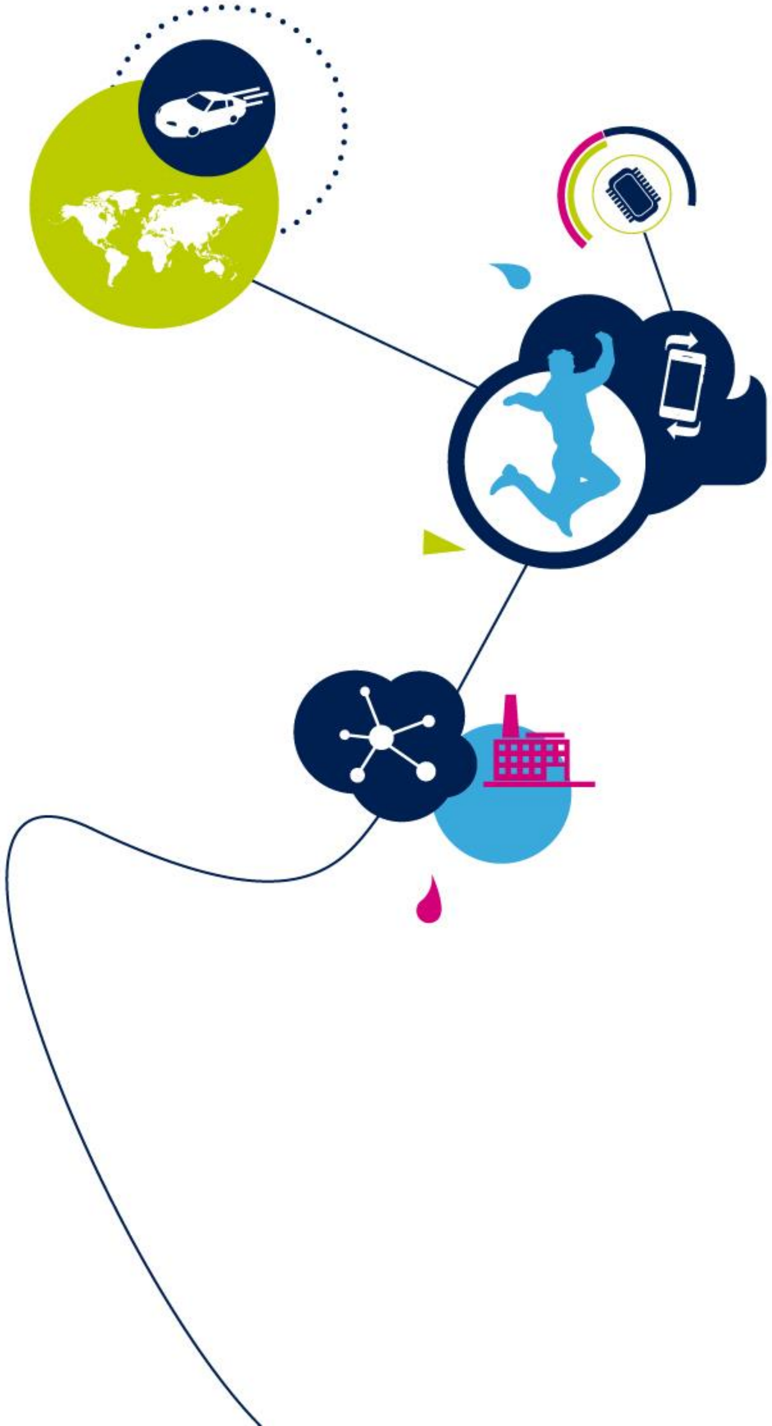
STEVAL-CTM010V1

1.5 kW dual motor drive with digital PFC based on SLLIMM™ IPMs and STM32F3



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Summary

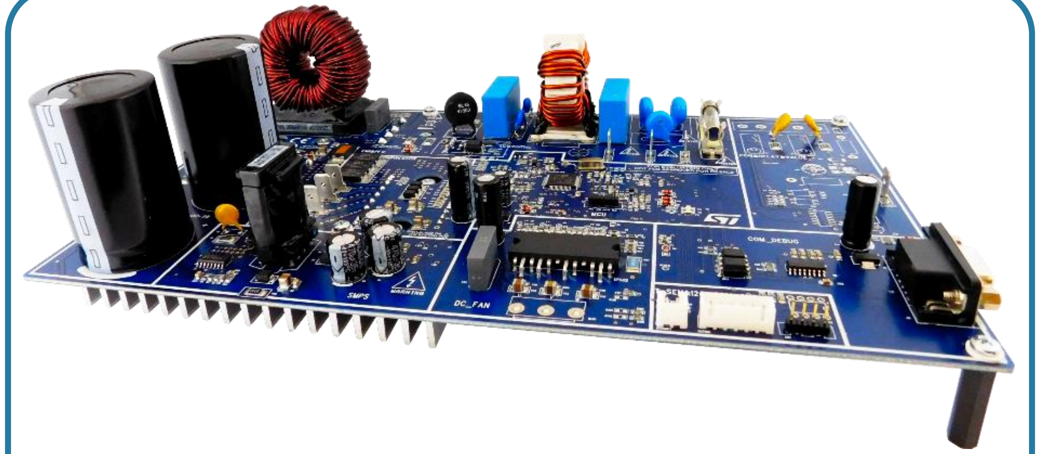
- Solution Architecture
- Block diagram, example of product selection
- Functions
- STM32F3 cpu load in the application
- IPM, STGIB10CH60TS energy efficiency
- Digital PFC, bench experimental results, THD and PF
- Digital PFC Diode experimental results,
- Digital PFC IGBT experimental results,
- AirCon IPs performed from STM32

Room AirCon Evaluation Boards

1.5 kW Dual motor drive with digital PFC (boost single stage) based on SLLIMM™ IPMs and STM32F3

Key Features

- Input voltage: 230VAC 50Hz / 60Hz
- Max Power: up to 2kW
- **PFC topology**: digital control, **boost single stage**
- PFC Protections: Over Current, Over Voltage, Under Voltage Lock Out.
- Inrush current limiter based on Overvoltage protected AC switch
- **Motor 1 stage (i.e compressor of out door unit)**:
  - Max current: up to 10A, 0-to-peak (current sensing network threshold)
  - 1/ 2/ 3 shunt resistors for current sensing
  - Protections: Over current, over temperature, Under voltage lock out
- **Motor 2 stage (i.e fan of out door unit)**: :
  - Max Power: 60W (no heatsink)
  - Max current: up to 1A, 0-to-peak (current sensor network threshold)
  - 1 shunt resistor for current sensing
  - Protections: Over current, over temperature, Under voltage lock out
- **Centralized driving stage**
  (motor 1, motor 2, PFC) from one MCU only the STM32F303RB
- ~150*265 mm



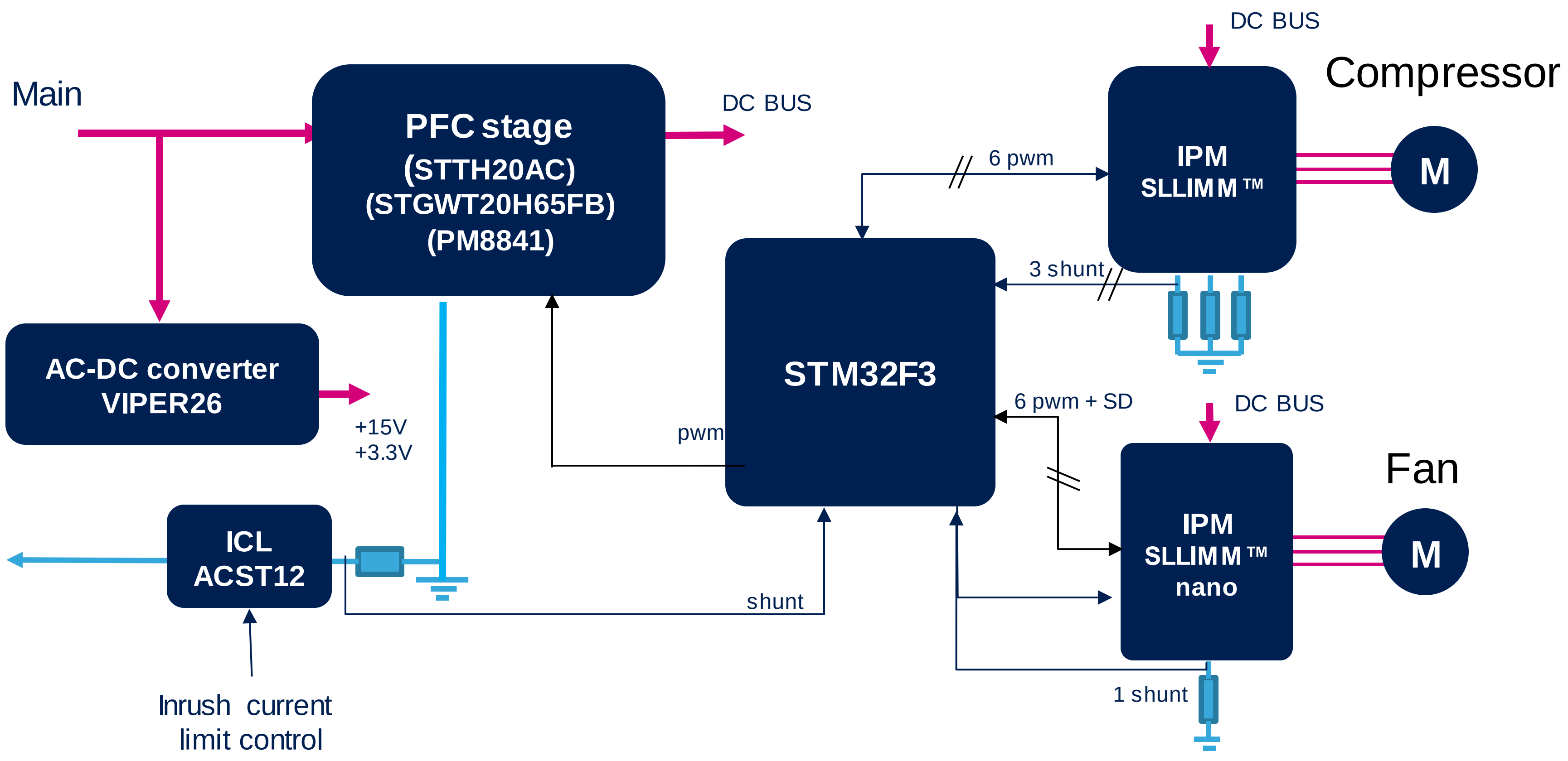
STEVAL-CTM010V1

Key Products

- MCU: STM32F303RBT6
- Motor 1: STGIB10CH60TS-L (IPM); Motor 2: STGIPQ3H60T-HZ (IPM)
- PFC: STGWT20H65FB (IGBT); STTH20AC06FP (DIODE); PM8841D (Gate driver)
- VIPER26LD (auxiliary AC-DC converter)
- Inrush Current Limiter (ICL): T1235T-8FP
- TS391RILT (Comp.)
- LD1117S50TR, LD1117S50TR (V.R.)

