A Multi-Pulse Pattern Modulation Scheme for Harmonic Mitigation in Three-Phase Multi-Motor Drives

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Outline

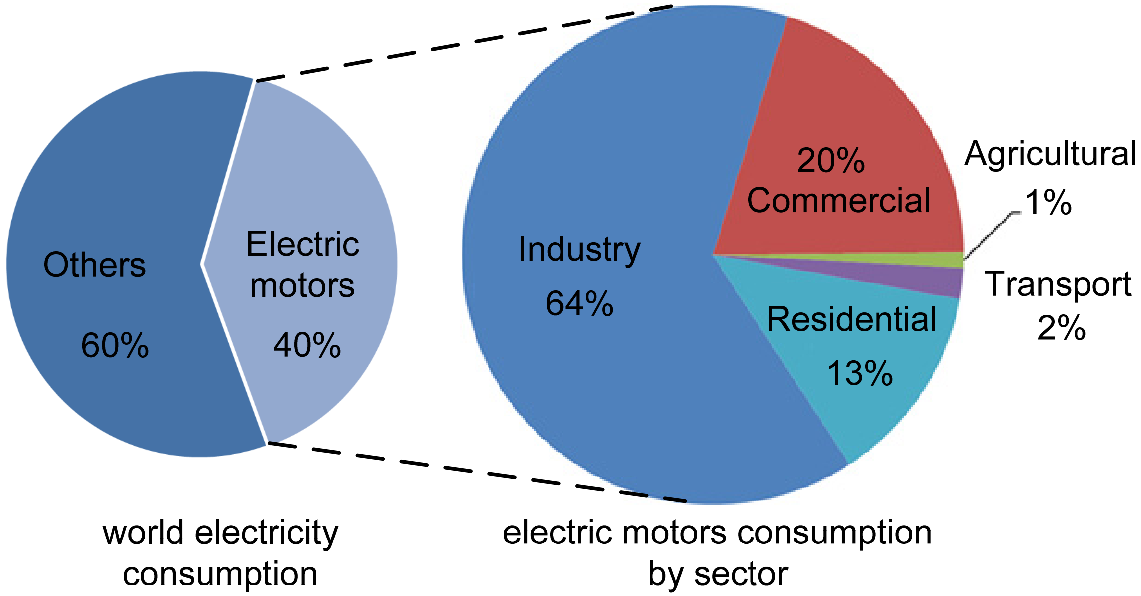
- Introduction (Standard Three-Phase Motor Drive Systems)
- Electronic Inductor
- Proposed Method (Multi-drive configuration)
- Experimental Results
- Conclusion

Introduction

■ Estimated share of electricity consumption for all electric motors

- Developing energy efficient motor drive systems holds a great potential for reducing the worldwide energy consumption.

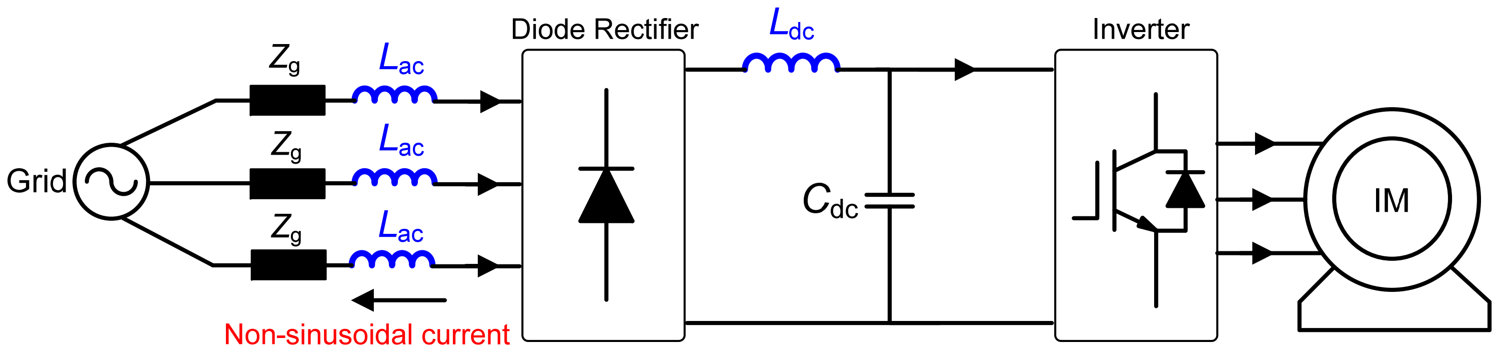
- Introducing Adjustable Speed Drive (ASD) based on power electronics technology leads to more energy efficient motor drive systems.



- From power quality point of view the main concern with ASD systems is the generation of current harmonics which may lead to high losses and stability issues in the grid

Introduction

■ Standard Three-Phase Motor Drive System



- Diode rectifier: simple, cost effective and efficient solution. **But** it imposes high level of input current harmonics.
- AC or DC side passive filtering (inductor): simple and effective to some extent. **But** they are bulky, costly, causes resonance, worsen system dynamic, and etc.
- Active harmonic mitigation solutions have been introduced to improve the input current quality. **But** they are complex, costly and reduce system efficiency.

Introduction

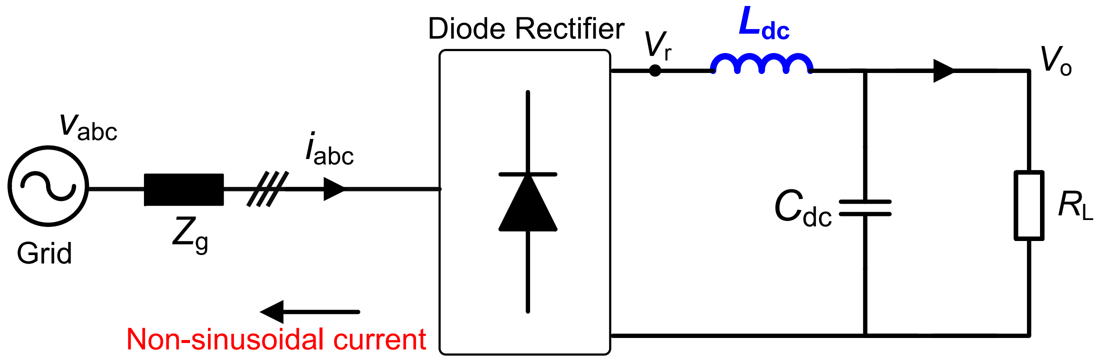
■ Three-Phase Diode Rectifier with DC Side Passive Filtering

