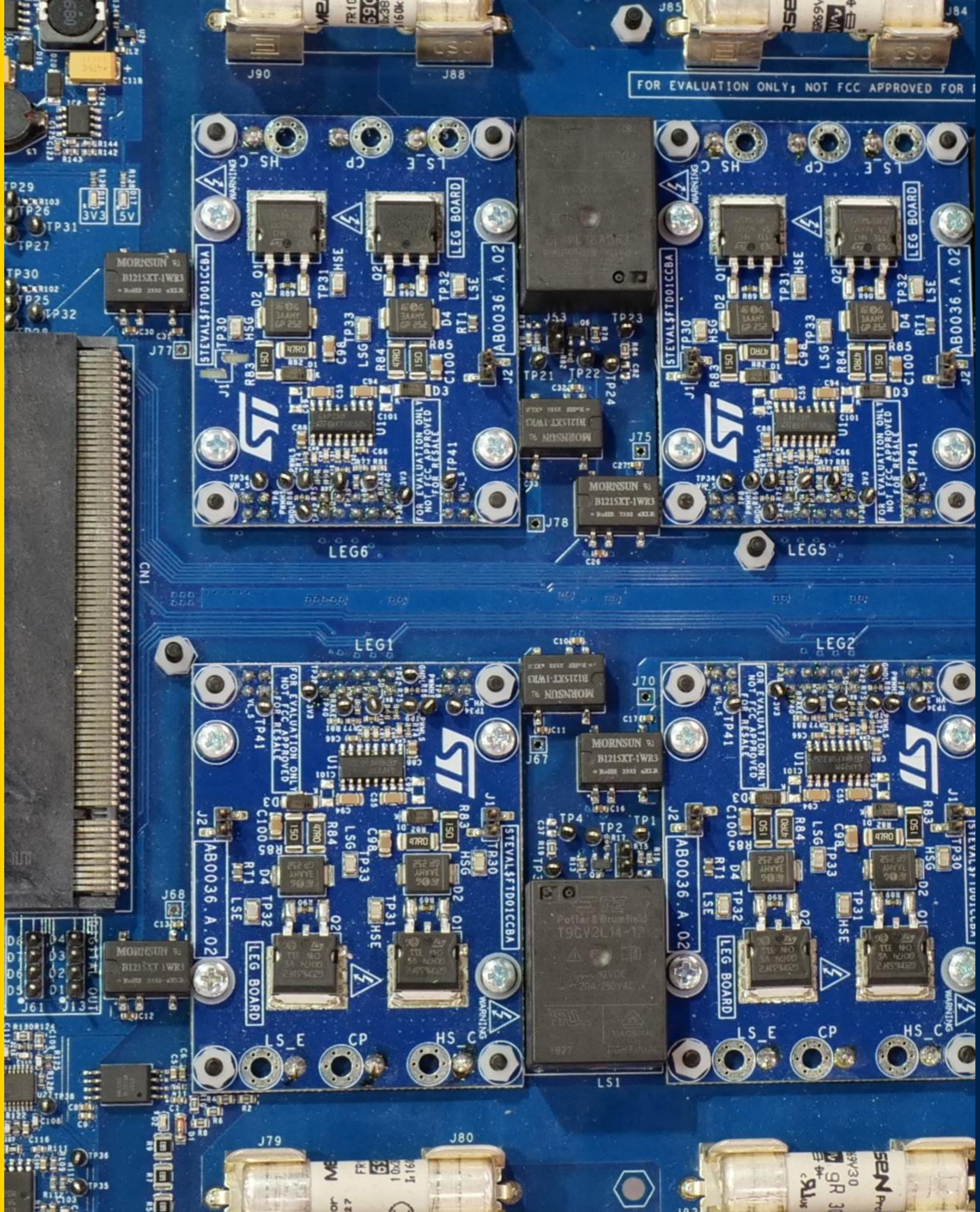


Fault Tolerant Motor Control Algorithms and Architecture of the ST Solution

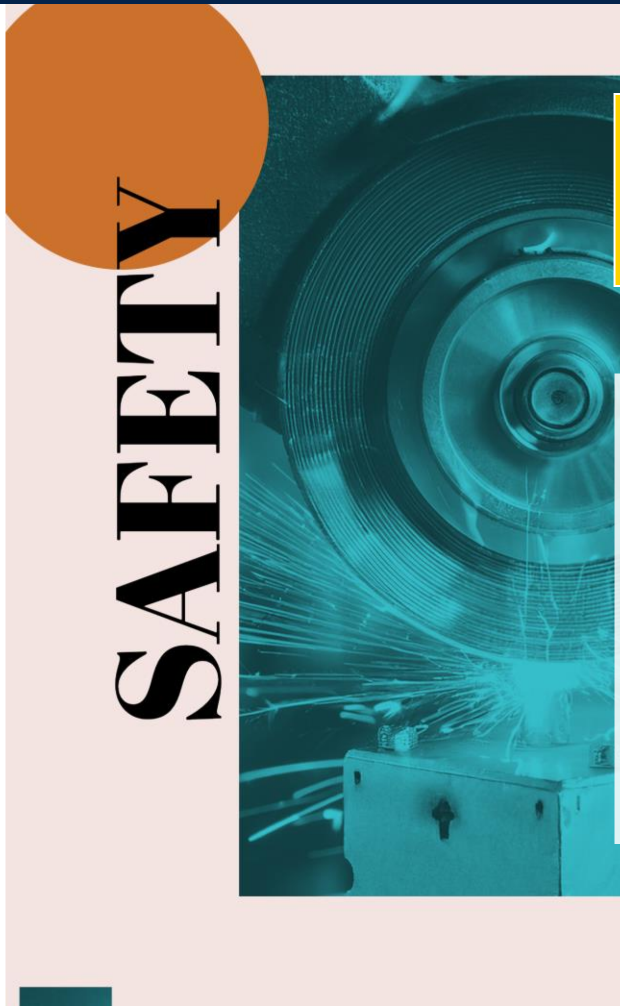
STMicroelectronics
최현우 과장

Agenda

Introduction on Fault Tolerant System

Fault Tolerant Motor Control System

Definitions

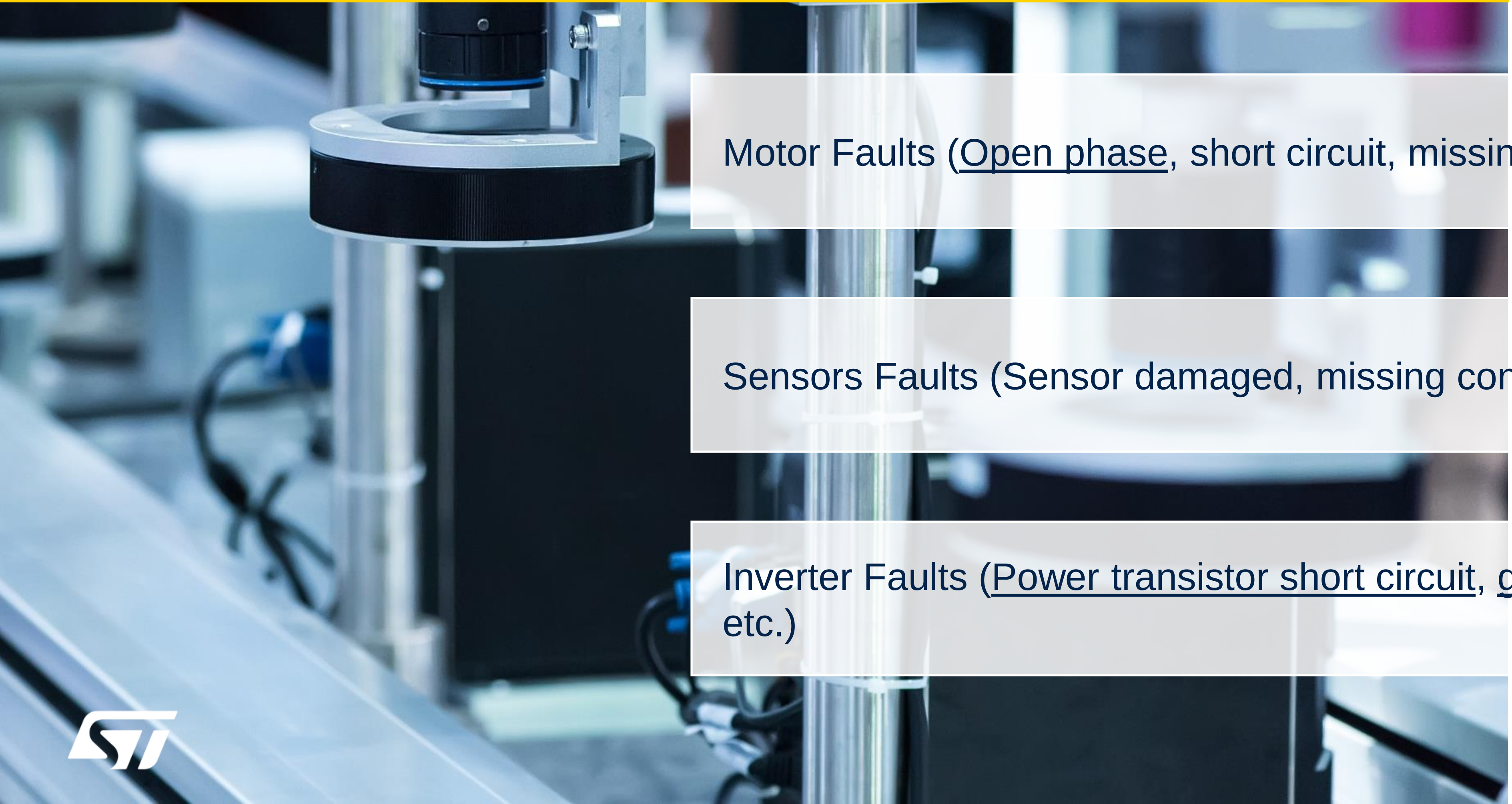


It is a System able to provide the Continuity of Service even in case of Fault

- Motor Control System is composed by the motor, the inverter and the algorithms.
- Continuity of Service in MC system is the capability of the motor to produce the required torque.
  - *Without derating*: the motor can produce the same torque (speed) even in fault condition.
  - *With derating*: the motor produce a reduced torque (speed) in fault condition. It must be accepted by the application.

