

Multi-objective Optimal Dimensioning of Modular Power Converters



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ABSTRACT

This master thesis was carried out at Lund University in collaboration with the European Spallation Source (ESS). It brings up the question of whether it's possible to find an optimal solution for complex power electronic topologies, using a well formulated global optimization methodology.

The commercially available software tool MATLAB was adopted for these studies, including its own toolbox for optimization. These tools and associated solvers will be described for the optimal design of two different problems:- a power inductor and a multilevel DC/DC power converter. In both cases, the objective function consists of the sum of the capital costs (price of the systems in question) and of the long term operating costs (power losses and maintenance costs). A set of constraints to which the design should comply with is also defined for each case and these will comprise parameters like maximum volume of the system, minimal output performance (value of inductance, maximal saturation field density, maximal current density for the first example or output voltage ripple, volume for the second example), etc.

The methodology consists of five steps, the first one is to describe the problem to be optimized. In the second step all the data and information needed to give an accurate view of the problem is to be collected. The third step contains a description of the problem with an objective function that should be optimized. The fourth step corresponds to the definition of the boundaries or constraints. Finally, the fifth step consists on the evaluation of the obtained results

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CONTENTS

1	INTRODUCTION	7
1.1	Background	7
1.2	Problem and goal	7
1.3	Limitations	8
1.4	Approach	8
i	OPTIMIZATION THEORY	9
2	OPTIMIZATION	10
2.1	Overview	10
2.2	Problem Formulation	10
2.3	Multi-objective vs Single-objective	11
2.4	Pareto	12
2.5	Choice of optimization software and algorithm	13
2.5.1	MATLAB optimization toolbox	13
2.5.2	MATLAB constraints	14
2.5.3	Choosing of a solver	15
2.5.4	Fmincon	16
2.5.5	Global Search	17
ii	APPLIED OPTIMIZATION	19
3	OPTIMAL DIMENSIONING OF THE ELECTROMAGNETIC DESIGN OF AN INDUCTOR	20
3.1	Inductor Basics	20
3.2	Optimization of an inductor	20
3.2.1	Inductor Optimized by Losses	21
3.2.2	Inductor optimized by cost	25
3.3	Validation using FEMM	30
4	OPTIMAL DIMENSIONING OF A MULTI-LEVEL POWER ELECTRONIC CONVERTER	31
4.1	Power Electronic Converters	31
4.2	Problem motivation	33
4.3	Buck Converter Theory	34
4.3.1	Dimensioning of inductance	34
4.3.2	Model of capacitance	36
4.3.3	Model of power losses	37
4.3.4	Multi-level buck converter	39
4.4	Optimization of a multi-level Buck converter	41
4.5	Results and Validation	45
4.5.1	Optimization with an output voltage of 10kV	45
4.5.2	Optimization with an output voltage of 2kV	50
4.6	Validation using Simulink	52

Contents

5	CONCLUSIONS	55
5.1	Discussion	55
5.2	Future work	56
iii	APPENDIX	66
A	APPENDIX A - MATHWORKS SHORT REFERENCE FOR CHOICE OF SOLVER	67
B	APPENDIX B - MATLAB CODE	70
C	APPENDIX C - DATASHEETS	86

INTRODUCTION

1.1 BACKGROUND

Many modern power electronic converters today are based on a modular topologies where several sub-converters are associated in a series parallel combination. For a given functional specification the dimensioning of such complex structures becomes a difficult task. This is mainly due to the large number of possible combinations available, each one leading to several end results according to different goals and respecting the entire domain of constraints. In conventional dimensioning techniques the expertise of the design engineer in charge may have a large impact on the end result. Furthermore, one might never be sure if a given solution is the optimal one or if a better design would be possible. If the possibility of finding the optimal solution with a well formulated methodology would exist, the dimensioning of these systems can save a lot of energy and cost.

1.2 PROBLEM AND GOAL

The European Spallation Source (ESS) will be the world's first sustainable research facility [1]. This lead to a big challenge to reduce the facility's energy consumption and costs related to it. Therefore to develop each component of the research facility as efficient as possible in both the manner of energy consumption and cost is wanted.

The objective of this thesis is to derive a methodology allowing for the optimization of both single components and complex circuits according to given goals and respecting several constraints given from the requirements list.

The methodology developed in this work will later be applied to the optimal dimensioning of the Stacked Multi-Level klystron modulator used to power the linear accelerator of the ESS project.

This thesis will show that it is possible to evaluate several aspects of a converter using basic power electronic formulas and commercially available numerical optimization software.

1.3 LIMITATIONS

The component parameters and formulas for pricing and volume calculations used in the optimizations are rough approximations and will affect the precision of the results. For this reason, the results presented in this work are rather to show tendencies than actual numbers. When total volume of the converter is calculated, this calculation does not include the space needed between the components such as heatsink or space needed to assemble the components. The aspect of reliability is an important factor to consider when designing power electronics but is not included in this work. Validations of the results performed in this work are done with simulations using available software and no experimental results are collected for comparison and validation.

1.4 APPROACH

The approach of this thesis is to first formulate a methodology for optimization of power electronics. This methodology is then applied to find the optimal solution of an inductor and then also a multi-level DC/DC converter.

In chapter 2 the theory behind the methodology is given and it includes an introduction to optimization and how it can be implemented in the chosen optimization software. Chapter 3 includes an example of optimization of an inductor using two different goals, first the losses and later the total cost. In chapter 4 a power electronic converter is introduced and is optimized with the goal of minimizing the total cost. The approach of chapter 3 and 4 is to formulate equations that describe the given task, these equations are thoroughly explained and later on used in the optimization. The solutions given from each optimization are presented and discussed in each individual chapter. The last chapter contains conclusions about the methodology and possible further work.

Part I

OPTIMIZATION THEORY

OPTIMIZATION

This chapter will present the relevant theory behind the optimization method developed in this thesis.

2.1 OVERVIEW

To optimize means to find the best, "optimal" solution to a problem. There are often several solutions that can accomplish a single task. Some of these solutions might be better than others and finding the best one out of these better solutions is to find the optimum solution of the problem. Optimization can be used in most professions and can save a lot of time and resources if done right. An example of a problem where optimization can be used is when an engineer should build a bridge with the purpose of taking pedestrians over a river. There are many ways to design a bridge that will fulfil this assignment. The problem can however be formulated as a problem of optimization in which a performance measure is optimized under the circumstance that all other requirements are satisfied. For the engineer the bridge can be formulated as a problem of finding the cheapest way to get the pedestrians over the river. While the cost should be as low as possible, the engineer also have some requirements that needs to be fulfilled. For example, it needs to withstand at least 50 persons at the same time and it should be at least 4 meters above the river. To find the optimal solution the engineer needs to optimize the problem and make sure that the requirements are fulfilled.

The field of optimization is large and widely used in many disciplines such as physics, engineering, biology and economics. One reason why the field is so large is because all these disciplines have important mathematical elements in common, and because of this commonality, many problems can be formulated and solved by using unified set of ideas and methods.

2.2 PROBLEM FORMULATION

It is not easy and obvious how to formulate an optimization problem, but it's important to do this correctly since this is the way of telling the computation software what the problem is. The four steps below will describe how to formulate an optimization problem.

1. Problem description

To start with, a descriptive statement of the problem needs to be formulated. In this statement the scope of the problem is outlined. The overall objectives to be optimized and the limitations of the problem are described.

2. Data and information collection

In this step all the information needed to formulate the problem as a strictly mathematical problem should be collected. This information can for example be material properties, performance requirements, resource limits and cost of raw materials.

3. Optimization criterion

The objective to be optimized needs to be described as a function. This function is called the **objective function**, and is the function that should be either minimized or maximized, depending on the problem formulation. In some cases two or more objective functions may be identified, and the problem formulation can then be described as either a **multi- or single-objective problem** (see section 2.3).

Constraints make up the design space of the optimization problem with respect to physical boundaries, restrictions regarding performance and other possible criteria. They are, together with the objective function, needed as the mathematical description of the problem. There are several different types of constraints and the choice of these play an important role in the choosing of an optimization solver.

4. Definition of design variables

Design variables, or **optimization variables**, are the set of variables needed to mathematically describe the problem with constraints and objective functions. These variables are altered by the optimization algorithm in order to optimize the objective function. They are regarded free since they are able to assume any value possible within the bound of satisfying the constraints. The design variables should in the greatest extent possible be independent of each other in order to add flexibility to the problem. Once all the design variables are determined, these are given start points. Some solvers require the start points to be located in the feasible design space. [2]

2.3 MULTI-OBJECTIVE VS SINGLE-OBJECTIVE

In many practical applications there are more than one objective function that simultaneously should be optimized, this is called multi-objective optimization.

An example of a multi-objective optimization problem in everyday life is when one goes to the supermarket and buys apples. Maybe one

wants the apples to be cheap and at the same time to taste good. This problem has two objectives which can be formulated as two objective functions. A function of taste and a function of price. It is often hard to fulfil both functions since the cheapest apples might not taste as good as the more expensive ones. A common problem in multi-objective optimization is that all the objectives can not be fulfilled at the same time, a single solution that simultaneously optimizes each objective does not exist. It is said that the objective functions are conflicting and that there exists a Pareto optimal solution (see section 2.4).

If a problem has only one objective to be optimized it is called a single-objective optimization problem. To use the apple example again, maybe the only interesting part is buying a cheap apple. Price can if so be made the only objective function and the optimization will find the cheapest apple.

Even if the only objective function is the price it is still possible to make sure the apple won't be so cheap that it will taste bad. This can be done by weighting the taste in the objective function. By doing this, the problem is still a single-objective problem, but the optimization takes notice to more than one objective. A simple example of such an objective function is shown below.

$$\text{minimize } f = 0.7 * \text{Apple}(\text{cost}) - 0.3 * \text{Apple}(\text{taste}) \quad (2.1)$$

2.4 PARETO

When two or more objective functions are conflicting it occurs a **Pareto optimality** situation. The Pareto optimality or Pareto efficiency is a state of allocation where it's impossible to make one function better without making at least one other worse. The Pareto optimality situation is possible to show as a Pareto front. This is illustrated in figure 2.1, where the Pareto front of two objectives are marked with red stars. On the left side of the front it's possible to get a valid function value by combining the two objects, but on the right side this is impossible.

The Pareto optimality can be formulated as:

"A point x^ in the feasible design space S is Pareto optimal if and only if there does not exist another point x in the set S such that $f(x) \leq f(x^*)$ with at least one $f_i(x) < f_i(x^*)$." [2]*

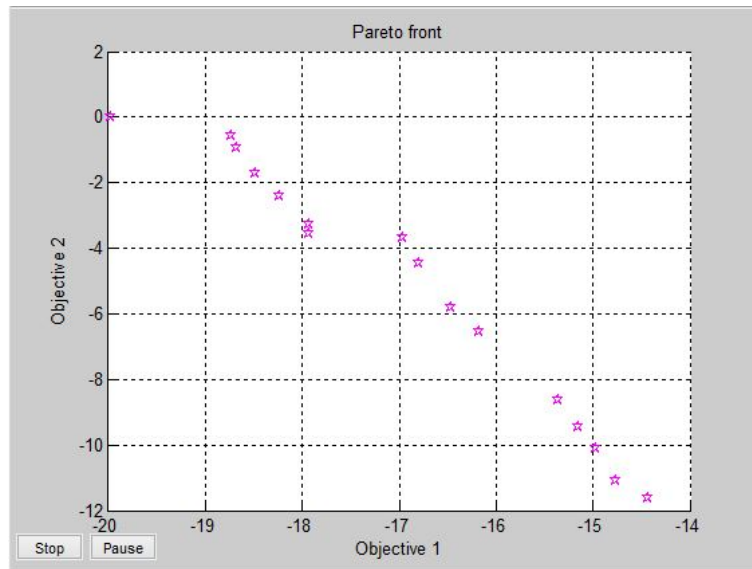


Figure 2.1.: Pareto Front

2.5 CHOICE OF OPTIMIZATION SOFTWARE AND ALGORITHM

For optimization problems, there are different ways to optimize one and the same problem. Both in the choice of calculation software and in choice of optimization algorithm to use. This thesis is focusing on using MATLAB as the calculation software.

2.5.1 MATLAB optimization toolbox

The optimization toolbox provides an optimization environment in MATLAB with solvers that can handle both linear and nonlinear optimization [3]. The toolbox contains twenty different solvers and the choice of these depend on how the problem is formulated (see section 2.5.3).

The toolbox can be used either in the Optimization application or in the regular MATLAB workspace.

The optimization app provides a user friendly GUI, see figure 2.2. Using this app, the solver is chosen in a list and the objective function, constraints, starting points, bounds, etc, are inputted in forms.

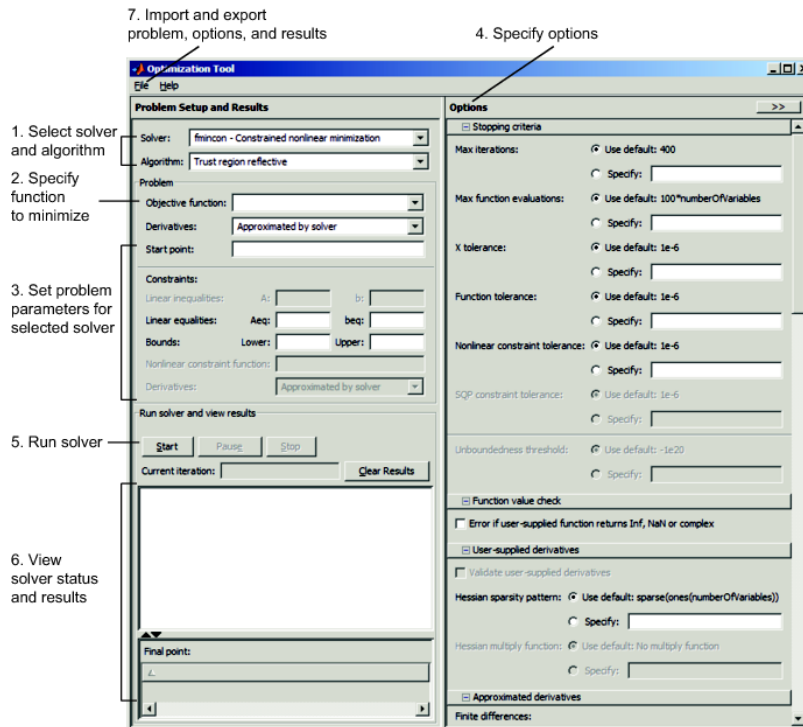


Figure 2.2.: Optimization toolbox, [3]

The workspace version is written in the workspace and the choice of solver and inputs are made with special optimization commands (these can be read about in [3]). One feature with the workspace version is that it can be written and saved as a script and the variables and settings doesn't need to be rewritten if the program is restarted.

Regardless if using the optimization app or the workspace version, the constraints and objective functions need to be written as scripts. These scripts are functions having a vector containing all design variables as input argument. The script for constraints returns one vector with the equality constraints and one vector with the inequality constraints and the script for the objective function returns the objective function.

2.5.2 MATLAB constraints

In the optimization toolbox there are four different types of constraints [3]. These are the ones taken into account when formulating the problem.

- Bound Constraints
These constraints involve lower and upper bound on individual design variables: $x \geq lb$ and $x \leq ub$.

- **Linear Inequality Constraints**
These constraints have the form $A * x \leq b$. When A is an m -by- n matrix, there are m constraints on a variable x with n components, b is a m -dimensional vector.
- **Linear Equality Constraints**
Linear equality constraints have the form $Aeq * x = beq$. When Aeq is an m -by- n matrix, there are m constraints on a variable x with n components, beq is a m -dimensional vector.
- **Nonlinear Constraints**
These constraints have the form $c(x) \leq 0$, where c is a vector with one component for each constraint.
- **Nonlinear Equality Constraints**
The nonlinear equality constraints have the form $ceq(x) = 0$, where ceq is a vector with one component for each constraint.

2.5.3 *Choosing of a solver*

Different optimization solvers use different algorithms to optimize a given problem. The efficiency and success rate of these algorithms vary depending on the outlining of the problem. In general, an optimization algorithm starts with an initial estimate that makes a starting points somewhere in the design space. From this starting point the algorithm iteratively finds a new candidate for the optimal point. This process continues until a point satisfies the optimality criteria. Exactly how the algorithm guides the search for a optimum varies with different types of algorithms.