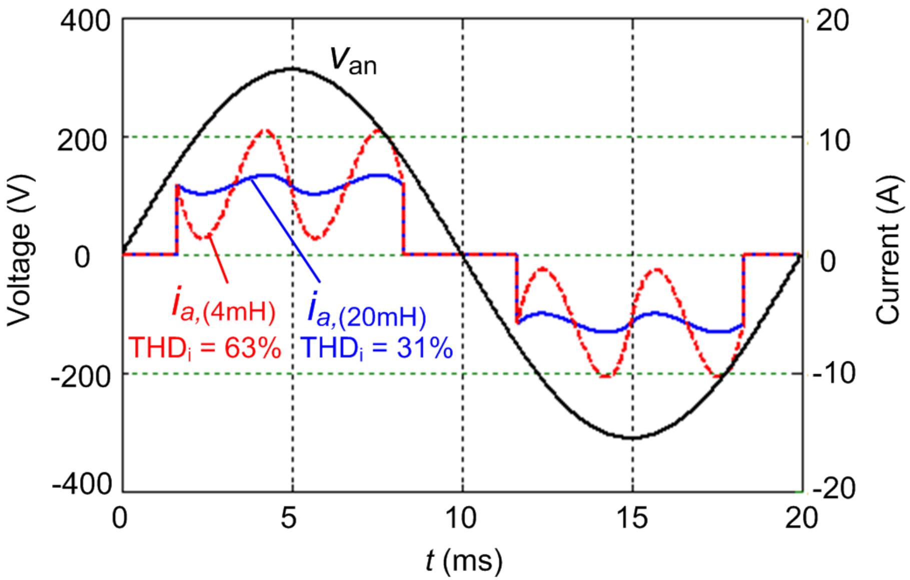
$V_{ph,rms}$ = 3 X 220 V

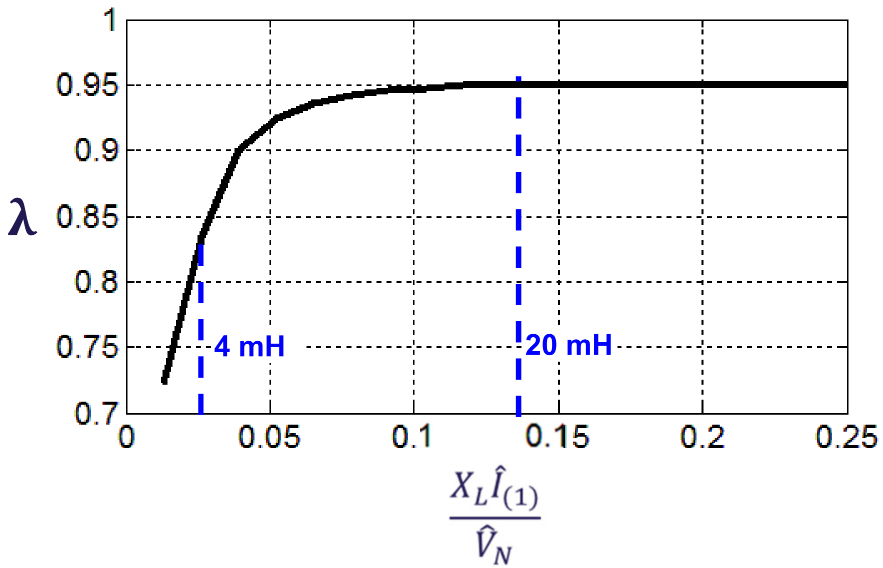
f_g = 50 Hz

P_o = 3 kW

C_{dc} = 470 μF



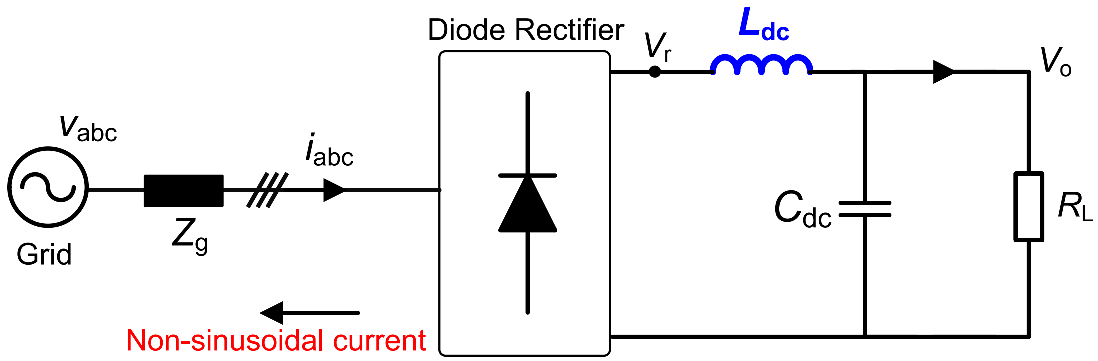


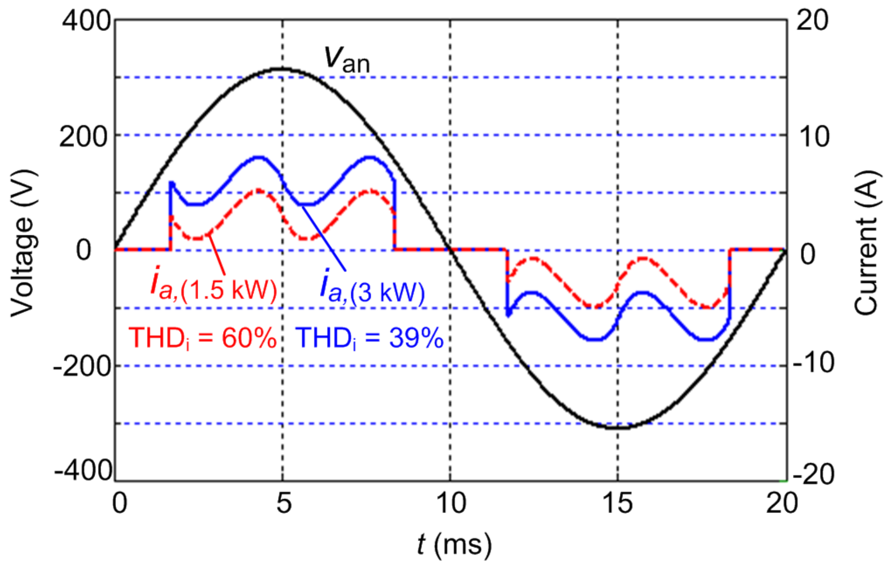


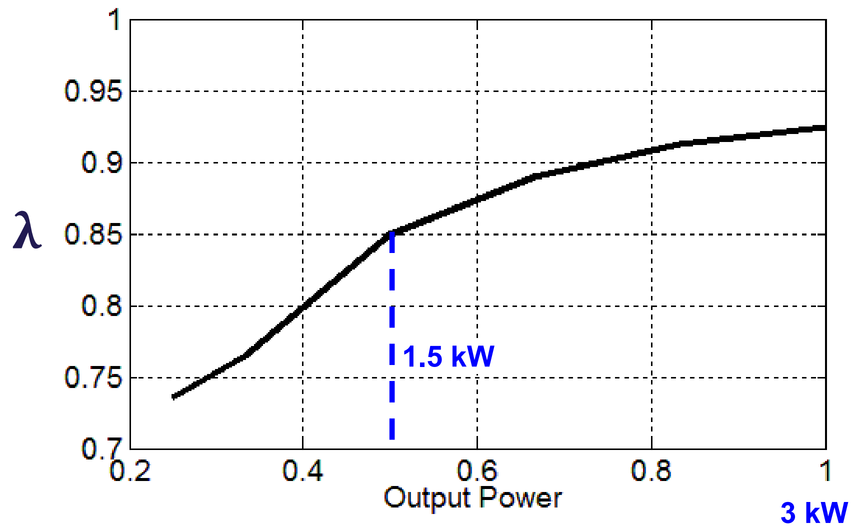
Introduction

■ Three-Phase Diode Rectifier with DC Side Passive Filtering

$V_{ph,rms}$ = 3 X 220 V
f_g = 50 Hz
P_o = 0.75 kW – 3 kW
L_{dc} = 8mH
C_{dc} = 470 μF



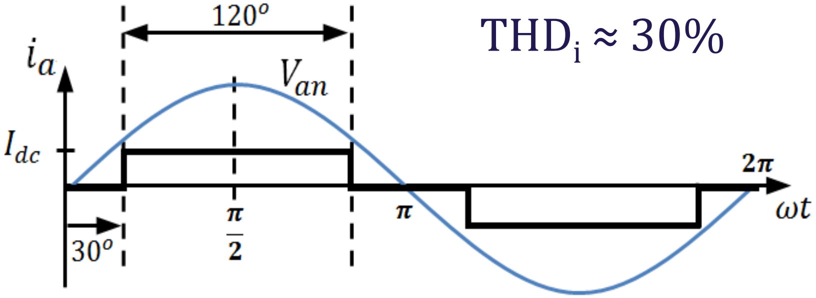




● **The effective impedance reduces proportionally with the reduction in the load current.**

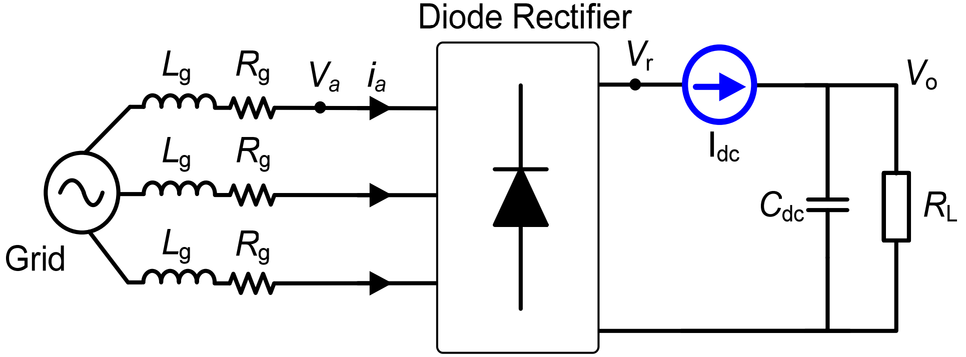
Electronic Inductor

■ Basic Concept



$\lambda \approx 0.95$

$THD_i \approx 30\%$



$$i_a = \frac{4}{n\pi}[I_{dc}\cos(n30)]$$

- **Emulating the behavior of an ideal infinite inductor**
- **THD_i and Power Factor (λ) independent of the load profile.**

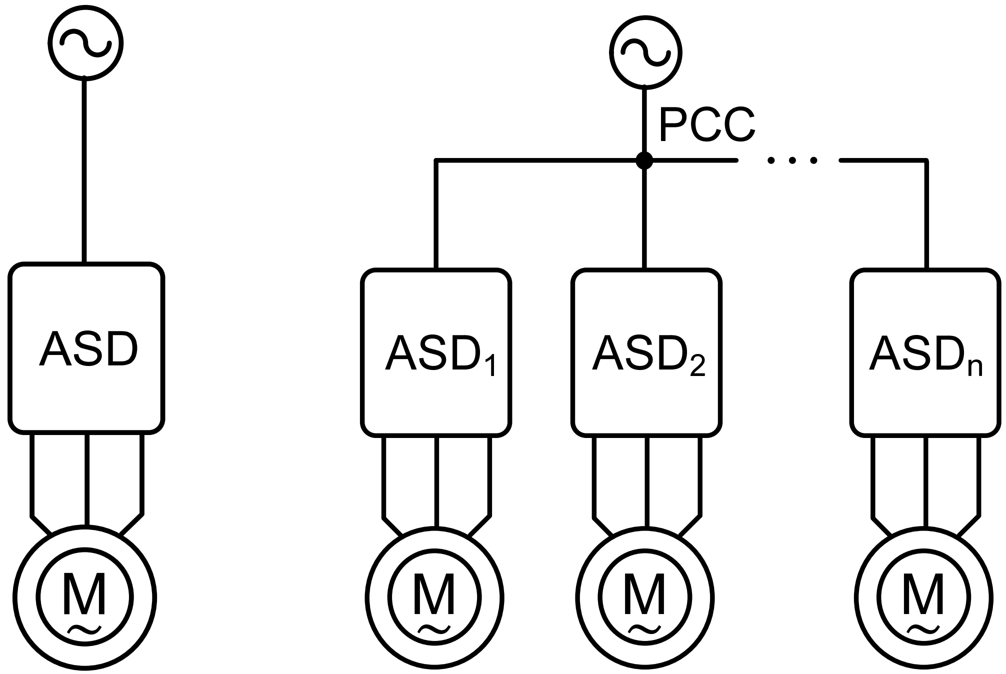
Multi-Drive

■ Improving the input current quality by combining the nonlinear loads

- In many applications it is a common practice to employ parallel connected drive units. In this situation the application demand is met using multiple modestly sized motor units rather than one single large unit.