Fault Conditions in Motor Control System

All possible causes that make system unable to work



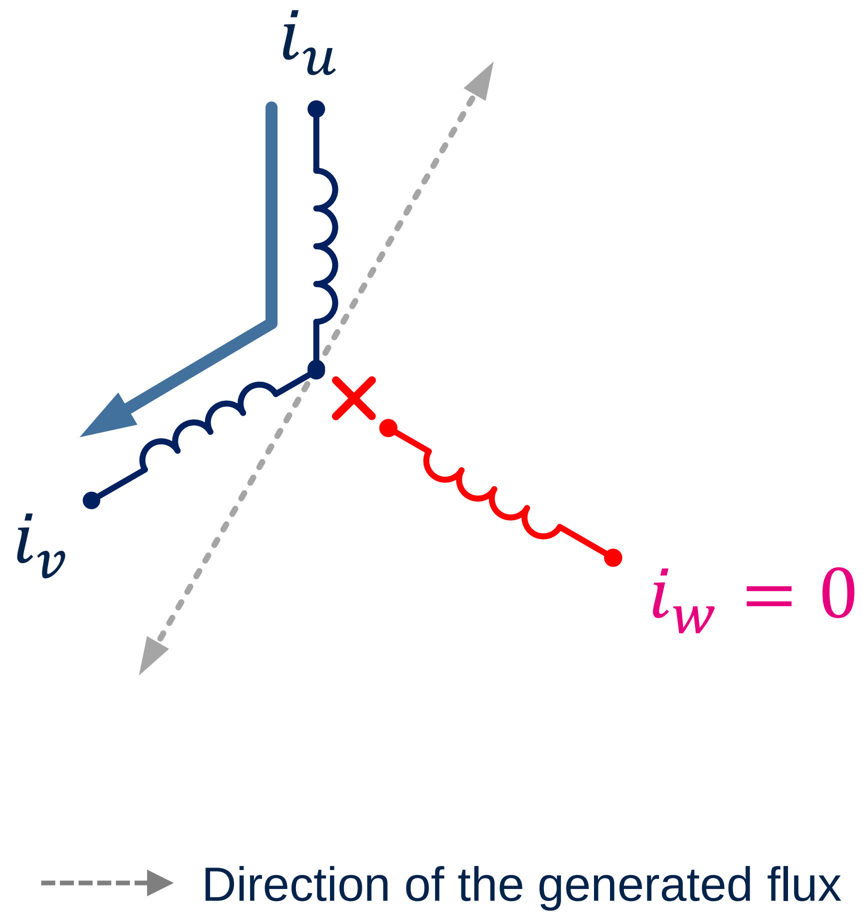
- Motor Faults (Open phase, short circuit, missing connections, etc.)
- Sensors Faults (Sensor damaged, missing connection, etc.)
- Inverter Faults (Power transistor short circuit, gate driver fault, supply, etc.)

The Problem

- In a three-phase system when a phase is no more usable due to a fault the other two currents becomes dependent.

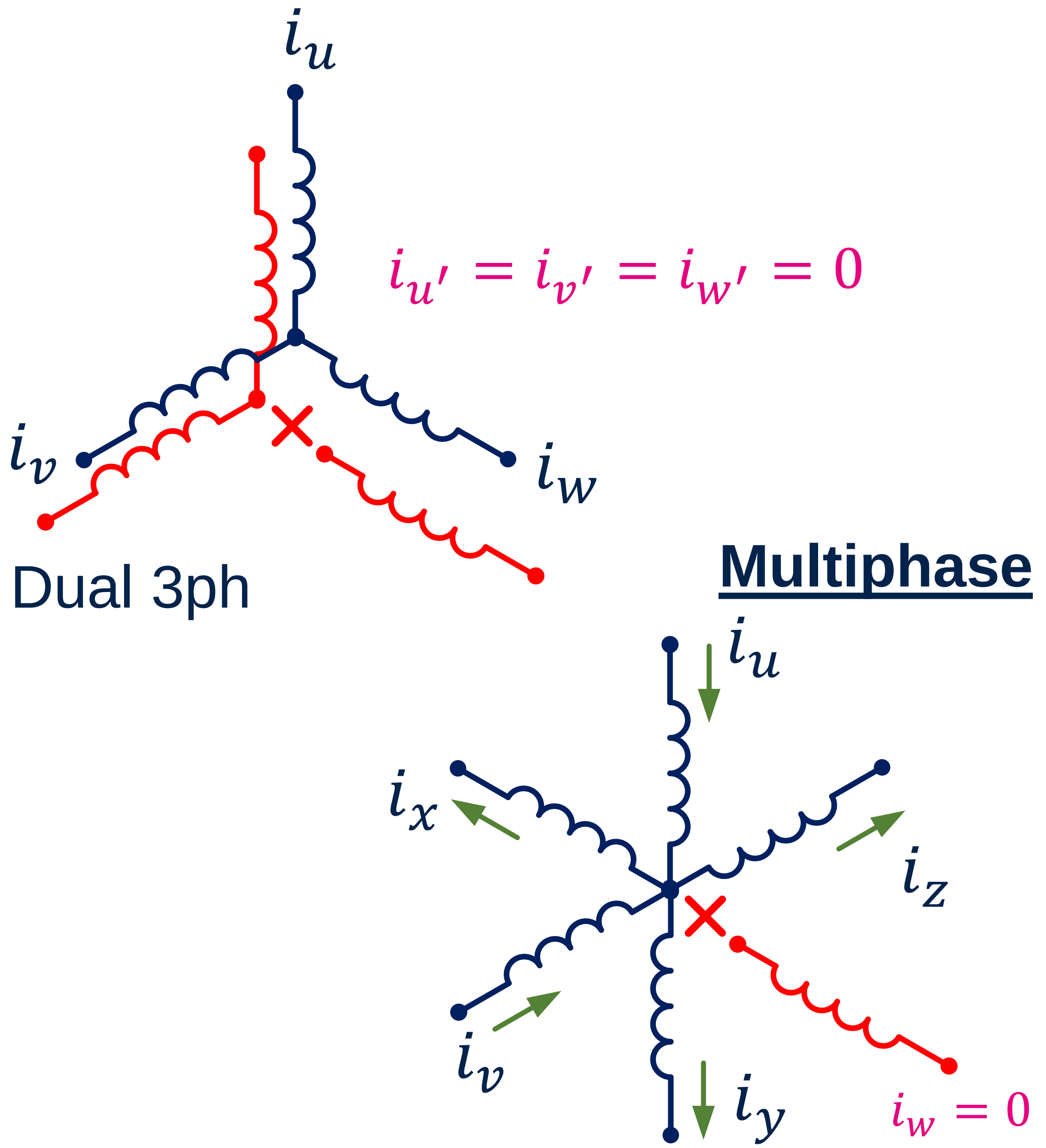
$$i_u = -i_v$$

- In this condition is no more possible to generating a rotating stator magnetic field whatever the voltage applied to the motor.



The Solution

- Increase system redundancy:
  - Complete redundancy duplicating the three-phase system (Dual 3ph).
  - **<u>Multiphase</u>** (>3), when a phase is no more available the remaining phases are used to generate the rotating filed and to produce the torque.



Advantages of six-phases vs three-phases

A six-phase motor can produce the torque with half of the current required by a three-phase motor

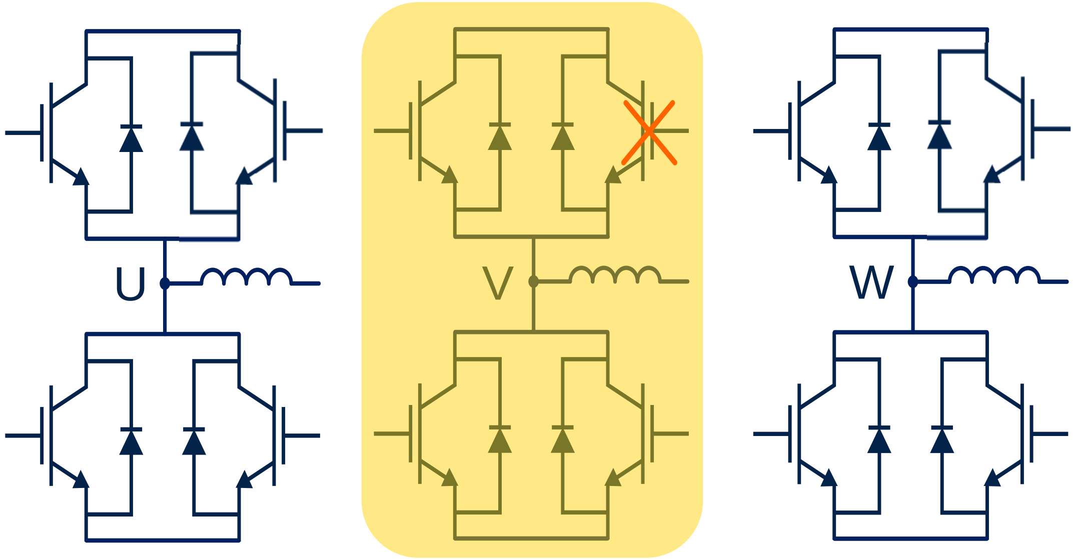
- This means that:
  - **Each motor phase** works with **half** of the **current**
  - The **power switches** of the inverter work with **half** of the **current**
  - **Lower** current ripple and better THD %
  - **Thinners** cables
  - Ready to be **fault** tolerant

6-Phases vs 3-Phases (with parallelized devices)

Double components is used in both case

Usually for high power are used devices in parallel

E.G. Total devices for 3 legs is N_{dev} = 12



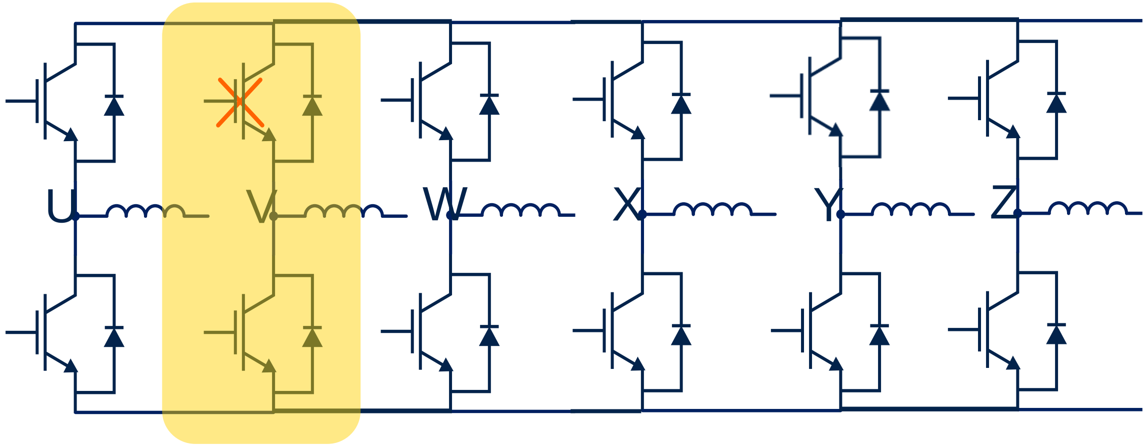
Losing 1 device the faulty leg is unusable:

- **8/12 suitable devices** remaining but with only **2 phases**

Current control is not possible! (Service is interrupted)

Same number of devices but in a smart way!

Total devices for 6 legs is N_{dev} = 12



Losing 1 device the faulty leg is unusable:

- **10/12** suitable devices remaining but with **5 phases**

Current control is possible (service continuity)

Really a drawback?

