CERN

CLIQ components redundancy

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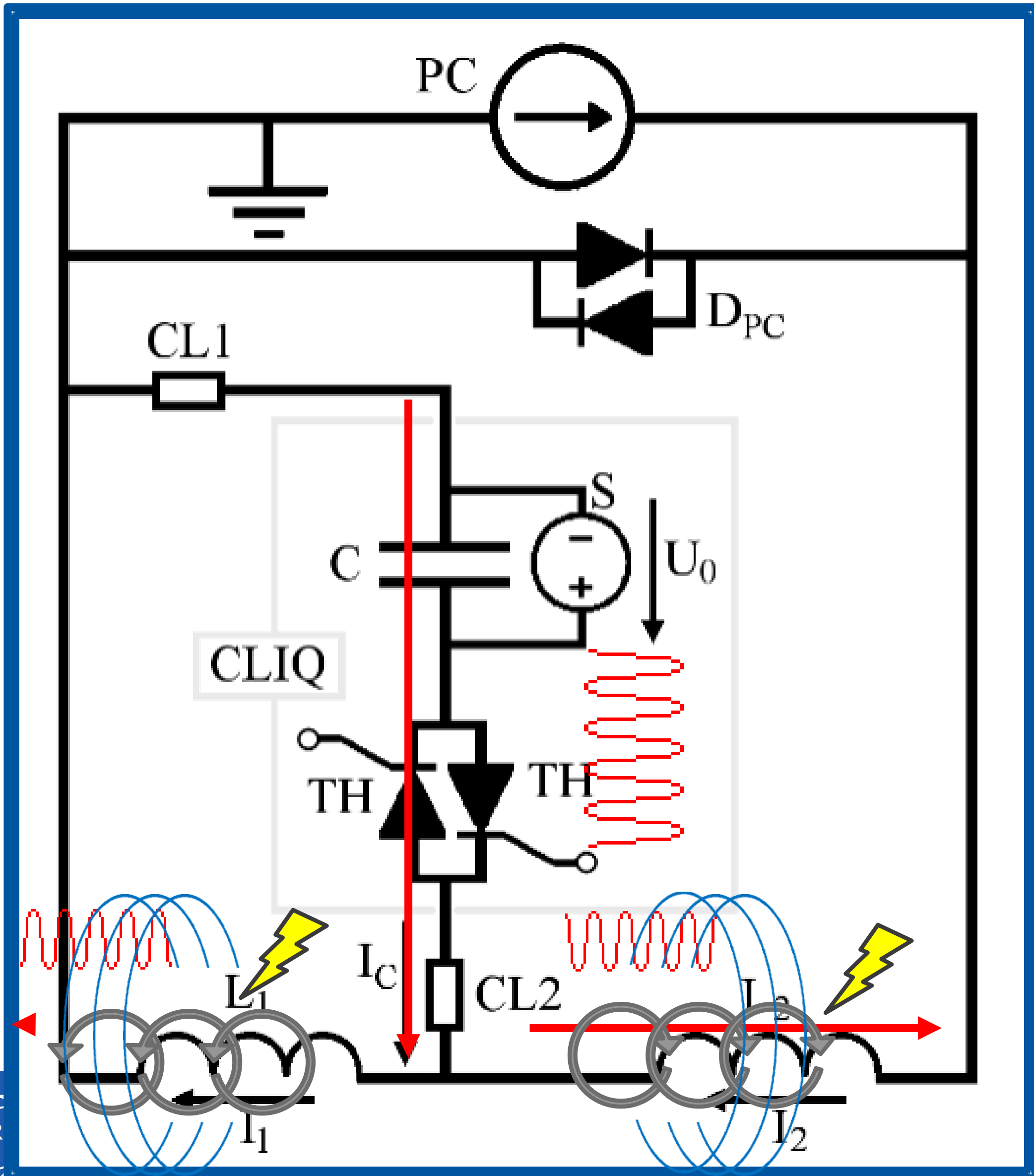
Outline

- Introduction
- CLIQ failure rate study
- Capacitor bank configuration
- Conclusions

CLIQ (Coupling-Loss Induced Quench)



Current change

Magnetic field change

Coupling losses (Heat)

Temperature rise

QUENCH

Introduction

- **Manufactured and successfully tested the first two versions of CLIQ units (2015-2017). The third version, intended to be the final version, under development.**

- **Three CLIQ v1 units tested on an LHC main dipole within the HL-LHC program (2015-2017).**

- **Three CLIQ v2 units successfully qualified (2017) and ready to be used in an extensive R&D program at the SM18 test facilities at CERN. Five CLIQ v2 units to be manufactured by the industry.**

- **A further optimization of parameters is expected in the following months. CLIQ v3 prototype to be manufactured at CERN.**

- **CLIQ v3 is intended to protect the LHC inner triplet magnets following their installation in 2024-25.**

CLIQ failure rate study

Goal: To assess the **appropriate level of redundancy** of the internal CLIQ components.

