Operational Performance and Grid Impact of Modern LV Power Electronic Equipment

(Radne Karakteristike Moderne Niskonaponske Elektronske Opreme I Uticaj Ove Opreme Na Mrežu)

ELEKTRONSKI FAKULTET, UNIVERSITY OF NIŠ

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INTRODUCTION

OVER THE PAST FEW DECADES, PROFOUND CHANGES IN PRINCIPLES OF OPERATION AND CONTROL OF POWER SUPPLY SYSTEMS TOOK PLACE IN GENERATION, TRANSMISSION AND DISTRIBUTION SYSTEMS, AS WELL AS ON THE CONSUMPTION SIDE (AND CHANGES ARE CONTINUING…)

IN TERMS OF MODERN POWER ELECTRONIC EQUIPMENT

EXTRAORDINARY INCREASE OF VARIOUS POWER ELECTRONIC EQUIPMENT AT ALL VOLTAGE LEVELS, FOR DIFFERENT APPLICATIONS AND IN ALL POWER RANGES

- Improved Controllability
- Higher Part-Loading Efficiency
- Enhanced Control
- Better Regulation of Voltages and Reactive Powers (PF, Harmonic Emission…)
- Easier Monitoring, Networking and Remote Control
- …

…FROM A FEW WATT LED LAMPS TO MULTI-MW-RANGE HVDC SYSTEMS…

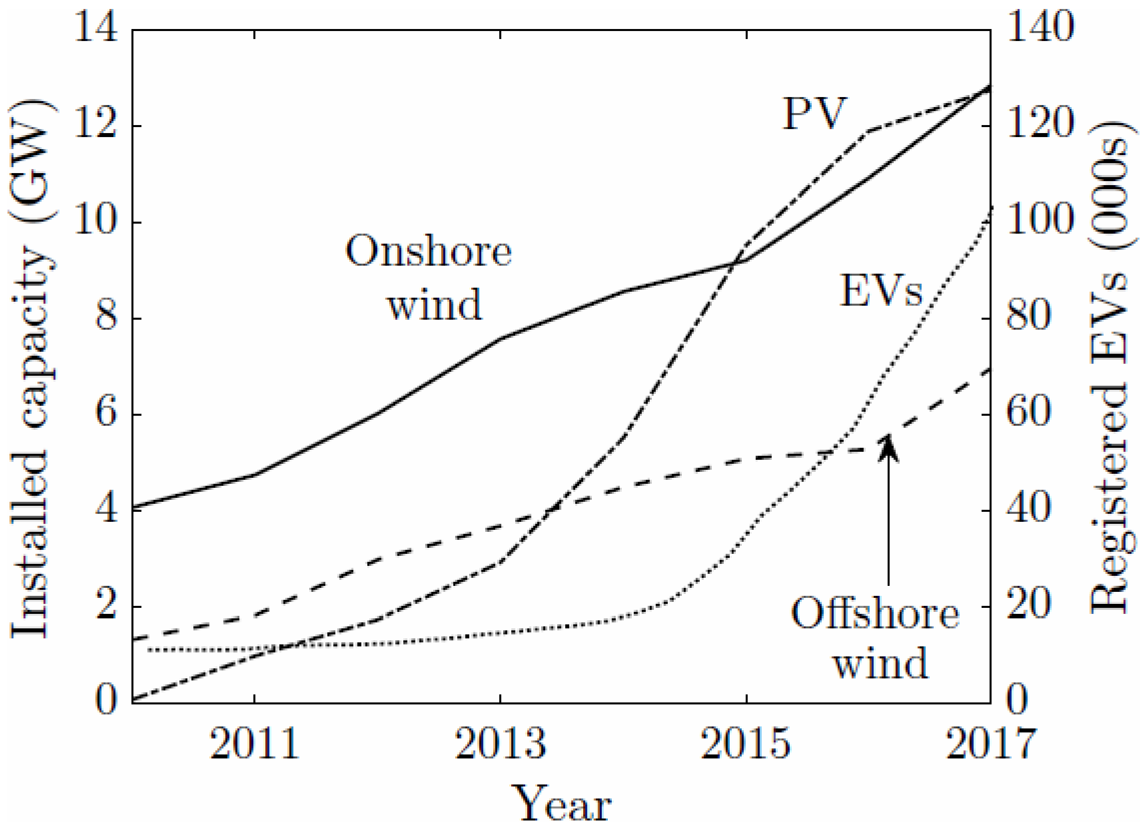
INTRODUCTION

…FROM A FEW WATT LED LAMPS TO MULTI-MW-RANGE HVDC SYSTEMS…

Order of power	Application
1 W – 10 W	LED lamps, phone charger
10 W – 100 W	Laptop power supply, CFLs
100 W – 1 kW	TV power supply, typical 1-phase SMPS
1 kW – 10 kW	Rooftop PV system inverter , EV charger (on-board)
10 kW – 100 kW	EV charger (fast), large 3-phase SMPS
100 kW – 1 MW	Standalone PV system inverter
1 MW – 10 MW	Wind turbine converter, large inverters
10 MW – 100 MW	Static Synchronous Compensator
100 MW – 1 GW	HVDC station

INTRODUCTION

UK-BASED DATA



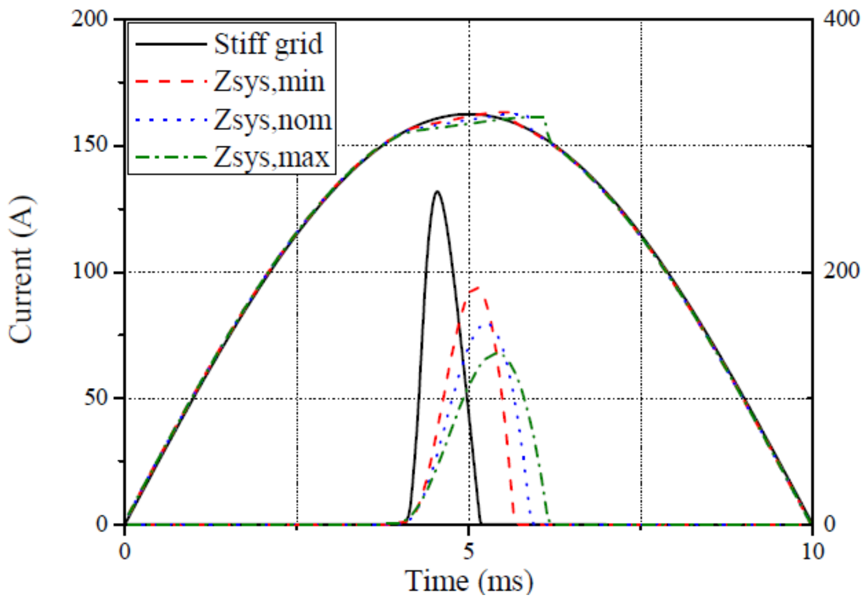
CHANGES IN POWER ELECTRONIC EQUIPMENT

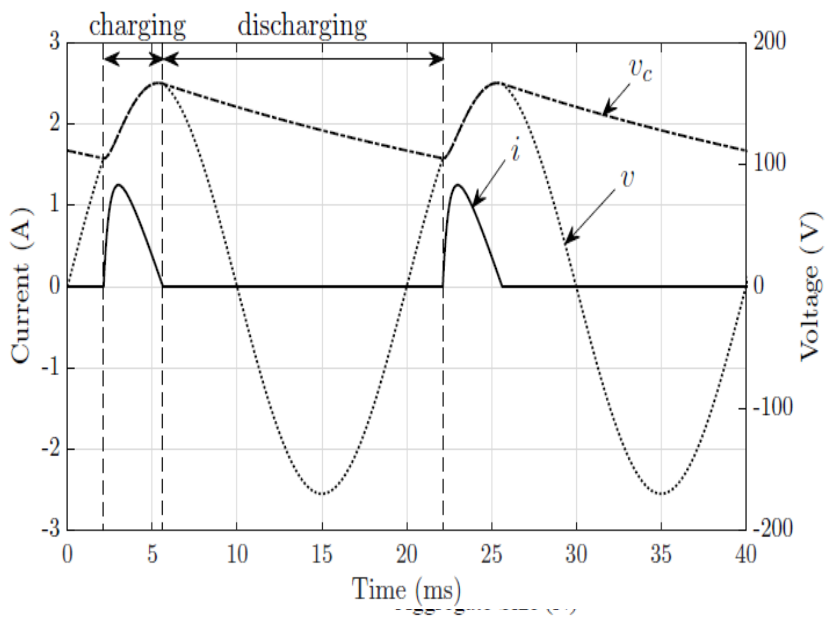
SIGNIFICANT DIFFERENCE FROM A PERIOD AS RECENT AS A DECADE OR TWO AGO WHEN MOST POWER ELECTRONIC EQUIPMENT HAD ONLY SIMPLE TOPOLOGIES WITHOUT POWER FACTOR CORRECTION (PFC) CIRCUIT, OR WITH ONLY PASSIVE PFC

POWER ELECTRONIC EQUIPMENT: SWITCH-MODE POWER SUPPLIES (SMPS')

SELF-REGULATION OF HARMONIC EMISSION

(OLD TYPES OF SMPS' WITH NO PFC, OR WITH PASIVE PFC)





HARMONIC LIMITS ARE ESTABLISHED BASED ON THESE TYPES OF POWER ELECTRONIC EQUIPMENT – ARE THESE LIMITS STILL APPLICABLE TODAY?

EVALUATING CHANGES IN POWER ELECTRONIC EQUIPMENT

FOR EVALUATION, WE NEED SOME "PERFORMANCE INDICATORS"

Some formulas (Old & New):

$$THC = \sqrt{\sum_{h=2}^{H} (I_h)^2}$$

$$THD_I = \frac{1}{I_{fund}} \sqrt{\sum_{h=2}^{H} (I_h)^2} \times 100 = \frac{THC}{I_{fund}} \times 100$$

$$TDD = \frac{1}{I_{rated}} \sqrt{\sum_{h=2}^{H} (I_h)^2} \times 100 = \frac{THC}{I_{rated}} \times 100$$

LF Harmonics Only (up to 40th or 50th)

All Distortion (LF Harmonics, Sub-Harmonics, Interharmonics & HF Harmonics)

$$FF(P) = \frac{I_{fund}(P)}{I_{tot}(P)}$$

$$TDC(P) = \frac{I_{non\_fund}(P)}{I_{tot}(P)} = \frac{\sqrt{I_{tot}^2(P) - I_{fund}^2(P)}}{I_{tot}(P)} = \sqrt{1 - FF^2(P)}$$

$$THF_{LF}(P) = \frac{THC(P)}{I_{tot}(P)} = \frac{THD_I(P) \cdot FF(P)}{100}$$

Total Harmonic Factor (for LF Harmonics)

Total non-LF-Harmonic Distortion

$$TNHDF(P) = \frac{I_{non\_harm}(P)}{I_{tot}(P)} = \frac{\sqrt{I_{tot}^2(P) - I_{fund}^2(P) - THC^2(P)}}{I_{tot}(P)} = \sqrt{1 - FF^2(P) \cdot (1 + (THD_I(P)/100)^2)}$$

EVALUATING CHANGES IN POWER ELECTRONIC EQUIPMENT

FOR EVALUATION, WE NEED SOME "PERFORMANCE INDICATORS"

Some more formulas (Old & New):

LF Harmonics

$$THDS_{ILF} = \sqrt{\sum_{h=2}^{h=40} \left(\frac{I_{sg,h}}{I_{sg,1}}\right)^2}$$

LF Interharmonics

$$TIHDS_{ILF} = \sqrt{\sum_{h=2}^{h=40} \left(\frac{I_{isg,h}}{I_{sg,1}}\right)^2}$$

HF Harmonics & Interharmonics

$$TH\&IHDS_{IHF} = \sqrt{\sum_{h=41}^{h=1000} \left[\left(\frac{I_{sg,h}}{I_{sg,1}}\right)^2 + \left(\frac{I_{isg,h}}{I_{sg,1}}\right)^2\right]}$$

"Total" Efficiency

$$\eta_{PE,I} = \frac{P_{PE,out}}{P_{PE,in}} = \frac{P^1_{PE,out} + P^h_{PE,out}}{P_{PE,in}}$$

"Fundamental" Efficiency

$$\eta'_{PE,I} = \frac{P^1_{PE,out}}{P_{PE,in}}$$

"Distortion-Adjusted" Efficiency

$$\eta_{PE,dist} = \frac{P^1_{PE,out}}{P_{PE,eq}} \quad (\mathrm{x}\ \eta_{tot})$$

See later...

