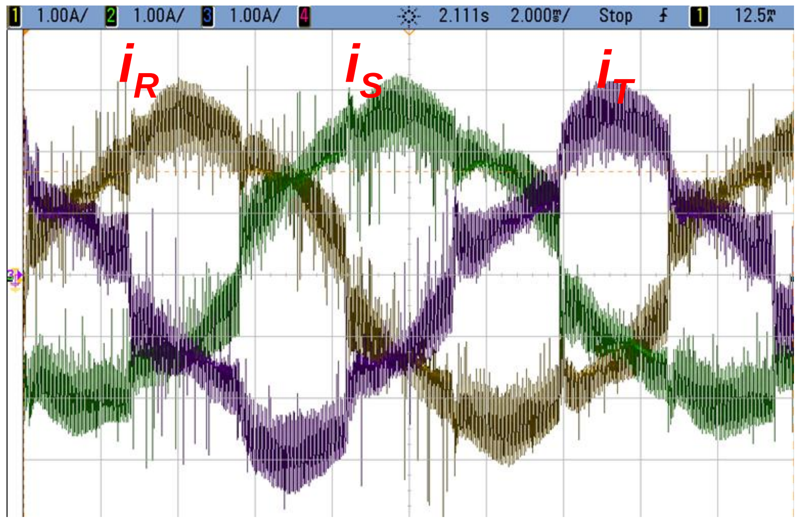
(a) 10 kW **(b) 9 kW**

considering wide inductance variation

(Rectification Mode)

Experimental Results





(i_R, i_S and i_T: 10A/div; time: 2ms/div)