Selection of an optimization solver is not arbitrary and will typically consider several aspects of the problem to be optimized. The typical factors are listed below but the choice of optimization solver is not necessary limited to these.

- Type of constraints.
- Linearity of the objective function.
- Number of design variables.
- Type of design variables.
- Amount of objective functions
- Feasibility of initial starting points.
- Evaluation time.

The focus of this thesis lies not in the mathematics behind these numerical methods and wont therefore be thoroughly discussed. The choice of solver is based on Mathworks short reference for choice of

optimization method. In this thesis `fmincon` and Global Search are chosen as solvers (see 2.5.4 and 2.5.5).

2.5.4 *Fmincon*

`Fmincon` is a MATLAB local solver included in the optimization toolbox. Its goal is to find the minimum value of constrained nonlinear multi-variable functions. In the case of many potential solutions, the solution closest to the starting point is obtained. `Fmincon` does not require the initial estimate to be strictly feasible since it has a method of choosing a new strictly feasible starting point [3]. The minimization problem for `fmincon` is specified by equation 2.2.

$$\min_x f(x) \text{ such that } = \begin{cases} c(x) \leq 0 \\ ceq(x) = 0 \\ A * x = b \\ Aeq * x = beq \\ lb \leq x \leq ub \end{cases} \quad (2.2)$$

The `fmincon` solver has four different kinds of algorithms to use for the iteration through the function when searching for the optimal solution.

- Interior Point
- Trust Region Reflective
- Sequential Quadratic Programming (SQP)
- Active Set

How each one of these works and when to choose which one is a complex matter and for that reason Mathworks has made a list of recommendation on how to choose algorithm.

1. Use the Interior Point algorithm first
2. To run an optimization again to obtain more speed try SQP next and Active Set last.
3. Use Trust Region Reflective when applicable. For this to be possible the objective function must include a gradient and the constraints can only be bounds or linear equality constraints (but not both).

The reasoning behind these recommendations can be read at [3] s2.7-2.8.

2.5.5 *Global Search*

The chance of ending up in a local minimum is substantial when using a local solver such as `fmincon`. It is in many cases hard to know that the solution is just a local optimum and that the optimal solution of the optimization problem is something else. It is, by running the optimization solver several times starting at different points, possible to explore more of the function and in that way increase the chances of finding the global minimum. The MATLAB optimization toolbox contains elaborate methods for finding the global minimum of functions. One of these methods are Global search. It uses a scatter search method to generate trial points which after filtering becomes starting points. These different starting points are then used by `fmincon` to find an optimal solution for the objective function. The optimal solution for each starting points is stored in a vector and when the all the starting points are evaluated they are compared and the minimum is presented as the optimal solution. [4].

If for example, only using the `fmincon` solver to find the minimum of the Rastrigin's ¹ function, equation 2.3 and shown in plot 2.3, it's hard to be certain that the found minimum is the global minimum. This can be found out if the starting point of the solver is changed and run again, the optimization will probably find another minimum than the last time.

$$Ras(x) = 20 + x_1^2 + x_2^2 - 10 * (\cos 2\pi x_1 + \cos 2\pi x_2) \quad (2.3)$$

By looking at the plot in figure 2.3, it's easy to see that there exists more than one local minimum in the function. This makes the starting point an important factor to the outcome of the optimization and the use of Global search will therefore be helpful.

¹ In mathematical optimization, the Rastrigin function is a non-convex function used as a performance test problem for optimization algorithms.

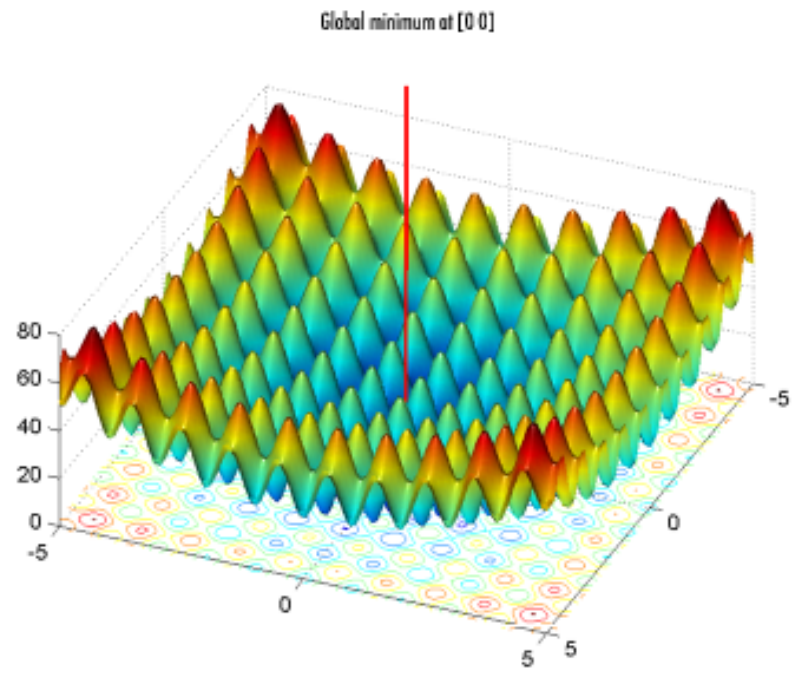


Figure 2.3.: Rastrigin function [4]

Part II

APPLIED OPTIMIZATION

3

OPTIMAL DIMENSIONING OF THE ELECTROMAGNETIC DESIGN OF AN INDUCTOR

The aim of this chapter is to thoroughly explain how the optimization method can be applied on a passive component such as the inductor. The information needed to optimize the inductor are first developed and then implemented in the optimization software. The last part of this chapter shows one possible method of how verification of the solution can be done.

3.1 INDUCTOR BASICS

The most basic form of an inductor is a coil of wire wound around a central core. Inductors store electrical energy temporarily in form of magnetic energy. This magnetic energy occurs when current flows through the inductor, and it has an associated electromotive field which opposes the applied voltage. This means that an inductor will resist changes in current but passes a steady state DC current. This ability of an inductor to resist changes in current and which also relates current, I , with its magnetic flux linkage, $N\Phi$, as a constant of proportionality is called Inductance which is given the symbol L and the unit Henry [H].

An inductor can be made both with and without an air gap in the core. With an air gap it is possible to achieve a higher inductance without the inductor saturating, [5], this is often used in power electronic circuits where high inductance is needed.

3.2 OPTIMIZATION OF AN INDUCTOR

Optimization of an inductor with an air gap is a good example of how optimization can be used in the matter of power electronics. An inductor is a fairly simple passive electromagnetic component, yet finding the optimal design without using a computer aided optimization method is hard and time consuming. The complexity of the matter can be acknowledged by looking at the close correlation between the parameters of an inductor.

3.2 OPTIMIZATION OF AN INDUCTOR

To understand that the efficiency of an inductor depend on the size of the iron core and copper wire might be straight forward. But what about for example the relation between the number of windings and the efficiency, or even the relation between efficiency, the number of windings and the cross section area of the copper wire. And while having these factors in mind still make sure that the flux density won't be to high and the inductance not to low.

There are several variables to have in mind when trying to find the best solution for an inductor design. The best solution can also imply different designs depending on the field of application of the inductor. An inductor located in an airplane or truck might have the primary goal of being light while the efficiency might be the most important property for an inductor used in an environment with limited power resources.

This chapter describes how the inductor shown in figure 3.1 can be optimized, both with regard to power losses and later with regards to cost. This optimization is performed using MATLAB's optimization software.

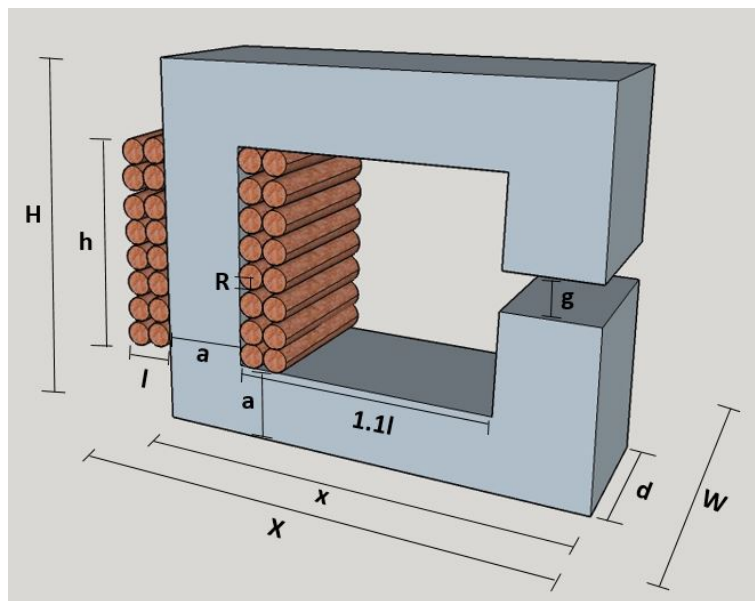


Figure 3.1.: Basic inductor structure

3.2.1 Inductor Optimized by Losses

To optimize the efficiency of an inductor means to make the efficiency as large as possible or equivalently, to minimize the power losses. The optimization problem can hence be considered as an minimization problem where the optimal solution is the one with the lowest

power losses. The objective function for this optimization problem is therefore set to be the power losses of the inductor.

DC current is considered for this problem and the power losses are thus limited to the resistive losses of the copper windings. The objective function is described by equation 3.1.

$$Losses_{inductor} = \rho * N_I * \frac{2 * (l + a) + 2 * (l + d)}{S_{cu}} * I^2 \quad (3.1)$$

Where ρ is the resistivity of copper, $\rho = 1.72 * 10^{-8} \Omega m$. N_I is the number of windings for the copper wire, S_{cu} is the cross section area of the copper wire and the DC current is $I = 100A$.

How much and in what way the power losses can be reduced is physically limited in several ways and depend on other requirements of the inductor. For instance a certain inductance might be desired and for EMC reasons the magnetic fields might need to be limited. Also the size and weight of the inductor might be limiting factors. All these factors among others must be formulated as constraints and included in the optimization. The constraints are described by equation 3.2 through 3.8.

Constraints for the physical size need to be added for the optimization to respect the geometry of the basic structure shown in figure 3.1. Equations 3.2, 3.3 and 3.4 express the constraints for width, height and depth respectively.

$$X = 2.1 * l + 2 * a \quad (3.2)$$

$$H = h + 2 * a \quad (3.3)$$

$$W = 2 * l + d \quad (3.4)$$

The inductance of the inductor has a given lower bound of 20 mH and the expression for this is given by equation 3.5.

$$L = \mu_0 * N_I^2 * \frac{a * d}{g} \geq 20mH \quad (3.5)$$

Where $\mu_0 = 4 * \pi * 10^{-7}$ is the permeability of vacuum and the air gap length is $g = 0.001m$.

The flux density of the inductor has a given upper bound of 1 T and can be expressed as equation 3.6.

$$B = \mu_0 * \frac{N_I * I}{g} \leq 1 T \quad (3.6)$$

Equation 3.7 gives the relationship between the radius of the wire cross section area, R , and the total area of windings, $l * h$. Since the

wire cross section area is circular there will be empty spaces between the windings which is accounted for by a filling factor of 80 %.

$$l * h \geq \frac{N_I * \pi * R^2}{0.8} \quad (3.7)$$

The current density of the copper wire has a upper bound of 5 Amm^{-2} and is expressed by equation 3.8.

$$J = \frac{I}{\pi * R^2} \leq 5 \text{ } Amm^{-2} \quad (3.8)$$

The design variables are the parameters allowed to assume any values during the optimization. The chosen design variables are shown in table 3.1.

a	d	l	N_I	R	h
---	---	---	-------	---	---

Table 3.1.: Design variables

The choice of optimization solver depend on the outlining of the constraints and objective function as described in section 2.5.3. In this optimization problem there are both linear and nonlinear constraints and which in turn contains both equalities and inequalities. Since there is not more than one objective function, the solver will only need to handle single-objective optimization. This information together with the fact that the optimization problem is a minimization problem is enough to choose a solver. The choice of solver for this problem is `fmincon` (see section 2.5.4) by recommendation from the Mathworks short reference for choice of optimization method (see Appendix A). To make sure the result of the optimization will be a global optimum the Global search method (see section 2.5.5) is used together with `fmincon`.

One problem with the `fmincon` solver is that it can't handle variables constrained to be integers. This optimization problem has a variable describing the number of turns of the copper wire around the inductor core, N_I , which is physically limited to be kept an integer. This imposes a problem which is solved by first calculating the optimal decimal value of N_I . And then round the result to the nearest possible integer and run the optimization with this number of turns as a constant

With the objective function and the constraints formulated as above it is understandable that the power losses will move towards zero at the expense of the inductor size which moves towards infinity. It is theoretically viable since as to reduce the power losses the cross section area of the copper wire will increase which in turn forces the core size to increase. To restrain the two magnitudes to reasonable values upper bounds for the inductor size are added as constraints.

The upper bounds for the dimensions are now:

$$X, H, W \leq 1m \quad (3.9)$$

3.2.1.1 Results and evaluation

The optimal criteria is met and the optimization algorithm finishes with a resulting size of the inductor of one cubic meter. That is with values of X, H and W of 1 meter which are the maximum allowed values.

By rearranging equation 3.6 and solve for the number of winding turns one finds the maximum allowed value of N_I to be 7.96. The number of winding turns rounded to the nearest possible integer is therefore 7. The volume of the inductor is largely overdimensioned which results in extremely low power losses.

The optimal value of the power losses for this set of parameters and with these constraints are shown in table 3.2. The values of the design variables at the optimal solution are shown in table 3.3

	N_I [turns]	$Losses_{inductor}$ [W]	Vol_{tot} [m ³]
Variable N_I	7.96	0.87	1
Fixed N_I	7	1.58	1

Table 3.2.: Power losses

a [m]	d [m]	l [m]	N_I [turns]	R [m]	h [m]
0.4003	0.8114	0.0943	7	0.0262	0.1994

Table 3.3.: Optimized design variables

One can realise that the constraints are strictly dependent on each other which reduces the flexibility of changing the variables in the optimization problem. Since it's possible to calculate the maximum number of N_I , it can be used to calculate the minimum value of a*d, the cross section area of the iron core. Equations 3.5 and 3.6 gives:

$$a * d \geq \frac{0.02 * g}{\mu_0 * \frac{g}{I * \mu_0}} \Leftrightarrow a * d \geq \mu_0 * \frac{0.02}{g} * I^2 \quad (3.10)$$

Inserting the values of the constants μ_0 , I and g gives:

$$a * d \geq 0.251 \quad (3.11)$$

By supposing the core to be quadratic with a and d equally sized, one can from equation 3.11 find that the values of both a and d can't

be smaller than the square root of $a*d$ simultaneously, expressed by 3.12.

$$a = d = \sqrt{0.251} = 0.5 \quad (3.12)$$

This gives an inevitable lower bound of the size of the inductor. By changing the constant air gap, g , in the constraint to a design variable this conflict can be eased. The degree of freedom of the design can typically be enhanced by exchanging constants with variables.

This objective function only concerning the power losses is flawed in the sense that it doesn't really consider other important properties such as the size and cost of the inductor. To get a more purposeful optimization the objective function should be extended or reformulated to cover a wider set of criteria.

3.2.2 Inductor optimized by cost

To get a more realistic volume of the inductor described in section 3.2.1, the aspect of price is included in the optimization problem. To do this, the objective function is reformulated to become a function of the total cost of the inductor. The total cost is divided into two parts, capital investment cost and operational cost. The operational cost is considered the running costs of the inductor and depends entirely on the power losses. Capital investment cost depends on the amount of copper and iron needed for constructing the inductor. The optimization is done as single-objective where the price of copper, iron and electricity are weighting factors in the new objective function.

The new objective function $Cost_{tot}$ is described by equation 3.13.

$$Cost_{tot} = Cost_{capital} + Cost_{operational} \quad (3.13)$$

The capital cost in this example comprises cost of iron and copper and is described as equation 3.14.

$$Cost_{capital} = Vol_{cu} * \delta_{cu} * Price_{cu} + Vol_{fe} * \delta_{fe} * Price_{fe} \quad (3.14)$$

The volumes of copper and iron are found directly from the measures of the inductor.

$$Vol_{cu} = (2 * a + 2 * d + 4 * l) * R^2 * \pi * N_I \quad (3.15)$$

$$Vol_{fe} = (2 * a + 1.1 * l) * (2 * a + h) * d - (1.1 * l * h * d) \quad (3.16)$$

Material density, δ , and cost of raw material are constants shown in table 3.4.