CHANGES IN POWER ELECTRONIC EQUIPMENT: SMPS'

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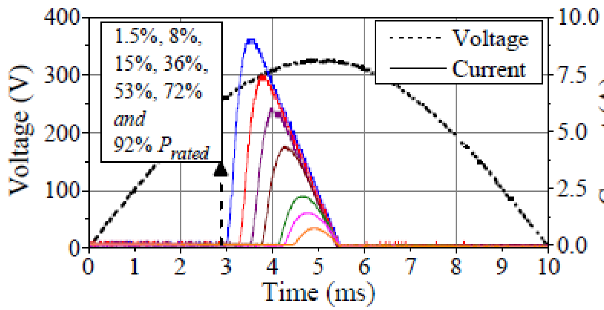
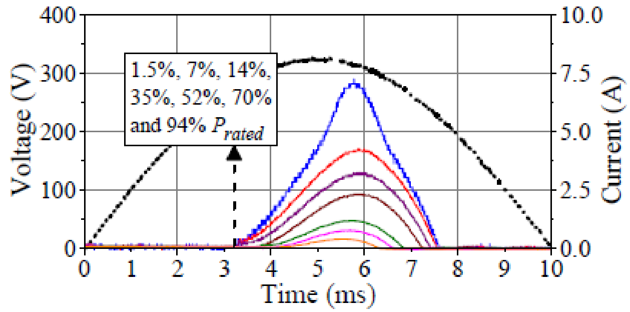
MODERN POWER ELECTRONIC DEVICES HAVE ACTIVE PFC CONTROLS

THERE IS STRONG POWER-DEPENDENCY OF CHARACTERISTICS

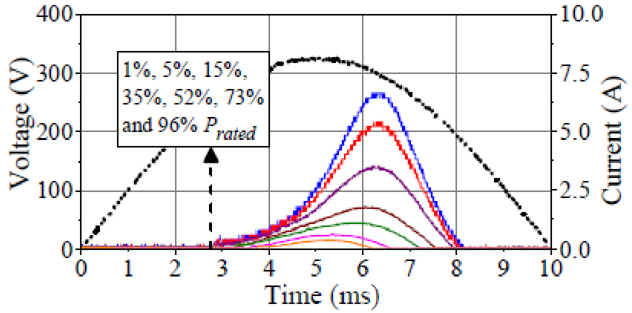
POWER ELECTRONIC EQUIPMENT: SWITCH-MODE POWER SUPPLIES (SMPS')



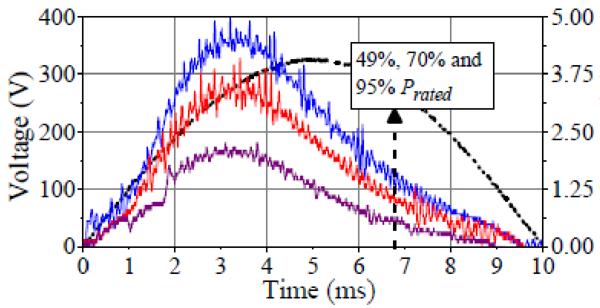
a) SMPS1 with no-PFC



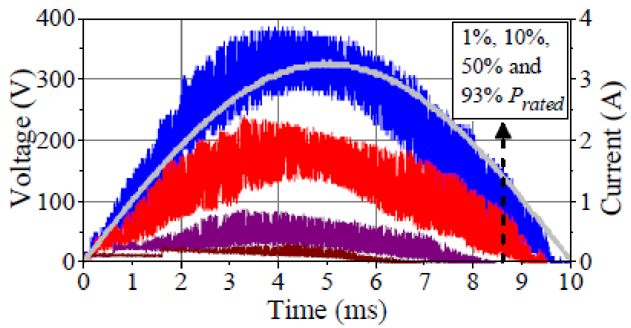
b) SMPS2 with p-PFC



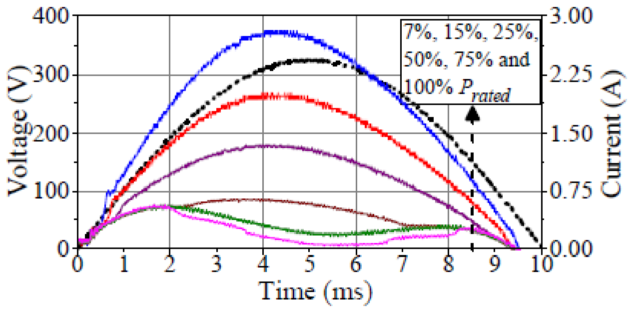
c) SMPS3 with p-PFC



d) SMPS4 with a-PFC



e) SMPS5 with a-PFC



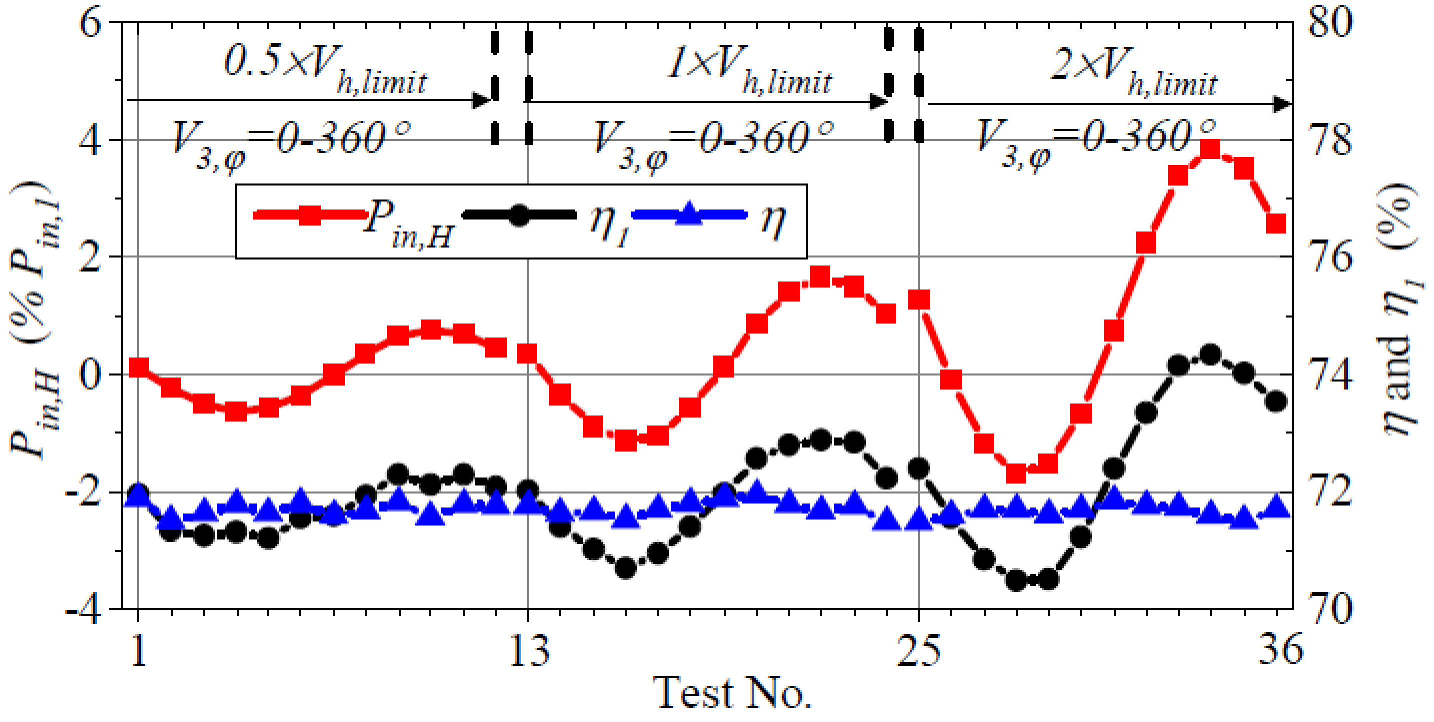
f) SMPS6 with a-PFC

CHANGES IN POWER ELECTRONIC EQUIPMENT: SMPS'

TESTS WITH INDIVIDUAL HARMONICS USING LIMITS FROM [EN 50160]:

$0.5 \times V_{h,limit}$
$1 \times V_{h,limit}$
$2 \times V_{h,limit}$

each with phase angles 0, 30, 60, … , 330 degrees



$$P_{in,H} = P_{in-ac} - P_{in,1}$$

CHANGES IN POWER ELECTRONIC EQUIPMENT: SMPS'

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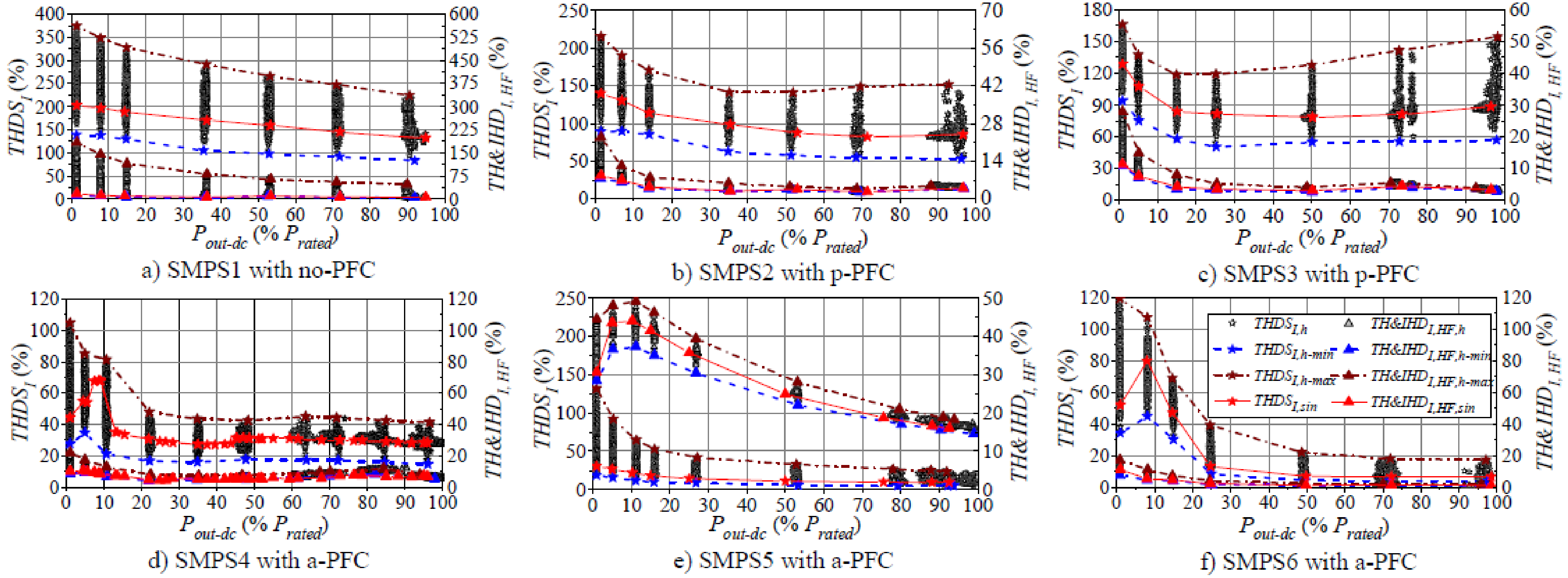
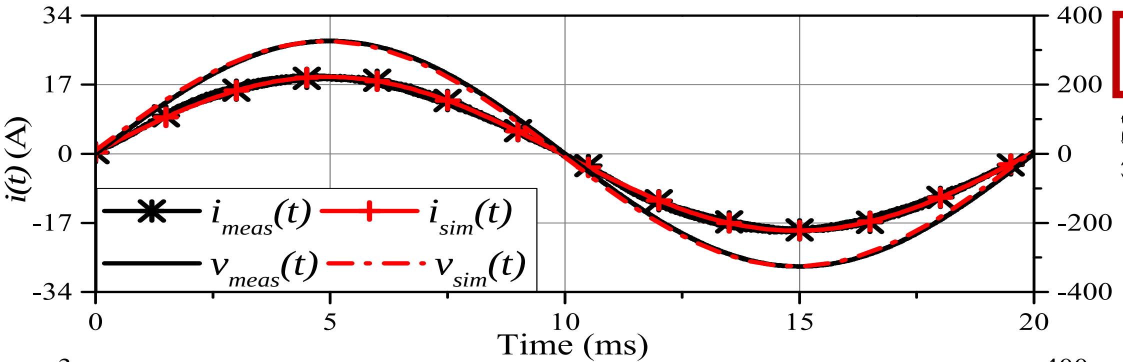