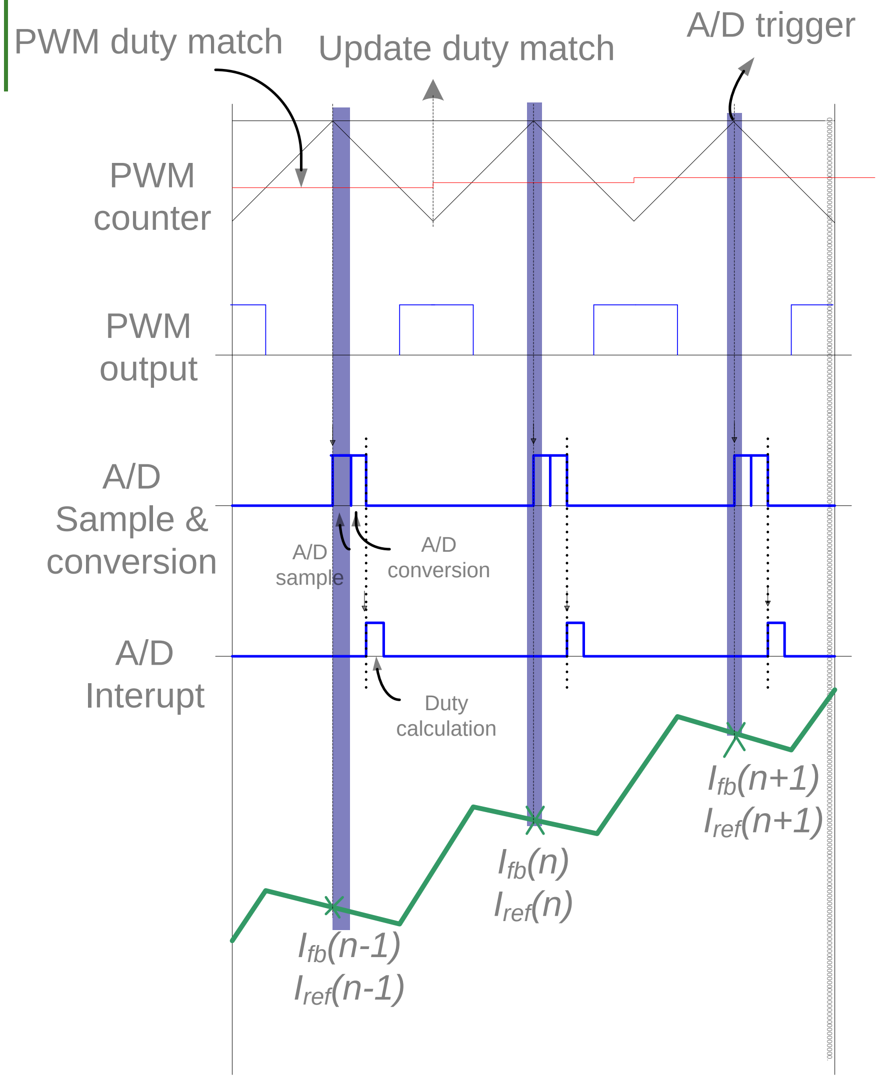
(a) 7kW **(b) 500 W**

- *Current distortion at low power level*

➢ ***Mid-point Current Sampling*** ➢ ***Smooth Region Transition***

➢ ***Current Interleaving*** ➢ ***Duty Splitting***

Current Improvement



➢ ***Mid-Point Current Sampling***

- ***$i_{v(.)}$ is inductor current variation during one period.***

- ***i_e is current error between $i_{fb}(n)$ and $I_{ref}(n-1)$.***

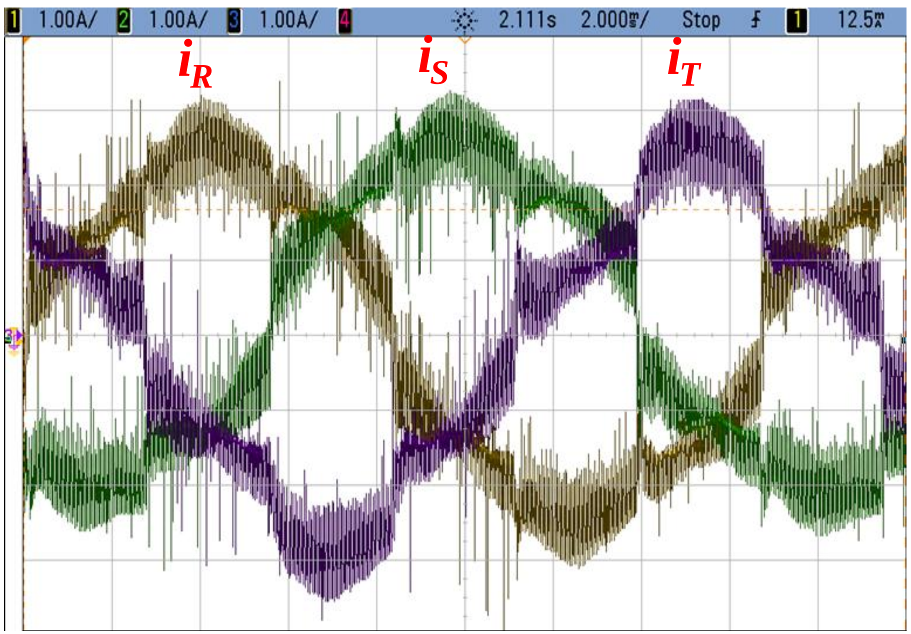
$$i_{v(\bullet)}(n+1) = I_{ref}(n+1) - I_{ref}(n)$$

$$i_e(n+1) = I_{ref}(n) - i_{fb}(n)$$

Experimental Results

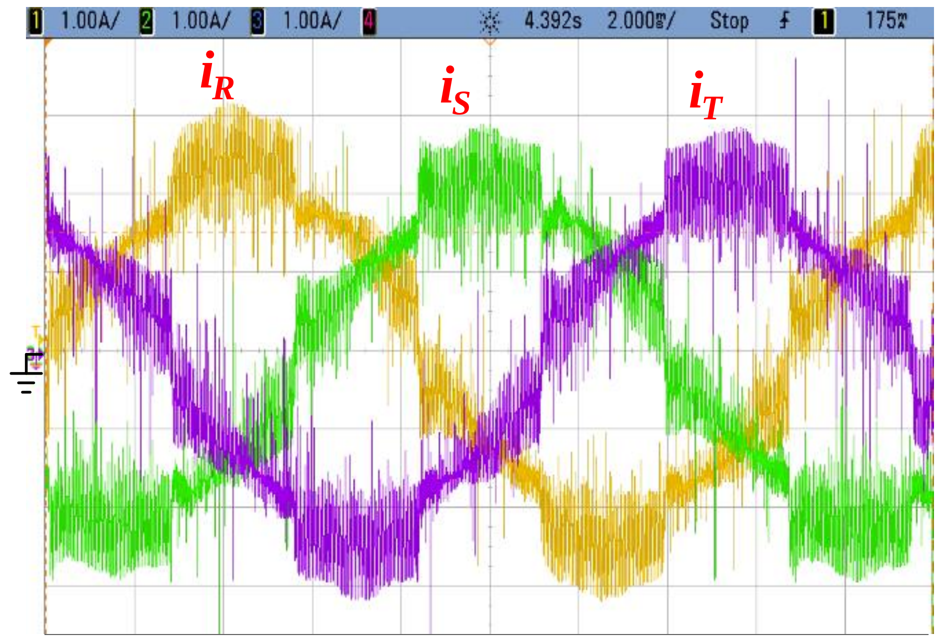
500 W at Grid-Connection Mode

- *with ramp carrier signal & multiple sampling*
- *with triangle carrier signal & mid-point sampling*



THD = 10.6 %

(a)