3.2 OPTIMIZATION OF AN INDUCTOR

	Density [kg/m^3]	Price [€/kg]
Copper	8920	5.05
Iron	7874	0.81

Table 3.4.: Material properties

The operational cost is described as equation 3.17, where the inductor is assumed to be used 5500 hours a year for 25 years and with a fixed price of electricity, $Price_{el}$, of 0.05 euro/kWh.

$$Cost_{operational} = Losses_{inductor} W * 10^{-3} * 5500 h/year * 25 years * Price_{el} \text{ €/kWh} \quad (3.17)$$

The power losses of the inductor, $Losses_{inductor}$, is described in equation 3.1 in section 3.2.1.

As opposed to the optimization by losses in section 3.2.1, the air gap of the inductor, g , is now a design variable. This will grant the variables wider intervals where they satisfy the constraints.

Since the objective function is still described as a single-objective and has the same constraints as before (equation 3.2 to 3.8), the choice of solver remains to be `fmincon`. Global search is, as before, used to make sure the global optimum is found.

3.2.2.1 Results and evaluation

The optimization gives a solution where the total cost becomes **991€** with a power loss of **54 W**. The answer given from MATLAB is shown in figure 3.2. The resulting design variables from this optimal solution are shown in table 3.5.

a [m]	d [m]	l [m]	N_I [turns]	R [m]	h [m]	g [m]
0.1544	0.3598	0.0385	36	0.0066	0.1583	0.0045

Table 3.5.: Optimized design variables

Table 3.6 shows the outer measures of the inductor which are considerably lower than the upper bounds of one meter. The optimization algorithm no longer maximize the inductor size to push down the power losses. A Pareto optimality (see section 2.4) is met where the capital cost of building a bigger inductor exceeds the savings of lower power losses.

Since price affects the weighting factors in the objective function, a change in pricing will move the Pareto front resulting in different optimal solutions. The four different graphs shown in figure 3.3 are

3.2 OPTIMIZATION OF AN INDUCTOR

```

Command Window
Calculated Values by the optimized values
TotalCost = 991.357 Euro
PCopperLosses = 53.9961 W
Electricity price = 0.05 Euro/kwh
Copper weight and price = 51.4943 kg, 5.03 Euro/kg
Iron weight and price = 445.8243 kg, 0.81 Euro/kg
a = 0.15442, d = 0.35976, l = 0.03854, N = 36, R = 0.00657, h = 0.15833, g = 0.0045239
X = 0.38978, H = 0.46718, W = 0.43684, L = 0.02, B = 1, J = 737428.3677, lh = 0.0061023
L from FEMM = 0.022093 H
    
```

Figure 3.2.: Command Window fixed N_I

X[m]	H[m]	W[m]
0.39	0.47	0.44

Table 3.6.: Optimized inductor outer dimensions

results from optimizing the inductor by cost using different prices of material and electricity. The prices used are shown in table 3.7 and the optimized losses and costs are shown in table 3.8.

The lower price of electricity is approximately the accurate price of today. Without scientific support or deeper analysis the price of electricity has been assumed to increase in the future and for the purpose of testing the optimization two higher prices are used, medium and high. The in the table called medium prices for iron and copper are approximately the values of today. Without speculating in future change of material prices a higher and a lower price are used.

Object	Price Low	Price Medium	Price High
$Price_{cu}$ [€/kg]	1.00	5.03	10.00
$Price_{fe}$ [€/kg]	0.05	0.81	1.81
$Price_{el}$ [€/kWh]	0.05	0.1	0.15

Table 3.7.: Different prices of copper, iron and electricity

	$Losses_{inductor}$ [W]	$Cost_{tot}$ [€]
A	35.06	1285.6
B	47.58	1744.5
C	27.21	1496.8
D	42.34	1552.4

Table 3.8.: Losses and cost for A,B,C,D examples

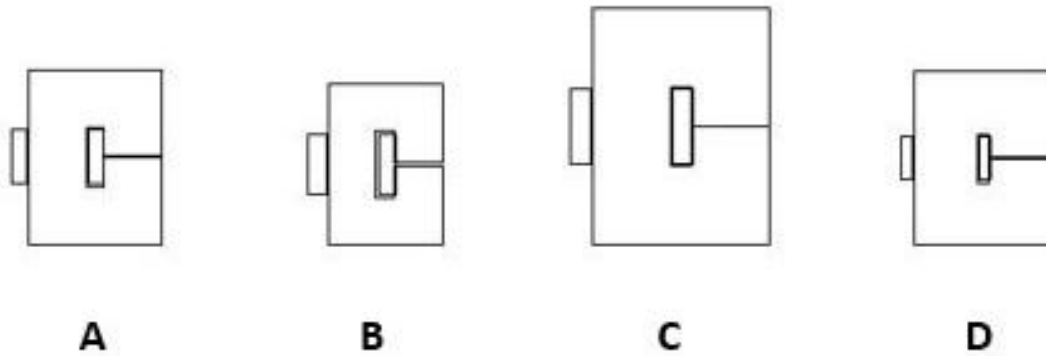


Figure 3.3.: Iterations

- In example A, all prices are set to medium to work as a reference for the other graphs.
- In example B, the iron price is increased. The optimization will find it beneficial to minimize the iron core at expense of higher power losses. To keep the power losses down more copper is then used.
- In example C, the price of electricity is increased giving the power losses a more significant impact on the total cost. The inductor will get bigger, using more iron and copper to keep the power losses down.
- In example D, the copper price is high. A high price of copper means it is favourable to reduce the amount of copper used and for geometrical reasons the amount of iron used will also decrease. The result is higher power losses.

Figure 3.4 shows optimized results of all different possible combinations of the prices given in table 3.7. The copper, iron and electricity prices are located on the axes and the size of the dots represents the magnitude of the power losses. The volume of copper and iron (Vol_{cu} and Vol_{fe}) for each result are also shown in the figure. This figure helps illustrate how the different prices influence the outcome of the optimization but it also means to show how they can be used as weighing factors to change the goals of the optimization.

3.2 OPTIMIZATION OF AN INDUCTOR

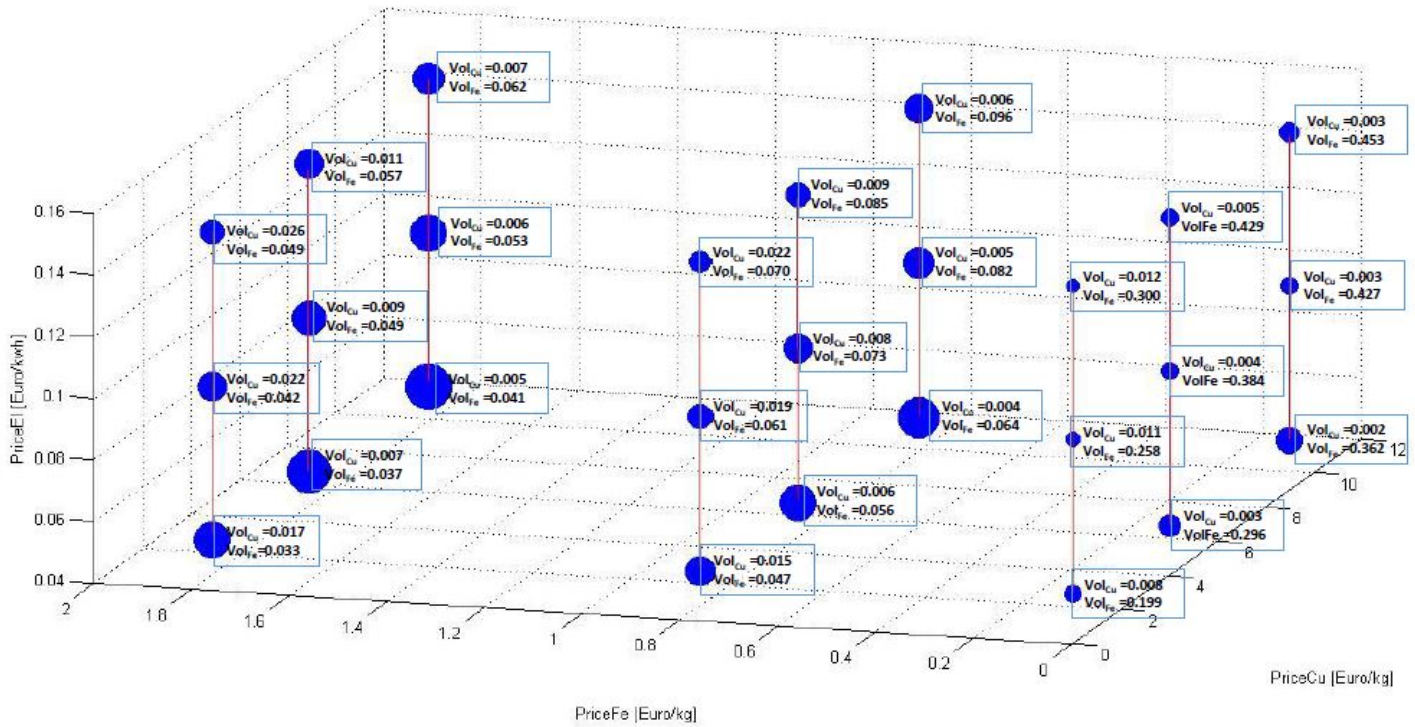


Figure 3.4.: Powerlosses for different prices

Consider for example the left- and bottom-most dot. For this dot the price of material is very expensive while the price of electricity is very cheap resulting in an inductor design with high power losses and a minimized volume. The high material prices in relation to the low electricity price make the capital investment cost part of the objective function weigh heavier than the operational cost part. The primary objective of the optimization is therefore to reduce the capital cost which is accomplished by reducing the size of the inductor. The optimal solution with these pricing conditions is thus to allow higher losses to compensate for the more expensive material costs.

For the case of high electricity cost and low material costs the optimal solution is the contrary. With these pricing conditions the optimal solution is instead to allow a greater material usage to keep the losses down. An example of this is the right- and front-most dot where the primary objective of the optimization is to reduce the operational cost.

By changing the relation between capital investment cost and operational cost it is possible to decide how strongly the optimization solver should focus on minimizing one part of the objective function and in what extent it can neglect another. It is also possible to change

the goal of the optimization by adjusting the weighting factors in the objective function. If the two inductor designs above were considered for the same pricing conditions they would serve as extremes. The left- and bottom- most design would have the lowest capital investment cost, i.e be the cheapest one to buy while the right- and front-most design would have the lowest operational cost and thus be the most efficient one. Both these designs can be the optimal design in their own field of application even though neither one of them are the optimal solution to the design problem.

3.3 VALIDATION USING FEMM

After the optimization algorithm finish and the design variables are given their values these are automatically sent to FEMM. FEMM is a software using the finite element method to numerically solve partial differential equations. The design variables are used in FEMM to draw a two dimensional image of the inductor, see figure 3.5. A three dimensional calculation of the magnetic properties is then performed. The results are sent back to MATLAB to confirm that the constraints on the inductance and flux density is not violated. The flux density in different points is directly fed back from FEMM while the inductance is calculated from the magnetic field energy trough equation 3.18

$$E = \frac{1}{2} * L * I^2 \Leftrightarrow L = 2 * \frac{E}{I^2} \quad (3.18)$$

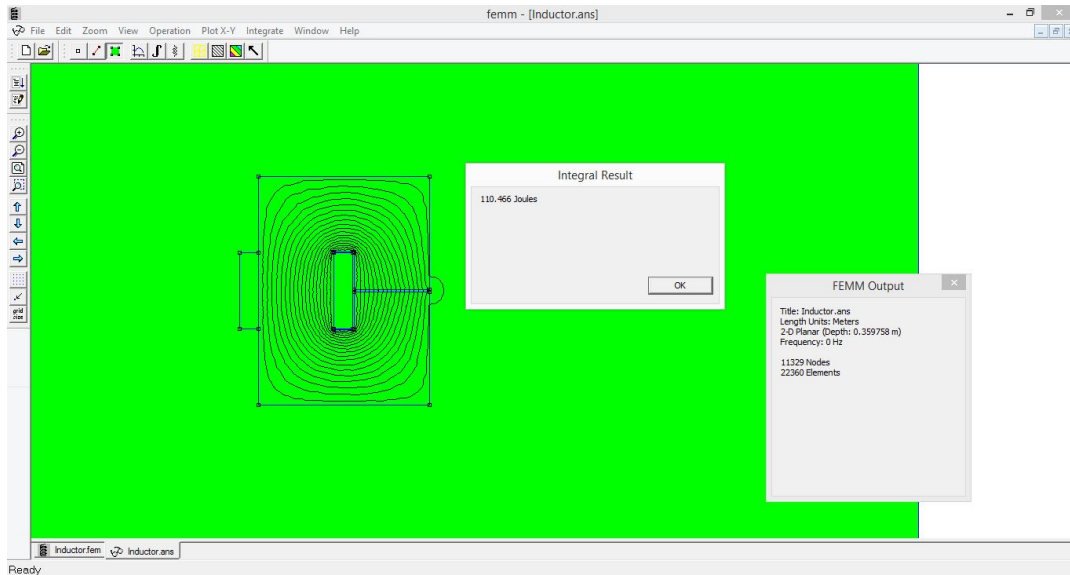


Figure 3.5.: Inductor designed in FEMM

4

OPTIMAL DIMENSIONING OF A MULTI-LEVEL POWER ELECTRONIC CONVERTER

The aim of this chapter is to find the optimal solution of a multi-level DC/DC converter. The layout of the chapter is first to develop all the needed information to describe the problem, then with this information the converter is optimized and the last part contains a verification of the solution.

4.1 POWER ELECTRONIC CONVERTERS

Power electronic converters are used almost everywhere but the design differs depending on the purpose of the converter. Power electronic converters can typically be divided into three categories [6]:

1. Conversion between different direct current sources, *DC-to-DC* converters.
2. Conversion between different alternating current sources, *AC-to-AC* converters.
3. Conversion between one direct current source and one alternating source, *AC-to-DC* or *DC-to-AC* converters.

If high power conversion is desired, there are mainly two different approaches to designing a power electronic converter. Conventional converter topologies using semiconductors with high voltage and current ratings or multi-level topologies using several semiconductors with smaller ratings. The semiconductors used in conventional converter topologies usually become large and expensive with considerable power losses due to the high nominal voltage and current they need to withstand. The multi-level topologies use several semiconductor switches in series, each with a lower input voltage source compared to a conventional converter. This makes it possible to use smaller semiconductors with lower power losses as the required voltage rating is lower. The semiconductors become less expensive but the concept requires a greater number of them. Power conversion

is performed by synthesizing the sources to create a staircase output voltage, see figure 4.1. As more levels are added to the converter, more steps are added in the output waveform which approaches a sinusoidal wave with minimum harmonic distortion.

Some of the most attractive features of multi-level converters are the low distortion on the generated output voltage and the fact that it can operate with lower switching frequency compared to a conventional converter. The lower switching frequency results in lower switching losses. The smaller voltage steps of a multi-level converter also affects the voltage derivative which imposes EMC compliance to international standards.

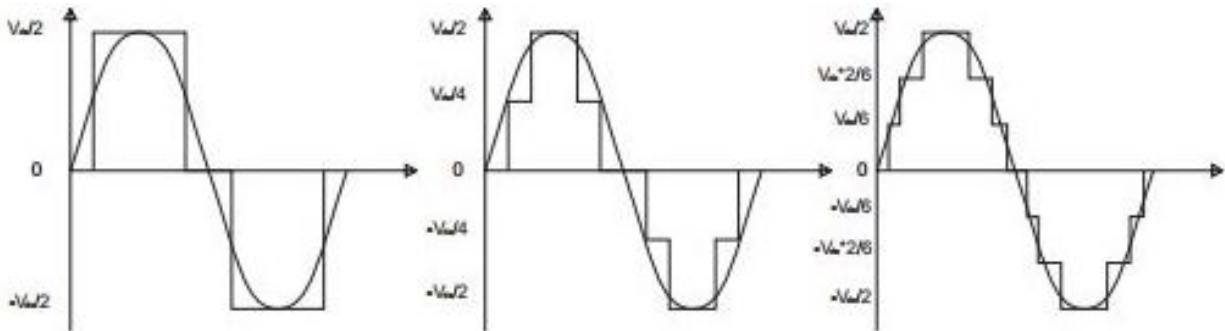


Figure 4.1.: A three-level waveform, a five-level waveform and a seven-level waveform, switched at fundamental frequency, [7]

In order to generate an electromagnetic field for the beam acceleration at ESS, radio frequency (RF) power sources are required. To convert electrical power into this RF power, klystrons will be used. These klystrons need a high voltage DC input and it is in the "creating" of this source a converter is needed, called the Stacked Multi-level klystron modulator.

