Multiphysics Analysis of Power Electronics Phase Module using TRIZ

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Abstract. The present work reflects a complete TRIZ analysis of a power electronics component from a Multiphysics (Electric conduction, Electromagnetic, Thermal, Structural, Signal) point of view, taking into account real-life constraints. The object of analysis and improvement is a phase module, the part connecting the switches to the load in a power electronics converter, in a typical configuration. The project goal is to enhance the overall serviceability, secure or increase performance and reduce cost as well; the notion of performance includes reducing electric losses and thermal load. The usual approaches are virtual prototyping and circuit simulation to define project specifications, reduce inductance influencing the current paths and verify if the copper cross section sustains the current loads, adopting thicker laminations when needed. Neither a systematic nor an innovative approach is usually applied. The analysis presented here will show results of the application of different TRIZ tools, as well as the key learnings.

Keywords: Power Electronics, Phase module, Busbars, Multiphysics approach, TRIZ.

1 Introduction, Project Description and S-Curve Considerations

Power electronics converters are used in all kinds of applications: electric drives to drive motors in industrial installations (fans, compressors, conveyors), solar power generation, wind power generation, transportation, etc. [1], usually installed as interface between the electric utility or any power supply (connected as input) and the loads (connected output). They represent crucial technology enablers for energy saving applications, adjustable speed drives, transportation and energy conservation systems. Their main function consists in shaping the voltage and current waveforms supplied by the input in a suitable fashion, as requested by the output, by means of power switches mostly made of solid state semiconductors. In typical configurations switches and loads are electrically and mechanically connected by means of copper busbars (metallic strips or bars); laminated rectangular busbar technology is widely used in the form of stacks of copper sheets separated by dielectrics and connected to other elements, like power terminals, by means of screws and bushings. This technology offers several advantages over ordinary cabling or use of massive conducting bars: along with good thermal per-

formance and convenient packaging it represents the most effective way to reduce interconnection parasitic inductances. These represent the Achilles heel of fast switching devices due to the over-voltages they induce and their relevance is increasing as power converters evolve towards higher operating frequencies, following the Trend of Increasing Dynamization. Busbars used with phase modules in fact need to be designed so as to maximize the electric current conduction efficiency, help minimize losses while keeping commutation parameters suitable (to avoid commutation over-voltages [2]) and compromise between electrical and thermal requirements.
The best practice approaches in high power electronics busbar design activity are usually circuit simulation to define specifications and prototyping to verify if copper cross section sustains the current loads and reduce the inductance influencing the current paths. *Ad hoc* engineering methods are typically used; the normally adopted solutions consist in increasing the copper cross section of laminations when currents are high and increasing the size of the heat sink or the speed of air/coolant when heat removal is insufficient.
Another aspect, fundamental for the production stage and the whole electric drive lifetime is serviceability, formally defined as the measure of and the set of the features that support the ease and speed of which maintenance (both corrective and preventive) can be conducted on a system [3], embracing all the practices needed to achieve the required availability. It also includes the needed tools, personnel qualification, time to mount/dismount and part count.
A TRIZ project was thus set up, aimed to improve the overall serviceability of a so-called Phase Module, that is, a subsystem of the power converter delivering voltage and current to one phase of an output load shown in Fig. 1:

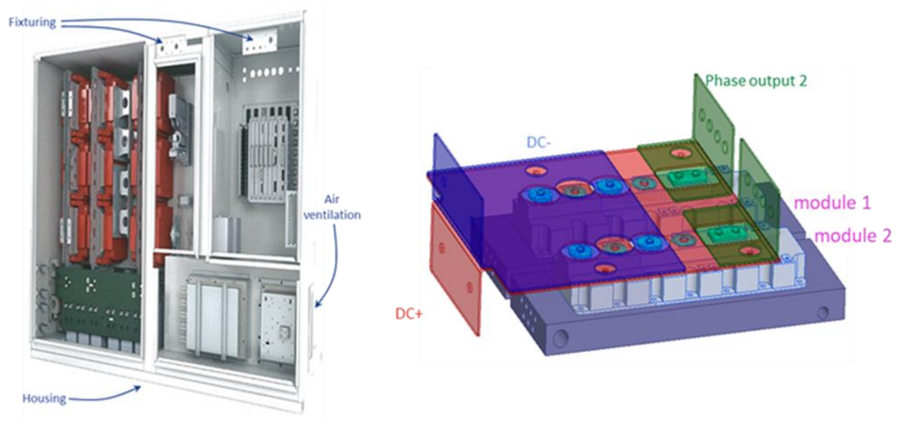


Fig. 1. Power Converter cabinet (left) and detail of a typical Phase Module (right).

For a better description of the electrical subsystem, a circuit diagram of a 3-phase two-level inverter based on IGBTs and diodes is depicted in Figure 2. An important detail is that the capacitance needed for commutation, is in our case the DC-link capacitor external to the phase module. Other components of the phase module are the drivers for the gate signals, the heatsink and the housing. Fig 3 shows the voltage overshoot during current switch off, which represents the major phenomena to be taken into account during the design activity.

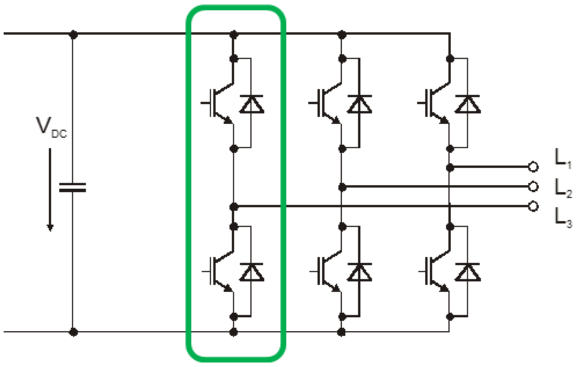


Fig. 2. Power Converter circuit diagram with Phase Module (in green)

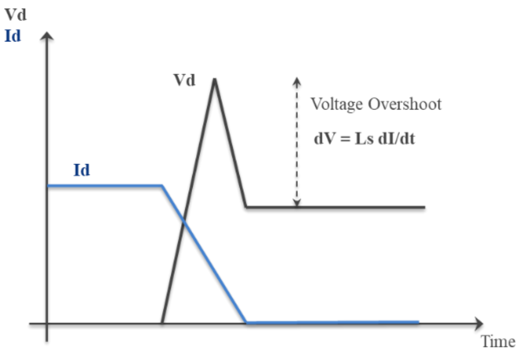


Fig. 3. Voltage overshoot due to busbar commutation inductance

The project goal, defined as Phase Module serviceability improvement, is rather broad; a thorough TRIZ analysis is thus required, encompassing all the observable and relevant physical phenomena occurring during system operation. From the physical point of view, the examined Engineering System (ES) can be seen as a Multiphysics-multiport system, being the relevant phenomena ascribable to the following physical domains:

- Electric conduction
- Electromagnetic low frequency (stray magnetic field, inductive coupling)
- Electromagnetic radiation
- Thermal
- Structural

- Signal

Paragraph 1.1 and 1.2 describe in detail the project initial definition.

1.1 Project Description

Object for analysis/improvement (Engineering System): Phase Module, the part connecting the switches to a phase of the load in a power electronics converter

Project goal: It is necessary to increase the overall serviceability of the Phase Module, while increasing performance (reducing electric losses and managing the unwanted thermal load) as well as reducing cost.