- The undesirable nonlinearity of the conventional AC-DC conversion stage becomes significant, when a large number of industrial converters and ASD systems are connected to the Point of Common Coupling (PCC).

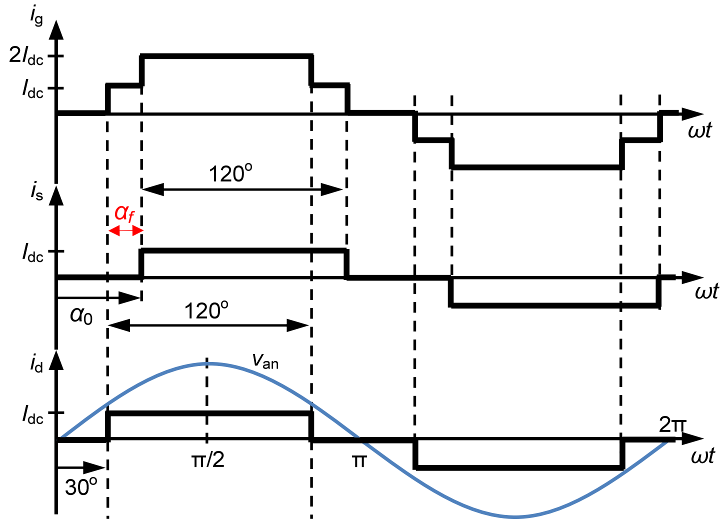
- The feasibility of this solution is attained only when suitable and accessible communication among the nonlinear units can be performed.

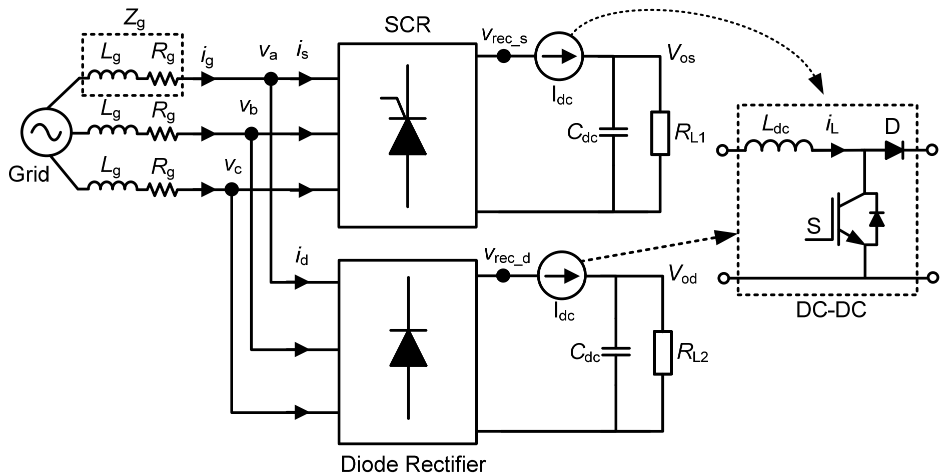


Single-Drive **Multi-Drive**

Multi-Drive (Proposed method)

Basic Concept





$$i_s(n)=\sqrt{(a_n)^2+(b_n)^2} \rightarrow \begin{cases} a_n=\dfrac{2I_{dc}}{n\pi}\left[-\sin(n\alpha_0)+\sin\left(n\alpha_0+\dfrac{2\pi n}{3}\right)\right] \\ b_n=\dfrac{2I_{dc}}{n\pi}\left[\cos(n\alpha_0)-\cos\left(n\alpha_0+\dfrac{2\pi n}{3}\right)\right] \end{cases}$$

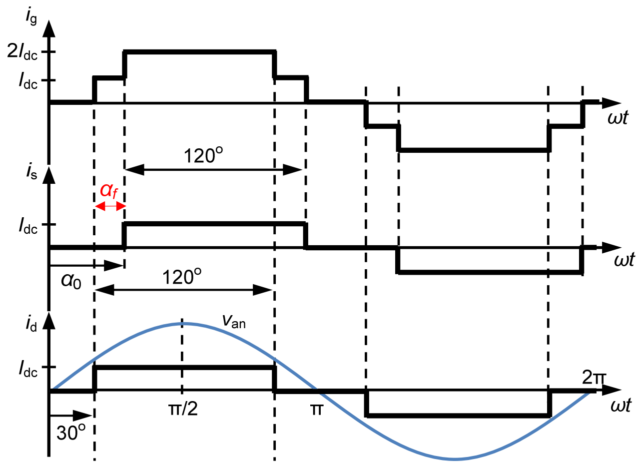
$$i_d(n)=\frac{4I_{dc}}{n\pi}\cos\left(\frac{n\pi}{6}\right)$$

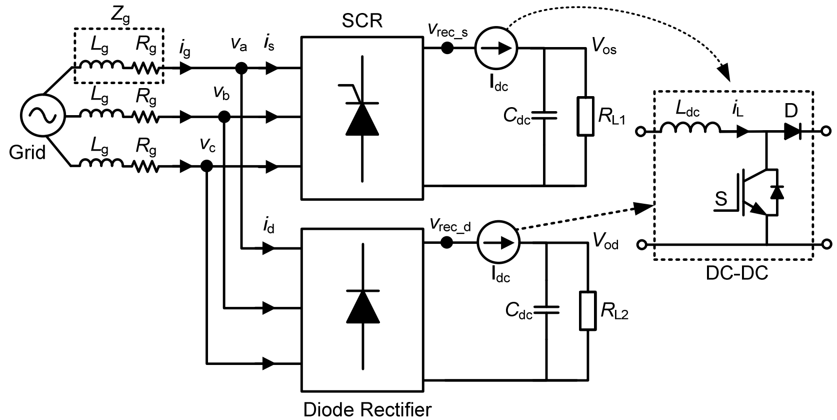
$$\rightarrow i_g(n)=\sqrt{(a_n)^2+\left(i_d(n)+b_n\right)^2}$$

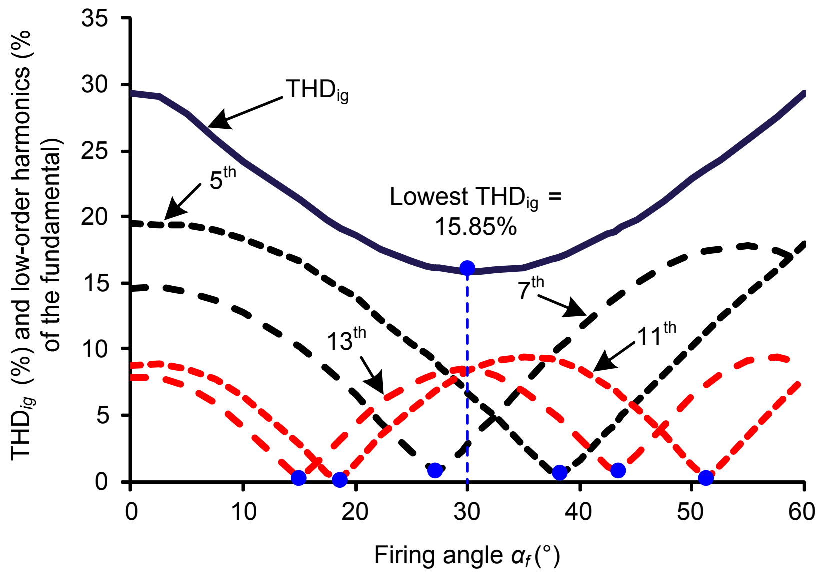
- **Emulating the behavior of an ideal infinite inductor**
- **THD_i and Power Factor (λ) independent of the load profile.**

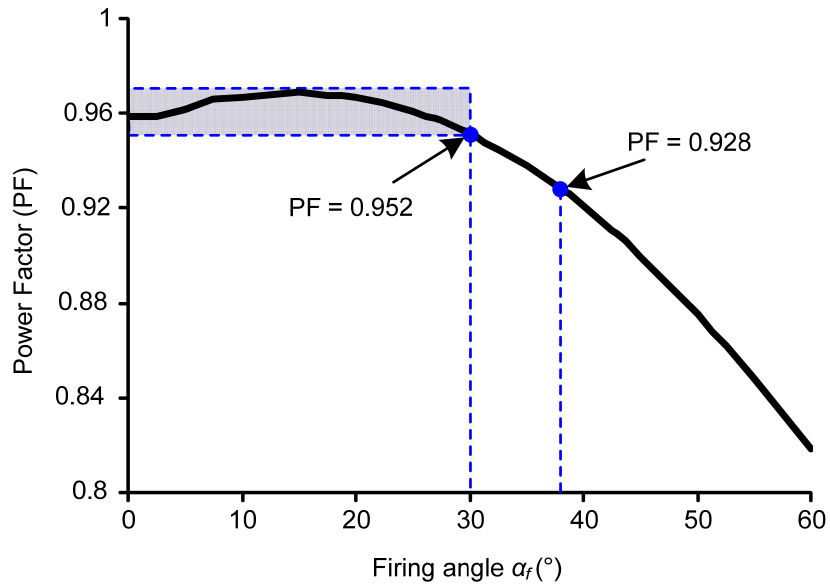
Multi-Drive (Proposed method)