The converter considered in this chapter is a multi-level Buck converter. The design of the SML topology is more complex but the methodology developed in this work can by small means of revision be applied even for other converter topologies. A Buck converter, see figure 4.2 is a transistor based power electronic converter with the purpose to convert a input DC voltage to an average output voltage that is lower or equal to the input voltage. This puts the buck converter under the category DC-to-DC converter and is also called to be a step down converter. In this chapter a multi-level Buck converter will be optimized with regard to total cost. The total cost of the converter will be composed of capital cost and operational cost considering a time period of 25 years.

4.2 PROBLEM MOTIVATION

If neither money, resource usage nor weight and volume were factors of concern when designing a Buck converter, the only restraint would be to limit the output voltage ripple to comply with other appliances. This is rarely, or never, the case in reality but as a mean of illustrating the complexity of the design problem that is dimensioning of a power electronic converter, this restriction is useful. To achieve a sufficiently low voltage ripple, there are three parameters of concern. The switching frequency of the converter, the inductance and the capacitance. These three parameters can be arbitrarily dimensioned to the extent of still satisfying the voltage ripple constraint. For multi-level topologies a fourth parameter that is the number of modules, deciding the size of a voltage step is involved granting even more flexibility to the choosing of the parameters.

If taking into account the cost of the converter, these parameters can no longer be chosen arbitrarily. With the capital investment cost of a multi-level Buck converter in mind, the design problem becomes choosing the parameters in a way that results in the lowest possible capital cost. This is done by increasing the switching frequency, thus making the inductance and capacitance smaller and less expensive. If both capital investment cost and operational cost are considered in the design problem, as is the case for this work, an increased switching frequency will result in bigger switching losses and the resulting total cost might therefore not be the lowest. Increasing the number of modules of the converter reduces the voltage steps and the inductance can be made smaller or the switching frequency can be reduced while keeping the same performance. More modules result in both a higher capital cost and a higher operational cost because of more losses while a smaller inductance and lower switching frequency reduces the costs. The difficulty of designing a converter with regard to the total cost is finding the Pareto front between the capital investment cost and the operational cost.

How all the parameters in a design problem such as a multi-level Buck converter shall be decided to result in an optimal solution while still respecting the constraints based on system requirements is difficult. What the optimal solution might be vary and is dependent on what the purpose of the converter is. A converter designed to fit in a small place or where weight is of importance, the primary objective might be to design it as compact as possible. In a situation where energy resources are limited the efficiency of the converter is of utter importance and the optimal design is the one with the smallest power losses. A combination of cost, volume and efficiency are in most cases required and a multi-objective approach is then needed. To calculate and compare all the possible combinations of parameter

values would be time consuming, if not impossible and the result very dependent on the expertise and background of the designer. A computer based optimization method is therefore in many cases vital.

4.3 BUCK CONVERTER THEORY

The methodology developed in this chapter attempts in providing a systematic and automatized tool to solve the problem of multi-objective dimensioning. To be able to optimize the multi-level Buck converter, a mathematical model of the converter needs to be established. The model needs to describe the dynamics as well as the physical properties and limitations of the converter. This section will in three parts derive a model describing the dynamics of a buck converter including formulas for dimensioning of inductance, capacitance and losses in the semiconductor switches. These formulas are in a forth part extended to define a multi-level design.

4.3.1 Dimensioning of inductance

The current flowing through the inductor in figure 4.2 is the sum of the average output current and the current ripple, expressed in equation 4.1. It has a triangular shape due to the switching nature of the converter.

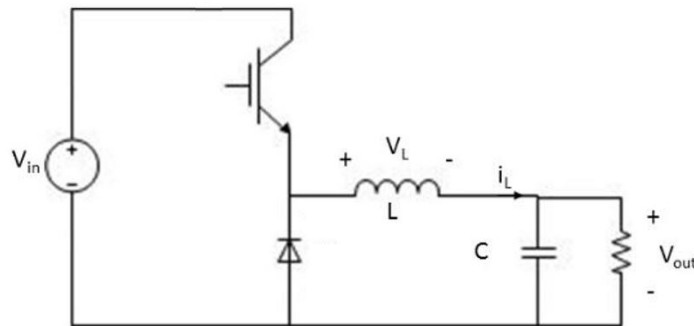


Figure 4.2.: BuckConverter

$$i_L(t) = I_{out} + i_{ripple}(t) \quad (4.1)$$

The current ripple is composed by two piece-wise linear slopes with an average value of zero due to the charge-second balance principle, see figure 4.3. The first slope shows the positive current derivative when the switch is closed while the second slope is the negative current derivative when the switch is open.

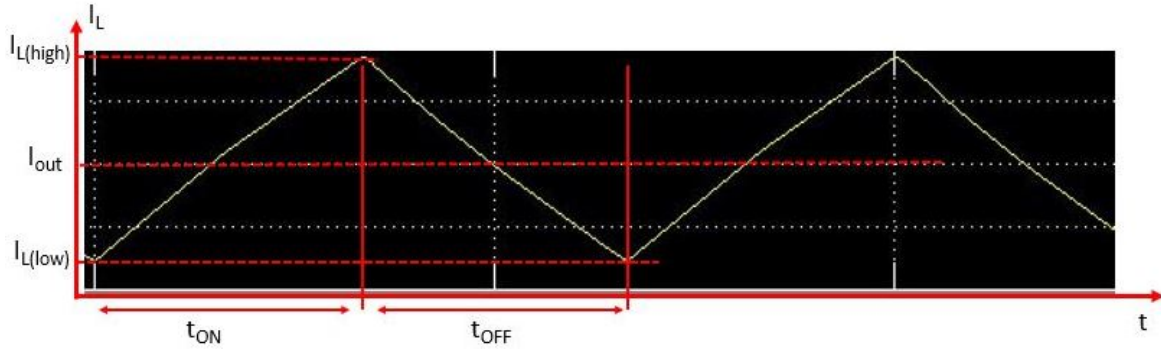


Figure 4.3.: The current ripple with a duty cycle, D , of 50%.

The magnitude of the current ripple can be calculated from equation 4.2 by using the conducting part of a switching period as the time interval dt . During this time the converter runs in on-state and the voltage drop over the inductor is defined by 4.3 as illustrated in figure 4.4. The current ripple is expressed by equation 4.4.

$$\frac{di_L}{dt} = \frac{V_L}{L} \quad (4.2)$$

$$V_{L(\text{ON})} = V_{in} - V_{out} \quad (4.3)$$

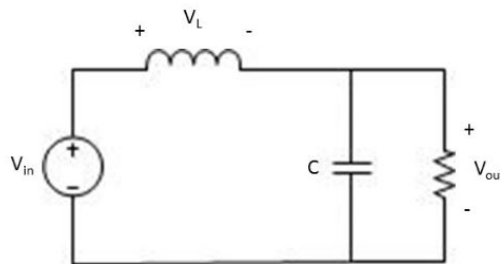


Figure 4.4.: Equivalent circuit for the converter during on-state.

$$\Delta I_L = \frac{(V_{in} - V_{out})}{L} * D * T_{sw} \quad (4.4)$$

It is in most applications desirable to limit the current ripple to a certain level and since the duty cycle is variable the inductance should be dimensioned for the worst case scenario. By rewriting the output voltage as 4.5 it is possible to show that the maximum current ripple occurs at a duty cycle of 50%. An equation for the inductance can for this case be formed as equation 4.6.

$$V_{out} = V_{in} * D \quad (4.5)$$

$$L = \frac{V_{in}}{4 * \Delta I_{L(max)}} * \frac{1}{f_{sw}} \quad (4.6)$$

4.3.2 Model of capacitance

The DC component of the current has no impact on the capacitor and it is thus only the AC component, i.e the current ripple, that flows through the capacitor.

The change of voltage over a capacitor is given by the capacitance and the change of charge of the capacitor. Since the capacitor is in parallel with the load, this change of voltage is the same as the output voltage ripple, equation 4.7.

$$\Delta V_{out} = \frac{\Delta Q}{C} \quad (4.7)$$

Charge is the same as the integral of current and can thus be calculated as the area under the positive part of the current ripple. The change of charge is described by equation 4.8 and illustrated by Figure 4.5.

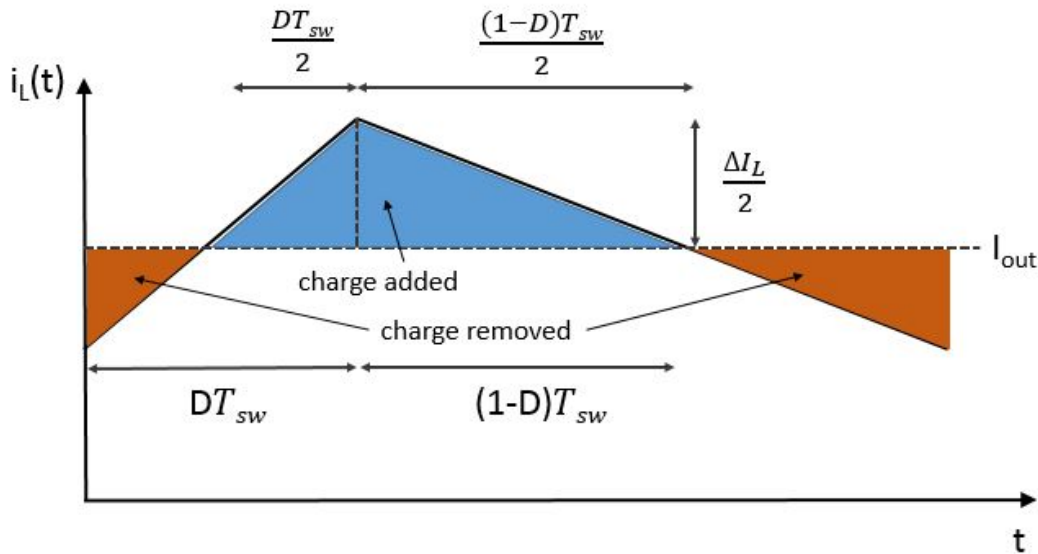


Figure 4.5.: Ripple of inductor current

$$\Delta Q = \int_{\frac{DT_{sw}}{2}}^{\frac{(1-D)T_{sw}}{2}} i dt = \frac{T_{sw}}{2} * \frac{\Delta I_L}{2} * \frac{1}{2} \quad (4.8)$$

By inserting 4.8 into 4.7 the voltage ripple can be expressed as 4.9.

$$\Delta V_{out} = \frac{\Delta I_L}{8 * C} * T_{sw} \quad (4.9)$$

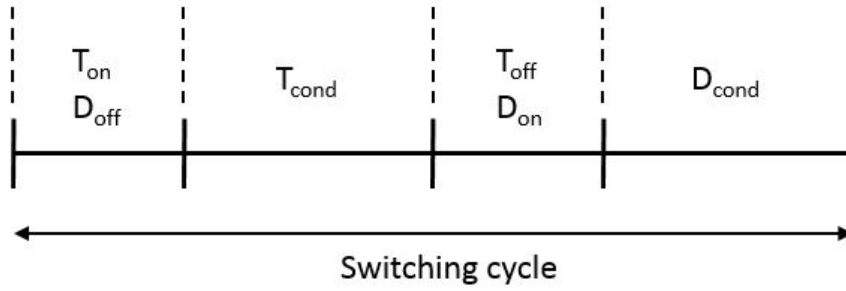


Figure 4.6.: The different states during one switching cycle, T stands for transistor and D the freewheeling diode

In most cases the maximum allowed output voltage ripple needs to be limited to a certain level. It is therefore important to dimension the capacitor for the case when the voltage ripple becomes the greatest. This occurs when the current ripple reaches its maximum corresponding to a duty cycle of 50%. An expression for the capacitance at this instance can be formulated as equation 4.10

$$C = \frac{\Delta I_{L(max)}}{8 * \Delta V_{out(max)}} * \frac{1}{f_{sw}} \quad (4.10)$$

4.3.3 Model of power losses

The inductance and capacitance losses are neglected in this example. The losses that occur on the power semiconductors are divided into two parts, the switching losses and the conduction losses, see figure 4.6. The total energy dissipation during one switching cycle can be expressed as the sum of the energies shown in equation 4.11. This energy is divided by the switching period to give the average power losses of the converter stated in equation 4.12. The turn on losses of the freewheeling diode are very small and can therefore be considered negligible [8].

$$E_{T,D}(T_{sw}) = \int_{T_{sw}} p_s(t) dt = E_{T(on)}(T_{sw}) + E_{T,D(off)}(T_{sw}) + E_{T,D(cond)}(T_{sw}) \quad (4.11)$$

$$Losses_{converter} = P_{T(cond)} + P_{T(on)} + P_{T(off)} + P_{D(cond)} + P_{D(off)} \quad (4.12)$$

4.3.3.1 Conduction losses

Conduction losses are alternating between the transistor and the free-wheeling diode. The conduction energy dissipated during one switching period can be expressed as 4.13.

$$E_{T,D(cond)}(T_{sw}) = \int_{t_{T,D(cond)}} p_s(t) dt = V_{T,D(cond)} * I_{out} * t_{T,D(cond)} \quad (4.13)$$

Where I_{out} is the average output current as well as the average inductor current and $V_{T,D(cond)}$ is the forward voltage characteristic of the respective semiconductor, expressed by equation 4.14.

$$V_{T,D(cond)} = V_{T,D(0)} + r_{T,D(cond)} * I_{out} \quad (4.14)$$

By linearizing the IV-characteristics for the IGBT module supplied by the manufacturer, the resistance, $r_{T,D(cond)}$ and internal voltage drop, $V_{T,D(0)}$ of the diode and transistor can be calculated.

Dividing the conduction energy by the switching time, the average power losses for the transistor, 4.15, and diode, 4.16, are calculated separately.

$$P_{T(cond)} = V_{T(cond)} * I_{out} * D = (I_{out}^2 * r_{T(cond)} + I_{out} * V_{T(0)}) * D \quad (4.15)$$

$$P_{D(cond)} = V_{D(cond)} * I_{out} * D_D = (I_{out}^2 * r_{D(cond)} + I_{out} * V_{D(0)}) * D_D \quad (4.16)$$

Where D_D is the duty cycle of the freewheeling diode, since this is conducting while the transistor is closed this gives $D_D = (1 - D)$.

4.3.3.2 Switching losses

During one switching cycle both the transistor and the freewheeling diode are turned on and off once. During these transitions the semiconductors are exposed to high voltage and high current which causes considerable energy losses. This energy can be expressed as 4.17 and 4.18.

$$E_{T(on)}(T_{sw}) = \frac{E_{T(on),n}}{V_{in,n} * I_{L,n}} * V_{in} * I_{out} \quad (4.17)$$

$$E_{T,D(off)}(T_{sw}) = \frac{E_{T,D(off),n}}{V_{in,n} * I_{L,n}} * V_{in} * I_{out} \quad (4.18)$$

Where the turn-on ($E_{T(on)}$) and the turn-off ($E_{T,D(off)}$) energies are specified in the datasheet. These energies are given for a certain voltage ($V_{in,n}$) and current ($I_{L,n}$), also given in the data sheet.

The average power losses during one switching period are then dependent on the frequency as shown in 4.19 and 4.20.

$$P_{T(on)} = \frac{E_{T(on)}}{T_{sw}} = \frac{E_{T(on),n}}{V_{in,n} * I_{L,n}} * V_{in} * I_{out} * f_{sw} \quad (4.19)$$

$$P_{T,D(off)} = \frac{E_{T,D(off)}}{T_{sw}} = \frac{E_{T,D(off),n}}{V_{in,n} * I_{L,n}} * V_{in} * I_{out} * f_{sw} \quad (4.20)$$

Note that I_{out} is the average output current.

4.3.4 Multi-level buck converter

By putting several buck converters in series a multi-level design is achieved. Figure 4.7 illustrates a multi-level buck converter.