STEVAL-CTM010V1

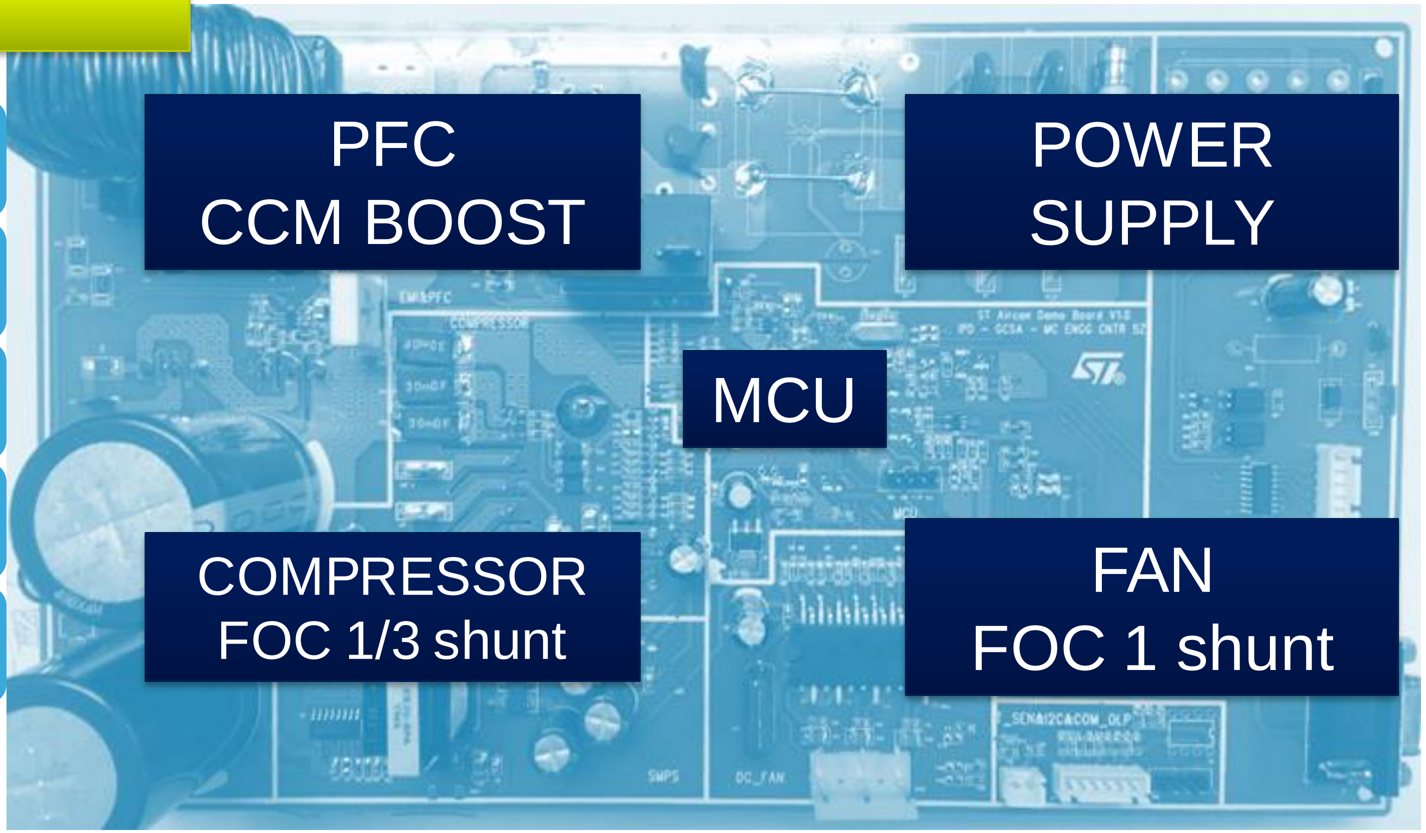
Block diagram



STEVAL-CTM010V1
Outdoor Unit Architecture: dual motor FOC + dPFC

FW Available

- Compressor Protections: OC, OT, UVLO
- Fan Protections: OC, OT, UVLO
- PFC Protections: OC, UVLO, OV
- Power scalability 1 HP – 3HP
- Reduced BOM High Integration



STEVAL-CTM010V1

All Functions inside a 64 pins STM32F3 + 2 SLLIMMs

Function	Digital I/O	Analog I/O	Total
Compressor	6	9	**15**
Fan	7	1	**8**
PFC & ICL	4	6	**10**
USART comm	2		**2**
SWD debug	2		**2**
I2C EEPROM	2		**2**
Stepper valves	4		**4**
Other analogs		6	**6**
Other digitals	4		**4**
MCU functional			**11**
GRAND TOTAL			**64**

OCP & Temperature sensing by MCU

OCP & OTP by IPM

OCP & OVP by MCU

Vdd, Vss, Boot, Vdda, Vssa, NRST

STEVAL-CTM010V1

STM32F3, CPU load driving all functions (<56% !)

Task	PWM frequency	Control frequency	Task duration	CPU load
Compressor FOC (sensorless, 1shunt)	6 kHz	6 kHz	22 us	13.2 %
Fan FOC (sensorless, 1shunt)	18 kHz	9 kHz	22 us	19.8 %
PFC current regulation	40 kHz	40 kHz	4.39 us	17.56 %
PFC voltage regulation		2 kHz	4.095 us	0.82 %
Compressor, speed loop and other tasks		0.5 kHz	42 us	2.1 %
Fan, speed loop and other tasks		0.5 kHz	42 us	2.1 %
TOTAL				**55.6 %**

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Focus on SLLIMM® IPM - compressor driving

- energy efficiency test at the bench
- energy efficiency test in application

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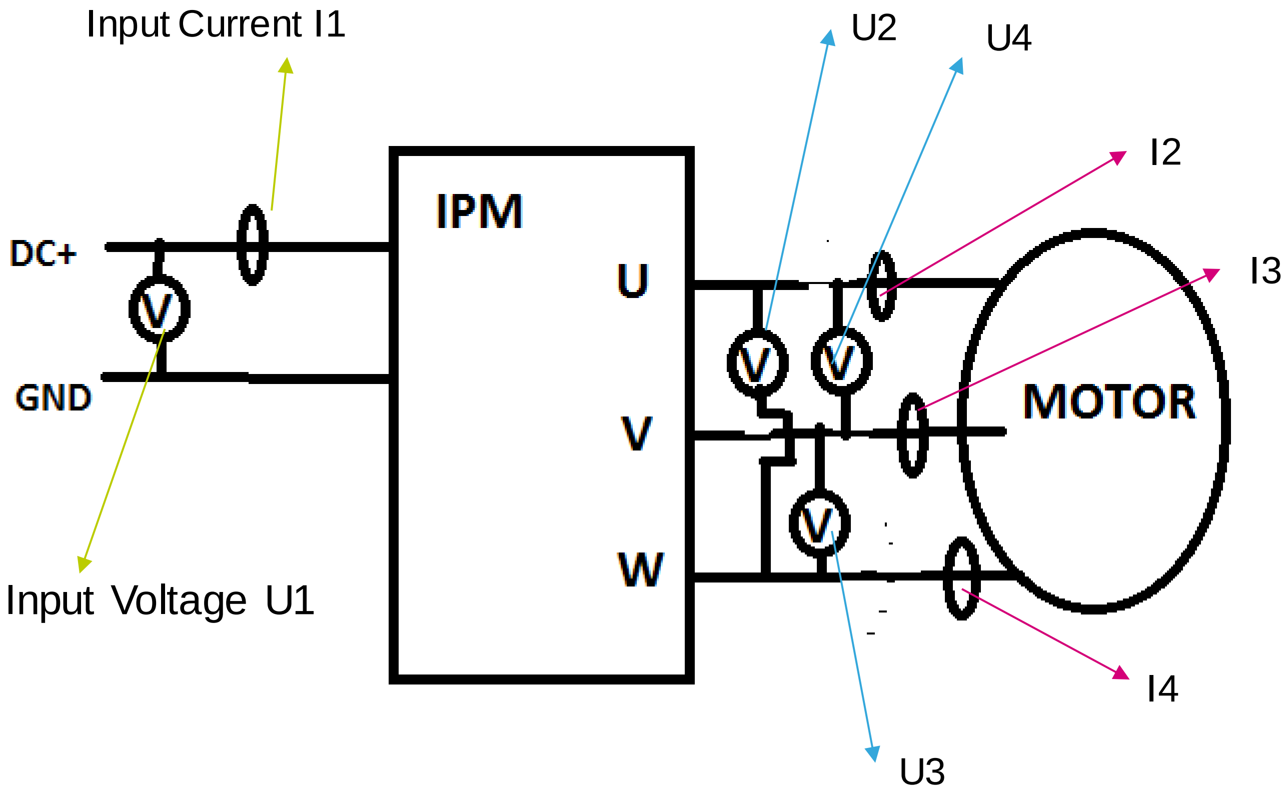
STEVAL-CTM010V1
Efficiency test, measurements diagram



Active Power $P_x = AVG[u_x(n) \cdot i_x(n)]$
($x=1,2,3,4$; $n = n^{th}$ measurement period)

- P_{in} = IPM Input Power = P_1
- P_{out} = IPM Output Power = $P_2 + P_3 + P_4$
- Efficiency = $P_{out}/P_{in} \times 100$ (%) (used for dynamometer bench test)
- $Energy_{in} = P_{in}$ * time
- $Energy_{out} = P_{out}$ * time
- Efficiency = $Energy_{out} / Energy_{in} \times 100$ (%) (used for in application test)

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Load test at dynamometer bench - ST lab

1) Test conditions

Parameters	Designation	Values
$V_{in(DC)}$	Input DC voltage for IPM	380V DC
F_{sw}	Switching frequency for IPM	6.6kHz
T_{amb}	Ambient temperature	24 ℃
T_{case}	All data for energy efficiency measurement were captured at similar IPM's pre-heated case temperature	75±2℃
	Test duration for steady state for thermal comparison	40 min

2) Test tools

Tools	Designation
Inverter board	ST 1.5HP A/C demo board
Firmware	STM32 FOC SDK v4.3
Power source	-
Power meter	-
Thermocouple	-
Oscilloscope	-
Dynamometer (*)	-

(*) A general purpose 3phase PMSM motor (parameters available on request) has been coupled with the dynamometer for this lab test

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STEVAL-CTM010V1
Efficiency comparison

DYNAMOMETER TESTING

STGIB10CH60TS-L :

No.	Input Voltage U1 (V)	Phase current I2 (A)	**Input Power Pin (W)**	Output power Pout (W)	**Efficiency(%)**
1	379.8	1.033	**284.7**	278.6	**97.86**
2	379.5	1.821	**596.6**	585.4	**98.12**
3	378.9	2.81	**1047.2**	1028.1	**98.18**
4	378.8	3.49	**1206.2**	1181.2	**97.93**

device "M" :

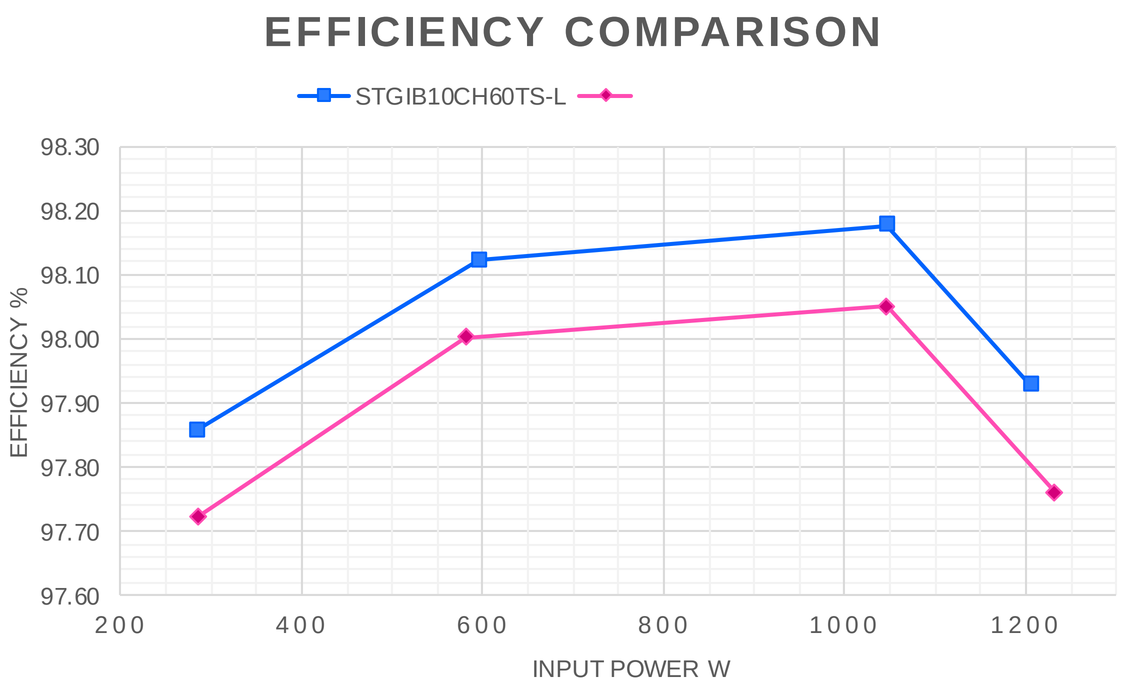
No.	Input Voltage U1 (V)	Phase current I2 (A)	**Input Power Pin (W)**	Output power Pout (W)	**Efficiency(%)**
1	379.7	1.028	**285.4**	278.9	**97.72**
2	379.4	1.781	**580.4**	568.8	**98.00**
3	378.9	2.79	**1046.4**	1026	**98.05**
4	378.7	3.539	**1232.1**	1204.5	**97.76**

Efficiency Test Data

*__All the data are captured at similar IPM's case temperature pre-heated @ 75±2℃__
** Active Power P = AVG[u(n)·i(n)]
*** True RMS Current I = SQRT(AVG(i(n)²))
**** True RMS Voltage V = SQRT(AVG(v(n)²))

STEVAL-CTM010V1
Efficiency comparison

DYNAMOMETER TESTING



Efficiency measured on IN/OUT of the IPM, while driving a BLDC motor with field oriented control (FOC) thanks the ST MC SDK

- ST's IPM has 0.12%~0.17% higher efficiency than device "M", which means for instance 2.55W advantage @ 1500 W .