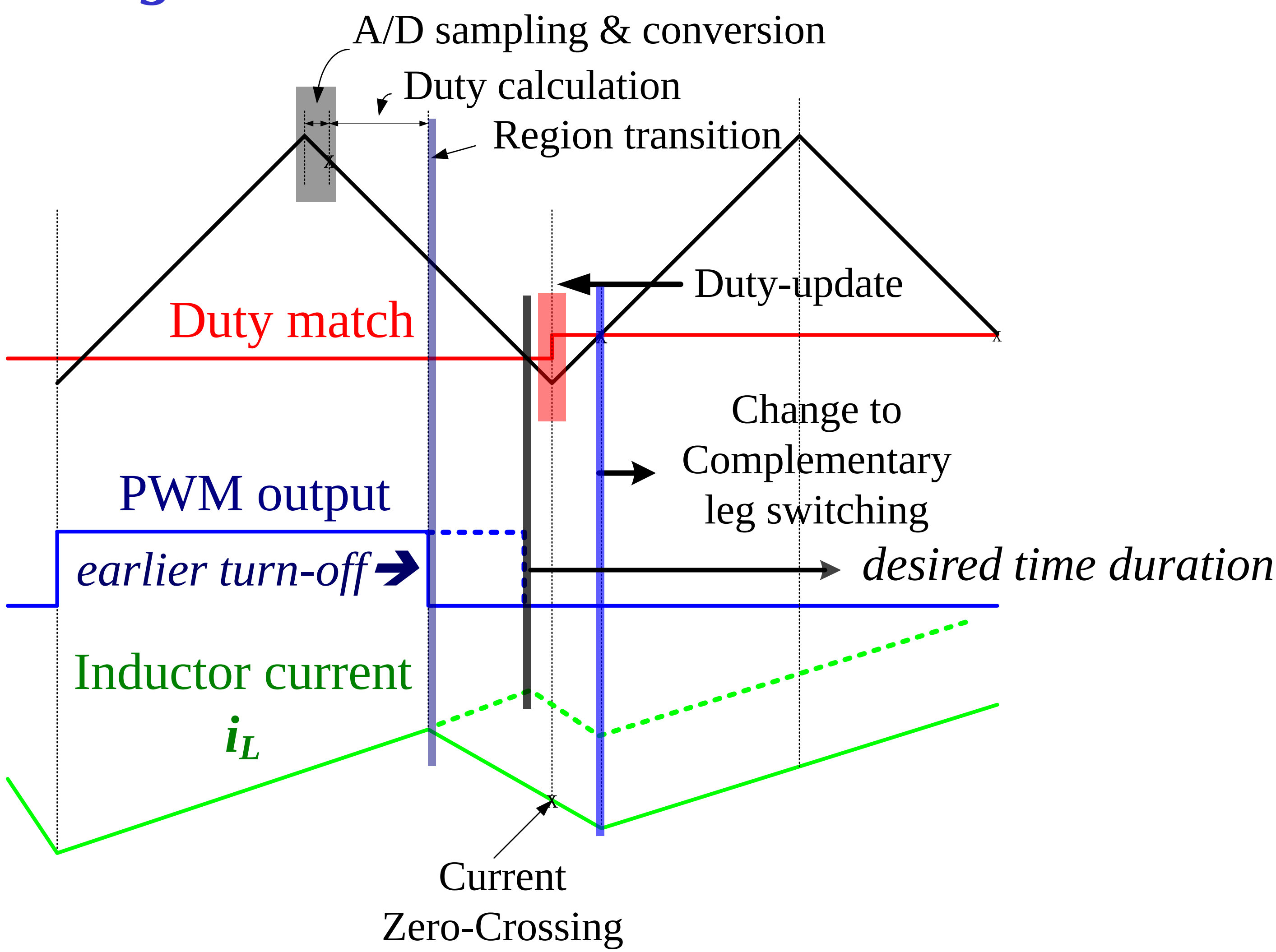
THD = 6 %

(b)

(i_R, i_S and i_T: 1A/div; time: 2ms/div)