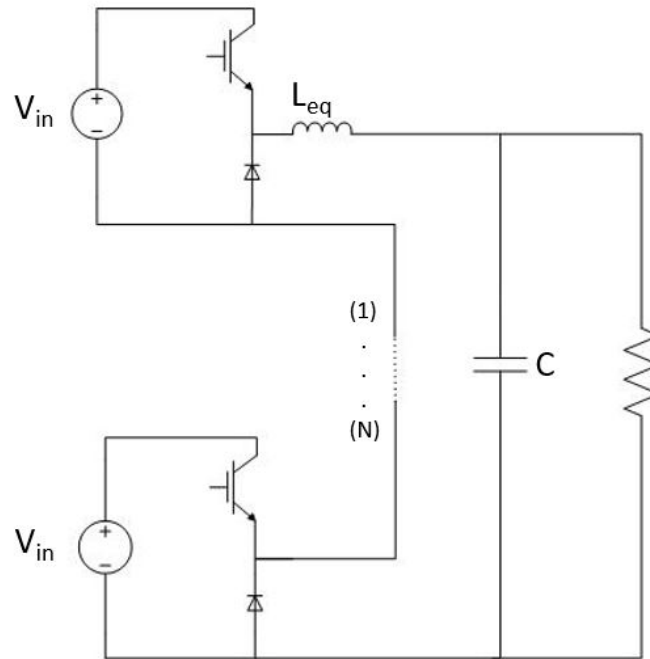


Figure 4.7.: Multi-level buck converter

Each individual buck converter, or module, has an input voltage source that corresponds to a fraction of the equivalent input voltage of a conventional buck converter. The multi-level topology offers a possibility to reduce the input voltage sources used by adding additional levels to the converter. The relation between the input voltage source of an individual buck converter used in a multi-level design

and the input voltage source of a conventional buck converter is described by equation 4.21.

$$V_{in} = \frac{V_{in(eq)}}{N_C} \quad (4.21)$$

Where N_C is the number of levels of the converter. The switching frequency is also different for a multi-level design compared to a conventional buck converter. By phase shifting the conduction part of a switching period symmetrically between the individual modules, the equivalent switching frequency of the multi-level buck converter is increased by a factor of N_C . The multi-level topology offers the possibility of switching the semiconductors at a lower switching frequency without reducing the equivalent switching frequency of the converter. Equation 4.22 describes the relation between the switching frequency of a conventional buck converter and a multi-level buck converter.

$$f_{sw} = \frac{f_{sw(eq)}}{N_C} \quad (4.22)$$

When putting several Buck converters in series the inductor of each individual module can be replaced by an equivalent inductor. The worst case current ripple occurs as for the conventional buck converter at a duty cycle of 50%. This is the case when the desired output voltage is right in between two input voltage levels of the converter. An expression for the inductance at the occurrence of maximum current ripple is formulated as equation 4.23. The expression for the capacitance at this instance is the same as for the conventional buck converter except for the switching frequency which is now N_C times as high. The capacitance for the multi-level design is formulated as equation 4.24.

$$L_{eq} = \frac{V_{in}}{4 * \Delta I_{L(max)}} * \frac{1}{N_C * f_{sw}} \quad (4.23)$$

$$C = \frac{\Delta I_L}{8 * \Delta V_{out(max)}} * \frac{1}{N_C * f_{sw}} \quad (4.24)$$

Note that f_{sw} and V_{in} are the parameters for an individual buck converter module.

The power losses associated with a multi-level buck converter are in principle the same as for a conventional buck converter. The multi-level design has equal losses in all modules which gives the converter losses the expression of equation 4.25. The losses for a multi-level buck converter are N_C times as many but the losses per module are

lower since both the input voltage and the switching frequency are lower relative to a conventional buck converter.

$$Losses_{converter} = N_C * (P_{T(cond)} + P_{T(on)} + P_{T(off)} + P_{D(cond)} + P_{D(off)}) \quad (4.25)$$

4.4 OPTIMIZATION OF A MULTI-LEVEL BUCK CONVERTER

It is desirable to invest in an as cheap converter as possible. It is also desirable to invest in a converter that run as efficient as possible since it will save money in the long run. These two properties almost never coincide and the objective here is to find the optimal compromise resulting in the lowest total cost (equipment and installation cost and operational cost integrated over the lifetime of the components). It is called to find the Pareto optimality as described in section 2.4. The objective function used for this optimization is 4.26.

$$Cost_{tot} = Cost_{operational} + Cost_{L(eq)} + Cost_C + N_C * Cost_{IGBTmodule} + N_C * Price_{instal} \quad (4.26)$$

$Cost_{L(eq)}$, $Cost_C$, $Cost_{IGBTmodule}$ and $Price_{instal}$ are the capital cost of the inductance, capacitance, the IGBT module and installation of the modules (assembling, cabling, testing, repair, etc.).

The operational cost ($Cost_{operational}$), explained in equation 4.27 depends on the converter losses, 4.25 and is calculated for a time period of 25 years considering 5500 effective full power hours.

$$Cost_{operational} = Losses_{converter} W * 10^{-3} * 5500 h/year * 25 years * Price_{el} \text{ €/kWh} \quad (4.27)$$

To prevent the converter from assuming unreasonably large values, a constraint for the maximum volume is imposed as 4.28.

$$Vol_{tot} = Vol_{L(eq)} + Vol_C + N_C * Vol_{IGBTmodule} \leq 0.3m^3 \quad (4.28)$$

The volume of the inductor ($Vol_{L(eq)}$) is the total volume of the equivalent inductor.

To invoke the correlation between the input voltage for each module and the output voltage, the constraint 4.29 is needed. In this optimization the converter is optimized for a duty cycle of 90%, which is also the maximum allowed duty cycle for the converter. At this duty cycle the output voltage is the nominal voltage, $V_{out,n}$, of the converter. The converter is considered running with maximum allowed current

output. For this reason the output current is the same as the nominal current of the converter.

$$V_{out} = V_{in} * D * N_C \quad (4.29)$$

It is crucial to impose constraints for the maximum allowed levels of current and voltage ripple respectively on the inductor and in the output voltage. For this optimization the maximum tolerated voltage ripple is set to 1% of the nominal output voltage. For the current, this level is set to 10% of the nominal output current defined by the constraint 4.31.

$$\Delta V_{out(max)} \leq 0.01 * V_{out,n} \quad (4.30)$$

$$\Delta I_{L(max)} \leq 0.1 * I_{out} \quad (4.31)$$

The input voltage is also constrained not to exceed a specified maximum value related to the rated voltage of the transistor. To guarantee safe operation this upper bound is added as a constraint expressed as equation 4.32.

$$V_{in,UB} = \frac{V_{rated}}{1.4} \quad (4.32)$$

The multi-level typology opens up for several different configurations of modules and input voltages, that all satisfy the constraint of equation 4.29. By letting the number of modules and the input voltage be design variables, allowing them to assume any value within its bounds, all possible combinations can be evaluated in the optimization. Since the physical properties and prices of the IGBT-modules vary for different voltage ratings the optimization is run several times applying different module set ups. By adding the results of the optimizations together, a complete representation of the problem is established.

IGBT-modules on the market usually come with rated voltages of 600, 1200, 1700 and 3300 Volt. In this optimization one transistor from each voltage level is arbitrary chosen giving four set ups with parameters shown in table 4.1.

	SKM 145GB066D	SKM 150GB12T4	SKM 400GB176D	FF200R33KF2C
$V_{rated}[V]$	600	1200	1700	3300
$V_{in,n}[V]$	300	600	1200	1800
$I_{L,n}[A]$	150	150	300	200
$E_{T,on}[mJ]$	8.5	19.2	170	365
$E_{T,off}[mJ]$	5.5	15.8	118	255
$E_{D,off}[mJ]$	3.5	13	78	255
$r_{T,cond}[m\Omega]$	7.9	10	5.6	12.5
$V_{D,0}[V]$	0.8	1	0.9	1.3
$V_{T,0}[V]$	0.6	0.9	1	1.9
$r_{D,cond}[m\Omega]$	5	9.1	3.2	15.2
$Cost_{IGBT} [€]$	82	109	237	749

Table 4.1.: Parameter values are taken from respective datasheet see Appendix [chap:AppendixC]. Prices for the 600, 1200 and 1700 Volt modules taken from farnell [9] and the price for the 3300 Volt module taken from Mouser Electronics [10]

The cost and volume of a capacitor is related to the energy it stores. Since the rated voltage over the capacitor is constant, this energy is proportional to the capacitance. Approximations of the cost and volume of the capacitor in this optimization are made as linear functions of energy expressed in equation 4.33 and 4.34

$$Cost_C = k_{C,cost} * \frac{1}{2} * C * V_{out,n}^2 \quad (4.33)$$

$$Vol_C = k_{C,vol} * \frac{1}{2} * C * V_{out,n}^2 \quad (4.34)$$

To get the values of $k_{C,cost}$ and $k_{C,vol}$, an estimation of the optimal capacitance is done and capacitors on the market close to that value are examined. These capacitors are shown in table 4.2. The *price/energy* and *volume/energy* values of the four capacitors are all close to each other and the third capacitor (B2586K7405K003) is arbitrarily chosen to represent the capacitor in the optimization with regard to price and volume.

For the cost and volume of the inductor the same approach as for the capacitor explained above is used. The approximative functions for the inductor are described by equation 4.35 and 4.36.

$$Cost_L = k_{L,cost} * \frac{1}{2} * L_{eq} * I_{out}^2 \quad (4.35)$$

$$Vol_L = k_{L,vol} * \frac{1}{2} * L_{eq} * I_{out}^2 \quad (4.36)$$

The inductors on the market that are examined are shown in table 4.3. For this optimization the values of $k_{L,cost}$ and $k_{L,vol}$ are taken from the second inductor (195C100).

<i>Modelnr</i>	B25856K7205K003	B25856J7305J003	B25856K7405K003	B25856K7505K003
Capacitance [μF]	2	3	4	5
Price [€]	313	494	578	503
Energy [J]	9	13.5	18	22.5
Price/energy [€/J]	34.8	36.6	32.1	22.4
Volume [m^3]	0.00060819	0.00086364	0.00107100	0.00155285
Volume/Energy [m^3/J]	0.00006758	0.00006397	0.00005950	0.00006902

Table 4.2.: Capacitance values taken from Mouser Electronics [10]

Model nr	195B150	195C100	195E100
Inductance [mH]	0.5	1	2.5
Price [€]	265	206	464
Energy [J]	5.6	5	12.5
Price/energy [€/J]	47.3	41.1	37.1
Volume [m^3]	0.0003278	0.0003875	0.0017
Volume/Energy [m^3/J]	0.00005823	0.00007749	0.0001337

Table 4.3.: Inductance values taken from Mouser Electronics [10]

Together with the characteristics of the IGBT-modules in table 4.1, table 4.4 concludes the parameters and values used in the optimization. The design variables in this optimization is compiled in table 4.5.

$V_{out,n}$ [V]	10000/2000
I_{out} [A]	100
$k_{C,cost}$ [€/J]	32.1
$k_{C,vol}$ [m^3/J]	0.0000595
$k_{L,cost}$ [€/J]	41.1
$k_{L,vol}$ [m^3/J]	0.00007749
$Price_{el}$ [€/kWh]	0.1
$Price_{Instal}$ [€/module]	3000

Table 4.4.: Summary of values used in the optimization

f_{sw}	V_{in}	N_C	$\Delta I_{L(max)}$	$\Delta V_{out(max)}$
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Table 4.5.: Design variables

In this problem the constraints are all linear and contains both equalities and inequalities. Since there are not more than one objective function, the choice of solver can be limited to the capability of handling single-objective optimization problems. The outlining of

the constraints and the objective function together with the fact that the optimization problem is a minimization problem gives enough information to choose a solver. From recommendations by Mathworks short reference for choice of optimization method (see appendix A), the choice of solver for this problem is `fmincon`. To increase the chance of finding the best solution the Global search method is used together with `fmincon`.

4.5 RESULTS AND VALIDATION

The optimization is run for two voltage requirements, 10 kV and 2 kV.

4.5.1 *Optimization with an output voltage of 10kV*

The optimization evaluates solutions based on the four different IGBT modules with regards to total cost and the resulting design parameters are presented in table 4.6. By comparing the total cost, the optimal design of the converter is found to be the one using $IGBT_{module3}$ with 10 modules.

IGBT-module	$IGBT_{module1}$ SKM145GB066D	$IGBT_{module2}$ SKM150GB12T4	$IGBT_{module3}$ SKM400GB176D	$IGBT_{module4}$ FF200R33KF2C
fsw [Hz]	293	421	371	404
Vin [V]	427	855	1111	2222
Nr of modules	26	13	10	5
L (total) [mH]	4.24	8.35	14	36.49
C [μF]	0.54	1.07	1.8	4.67
Total cost [€]	132990	81257	64884	70158
Capital cost [€]	81878	43847	38136	33736
Operational cost [€]	51112	37410	26748	36422
Installation cost (1 module) [€]	3000	3000	3000	3000
Installation cost (N modules) [€]	78000	39000	30000	15000
Cost L (N modules) [€]	871	1715	2883	7496
Cost C [€]	2033	1715	2883	7496
Cost IGBT (1 module) [€]	82.2	109	237.1	748.8
Cost IGBT (N modules) [€]	2136	1417	2371	3744
Price electricity [€]	0.1	0.1	0.1	0.1
Converter losses (N modules) [W]	3717	2721	1945	2649
Conduction losses (N module) [W]	3591	2471	1526	1559
Switching losses (N module) [W]	127	250	419	1090
Total volume [m^3]	0.0058	0.0077	0.0127	0.03
Volume L (N modules) [m^3]	0.0016	0.0032	0.0054	0.014
Volume C [m^3]	0.0016	0.0032	0.0054	0.014
Volume IGBT (N modules) [m^3]	0.0025	0.0012	0.002	0.0016

Table 4.6.: Optimized values for four different IGBT-modules [output voltage of 10 kV]

The table above gives a lot of information that demonstrate the complexity of this optimization problem.

Notice that the capital cost of $IGBT_{module3}$ is not the lowest. The operational cost is by far lower than for the other IGBT-modules. The main part of the capital cost is, for all IGBT modules except $IGBT_{module4}$, the installation cost. For $IGBT_{module1}$ it is as much as 95% of the total capital cost and for $IGBT_{module3}$ it is 79%. Even if the installation cost would be neglected, the best solution would still be $IGBT_{module3}$. The reason for this is the great impact the number of modules have on the power losses.

The optimization chooses to decrease the number of modules to be as low as possible for all the IGBT modules. The lower restriction on the number of modules is because of the limiting ratings on the input voltage of each module. This will give an inevitable lower bound to the installation cost.

The price of the inductor and capacitor depend on the capacitance and inductance which are linked to the input voltage, switching frequency, the number of modules and current- and voltage ripple. Since the input voltage is maximized to allow a minimum amount of modules, the switching frequency and both ripples can be changed to decrease the both inductance and capacitance. The current ripple is represented in both the equation for inductance and the equation for capacitance, see 4.23 and 4.24. To get the inductance small the current ripple should be increased as high as possible, but this maximization is in direct conflict with the value of the capacitance which wants to decrease the ripple to get smaller. A Pareto optimality is found where the cost of inductance and cost of capacitance is equally high. The voltage ripple is, due to equation 4.24, set to it's higher bound to decrease the capacitance. A change in the switching frequency will affect the capacitance and inductance in the same way, and for both cases a higher frequency provides lower values.

One reason why the frequency remains below the upper bound is because of the operational cost which depend on the power losses. A higher switching frequency results in higher switching losses and as can be seen in the table above, $IGBT_{module3}$ does not have the highest frequency but neither the lowest. This means that the optimization has found a switching frequency that gives the optimal point on the Pareto front between capital- and operational cost.

Another observation from the table is the small total volume. For all the IGBTs the total volume is far below the maximum allowed volume. The volume constraint of $0.3 m^3$ has clearly no or, very a small, impact on the solution. By letting the upper bound of the total volume increase from low value to a higher value the impact of this constraint can be plotted, this is shown in figure 4.8.

