Harmonics in Grid-Connected Converters:
challenges and cost-effective opportunities in ASD systems

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New Harmonic Reduction Techniques for Motor Drives (NHTD)

NHTD has two work-packages based on the harmonic mitigation techniques and solutions as follows:

1- *Single Drive Systems*

2- *Multi Drive Systems*

MAY 2014 → APRIL 2017

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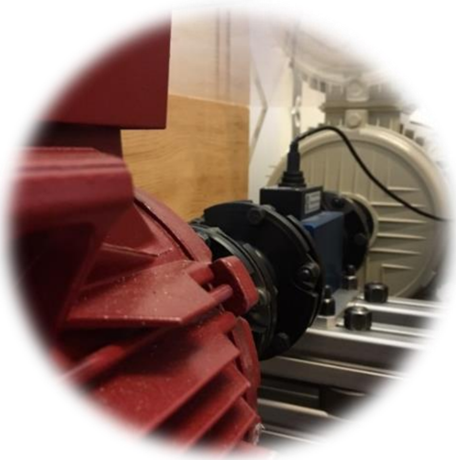
Outline

- Introduction (three-phase diode front-end)
- Electronic Inductor (EI) Concept
- *Proposed Selective Harmonic Mitigation*
- *Multi-Drive Systems*
- *Experimental Results*
- Conclusion

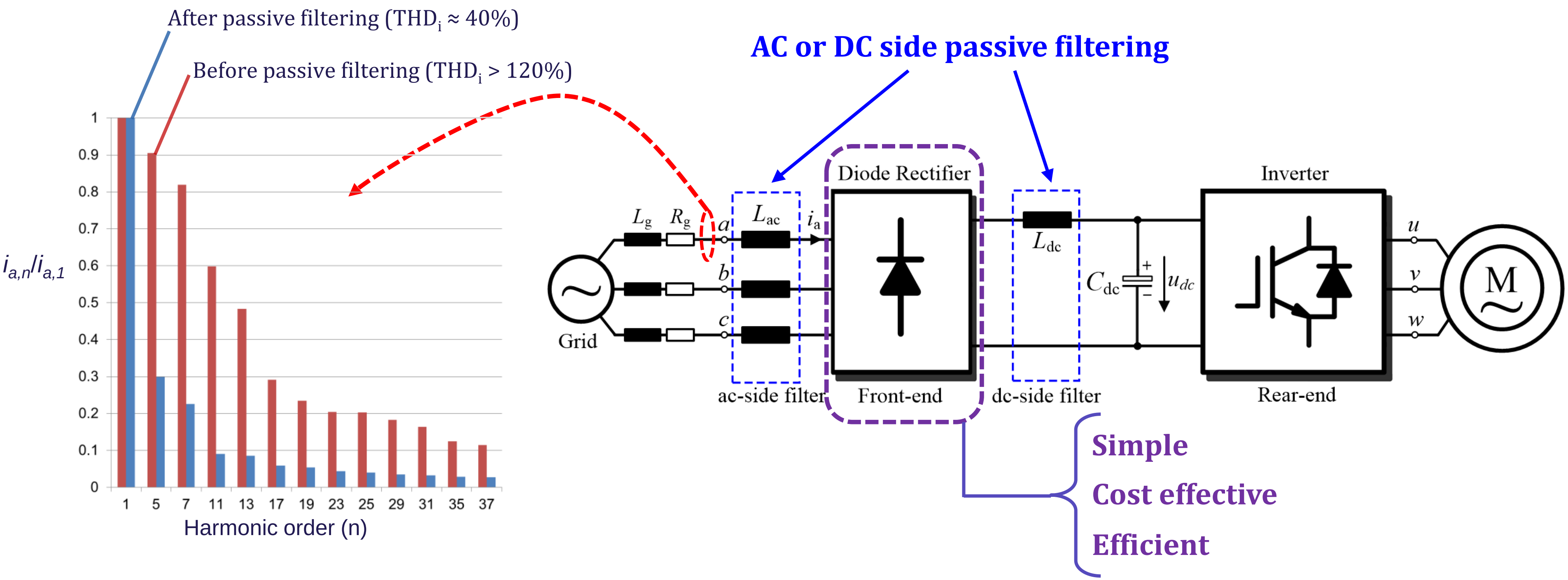
Introduction

- *Three-Phase Diode Front-End System* →



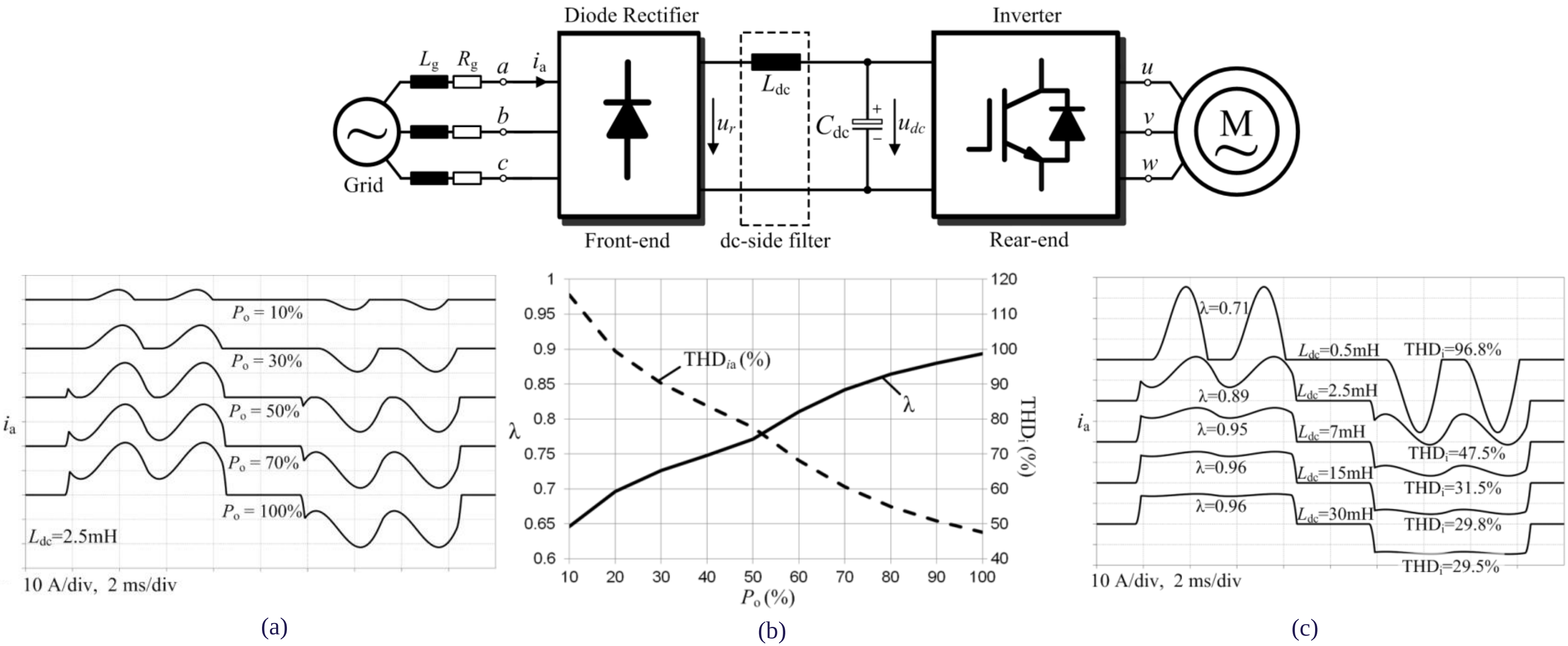
Typical ASD System

Passive Filtering Solution



- *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*** *most of them are complex, costly and reduce system efficiency.*

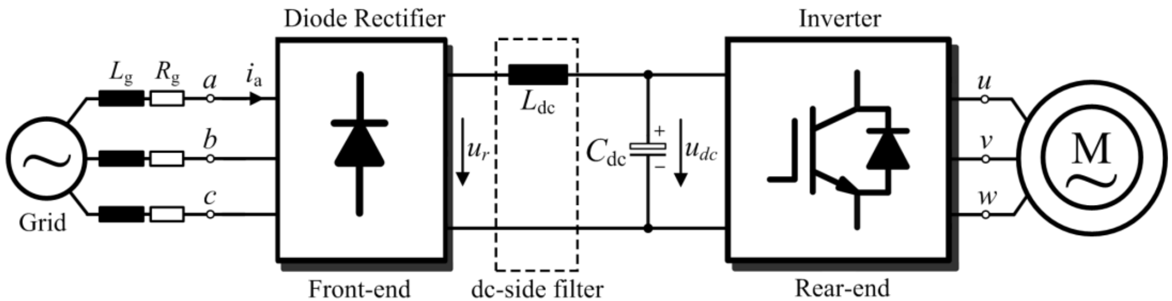
Three-Phase Diode Rectifier Passive Filtering Challenges

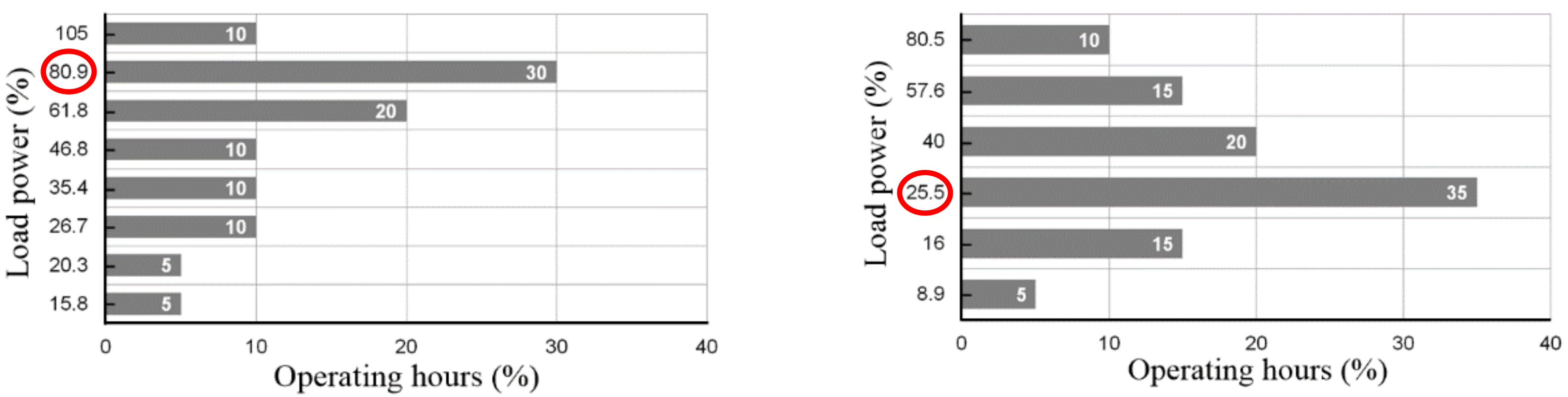


Performance of three-phase diode rectification using dc-side passive filtering: (a) effect of loading condition, (b) corresponding power factor λ and input current THD at different power levels, (c) effect of dc-link inductor size.

Typical ASD System

Three-Phase Diode Rectifier Passive Filtering Challenges



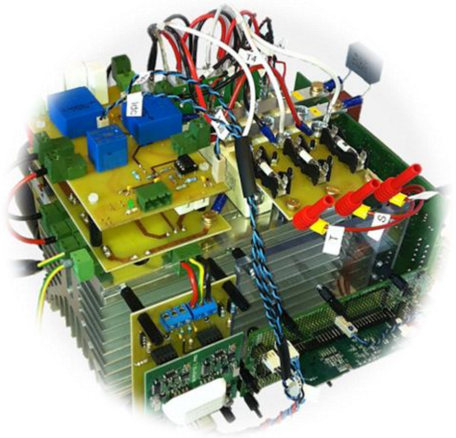


(a) (b)

Typical annual loading profile of adjustable speed drive applications: (a) water pump, (b) cooling tower.