Main function: alternatively connect the load lamination to the DC+ and DC- laminations (switch between supply phases in a Pulse Width Modulation manner)

Main Parameters of Values (MPVs):
MPV 1: Deliver Voltage and Current to one phase of an output load
MPV 2: Minimize commutation over-voltages

Constraints: Material properties, space limitations

Restriction and Limitations:

- Phase Module should fit in the assigned envelope
- Phase Module should be mechanically stiff
- Signal system not to be disturbed
- Temperature below 125°C at semiconductor junction
- Part Weight below 25 kg for single person manual mounting

1.2 S-Curve Analysis

Figure 4 shows the results of the express S-Curve Analysis [3]:

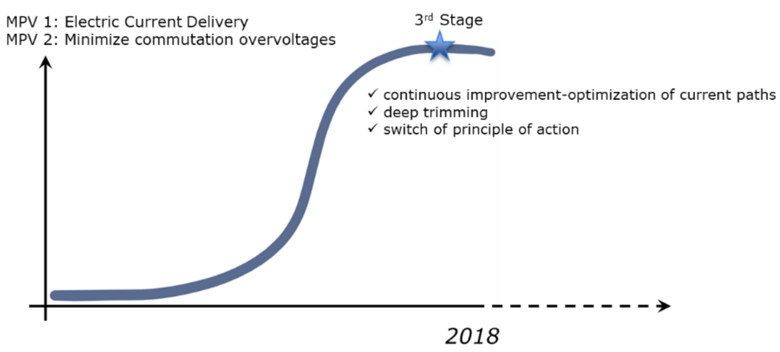


Fig.4. Express S-Curve Analysis.

with respect to the MPVs we can consider that the System Phase Module has reached maturity, that is, the 3rd stage on its S-Curve; the Engineering System is reaching its development limits; further progress is inhibited by its complexity. Modern TRIZ methodology recommends to pursue a continuous improvement and optimization of the design layout; for more disruptive solutions it is advisable to try deep trimming and switch the principle of operation, that is, research how to deliver the same main function- alternatively connect the load lamination to the DC+ and DC- laminations- taking advantage of another engineering system, introducing a new technology, or even physical law; for a more radical approach it could be investigated which other physical effects allow to deliver electric power to a 3-phase load.

2 Component and Function Analysis

For the considered ES the assembly is quite complex, with many different components and several interactions, thus it was chosen not to focus on the control and electromagnetic radiation aspects; the impact of the control subsystem parts on serviceability will be downplayed here; electromagnetic interference becomes an issue when:

- the system operates at high switching frequency, and/or fast switching flanks are present (e.g. the new Silicon-Carbide (SiC) based power switches)
- the electromagnetic radiation wavelength is comparable with the system dimension

Other components like the DC power supply (modeled as Vdc in Fig. 2) and cooling subsystem elements (e.g. fan) belong to the super-system and have been neglected in the following models.
In view of the above the construction of the function model focused solely on electric current conduction, mechanical-structural aspects and thermal behavior, as depicted in Figures 5, 6 and respectively, for simplicity and model manageability. In all graph models, system components are drawn as green boxes, super-system components as grey boxes and the Target component is highlighted in cyan. The Function Model for the Electric Conduction and Mechanical-Structural physical domains is shown in a compact version in Fig 5., where the busbar subsystem has been modeled as a compound object, including conductive and insulating layers, and potentially isolated bushings for supporting the busbar: this approach can be advantageous from a system perspective since it allows a hierarchical view, and allows to identify already three problematic spots. Figure 6 reports the same Function Model, with an exploded view of the busbar. The added dotted lines represent an insufficient useful interaction between the busbar components (conducting and isolating laminations) and the electric current (depicted twice with an * to ease the graph's readability) should interpreted not as a failure mode, but as a strategical need to improve the efficiency and serviceability of the system.