- **Assessment of the failure rates and failure modes of the CLIQ components:**

Using datasheets, inputs from experts, and Isograph Reliability Workbench (MIL-HDBK)

- **Identify the safety critical failure scenarios and analyze the combinations of failures leading to them:**

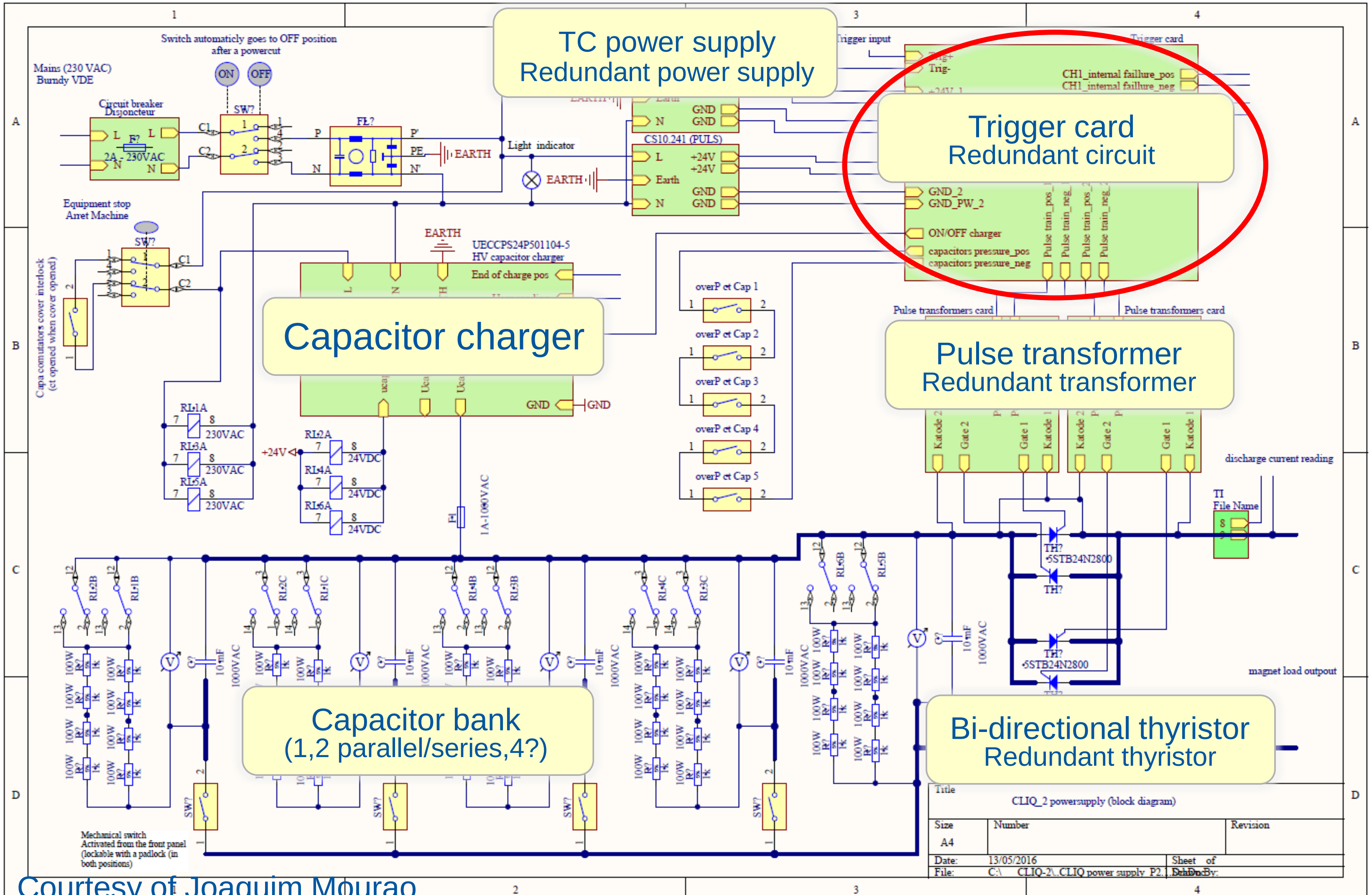
Inputs from previous failure scenarios studies of different CLIQ systems.