Electronic Inductor Concept

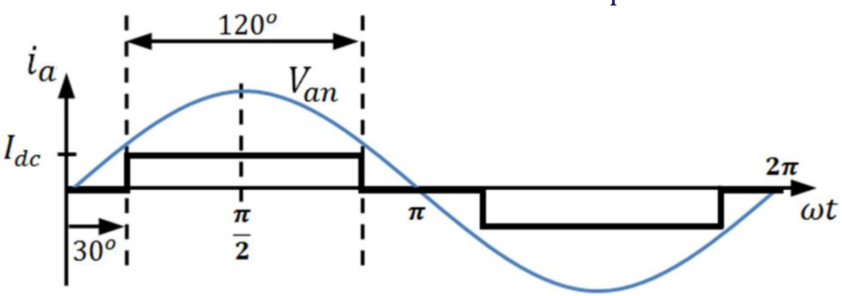
Basic Idea →

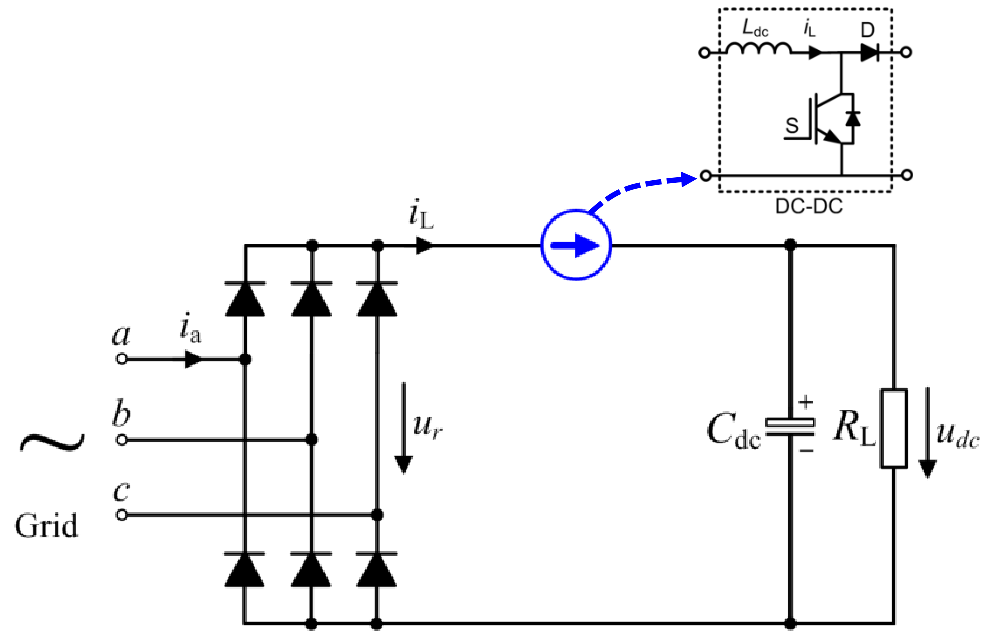


Basic Concept

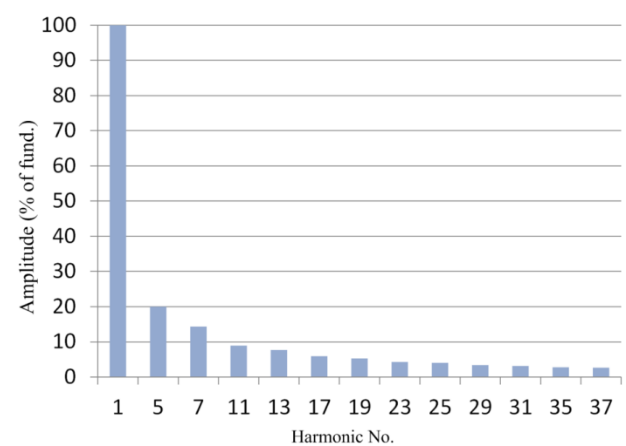
$\lambda \approx 0.95$

$THD_i \approx 29\%$



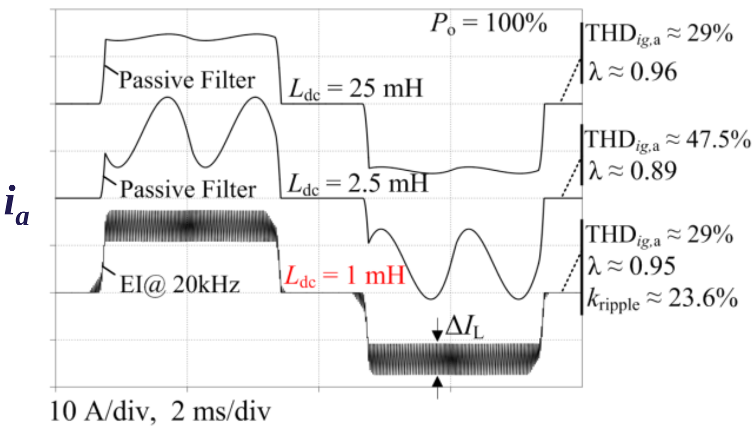


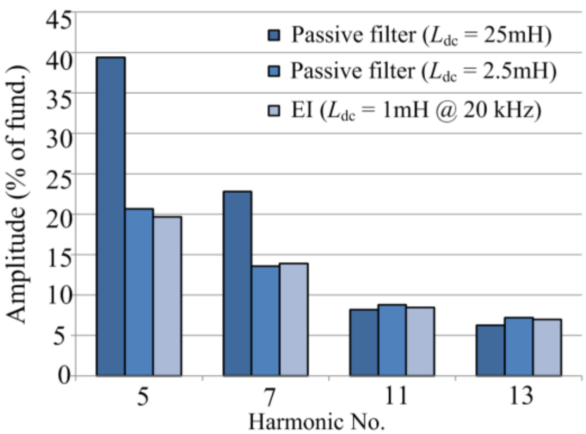
$$i_n = \frac{4}{n\pi} I_{dc1} \cos(n\alpha)$$

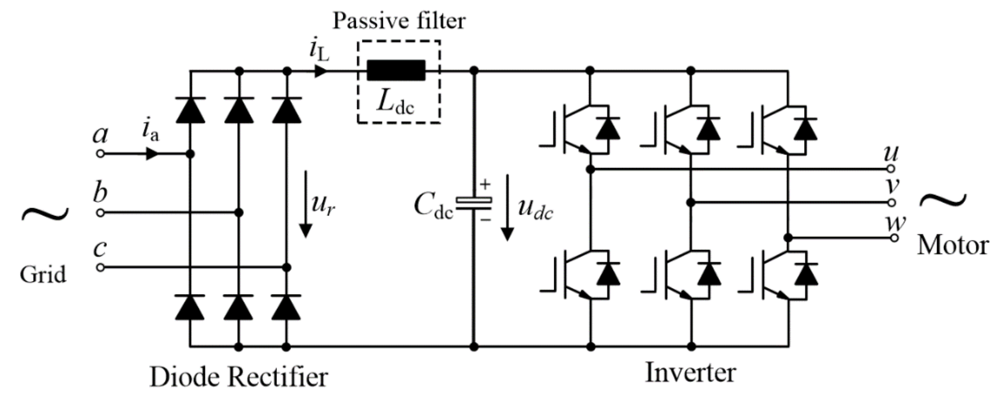


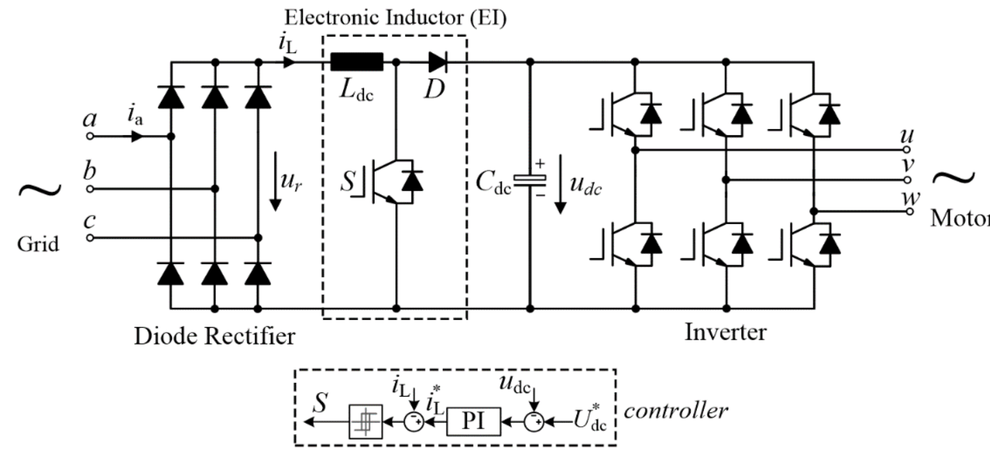
- *Emulating the behavior of an ideal infinite inductor*
- *THD_i and Power Factor (λ) independent of the load profile.*
- *Controlling dc-link (u_{dc}).*

Electronic Inductor Technique









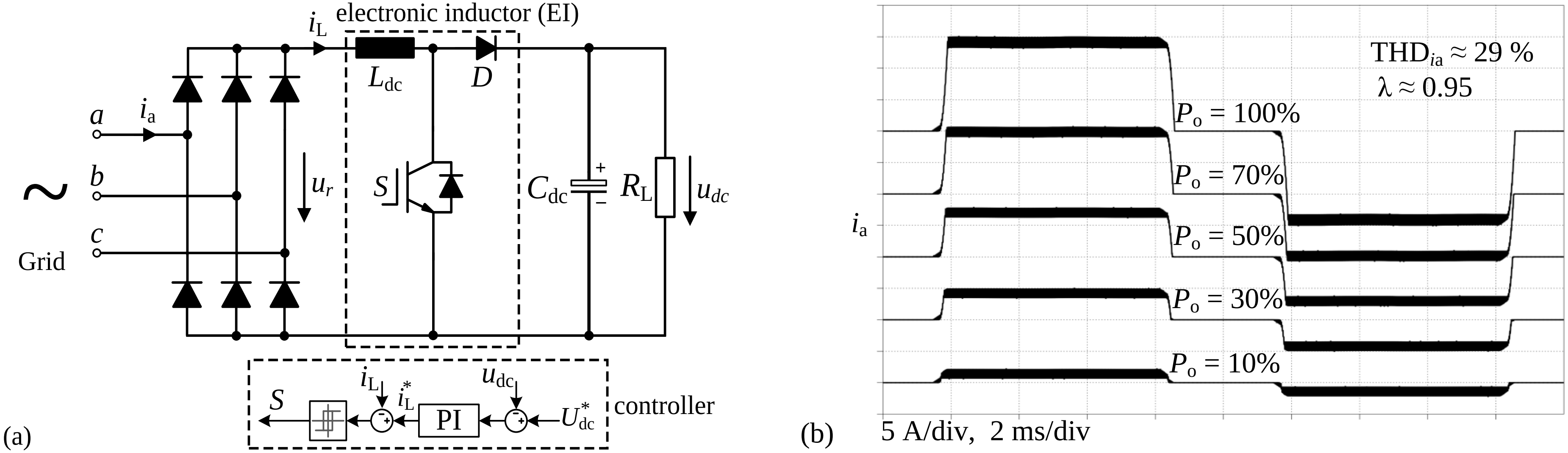
- *No major modification is imposed to the original system!*

Electronic Inductor Concept

Load Profile

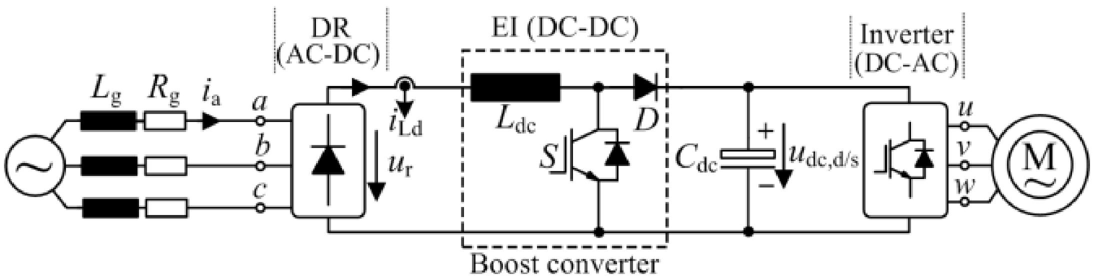
Independent performance
(10% to 100% P_o)

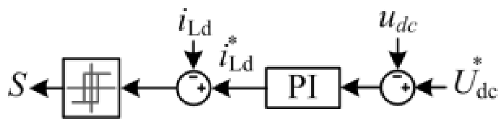
Assuring CCM operation → $L_{dc} > \dfrac{D(1-D)^2 U_{dc}^2}{2 P_{o,\min} f_{sw}}$



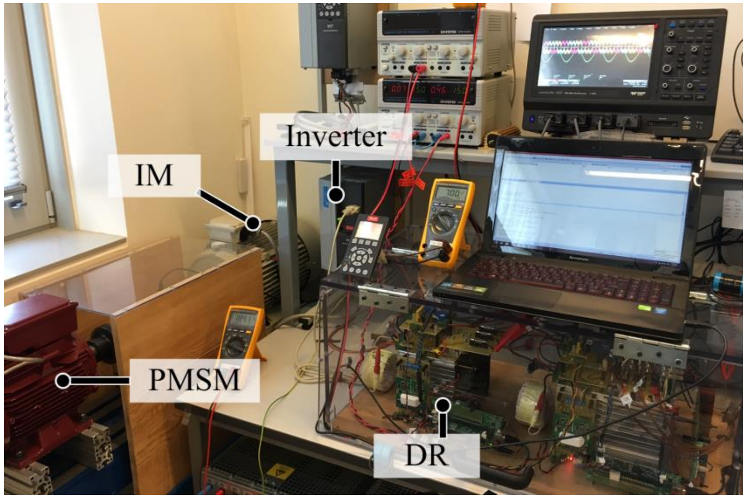
Implementation of electronic inductor using a boost dc-dc converter topology in a three-phase diode rectifier: (a) circuit schematic, (b) corresponding input current waveform (i_a) at different power levels. (Simulation parameters: rms line-to-line voltage $U_{g,LL,rms}$ = 400 V, grid frequency f_g = 50 Hz, grid impedance L_g = 0.18 mH, R_g = 0.1Ω , rated power $P_{o,max}$ = 7.5 kW, U_{dc} = 700V, f_{sw} = 40 kHz, dc-link capacitance C_{dc} = 470 µF, and dc-link inductance L_{dc0} = 2 mH.)