Current Improvement

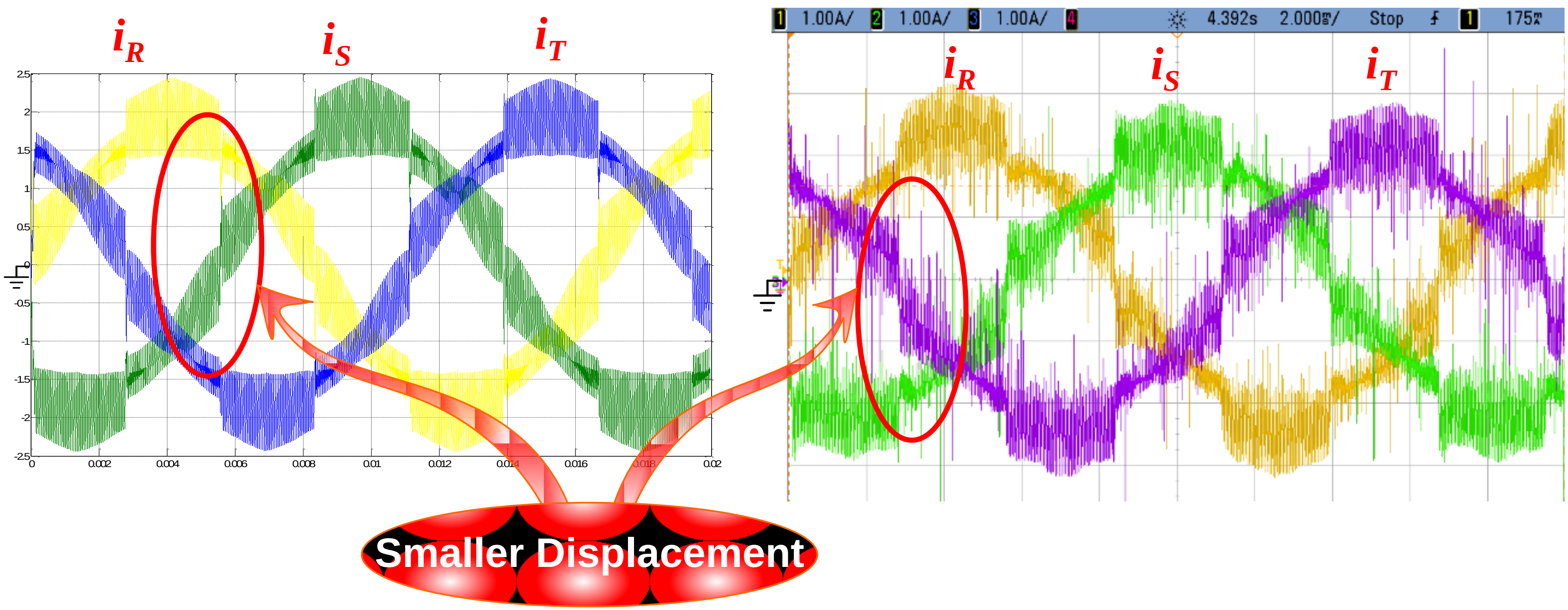
➢ *Smooth Region Transition*



Experimental Results

500 W at Grid-Connection Mode

- *Simulation*
- *Measurement*

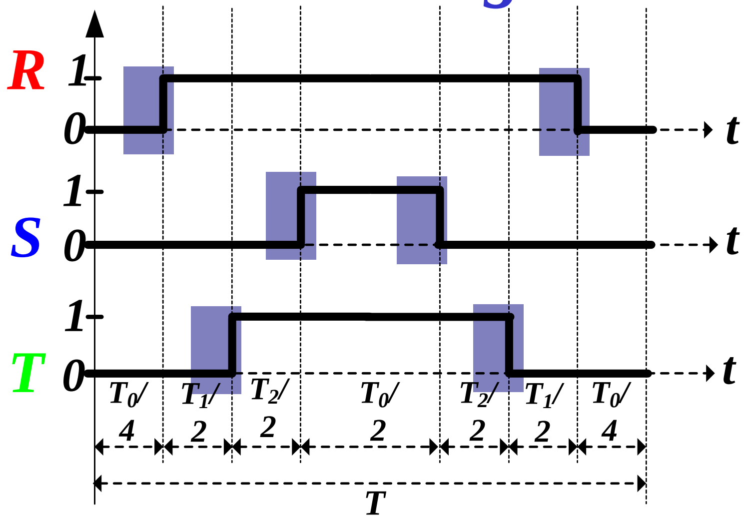


(a)

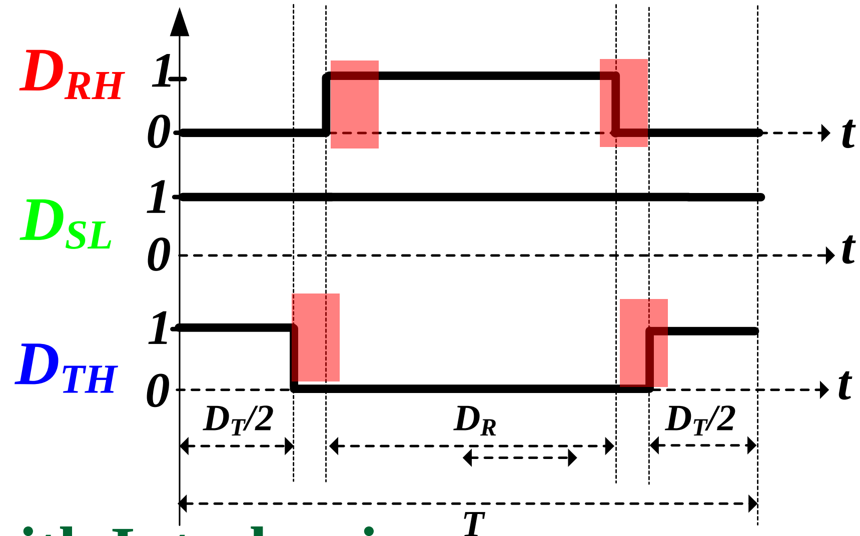
(b)