STEVAL-FTD01KCB – fault tolerant six-phase motor drive

STEVAL-FTD01KCB Custom Built Web Release
Fault-tolerant Six-phase Motor Drive for Industrial Applications

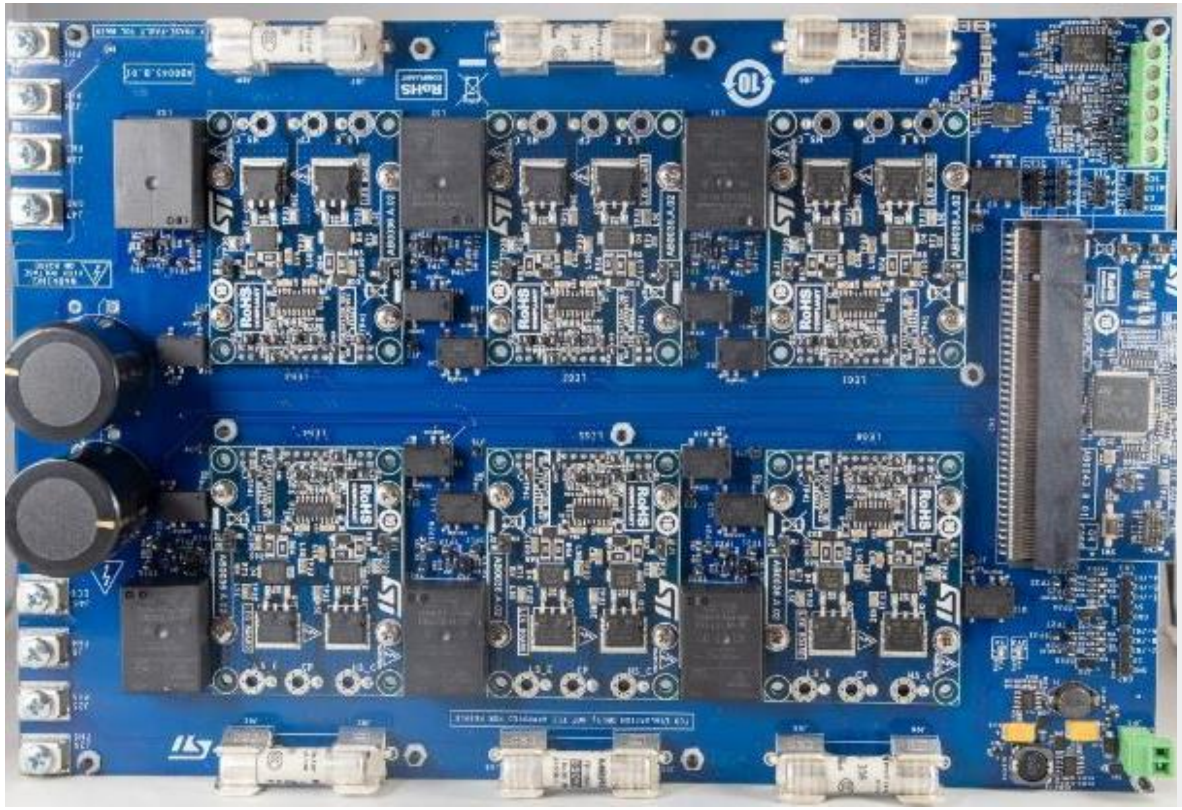
Key Features

- Inverter with 6 phase outputs
- 250-400V DC-Link up to 1.5 kW
- Motor phase current up to 14 Arms
- FOC compliance
- Able to sustain up to 3 concurrent failures
- Modular and scalable
- Compatible with Induction Motors (IM), Permanent Magnet Synchronous Motors (PMSM), Synchronous reluctance Motors (SynRM)
- MC Connector v2.0

Main Products

- **STM32G473QB:** Arm Cortex-M4 MCU 170 MHz with 128 Kbytes of Flash memory
- **STGB20M65DF2**: Trench gate field-stop IGBT M series, 650 V 20 A low loss
- **STGAP2D:** Galvanically isolated 4 A half-bridge gate driver

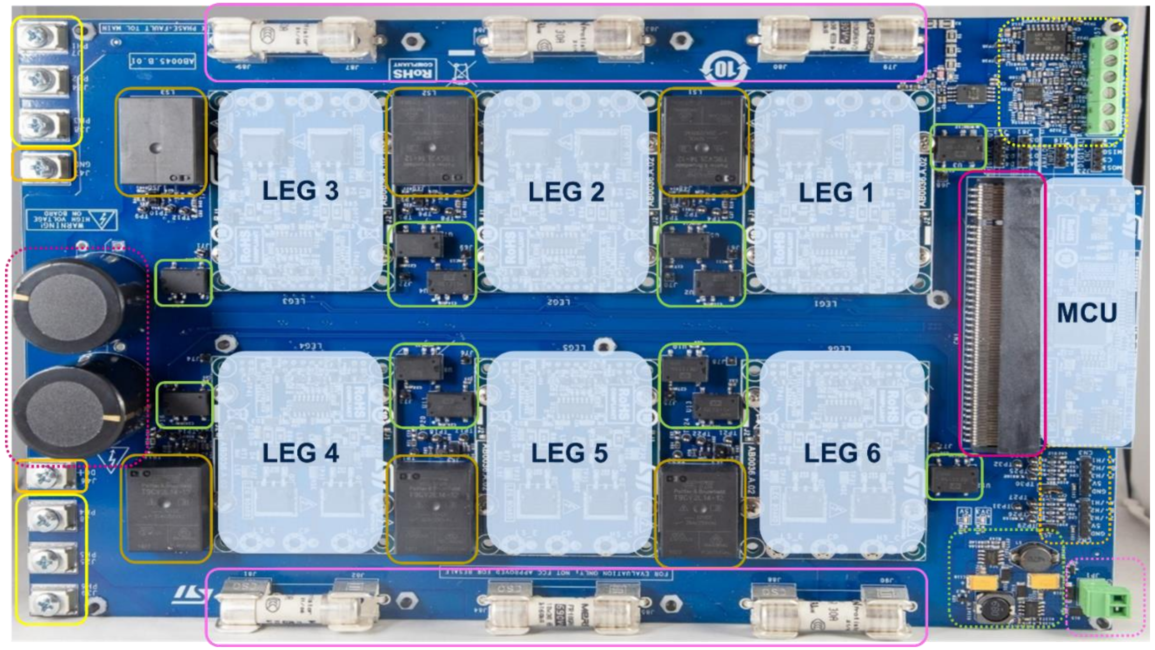
Modular six-phase motor drive

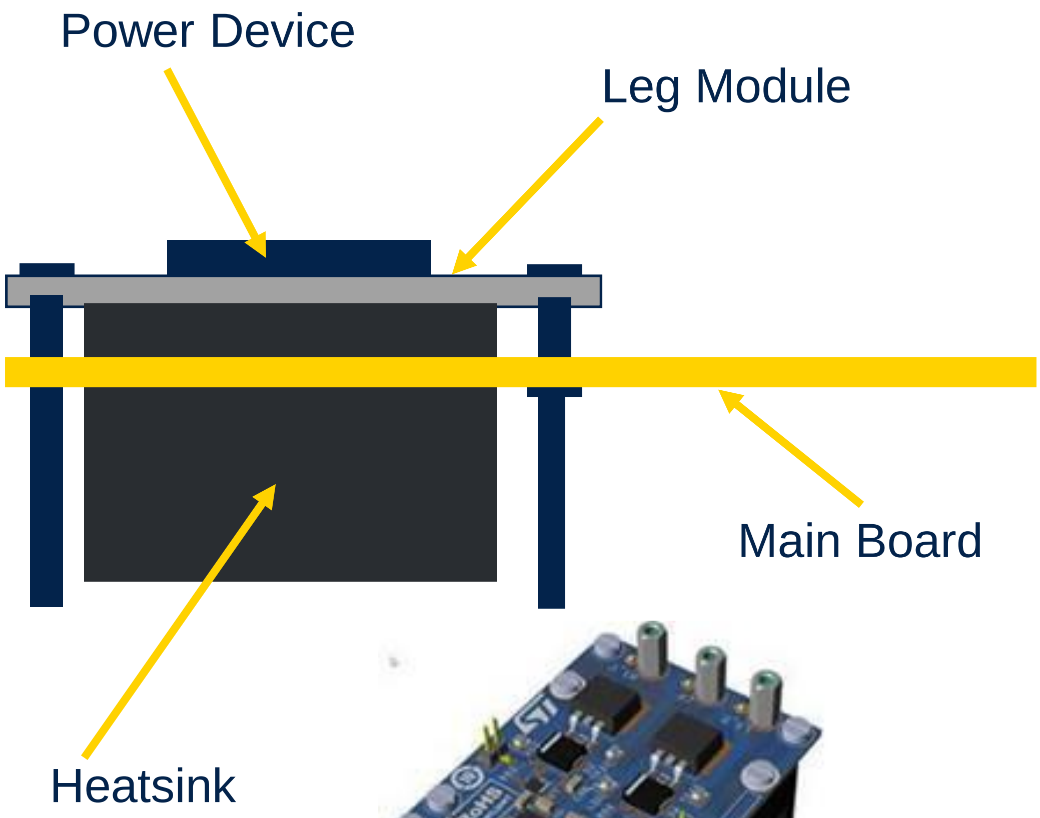


- **250-400 V** DC bus up to **3 kW**
- MC connector v2.0 → extend to multiple motors and new features
- **x6 half-bridge boards** leg hosting:
  - x2 **IGBTs** (**STGB20M65DF2**) in **D²PAK** package
  - x1 **half-bridge gate drivers (STGAP2D)**, up to 4A current capability, which isolates the gate driving channels from the low voltage control and interface circuitry.
- Support to **Hall effect**, **incremental encoder**, and **resolver** sensors for **rotor position measuring**
- DC bus voltage **sensing** network for **over & under voltage protection**
- **NTC sensing** network for overheating protection.
- **x6 ICS** (insulated current sensor) for phase current sensing
- **Galvanically isolation between logic and power voltage domains**
- **Fault-tolerant** support

Modular Approach

- System is composed by:
  - Main board (1pcs): it is the collector of all other boards, contains relays, fuses, current and voltage sensing.
  - Control board (1pcs): contains the STM32G4 microcontroller.
  - Leg boards (6pcs): contains gate driver, power transistor devices and the heatsink. Easy to be replaced after a destructive fault.