- **Study possible components redundancy to minimize the risk**

- **Calculation of failure rates depending on redundancy level of CLIQ components**

CLIQ failure rate study

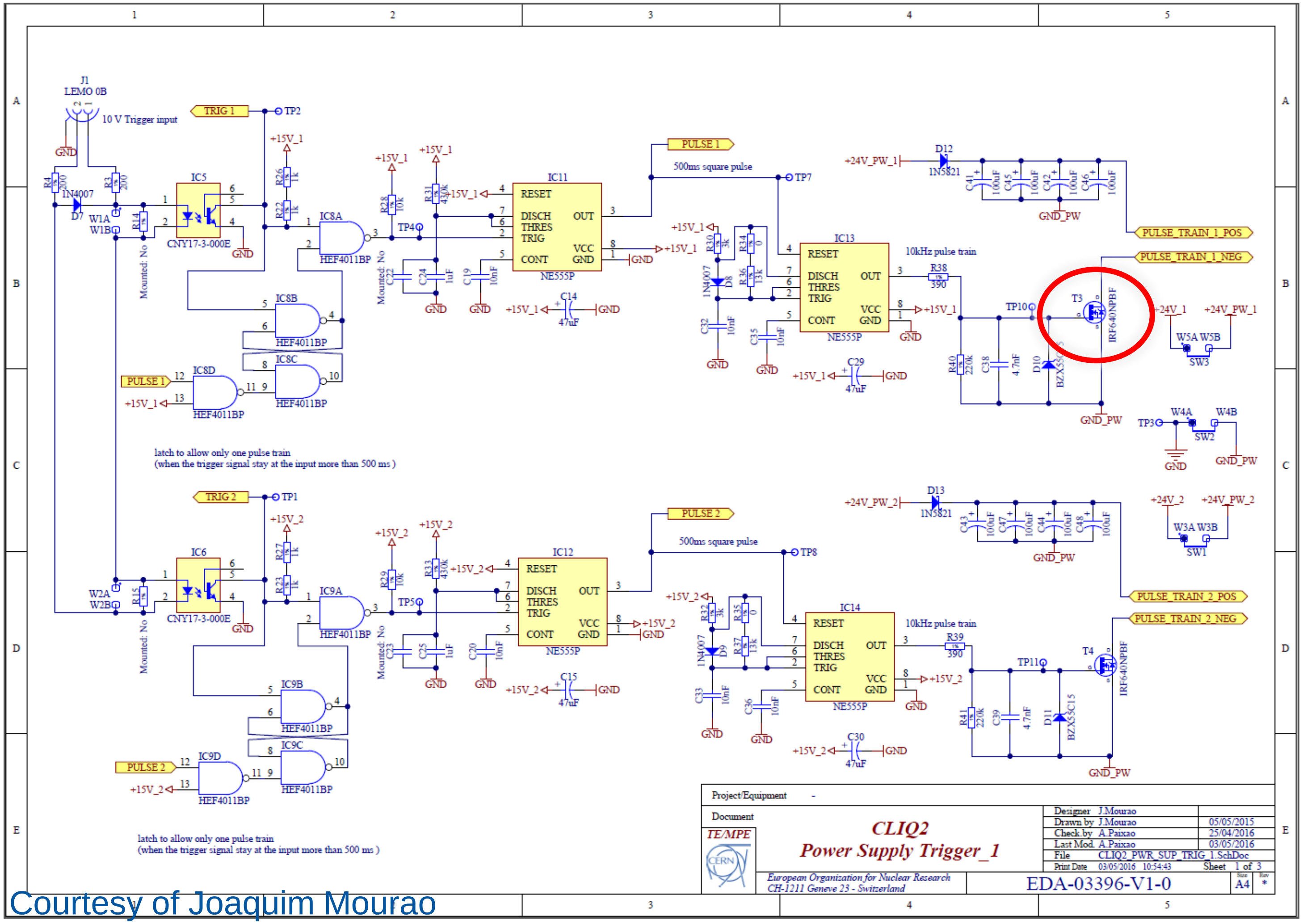