*<u>**All the data are captured at similar IPM's case temperature pre-heated @ 75±2℃**</u>

** Active Power P = AVG[u(n)·i(n)]

*** True RMS Current I = SQRT(AVG(i(n)^2)

**** True RMS Voltage V = SQRT(AVG(v(n)^2)

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STEVAL-CTM010V1
In application test - 1.5HP A/C - ST lab

IN-APPLICATION TESTING

Tool
Inverter board
Power source
Power meter
Thermocouple
Oscilloscope
Current probe
Diff voltage probe

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STEVAL-CTM010V1
In application test - 1.5HP A/C - ST lab

IN-APPLICATION TESTING

energy efficiency comparison

STGIB10CH60TS-L :

TEST CONDITON		IPM INPUT			IPM OUTPUT	RESULTS	
Frequency (Hz)	Aircon input power(W)	DC voltage(V) from PFC	Motor Current range (A)	5min Input Energy (Wh)	5min Output Energy (Wh)	Efficiency (%)	Tcase(Max) °C
20	255	293.84	1.38-1.39	13.5768	12.7738	94.085	35.6
30	450	403.04	1.88-1.89	28.7335	27.285	94.959	41.6
50	750	402.97	2.55-2.58	54.2288	52.6492	97.087	47.1
70	1140	402.85	3.36-3.38	85.1568	83.3029	97.823	50.6
90	1580	402.74	4.16-4.18	119.265	117.076	98.165	60.8

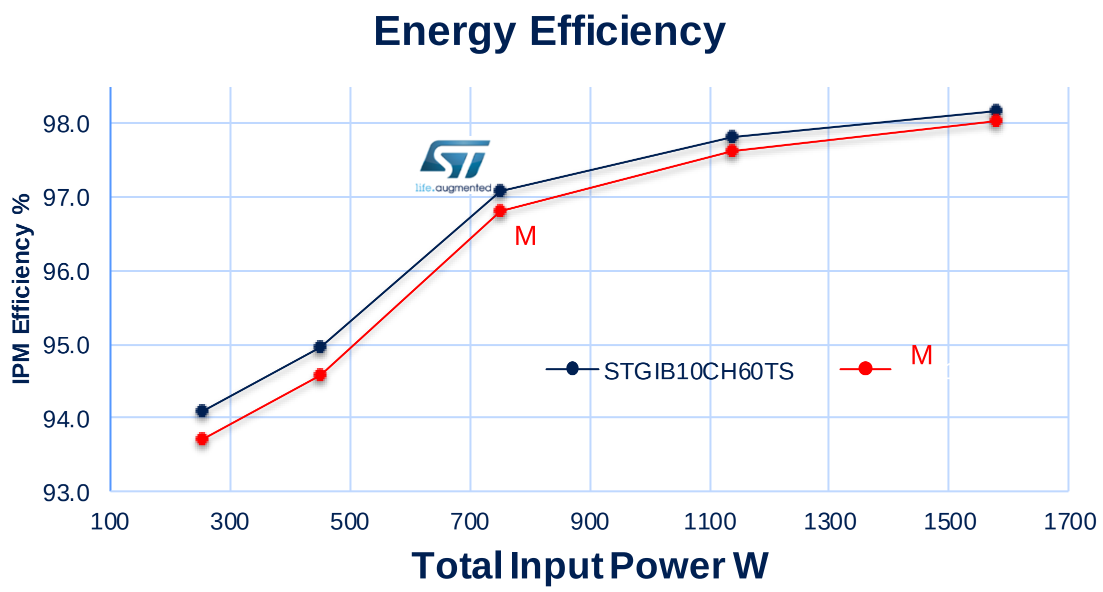
device “M”

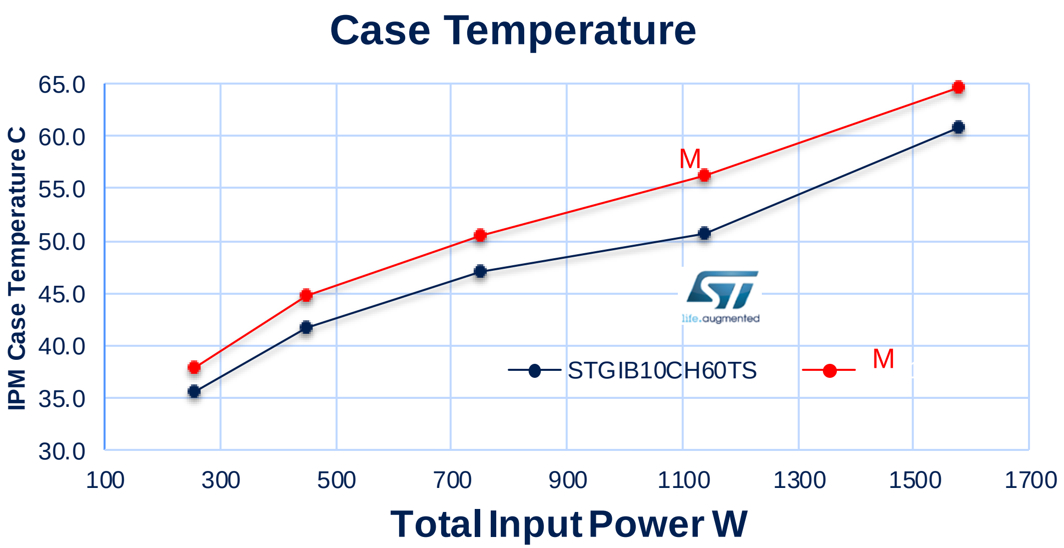
TEST CONDITON		IPM INPUT			IPM OUTPUT	RESULTS	
Frequency (Hz)	Total A/C input power(W)	DC voltage (V) from PFC	Motor Current range (A)	5min Input Energy (Wh)	5min Output Energy (Wh)	Efficiency (%)	Tcase(Max) °C
20	255	293.79	1.38-1.39	13.3522	12.5112	93.701	37.8
30	450	402.59	1.87-1.88	28.103	26.5781	94.574	44.8
50	750	402.49	2.55-2.58	53.4795	51.7705	96.804	50.5
70	1140	402.38	3.36-3.38	84.5334	82.536	97.637	56.2
90	1580	402.33	4.15-4.20	118.994	116.638	98.020	64.6

IN-APPLICATION TESTING

STEVAL-CTM010V1
In application test - 1.5HP A/C - ST lab

energy efficiency comparison





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STEVAL-CTM010V1
In application test - 1.5HP A/C - ST lab

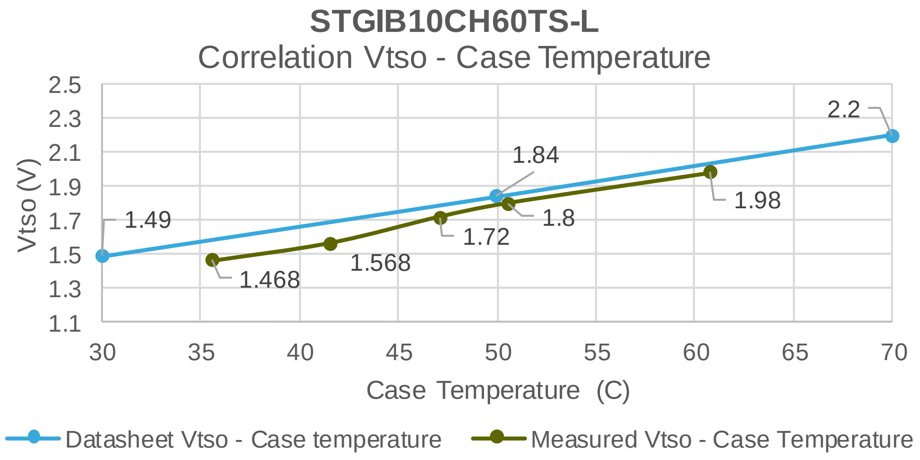
IN-APPLICATION TESTING

Correlation Case Temperature vs Vtso or Vot

- Comparison: IPM case temperature measured from an external thermocouple and from the built-in temperature sensor

STGIB10CH60TS-L

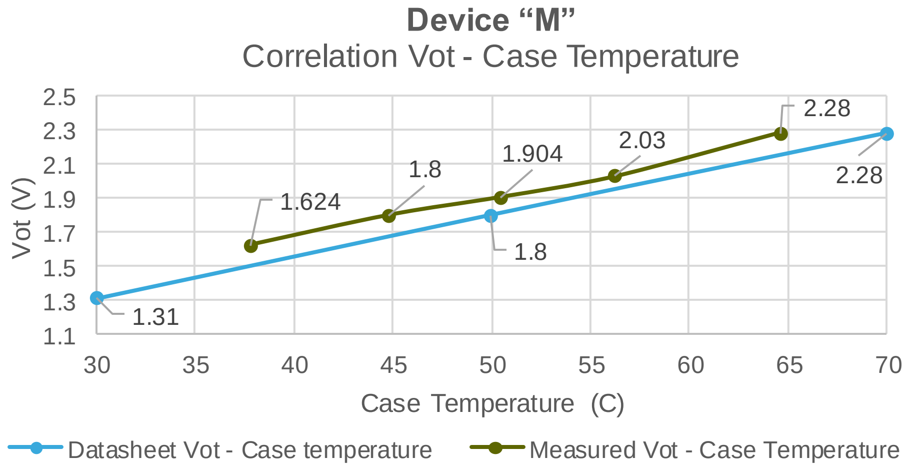
Tcase (°C probe)	Vtso (V)	Vtso (°C, datasheet typ)
35.6	1.468	28.8
41.6	1.568	34.5
47.1	1.72	43
50.6	1.8	47.6
60.8	1.98	57.7



Average ΔT = -4.8°C
ΔT = 3.1°C (@ Tcase 60.8°C)

Device “M”

Tcase (°C probe)	Vot (V)	Vot (°C, datasheet typ)
37.8	1.624	42.9
44.8	1.8	50.2
50.5	1.904	54.5
56.2	2.03	59.7
64.6	2.28	70



Average ΔT = 4.7°C
ΔT = 5.4°C (@ Tcase 64.6°C)

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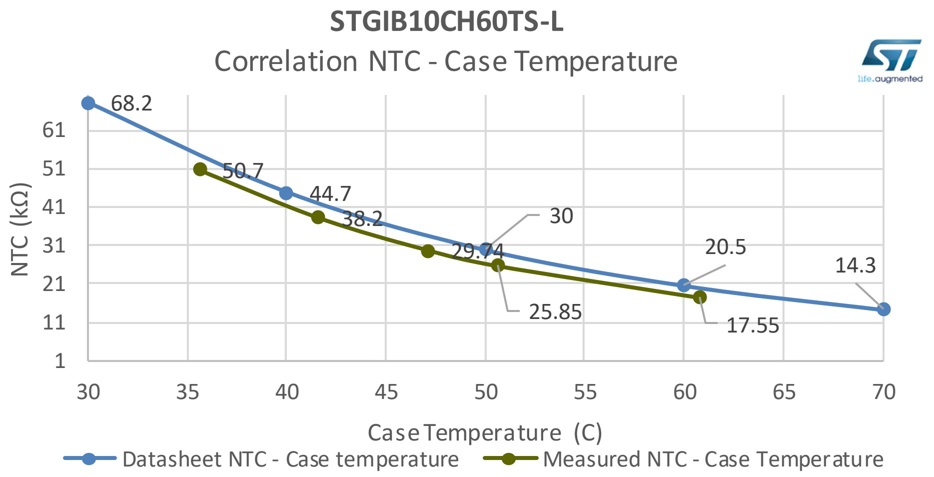
STEVAL-CTM010V1
In application test - 1.5HP A/C - ST lab

IN-APPLICATION TESTING

Correlation Case Temperature vs NTC or Vot

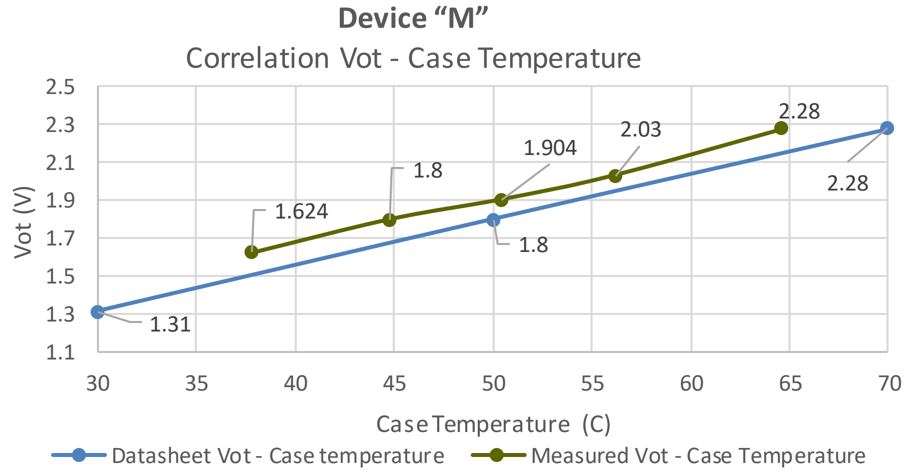
- Comparison: IPM case temperature as measured from an external thermocouple and from the built-in temperature sensor

STGIB10CH60TS-L		
Tcase (°C probe)	NTC (kΩ)	NTC (°C, datasheet typ)
35.6	50.7	37.5
41.6	38.2	44
47.1	29.74	49
50.6	25.85	54
60.8	17.55	64



Average ΔT = 2.5°C

Device "M"		
Tcase (°C probe)	Vot (V)	Vot (°C, datasheet typ)
37.8	1.624	42.9
44.8	1.8	50.2
50.5	1.904	54.5
56.2	2.03	59.7
64.6	2.28	70



Average ΔT = 4.7°C

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SLLIMM™ (Small Low-loss Intelligent Molded Module) ST Intelligent Power module (IPM)