ST solution for six-phase induction motor drives

- First 6-Phase FOC for induction motor
  - With position sensor (incremental encoder)
- Sin-Tri PWM modulation support
- Firmware example based on STM32G47x
- Firmware based on ST MC X-CUBE v.5.4.x

Modular fault-tolerant multiphase inverter (FTMI)

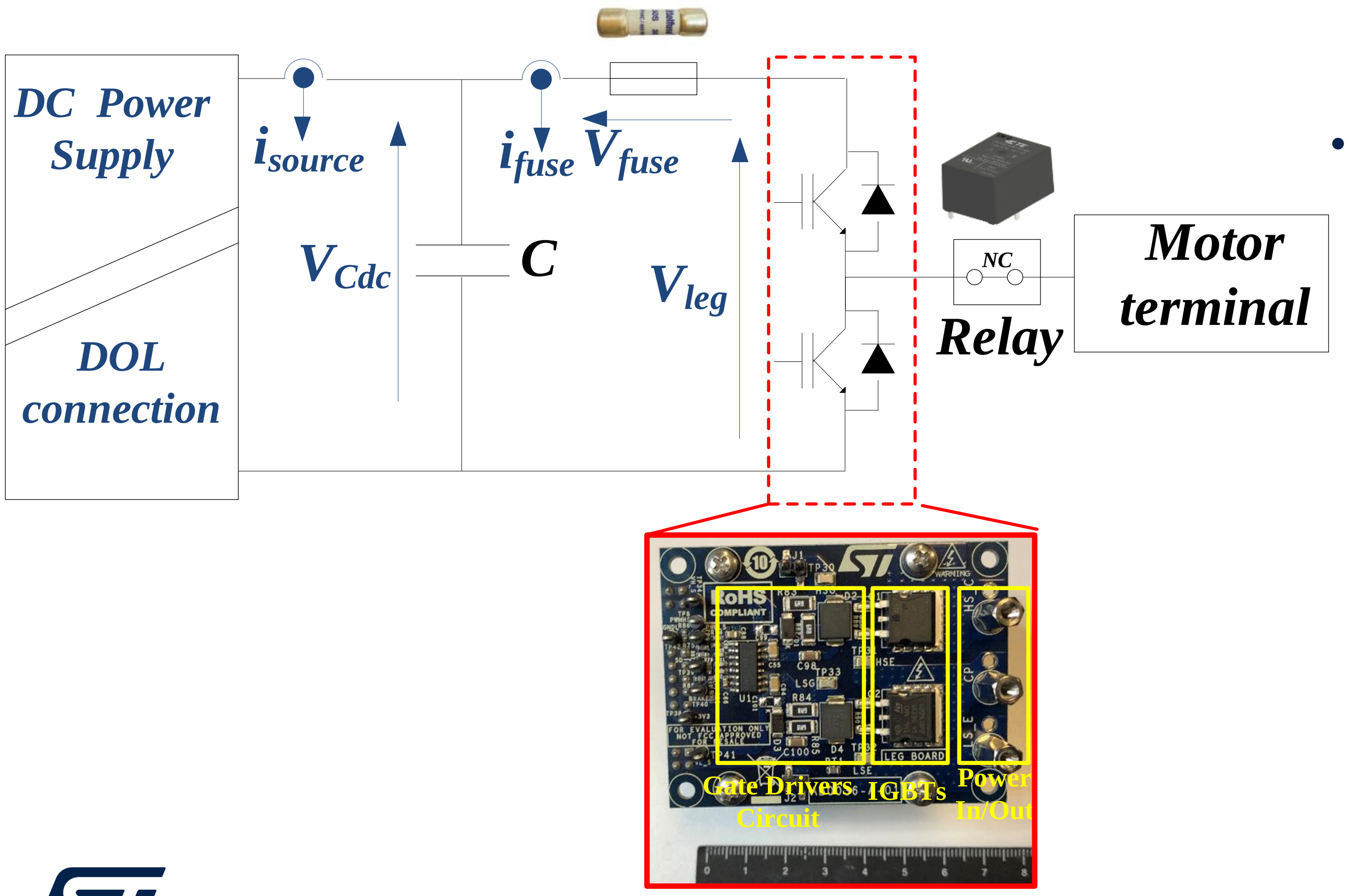
Service continuity even in case of inverter short-circuit fault

- **Service continuity even in case of fault**;
- **Automotive**, aeronautic, and **industrial applications**;
- **Higher degree of freedom for post-fault optimization strategies**;
- Reduced phase current amplitude at same power vs 3 phase

- **Modular and flexible fault-tolerant structure**;
    - **Straightforward detection, identification, and isolation of faulty part**;
    - Fast replacement of damaged parts;
- Embedded system based on STM32G4;
- Compactness through PCIE 164-pin connector;
- **Fast-acting fuse for short circuit energy limitation and faulty leg isolation.**

Fault isolation

Features and strategy

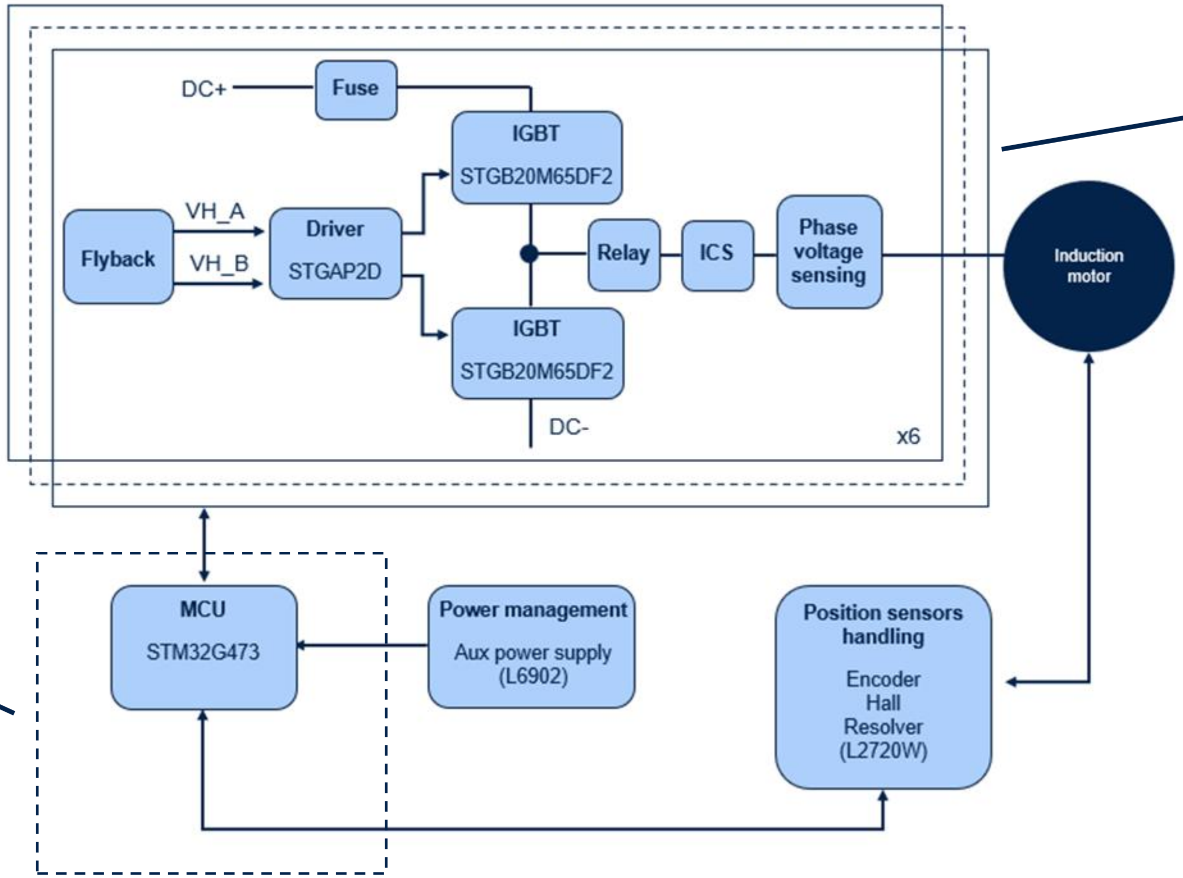


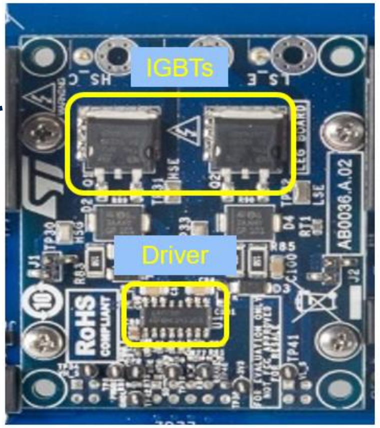
Leg board

- Inverter leg short circuit → <u>most critical fault among the supported by the FTMI</u>
  - **Isolation** from positive DC-Link terminal
    - Fast-fuses combined with the proper dimensioning of DC-Link capacitors → ~ tens of ms
  - **Isolation** from the motor terminal
    - Opening the phase relay contacts (normally closed) → ~ tens of ms

***fault detection patent pending**

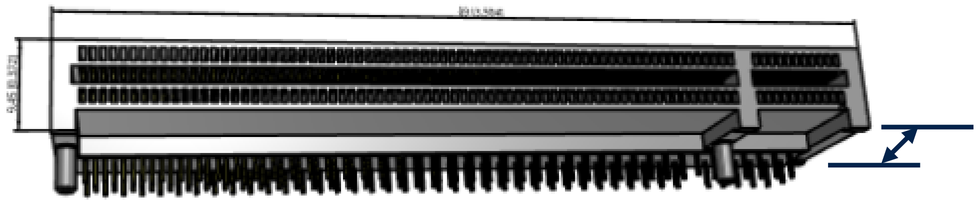
System Block Diagram





MC Connector v2

PCI-e 16x pinout



	Pin	Row A	Row B
	1	SPI nSS	SPI MISO
	2	SPI SCK	SPI MOSI
	3	SPI nSS	SPI MISO
	4	SPI SCK	SPI MOSI
	5	5V_to_CTRLB	5V_to_CTRLB
	6	3.3V_to_PWRB	VREF+
	7	DGND	DGND
	8	ID_enable	AGND
	9	ADC	ADC
	10	ADC	ADC
	11	ADC	ADC
Notch			
	12	Emergency (BKIN)	Emergency (BKIN2)
	13	INH/PWM	INL/EN
	14	INH/PWM	INL/EN
	15	INH/PWM	INL/EN
	16	Master EN	Encoder A
	17	Timer ETR	Encoder B
1x	18	Hall sensors H1	Encoder Z
	19	Hall sensor H2	Hall sensor H3
	20	DGND	DGND
	21	Shunt +	Shunt -
	22	Shunt +	Shunt -
	23	Shunt +	Shunt -
	24	AGND	AGND
	25	Ph Voltage +/BEMF zc	Ph Voltage -/BEMF ref
	26	Ph Voltage +/BEMF zc	Ph Voltage -/BEMF ref
	27	Ph Voltage +/BEMF zc	Ph Voltage -/BEMF ref
	28	Temperature/Board ID	Res. Ex/Curr. REF
	29	VBUS	Resolver Sin/GPIO_BEMF
	30	Dissipative brake	Resolver Cos
	31	DGND	DGND
4x	32	AGND	AGND

	Pin	Row A	Row B
	33	AC voltage	AC zero crossing
	34	PFC Current 1	PFC Current 2
	35	PFC BKIN OC	Inrush lim.
	36	PFC PWM1	PFC PWM2
	37	Emergency (BKIN)	Emergency (BKIN2)
	38	INH/PWM	INL/EN
	39	INH/PWM	INL/EN
	40	INH/PWM	INL/EN
	41	Master EN	Encoder A
	42	Timer ETR	Encoder B
	43	Hall sensors H1	Encoder Z
	44	Hall sensor H2	Hall sensor H3
	45	DGND	DGND
	46	Shunt +	Shunt -
	47	Shunt +	Shunt -
	48	Shunt +	Shunt -
8x	49	AGND	AGND