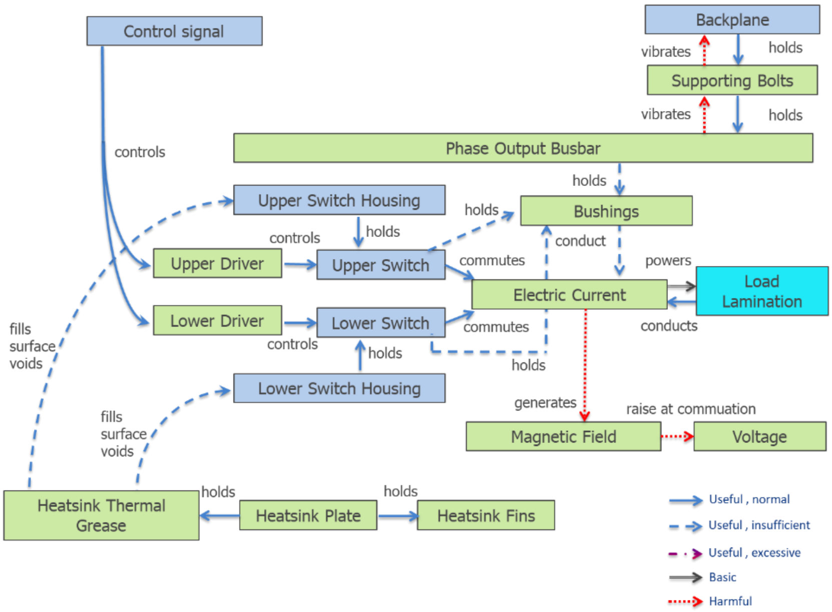


Fig. 5. Phase Module Function Analysis: Electric Conduction and Mechanical-Structural Physical Domains: busbar as a compound object

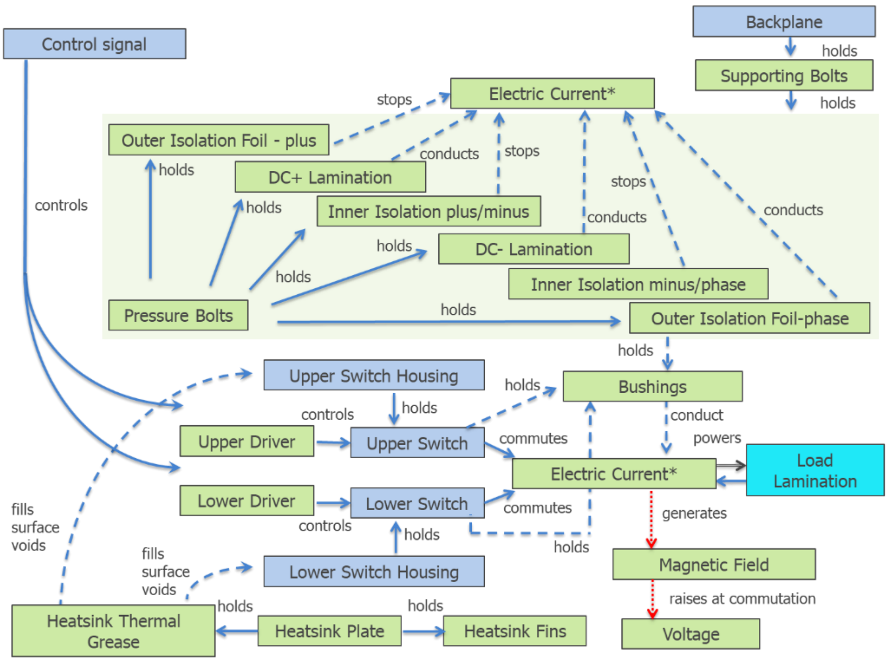


Fig. 6. Phase Module Function Analysis: Electric Conduction and Mechanical-Structural Physical Domains: busbar exploded view; same legend as in Fig. 5

The thermal function model has been drawn separately in Fig.7, in order to ease readability. The thermal model focused on the function/interaction "heats" between components, rated as harmful in case of electrically active components since higher temperature degrade the electrical performance; in all other cases, since electrically active components in turn heat all the surrounding components via convection and conduction, the same function/interaction "heats" has been rated as useful, insufficient, to capture the fact that allowing the heat flow towards ambient air contributes to the cooling of the above mentioned active systems. In this way there was no need to repeat a dual functional model for the cooling.