Circuit schematic of the CLIQ v2 unit



Courtesy of Joaquim Mourao

CLIQ failure rate study

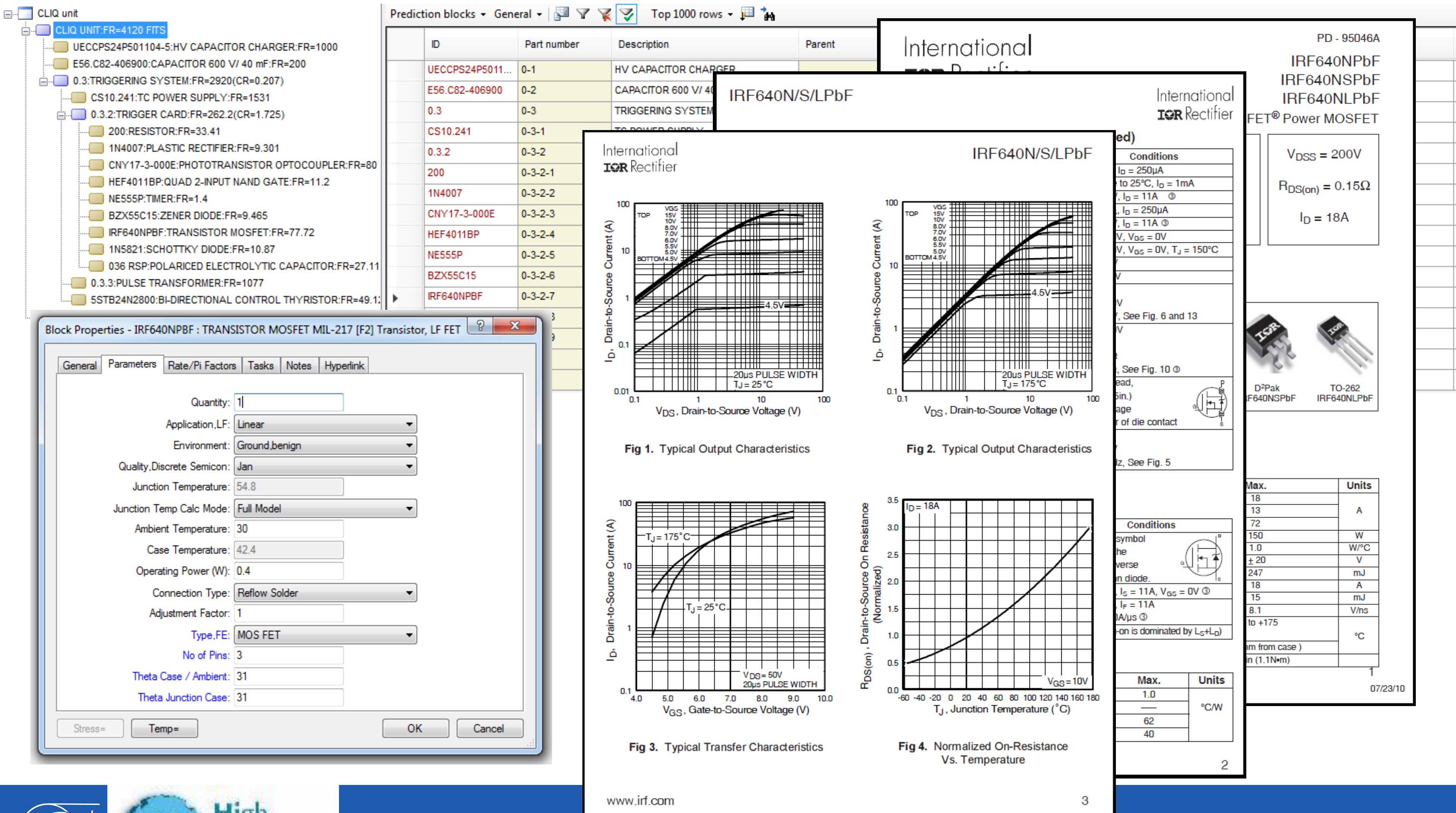
Example of calculation of components failure rates: trigger card