Current Improvement

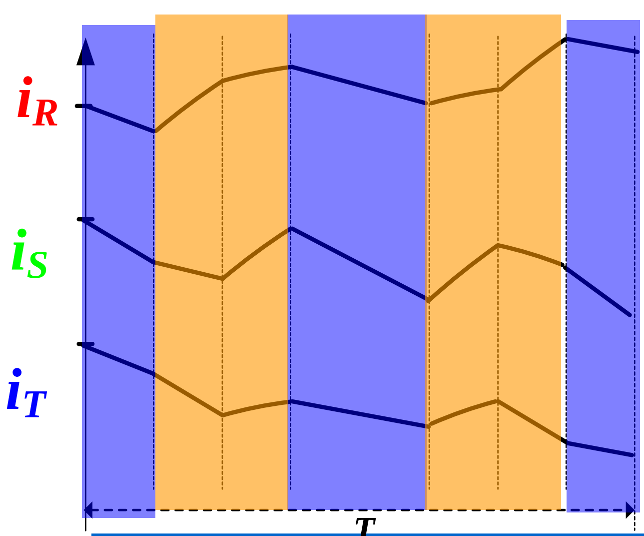
➢ Current Interleaving

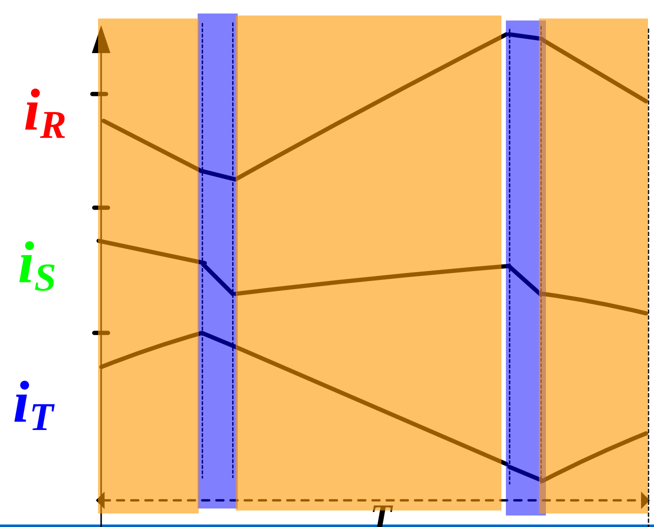


Conventional SVPWM



TPM with Interleaving



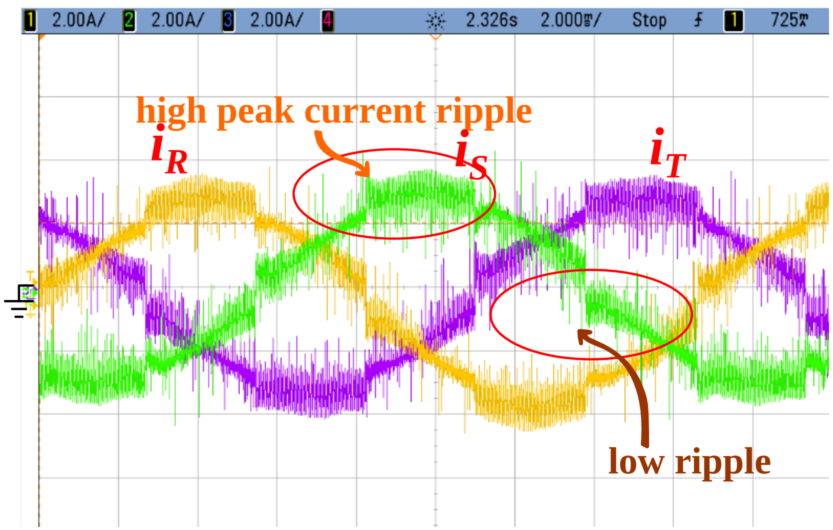