	Pin	Row A	Row B
	50	Ph Voltage +/BEMF zc	Ph Voltage -/BEMF ref
	51	Ph Voltage +/BEMF zc	Ph Voltage -/BEMF ref
	52	Ph Voltage +/BEMF zc	Ph Voltage -/BEMF ref
	53	Temperature/Board ID	Res. Ex/Curr. REF
	54	VBUS	Resolver Sin/GPIO_BEMF
	55	Dissipative brake	Resolver Cos
	56	DGND	AGND
	57	Emergency (BKIN)	Emergency (BKIN2)
	58	INH/PWM	INL/EN
	59	INH/PWM	INL/EN
	60	INH/PWM	INL/EN
	61	Master EN	Encoder A
	62	Timer ETR	Encoder B
	63	Hall sensors H1	Encoder Z
	64	Hall sensor H2	Hall sensor H3
	65	DGND	DGND
	66	Shunt +	Shunt -
	67	Shunt +	Shunt -
	68	Shunt +	Shunt -
	69	AGND	AGND
	70	Ph Voltage +/BEMF zc	Ph Voltage -/BEMF ref
	71	Ph Voltage +/BEMF zc	Ph Voltage -/BEMF ref
	72	Ph Voltage +/BEMF zc	Ph Voltage -/BEMF ref
	73	Temperature/Board ID	Res. Ex/Curr. REF
	74	VBUS	Resolver Sin/GPIO_BEMF
	75	Dissipative brake	Resolver Cos
	76	DGND	AGND
	77	ΣΔ CLKO/SPI nSS	ΣΔ DIN/Enable
	78	ΣΔ DIN/Enable	ΣΔ DIN/Enable
	79	ΣΔ CLKO/SPI nSS	ΣΔ DIN/Enable
	80	ΣΔ DIN/Enable	ΣΔ DIN/Enable
	81	ΣΔ CLKO/SPI nSS	ΣΔ DIN/Enable
16x	82	ΣΔ DIN/Enable	ΣΔ DIN/Enable

Motor 1
Motor 2
Motor 3
PFC
Extra

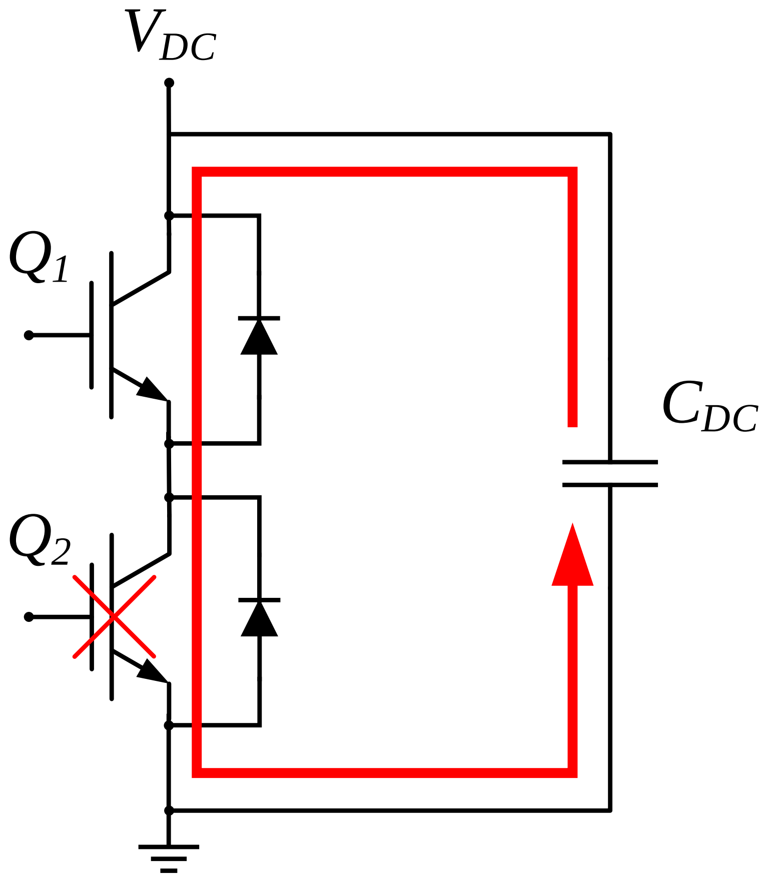
GND references
dual function signals
power supplies
shunt diff. pair
other signals

- Enable/Disable functionality for gate driving
- Dedicated inputs for embedded analogs OPAMP/COMP for current sensing/protection
- BEMF sensing (e.g., six step)
- Separate BRK/BRK2 inputs
- Allows multiple position and speed sensors for the same drive
- Support to resolver sensor
- Support to interleaved PFC
- Support to Sigma/Delta modulators
- Support to digital encoders

Fault Isolation

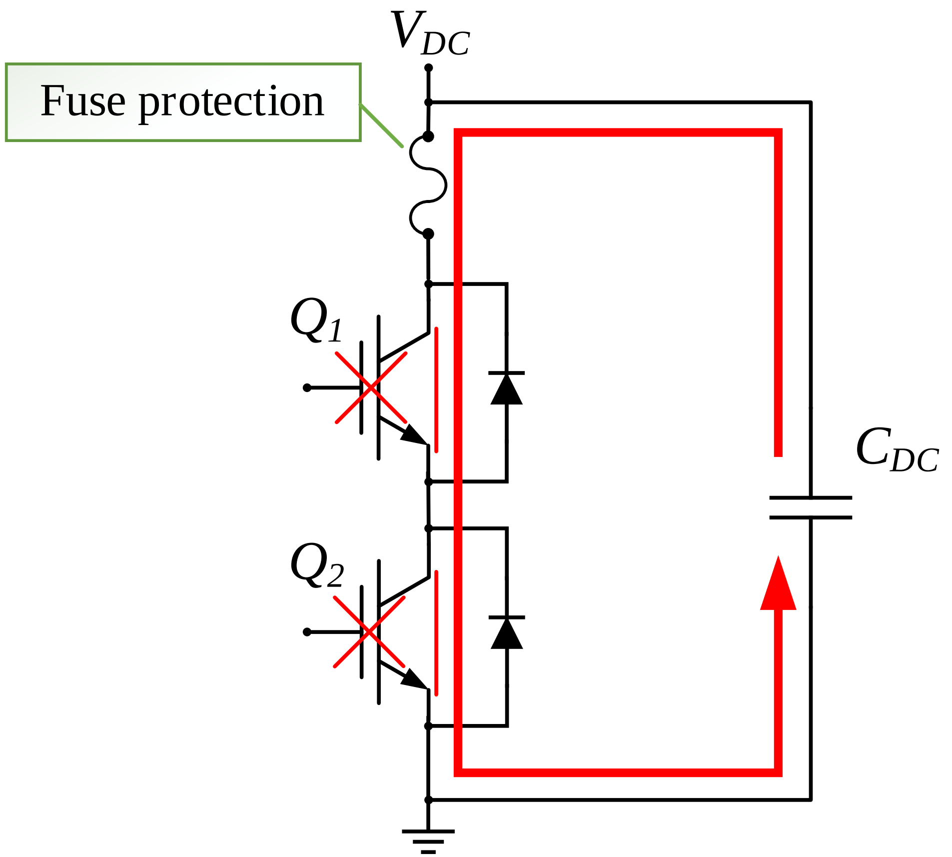
Short Circuit Fault

- Typically, the fault mode of a power transistor is a short circuit between drain and source.
- If one power transistor fails, e.g.Q_2, very soon also the complementary transistor Q_1 will fail due to a short circuit.
- This bring the full leg to a permanent short circuit condition.



V_{DC} Segmentation

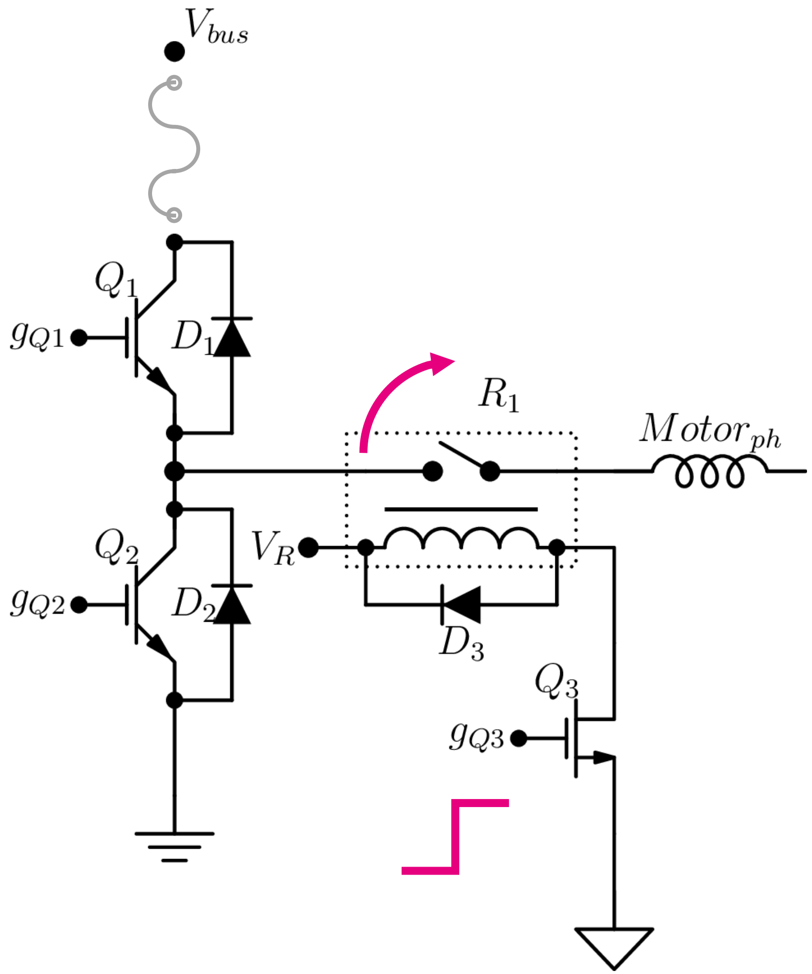
- To isolate the faulty leg, a dedicated fast-acting fuse is added.
- The correct selection of the DC capacitor C_{DC} and of the fuse is important to guarantee the fuse melting and to minimize the V_{DC} drop due to a short circuit*.
- When the fuse melts, the DC bus is isolated.



* A detailed study has been carried out in this paper: Performance Analysis of a Fault Isolation System for Fault-Tolerant Voltage-Fed PWM Motor Drives

Motor phase segmentation

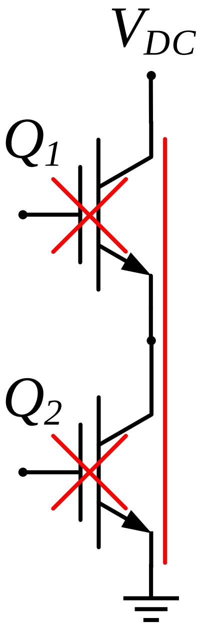
- During healthy operation, a 'normally-closed' relay connects the output of the leg with the motor phase.
- After the fuse melts, the relay is forced to open, disconnecting the motor phase from the faulty leg.
- This allows the inverter to continue operating using the remaining legs.