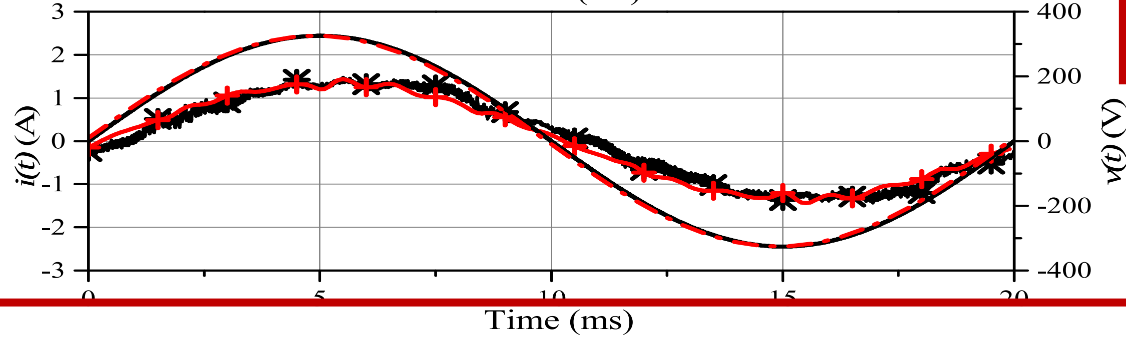
a) SMPS1 with no-PFC
b) SMPS2 with p-PFC
c) SMPS3 with p-PFC
d) SMPS4 with a-PFC
e) SMPS5 with a-PFC
f) SMPS6 with a-PFC

PERFORMANCE OF POWER ELECTRONIC EQUIPMENT: PVIs

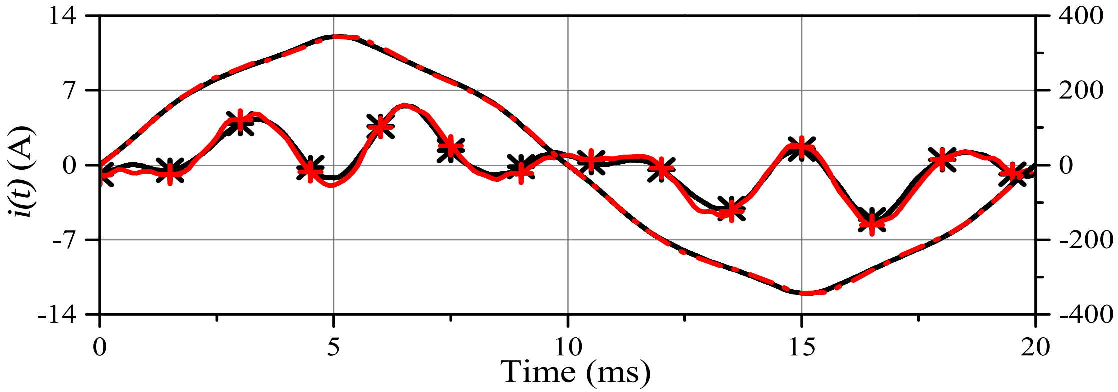
SURPRISING RESULTS FOUND FOR SOME PV INVERTERS (PVIs)



Ideally sinusoidal supply, P_{out}=100%



Ideally sinusoidal supply, P_{out}=10%



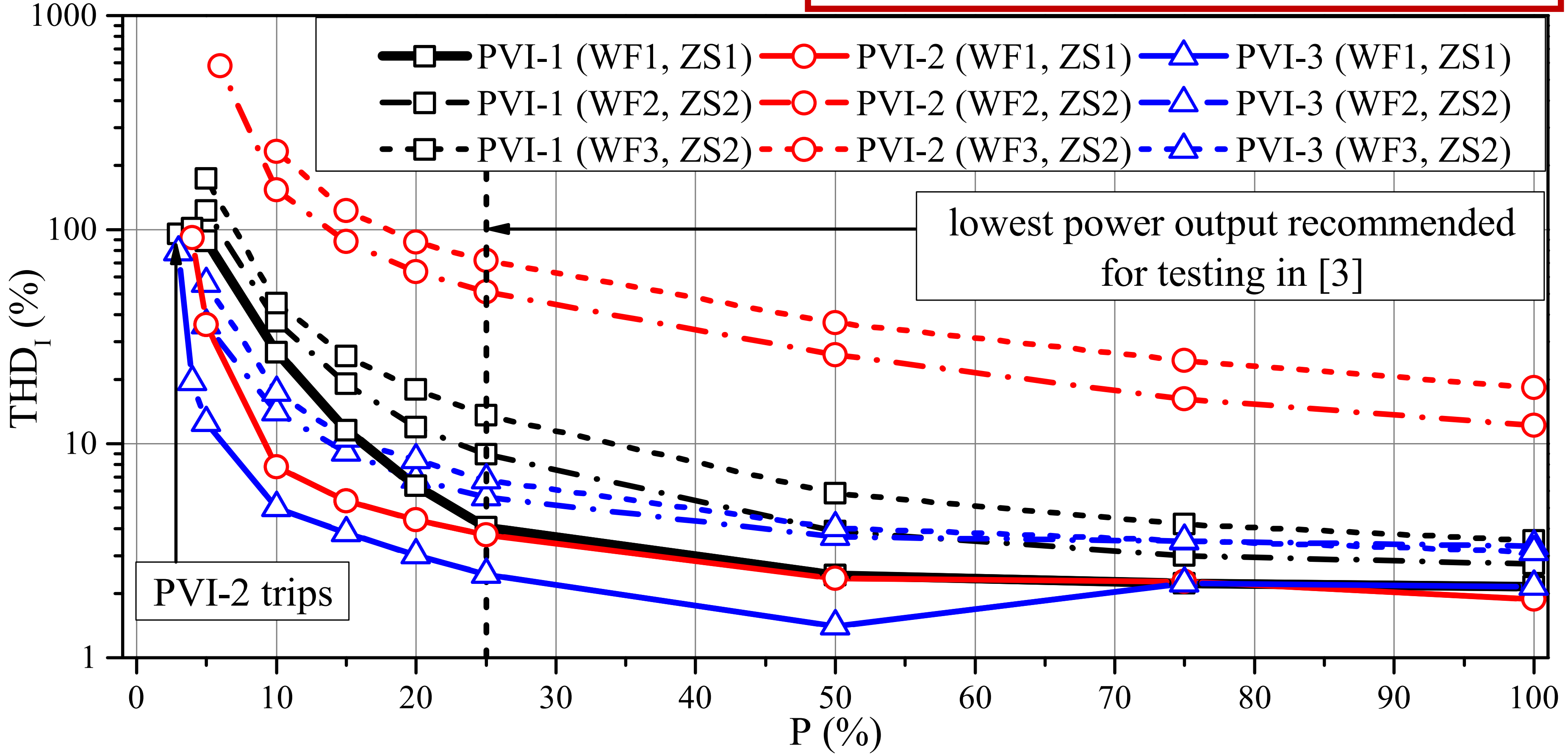
Distorted supply, P_{out}=10%

PERFORMANCE OF POWER ELECTRONIC EQUIPMENT: PVIs

SURPRISING RESULTS FOUND FOR SOME PV INVERTERS:

- WF1: SINUSOIDAL — ZS1 ~0
- WF2: "FLAT-TOP" — ZS2: REFERENCE
- WF3: "POINTED-TOP"

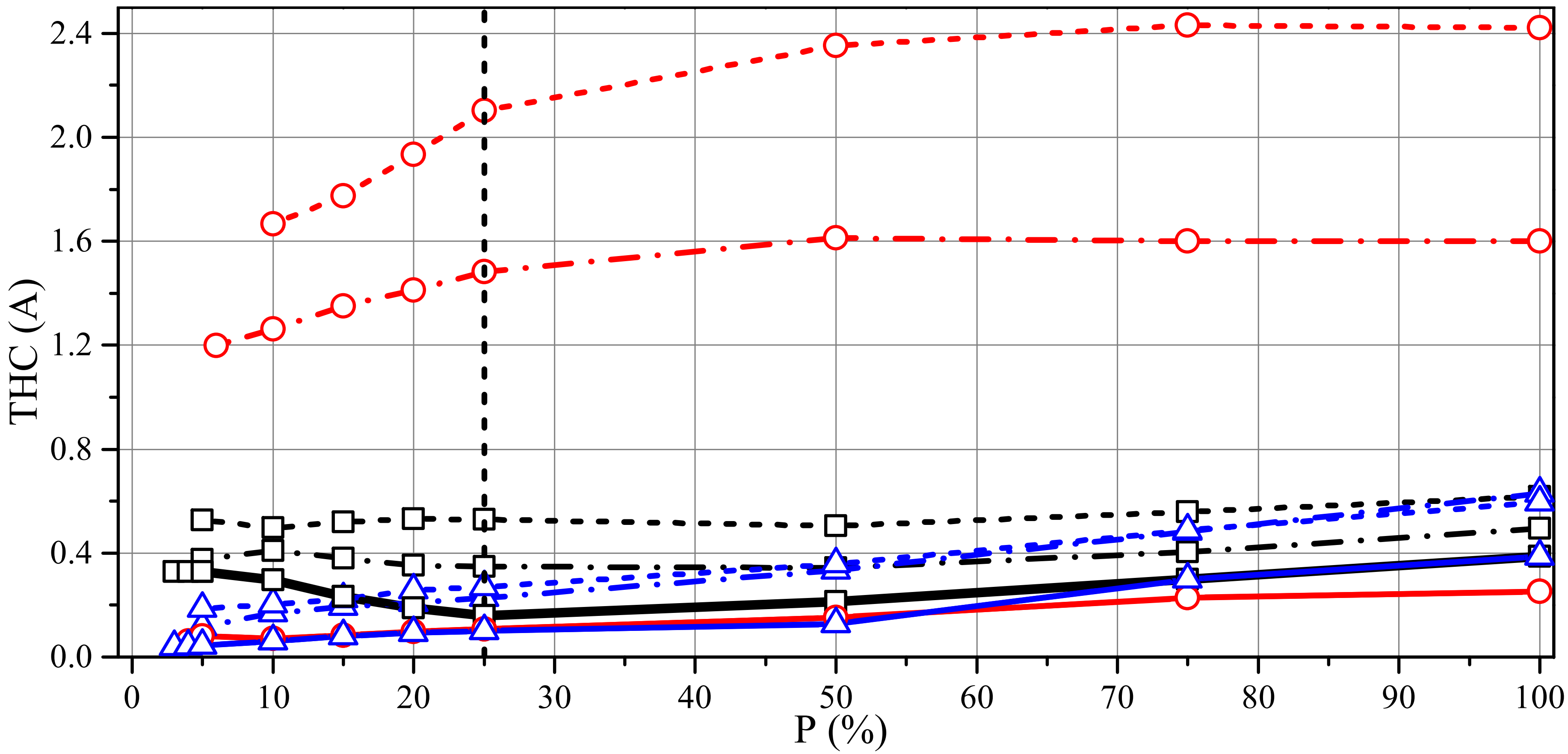
UK: >12 GW of PV installed (~50% < 4kW)
~10% Average Capacity Factor



PERFORMANCE OF POWER ELECTRONIC EQUIPMENT: PVIs

SURPRISING RESULTS FOUND FOR SOME PV INVERTERS:

- WF1: SINUSOIDAL — ZS1 ~0
- WF2: "FLAT-TOP" — ZS2: REFERENCE SOURCE IMPEDANCE
- WF3: "POINTED-TOP"