STGIB10CH60TS-L (mounted)

- IPM 15 A, 600 V, 3-phase IGBT inverter bridge including 2 control ICs for gate driving and freewheeling diodes
- 3.3 V, 5 V TTL/CMOS inputs with hysteresis
- Internal bootstrap diode
- Undervoltage lockout of gate drivers
- Smart shutdown function
- Short-circuit protection
- Shutdown input/fault output
- Comparator for fault protection
- Short-circuit rugged TFS IGBTs
- Very fast, soft recovery diodes
- 85 kΩ NTC
- UL recognized 1.5 kVrms: UL 1557, file E81734

SDIP2B-26L type L1

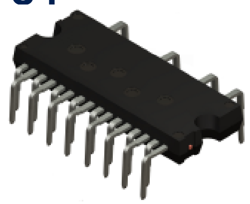
Alternative devices

- STGIB15CH60TS-L(E): SLLIMM 2nd series IPM, 3-phase inverter, 20 A, 600 V short-circuit rugged IGBTs
- STIB1060DM2T-L: SLLIMM 2nd series IPM, 3-phase inverter, 0.18 Ohm typ., 10 A, 600 V SJ-MOSFET MDmesh DM2
- STIB1560DM2T-L: SLLIMM 2nd series IPM, 3-phase inverter 0.15 Ohm typ., 15 A, 600 V SJ-MOSFET MDmesh DM2

SLLIMM™ nano (Small Low-loss Intelligent Molded Module) ST Intelligent Power module (IPM)

STGIPQ3H60T-HZ (mounted)

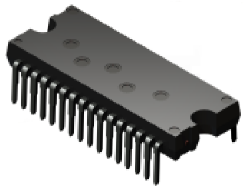
- IPM 3 A, 600 V, 3-phase IGBT inverter bridge including 3 control ICs for gate driving and freewheeling diodes
- 3.3 V, 5 V, 15 V TTL/CMOS input comparators with hysteresis and pull-down/pull-up resistors
- Internal bootstrap diode
- Undervoltage lockout
- Shutdown function
- interlocking function
- Op-amp for advanced current sensing
- Comparator for fault protection against overcurrent
- Isolation ratings of 1500 Vrms/min.
- Up to ±2 kV ESD protection (HBM C = 100 pF, R = 1.5 kΩ)
- NTC (UL 1434 CA 2 and 4)
- UL recognized 1.5 kVrms: UL 1557, file E81734



N2DIP-26L type Z

Alternative devices

- **STGIPQ5C60T-HZ** SLLIMM nano 2nd series IPM, 3-phase inverter, 5 A, 600 V short-circuit rugged TFS IGBTs
- **STIPQ3M60T-HL** SLLIMM-nano 2nd series IPM, 3-phase inverter, 3 A, 1.6 Ohm max., 600 V N-channel MDmesh DM2



N2DIP-26L type L

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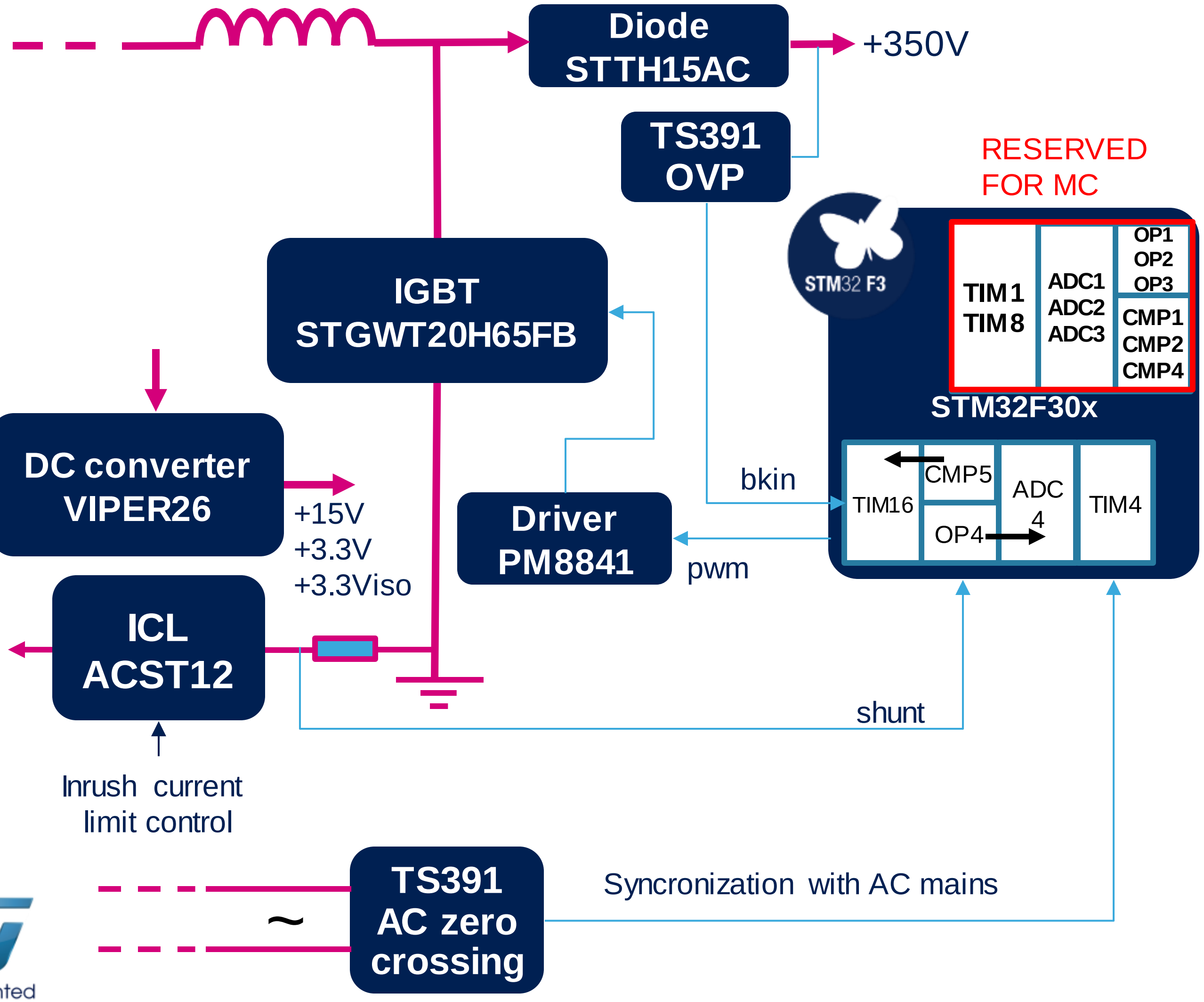
For More Information on SLLIMM™ family

Focus on digital PFC
- IGBT, AC series diode
- THD, Power Factor
- Energy Efficiency

Digital PFC boost single phase

Implementation on STM32F3

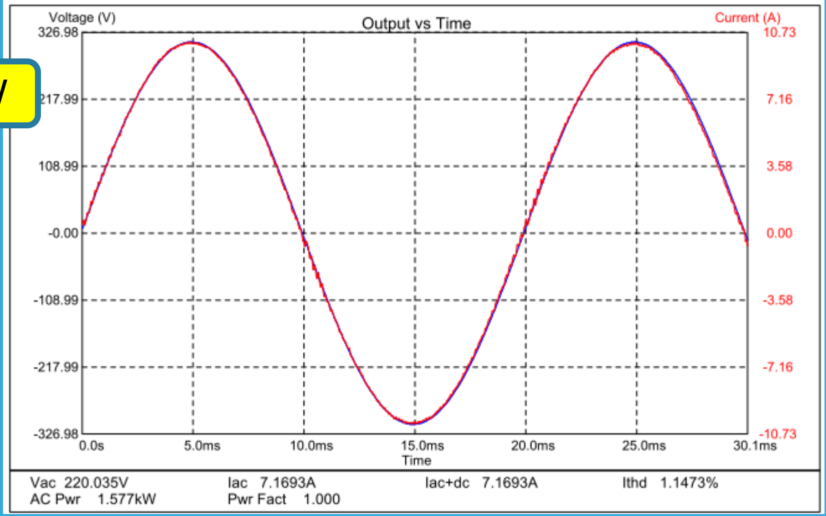


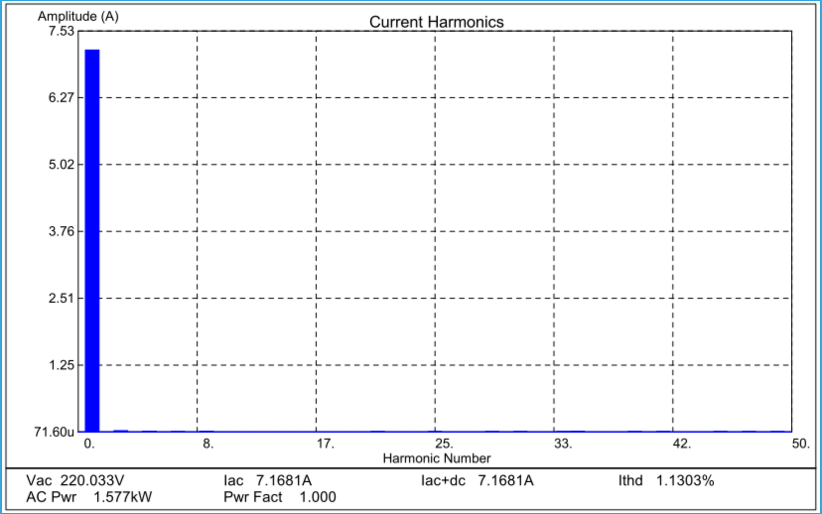
Peripheral assignment	
TIM16 ch1	PWM generation
TIM16 BKIN	EXT fault signal (OVP)
OP4	Current amplification
ADC4	Current sampling
CMP5	OCP
DAC1 ch2	OCP threshold definition
TIM4	AC mains voltage , frequency and phase detection

Digital PFC (dPFC), experimental results

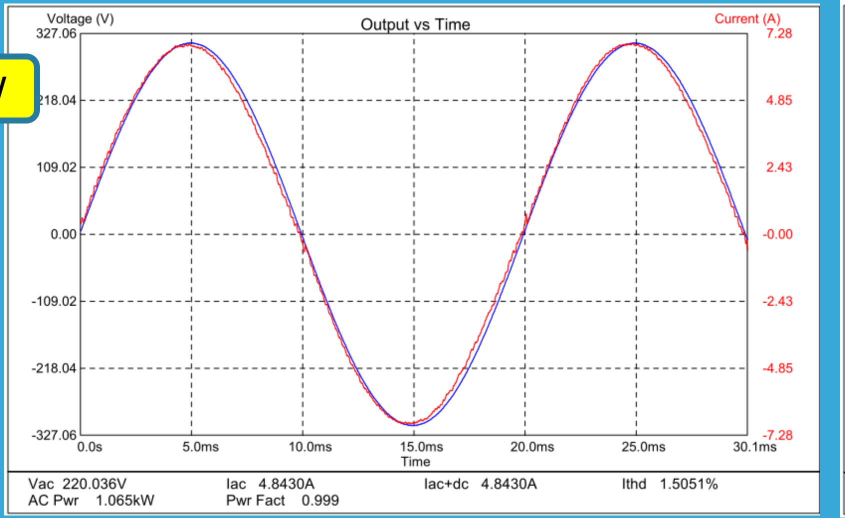
Outstanding THD and Power Factor (small 300uH)

