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Multidisciplinary Design of Power Inverter: Case Study

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Abstract This paper considers multi-disciplinary designing through a case study in which a medium voltage inverter is designed in collaborative work by departments of Energy Technology, Electrical Engineering and Mechanical Engineering at Lappeenranta University of Technology. Design will aim at high levels of optimization on aspects of electrical, thermal and mechanical designs and pursue a more compact and efficient end design. Successfulness of the multi-domain will be examined through viewpoints formed by former knowledge of challenges in multidisciplinary design an evaluated accordingly. A high demand for cross trained professionals in multi-domain design cases is also implicated by the case study and as a result a new model for tasking and result-reviewing in such cases is proposed.

1. Introduction

Cooling of electronics is and has been a critical matter in product design since semiconductors were applied for the first time. Almost all electrical devices in the modern world depend on the switching and current-blocking capabilities of semiconductors, but in return they also suffer from the maximum temperature restrictions set by them. Development in the field of semiconductor-based electronics – such as microprocessors and high power switching modules – has led to devices with small form factor and very high power densities. In terms of traditional heat transfer it means that developing of matching cooling and electronics – size, and efficiency-wise – is coming more and more difficult over time. (Jiang 2013, p. 1-5)
This study is mostly limited to cover views on intelligent design of power electronics based on three major reasons:

1. Basically all electricity that is used is also processed with power electronics at some point between generation and application, which directly affects the overall efficiency.
2. High efficiency and robust power electronics are needed in many fields, such as smart electricity grids, renewable energy systems, power supplies in information and communication technologies and in electrical vehicle business.

3. Design of power electronics utilizes expertise across different professions thus generating possibility for multidisciplinary optimization and intelligent design. (Popovic-Gerber 2012, p. 1-2)

For this case study, a 490 kVA medium voltage inverter with line-to-line voltage of 1420 V and DC link-voltage of 2000 V would be designed – and manufactured to some extent. Design process would cover electrical design, thermal design and mechanical design of inverter components and a suitable cabinet. The ultimate goals of this study are to analyze the capabilities of multidisciplinary design and development in creation of new products and to produce a robust and efficiently packed inverter, suitable for photovoltaic- and wind-power applications.

Usually grid-connected inverters in photovoltaic systems can achieve relatively high efficiencies of over 90 % when the load is more than 15 % of rated power (Notton 2010, p. 545). With the nominal power intended for the inverter, and with assumption of 95 % efficiency, the device would create over 24 kW of waste heat. Based on that approximation, challenges in the cooling of the device were also to be expected as the inverter would be enclosed in an airtight cabinet for extra shielding against elements.

Collaborating work on multidisciplinary design task can be rewarding as it enables the team to accomplish things which wouldn't be doable within individual professions. It also includes the educational aspect which results from mutual motivation on specific subject and the sharing of viewpoints. Collaborating work comes with some challenges though, as crossing over between design-domains can create misunderstandings caused by differing objectives, beliefs, and education. (Bernard 2008 p. 145, 146)

2. Planning and Reviewing of the Design Process

The generic approach of VDI Guideline 2221 presented in figure 1 will be followed closely in the case study. The inverter can be thought as a new product for which the VDI guideline should be very suitable (Pahl 2007, p. 19). To ensure passage of information, scheduled meetings and debriefings would be held.

Efficiency of the multidisciplinary design will be viewed through empirical observations during and after the design process. These observations will then define the successfulness of the design task as whole. Under special observation would be factors such as: meeting of the deadlines, realization of the VDI guideline, implementation of state of the art technology and fulfillment of the original goals of robustness and multidiscipline optimization.