PERFORMANCE OF POWER ELECTRONIC EQUIPMENT: PVIs

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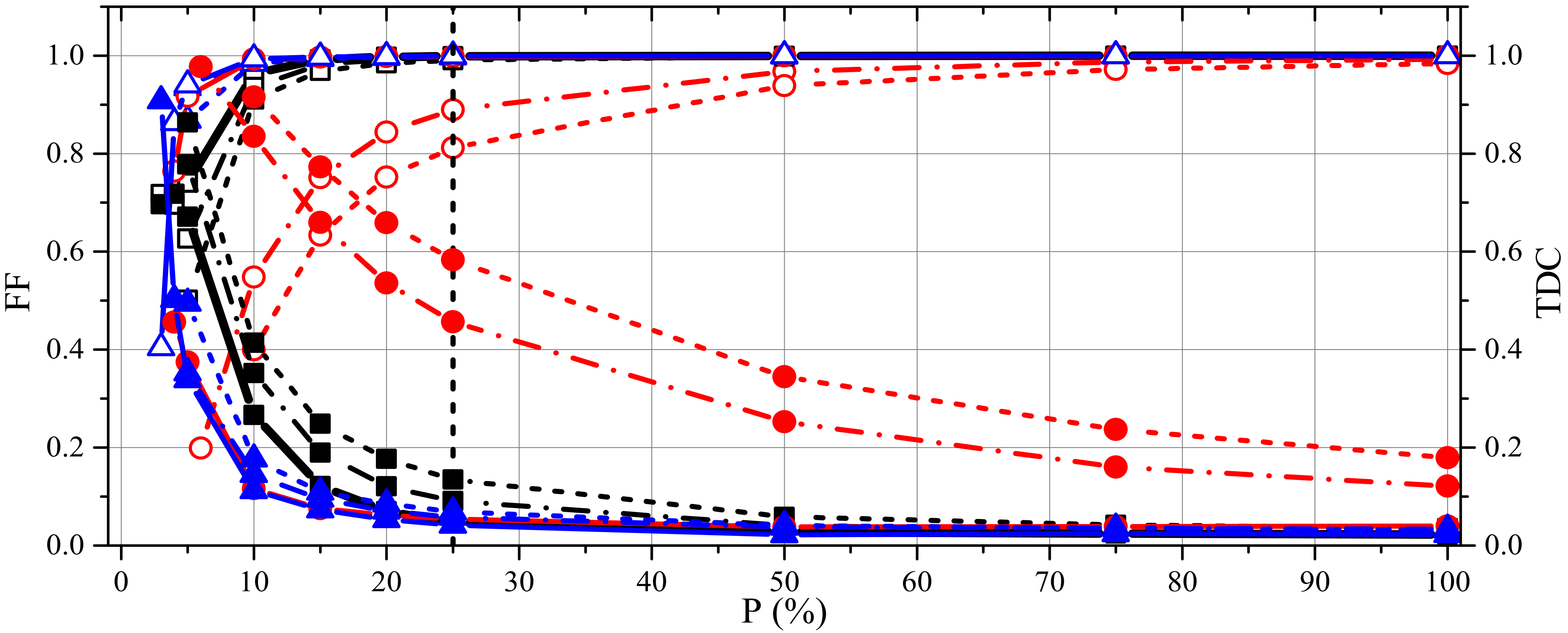

(FF, hollow symbols & TDC, solid symbols)

PERFORMANCE OF POWER ELECTRONIC EQUIPMENT: PVIs

SURPRISING RESULTS FOUND FOR SOME PV INVERTERS:

- WF1: SINUSOIDAL ZS1 ~0
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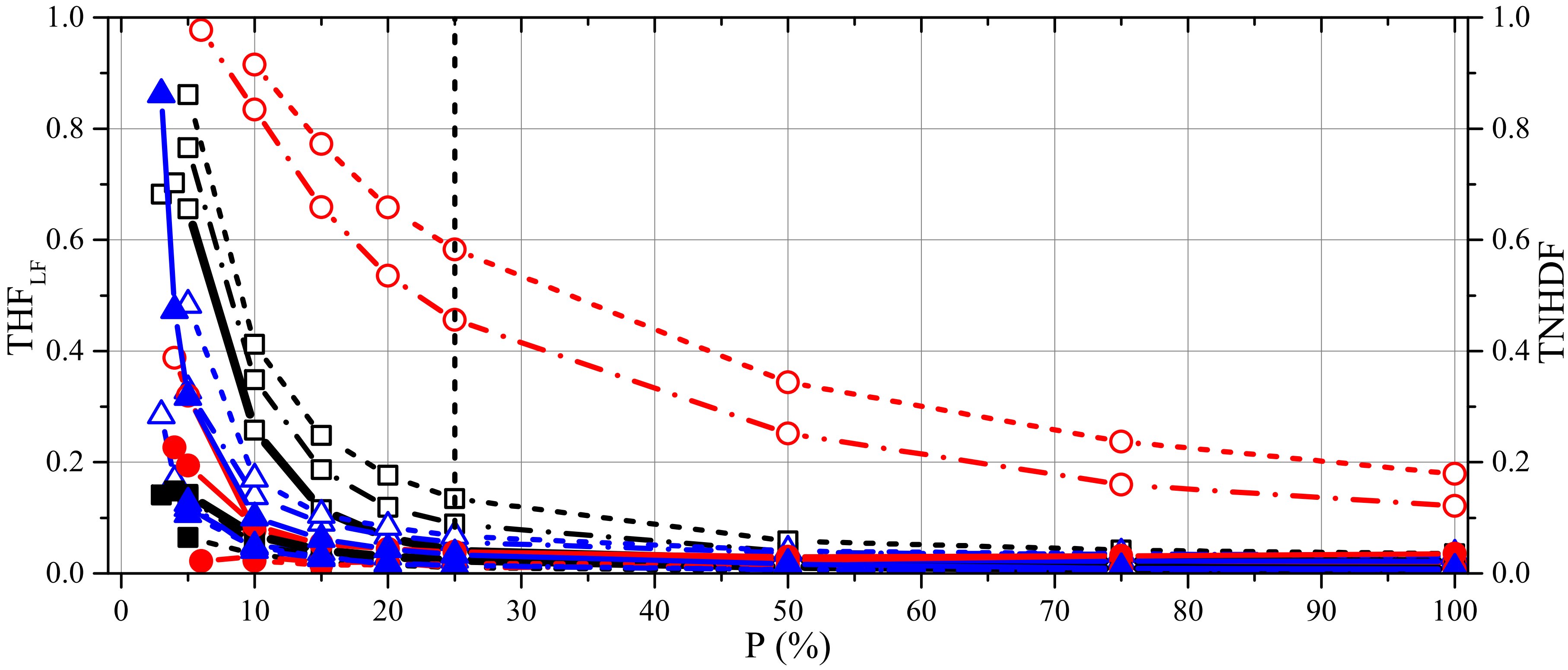
- WF3: “POINTED-TOP”

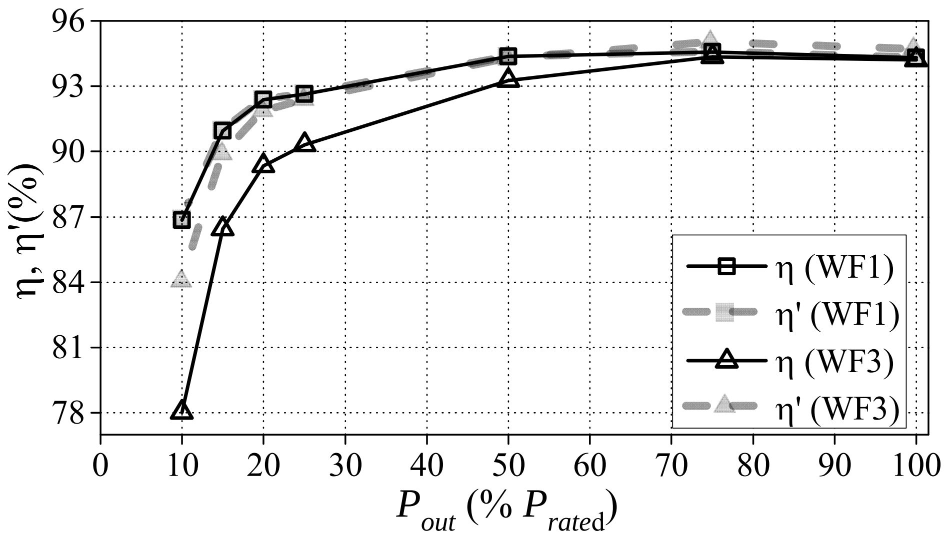


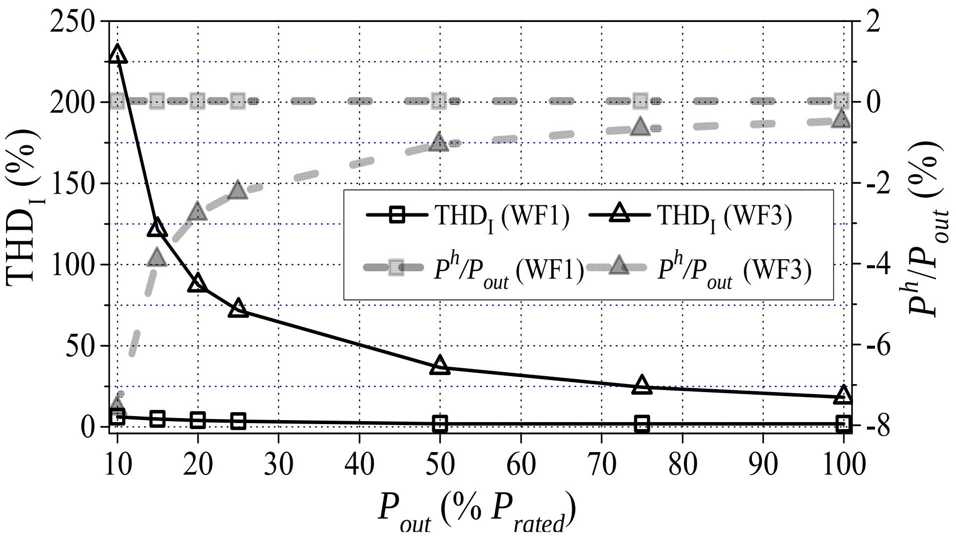
(THF_{LF}, hollow symbols & TNHDF, solid symbols)

PERFORMANCE OF POWER ELECTRONIC EQUIPMENT: PVIs

EFFICIENCY vs WAVEFORM DISTORTION :

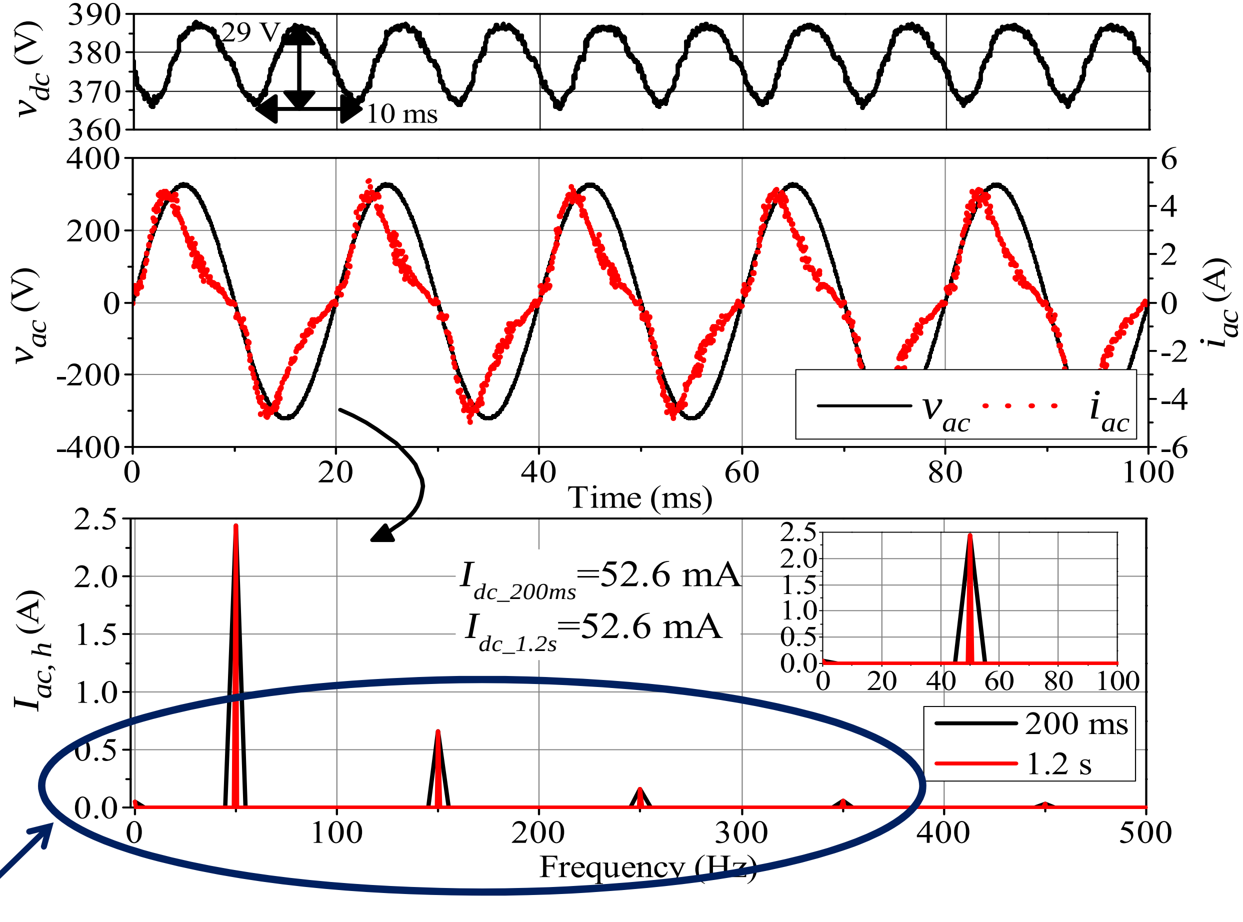
- WF1: SINUSOIDAL — ZS1 ~0
- WF2: "FLAT-TOP" — ZS2: REFERENCE SOURCE IMPEDANCE
- WF3: "POINTED-TOP"