■ Square wave current



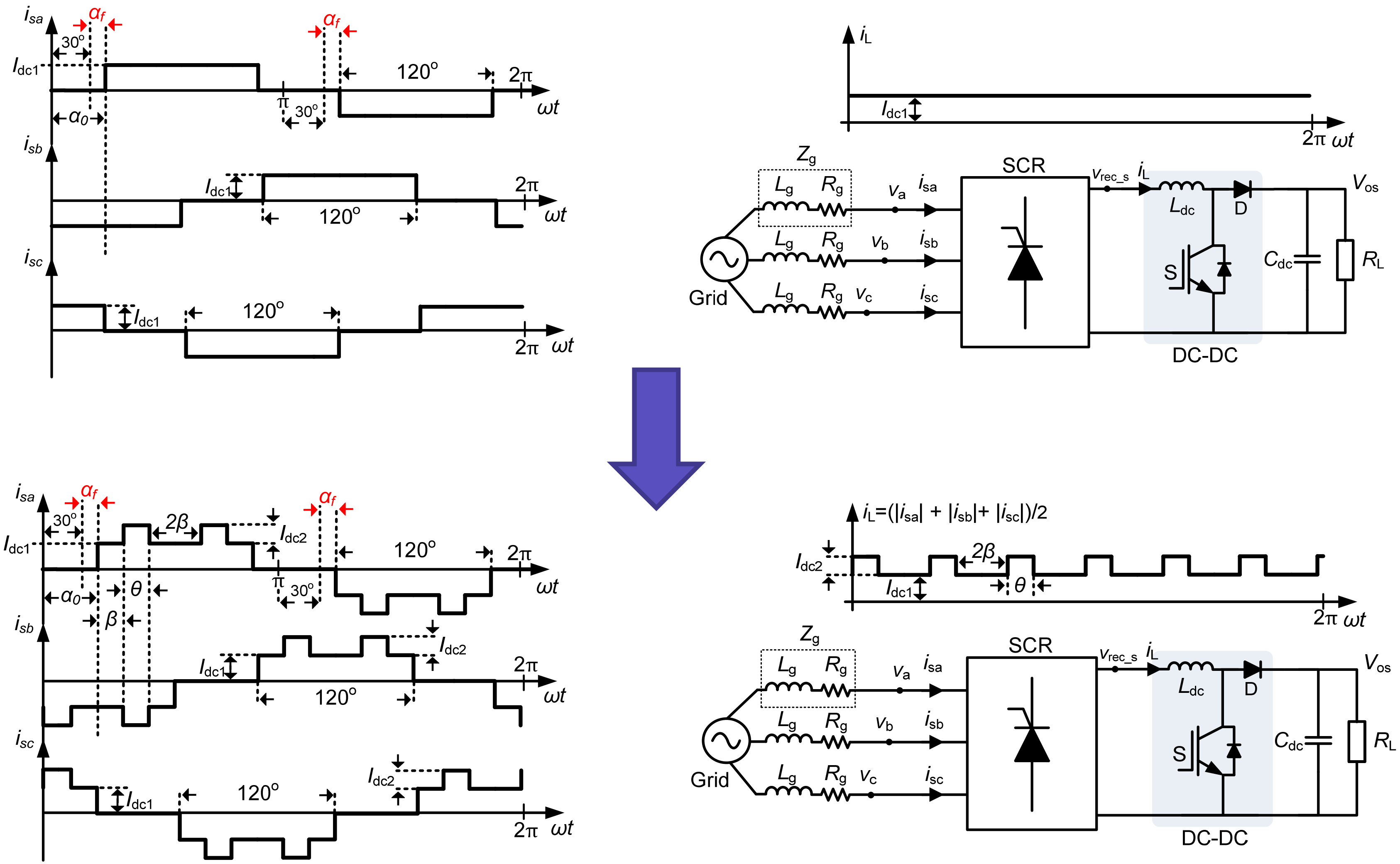






Single-Drive (Proposed method)

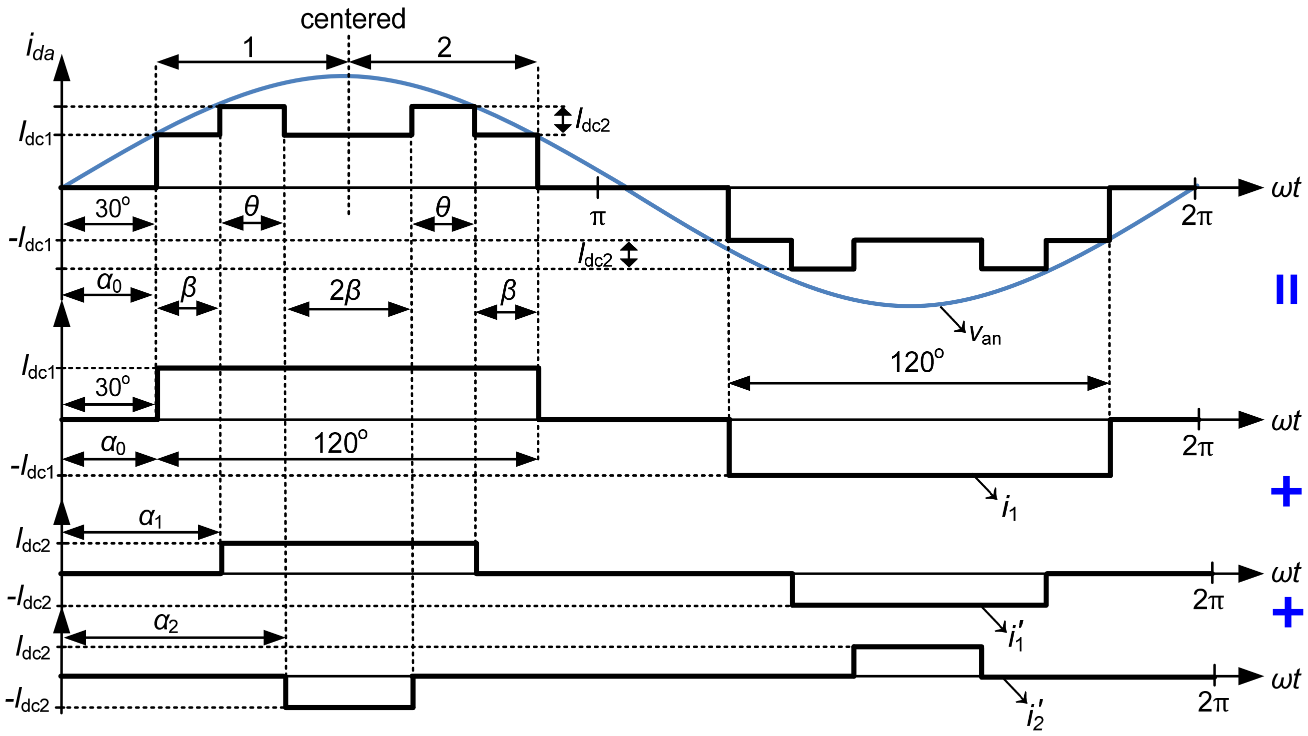
■ Pulse pattern current modulation (extending the system flexibility)



Single-Drive (Proposed method)

- **Pulse pattern current modulation**
  Harmonic Elimination ($\alpha_f = 0^o$)

$$i_d(n) = \frac{4}{n\pi}[I_{dc1}\cos(n30) + I_{dc2}\cos(n\alpha_1) - I_{dc2}\cos(n\alpha_2)]$$



$$= \frac{4}{n\pi}[I_{dc1}\cos(n\alpha_0)] + \frac{4}{n\pi}[I_{dc2}\cos(n\alpha_1)] + \frac{-4}{n\pi}[I_{dc2}\cos(n\alpha_2)]$$