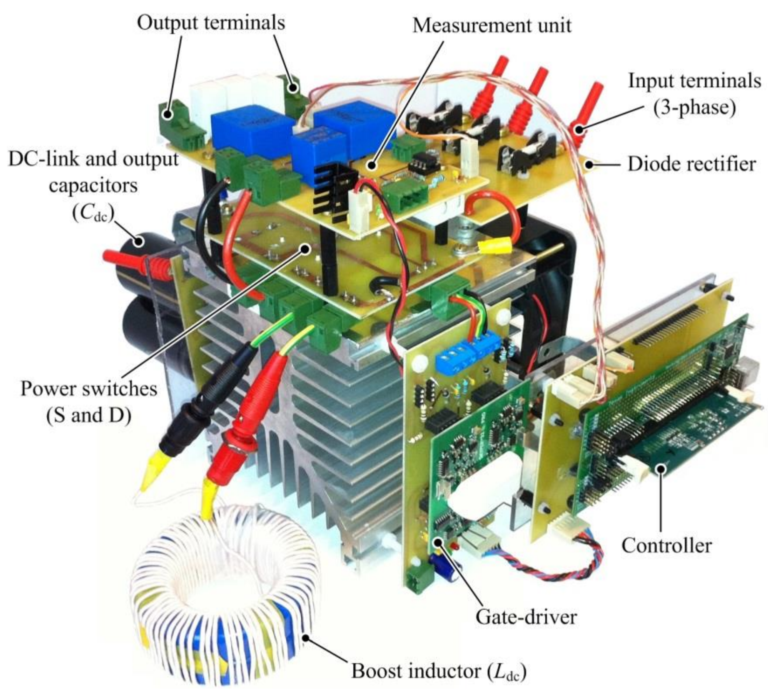
Experimental Setup





7.5 kW





System Specifications

$U_{g,LL,rms}$	f_g	L_g, R_g	P_{omax} (100%)	U_{dc}	f_{sw}	L_{dc0}	C_{dc}
400 V	50 Hz	0.18mH , 0.1 Ω	7.5 kW	700 Vdc	20 kHz	1 mH	470 µF

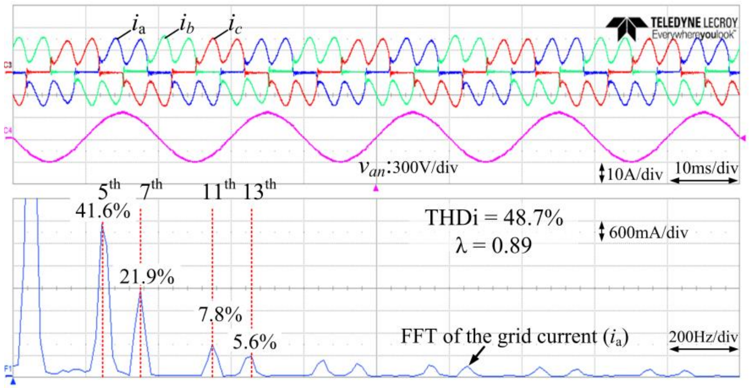
Employed components

Module	Part-Number
Three-phase diode rectifier	SKD30
IGBT-diode	SK60GAL125
IGBT gate drive	Skyper 32-pro
Controller	TMS320F28335

Experimental Results

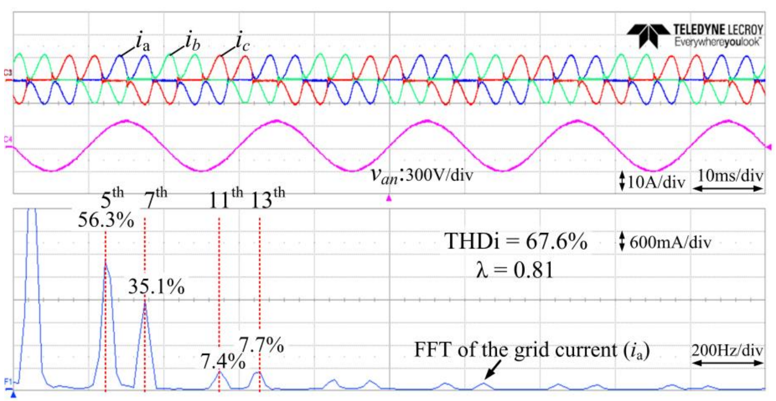
■ Original Drive (Passive Filter)

THD$_i$ = 48.7%, λ = 0.89 L = 2.5mH



P$_o$ = 5kW U_{dc} = 534V

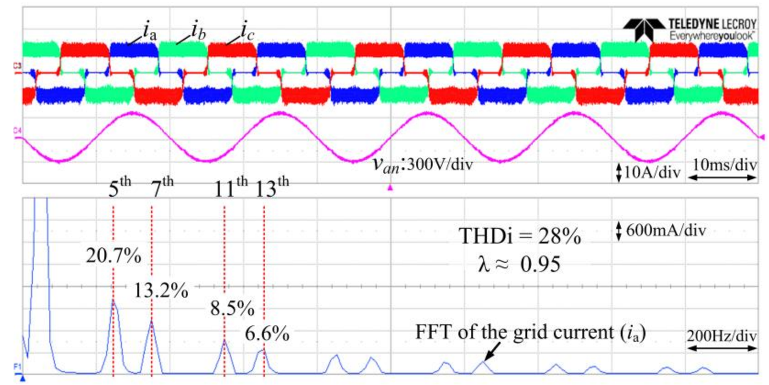
THD$_i$ = 67.6%, λ = 0.81 L = 2.5mH



P$_o$ = 3kW U_{dc} = 534V

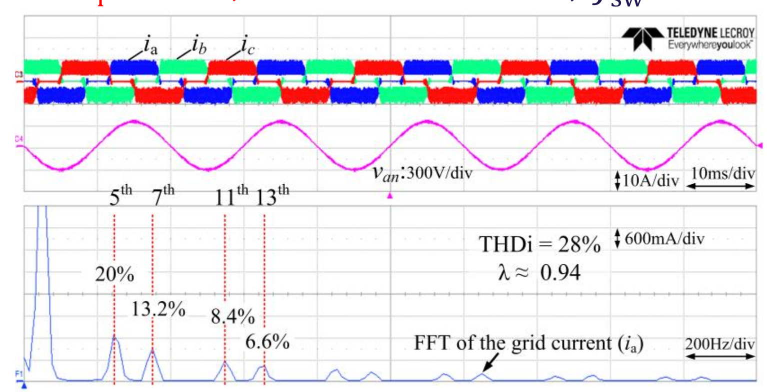
■ EI (flat current modulation)

THD$_i$ = 28%, λ = 0.95 L = 1mH, f_{sw} = 20 kHz



P$_o$ = 5kW U_{dc} = 700V

THD$_i$ = 28%, λ = 0.94 L = 1mH, f_{sw} = 20 kHz



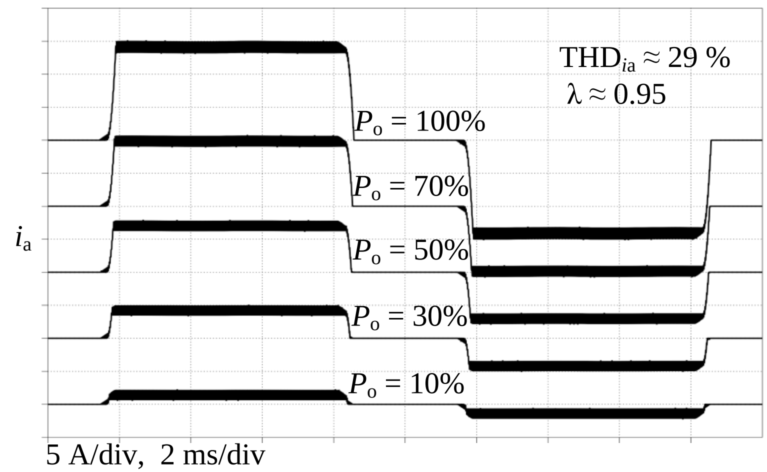
P$_o$ = 3kW U_{dc} = 700V

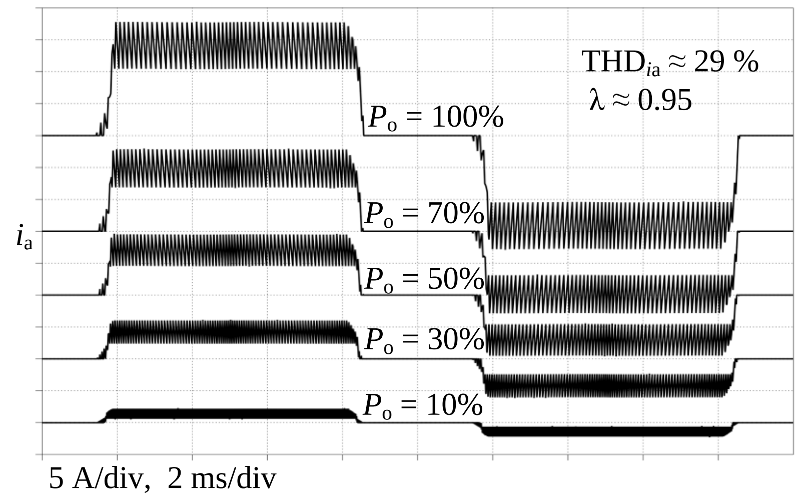
Improving Efficiency

- ***Adjustable Switching Frequency Scheme*** →

Proposed Solutions

Adjustable Switching Frequency

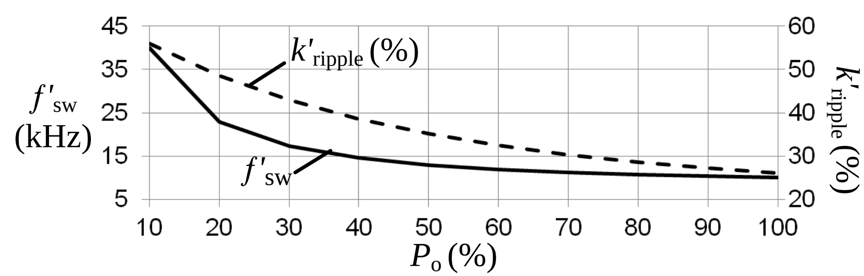




$$f_{sw} = \frac{D(1-D)^2 U_{dc}^2 I_L}{L_{dc} P_o \Delta I_{L,pk-pk}} \qquad HB = k_{ripple} I_L, \qquad HB = \frac{\Delta I_{L,pk-pk}}{2}$$

$$f'_{sw} = ceil\left(\frac{f'_{sw,\max} - f'_{sw,\min}}{f_{sw,\max} - f_{sw,\min}} (f_{sw} - f_{sw,\max}) + f'_{sw,\max} \right)$$

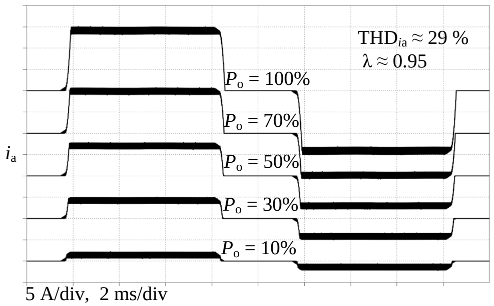
$$HB' = k'_{ripple} I_L \quad where \quad k'_{ripple} = \frac{U_{dc} D(1-D)}{2 L_{dc} f'_{sw} I_L} = \frac{k_{ripple}}{f'_{sw}} f_{sw}$$

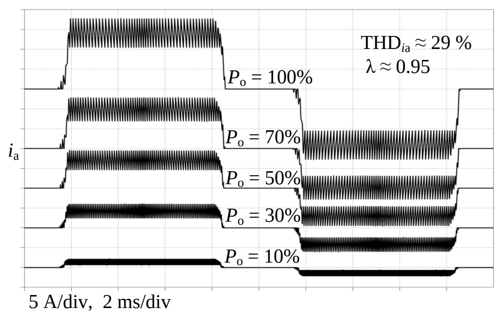


[1] P. Davari, Y. Yang, F. Zare, and F. Blaabjerg, “Energy Saving in Three-Phase Diode Rectifiers using Adjustable Switching Frequency Modulation Scheme,” *EPE-2016*.