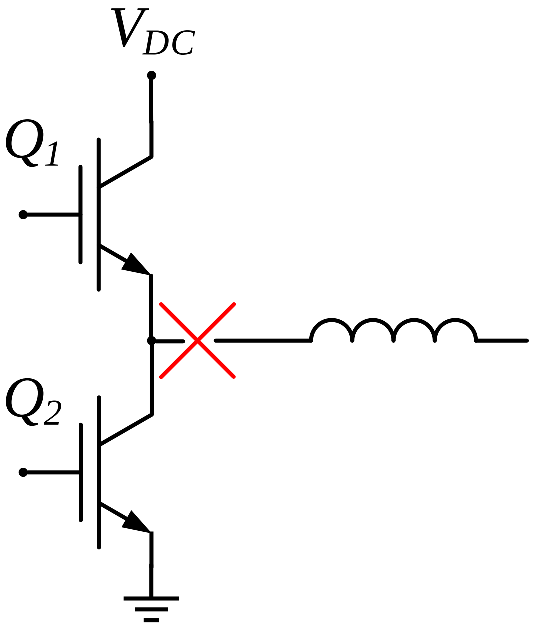
Fault Detection

Fault Detection

- A reliable fault detection technique is essential to perform actions such as opening the relay and managing fault compensation.
- The fault managed by the solution are leg short circuit and open phase.



Leg short circuit

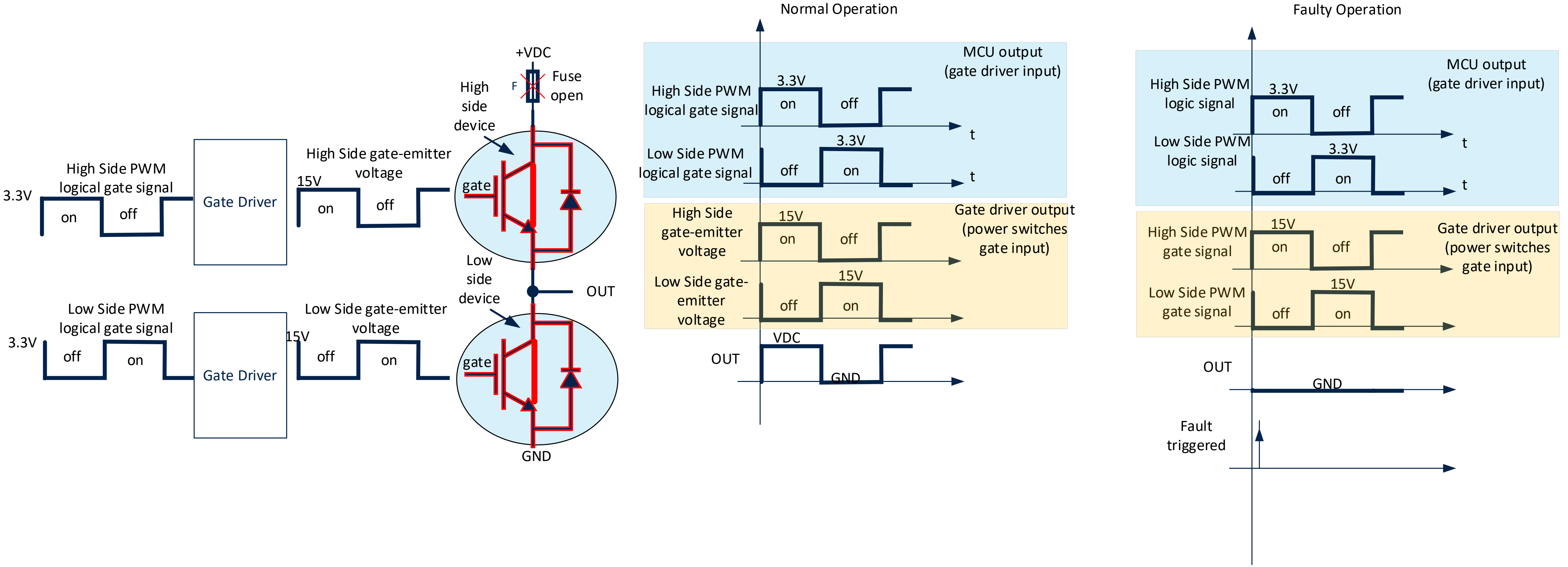


Open phase

Leg Short Circuit Fault Detection

Patent filed*

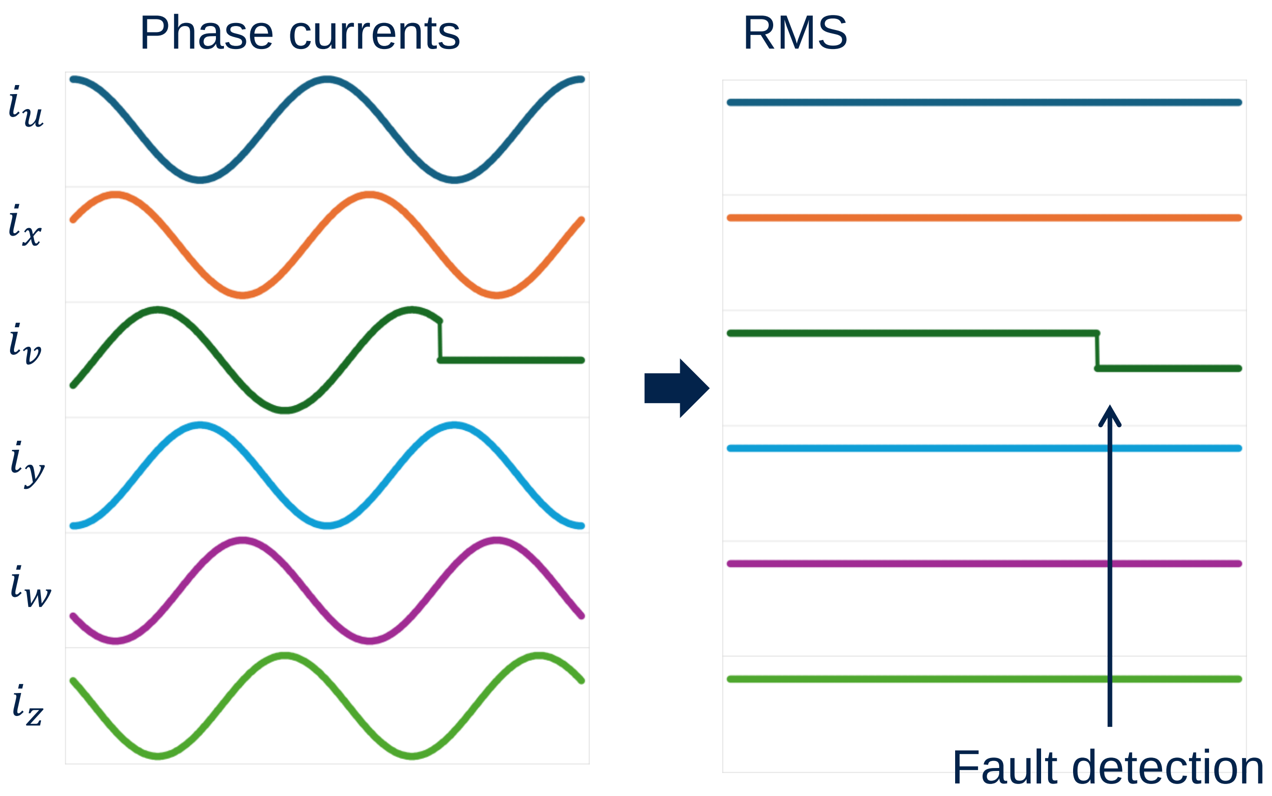
The fault is detected when the output measured voltages does not follow the high side PWM command signal.



* Patent filed: FAULT DETECTION METHODS AND DEVICES FOR PULSE WIDTH MODULATION CONVERTERS

Open Phase Fault Detection

- The open phase fault detection algorithm is based on calculating the RMS value of the motor phase currents.
- After measuring the RMS value, a statistical analysis is performed to establish a threshold.
- If any RMS value falls below the threshold, the corresponding phase is considered faulty

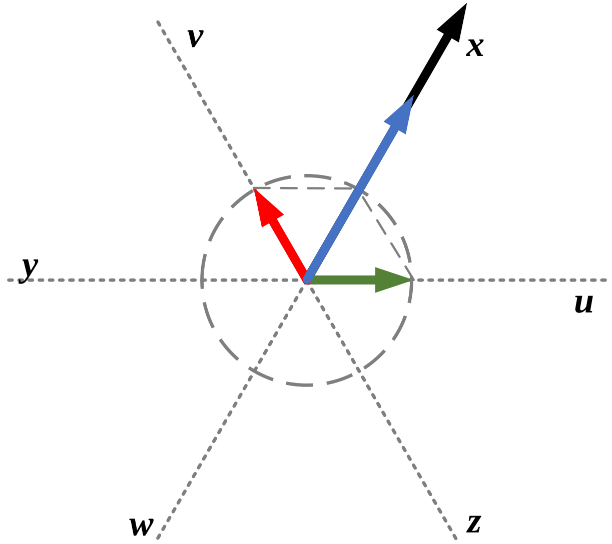


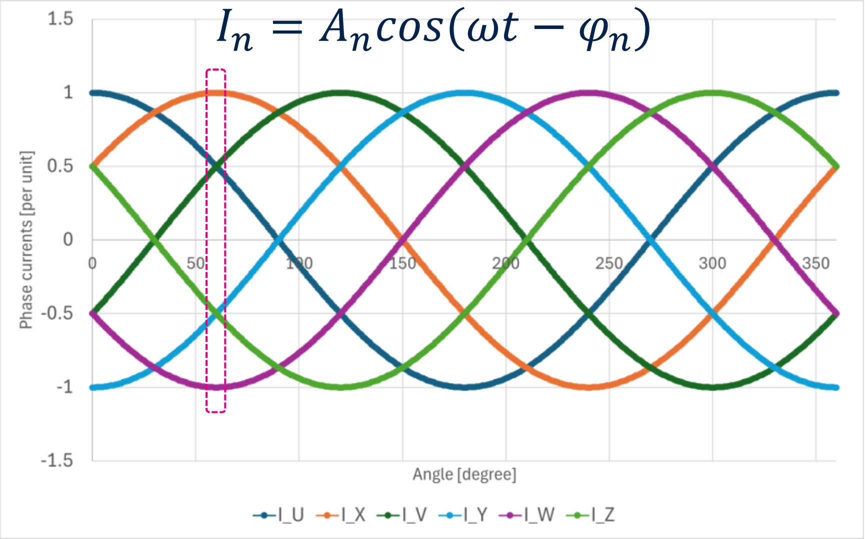
Fault Compensation

Healthy Conditions

- In healthy operation, all six phases contribute to producing the resultant magnetic flux.
- As shown in the figure, the U and Y phases contribute in the same direction, as do the other pairs VZ and WX.
- The green, red, and blue vectors represent the contributions of each pair.
- To produce a rotating flux with constant amplitude, all six phases must have the same amplitude and be displaced by 60° in phase.