- **Adding or subtracting phase-displaced current levels**

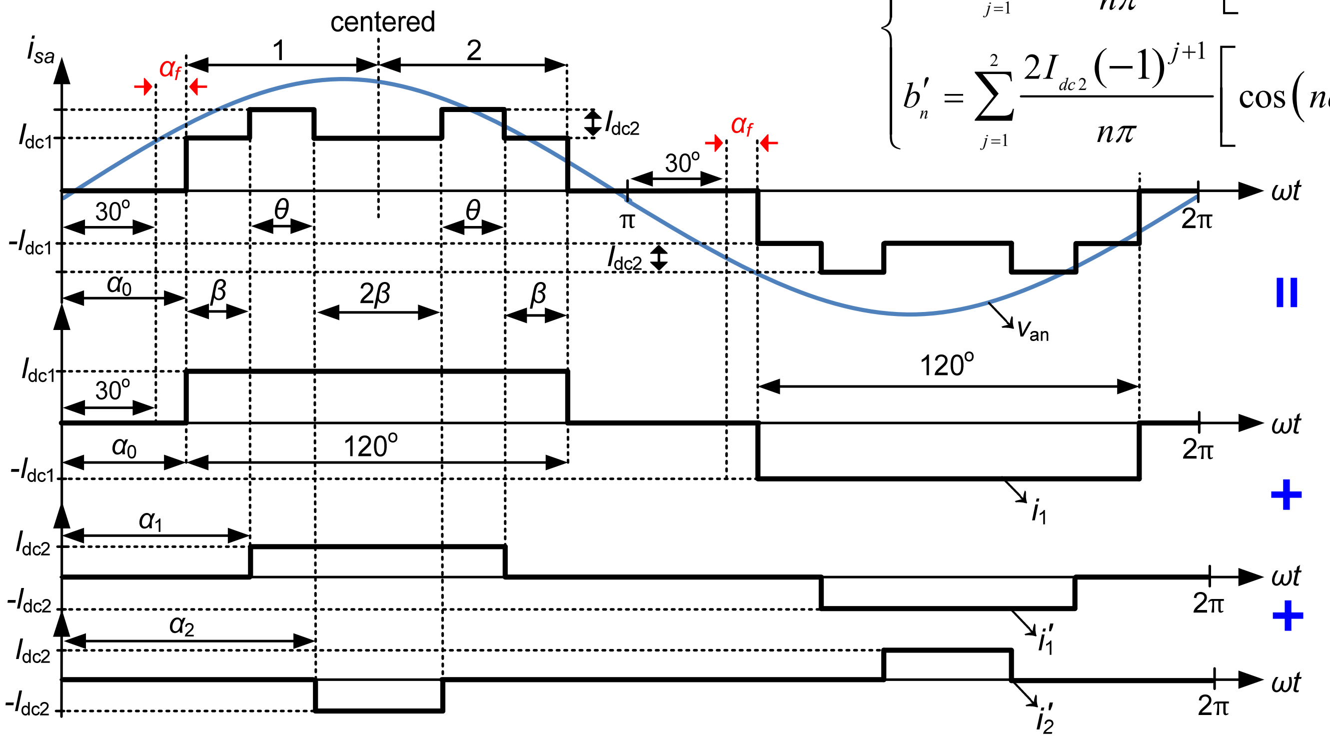
Single-Drive (Proposed method)

- **Pulse pattern current modulation Harmonic Elimination ($\alpha_f \neq 0^o$)**

$$i_s(n) = \sqrt{(a_n + a'_n)^2 + (b_n + b'_n)^2}$$

$$\begin{cases} a_n = \dfrac{2I_{dc1}}{n\pi}\left[-\sin(n\alpha_0) + \sin\left(n\alpha_0 + \dfrac{2\pi n}{3}\right)\right] \\ b_n = \dfrac{2I_{dc1}}{n\pi}\left[\cos(n\alpha_0) - \cos\left(n\alpha_0 + \dfrac{2\pi n}{3}\right)\right] \end{cases}$$

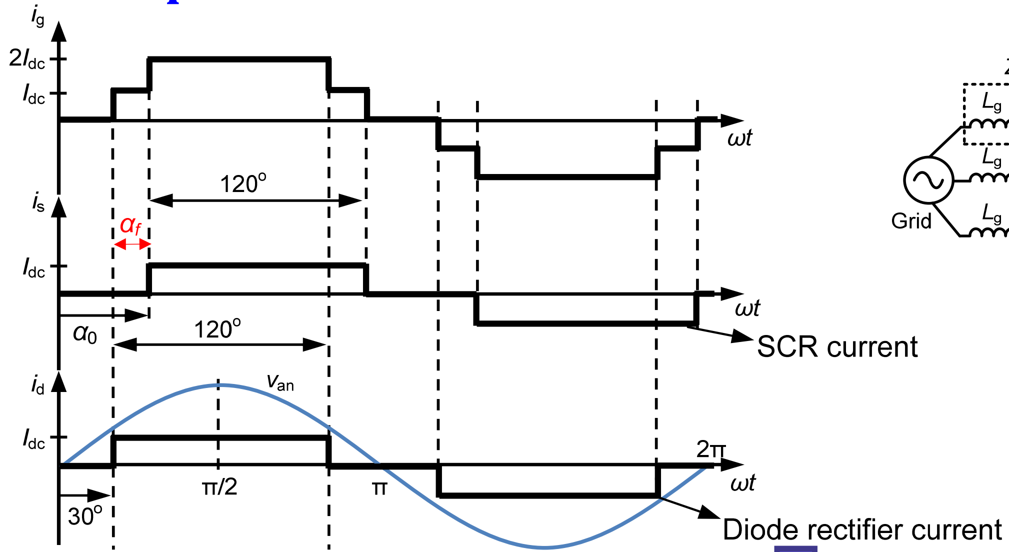
$$\begin{cases} a'_n = \displaystyle\sum_{j=1}^{2} \dfrac{2I_{dc2}(-1)^{j+1}}{n\pi}\left[-\sin(n\alpha_j) + \sin\left(2n\alpha_0 - n\alpha_j + \dfrac{2\pi n}{3}\right)\right] \\ b'_n = \displaystyle\sum_{j=1}^{2} \dfrac{2I_{dc2}(-1)^{j+1}}{n\pi}\left[\cos(n\alpha_j) - \cos\left(2n\alpha_0 - n\alpha_j + \dfrac{2\pi n}{3}\right)\right] \end{cases}$$

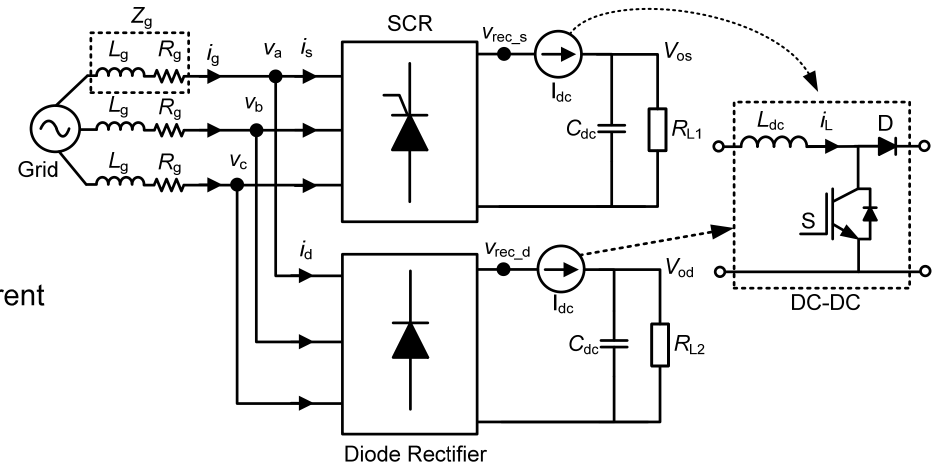


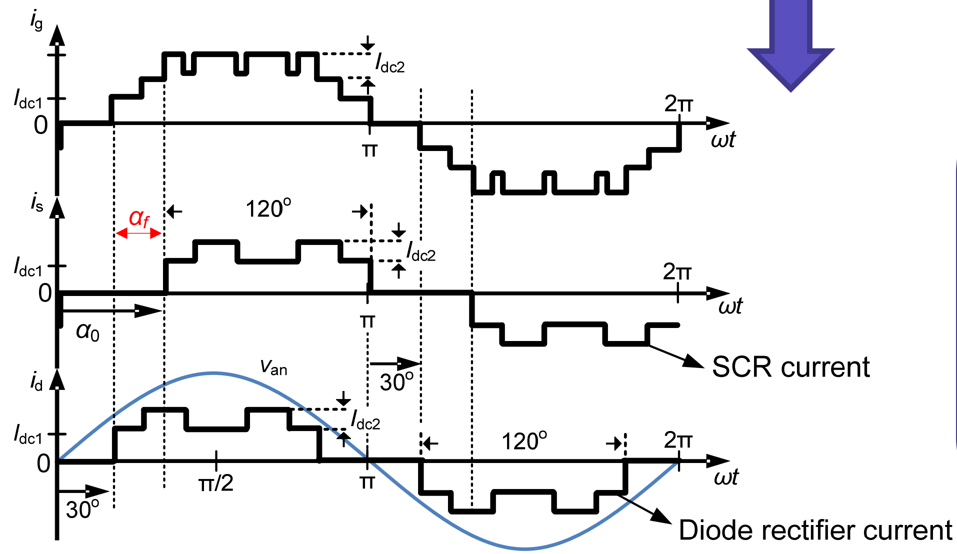
- **Adding or subtracting phase-displaced current levels**

Multi-Drive (Proposed method)

■ Pulse pattern current modulation







- Although an appropriate adjustment of the phase angle of the SCR unit can contribute to an improvement of the current quality, a new current modulation technique is applied to each DC-DC converter in order to further improve the current quality.