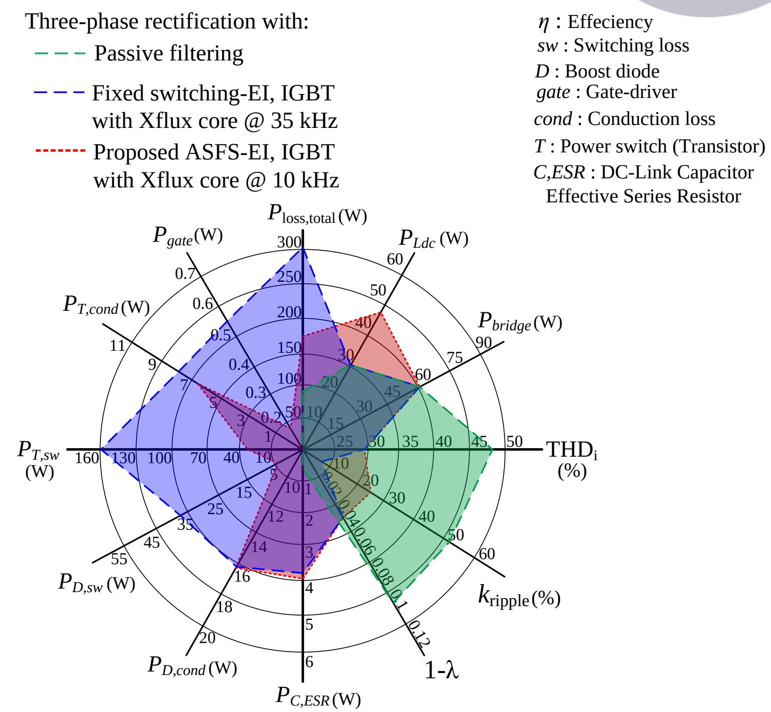
Proposed Solutions

Adjustable Switching Frequency



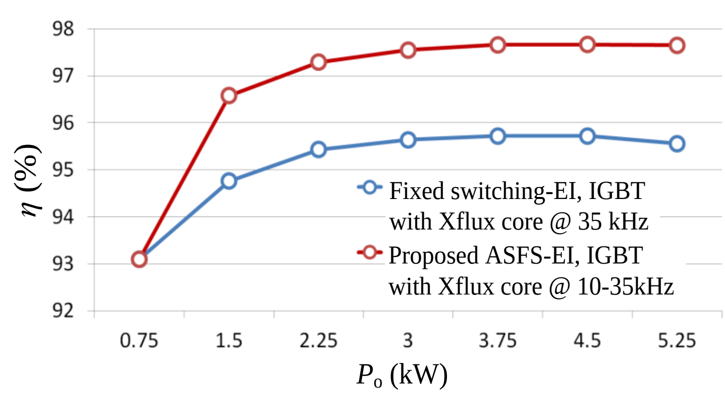


Using ASFM strategy improves efficiency from 315W losses to 173W losses (95.8% vs 97.7%)



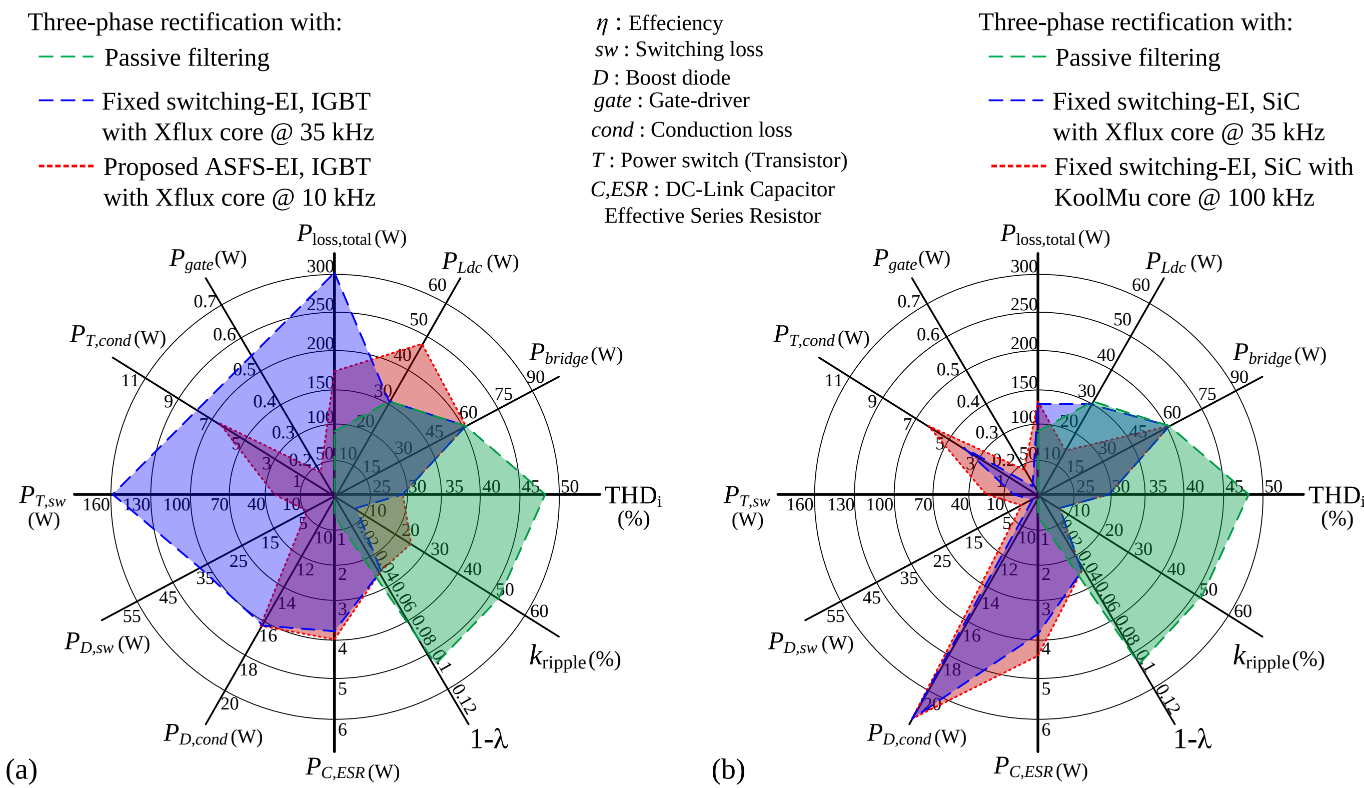
System Specs:

Parameter	Symbol	Value
Grid phase voltage	v_{abc}	230 Vrms
Grid frequency	f_g	50 Hz
Grid impedance	L_g, R_g	0.18 mH, 0.1 Ω
DC-link inductor	L_{dc-p}, L_{dc}	2.5 mH, 2 mH
DC-link capacitor	C_{dc}	470 µF
DC-link voltage	U_{dc-p}, U_{dc}	≈ 534V, 700 V
Rate power	$P_{o,max}$ (100%)	7.5 kW



Proposed Solutions

Using WBG Devices

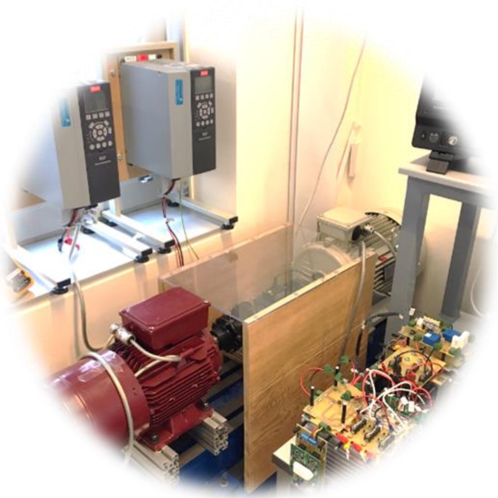


L_{dc} = 2 mH $\qquad$ L_{dc} = 1 mH

Applying SiC power devices reduces the size of magnetic components and losses (131 W vs 173 W)

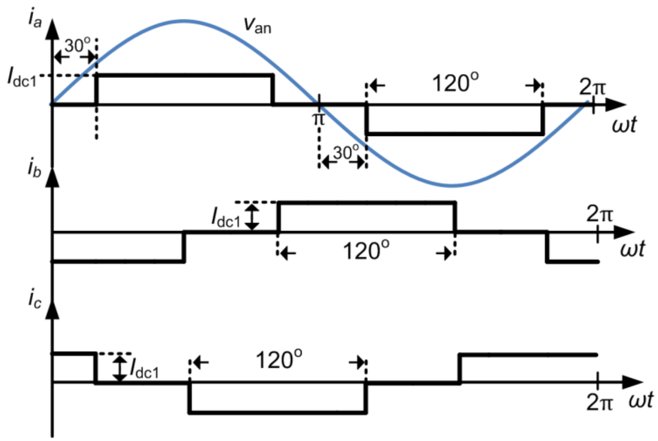
Proposed Solutions

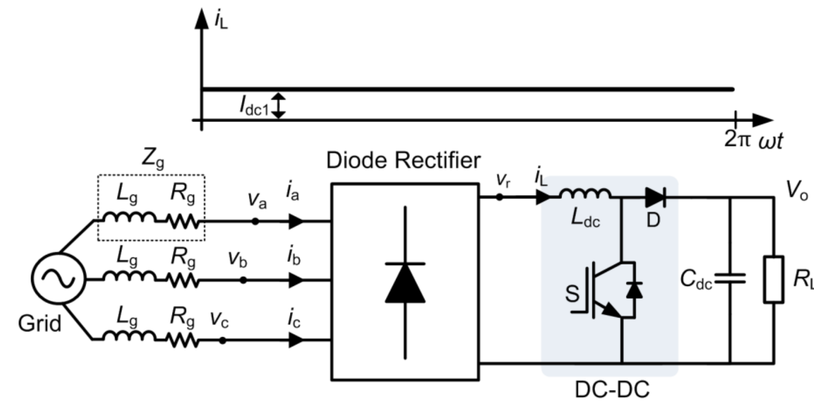
- *Pulse Pattern Modulation* →

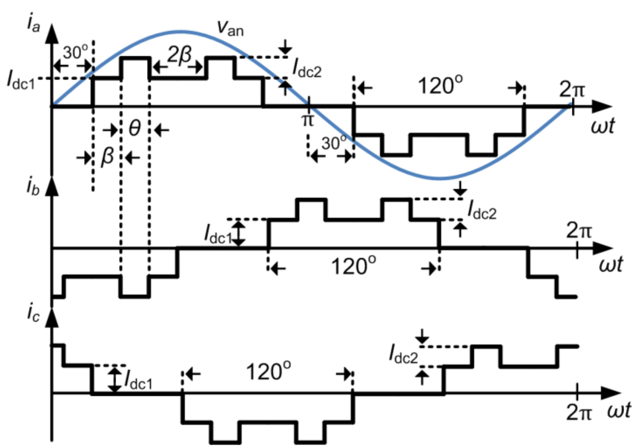


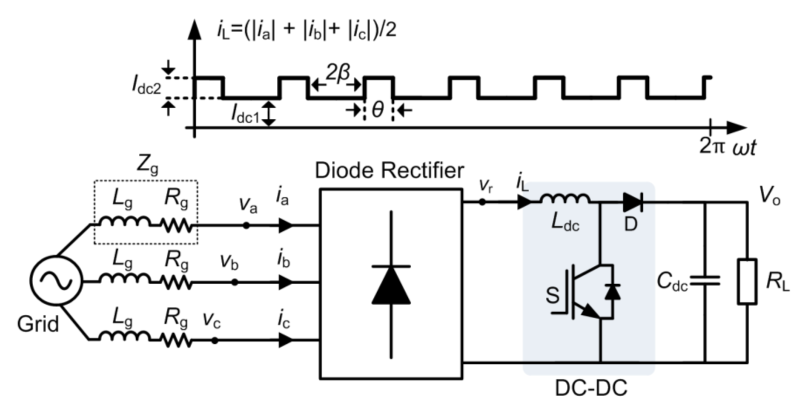
Proposed Solutions

Pulse Pattern Modulation





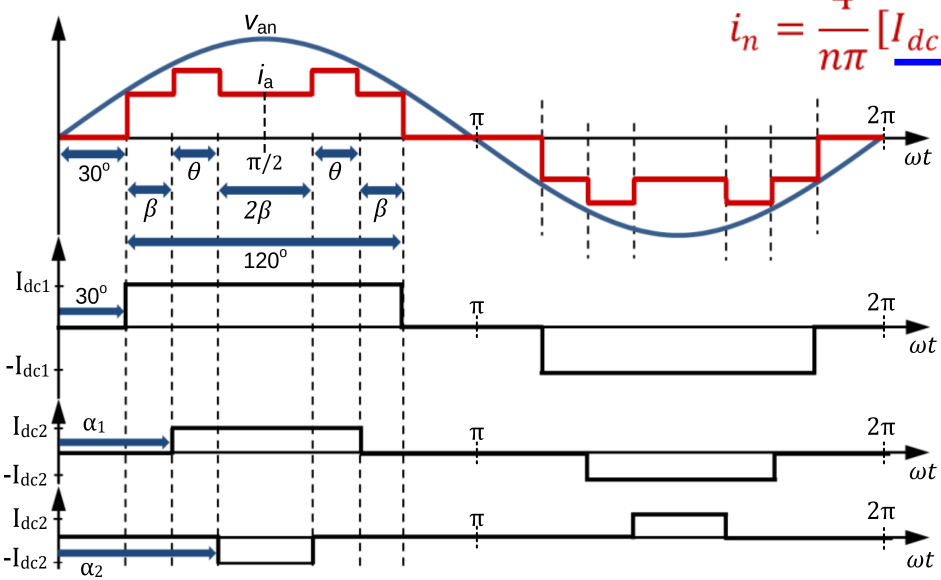




[1] P. Davari, F. Zare, and F. Blaabjerg, "Pulse pattern modulated strategy for harmonic current components reduction in three-phase ac-dc converters," *IEEE Trans. Ind. Appl.,* vol. 52, no. 4, pp. 3182-3192, July-Aug. 2016.

Proposed Solutions

Pulse Pattern Modulation



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

$$2\beta + \theta = 60$$

$$30° < \alpha_1 < 90°\,, \alpha_2 = 120° - \alpha_1$$

Adding or subtracting phase-displaced current levels

$$i_1 = \frac{4}{\pi}[I_{dc1}\cos(30) + I_{dc2}\cos(\alpha_1) - I_{dc2}\cos(\alpha_2)]$$

$$i_k = \frac{4}{k\pi}[I_{dc1}\cos(k30) + I_{dc2}\cos(k\alpha_1) - I_{dc2}\cos(k\alpha_2)] = 0$$

$$i_m = \frac{4}{m\pi}[I_{dc1}\cos(m30) + I_{dc2}\cos(m\alpha_1) - I_{dc2}\cos(m\alpha_2)] = 0$$

[1] P. Davari, F. Zare, and F. Blaabjerg, “Pulse pattern modulated strategy for harmonic current components reduction in three-phase ac-dc converters,” *IEEE Trans. Ind. Appl.*, vol. 52, no. 4, pp. 3182-3192, July-Aug. 2016.