PERFORMANCE OF POWER ELECTRONIC EQUIPMENT: SMPS'

LOST PERIODICITY:

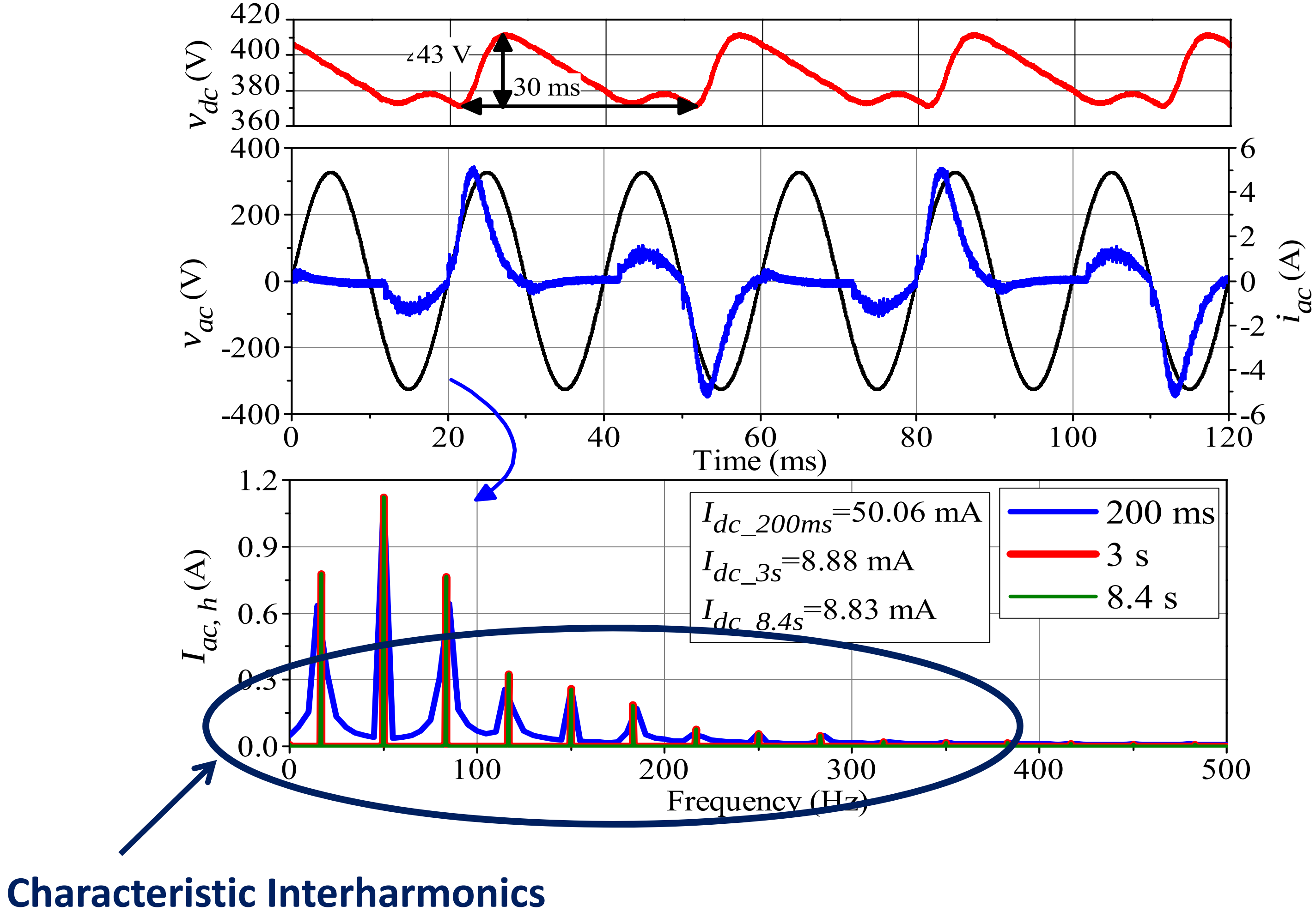


No interharmonics

96% of Prated

PERFORMANCE OF POWER ELECTRONIC EQUIPMENT: SMPS'

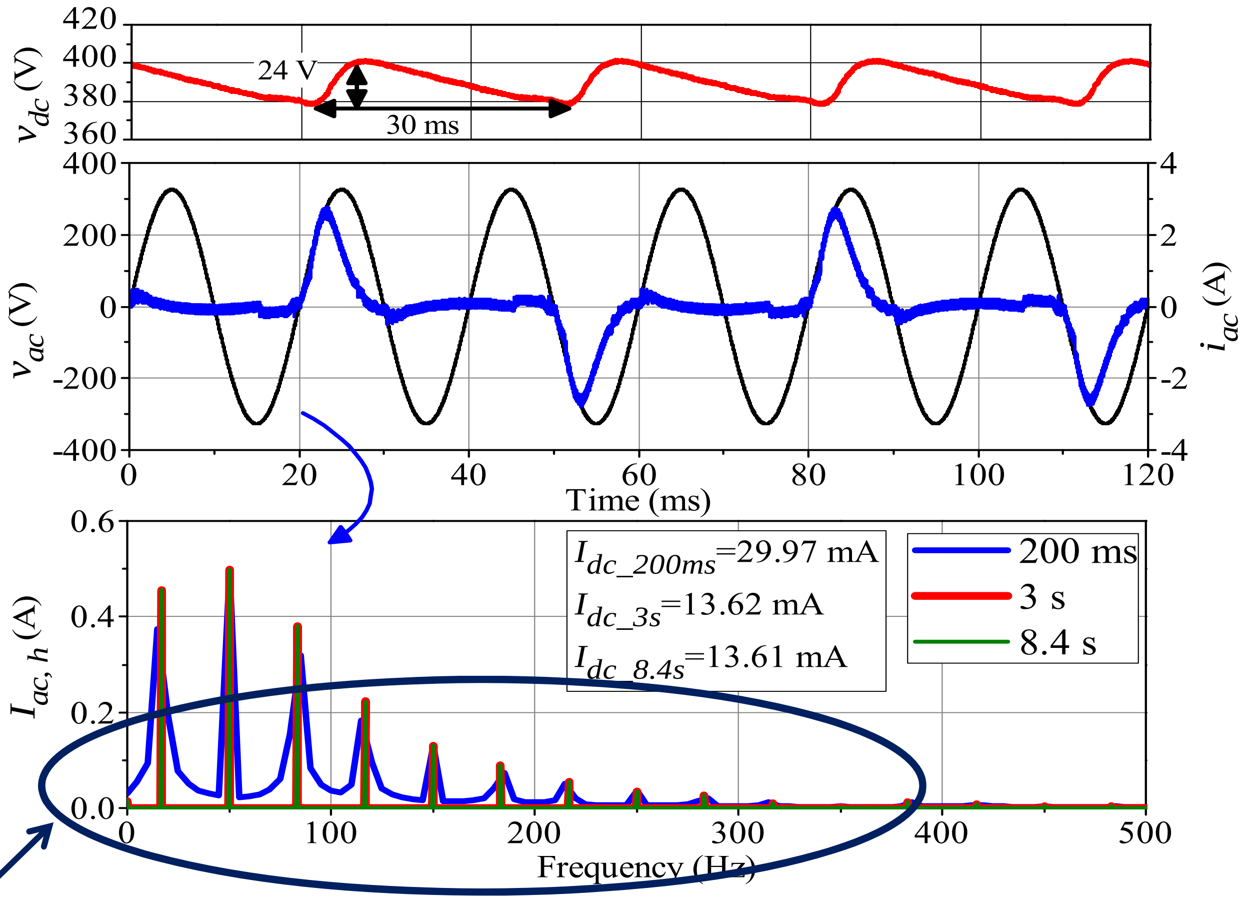
LOST PERIODICITY:



44% of Prated

PERFORMANCE OF POWER ELECTRONIC EQUIPMENT: SMPS'

LOST PERIODICITY:

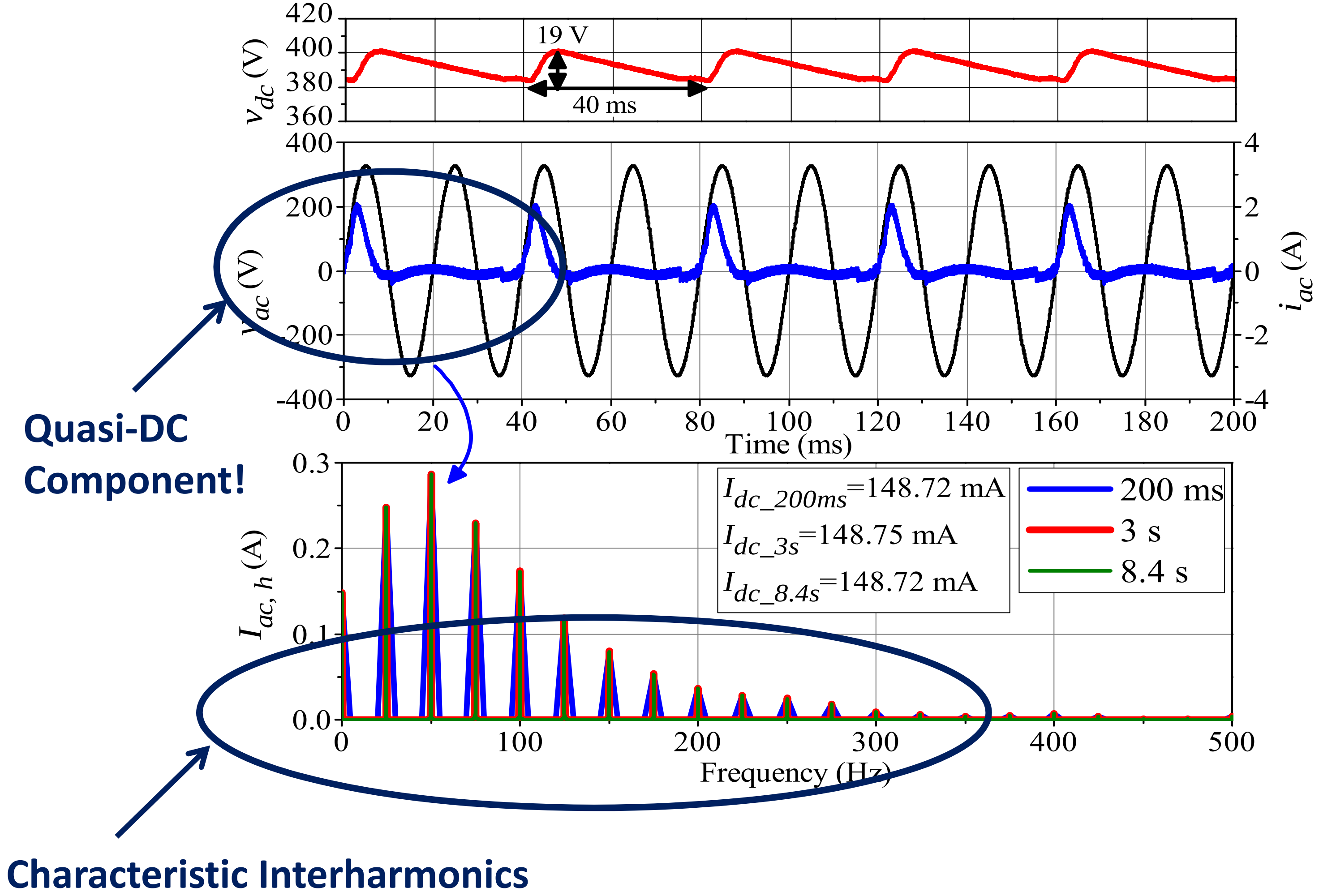


Characteristic Interharmonics

20% of Prated

PERFORMANCE OF POWER ELECTRONIC EQUIPMENT: SMPS'