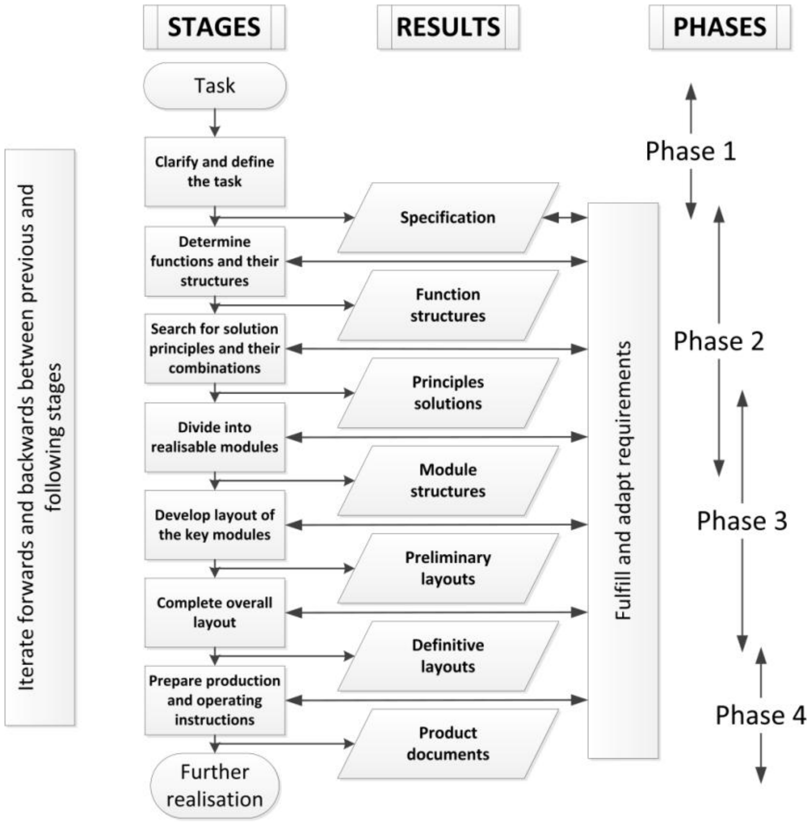

Figure 1. VDI guideline 2221 in a graphic form. This general approach will form the outline for design process of the case study. (Pahl 2007, p. 19)

Design process is led by professors from every contributing profession, but the teams of every department consist of people with varying amount of education and practical knowledge due to fact that teams were formed from different levels of education from students of technology to the PhD’s. This is taken into account when reviewing the performance of the whole team – as VDI guideline was composed by design methodologists and very experienced designers (Pahl 2007, p. 18). Due to strong guidance from industry-seasoned professors – the general experience and performance can be estimated to be on par with average industrial design teams.

3. Multi-Disciplinary Phenomena and Results of the Case Study

Difficulties in multidisciplinary design process can be roughly divided in three categories. Categorization of these challenges is based on what induces the possibility for misunderstandings or errors in design.

1. Difficulties in finding common terminology in design.
2. Inherent difficulties caused by many contributing stakeholders.
3. Difficulties caused by the multi-domain operation itself.
   (Tomiyama 2007, p. 185)

Difficulty categories 1 and 2 can also be named as misunderstanding in semantic layer and pragmatic layer respectively (Bernard 2008, p. 149). All of the mentioned forms of cross-domain difficulties can be found in the design process of the case study.

Misunderstandings in the semantic layer can be caused by unclear expressions as well as use of complex jargon. In the case study, this manifested in many situations – mostly as losing important factors in highly technical and domain-specific debriefings in the team-meetings. Effects of many contributing stakeholders could be seen in the pragmatic layer of misunderstandings when conflicted interest or profession-caused-biasing created false interpretations on subjects such as dimensioning of water cooling pipelines or EMC-protection. Some problems caused by multi-domain operation itself also appeared when conflict between robust enclosing and efficient yet simplistic cooling emerged. This was due to need for large heat transfer areas partly because of the high thermal resistance of a robust enclosing.

Another difficulty – purely related to simultaneous multi-domain development – noticed was that formation of even a rudimentary specification for cooling seemed arbitrary until the electrical components for the device were known. Dependencies between design areas also led to uneven workloads between designing sub-teams and deadlines, which slowed down the whole process. Due to delays, some iteration loops needed to be hurried and so it can be said that execution of the VDI guideline also suffered.

Application of state-of-art technologies was considered for cooling but with the given time span and the need for excessive knowledge on various fields of study to utilize the flow boiling in cooling, a decision for designing of a compact and effective water cooling was made. Utilizing of state-of-art technology may have also contradicted with the original goal of robustness due to inherent instabilities of boiling heat transfer (Suzuki 2011, p.127).

Despite the multiple difficulties during the design process, the finalized designs were considered compact with the approximate power density of 1.3 kW/dm^3. Design could also be described as robust with zero moving parts inside the ingress protected (IP67) inverter enclosure.