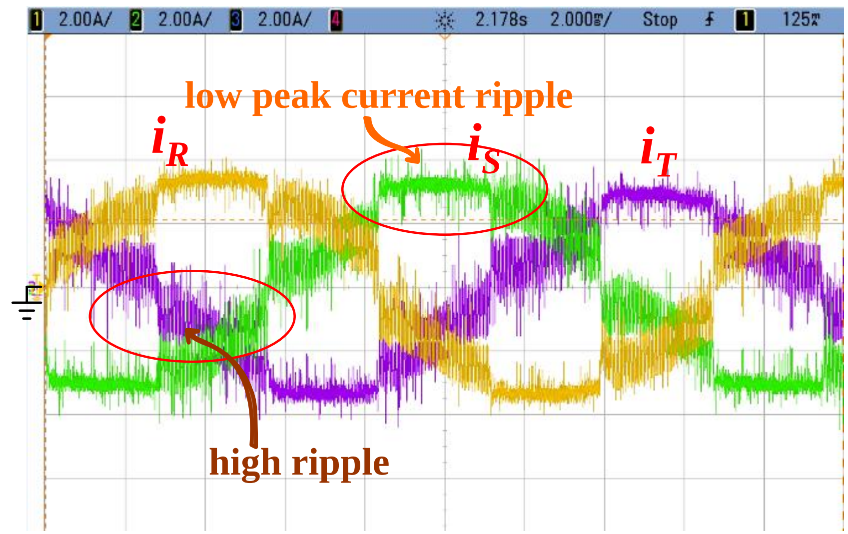
$$i_S = i_R + i_T$$

Experimental Results

800 W at GC Mode

- *Without current interleaving*
- *With current interleaving*





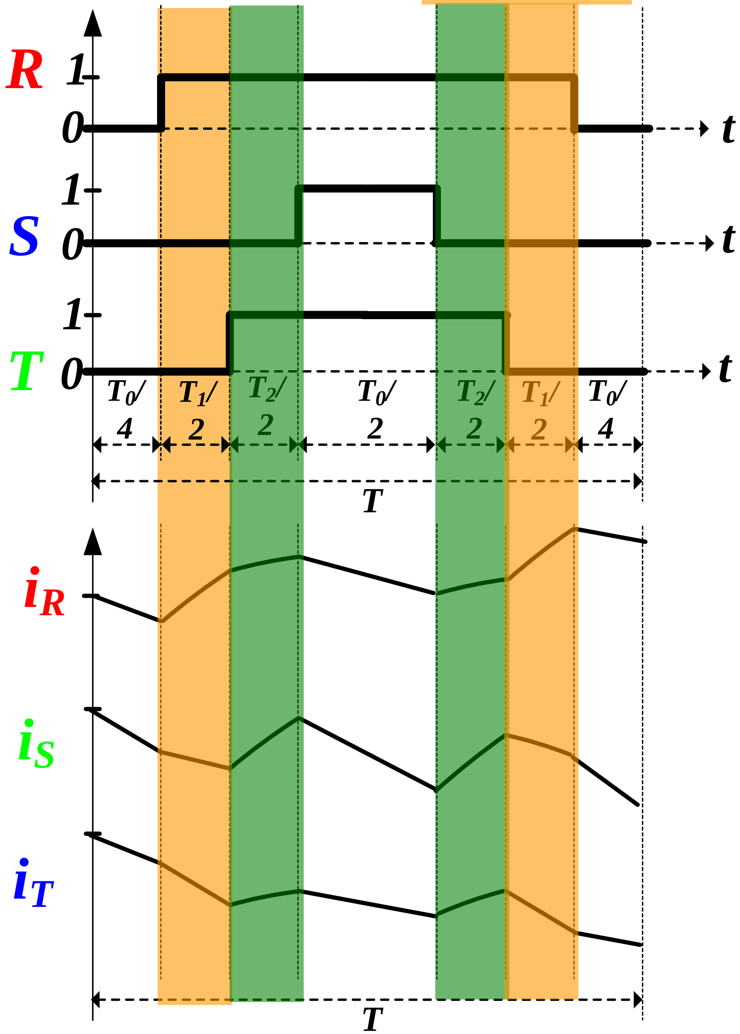
(i_R, i_S and i_T: 2A/div; time: 2ms/div)