By analyzing the figure it can be seen that depending on the maximum allowed volume, different IGBT module give the optimal solution. An interesting crossing point between $IGBT_{module4}$ and $IGBT_{module1}$ occurs at $0.006 m^3$. Before this point, $IGBT_{module1}$ is a better solution but this changes dramatically after this point where $IGBT_{module4}$ becomes the better solution. The low number of modules for $IGBT_{module4}$ forces the switching frequency to increase to be able to keep the volume of the passive components down. This results in high power losses as the volume restriction is enhanced. Another crossing point occurs between $IGBT_{module2}$ and $IGBT_{module3}$. The changes are not as dramatic as for $IGBT_{module1}$ and $IGBT_{module4}$ but the reason for the crossing is the same.

These crossing points show the importance of finding the optimal solution for every new case when designing a converter, and to find

these crossing points without using a methodology such as the one presented here would be difficult.

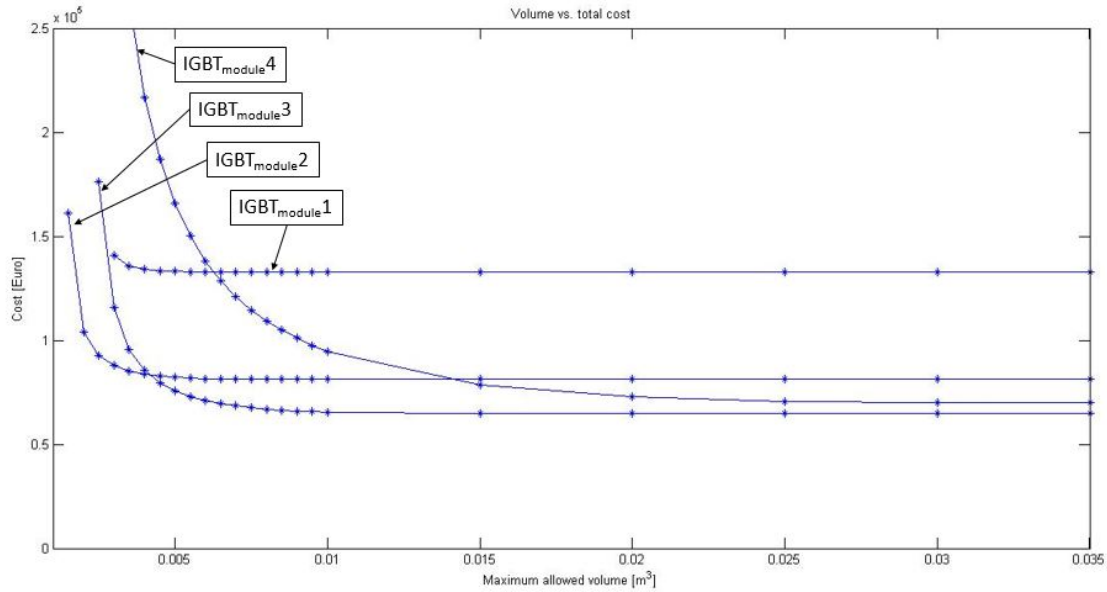


Figure 4.8.: Volume dependency of total cost. Optimization made at $V_{out} = 10kV$ and IGBT₁ = 400 V with $N = 26$, IGBT₂ = 1200 V with $N = 13$, IGBT₃ = 1700 V with $N = 10$ and IGBT₄ = 3300 V with $N = 5$.

The total cost can be divided into capital- and operational cost, shown in figure 4.9 and 4.10. As discussed above the installation cost is a big part for all the IGBT solutions, this can be seen in figure 4.9 where the maximum allowed volume has a small effect on the capital cost. The money to be saved in a smaller capacitor and inductor is very low compared to the installation price which is constant through the whole spectra. The ratio between installation cost and capital cost for the different $IGBT_{modules}$ can be seen by the slopes since the installation cost remains constant while the cost of inductance and capacitance changes. $IGBT_{module4}$, which has the lowest amount of modules and the highest switching frequency and thus has to reduce the inductance and capacitance the most, reduces the capital cost the most when the maximum allowed volume is reduced. The volume constraint has, on the contrary, nearly no impact on $IGBT_{module1}$ which can be seen by the almost non existing slope.

4.5 RESULTS AND VALIDATION

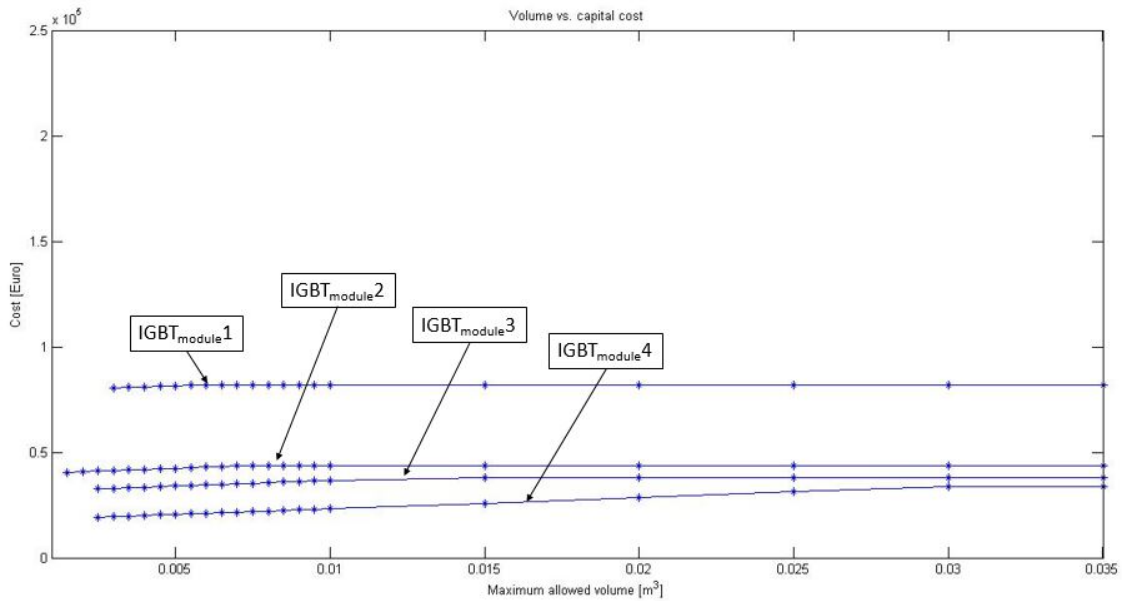


Figure 4.9.: Volume dependence of capital cost. Optimization made at $V_{out} = 10kV$ and IGBT₁ = 400 V with $N = 26$, IGBT₂ = 1200 V with $N = 13$, IGBT₃ = 1700 V with $N = 10$ and IGBT₄ = 3300 V with $N = 5$.

Unlike the capital cost, the maximum allowed volume has a very large impact on the operational cost, see figure 4.10. A smaller volume will force the inductor and capacitor to decrease, this will lead to an increase of the switching frequency and therefore also an increase of the power losses.

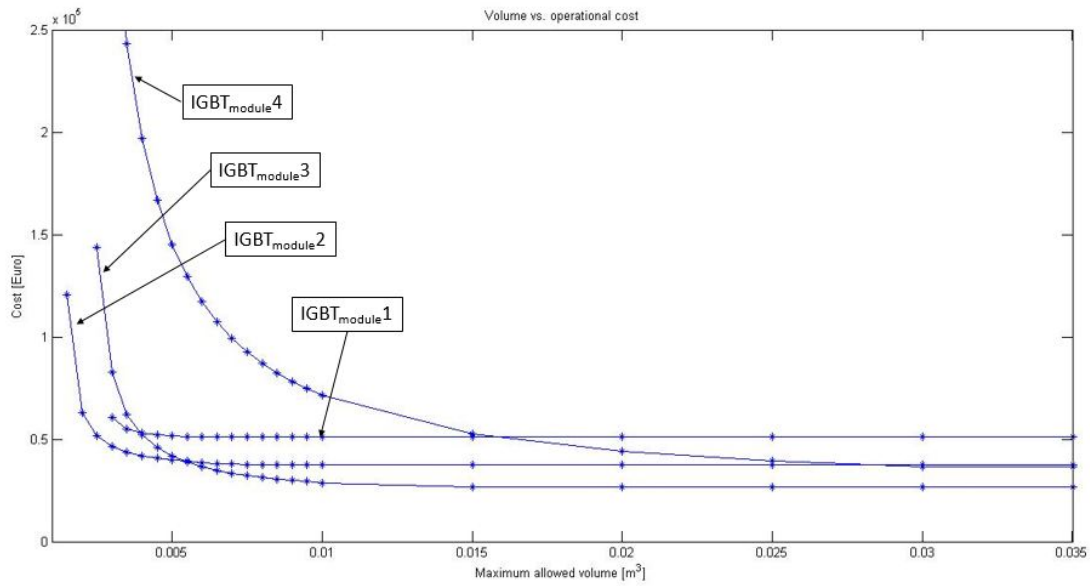


Figure 4.10.: Volume dependence of operational cost. Optimization made at $V_{out} = 10kV$ and $IGBT_1 = 400 V$ with $N = 26$, $IGBT_2 = 1200 V$ with $N = 13$, $IGBT_3 = 1700 V$ with $N = 10$ and $IGBT_4 = 3300 V$ with $N = 5$.

4.5.2 Optimization with an output voltage of 2kV

The optimization was also run for the case with an output voltage of 2kV. All other values and parameters are the same as for the 10kV case. The resulting design parameters are presented in table 4.7. As for the 10kV case, $IGBT_{module3}$ was calculated to be the optimal solution, although now with two modules instead of ten.

The most interesting result with this case is the number of modules the optimization chooses for $IGBT_{module4}$. For an output of 2kV it's possible to only use 1 module since the nominal input voltage of this IGBT is 3.3kV, but the optimization finds that the total cost is lower if using 2 modules. The values from the optimization when forcing the number of modules to be 1 is shown in table 4.8. Since only switching with one module the switching frequency needs to be increased which will lead to higher converter losses. The increased input voltage and the ratio between the change of number of modules and switching frequency leads to bigger inductor and capacitor for the 1-level converter. All these factors summed up together gives a higher total cost.

4.5 RESULTS AND VALIDATION

IGBT-module	$IGBT_{module1}$ SKM145GB066D	$IGBT_{module2}$ SKM150GB12T4	$IGBT_{module3}$ SKM400GB176D	$IGBT_{module4}$ FF200R33KF2C
fsw [Hz]	880	1264	1251	809
Vin [V]	370	741	1111	1111
Nr of modules	6	3	2	2
L (total) [mH]	2.55	5.01	11.1	17.17
C [μF]	8.15	16.05	24.98	38.63
Total cost [€]	31979	21289	18442	28084
Capital cost [€]	19539	11387	10360	13505
Operational cost [€]	12440	9902	8082	14579
Installation cost (1 module) [€]	3000	3000	3000	3000
Installation cost (N modules) [€]	18000	9000	6000	6000
Cost L (N modules) [€]	523	1030	2281	3527
Cost C [€]	523	1030	1604	2480
Cost IGBT (1 module) [€]	82	109	237	749
Cost IGBT (N modules) [€]	493	327	474	1497
Price electricity [€]	0.1	0.1	0.1	0.1
Converter losses (N modules) [W]	905	720	588	1060
Conduction losses (N module) [W]	829	570	305	623
Switching losses (N module) [W]	76	150	283	437
Total volume [m^3]	0.0025	0.0041	0.0077	0.0119
Volume L (N modules) [m^3]	0.00099	0.00194	0.0043	0.0067
Volume C [m^3]	0.00097	0.00191	0.00297	0.0046
Volume IGBT (N modules) [m^3]	0.00058	0.00029	0.00039	0.00064

Table 4.7.: Optimized values for four different IGBT-modules [output voltage of 2 kV]

Nr of Modules	1
Total cost [€]	29442
fsw [Hz]	1414
Vin [V]	2222
L (total) [mH]	38.55
C [μF]	43.37
Converter losses (N modules) [W]	1090
Conduction losses (N module) [W]	312
Switching losses (N module) [W] [1ex]	778

Table 4.8.: Optimized values for $IGBT_{module4}$ with 1 module [output voltage of 2 kV]

4.6 VALIDATION USING SIMULINK

In order to verify the solution from the optimization, MATLAB simulation software Simulink is used. The optimal solution of the multi-level buck converter with an output voltage of 10kV is designed using the optimal values received from the optimization and the circuit is drawn in Simulink as shown in figure 4.12.

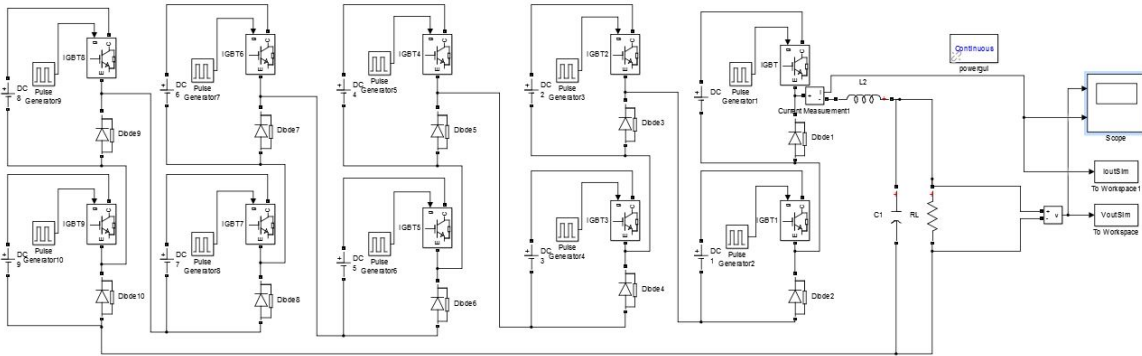


Figure 4.11.: Optimized 10kV converter designed in Simulink

The output resistance is set to be 100Ω , due to ohm's law and the requirement of a 100 A current output. The verification of the design consists of making sure that the output voltage ripple never exceeds its maximum allowed value.

The maximum voltage ripple occur when the desired output voltage is right in between two input voltage levels. In this case the converter has to switch between these two levels with a corresponding duty cycle of 50%. When simulating for the 10kV output using ten modules, a duty cycle of 85% is chosen which corresponds to switching between eight and nine modules. The resulting voltage and current ripple are shown in figure 4.12.

For the converter with an output voltage of 2kV a Simulink model with two modules are designed and the output resistance is set to be 200Ω . To simulate for the worst case a duty cycle of 75% is chosen which corresponds to switching between one and two modules. The resulting ripples are shown in figure 4.13.

As can be seen in the plots, both the current and the voltage ripple is within their respective bounds.