Courtesy of Joaquim Mourao

CLIQ failure rate study

Calculation of failure rates with Isograph Reliability Workbench (MIL-HDBK-217F)

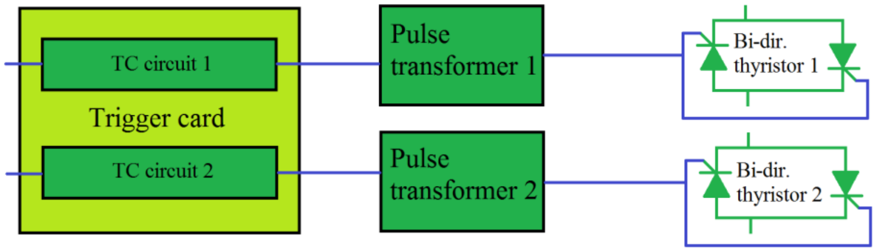


CLIQ failure rate study

Failure rates and failure modes of the CLIQ components

Component	ID	Description	MTBF (years)	Failure rate (FIT= $10^{-9}h^{-1}$)	Failure mode	Mode probability	Mode failure rate (FIT)	FMEA probability factor	Failure rate data source
Capacitor Electronicon 40 mF/500 V	E56.C82-406900	MKP-DC self-healing plastic thin film capacitor for power electronics	570.4	200	> 10 % loss of capacitance	0.8	160	4	Manufacturer data (hotspot 55 ºC) with inputs for the application and mode probabilities from Dr. Volker Geitner, Director of Research and Development of Electronicon.
					Short-circuit	0.2	40	3	
HV capacitor charger	UECCPS24P501104-5	With charging voltage monitoring	114.1	1000	No output	0.52	520	5	Manufacturer data AIT02ZPFC-01NL (max. temp. 100 ºC).
					Incorrect output	0.48	480	5	To be updated: new capacitor charger of reference
Trigger card (Considered 1 TC circuit)		With internal failure signal due to voltage supplied lower than expected	435.4	262	No output	1	262	4	Calculated by components according to MIL-HDBK-217F (environment Ground Benign, fixed, 30 ºC, GB30).
Trigger card power supply Puls	CS10.241	Output 24 V, 10 A DC	74.5	1531	No output	0.52	796.1	5	Manufacturer data according to MIL-HDBK-217F (environment Ground Benign, fixed, 25 ºC, GB25).
					Incorrect output	0.48	734.9	5	
Pulse transformer Socomec		Transformer ratio 2:1	105.9	1077	No output	1	1077	6	Manufacturer data (max. temp. 80 ºC).
Bi-directional control thyristor ABB	5STB 24N2800	Two thyristors integrated into one wafer. Free-floating silicon technology. Blocking voltage 2800 V.	2328.1	49	Open-circuit	0.2	9.8	2	Calculated according to MIL-HDBK-217F (environment Ground Benign, fixed, 30 ºC, GB30) with inputs for the application from manufacturer (Joerg Berner, ABB Customer Support Manager).
					Short-circuit	0.8	39.2	3	

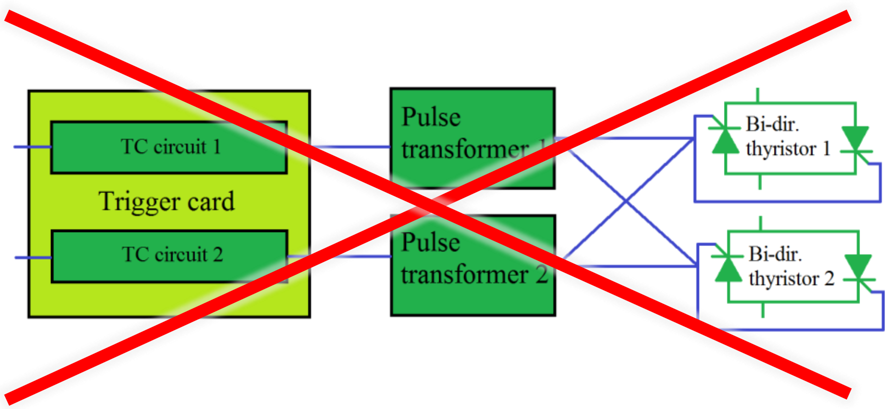
Thyristors, straight Vs. cross connection