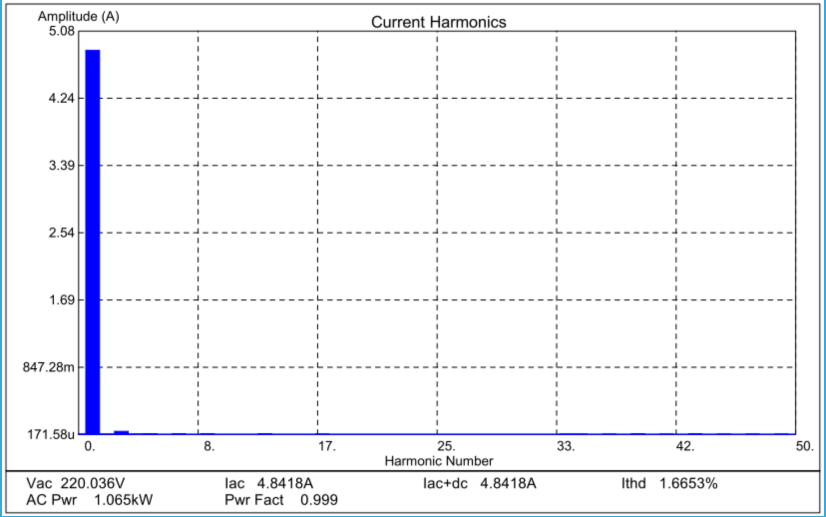
1.6kW





1.0kW





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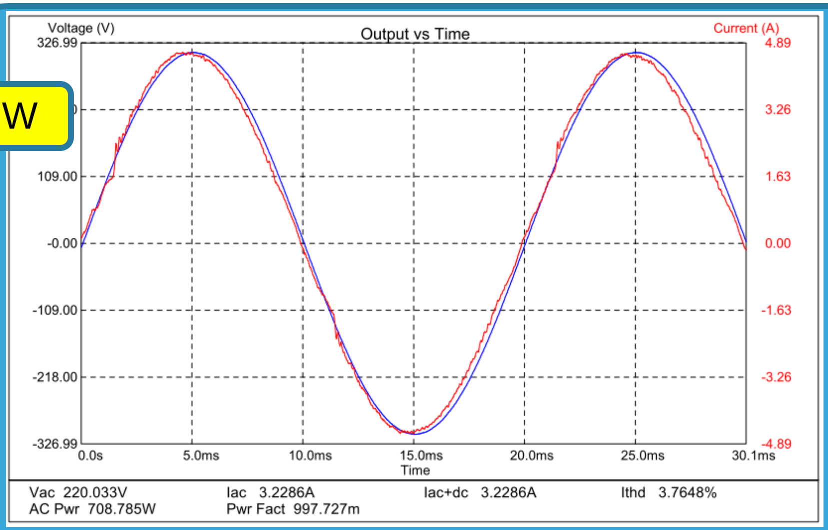
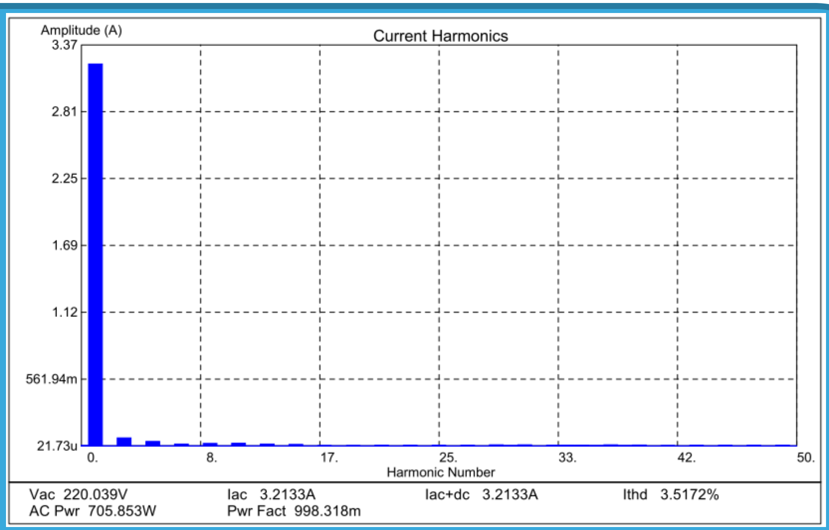
Digital PFC FW, experimental results

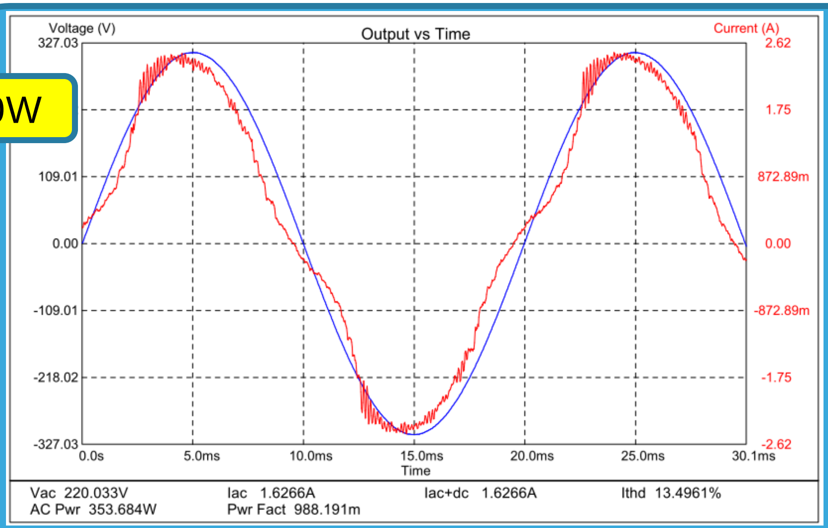
Outstanding THD and Power Factor (small 300uH)

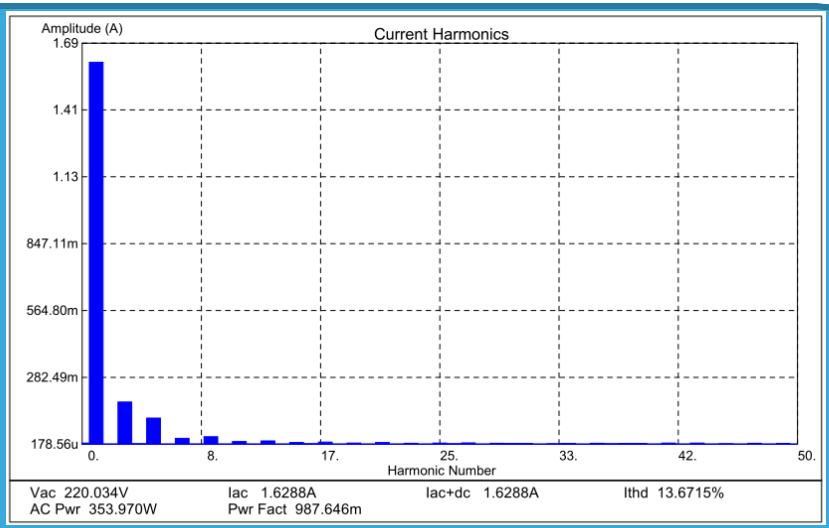
700W





350W





dPFC, ST IGBT, experimental results, bench test vs other key player

STTH60AC06CW+**STGWT40H65**

DC Load output (A)	Input power (W)	Output Power (W)	Efficiency	Tcase (℃)	PF value
1	374.7	361.7	96.53%	48.1	0.978
2	748.5	722.6	96.53%	58.4	0.994
3	1131.8	1089.6	96.27%	74.9	0.997
4	1512.1	1450.2	95.91%	83.5	0.999
5	1895.6	1809.5	95.46%	>90*	0.999

ST is better than device F on all figures of merit

STTH60AC06CW+**device F**

DC Load output (A)	Input power (W)	Output Power (W)	Efficiency	Tcase (℃)	PF value
1	376.2	361.9	96.20%	49.7	0.978
2	750.2	722.4	96.30%	56	0.995
3	1134.2	1090.6	96.15%	79.5	0.997
4	1516.4	1448.6	95.53%	87.4	0.999
5	1902.0	1812.1	95.27%	>90*	0.999

dPFC, ST "AC" diode, experimental results,

bench test vs other key player

STTH60AC06CW + STGWT40H65

LOAD (A)	Input power (W)	Output Power (W)	I_{RM} (A)	IF (A)	Trr (ns)	Efficiency	Tcase (℃)	PF value
1	383.8	370.7	5.84	1.72	38.8	96.58%	37.6	0.978
2	757.1	732.2	8.04	3.96	45.2	96.71%	44.2	0.994
3	1139.1	1101.3	10.0	6.28	51.6	96.60%	49	0.997
4	1519.9	1461.3	12.1	8.2	58.2	96.14%	54.8	0.999
5	1903.5	1823.5	14.2	10.8	65.2	95.79%	>60*	0.999

ST is better than device F on all figures of merit

Device V + STGWT40H65

LOAD (A)	Input power(W)	Output power (W)	I_{RM} (A)	IF (A)	Trr (ns)	Efficiency	Tcase (℃)	PF value
1	385.5	371.4	5.92	1.84	49.6	96.34%	39.7	0.978
2	760.7	728.5	8.64	4.0	64.8	95.76%	46.3	0.994
3	1146.2	1106.0	11.2	6.36	71.6	96.49%	54.7	0.997
4	1527.5	1469.2	12.9	8.6	76.4	96.18%	57.6	0.999
5	1914.3	1829.2	14.8	10.8	80.0	95.55%	>60*	0.999

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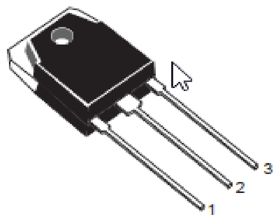
dPFC, ST "AC" diode and IGBT

STTH30AC06CPF (Mounted)

600 V, 60 A dual Interleave Boost Ultrafast Diode

- Insulated package TO-3PF (2500 V DC)



TO-3P

STGWT20H65FB (Mounted)

Trench gate field-stop IGBT, HB series 650 V, 20 A high speed series

- switching frequency: 16 ÷ 60 kHz
- Maximum junction temperature: T_J= 175 °C
- $V_{CE(sat)}$= 1.55 V (typ.) @ I_C= 20 A

Alternative devices

- **STGWA30HP65FB2 (/STGWA40HP65FB2)** Trench gate field-stop, 650 V, 30 (/40) A, high-speed HB2 series IGBT in a TO-247 long leads package (for more information)
- **STTH60AC06:** 600 V, 60 A dual Interleave Boost Ultrafast Diode (for more information)

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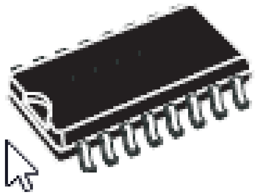
ST Products ….more (1/2)

- Auxiliary AC-DC converter: VIPER26LD

VIPerPlus family: Energy saving 12W high voltage converter with direct feedback

- 800 V avalanche rugged power section
- PWM operation with frequency jittering for low EMI
- Operating frequency: 60 kHz
- Standby power < 50 mW at 265 VAC
- Limiting current with adjustable set point
- On-board soft-start
- Safe auto-restart after a fault condition
- Hysteretic thermal shutdown



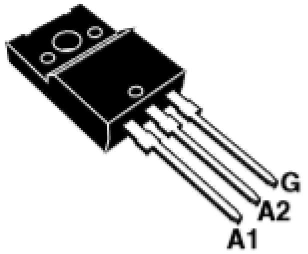
SO16 narrow

ST Products ….more (2/2)

- Inrush Current Limiter (ICL): T1235T-8FP

  12 A Snubberless™ Triac

  - High static and dynamic commutation
  - Three quadrants
  - ECOPACK®2 compliant component
  - Complies with UL standards (File ref: E81734)



TO-220FPAB
(T1235T-8FP)

ST Triacs

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STM32 FOC SDK
Dual Motor Control AirCon IPs

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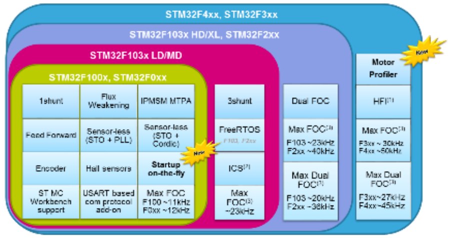
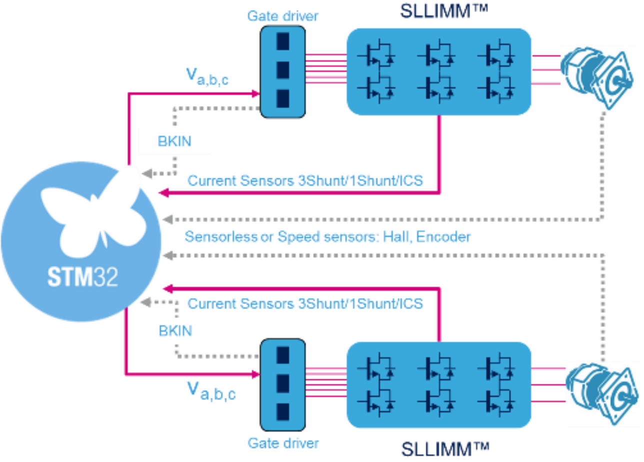
AirCon IPs





Dual Driving

High Frequency Injection (HFI)
Reliable and efficient start up, low speed operation

Flux Weakening
Expand the speed limits of a PMSM → reach compressor's maximum power capability

Maximum Torque Per Ampere (MTPA)
Optimize of the torque for each load → energy efficiency

On-the-fly startup (OTF)
Smooth drive insertion when the outdoor fan is moving due to the wind.