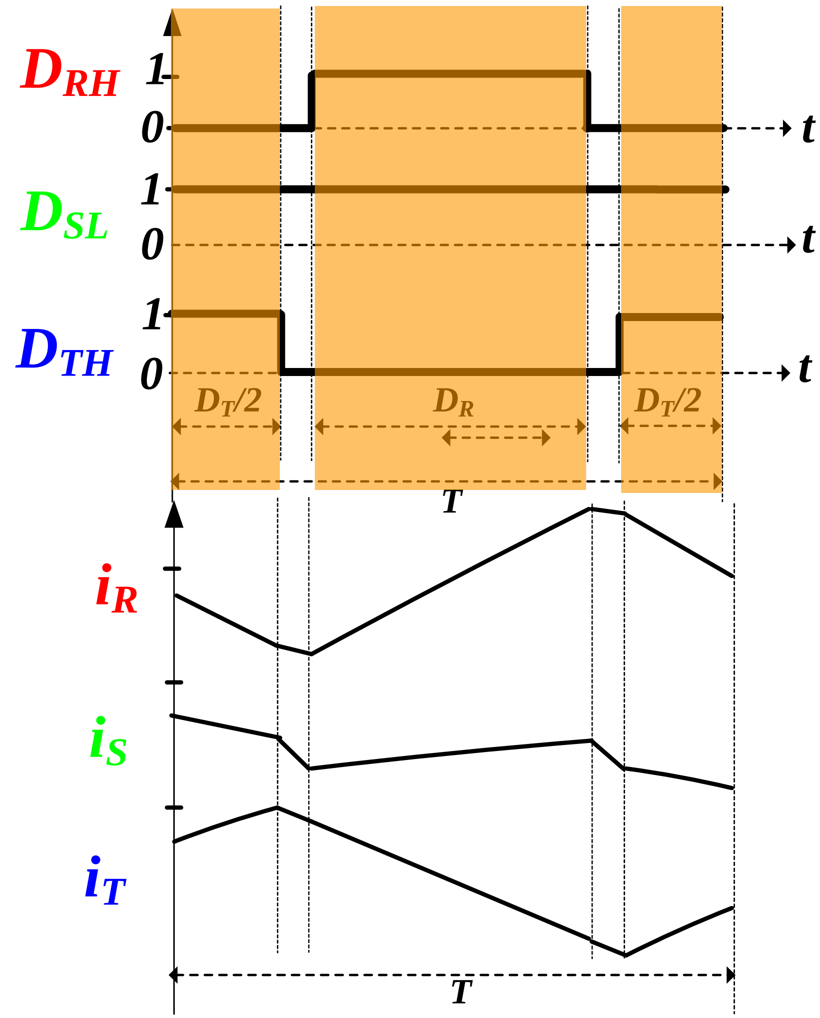
(a) (b)