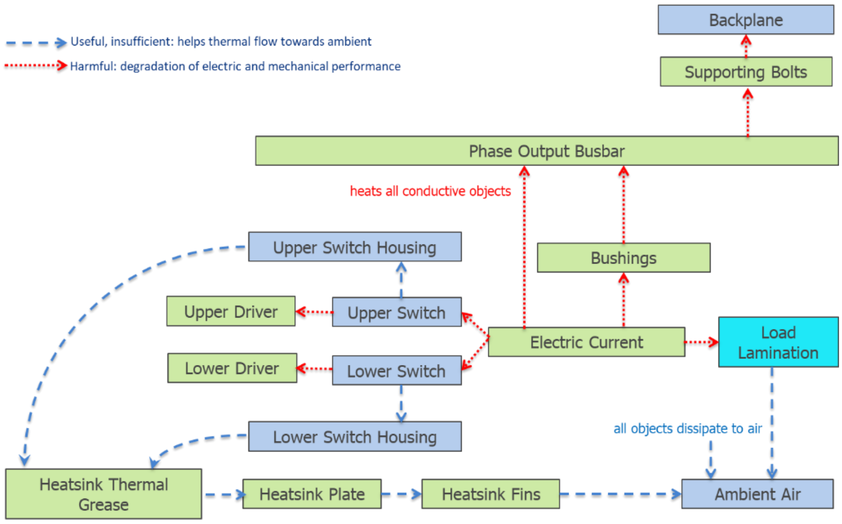


Fig. 7. Phase Module Function Analysis: detail of heat transfer phenomena.

Both the identified harmful and inadequate functions refer to the insufficient heat transfer due to poor conductive and convective performance, localized in correspondence of the components thermal grease, air and coolant. Still this Function Model does not offer an accurate picture, so for a better description and comprehension of the overall thermal performance, a Flow Analysis is advisable, as described in Paragraph 3.

3 Flow Analysis and its relevance

The Flow Analysis is an analytical tool that identifies Disadvantages in flows of energy, substances and Information for an Engineering System [3]. In the examined system by means of the Flow Partition Analysis three flows can be identified:

- Electric conduction (useful flow)
- Air (useful flow)
- Heat (harmful flow)

The flow Passage of air and thus heat is restricted due to multiple impediment zones, presenting disadvantages that restrict system performance and impede serviceability. Tables 1 and 2 show the results of the Flow analysis performed for the heat flow; Table 1 captures the main heat flow, from the power switches through their baseplate and into the cooling subsystem. The heat flow mechanism is the same for both upper and lower switch and has thus been modeled only once; the interaction between the fin structure and the air flow in the channels is rather complex, since both laminar and turbulent flows may occur; to capture this peculiar situation, specific to this flow, an additional entry has been listed, that is, the Fin-Air- Interface. Table 2 represents the heat flow from the power switches to air from the power switch electrical terminals into the bus-bar and across the insulation subsystem. This is a secondary heat path. Each component has been classified (column 2 for both Tables); the considered TRIZ tools have been listed (column 3), as well as the preliminary ideas (column 4); it has been also recorded if the concept had already been explored (column 5) during the project regular activity. The identified problematic locations have been addressed with a proper contradiction formulation, explained in Paragraph 4.

Table 1. Heat flow through the cooling subsystem.

Flow	Component	Type	TRIZ	Recommendation/Ideas	Explored (Y/N)
Heat	Switch (IGBT)	Source			
	Thermal grease	Bottleneck	PC, IP35. Parameter Changes	redesign themal interface/ use alternatives to thermal grease (pads explored)	Y
	Heat sink	Grey Zone	IP35. Parameter Changes IP36. Phase Transitions	Decrease its thermal resistance using different geometries/materials or heatpipes	Y
	Fins	High channel resistance	IP35. Parameter Changes	optimize fin geometry (number/spacing/shape)	Y
	Fin-Air- Interface	Large number of flow transformations		Connect fins to another surface which is exposed to air	N
	Air	Stagnant zone	PC1	Move air	Inventive Problem

Table 2. Heat flow from the power switches to air through the insulation subsystem

Flow	Component	Type	TRIZ	Recommendation	Explored (Y/N)
Heat	Switch (IGBT)	Source			
	Bolts	High channel resistance	PC1	Alternative fixing system	N
	Lamination	Stagnant zone	IP31. Porous materials	Have holes in the bus-bar for air flow	N, EC1: Inventive Problem
	Insulation	Bottleneck/ High channel resistance	Trend of Flow Enhancement	1a: Improve useful flows: increase conductivity	Have a parallel system of conduction and convection
	Air	Stagnant zone	PC2, PC3	Move air	

4 Contradiction Formulation

Table 3 presents some of the disadvantages emerged during the problem identification stage (Function Analysis and Flow Analysis); they were reformulated as Physical Contradictions, more effective when it is necessary to solve problems at a fundamental level, such as in mature technologies. When applicable, also the used Inventive Principles (IPs) have been listed.