$$\left.\begin{aligned}\lambda_{TCf} &= 262\ FIT\\ \lambda_{PTf} &= 1077\ FIT\\ \lambda_{BTf} &= 49\ FIT\end{aligned}\right\} P_{if} = 1 - e^{-\lambda_{if}t}$$

$$P_{notTrigg} = P_{TCf}^2 + P_{PTf}^2 + P_{BTf}^2 + 2P_{TCf}P_{PTf} + 2P_{TCf}P_{BTf} + 2P_{PTf}P_{BTf} = 1 - e^{-\lambda_{notTrigg}t}$$

$$\lambda_{notTrigg} = 16.7\ FIT$$



The very little difference in failure rates doesn't justify the risk of loosing both triggering channels because of a short-circuit from anode to gate.

⇒ Keep the triggering channels independent (straight connection)

$$P_{notTrigg} = P_{TCf}^2 + P_{PTf}^2 + P_{BTf}^2 + 2P_{TCf}P_{PTf} + \underbrace{2P_{TCf}P_{BTf}^2}_{\sim 0} + \underbrace{2P_{PTf}P_{BTf}^2}_{\sim 0} = 1 - e^{-\lambda_{notTrigg}t}$$

$$\lambda_{notTrigg} = 15.6\ FIT$$

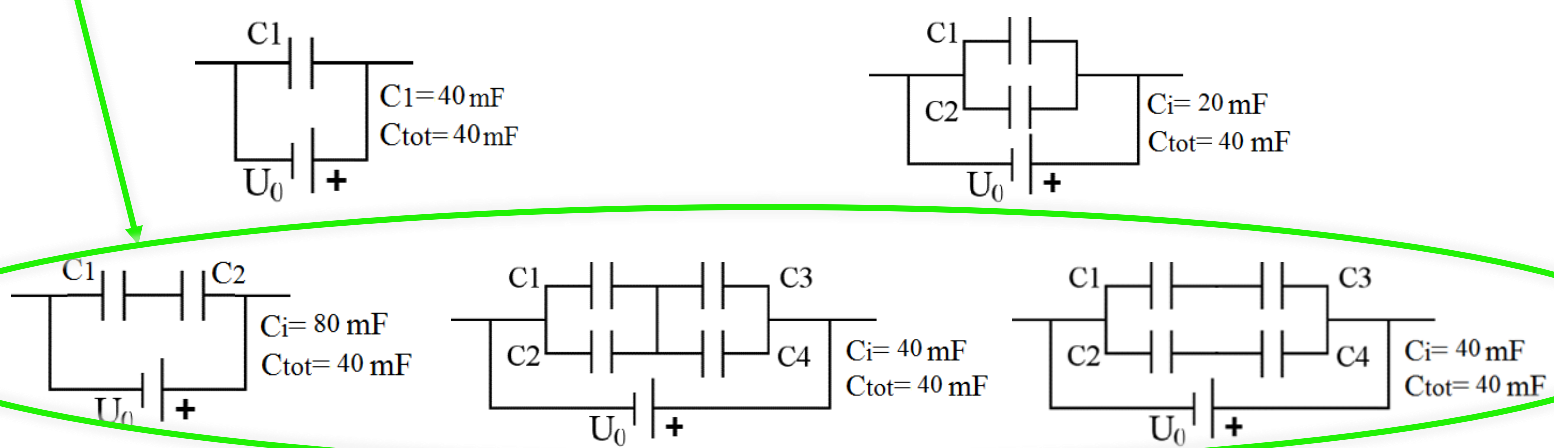
CLIQ failure rate study

Failure scenarios

- Triggering delay of 1 ms of the CLIQ unit
- Spurious triggering of the CLIQ unit
- Not-triggering of the CLIQ unit → Triggering system redundancy
- Non-nominal discharge due to one/several capacitors in open/short circuit (depending on the capacitor bank configuration)
- Short-circuit of the capacitor bank of one CLIQ unit

Safety critical

Capacitor bank redundancy possibilities



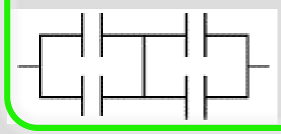
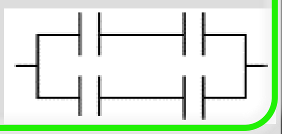
Total CLIQ failure rate and price depending on redundancy level