Proposed Solutions

Pulse Pattern Modulation

Optimization

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

Constraint

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

Objective Function

Weighting Factor

where $n = 6k\pm1$ with k being 1, 2, 3, ...

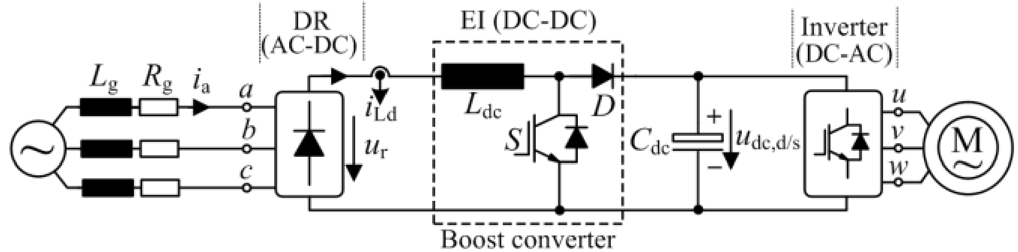
$$\alpha_0 < \alpha_1 < \alpha_2 < \cdots < \alpha_m < \alpha_0 + \frac{\pi}{3}$$

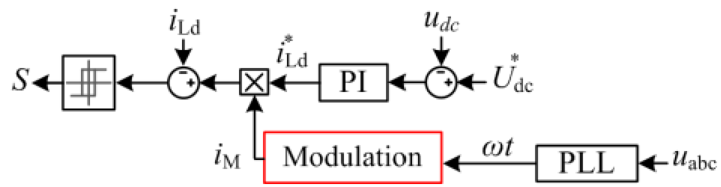
- Instead of fully nullifying the distortions, the harmonics could be reduced to acceptable levels by adding suitable constraints (L_n).

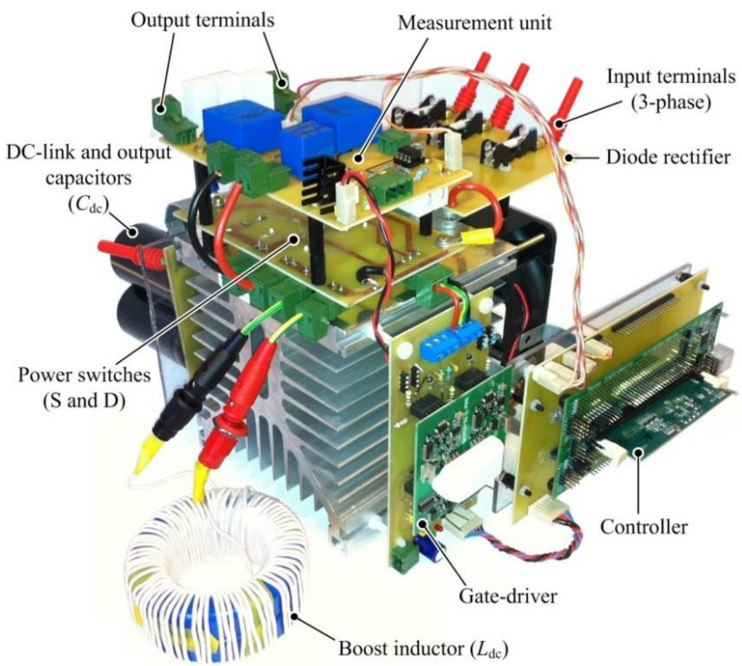
- Here, F_{obj} is formed based on a squared error with more flexibility by adding constant weight values (w_n) to each squared error function

[1] P. Davari, F. Zare, and F. Blaabjerg, "Pulse pattern modulated strategy for harmonic current components reduction in three-phase ac-dc converters," *IEEE Trans. Ind. Appl.,* vol. 52, no. 4, pp. 3182-3192, July-Aug. 2016.

Experimental Setup





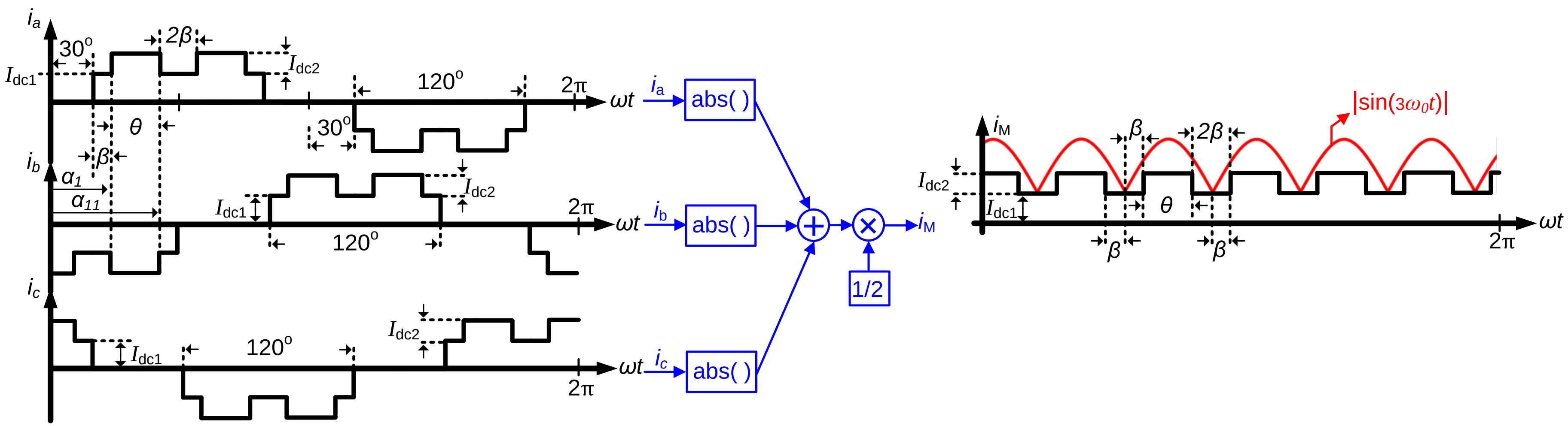


Employed components

Module	Part-Number
Three-phase diode rectifier	SKD30
IGBT-diode	SK60GAL125
IGBT gate drive	Skyper 32-pro
Controller	TMS320F28335

Experimental Setup

Synthesis of the modulation signal



$\alpha_1 < \alpha_{11}:$

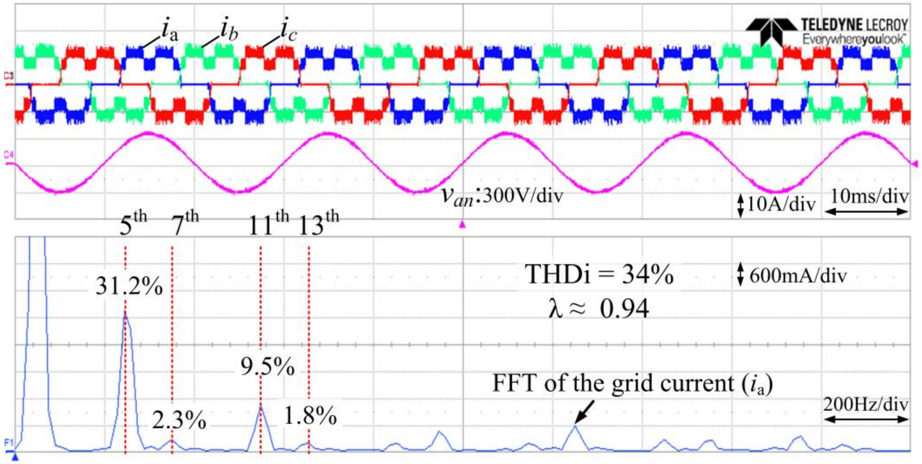
$$\begin{cases} if\ (|\sin(3\omega_0 t)| > \sin(3\beta)) \\ i_M = I_{dc1} + I_{dc2} \\ else \\ i_M = I_{dc1} \end{cases}$$

$\alpha_1 > \alpha_{11}:$

$$\begin{cases} if\ (|\sin(3\omega_0 t)| > \sin(3\beta)) \\ i_M = I_{dc1} - I_{dc2} \\ else \\ i_M = I_{dc1} \end{cases}$$

Experimental Results

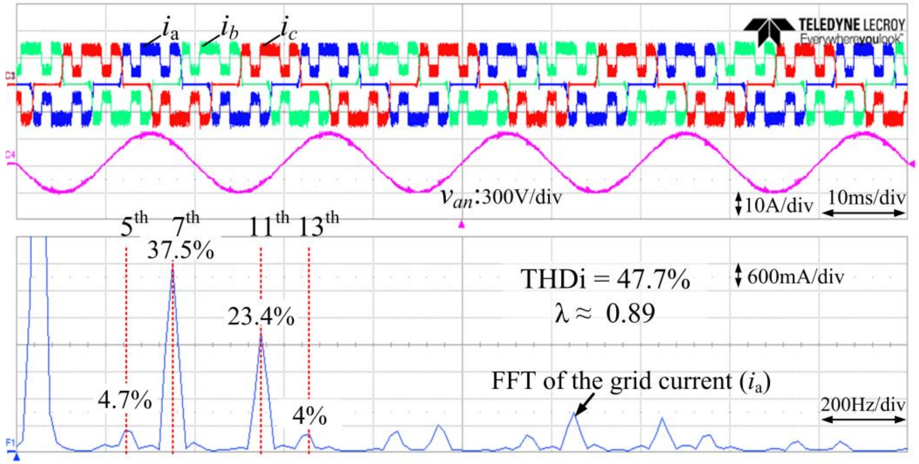
Harmonic Elimination [7th and 13th]



P_o = 5kW U_{dc} = 700V

$Idc_1 = 1$, $Idc_2 = 0.618$, $\alpha_1 = 42^o$

Harmonic Elimination [5th, 13th]



P_o = 5kW U_{dc} = 700V

$Idc_1 = 1$, $Idc_2 = 0.653$, $\alpha_1 = 70^o$

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$_i$
7th and 13th harmonic cancellation	31.2	**2.3**	9.5	**1**	34
5th, 13th harmonic cancellation	**4.7**	37.5	23.4	**4**	47.7
Conventional method (square wave)	20	14	8.7	7.3	28.6

Proposed Solutions

- *Multi-drive* →

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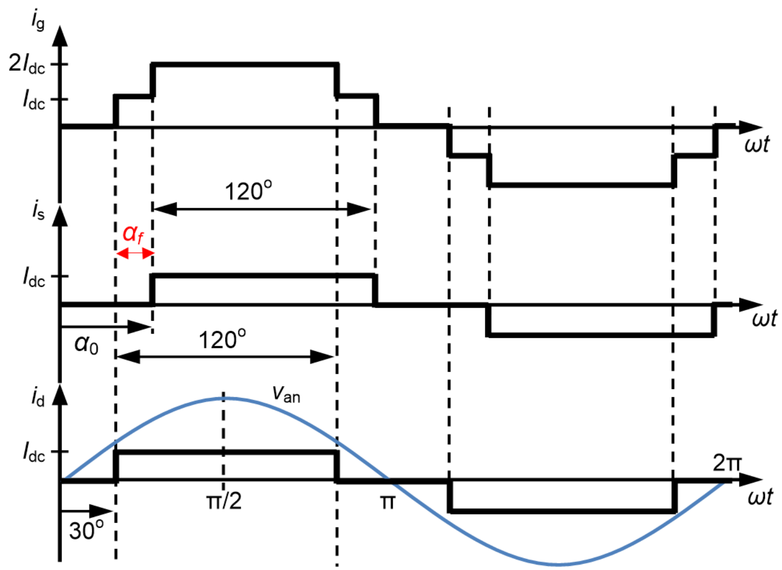
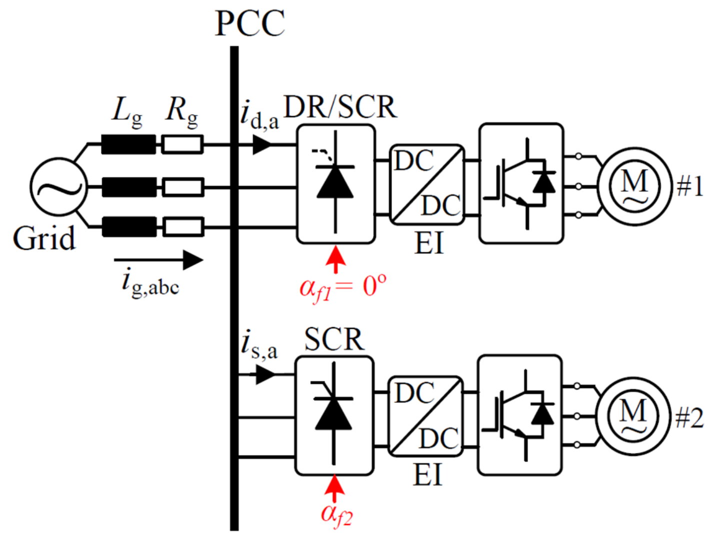
Basic Concept

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.