Reduction of the acoustic noise (ST patent)
Torque Ripple Compensation

Digital PFC single stage

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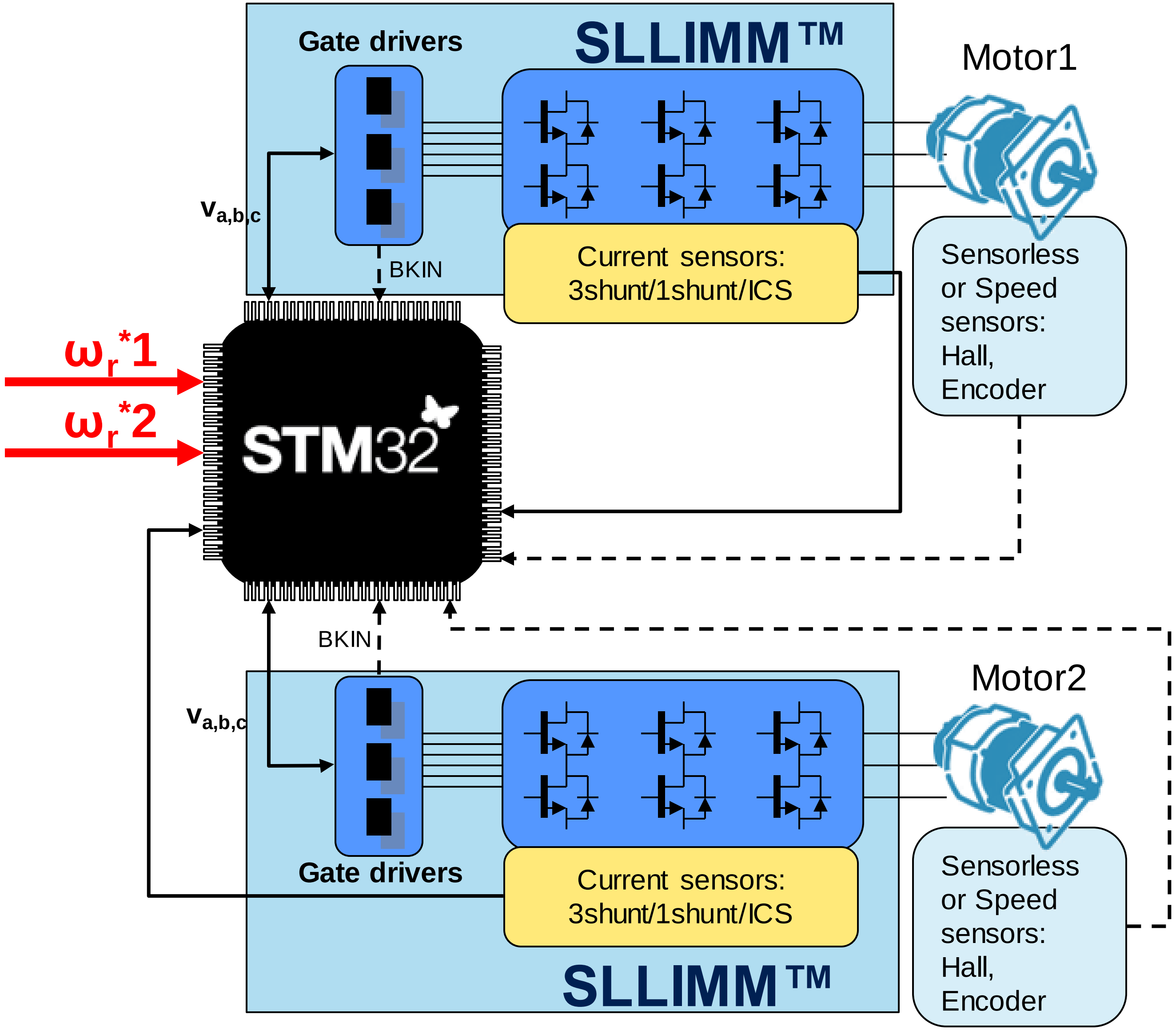
Dual PMSM FOC
Block Diagram



Dual PMSM FOC with 1 MCU

Advantages

- Flash size required is easily less than two times.
- Design and development of an application layer aimed at the coordination of the 2 motors' activities is simplified
- The effort of appliance certification for IEC 60335-1 Class B compliancy can be focused on only one microcontroller.
- Current consumption, in run or sleep mode, is straightforwardly halved.
- Dedicated space and routing on the PCB are reduced, for instance a 64-pin MCU is suitable
- External components count is reduced (in terms of oscillators, connectors, opto-isolators, passives).
  - With **STM32F3**: comparator and Operational amplifiers are embedded reducing more the external components.
- With STM32F3 the CPU load is <27% (at @16kHz PWM/8kHz FOC)
  → more room for more tasks, i.e. for digital boost PFC (around 15%)

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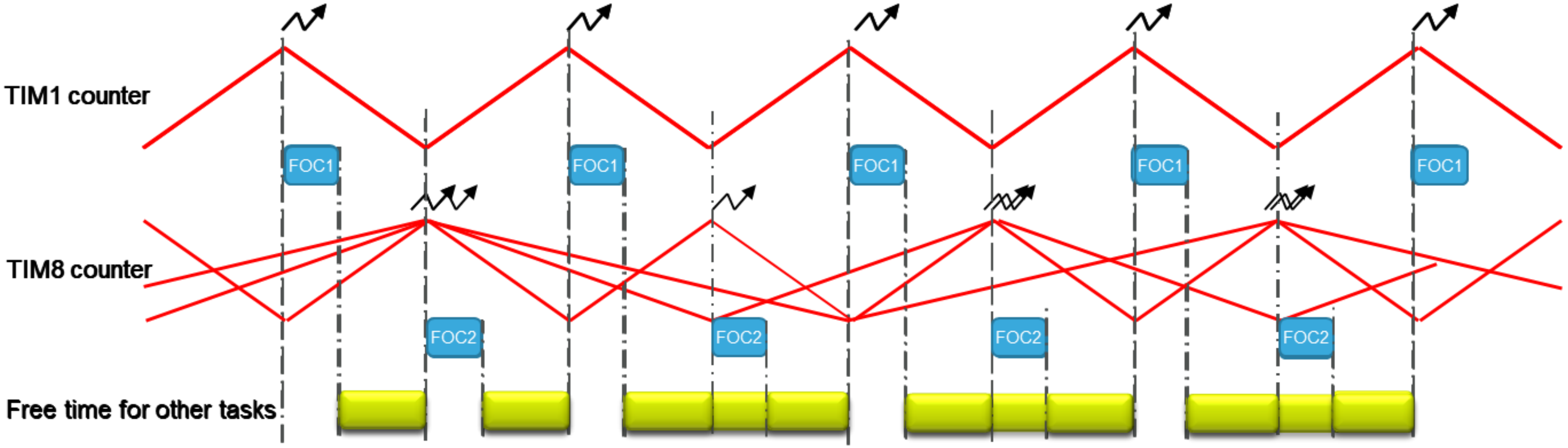
Dual PMSM FOC with 1 MCU

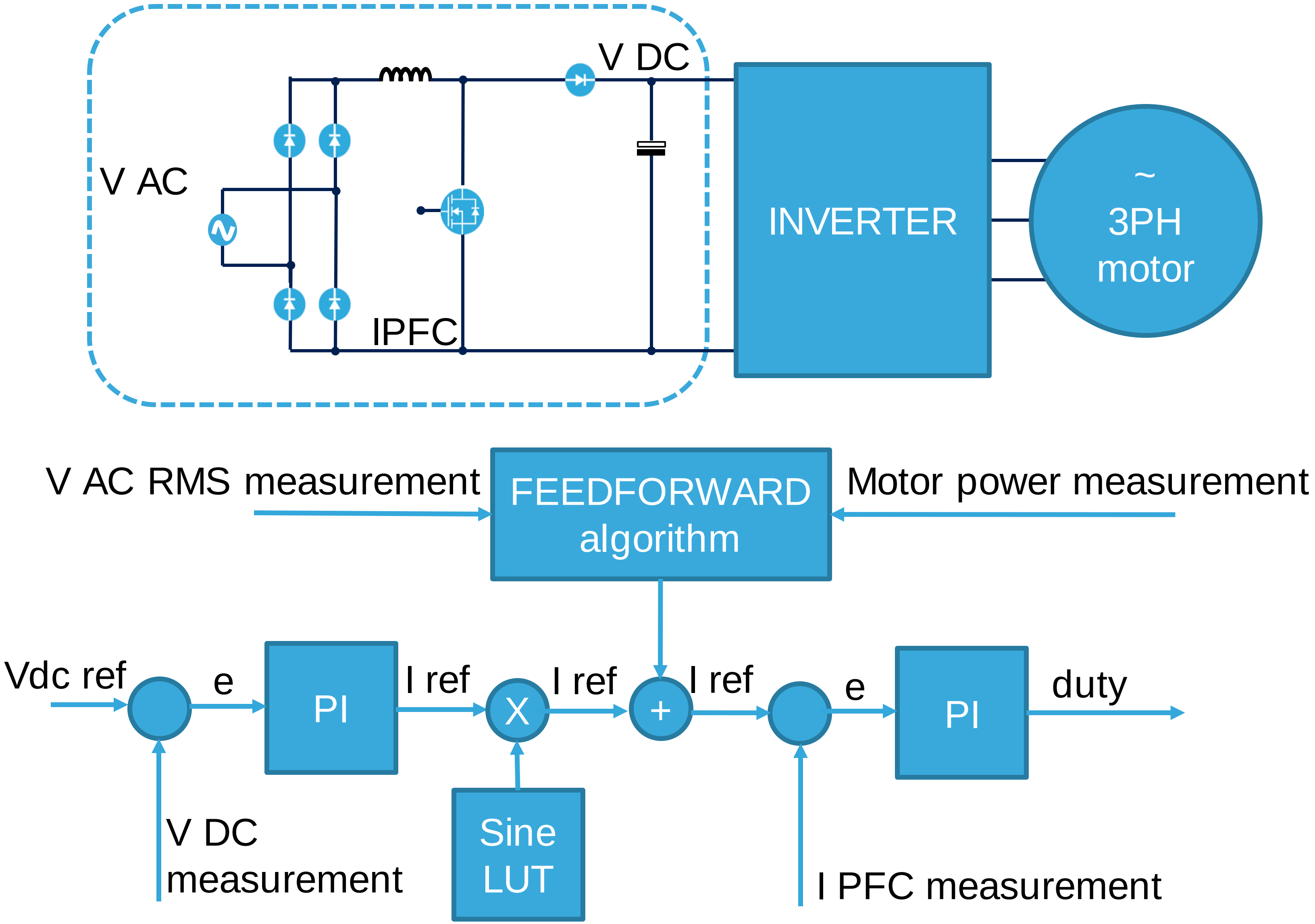
- STM32 has up to 2 advanced timers and up to 4 fast ADC, 1 shunt / 3 shunt topologies can be combined as preferred, together with digital PFC
- The FOC library arranges so as to share CPU time between the two drives, compressor and fan

Same PWM frequency
Proportional PWM frequency 1/2
Proportional PWM frequency 1/3



Digital PFC FW STM32F30x

Digital PFC
Topology & control diagram



- Advantages of software programmable digital PFC

Flexibility

- **Differentiate** the control performances keeping same HW
- **Algorithm upgrade and customization** is painless
- **Add/remove features** at any time

Solution cost

- Components count may be reduced
  → **save PCB and validation time**

- Enabling execution of digital PFC **and (dual) motor control** on same MCU, STM32 makes it possible to get much more….

Increased efficiency

- **PFC turned-on only when needed**
- Flux-weakening region can be entered at higher speeds → **higher motor efficiency**

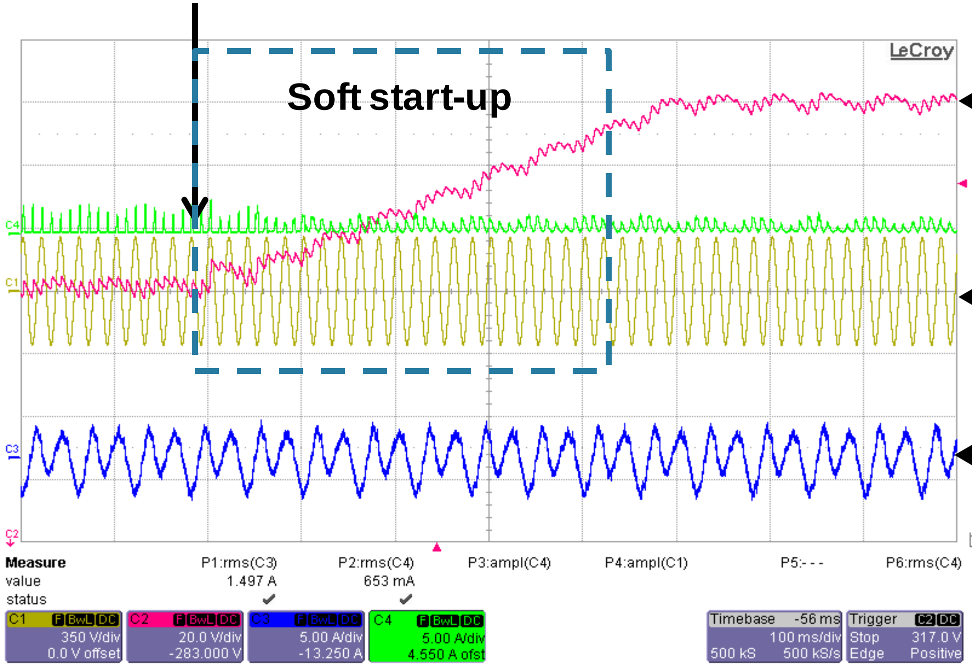
Improved performances

- **Better bus voltage regulation**
- **Faster motor(s) dynamic response**
- In case of dual MC, **remove unwanted interactions between drives.**

Digital PFC

On-the-fly Turn On/Off

- Turning on PFC only when needed eliminates PFC stage power losses in low-load conditions
  - Specific algorithm for *PFC soft start*