	Capacitor bank redundancy	Cap. bank short-circuit failure rate (FIT)	Triggering system redundancy	Not-triggering failure rate (FIT)	Total safety critical failure rate (FIT)	Total safety critical MTBF (years)	Price (€)
Hypothetical no redundant CLIQ unit	Single capacitor (600V / 40 mF)	40	Single TC power supply Single TC circuit Single pulse transf. Single bi-direc. Thyristor	2919	2959	38,6	9470
1st Generation of CLIQ units (2015, shipped to FNEAL)	No redundant capacitor bank (2 x 500 V / 40 mF)	80	Single TC power supply Redundant TC circuit Redundant pulse transf. Single bi-direc. Thyristor	1596	1676	68,1	11330
2nd Generation of CLIQ units (2016)	No redundant capacitor bank (5 x 1000 V / 10 mF)	200	Redundant TC power supply Redundant TC circuit Redundant pulse transf. Redundant bi-direc. Thyristor	73	273	417,9	14380
3rd Generation of CLIQ units. Proposal 1	Single capacitor (600 V / 40 mF)	40	Redundant TC power supply Redundant TC circuit Redundant pulse transf. Redundant bi-direc. Thyristor	73	113	1009,5	11530
3rd Generation of CLIQ units. Proposal 2	2 capacitors in series (2 x 600 V / 80 mF)	0,01	Redundant TC power supply Redundant TC circuit Redundant pulse transf. Redundant bi-direc. Thyristor	73	73,01	1562,5	15920
3rd Generation of CLIQ units. Proposal 3	4 capacitors in H or square configuration (4 x 600 V / 40 mF)	0,05	Redundant TC power supply Redundant TC circuit Redundant pulse transf. Redundant bi-direc. Thyristor	73	73,05	1561,6	16440

The series production of the CLIQ units will significantly reduce these estimated prices

Capacitor bank configuration

- Assumption 1: if the short-circuit occurs > 10 minutes before the CLIQ discharge, the rest of capacitors will be charged until their new charging voltage.
- Assumption 2: In case of short-circuit, the rest of capacitors would be able to discharge their energy through the shorted one.

	Failure probability for one capacitor	**Remaining energy** H configuration 	Square config. 	**Failure probability for one capacitor**	**Remaining energy** 2 in series 
Short-circuit (>10 min before discharge)	Low*	$2 * E_{nom}$	$\frac{3}{2} E_{nom}$	$\frac{\text{Low}}{2}$	$2 * E_{nom}$
Short-circuit (just before discharge)	Negligible*	$\frac{E_{nom}}{2}$	$\frac{3}{4} E_{nom}$	$\frac{\text{Negligible}}{2}$	$\frac{E_{nom}}{2}$
Open-circuit (no matter when)	Very low**	$\frac{2}{3} E_{nom}$	$\frac{E_{nom}}{2}$	$\frac{\text{Very low}}{2}$	Not firing

* Probability estimated considering random failures (constant failure rates); capacitors are charged all the time, but they are triggered only ~ once a month. According to experts: the risk $\sim U^2$, it is considered not significant the impact of firing event on the risk of failure.

**Open-circuit only realistically possible in the capacitor connection points. Estimation based on experts opinions.

Conclusions

General:

- **Full redundancy of the triggering system is already implemented in CLIQ v2 and will be used for CLIQ v3** (from the power supply of the trigger card to the bi-directional thyristors). The two **triggering channels are independent. Just one not-triggering failure every 1563 years is expected.**
- **There is not a technological limit for further redundancies or monitoring systems, but a cost increase.**

Capacitor bank configuration for CLIQ v3:

- **Either H or square configurations are recommended for CLIQ v3. CLIQ will fire with partial energy in case of short-circuit or open circuit of one capacitor, and the probability of short-circuit or open-circuit of the whole capacitor bank is negligible.** The series configuration shows lower failure probabilities (factor 2) but will not fire in case of open-circuit of one capacitor.
- **Between H and square configurations, both options show advantages and disadvantages depending on the type of failure. Further risk analysis is on-going to make this choice.**
- Short-circuit of one capacitor can be detected if there is **monitoring charging voltage across every capacitor.** Open-circuit cannot be detected without triggering the system. A maintenance strategy will be defined.

Annex

Safety first

- Equipment stop button stop, mains current breaker, on/off switch
- Interlock triggers when user opens the door for capacitance selection
- Padlocks on the capacitance selectors

  -> The stored energy is dissipated in the resistor bank