4.6 VALIDATION USING SIMULINK

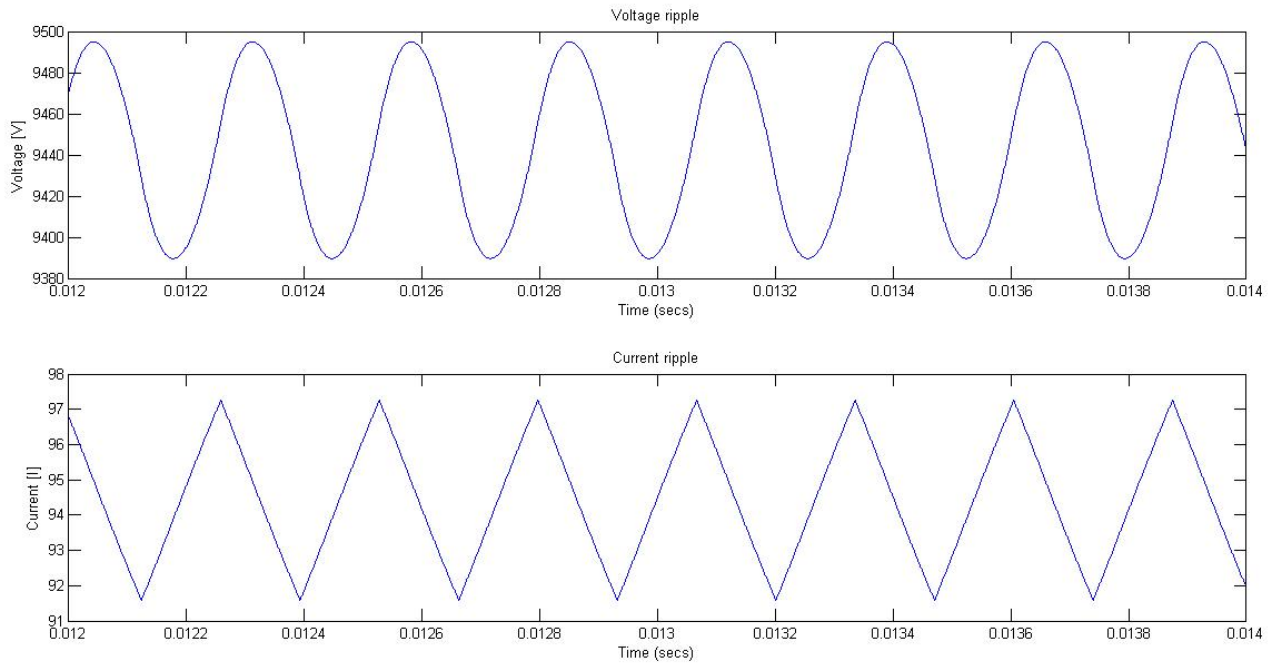


Figure 4.12.: Simulated output voltage- and current ripples for the 10kV converter

4.6 VALIDATION USING SIMULINK

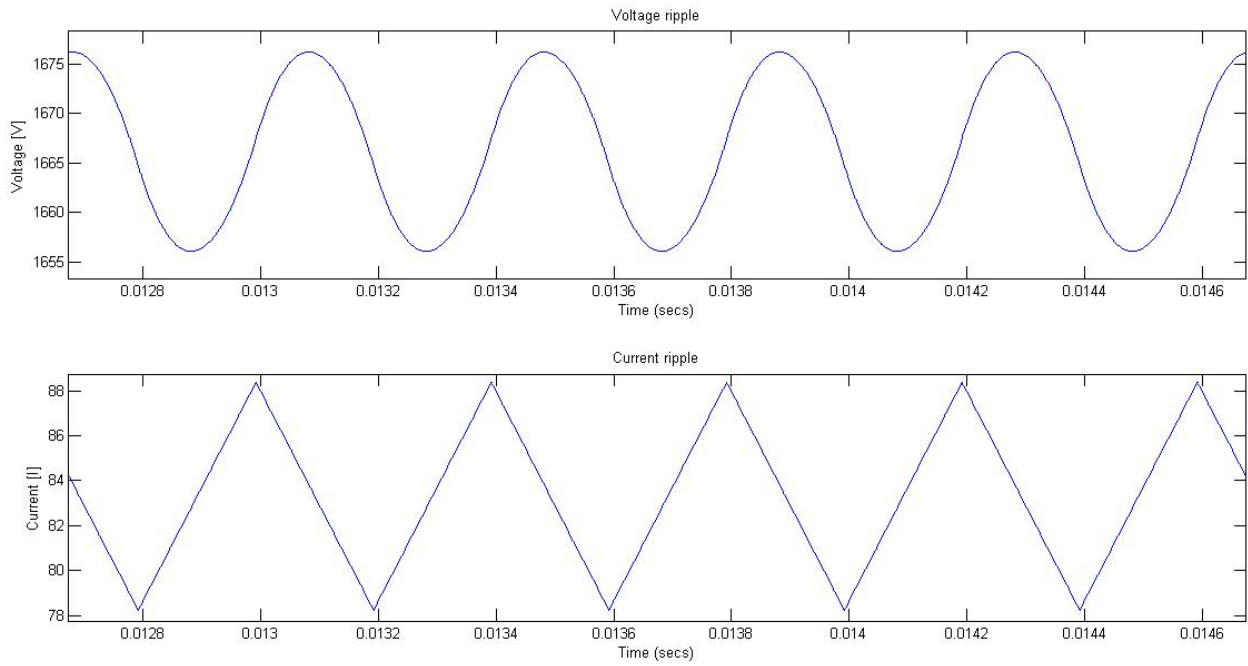


Figure 4.13.: Simulated output voltage- and current ripples for the 2kV converter

CONCLUSIONS

This chapter contains a discussion of the thesis and also proposes some future work.

5.1 DISCUSSION

The results from the two optimization problems show that a well working method has been developed. The two validation methods used confirm that the results satisfy the requirements. In order to further analyze these results, an experimentally developed validation needs to be done. This is presented as future work.

The results from the converter example point out that it can be advantageous to use a multi-level typology not only in terms of lower distortion and less harmonics but that it also can compete with conventional two-level converters with regards to cost, volume and efficiency.

The inductor example shows that finding the optimal solution of a single passive component may sound easy, but once the description of the component is done, the boundary conditions are set and the multiple objectives are defined, it can be seen what a difficult task it is. Or even impossible to be done by the most experienced designer. When done for a circuit with several components like in the converter example it gets even more intricate. A change in one variable often leads to changes in many others, and to find where the relationship between all these variables make up the optimal solution is complicated. If the optimal solution is related to cost it is worth mentioning that the aspect of time makes it hard to compare operational cost with capital cost. In the case of modular power converters the relation between conduction losses and switching losses and their respective influence on the operational cost makes it even harder. The complexity of figuring out these results by hand even for a experienced engineer points out the importance of this kind of methodology.

An optimization is easily configured in the software using the presented methodology. It is describing the system that is the time consuming part but for an experienced engineer this can often be done easily. Many of the formulas needed to perform an optimization is also used in the conventional approach of designing. The extra work

of putting them into the optimization software and using this methodology is small compared to the energy and money that can be saved if an optimal design can be proven found.

One main feature with this methodology is that it is not limited to be used only with power electronics. The methodology can be used on nearly anything that can be expressed with a mathematical model and translated into objective functions and constraints. We believe that the increasing importance of energy efficiency is forcing a paradigm change in the methodology of designing power electronics. This will make a methodology like the one presented in this work a necessary approach in the future.

5.2 FUTURE WORK

Proposal for future work in this field are:

- Investigate the option of using nested functions to increase the accuracy of the optimization. As for example using the inductor optimization to find optimal values for the inductance in the converter while optimizing the converter. This approach can be extended for all components.
- Develop more accurate models for volume and cost. For example include space for assembling and heatsinks into the model of volume.
- Validate the methods and optimized solutions with experimental results and not only by simulation tools.
- Investigate the option of making a more user friendly GUI for the optimization software. For now the user needs to write MATLAB scripts even when using the optimization app. This could be done automatically when the user feeds in the objective functions and constraints into the input fields.
- Include an aspect of reliability to the optimization problem. For example adding a cost for maintenance and down time that scales with the complexity of the design that is adding more levels.

BIBLIOGRAPHY

- [1] Erica Lindström. *Energy & Sustainability*. URL: <http://europeanspallationsource.se/energy-sustainability> (visited on 09/29/2014).
- [2] Jasbir S. Arora. *Introduction to Optimum Design, third edition*. Iowa City, Iowa: The University of Iowa College of Engineering, 2012.
- [3] *Optimization Toolbox User's Guide, R2014a*. Mathworks, 2014.
- [4] *Global Optimization Toolbox User's Guide, R2014a*. Mathworks, 2014.
- [5] Rajeev Bansal. *Handbook of Engineering Electromagnetics*. CRC Press, 2004.
- [6] Lars Gertmar Mats Alaküla and Olof Samuelsson. *Elenergiteknik*. Lund Institute of Technology: Department of Industrial Electrical Engineering and Automation (IEA), 2011.
- [7] Andreas Nordvall. "Multilevel Inverter Topology Survey". MA thesis. Chalmers University of Technology, 2011.
- [8] Mats Alaküla and Per Karlsson. *Power Electronics - Devicec, Converters, Control and Applications*. Lund Institute of Technology: Department of Industrial Electrical Engineering and Automation (IEA).
- [9] Farnell element14. URL: <http://www.farnell.com> (visited on 09/02/2014).
- [10] Mouser Electronics. URL: <http://www.mouser.com> (visited on 09/02/2014).

LIST OF FIGURES

Figure 2.1	Pareto Front	13
Figure 2.2	Optimization toolbox, [3]	14
Figure 2.3	Rastrigin function [4]	18
Figure 3.1	Basic inductor structure	21
Figure 3.2	Command Window fixed N_I	27
Figure 3.3	Iterations	28
Figure 3.4	Powerlosses for different prices	29
Figure 3.5	Inductor designed in FEMM	30
Figure 4.1	A three-level waveform, a five-level waveform and a seven-level waveform, switched at fundamental frequency, [7]	32
Figure 4.2	BuckConverter	34
Figure 4.3	The current ripple with a duty cycle, D , of 50%.	35
Figure 4.4	Equivalent circuit for the converter during on-state.	35
Figure 4.5	Ripple of inductor current	36
Figure 4.6	The different states during one switching cycle, T stands for transistor and D the free-wheeling diode	37
Figure 4.7	Multi-level buck converter	39
Figure 4.8	Volume dependency of total cost. Optimization made at $V_{out} = 10kV$ and IGBT1 = 400 V with $N = 26$, IGBT2 = 1200 V with $N = 13$, IGBT3 = 1700 V with $N = 10$ and IGBT4 = 3300 V with $N = 5$.	48
Figure 4.9	Volume dependence of capital cost. Optimization made at $V_{out} = 10kV$ and IGBT1 = 400 V with $N = 26$, IGBT2 = 1200 V with $N = 13$, IGBT3 = 1700 V with $N = 10$ and IGBT4 = 3300 V with $N = 5$.	49
Figure 4.10	Volume dependence of operational cost. Optimization made at $V_{out} = 10kV$ and IGBT1 = 400 V with $N = 26$, IGBT2 = 1200 V with $N = 13$, IGBT3 = 1700 V with $N = 10$ and IGBT4 = 3300 V with $N = 5$.	50
Figure 4.11	Optimized 10kV converter designed in Simulink	52
Figure 4.12	Simulated output voltage- and current ripples for the 10kV converter	53

List of Figures

Figure 4.13 Simulated output voltage- and current ripples
for the 2kV converter 54

LIST OF TABLES

Table 3.1	Design variables	23
Table 3.2	Power losses	24
Table 3.3	Optimized design variables	24
Table 3.4	Material properties	26
Table 3.5	Optimized design variables	26
Table 3.6	Optimized inductor outer dimensions	27
Table 3.7	Different prices of copper, iron and electricity	27
Table 3.8	Losses and cost for A,B,C,D examples	27
Table 4.1	Parameter values are taken from respective datasheet see Appendix [chap:AppendixC]. Prices for the 600, 1200 and 1700 Volt modules taken from farnell [9] and the price for the 3300 Volt module taken from Mouser Electronics [10]	43
Table 4.2	Capacitance values taken from Mouser Electronics [10]	44
Table 4.3	Inductance values taken from Mouser Electronics [10]	44
Table 4.4	Summary of values used in the optimization	44
Table 4.5	Design variables	44
Table 4.6	Optimized values for four different IGBT-modules [output voltage of 10 kV]	46
Table 4.7	Optimized values for four different IGBT-modules [output voltage of 2 kV]	51
Table 4.8	Optimized values for $IGBT_{module4}$ with 1 module [output voltage of 2 kV]	51

ACRONYMS

AC Alternating Current

DC Direct Current

EMC Electromagnetic compatibility

ESS European Spallation Source

IGBT Insulated-gate bipolar transistor

LB Lower bound

SQP Sequential Quadratic Programming

UB Upper bound

NOMENCLATURE

ΔI_L	Current ripple
$\Delta I_{L(max)}$	Maximum current ripple
ΔQ	Capacitor change of charge
$\Delta V_{out(max)}$	Maximum output voltage ripple
ΔV_{out}	Output voltage ripple
δ_{cu}	Copper density
δ_{fe}	Iron density
μ_0	Vacuum permeability
Φ	Magnetic Flux
ρ	Resistivity of copper
a	Dimension of the inductor, width
B	Flux density
C	Capacitance
$Cost_C$	Capital cost of capacitor
$Cost_{capital}$	Capital cost
$Cost_{IGBT}$	Capital cost of IGBT module
$Cost_{L(eq)}$	Capital cost of equivalent inductor
$Cost_{operational}$	Operational cost
$Cost_{tot}$	Total cost
D	Duty cycle
d	Dimension of the inductor, depth
D_D	Duty cycle of diode
E	Magnetic field energy
$E_{D(on)}$	Diode turn on energy
$E_{T(on),n}$	Transistor turn on energy for a nominal voltage and current

List of Tables

$E_{T(on)}$	Transistor turn on energy
$E_{T,D(cond)}$	Transistor/Diode energy diversion during conduction
$E_{T,D(off),n}$	Transistor/Diode turn off energy for a nominal voltage and current
$E_{T,D(off)}$	Transistor/Diode turn off energy
$E_{T,D}(T_{sw})$	Transistor/Diode total energy diversion during one switching cycle
$f_{sw(eq)}$	Equivalent switching frequency
f_{sw}	Switching frequency
g	Air gap length
H	Inductor total height
I	Current
$i_L(t)$	Function of inductor current
$I_{L,n}$	Nominal current ripple
I_{out}	Average output current
$i_{ripple}(t)$	Function of current ripple
J	Current density
$k_{C,cost}$	Constant for calculation of $Cost_C$
$k_{C,vol}$	Constant for calculation of Vol_C
$k_{L,cost}$	Constant for calculation of $Cost_I$
$k_{L,vol}$	Constant for calculation of $Vol_{L(eq)}$
L	Inductance
l	Width of wires
$Losses_{converter}$	Average converter losses
$Losses_{inductor}$	Power losses of inductor
N_C	Number of levels in the multi-level topology
N_I	Number of windings
$p_s(t)$	Instantaneous loss
$P_{D(cond)}$	Diode average conduction losses

List of Tables

$P_{D(off)}$	Diode average turn off losses
$P_{T(cond)}$	Transistor average conduction losses
$P_{T(off)}$	Transistor average turn off losses
$P_{T(on)}$	Transistor average turn on losses
$Price_{cu}$	Copper price
$Price_{el}$	Electricity price
$Price_{fe}$	Iron price
$Price_{instal}$	Installation cost for 1 module
R	Wire cross section radius
$r_{T,D(cond)}$	Transistor/Diode resistance
S_{cu}	Cross section area of copper wire
T_{sw}	Switching time period
$t_{T,D(cond)}$	Transistor/Diode conduction time
V	Voltage
V_L	Voltage over inductor
$V_{in,n}$	Nominal input voltage
$V_{in,UB}$	Upper bound of input voltage
V_{in}	Input voltage
$V_{L(ON)}$	Voltage applied on inductor during on-state
$V_{out,n}$	Nominal output voltage
V_{out}	Output voltage
V_{rated}	Rated voltage
$V_{T,D(0)}$	Forward voltage at zero current
$V_{T,D(cond)}$	Transistor/Diode forward voltage characteristic
Vol_C	Capacitor volume
Vol_{cu}	Copper volume
Vol_{fe}	Iron volume
Vol_{IGBT}	IGBT module volume
$Vol_{L(eq)}$	Equivalent inductor volume

List of Tables

Vol_{tot}	Total volume
W	Inductor total depth
X	Inductor total width

Part III

APPENDIX

A

APPENDIX A - MATHWORKS SHORT REFERENCE FOR CHOICE OF SOLVER

Minimization Problems

Type	Formulation	Solver
Scalar minimization	$\min_x f(x)$ <p>such that $lb < x < ub$ (x is scalar)</p>	fminbnd
Unconstrained minimization	$\min_x f(x)$	fminunc, fminsearch
Linear programming	$\min_x f^T x$ <p>such that $Ax \leq b, Aeqx = beq, lb \leq x \leq ub$</p>	linprog
Mixed-integer linear programming	$\min_x f^T x$ <p>such that $Ax \leq b, Aeqx = beq, lb \leq x \leq ub,$ $x(\text{intcon})$ is integer-valued.</p>	intlinprog
Quadratic programming	$\min_x \frac{1}{2} x^T Hx + c^T x$ <p>such that $Ax \leq b, Aeqx = beq, lb \leq x \leq ub$</p>	quadprog

Minimization Problems (Continued)

Type	Formulation	Solver
Constrained minimization	$\min_x f(x)$ <p>such that $c(x) \leq 0, ceq(x) = 0, Ax \leq b,$ $Aeqx = beq, lb \leq x \leq ub$</p>	fmincon
Semi-infinite minimization	$\min_x f(x)$ <p>such that $K(x,w) \leq 0$ for all $w, c(x) \leq 0,$ $ceq(x) = 0, Ax \leq b, Aeqx = beq, lb \leq x \leq ub$</p>	fseminf