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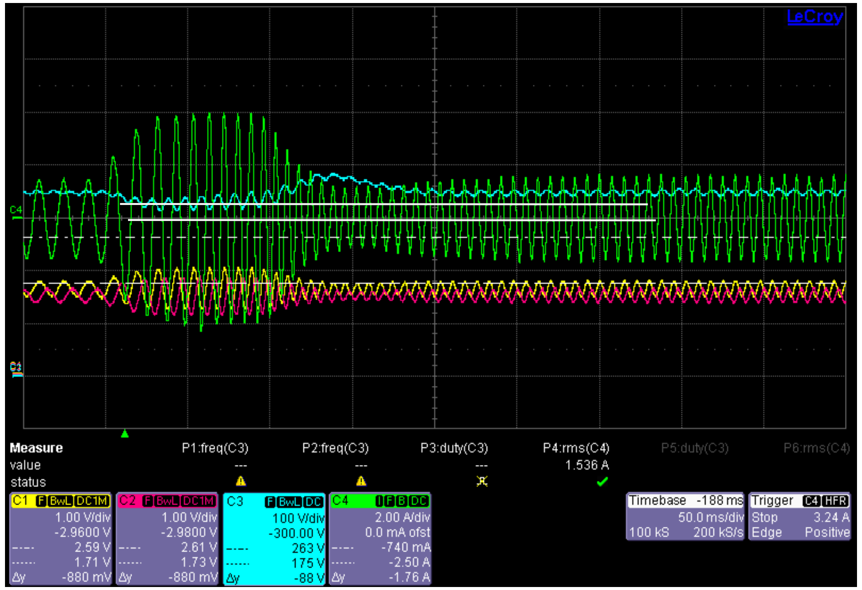
Digital PFC

Load feed-forward

Based on motor power consumption estimation

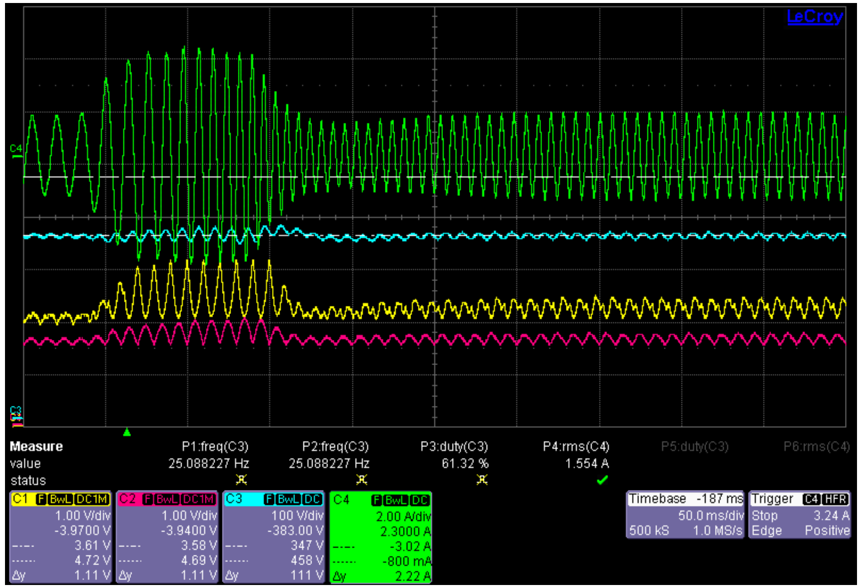
- Motor dynamic response can be improved if load suddenly increases
- Dangerous bus voltage raisings can be eliminated when load decreases
- In case of dual control, remove unwanted interactions between drives



V_{BUS} response (cyan) to load steps w/o feed-forward

Feature disabled

+40V DC bus increase
to ~60% load decrease



V_{BUS} response (cyan) to load steps with feed-forward

Feature enabled

No DC bus variations
to ~60% load decrease

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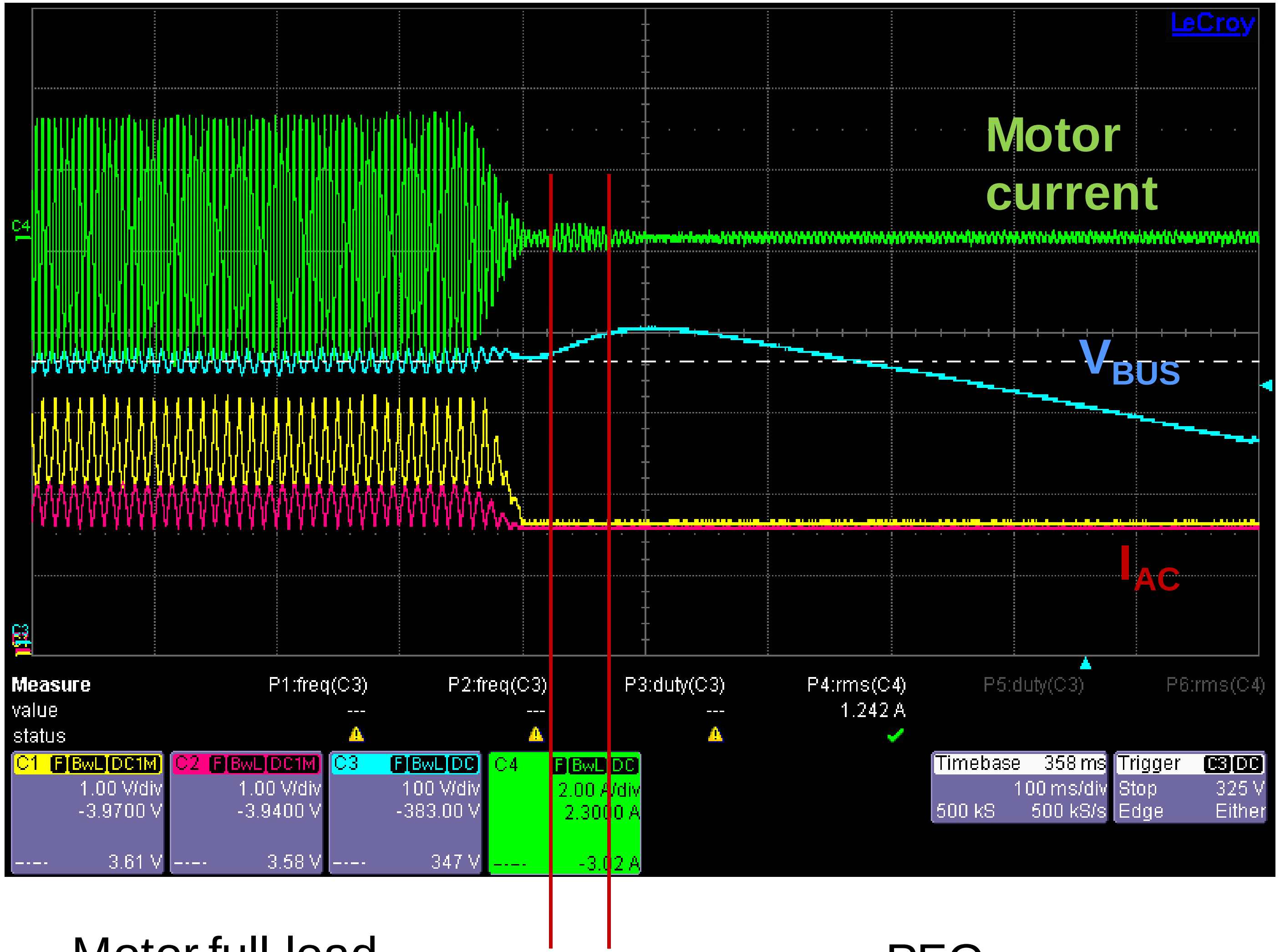
Digital PFC

Load feed-forward & PFC turn-off on the fly



Motor full load operations

Load set to zero

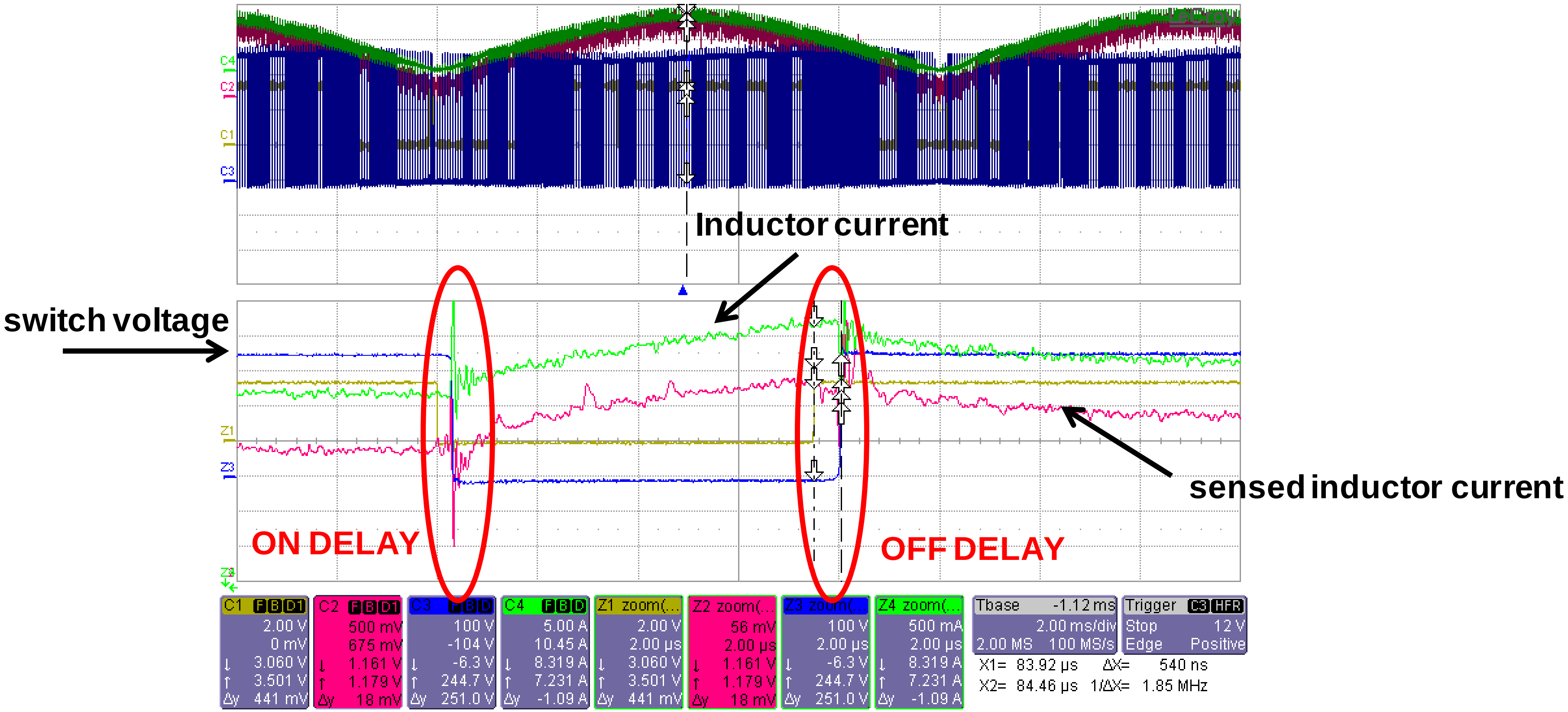
PFC switched off

Digital PFC

Propagation delay compensation

Propagation delay through driver and switch could be easily compensated

- harmonic distortion can be improved
- switch and/or driver part numbers may be replaced more easily