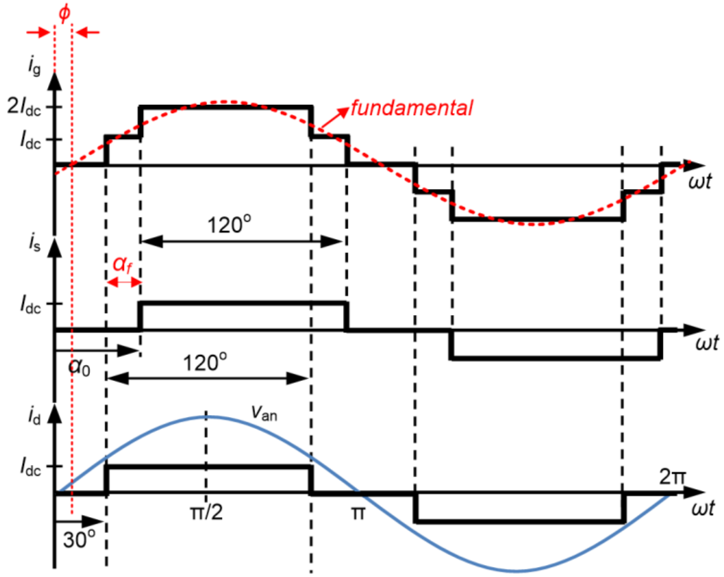


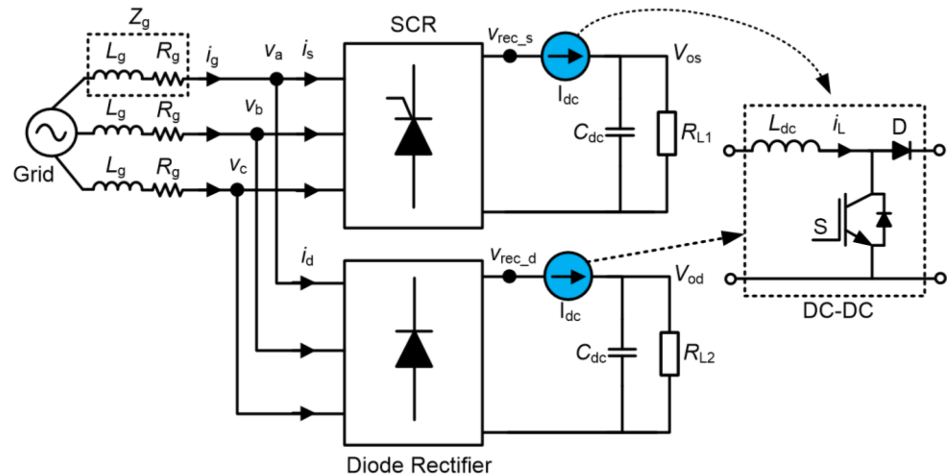


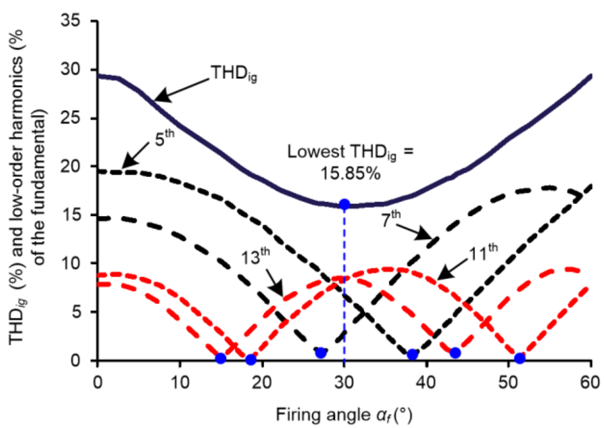
- *Generating staircase total input current by proper combination*

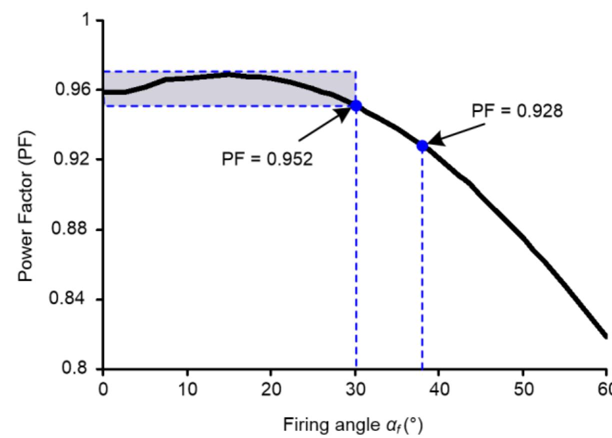
Multi-Drive Configuration

■ Phase-shifted Flat Current Control





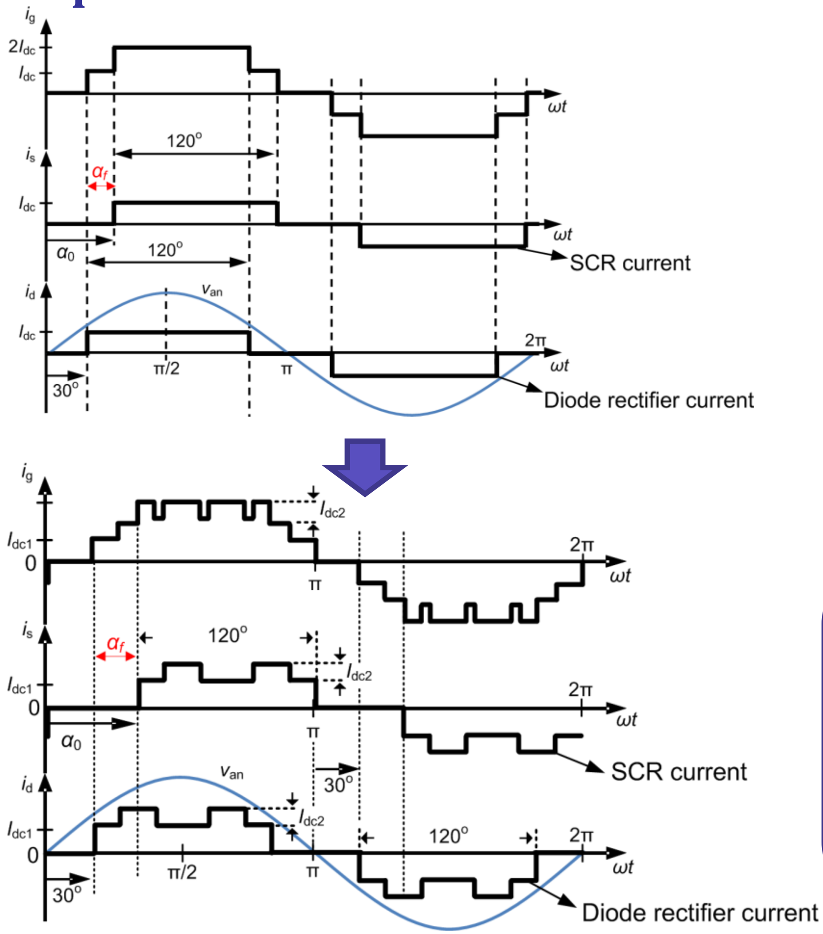


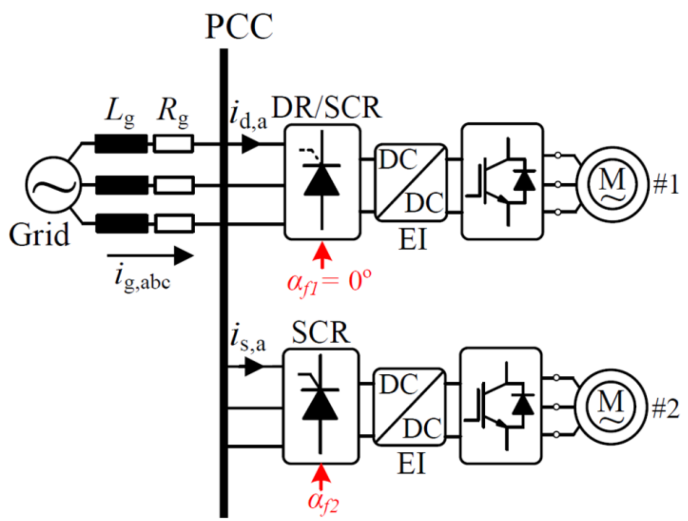


[1] Y. Yang, P. Davari, F. Zare, and F. Blaabjerg, "A dc-link modulation scheme with phase-shifted current control for harmonic cancellation in multi-drive applications," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 1837-1840, Mar. 2016.

Multi-Drive Configuration

Pulse pattern current modulation





- *The new current modulation technique is applied to each DC-DC converter in order to further improve the current quality. However, it requires* ***PLL*** *for synchronization purpose.*

[1] P. Davari, Y. Yang, F. Zare, and F. Blaabjerg, “A multi-pulse pattern modulation scheme for harmonic mitigation in three-phase multi-motor drives,” *IEEE J. Emerg. Sel. Top. Power Electron.,* vol. 4, no. 1, pp. 174-185, Mar. 2016.

[2] P. Davari, Y. Yang, F. Zare, and F. Blaabjerg, “Predictive pulse pattern current modulation scheme for harmonic reduction in three-phase multi-drive systems”, *IEEE Trans. Ind. Electron,* vol. 63, no. 9, pp. 5932-5942, Sept. 2016.

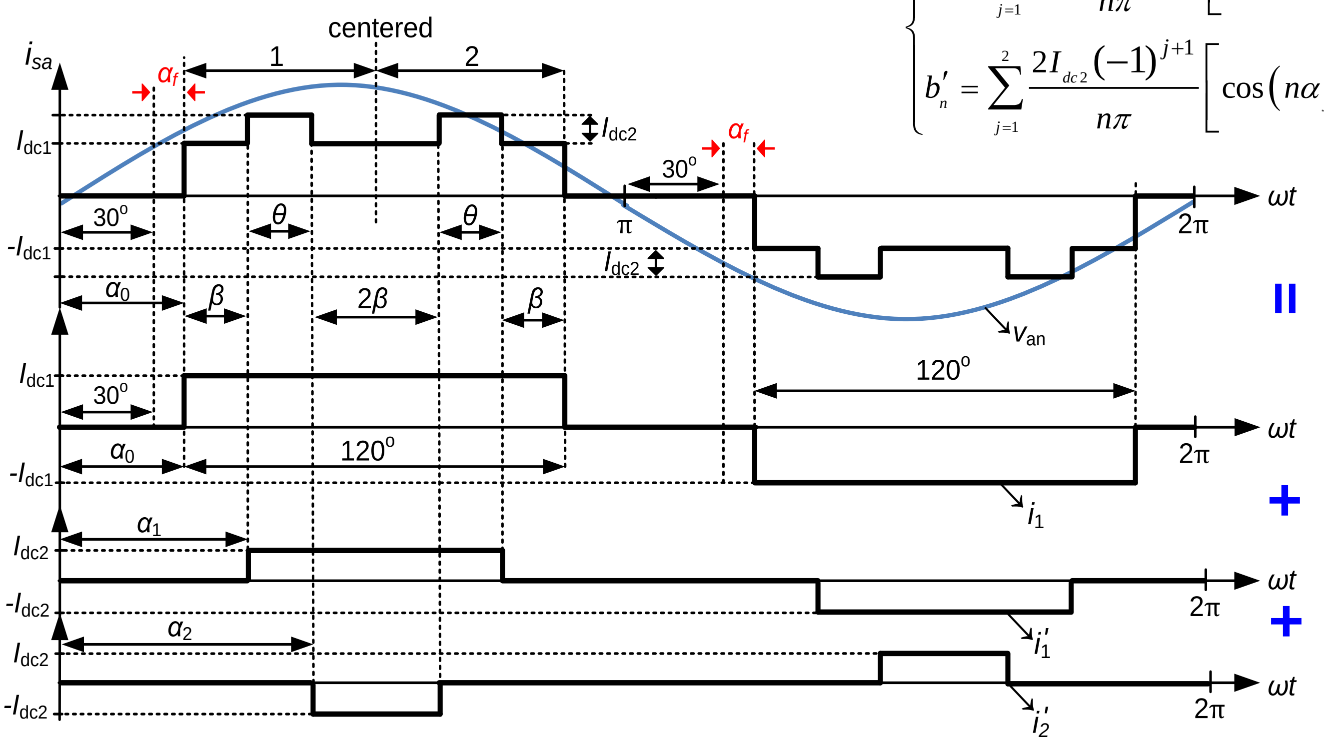
Multi-Drive Configuration

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

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

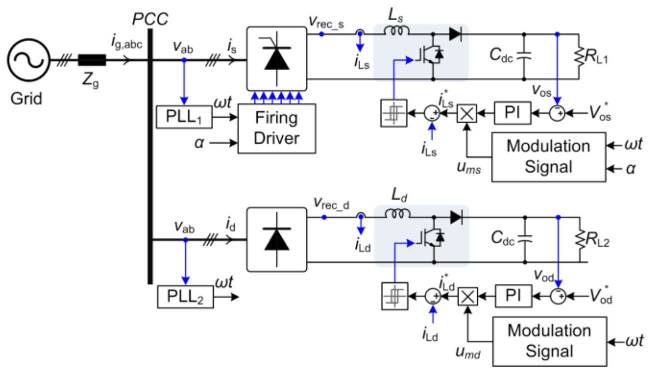
$$\begin{cases} a_n = \dfrac{2I_{dc1}}{n\pi}\left[-\sin(n\alpha_0) + \sin\left(n\alpha_0 + \dfrac{2\pi n}{3}\right)\right] \\ b_n = \dfrac{2I_{dc1}}{n\pi}\left[\cos(n\alpha_0) - \cos\left(n\alpha_0 + \dfrac{2\pi n}{3}\right)\right] \end{cases}$$