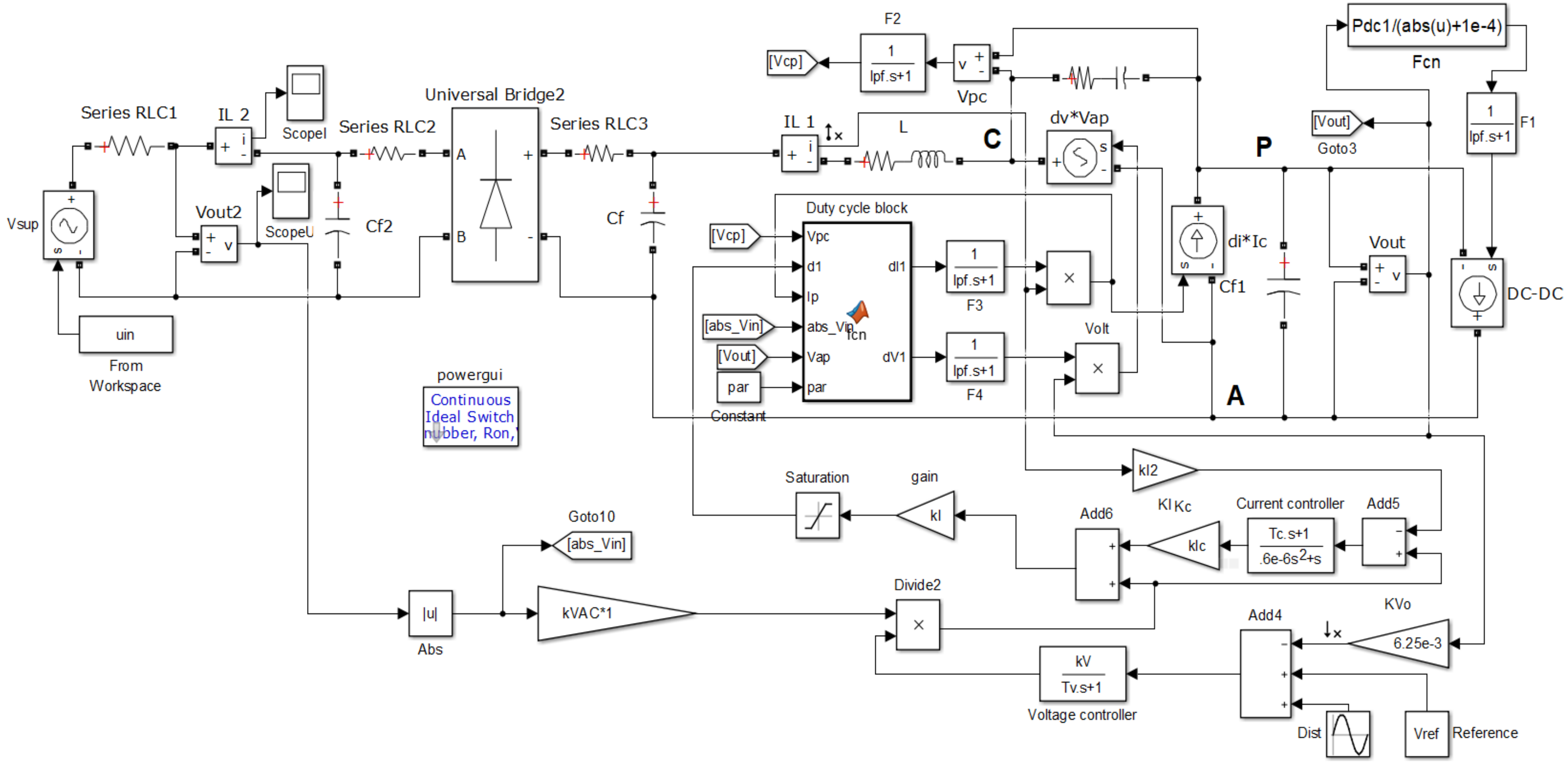
LOST PERIODICITY:



10% of Prated

PHENOMENA OF LOST PERIODICITY

MODELLING (COMPONENT-BASED MODEL):

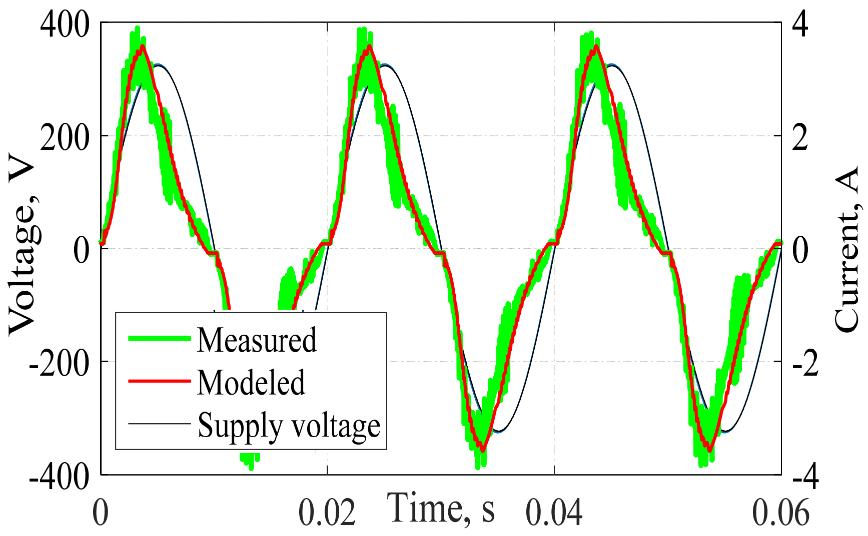


CIRCUIT PARAMETERS

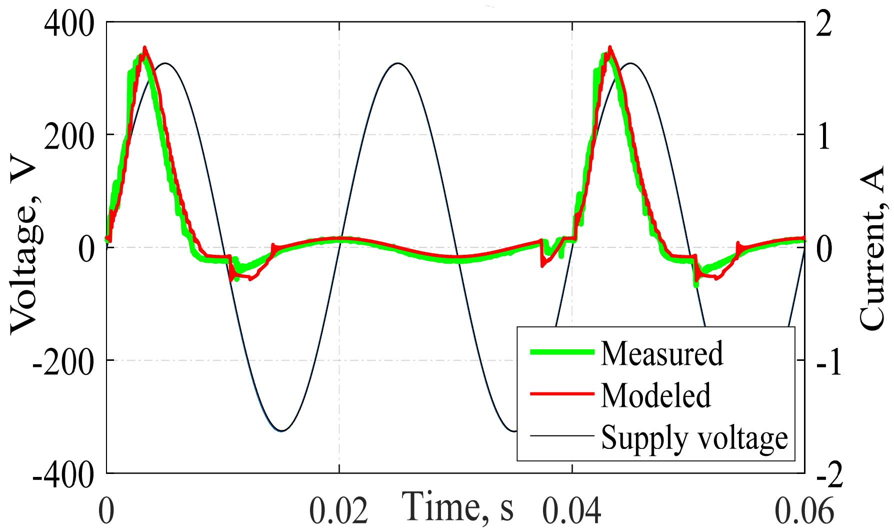
Components					Control							
C_{out} uF	L uH	f kHz	C_f uF	C_{f2} uF	k_I	k_{I2}	k_{IC}	T_C ms	k_{V1}	T_V ms	V_{ref} V	k_{VAC}
200	500	100	1	0.8	0.32	0.32	$3.5 \cdot 10^3$	0.51	6.5	1	2.5	$3 \cdot 10^{-3}$

PHENOMENA OF LOST PERIODICITY

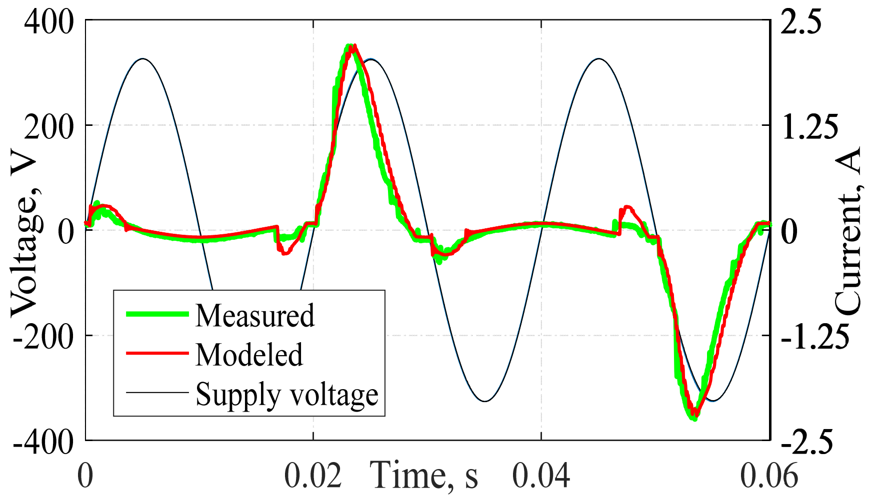
COMPARISON OF SIMULATIONS & MEASUREMENTS:



75% of P_{ated}



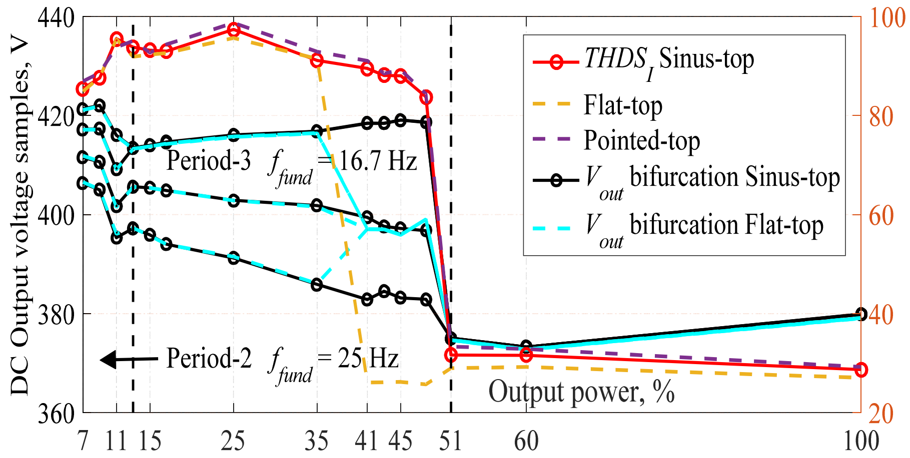
16% of P_{ated}



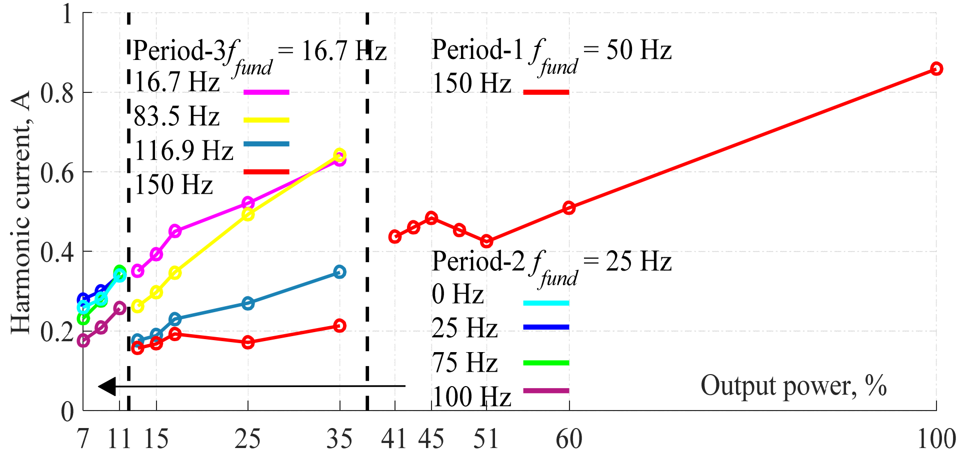
8% of P_{ated}

PHENOMENA OF LOST PERIODICITY

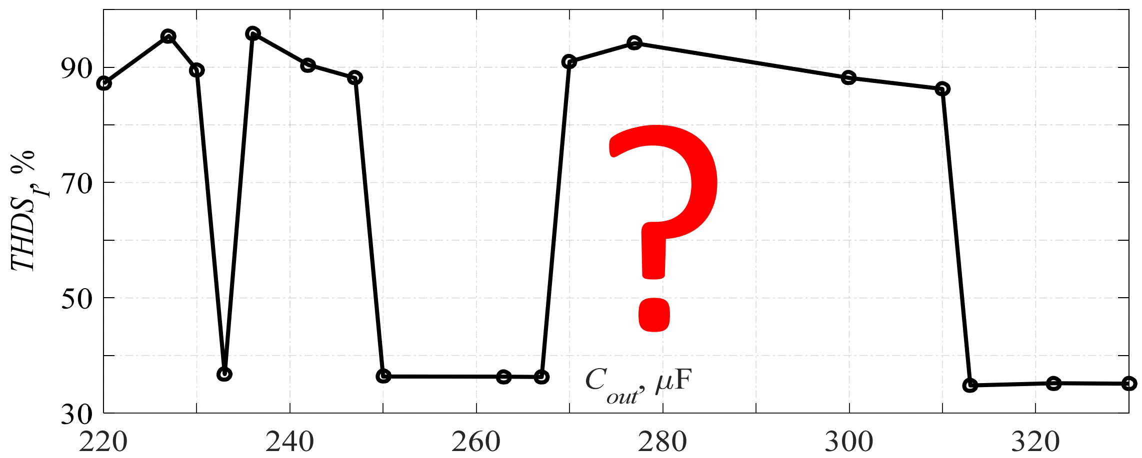
Analysis of Power-Dependent Changes:



output dc voltage and THDSI



dominant current harmonics

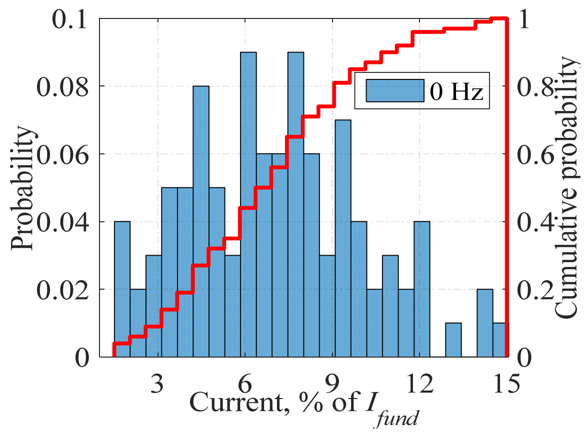


THDS_I for different output capacitance (at 30% of P_{ated})

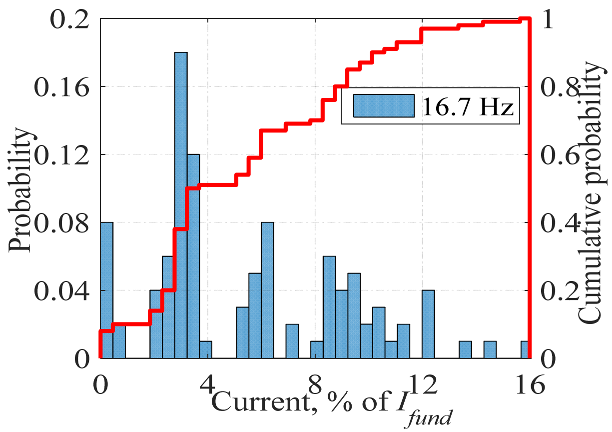
PHENOMENA OF LOST PERIODICITY

AGGREGATE IMPACT ON LV GRID (Monte-Carlo Simulations):

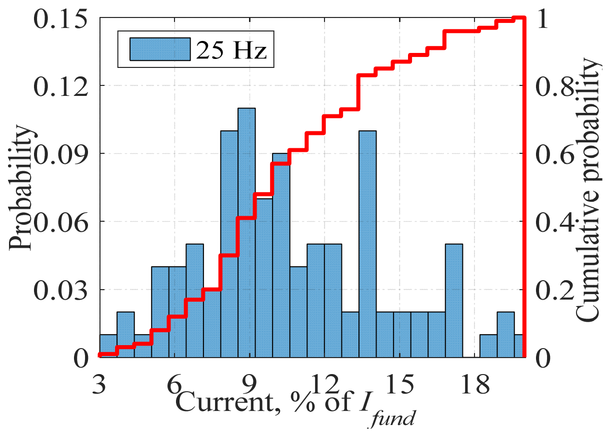
Operating mode	Mean output power % of P_{rated}	Standard deviation W	Input ac current period	Duty cycle %
Active	40	25	Period-1 (50 Hz)	30
Idle	20	10	Period-3 (16.7 Hz)	20
“Sleep”	10	10	Period-2 (25 Hz)	50



0 Hz (dc component)



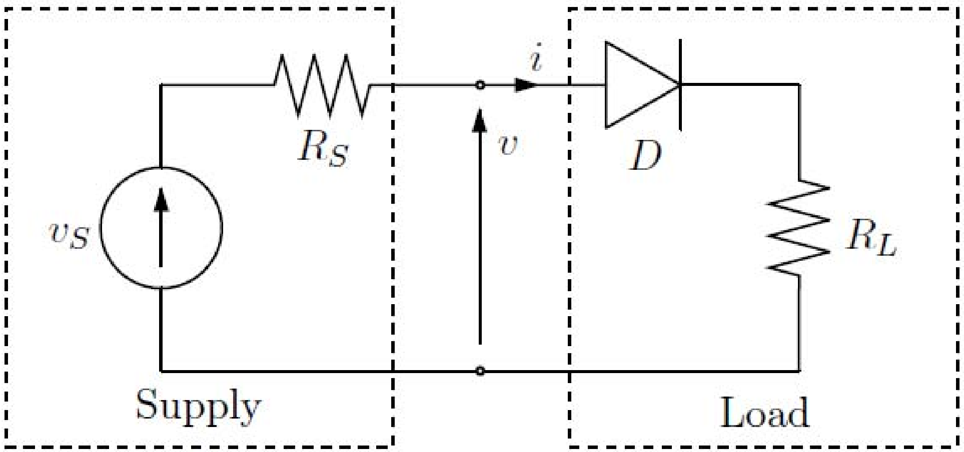
16.7 Hz (period-3 subharmonic)



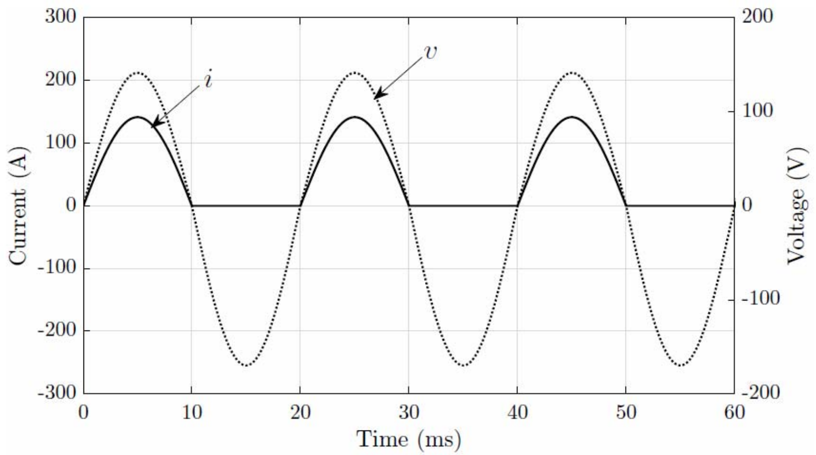
25 Hz (period-2 subharmonic)

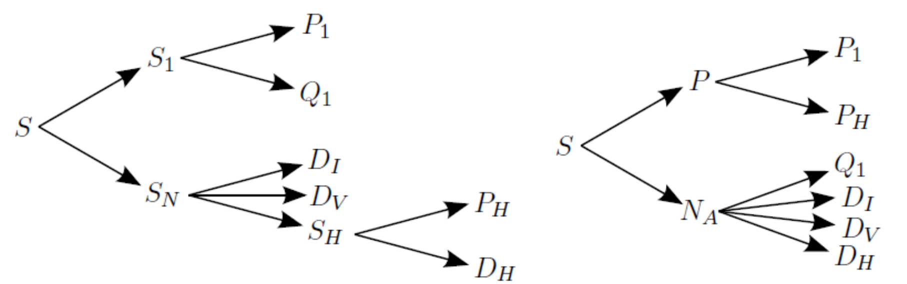
EQUIVALENT SINUSOIDAL (FUNDAMENTAL) REPRESENTATION…?

LET US CONSIDER A SIMPLE HALF-WAVE RECTIFIER CIRCUIT:



Component	Value
V_S	$120\,V$
R_S	$1\,\Omega$
R_L	$1\,\Omega$





(a) Fundamental/Nonfundamental (b) Active/Nonactive

EQUIVALENT SINUSOIDAL (FUNDAMENTAL) REPRESENTATION…?

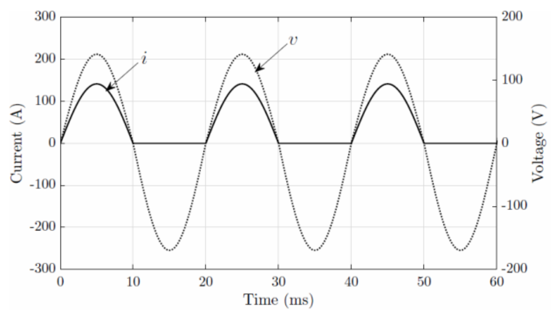
FULL-CYCLE ANALYSIS:

h	I_h (A)	β_h (°)	V_h (V)	α_h (°)
0 (DC)	45.02	+	9.00	–
1	50.00	0	110.00	0
2	21.22	-90	4.24	90
4	4.24	-90	0.85	90
6	1.82	-90	0.36	90
8	1.01	-90	0.2	90
10	0.64	-90	0.13	90

(a) Individual harmonics

Parameter	Value
I	70.71 A
I_1	50.00 A
I_H	50.00 A
V	110.45 V
V_1	110.00 V
V_H	10.00 V
THD_I	100%
THD_V	9.09%

(b) Distortion parameters



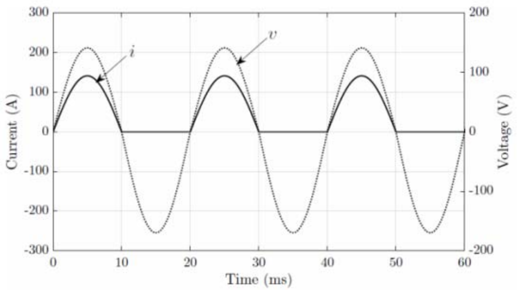
Parameter	Value
P	5000 W
P_1	5500 W
P_H	-500 W
S	7810 VA
S_1	5500 VA
S_N	5545 VAr
S_H	500 var

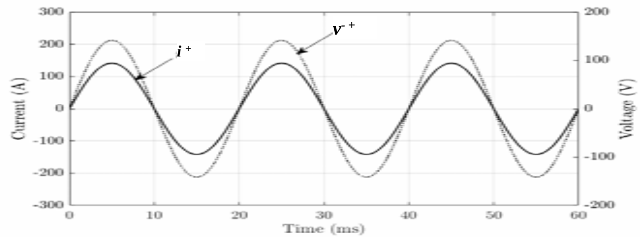
Parameter	Value
N_A	6000 VAr
Q_1	0 VAr
D_I	5500 var
D_V	500 var
D_H	0 var

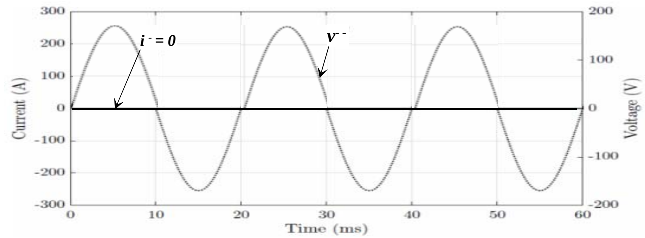
Parameter	Value
PF	0.64
PF_1	1.00
PF_d	0.64

EQUIVALENT SINUSOIDAL (FUNDAMENTAL) REPRESENTATION…?