4. Discussion on findings and development of multidisciplinary design

General difficulties in multi-domain collaboration in research and design which were present in the conducted case study are recognized by the science community (Bernard 2008, p. 146). Some of the difficulties considering communication between professions could be blamed on the general lack of practical experience of the design team. But if personal experience and formation of biased views are considered to be linked, then that same lack of experience could be considered beneficial when attending in multi-discipline design cases.

Most of the difficulties and problems mentioned in literature and found in the conducted study seem to culminate onto cross-scientific communication and deeper understanding of multiple professions. The important role of the cross trained inter group stars seemed to be passing from participant to another corresponding to the subject under discussion. Due to the changing roles, also the terminology and reasonability of designs changed over time.

A practical example of the necessity of cross-functional expertise can be found in the electrical component selection of the case-study equipment. For the electricity conversion process in the inverter, Insulated-Gate Bipolar Transistors (IGBT) are needed. These components have several model-, and manufacturer specific electrical- and thermal properties. IGBTs are also the main waste heat source of the inverter, which makes the differences in thermal properties very significant.

Difference in IGBT overall thermal resistance from the semiconducting material to heat sink between manufacturers can be for example 0.0450 K/W, which means that to keep the component from overheating when cooling fluid temperature is 20 °C and waste heat flow is 1000 W, the component with higher thermal resistance should be equipped with approximately three times more powerful cooling system (Semikron 2010, p. 1-2.; Infineon 2013, p.2). In terms of design, this means one of three things:

1. Up to three times larger heat transfer area needed in the heatsinks.
2. Increase in the the fluid flow speed in heat-sinks – which may lead to more premature wear, and possibly lower overall efficiency – for compensation of cooling power.
3. Lower IGBT operation current or switching frequency to reduce waste heat and to meet the thermal design point.

When covering all the aspects, selection of suitable components and designing of an inverter thereby requires vast knowledge of not only electrical properties needed, but also knowledge of material physics, heat transfer and even chemistry. Due to this entanglement of electrical, thermal and mechanical designs – instead of one technical decision, the designer could be making a decision which spans over all design domains. So when comparing to figure 1, it can be seen that most of the difficulties occur during design process phases 1 and 2, which consist mostly of discussion on the task, target functions, and their realization methods.

These kinds of design tasks raise a question, would it be economical to train people to work as highly cross-functional liaisons between practices? Proposed model of communication roles that emerge in design situations by Sonnewald (1996), suggests that role “Intergroup star” handles the communication consisting of discussion of results, failures and plan alterations with other “intergroup stars”. In the light of the results from the case study conducted in this paper, it would seem that high level of multi-domain education of these “intergroup stars” could lead in better design-team-performance through improvement in communication quality, and deeper understanding of the co-dependencies of design tasking; these two could also induce enhanced decision making.

If the tasking of sub-teams was done in an agreement by the cross-trained liaisons, a higher degree of freedom might be possible to preserve between design domains, which in return might encourage innovations and use of state of the art technologies to resolve design problems. This would be possible through the “intergroup star”-teams’ capability to break down the design task into slightly overlapping pieces combined with mandatory initial values, instead of traditional way of passing highly refined technical details and demands between design-domains. Proposed model for utilizing the cross trained task force is presented in the figure 2.