Multi-Drive (Proposed method)

■ Pulse pattern current modulation

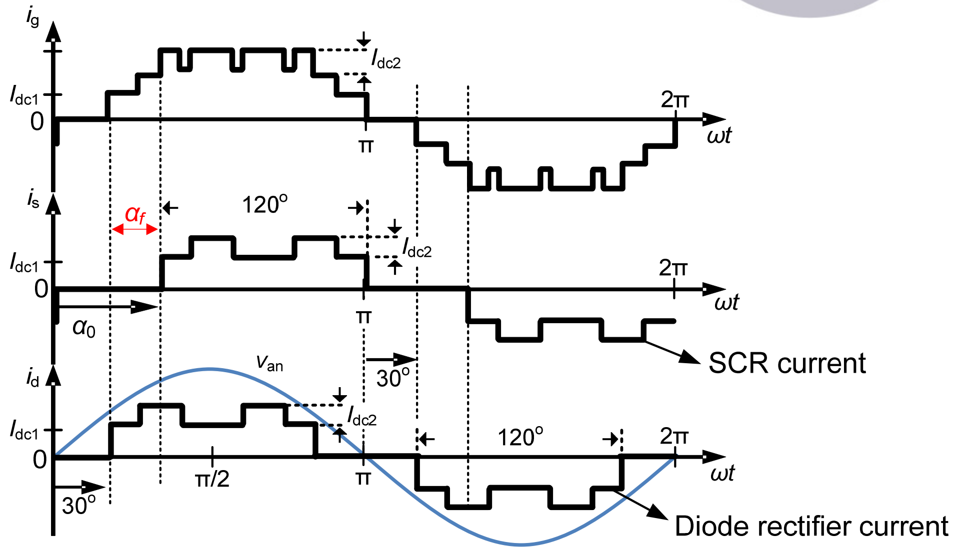
FFT equations

$$i_g(n)=\sqrt{(a_n+a'_n)^2+(i_d(n)+b_n+b'_n)^2}$$

$$\begin{cases} a_n=\dfrac{2I_{dc}}{n\pi}\left[-\sin(n\alpha_0)+\sin\left(n\alpha_0+\dfrac{2\pi n}{3}\right)\right] \\ b_n=\dfrac{2I_{dc}}{n\pi}\left[\cos(n\alpha_0)-\cos\left(n\alpha_0+\dfrac{2\pi n}{3}\right)\right] \end{cases}$$

$$\begin{cases} a'_n=\sum_{j=1}^{2}\dfrac{2I_{dc2}(-1)^{j+1}}{n\pi}\left[-\sin(n\alpha_j)+\sin\left(2n\alpha_0-n\alpha_j+\dfrac{2\pi n}{3}\right)\right] \\ b'_n=\sum_{j=1}^{2}\dfrac{2I_{dc2}(-1)^{j+1}}{n\pi}\left[\cos(n\alpha_j)-\cos\left(2n\alpha_0-n\alpha_j+\dfrac{2\pi n}{3}\right)\right] \end{cases}$$

$$i_d(n)=\frac{4}{n\pi}\left[I_{dc1}\cos\left(\frac{n\pi}{6}\right)+I_{dc2}\cos(n\alpha_1)-I_{dc2}\cos\left(\frac{2\pi n}{3}-n\alpha_1\right)\right]$$



Harmonic Elimination

$$\begin{cases} i_g(1)=M_a \\ a_n+a'_n=0 \\ i_d(n)+b_n+b'_n=0 \end{cases}$$

Multi-Drive (Proposed method)

Optimum Harmonic Solution

Constraint

$$\begin{cases} Obj_1 = M_a - |i_g(1)| \le L_1 \\ Obj_n = \dfrac{|i_g(\mathrm{n})|}{|i_g(1)|} \le L_n \end{cases}$$

$$F_{obj} = \sum w_n \cdot (Obj_n - L_n)^2$$

Objective Function

Weighting Factor

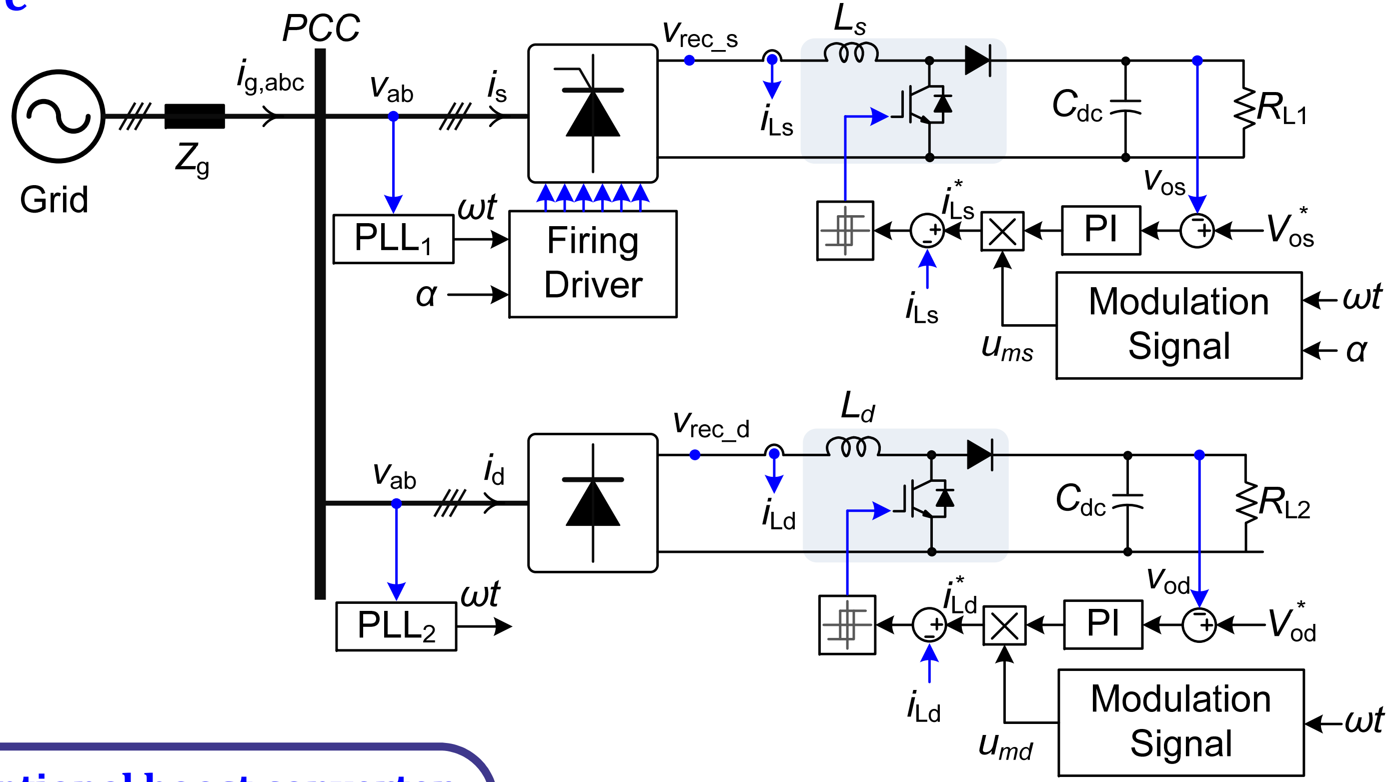
where $n = 6k \pm 1$ with k being 1, 2, 3, ….

$$\alpha_0 < \alpha_1 < \alpha_2 < \cdots < \alpha_m < \alpha_0 + \frac{\pi}{3}$$

- Instead of fully nullifying the distortions, the harmonics could be reduced to acceptable levels by adding suitable constraints (L_n).

- Here, F_{obj} is formed based on a squared error with more flexibility by adding constant weight values (w_n) to each squared error function

System Structure



- Employing conventional boost converter
- Employing fast current control method
- Boosting the output voltage

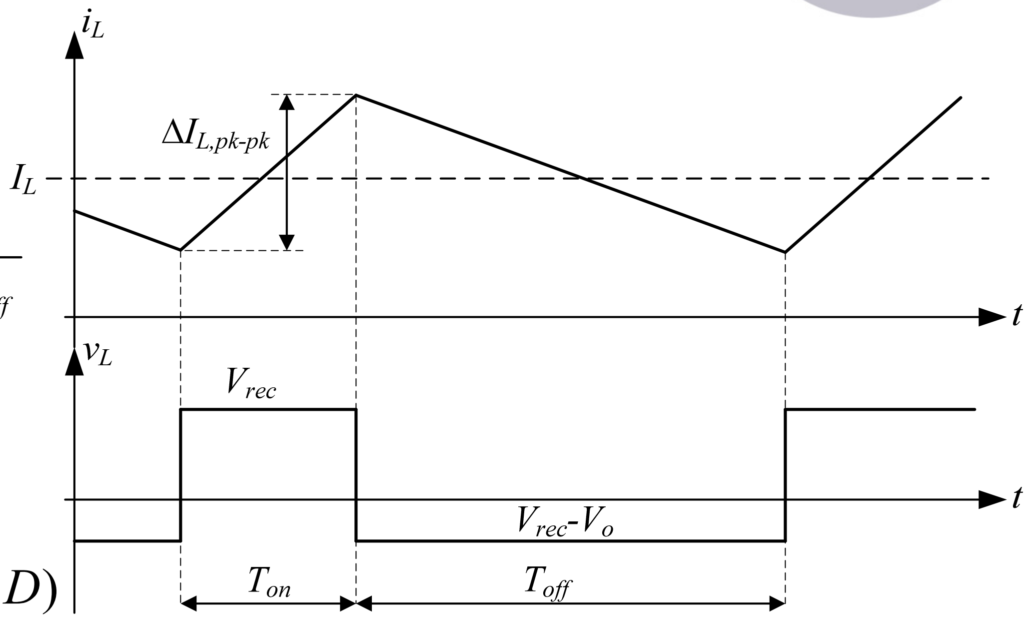
Multi-Drive (Proposed method)