HALF-CYCLE ANALYSIS (TWO DIFFERENT HALF-CYCLES USED TO RECONSTRUCT TWO FULL CYCLES):







h	I_h^+ (A)	β_h^+ (°)	V_h^+ (V)	α_h^+ (°)
0 (DC)	0	–	0	–
1	100	0	100	0
≥ 2	0	–	0	–

(a) Positive/First half cycle

h	I_h^- (A)	β_h^- (°)	V_h^- (V)	α_h^- (°)
0 (DC)	0	–	0	–
1	0	–	120	-180
≥ 2	0	–	0	–

(b) Negative/Second half cycle

Parameter	+	−
I	100 A	0 A
I_1	100 A	0 A
I_H	0 A	0 A
V	100 V	120 V
V_1	100 V	120 V
V_H	0 V	0 V
THD_I	0 %	0 %
THD_V	0 %	0 %

(c) Half cycle distortion parameters

$$V = \sqrt{\frac{(V^+)^2 + (V^-)^2}{2}} = 110.45\,V$$

$$I = \sqrt{\frac{(I^+)^2 + (I^-)^2}{2}} = 70.71\,A$$

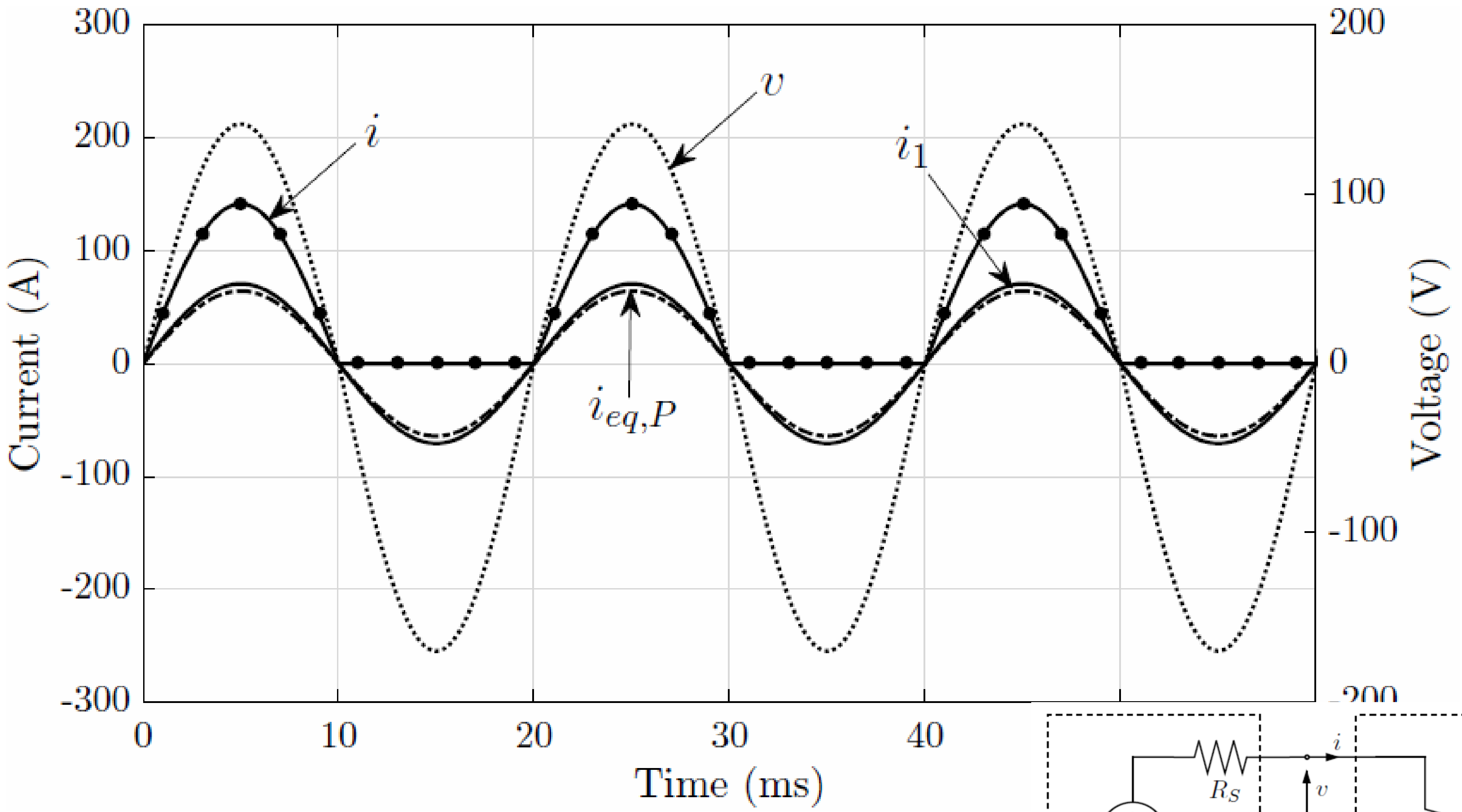
$$S = 7810 \text{ VA}$$

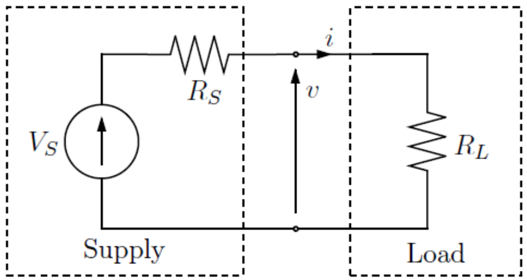
$$S_N = \sqrt{S^2 - S_1^2} = 6000\,\text{VAr}$$

EQUIVALENT SINUSOIDAL (FUNDAMENTAL) REPRESENTATION…?

FUNDAMENTAL COMPONENT = FOURIER TRANSFORMATION FUNDAMENTAL, BUT

ARE THERE <u>DIFFERENT</u> FUNDAMENTALS…?





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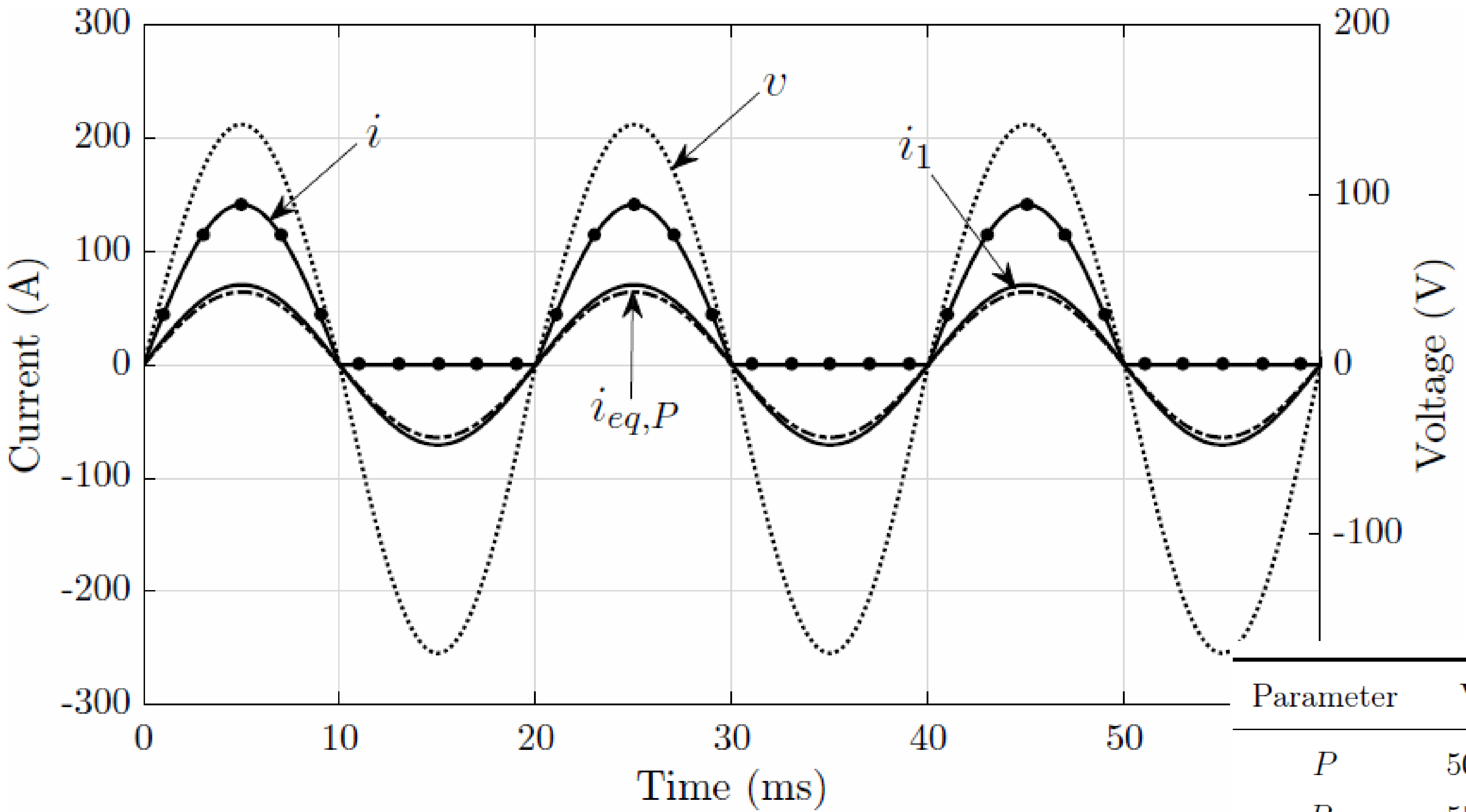

Parameter	Value
P	5000 W
P_1	5500 W
P_H	-500 W

WHAT ABOUT HARMONIC MITIGATION, E.G. BY ACTIVE FILTERS…?

(THERE IS 500 W DIFFERENCE)

CONCLUSIONS

CHANGES IN EQUIPMENT CHARACTERISTICS (AND PRINCIPLES OF OPERATION OF SUPPLYING NETWORKS) REQUIRE NEW METHODOLOGIES, MODELS, TOOLS AND METRICS (NEW PERFORMANCE INDICATORS) FOR ANALYSING, EVALUATING AND UNDERSTANDING EFFICIENCY AND POWER QUALITY PERFORMANCE OF MODERN LV POWER ELECTRONIC EQUIPMENT

GENUINELY NEW ISSUES ARE IDENTIFIED FOR CERTAIN OPERATING MODES OF MODERN LV POWER ELECTRONIC EQUIPMENT, WHICH REQUIRE CAREFUL EVALUATION AND IMPLEMENTATION OF NEW APPROACHES FOR THEIR ANALYSIS

UNDERSTANDING AND MODELLING THE IMPACT OF SOPHISTICATED CONTROLS OF MODERN LV POWER ELECTRONIC EQUIPMENT IS CRUCIAL FOR EVALUATING THEIR PERFORMANCE – USING ONLY CIRCUIT MODELS IS NOT SUFFICIENT

UPDATING TESTING PROCEDURES TO ACKNOWLEDGE BOTH PRESENCE OF TYPICAL DISTORTIONS IN LV POWER SUPPLY SYSTEMS AND OPERATION OF EQUIPMENT AT LOW POWERS MIGHT BE A GOOD IDEA

SAME REASONING MIGHT APPLY TO THE UPDATING OF EXISTING DISTORTION LIMITS IN STANDARDS, GRID CODES AND OTHER REGULATION

Operational Performance and Grid Impact of Modern LV Power Electronic Equipment

THANKS!

QUESTIONS & DISCUSSION?

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20th of august 2018

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