Table 3. Physical Contradictions.

	Physical Contradiction mech-1	**Physical Contradiction mech-2**	**Physical Contradiction el-1**
physical domain	mechanical	mechanical	electric current conduction
component	supporting bolts	supporting bolts	power switch
should be	mounted	rigid	low leakage current, high blocking voltage
In order to	to fix Phase Output to backplane	perform support function	reduce losses and cooling requirements
BUT			
component	supporting bolts	supporting bolts	power switch
should be not	part of the system	flexible	high current, low blocking voltage
In order to	lower part count, improve serviceability	avoid vibrations	improve system efficiency
Recommendation	satisfy contradictory demands	satisfy contradictory demands	separation in space, segmentation
Used IPs	28	28	1,2,7,35
	Physical Contradiction th-1	**Physical Contradiction th-2**	**Physical Contradiction th-3**
physical domain	thermal	thermal	thermal
component	heatsink thermal grease	air	air
should be	conductive	moved (forced air cooling)	liquid (at heatsink fins)
In order to	improve heat conduction	improve cooling efficiency	have liquid cooling (more efficient)
BUT			
component	heatsink thermal grease	air	air
should be not	oily	not forced to be moved	gaseous
In order to	fill the voids between touching surfaces	lower part count, improve serviceability	lower part count, improve serviceability
Recommendation	separation in relationship, satisfy, bypassing	separation in time, relationship	separation in space, relationship
Used IPs		3, 19, 31, 33	

5 Substance-Field Models

The mechanical aspects reflecting the serviceability did not emerge fully clearly during the analysis stage and were addressed by one Physical Contradiction only. It was observed that such Disadvantages are more effectively captured by means of a Substance-Field modelling. Tables 4 and 5 present some options and the corresponding models of solutions.

Table 4. Substance-Field Model: insufficient cooling.

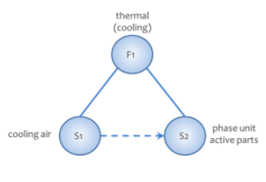
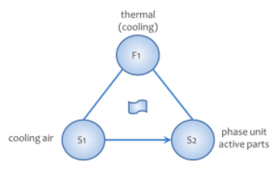
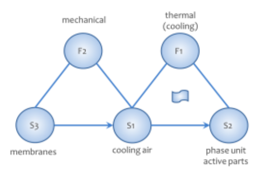
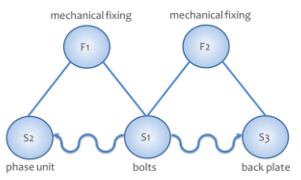
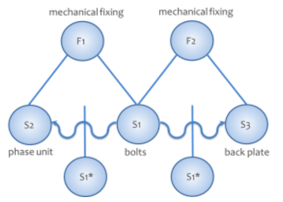
Su-F Model of the Problem	**Su-F Model of Solution 1**	**Su-F Model of Solution 2**
Class 2: Insufficient Interaction	SIS 2.2.4: Dynamization	SIS 2.2. +2.2.4: Chain+Dynamization
		

Table 5. Substance-Field Model: mechanical fixing.