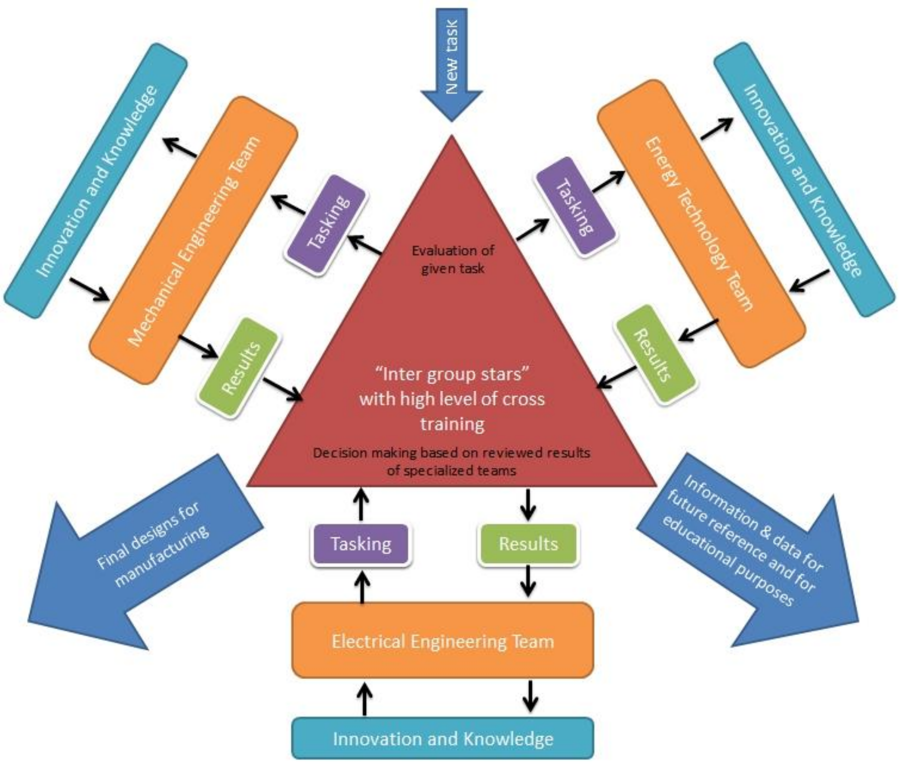

Figure 2. Proposed utilization model for the group of cross trained “inter group stars”.

Main point of the proposed model is high level of communication between inter group stars, and efficient tasking that follows. Logical distance between innovations and initial tasking also shortens, as technical challenges are presented to different sub-teams in their original form instead of as interpretations of other sub-teams. One major advantage of cross trained liaisons could also be their ability to mutually educate and debrief the specialized teams after each project. Main disadvantage of the proposed model may be the availability of cross trained professionals as well as the probable high cost of maintaining such team during design tasks involving only one domain.

5. Conclusions

Multidisciplinary design environment enables development from many aspects to happen in a single product generation. On the other hand, simultaneous development on multiple domains is known to be prone to misunderstandings caused by various reasons. A case study was conducted to examine both, possibilities and limitations of multidiscipline design task, and hypothesis considering challenges focusing on communication and communication related difficulties was confirmed. For development purposes, a new model utilizing highly cross-trained liaisons between designing sub-teams was introduced.
Proposed model was based on empirical observations regarding the challenges faced in design process, and due to the high amount of challenges caused by communication difficulties. Specialized cross-trained task force was seen as straight forward solution to communication problems, and also as a potent motivator for multi-discipline innovator. In continuous multi-disciplinary work the intergroup stars with cross training was thought to be efficient but feasibility of such team in practice was left to be determined.

References

Bernard, A., & Tichkiewitch, S. (Eds.). 2008. *Methods and tools for effective knowledge life-cycle-management*. Springer.

Infineon. 2013. *Technical Information* FF450R17IE4. [Online document]. Available at: https://www.infineon.com/dgdl/ds_ff450r17ie4_3_1_de-en.pdf?folderId=db3a304412b407950112b4095b0601e3&fileId=db3a30431ff98815012023af4c1b5a9f

Jiang, G., Diao, L., & Kuang, K. 2013. *Advanced thermal management materials*. Springer.

Notton, G., Lazarov, V., & Stoyanov, L. 2010. Optimal sizing of a grid-connected PV system for various PV module technologies and inclinations, inverter efficiency characteristics and locations. *Renewable Energy*, *35*(2), 541-554.

Pahl, G. 2007. *Engineering design: a systematic approach* (Vol. 157). K. Wallace, & L. Blessing (Eds.). Springer.

Popovic-Gerber, J., Oliver, J. A., Cordero, N., Harder, T., Cobos, J. A., Hayes, M., ... & Prem, E. 2012. Power electronics enabling efficient energy usage: Energy savings potential and technological challenges. *Power Electronics, IEEE Transactions on*, *27*(5), 2338-2353.

Sonnenwald, D. H. 1996. Communication roles that support collaboration during the design process. *Design studies*, *17*(3), 277-301.

Suzuki, K., Yuki, K., & Mochizuki, M. 2011. Application of Boiling Heat Transfer to High Heat Flux Cooling Technology in Power Electronics. In *Proceedings of the International Conference on Electronics Packaging, CD-ROM*.

Semikron. 2010. *SKM 400GB176D*. [Online document]. Available at: http://www.semikron.com/products/data/cur/assets/SKM400GB176D_22890710.pdf

Tomiyama, T., D'Amelio, V., Urbanic, J., & ElMaraghy, W. 2007. Complexity of multi-disciplinary design. *CIRP Annals-Manufacturing Technology*, *56*(1), 185-188.