Current Improvement

- *Current Ripple*

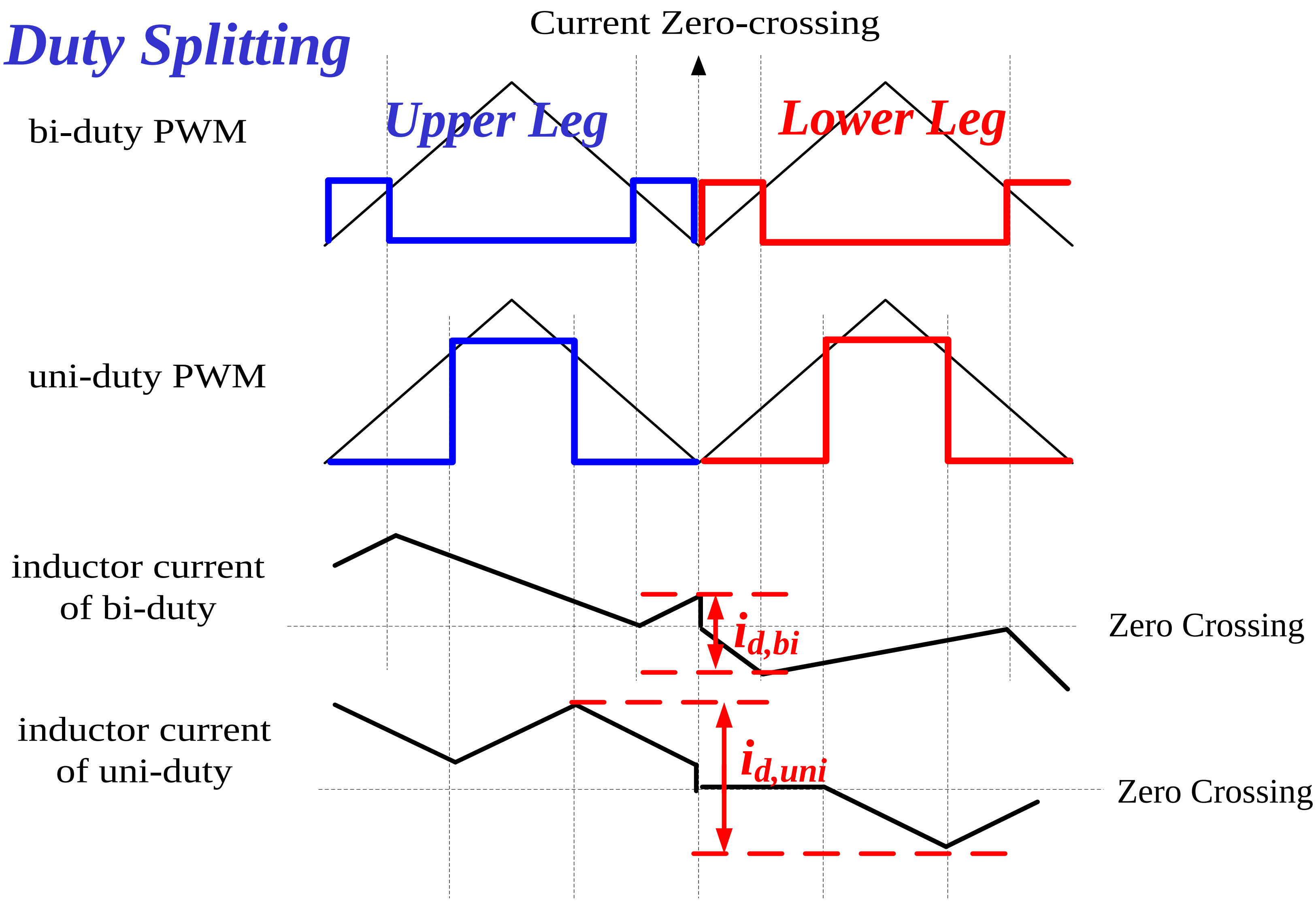
➔ *higher inductor crossing voltage*





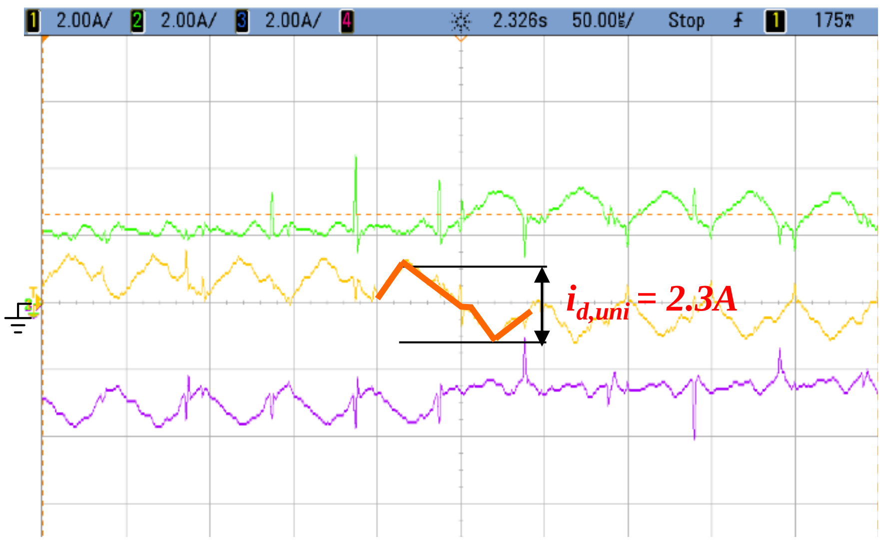
Current Improvement

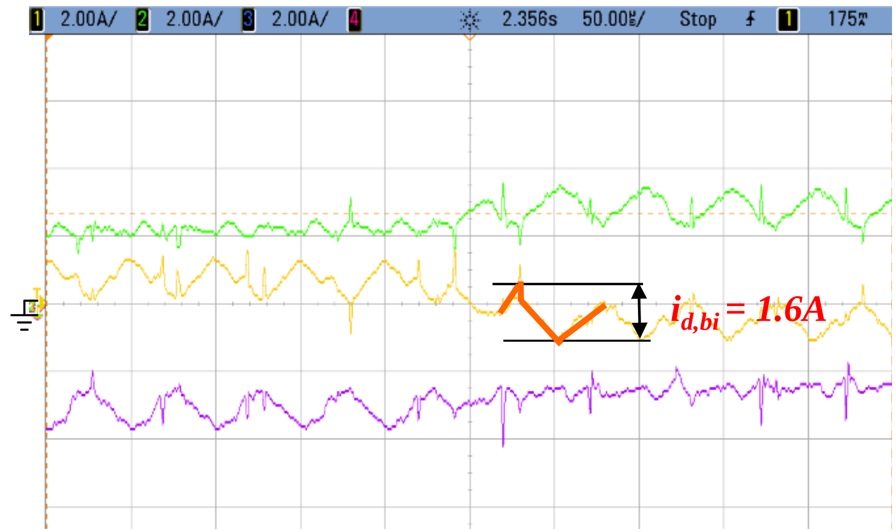
- *Duty Splitting*



Experimental Results

- *uni-duty PWM*
- *bi-duty PWM*





(i_R, i_S and i_T: 2A/div; time: 2ms/div)

(a) (b)

Conclusions

- This paper has derived the predictive current control laws to
  - accommodate wide inductance variation, and
  - reduce core size.
- Mid-point current sampling (with symmetric carrier signal) can improve current distortion.
- Current interleaving approach can be adopted at high power levels to reduce peak current ripple.
- Duty splitting approach: the bi-duty PWM can reduce current displacement at current zero crossing.