Su-F Model of the Problem	**Su-F Model of Solution 1**
Class 1: Harmful Interaction	SIS 1.1.2. + IP17 Another Dimension
	

6 Idea Down-Selection and Development Paths

During the Problem-Solving phase about 50 ideas have been generated; they equally addressed the three main physical domains considered separately, respectively electrical, thermal and mechanical.
The TRIZ theory offers virtually no tools to manage Idea Down-selection. On the other hand, TRIZ sessions usually produce a rather large output. In this project a Pugh Matrix was adopted for the idea evaluation and down-selection process, listing as decision factors: Cost (ideally no engineering cost), Ease of manufacture, Adaptability to current system, Serviceability improvement, Effect on Cooling, Realization potential. The solutions suggest system changes aimed both at short-term modifications and long-term more disruptive interventions; the scope of the project required a conservative approach, so the most promising, presented in the following Subparagraphs 6.1 and 6.2., address rather short-term improvement actions.

6.1 Electrical solution: parallel switches

This solution emerges when solving the Physical Contradiction el-1 in Table 3. The power switch selection during the converter design is a trade-off between switching losses and conduction losses; using two types of switches in parallel, with different electrical properties, such as described in Figure 8 (where E_{off} represents the Turn Off switching loss, while V_{ce} is the conduction collector-emitter voltage.), allows a design solution where a type 2 switch (e.g. a fast SiC switch) takes over the commutation function, while a type 1 switch (e.g. bipolar) actually implements the electric conduction function. In this way switching and conducting losses can be lowered, with less requirement on the cooling systems and consequently better serviceability.

Fig. 8. Electrical properties of power switches.

6.2 Mechanical solution: stack vertically

This solution embodies the Standard Inventive Solution depicted in Table 5 and envisions that the Phase Module is encapsulated in boxes stacked on top of each other; the busbar implements the electric connection only and fixing bolts to the back plane are no longer required: the structural function is taken over by the box arrangement, as shown in Fig. 9.

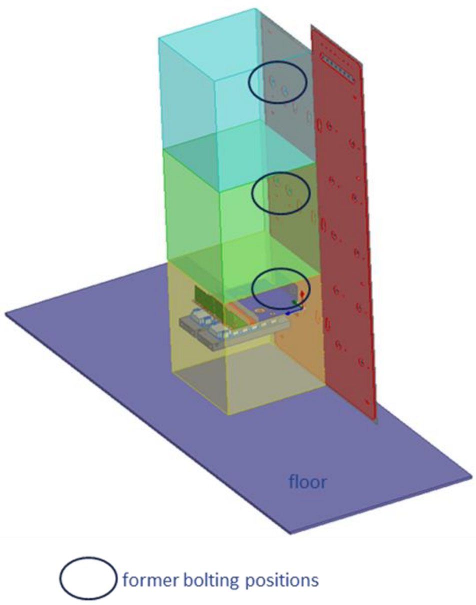


Fig. 9. Phase Unit arrangement with stacked box

7 Key Learnings and Conclusions

TRIZ offers a unique opportunity for the systematic analysis of complex systems, very useful for matured technologies, exposing several improvement opportunities; the prioritization of the solution outcomes constitutes an extremely useful long-term research and development planning guideline.
Multiphysics systems pose unique challenges so an approach that can capture the interdependencies of the different physical domains is highly desirable. For high power electronics systems Flow Analysis resulted in a very powerful tool even if for the present investigation the three domains were kept separated for simplicity reasons.
The presented analysis of a typical power electronics phase module showed how:

- Functional analysis for a Multiphysics system is rather complex and even the graphical function model poses readability issues
- Flow analysis keeps a holistic overview, select components relevant to each physical domain and is more manageable; it is highly recommendable to capture thermal phenomena, for which it proved to be preferable to Functional Analysis
- Electric circuit topology and all aspects related to spatial distribution are difficult to capture by the functional analysis
- Serviceability of a typical Phase Module is mostly influenced by the mechanical/spatial distribution and thermal aspects, as identified by the functional and flow analysis
- Optimization of the system follows the trend of Flow Enhancement and needs to embrace all aspects captured by the sub-trends [3]:
  - 1a: Improve useful flows: increase conductivity
  - 1b: Improve useful flows: improve flow utilization and so efficiency
  - 2a: reduce conductivity of the harmful/incidental flows
  - 2b: reduce impact of harmful flows

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