■ Adjustable Switching Frequency

$$f_{sw} = \frac{V_o D(1-D)}{L\Delta I_{L,pk-pk}} \quad \text{where} \quad f_{sw} = \frac{1}{T_{sw}} = \frac{1}{T_{on} + T_{off}}$$

$$f_{sw} = \frac{V_o D(1-D)^2}{L k_{ripple} I_o}$$

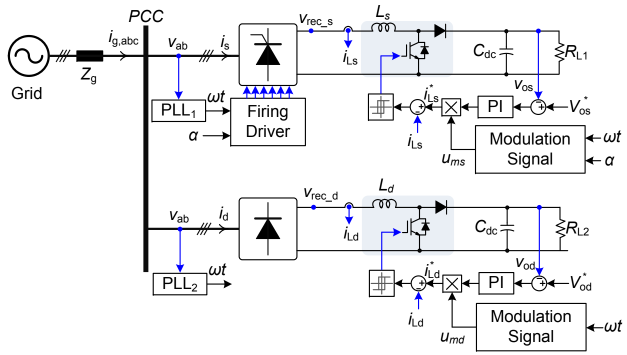
$$\text{where} \quad k_{ripple} = \frac{\Delta I_{L,pk-pk}}{I_L} = \frac{\Delta I_{L,pk-pk}(1-D)}{I_o}$$



- **Independent of the load profile**
- **Low switching frequency at high power and high switching frequency at low power**

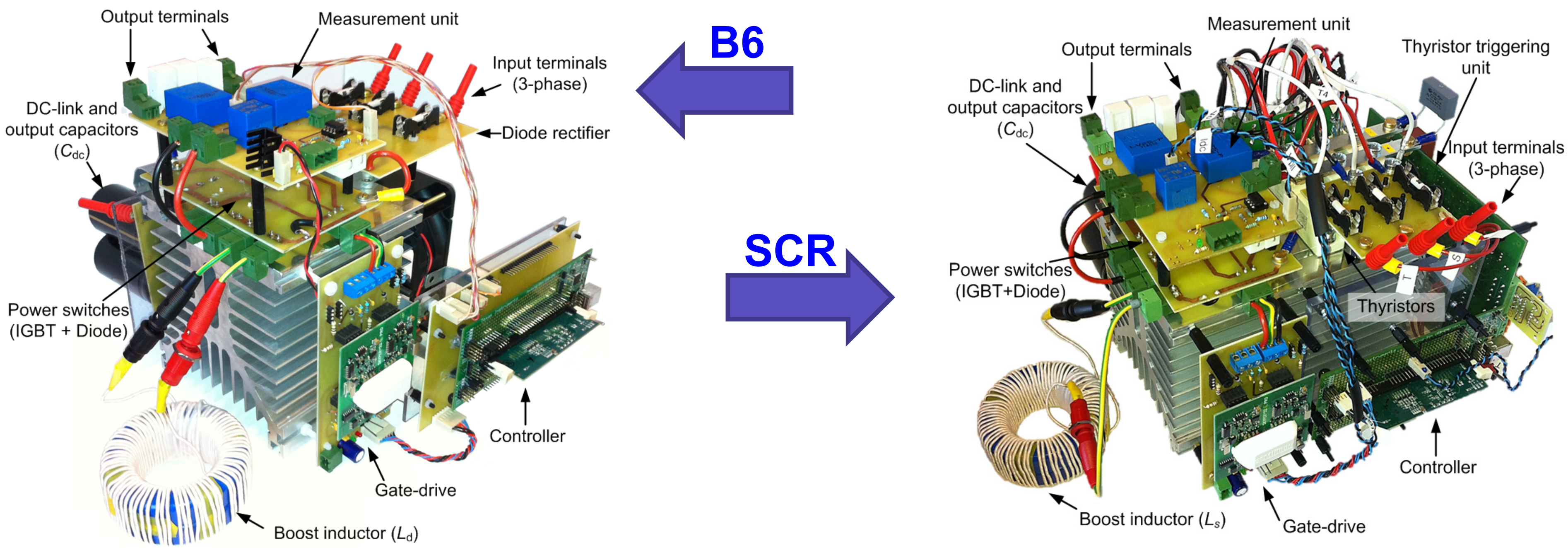
Multi-Drive (Proposed method)

Implemented Setup



Parameters of the multi-rectifier system

Symbol	PARAMETER	Value
$v_{g,abc}$	Grid phase voltage	220 V_{rms}
f_g	Grid frequency	50 Hz
Z_g (L_g, R_g)	Grid impedance	0.1 mH, 0.01 Ω
L_{dc}	DC link inductor	2 mH
C_{dc}	DC link capacitor	470 µF
V_o	Output voltage	700 V_{dc}
K_p, K_i	PI controller (Boost converter)	0.01, 0.1
K_f, t_s, ξ	PLL parameters	0.8, 0.2 s, 1.41
HB	Hysteresis Band	2A
P_{o_total}	Total output power	≈5.5 kW

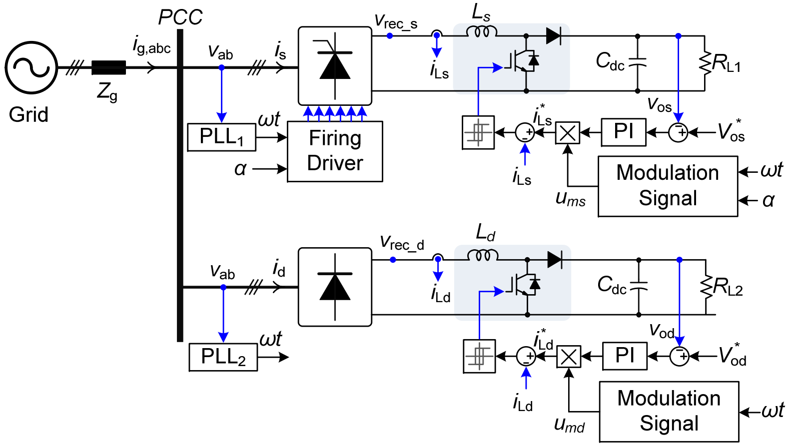


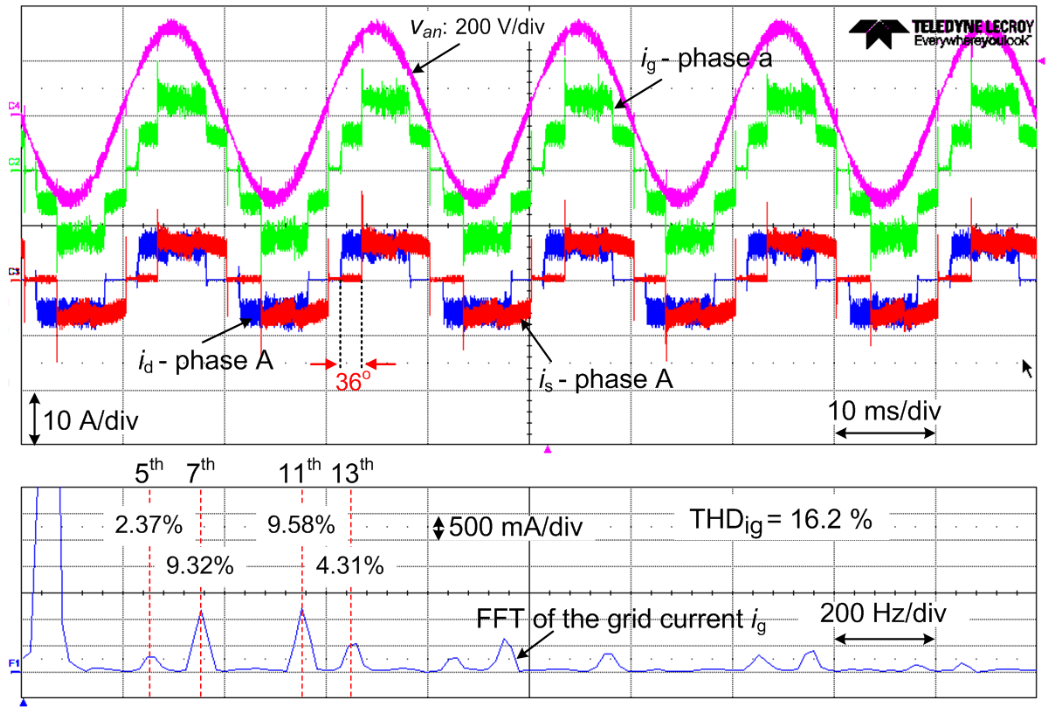
Experimental Results

■ Flat current ($\alpha_f = 36^o$)