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



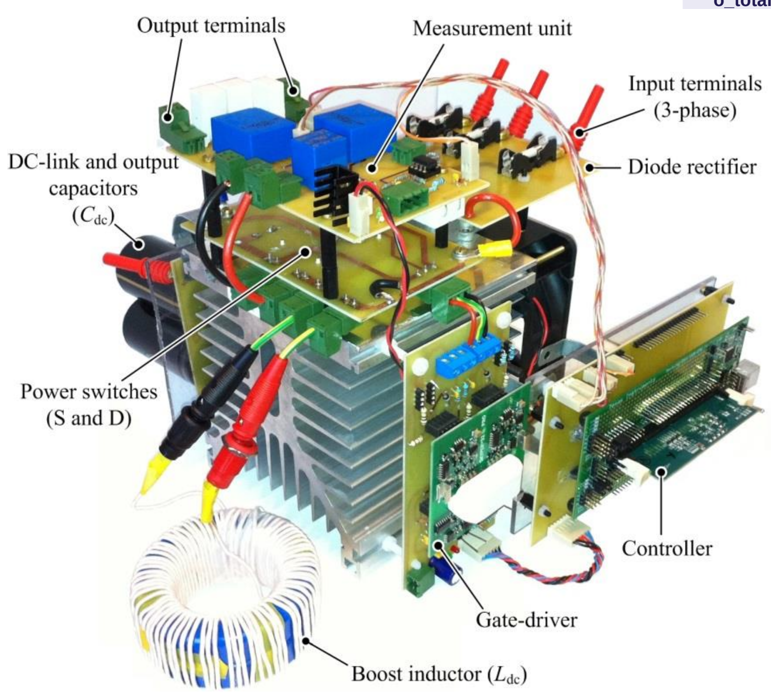
Multi-Drive Configuration

Implemented Setup



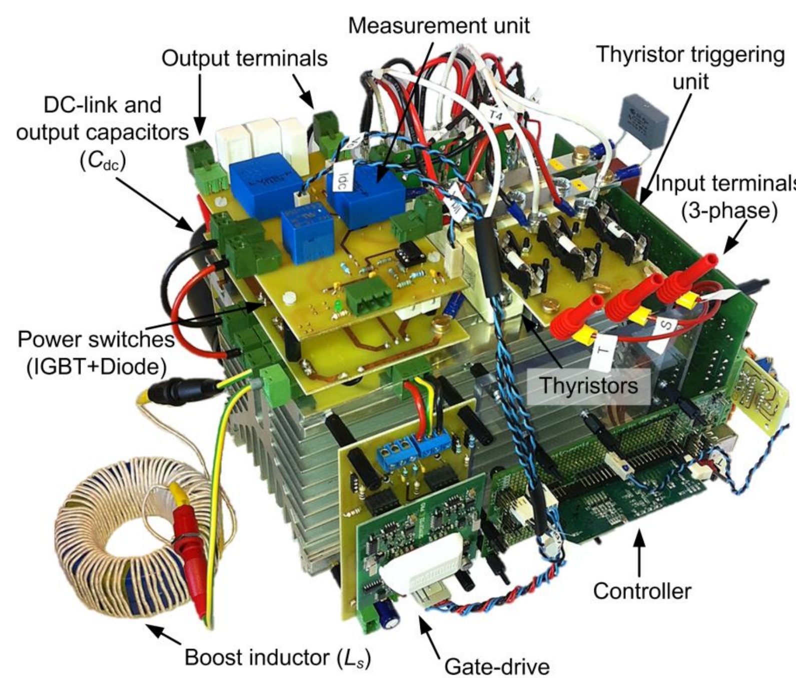
Parameters of the multi-rectifier system

Symbol	PARAMETER	Value
$v_{g,abc}$	Grid phase voltage	230 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	≈6.5 kW



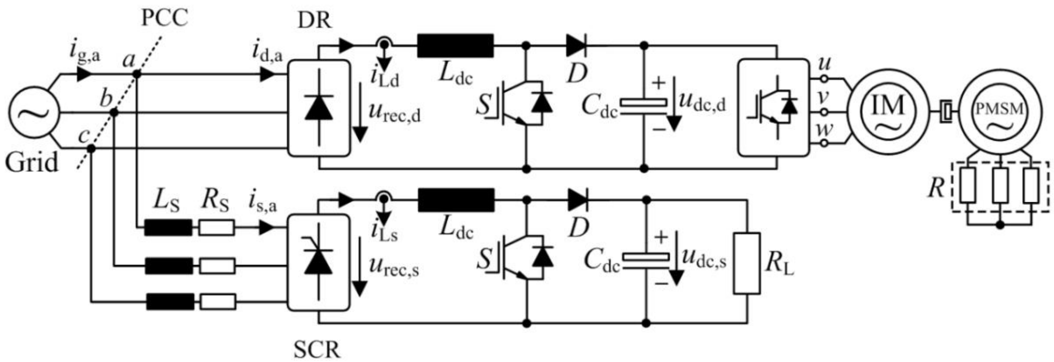
Diode Rectifier

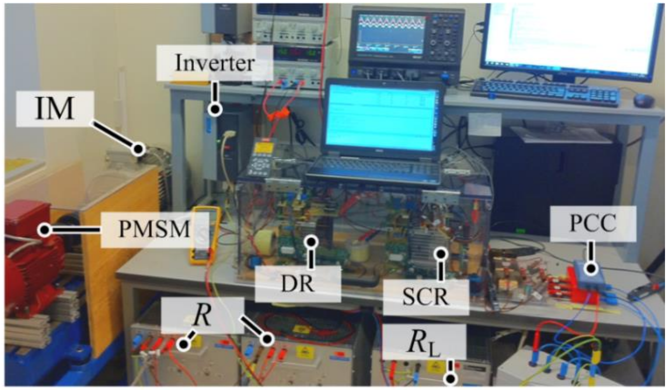
SCR



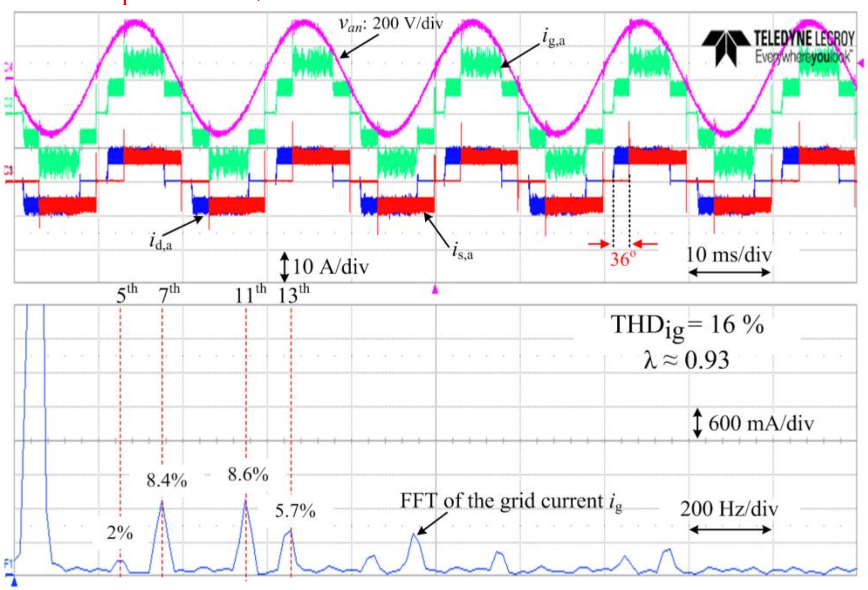
Multi-Drive Configuration

Experimental Results (phase shift control)



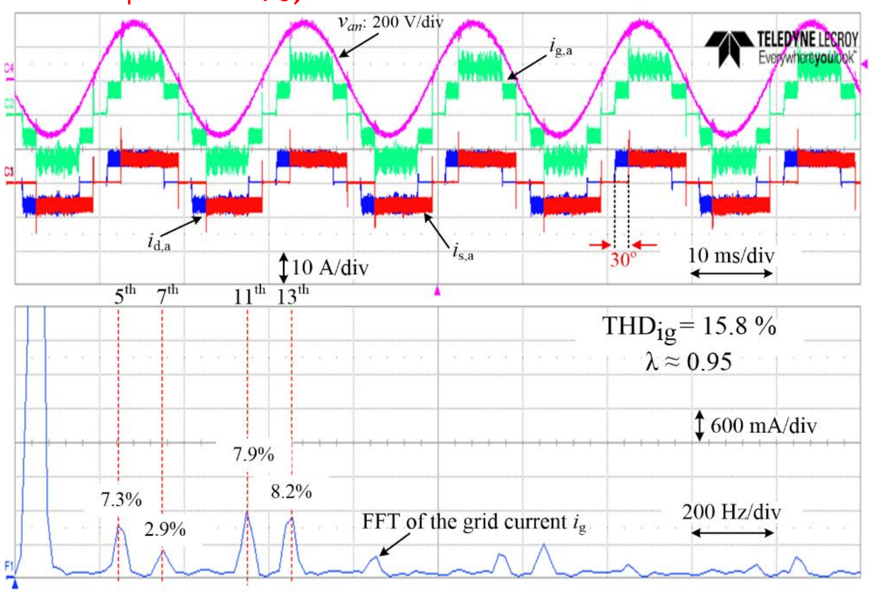


THD$_i$ ≈ 16%, λ = 0.93



P_{SCR} = 3 kW, P_{DR} = 3.63kW, U_{dc} = 700V

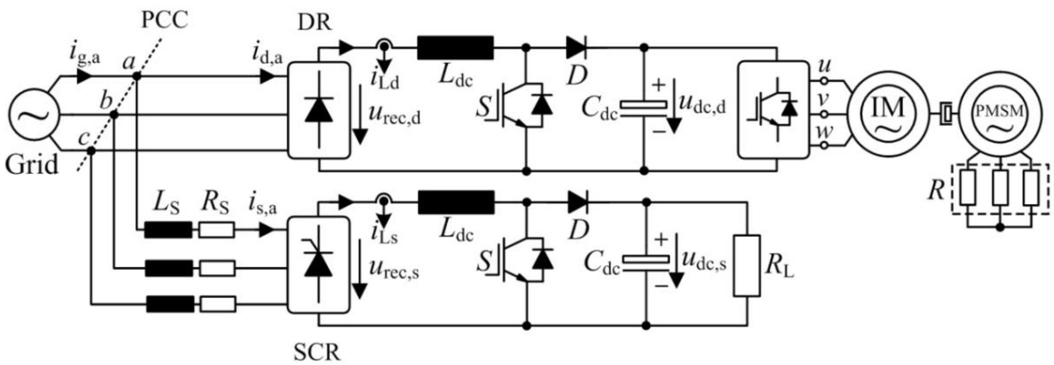
THD$_i$ ≈ 15.8%, λ = 0.95

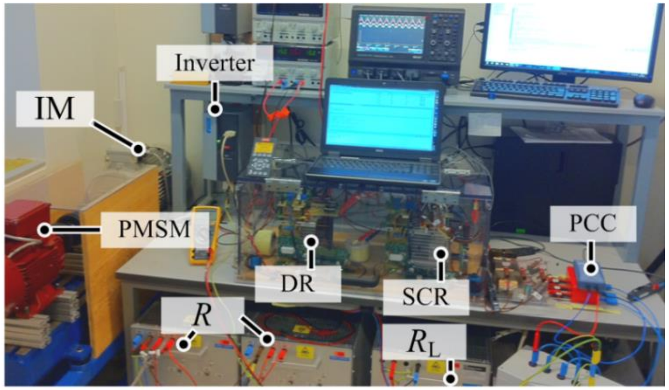


P_{SCR} = 3 kW, P_{DR} = 3.36kW, U_{dc} = 700V

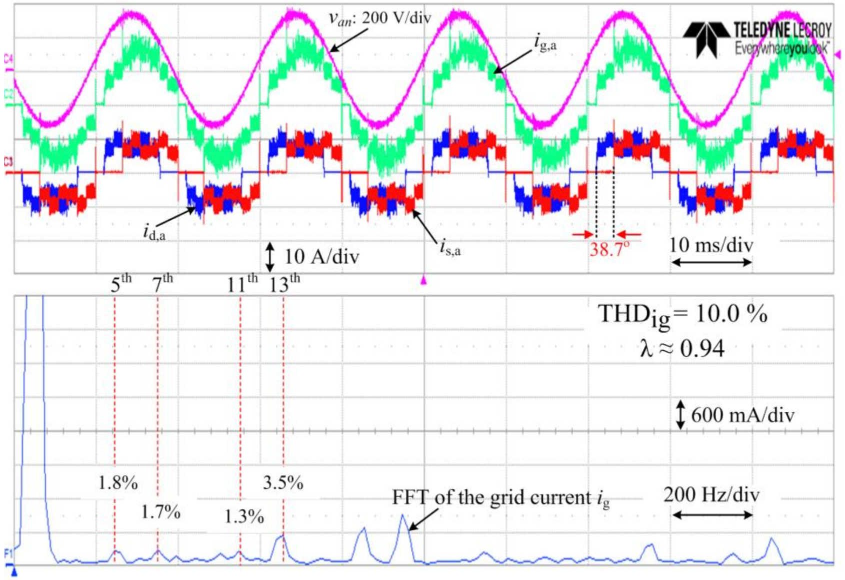
Multi-Drive Configuration

Experimental Results (current modulation)