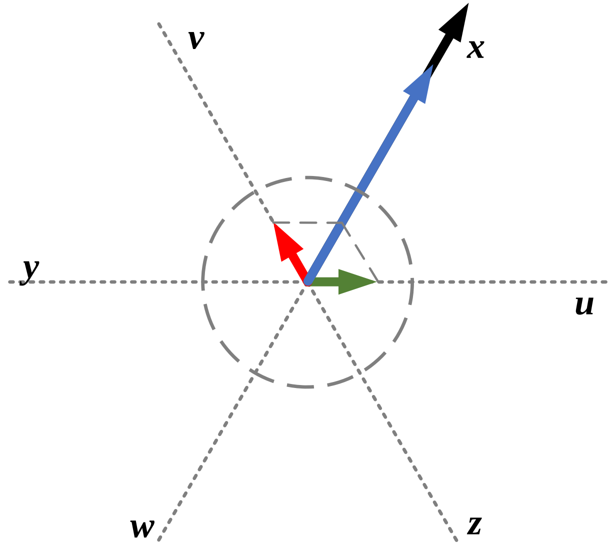
	I_u	I_x	I_v	I_y	I_w	I_z
A_n [p.u.]	1	1	1	1	1	1
φ_n	0	60	120	180	240	300



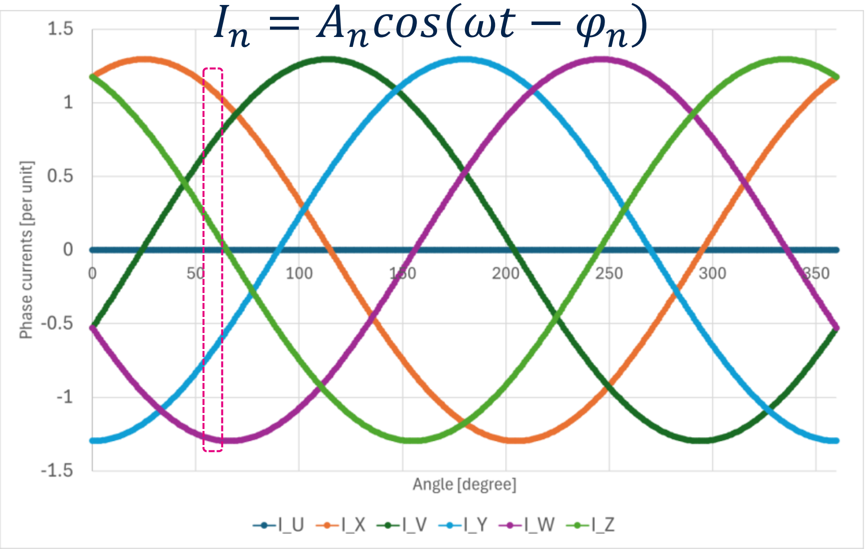


Faulty Condition

- In faulty condition, the contribution of the missing phase must be compensated by the other phases.
- The remaining currents are adjusted in amplitude and/or in phase to keep sinusoidal the m.m.f. and to optimize the efficiency.
- For example, if the faulty phase is the U the remaining phase are set as follow:



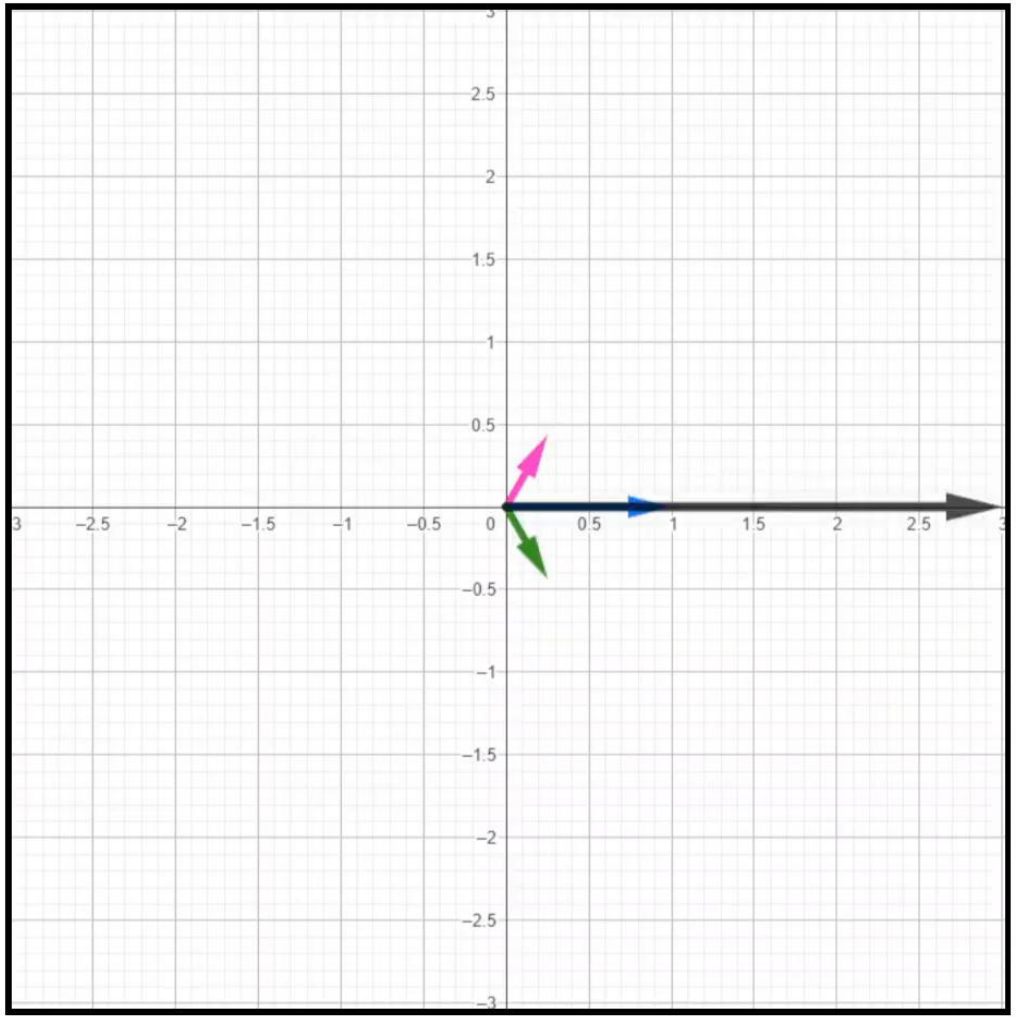
$$I_n = A_n cos(\omega t - \varphi_n)$$



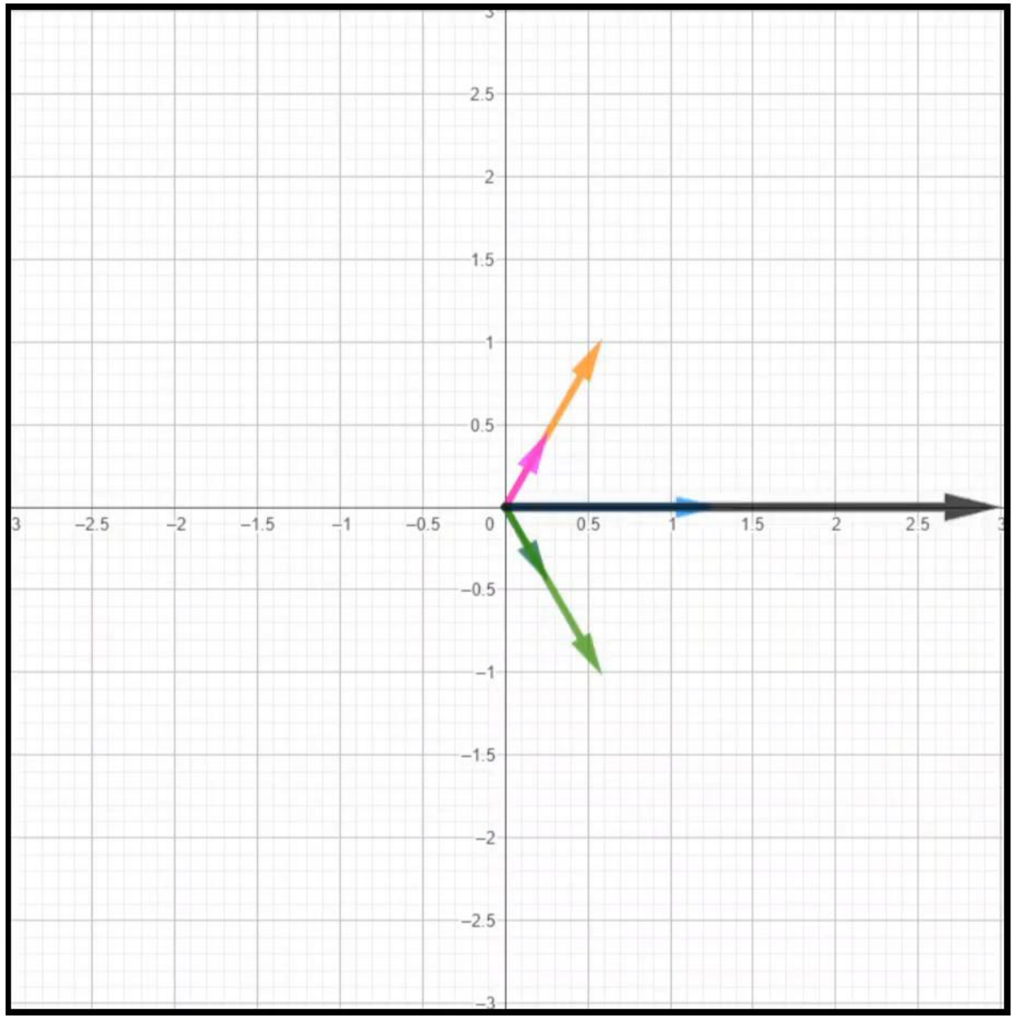
	I_u	I_x	I_v	I_y	I_w	I_z
A_n [p.u.]	0	1.296	1.296	1.296	1.296	1.296
φ_n	0	25	114	180	246	335