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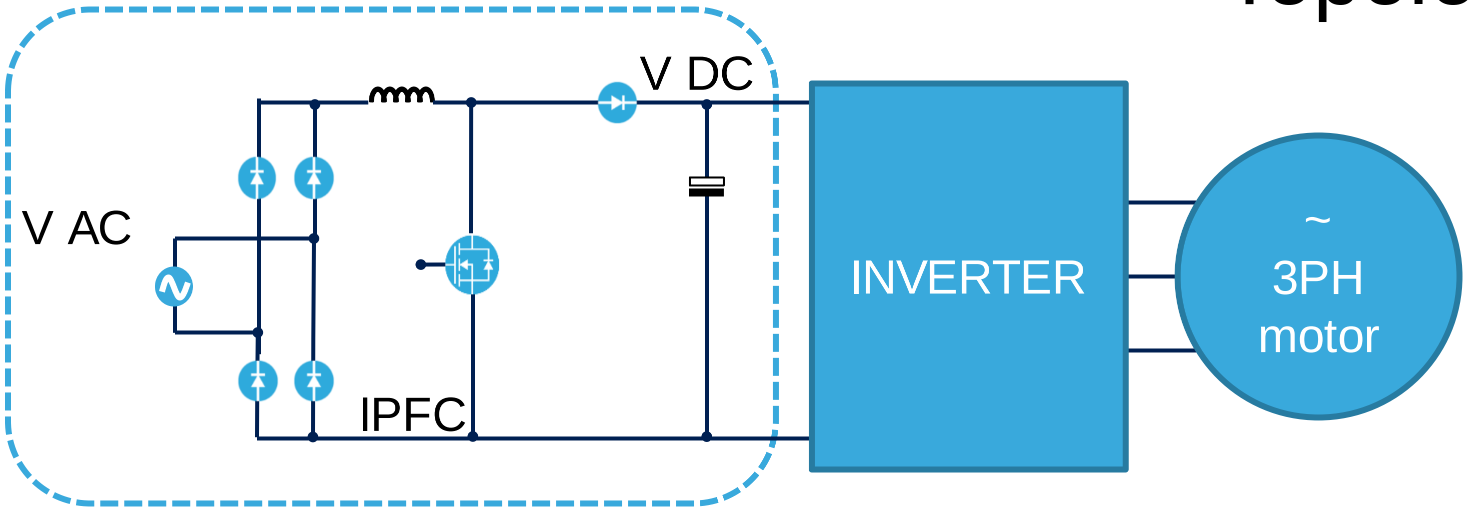
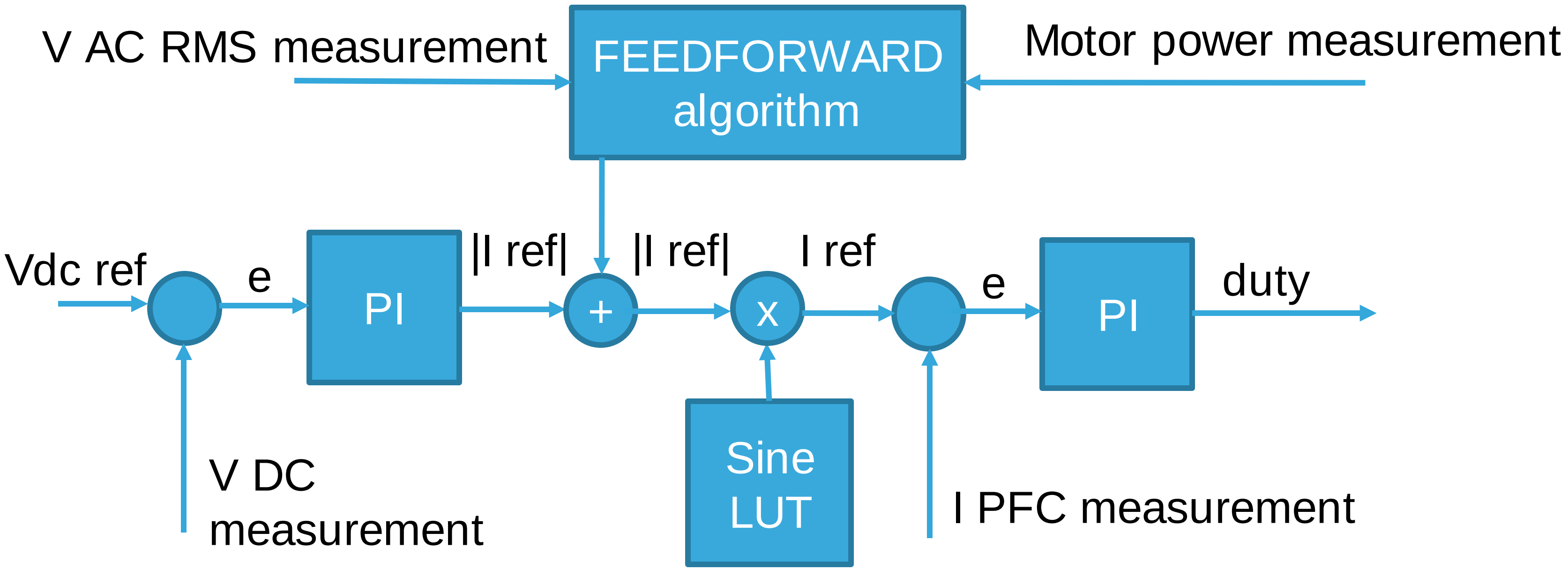
Digital PFC
Other Advantages

- Line waveform synthesizing and feed-forward from AC mains make DC bus voltage more insensitive to line surges and drops
- Voltage reference can be changed in run time, for instance in special conditions like high motor speed
- Mains frequency measurement could be exploited to protect appliances
- Digital HW filters can be applied on VAC synchronization and External Fault (OVP) protection signals

Digital PFC
Topology & control diagram





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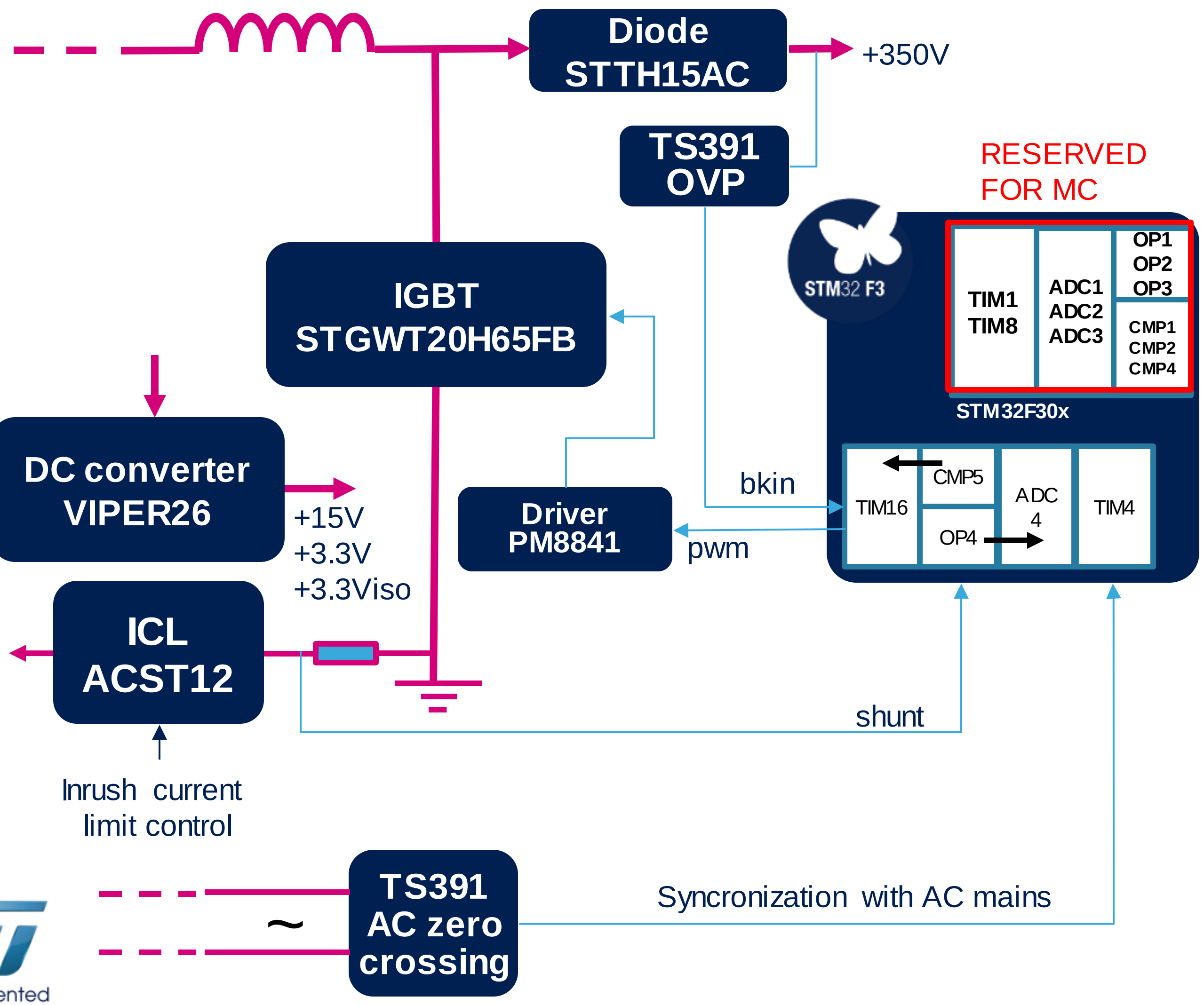
Digital PFC boost single phase
Implementation on STM32F3



Peripheral assignment	
TIM16 ch1	PWM generation
TIM16 BKIN	EXT fault signal (OVP)
OP4	Current amplification
ADC4	Current sampling
CMP5	OCP
DAC1 ch2	OCP threshold definition
TIM4	AC mains voltage , frequency and phase detection

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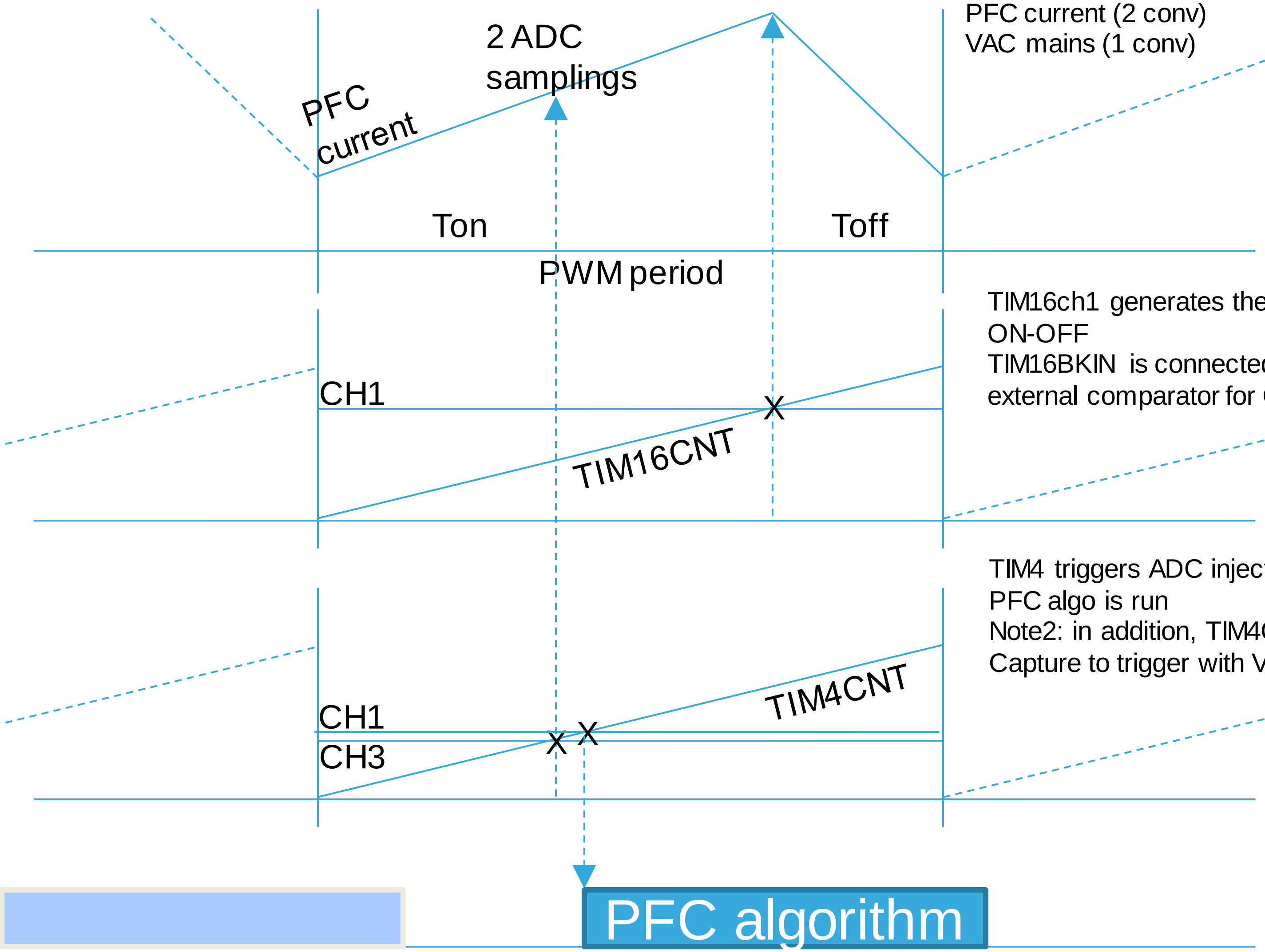
Digital PFC boost single phase

Time diagram, peripherals utilization

Note1:3 ADC injected conversions programmed:
PFC current (2 conv)
VAC mains (1 conv)



TIM16ch1 generates the PWM for switching the PFC device ON-OFF
TIM16BKIN is connected to the internal comparator for OCP, to external comparator for OVP

TIM4 triggers ADC injected conversion and the IRQ where the PFC algo is run
Note2: in addition, TIM4CH2 is also configured as Input Capture to trigger with VAC zero crossing signal

Conclusions

- ST SLLIMM® IPM has higher energy efficiency than competitor compared
- ST digital PFC has outstanding figures of merit on PF and THD
- ST devices used in digital PFC, both ST IGBT and AC series diode, give higher energy efficiency than compared competitors
- STM32F3 mcu is able to drive 2 motors and dPFC with low cpu load
- STM32F3 mcu has a very good pinout, so that a 64 pin package is enough for the whole solution

Motion control

Thanks

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ST Motion Control Ecosystem

Easy Plug and Spin