$V_o = 700\ V_{dc}$

$L_d = L_s = 2mH$



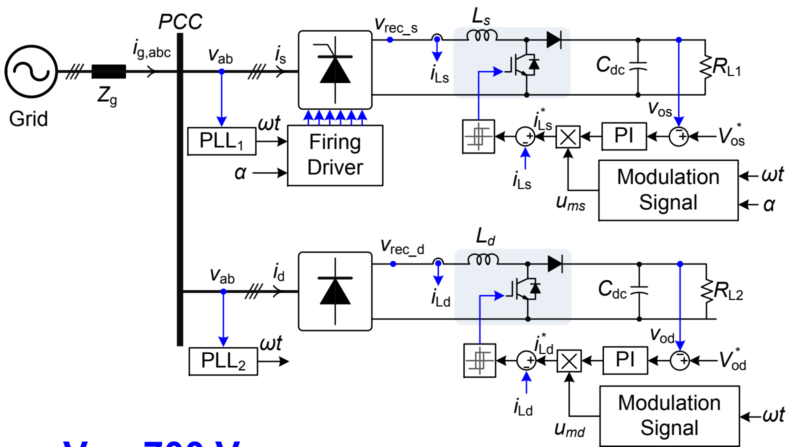


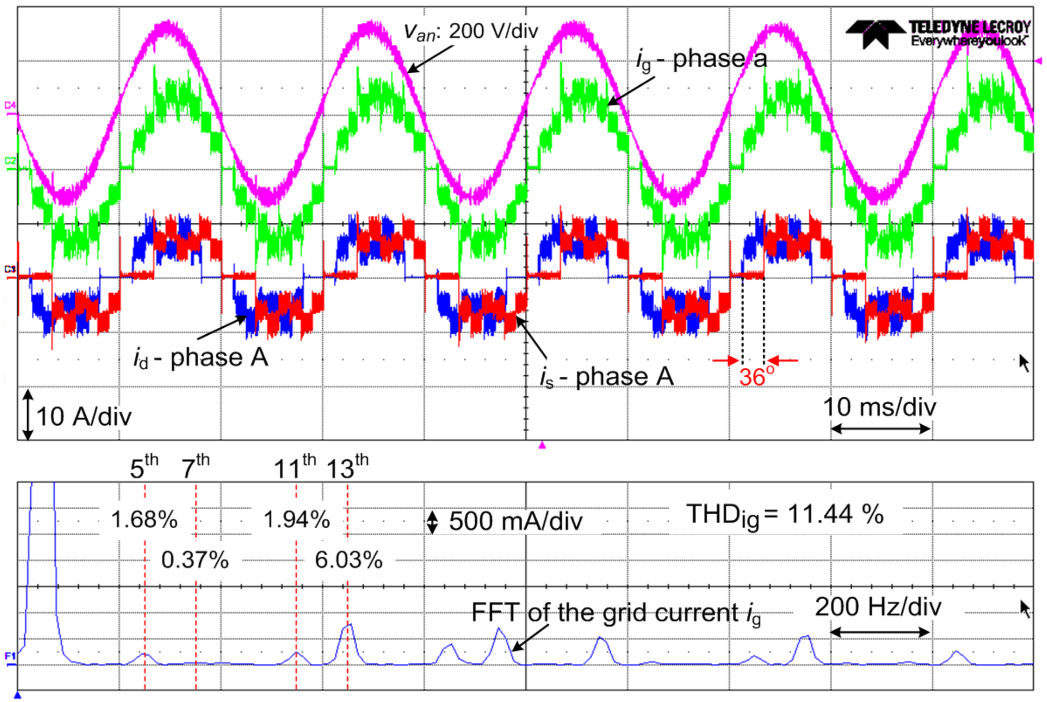
5 X 36° = 180°

Harmonic Mitigation Strategy	Harmonic Distribution and THD_i (%)				
	$i_a(5)/i_a(1)$	$i_a(7)/i_a(1)$	$i_a(11)/i_a(1)$	$i_a(13)/i_a(1)$	THD_i
Square wave ($\alpha_f = 36^o$)	2.4	9.3	9.6	4.3	16
Conventional method (square wave $\alpha_f = 0^o$)	20.8	13.1	8.8	7	29

Experimental Results

- **Optimized for low order harmonics (5^{th}, 7^{th} and 11^{th}) + $THD_i < 12\%$**





$V_o = 700\ V_{dc}$

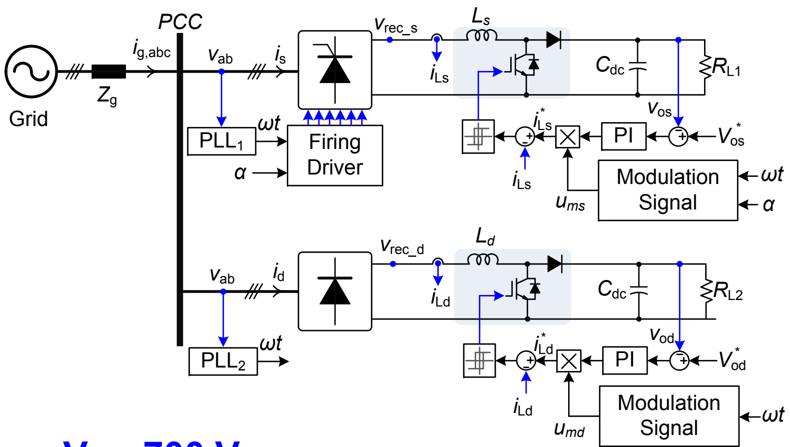
$L_d = L_s = 2mH$

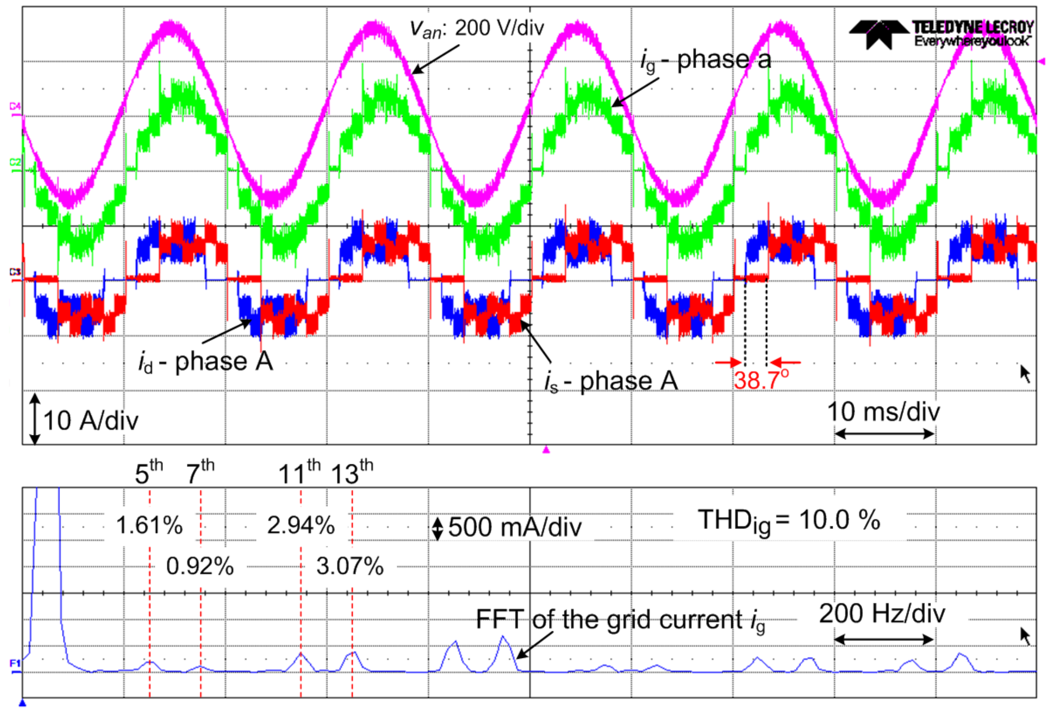
Diode Rectifier			SCR			
I_{dc1}	I_{dc2}	α_1^o	I_{dc1}	I_{dc2}	α_1^o	α_f^o
0.4	0.22	50	0.4	0.22	50	36

Harmonic Mitigation Strategy	Harmonic Distribution and THD_i (%)				
	$i_a(5)/ i_a(1)$	$i_a(7)/ i_a(1)$	$i_a(11)/ i_a(1)$	$i_a(13)/ i_a(1)$	THD_i
Optimized I	1.7	0.4	1.9	6	11.4
Conventional method (square wave α_f = 0°)	20.8	13.1	8.8	7	29

Experimental Results

■ Optimized for minimum THD_i





V_o = 700 V_{dc}

$L_d = L_s$ = 2mH

Diode Rectifier			SCR			
I_{dc1}	I_{dc2}	α_1°	I_{dc1}	I_{dc2}	α_1°	α_f°
0.41	0.2	50	0.41	0.2	49.9	38.7

Harmonic Mitigation Strategy	Harmonic Distribution and THD_i (%)				
	$i_a(5)/i_a(1)$	$i_a(7)/i_a(1)$	$i_a(11)/i_a(1)$	$i_a(13)/i_a(1)$	THD_i
Optimized II	1.6	0.92	2.9	3	10
Conventional method (square wave α_f = 0°)	20.8	13.1	8.8	7	29

Conclusion

- New harmonic elimination approach by combining different non-linear loads. By adjusting phase angle of SCR units.

- Applying a novel current modulation scheme to further improve the current quality.

- THD_i is independent of the load profile

- As long as the following equation holds true, the rectifiers will draw equal amount of current form the grid; otherwise it should be reflected in the optimization process.

$$\frac{P_{o\_d}}{P_{o\_s}} \times \cos(\alpha_f) = 1$$

Thank You