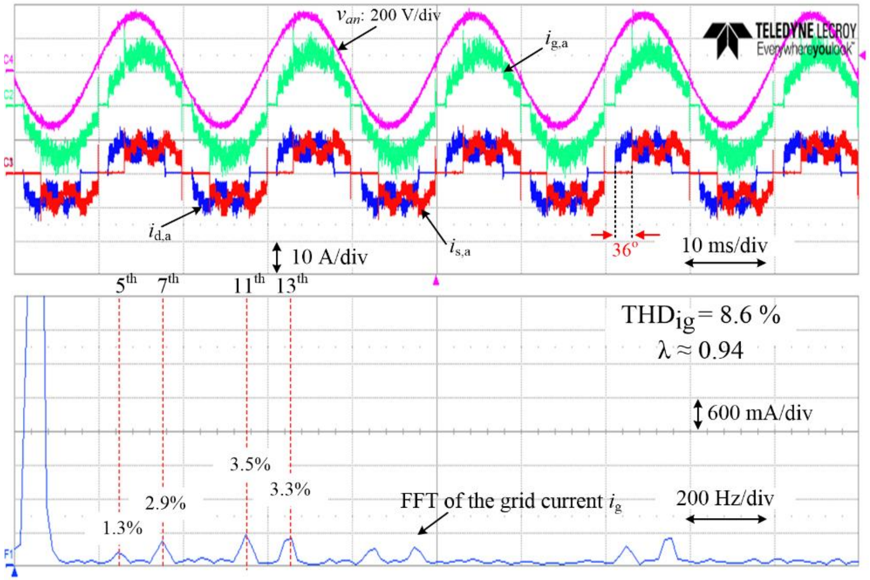


THD$_i$ ≈ 10%, λ = 0.94



P_{SCR} = 3 kW, P_{DR} = 3.86kW, U_{dc} = 700 V

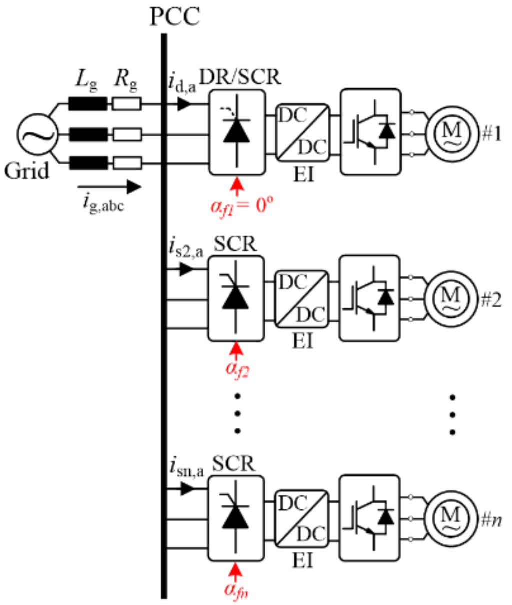
THD$_i$ ≈ 8.6%, λ = 0.94

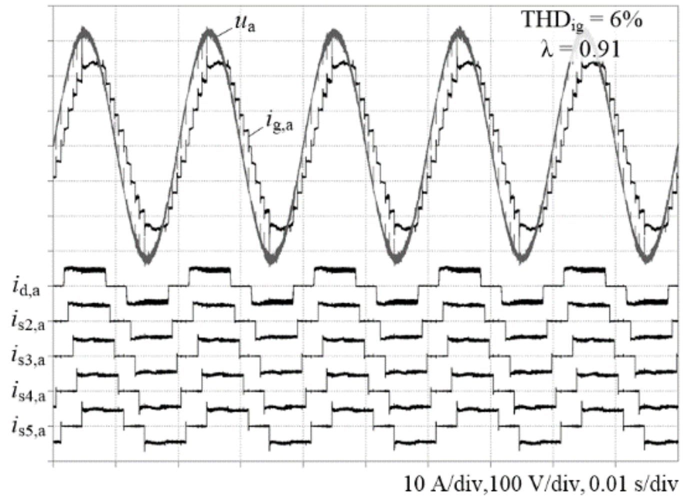


P_{SCR} = 3 kW, P_{DR} = 3.65kW, U_{dc} = 700 V

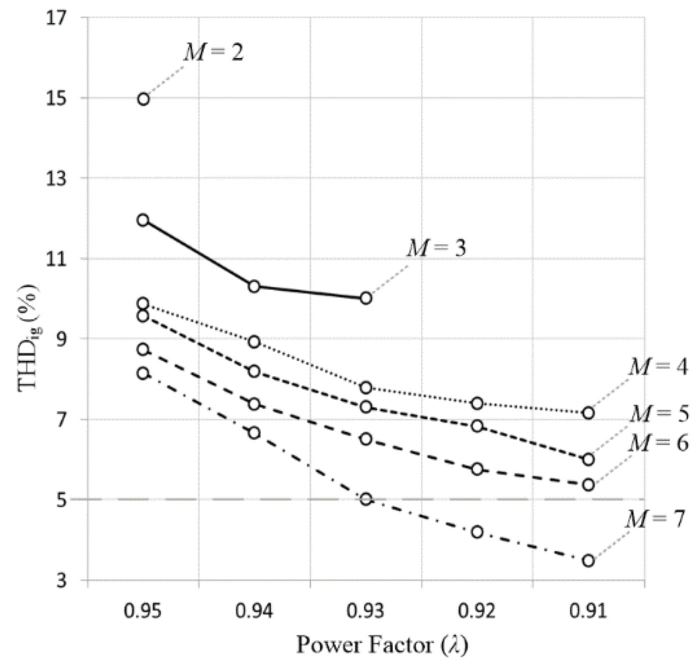
Multi-Drive Configuration

■ Extending number of the units (phase shift control)





Five parallel units (n = 5)

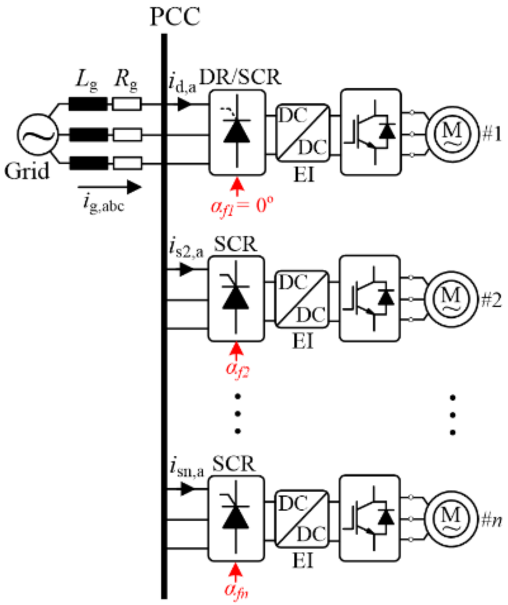


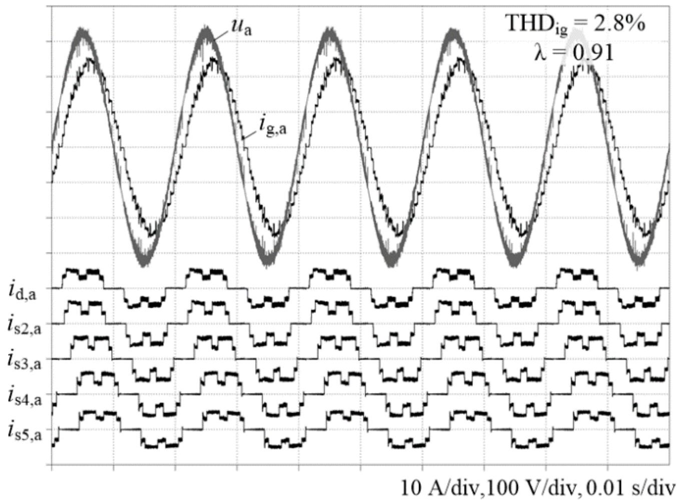
λ_{max} $THD_{i,min}$

- *More flexibility in obtaining desired THD_i and PF*

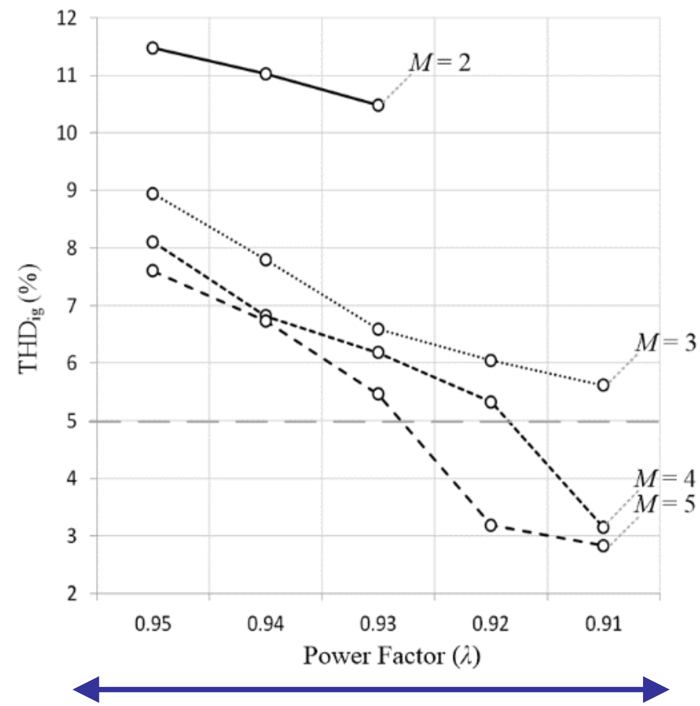
Multi-Drive Configuration

■ Extending number of the units (current modulation)





Five parallel units (n = 5)

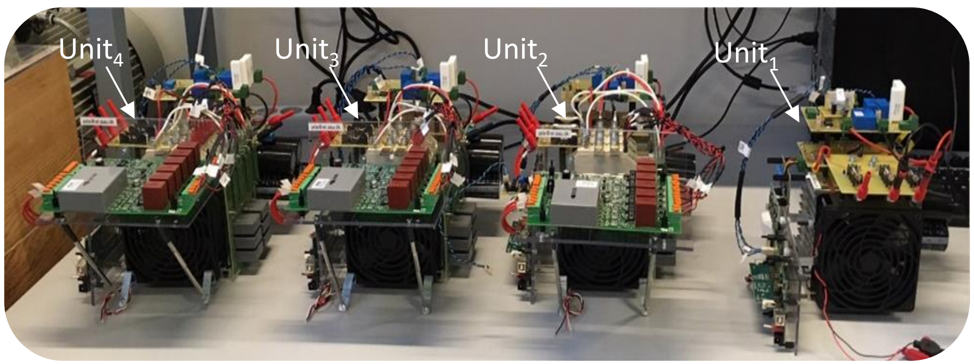


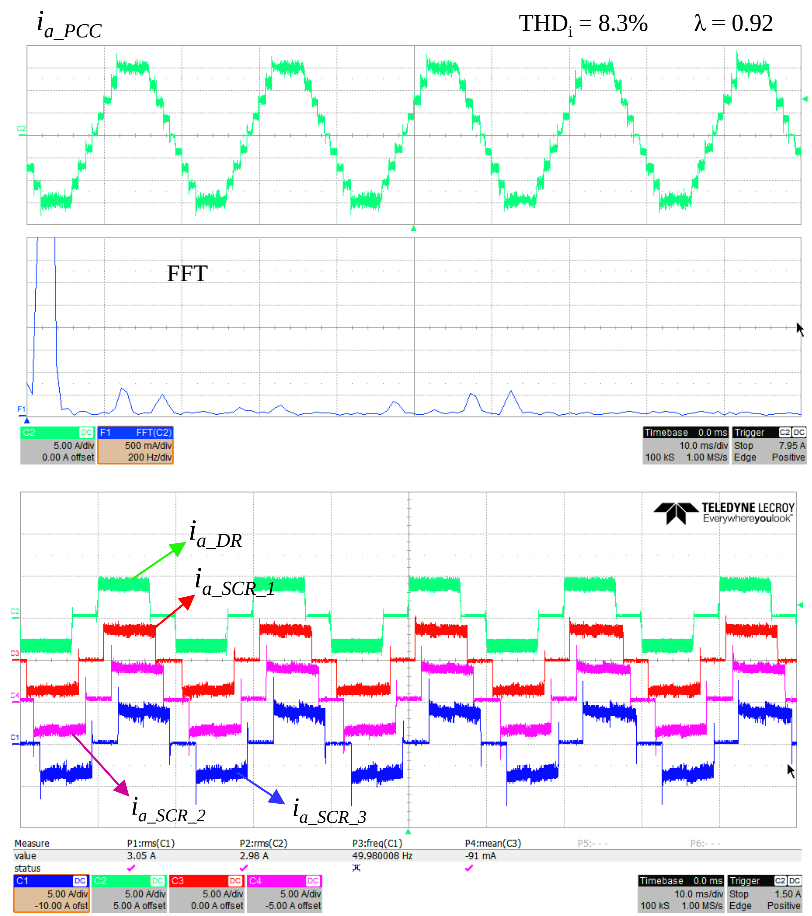
λ_{max} $THD_{i,min}$

● *Lower harmonic distortion can be obtained*

Multi-Drive Configuration

Experimental Setup





Conclusion

- *The EI technique can significantly improve the THD_i, λ and stable DC link*
- *The proposed pulse pattern modulation can eliminate low order harmonics*
- *With multi-drive configuration, the EI technique can further reduce the THD_i*
- *The EI technique can maintain the system performance under non-ideal operation conditions (e.g., unbalanced grid)*
- *The efficiency of EI technique can be significantly improved by employing WBG devices, alternative topologies and smart control techniques*

Thank You

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