Fault Compensation

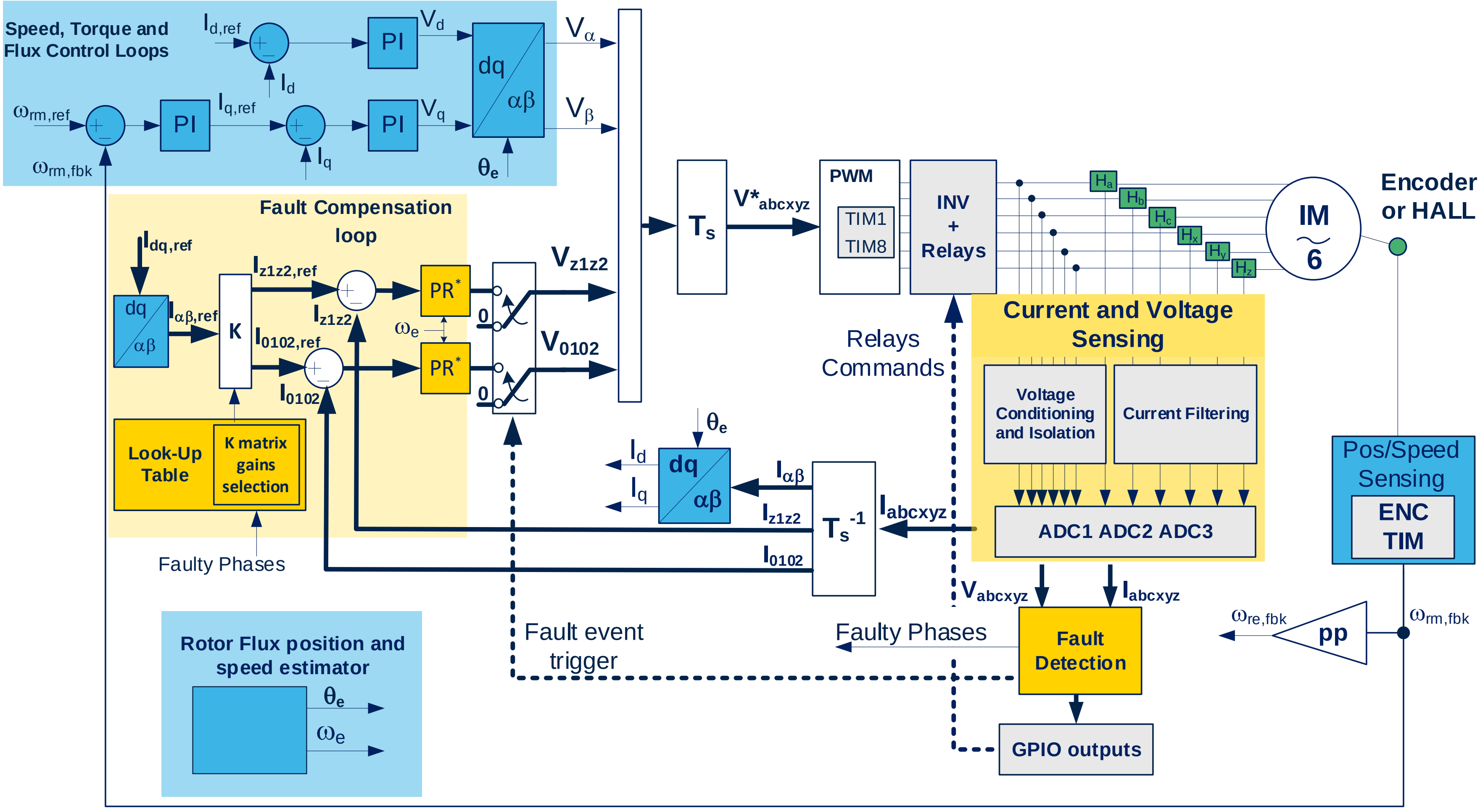
Healthy condition



Compensate after fault on phase A



Compensation and Control Algorithm Block Diagram



Firmware Development
Customization of XCUBE-MCSDK 5.x

Features and MCU peripherals

AVILABLE UDER REQUEST

- Speed FOC of 6-phase Motor (synchronous/asynchronous)
  - Pulse Width Modulation (PWM)
    - Sin-Tri PWM implemented (requires BUS voltage measurement using regular conversions)
      - TIM1, TIM8 advanced PWM timers (3+3 channels)
  - Current Sensing
    - 6 phase current measurement trough Insulated Current Sensors (ICS): Iu, Iv, Iw, Ix, Iy, Iz
- Inverter Output Voltage measurements (optional, Fault Detection)
    - 6 analog measurements: Vu, Vv, Vw, Vx, Vy, Vz
  - Speed/Position Sensing
    - Incremental Encoder: Same as MCDSK
- Relays command
    - 6 output GPIOs to control the phase terminals relays

Memory footprint of demo code

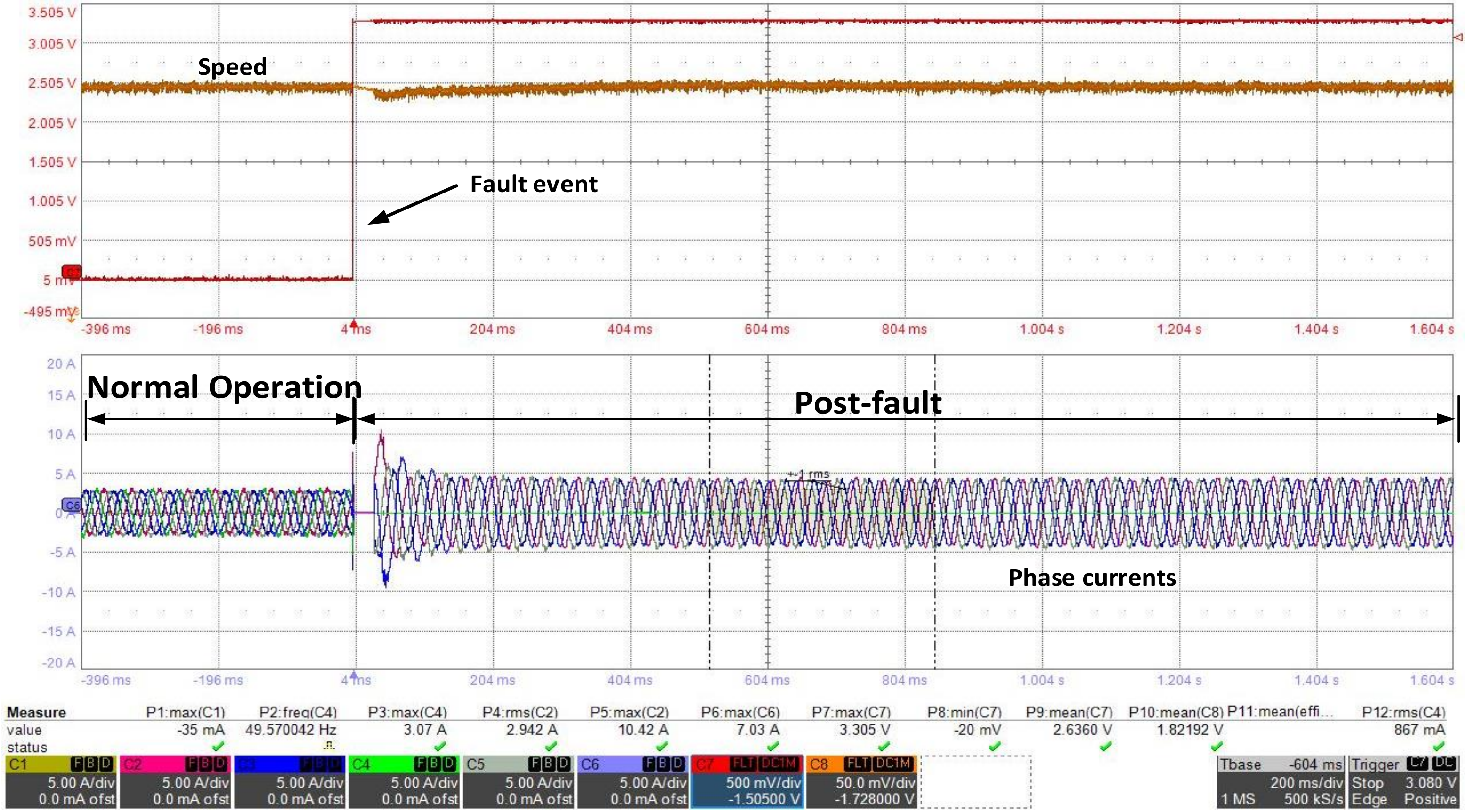
Memory type	Size
ROM	40k
RAM	31.5k
CCM RAM	9k

Conclusions

Experimental results

Speed IFOC at 700 rpm, 5 nm, during double phase fault (fault compensation activated)

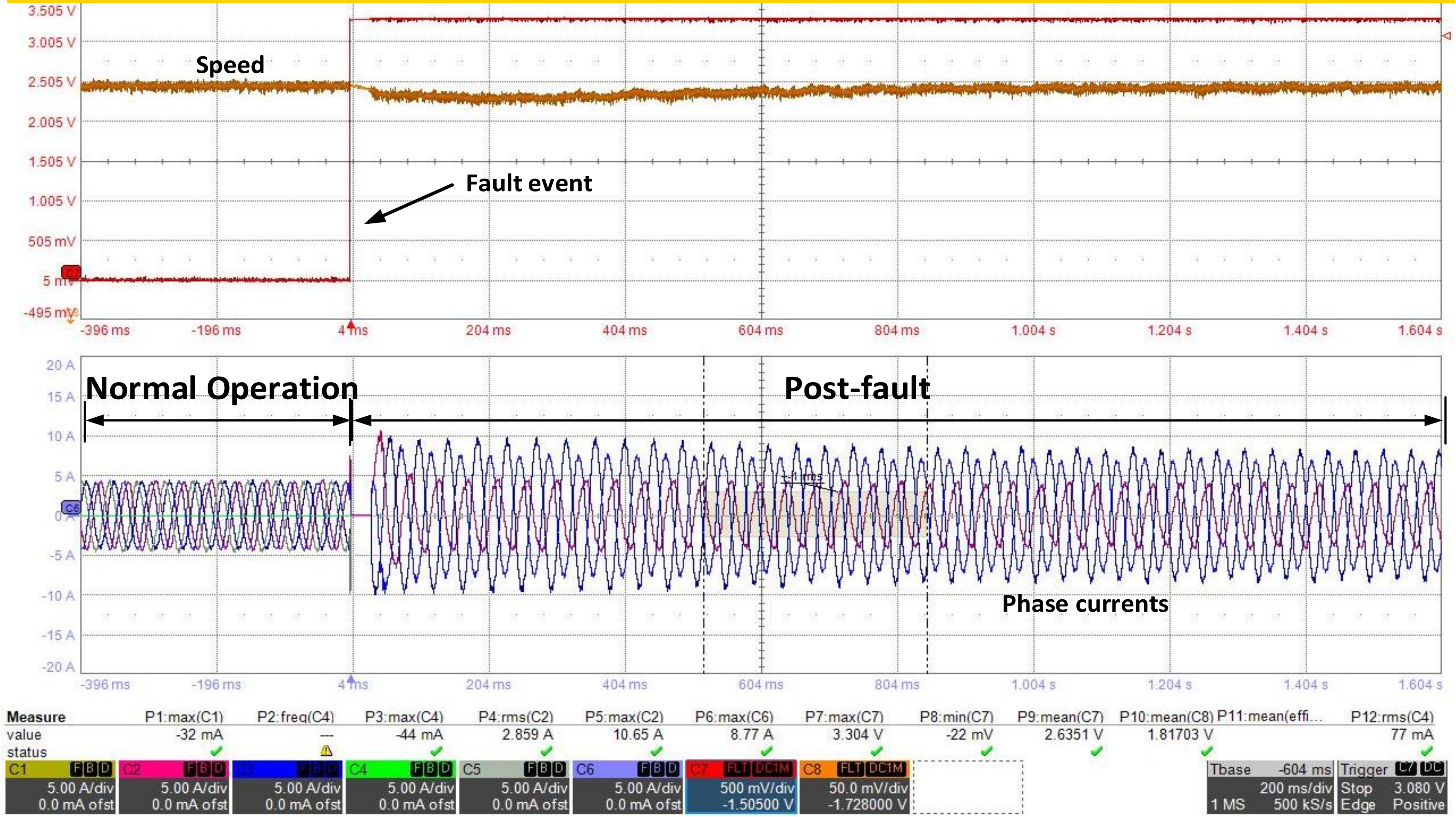
Speed is recovered and maintained without oscillations



Experimental results

Speed IFOC at 700 rpm, 5 nm, during triple phase fault (fault compensation activated)

Speed is recovered and maintained without oscillations



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