Multiobjective Problems

Type	Formulation	Solver
Goal attainment	$\min_{x,\gamma} \gamma$ <p>such that $F(x) - w\gamma \leq \text{goal}, c(x) \leq 0, ceq(x) = 0,$ $Ax \leq b, Aeqx = beq, lb \leq x \leq ub$</p>	fgoalattain
Minimax	$\min_x \max_i F_i(x)$ <p>such that $c(x) \leq 0, ceq(x) = 0, Ax \leq b,$ $Aeqx = beq, lb \leq x \leq ub$</p>	fminimax

Equation Solving Problems

Type	Formulation	Solver
Linear equations	$Cx = d$, n equations, n variables	\ (matrix left division)
Nonlinear equation of one variable	$f(x) = 0$	fzero
Nonlinear equations	$F(x) = 0$, n equations, n variables	fsolve

Least-Squares (Model-Fitting) Problems

Type	Formulation	Solver
Linear least-squares	$\min_x \frac{1}{2} \ C \cdot x - d\ _2^2$ m equations, n variables	\ (matrix left division)
Nonnegative linear-least-squares	$\min_x \frac{1}{2} \ C \cdot x - d\ _2^2$ such that $x \geq 0$	lsqnonneg
Constrained linear-least-squares	$\min_x \frac{1}{2} \ C \cdot x - d\ _2^2$ such that $Ax \leq b$, $Aeqx = beq$, $lb \leq x \leq ub$	lsqlin

Least-Squares (Model-Fitting) Problems (Continued)

Type	Formulation	Solver
Nonlinear least-squares	$\min_x \ F(x)\ _2^2 = \min_x \sum_i F_i^2(x)$ such that $lb \leq x \leq ub$	lsqnonlin
Nonlinear curve fitting	$\min_x \ F(x, xdata) - ydata\ _2^2$ such that $lb \leq x \leq ub$	lsqcurvefit

B

APPENDIX B - MATLAB CODE

Matlab code for inductor optimization

Main Script

```

%Main Script for the optimiazion of an inductor,
%The constrains are in the m-file constrains.m and the objective function
%in the m-file InductorFunction.m

clear all
global y0 I ra Xub Hub wub Bub Llb PriceCu PriceFe DensityCu...
    DensityFe PriceEl history searchdir

%history and searchdir saves values for each iteration
history.x = [];
history.fval = [];
searchdir = [];

%Different Values, Low(L), Medium(M) and High(H)
%Copper price
LC = 1;
MC = 5.03;
HC = 10;
%Iron price
LF = 0.05;
MF = 0.81;
HF = 1.81;
%Electricity price
LE = 0.05;
ME = 0.1;
HE = 0.15;

%Material Properties
PriceCu = MC;           %Copper price
PriceFe = MF;           %Iron price
PriceEl = LE;           %Electricity price
DensityCu = 8920;       %Copper density
DensityFe = 7874;       %Iron density
y0 = 4*pi*10^-7;       %Vacuum permability
I = 100;                %Current
ra = 0.0000000172;     %Resistivity of copper

%The upper bounds for X, H, w, B and lower bound for L
Xub = 1;
Hub = 1;
wub = 1;
Bub = 1;
Llb = 0.02;

```

APPENDIX B - MATLAB CODE

```

%Optimization variables for [a d l N R h g]
lb = [0.01 0.01 0.01 1 0.001 0.01 0.001]; %Lower Bounds
ub = [1 1 1 inf 1 1 0.01]; %Upper Bounds
startPoint =[0.3 0.3 0.05 7 0.003 0.15 0.001];%Start points
A = []; %Linear inequality constraint
b = []; %Linear inequality constraint
Aeq = []; %Linear equality constraint
beq = []; %Linear equality constraint

```

```

%Optimization algorithm
options = optimoptions(@fmincon,'OutputFcn',@outfun,...
    'Algorithm','sqp');
problem = createOptimProblem('fmincon', 'objective',...
    @InductorFunction,'nonlcon',@constrains,'x0', startPoint, ...
    'lb', lb, 'ub', ub,'options',options);
gs = GlobalSearch;
[x,fg,exitflag,output,solutions] = run(gs,problem)

```

ToFemm %Sends the values to FEMM and gets the L back

% All code below is for displaying in the commandwindow and is not
% important for the optimization!!!!!!

```

pointer = 1; %Pointer for displaying in commandwindow
if pointer == 1
    %The optimized values uses to calculatate the "size variables"
    X = 2.1*l+2*a;
    H = h+2*a;
    W = 2*l+d;
    L = y0*N^2*a*d/g;
    B = y0*N*I/g;
    J = I/(pi*R^2);
    NpiR = N*pi*R^2/0.8;
    lh = l*h;
    %Display the values in Command window
    PCopperLosses = ra*N*(2*(l+a)+2*(l+d))*I^2/(pi*R^2); %Copper Losses
    volCu = (2*a+2*d+4*l)*R^2*pi*N; % Volume Copper
    volFe = (2*a+1.1*l)*(2*a+h)*d-(1.1*l*h*d); %Volume Iron
    Ccap = volCu*DensityCu*PriceCu+volFe*DensityFe*PriceFe; %Capital cost
    Cop = PCopperLosses*(10^-3)*5500*25*PriceEl; %Operation cost
    ICost = Ccap+Cop;

    weightCu = volCu*DensityCu;
    weightFe = volFe*DensityFe;

    L_FEMM = E_FEMM^2/(I^2); %Calculates L from FEMM Magnetic Field Energy
    B_FEMM = sqrt(Bvalues(2)^2+Bvalues(3)^2);
    disp(' ')
    disp('Calculated Values by the optimized values')
    ITotalCost = ['TotalCost = ', num2str(ICost), ' Euro'];
    disp(ITotalCost)
    PCopper = ['PCopperLosses = ', num2str(PCopperLosses), ' W'];

```



```

disp(PCopper)
PriceElectricity = ['Electricity price = ',...
    num2str(PriceE1), ' Euro/kwh'];
disp(PriceElectricity)
weightandPriceCopper = ['Copper weight and price = ',...
    num2str(weightCu), ' kg, ', num2str(PriceCu), ' Euro/kg'];
disp(weightandPriceCopper)
weightandPriceIron = ['Iron weight and price = ', num2str(weightFe),...
    ' kg, ', num2str(PriceFe), ' Euro/kg'];
disp(weightandPriceIron)
Constants = ['a = ', num2str(a), ', d = ', num2str(d),...
    ', l = ', num2str(l), ', N = ', num2str(N), ', R = ', ...
    num2str(R), ', h = ', num2str(h), ', g = ', num2str(g)];
disp(Constants)

BigConstants= ['X = ', num2str(X), ', H = ', num2str(H), ', W = '...
    , num2str(W), ', L = ', num2str(L), ', B = ', num2str(B),...
    ', J = ', num2str(J), ', lh = ', num2str(lh), ', NpiR^2 = ', ...
    num2str(NpiR)];
disp(BigConstants)
L = ['L from FEMM = ', num2str(L_FEMM), ' H'];
disp(L)
%DrawInductor; %Draw inductor in Matlab
Ccap
Cop
end

```

Objective function

```

%Script for optimizing the efficiency of an inductor by price
%The constraints are in the file constrains.m and main file is in
%Mainscript.m

%Makes a funktion of P losses with x as a vector of a, d, l, N, R, h
function ICost = InductorFunction(x)

%Global values
global ra I PriceCu PriceFe DensityCu DensityFe PriceE1

%Variable values
a = x(1);
d = x(2);
l = x(3);
N = x(4);
R = x(5);
h = x(6);

%Variables in the objective function
p = ra*N*(2*(1+a)+2*(1+d))*I^2/(pi*R^2); %Copper Losses
volCu = (2*a+2*d+4*l)*R^2*pi*N; % Volume Copper
volFe = (2*a+1.1*l)*(2*a+h)*d-(1.1*l*h*d); %Volume Iron
Ccap = volCu*DensityCu*PriceCu+volFe*DensityFe*PriceFe; %Capital cost
Cop = p*(10^-3)*5500*25*PriceE1; %Operation cost

```

```

%Objective function to be optimized
ICost = Ccap+Cop;

end

```

Constraints

```

%Script for the constraints to the optimization of an inductor,
%The objective function are in InductorFunction.m and main file is in
%Mainscript.m

function [c, ceq] = constrains(x) %Constrains function.

%Global variables
global y0 I Xub Hub wub Bub Llb

%Variable values
a = x(1);
d = x(2);
l = x(3);
N = x(4);
R = x(5);
h = x(6);
g = x(7);

%Nonlinear equalities
ceq = [];
%ceq = x(4)-36; %Change to this when number should be fixed x(4)-constant

%The Nonlinear inequalities
c(1) = 2.1*l+2*a - Xub;           %X = l+a+1.1*l+a <= Xub
c(2) = h+2*a - Hub;             %H = h +2*a <= Hub
c(3) = 2*l+d - wub;             %W = l+d+l <= wub
c(4) = Llb - y0*N^2*a*d/g;       %L = y0*N^2*a*d/g >= Llb
c(5) = y0*N*I/g - Bub;          %B = y0*N*I/gm <= Bub
c(6) = (I/(pi*R^2)-5000000)/1000000; %J = I/Scu = I/(pi*R^2) <= 5A/mm2
c(7) = N*pi*R^2/0.8-l*h;        %N*pi*R^2/0.8 <= l*h

end

```

Communication with FEMM

```

%Script for sending and receiving data to and from FEMM, Main script is
%Mainscript.m

%Open the software FEMM
openfemm;
newdocument(0);

%Variable values
a = x(1);
d = x(2);
l = x(3);
N = x(4);
R = x(5);
h = x(6);
g = x(7);

%Calculate H and X
H = h+2*a;
X = 2*a+1.1*l;

%Draws the contours of the inductor.
mi_drawline(1,1, 1,(1+H));
mi_drawline(1,(1+H), (1+X),(1+H));
mi_drawline(1,1, (1+X),1);
mi_drawline((1+X),1, (1+X),(1+H/2-g/2));
mi_drawline((1+X),(1+H/2+g/2), (1+X),(1+H));

mi_drawline((1+a),(1+a), (1+a),(1+H-a));
mi_drawline((1+a),(1+a), (1+X-a),(1+a));
mi_drawline((1+a),(1+H-a), (1+X-a),(1+H-a));
mi_drawline((1+X-a),(1+a), (1+X-a), (1+H/2-g/2));
mi_drawline((1+X-a),(1+H/2+g/2), (1+X-a),(1+H-a));

mi_drawline((1+X-a),(1+H/2-g/2), (1+X),(1+H/2-g/2));
mi_drawline((1+X-a),(1+H/2+g/2), (1+X),(1+H/2+g/2));

%Coil area right of the core
mi_drawline((1+a+1),(1+a+0.0005), (1+a+1),(1+H-a-0.0005));
mi_drawline((1+a+0.0005),(1+a+0.0005), (1+a+0.0005),(1+H-a-0.0005));
mi_drawline((1+a+0.0005),(1+a+0.0005), (1+a+1),(1+a+0.0005));
mi_drawline((1+a+0.0005),(1+H-a-0.0005), (1+a+1),(1+H-a-0.0005));

%Coil area left of the core
mi_drawline((1-l),(1+a+0.0005), (1-l),(1+H-a-0.0005));
mi_drawline(1-0.0005,(1+a+0.0005), 1-0.0005,(1+H-a-0.0005));
mi_drawline(1-0.0005,(1+a+0.0005), (1-l),(1+a+0.0005));
mi_drawline(1-0.0005,(1+H-a-0.0005), (1-l),(1+H-a-0.0005));

% mi_probdef(freq,units,type,precision,depth,minangle,(acsolver))
mi_probdef(0, 'meters', 'planar', 1E-8, d, 30);

%Outer bounds
mi_drawrectangle(0,0, (x+2),(H+2));

```

APPENDIX B - MATLAB CODE

```

%Material properties
%mi_addmaterial('matname', mu x, mu y, H c, J, Cduct, Lam d, Phi hmax,
%lam fill, LamType, Phi hx, Phi hy, nstr, dwire)
mi_addmaterial('Iron', 14872, 14872, 0, 0, 10.44, 0, 0, 1, 0, 0, 0);
mi_addmaterial('Air', 1, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0);
mi_addmaterial('Copper', 1, 1, 0, 0, 58, 0, 0, 0, 5, 1, 0, 1, R*2);

mi_addblocklabel((1+a/2),(1+H/2));
mi_selectlabel((1+a/2),(1+H/2));
mi_setblockprop('Iron',0,0.5,'<none>',0,0,0);
mi_clearselected;

mi_addblocklabel((X+2-0.05), (H+2-0.05));
mi_selectlabel((X+2-0.05), (H+2-0.05));
mi_setblockprop('Air',0,0.5,'<none>',0,0,0);
mi_clearselected;

mi_addblocklabel((1-0.5*1),(1+0.5*H));
mi_selectlabel((1-0.5*1),(1+0.5*H));
mi_addcircprop('coil', 100, 1);
mi_setblockprop('Copper',0,0.5, 'coil', 0, 0, N);
mi_clearselected;

mi_addblocklabel((1+a+0.5*1),(1+0.5*H));
mi_selectlabel((1+a+0.5*1),(1+0.5*H));
mi_setblockprop('Copper',0,0.5, 'coil', 0, 0, -N);
mi_clearselected;

mi_saveas('Inductor.fem')
mi_analyze
mi_loadsolution
mi_zoomnatural

mi_selectblock((1+a/2),(1+H/2));
mi_selectblock((X+2-0.05), (H+2-0.05));
mi_selectblock((1-0.5*1),(1+0.5*H));
mi_selectblock((1+a+0.5*1),(1+0.5*H));

%Recieve values from FEMM
E_FEMM = mo_blockintegral(2);
Bvalues = mo_getpointvalues((1+a+1.1*1+0.5*a), H/2);

```

Draw 2D graph in Matlab

```

%Script for draw 2-d graph of inductor. Main script file is MainScript.m

close all;
global y0 I

automatic = 1; %To change if execute one drawing from Command Window

%Code below automatically draw shape of inductor of 4 iterations!!!!
if automatic == 1

    %Reads 4 empty .tif files
    for n=0:4
        figure
        shapeInserter = vision.ShapeInserter('Shape','Lines');
        if n == 0
            Q = imread('First.tif');
        end
        if n == 1
            Q = imread('Second.tif');
        end
        if n == 2
            Q = imread('Third.tif');
        end
        if n == 3
            Q = imread('Fourth.tif');
        end
        if n == 4
            Q = imread('Fifth.tif');
        end
        end

        sx=0.8;
        sy=0.3;
        i = 1+n*95; %i is the given iteration
        a = history.x(i,1);
        d = history.x(i,2);
        l = history.x(i,3);
        N = history.x(i,4);
        R = history.x(i,5);
        h = history.x(i,6);
        g = history.x(i,7);

        %Calculates dimensions
        x = 2.1*l+2*a;
        H = h+2*a;
        W = 2*l+d;
        L = y0*N^2*a*d/g;
        B = y0*N*I/g;
        J = I/(pi*R^2);
        NpiR = N*pi*R^2/0.8;
        lh = l*h;
        q = 0.007; %Constant to give air between copper and Iron

```

APPENDIX B - MATLAB CODE

```

%Draw shape of inductor
polygon = int32(200*[sx sy (sx+x-1) sy;...%Iron Core
(sx+x-1) sy (sx+x-1) (sy+0.5*h-0.5*g);...
(sx+x-1) (sy+0.5*h-0.5*g) (sx+a+1.1*l) (sy+0.5*h-0.5*g);...
(sx+a+1.1*l) (sy+0.5*h-0.5*g) (sx+a+1.1*l) (sy+a);...
(sx+a+1.1*l) (sy+a) (sx+a) (sy+a);...
(sx+a) (sy+a) (sx+a) (sy+a+h);...
(sx+a) (sy+a+h) (sx+a+1.1*l) (sy+a+h);...
(sx+a+1.1*l) (sy+a+h) (sx+a+1.1*l) (sy+0.5*h+0.5*g);...
(sx+a+1.1*l) (sy+0.5*h+0.5*g) (sx+x-1) (sy+0.5*h+0.5*g);...
(sx+x-1) (sy+0.5*h+0.5*g) (sx+x-1) (sy+h);...
(sx+x-1) (sy+h) sx (sy+h);...
sx (sy+h) sx sy;...
(sx-1-q) (sy+a+q) (sx-q) (sy+a+q);... %Copper winding left
(sx-q) (sy+a+q) (sx-q) (sy+h-a-q);...
(sx-q) (sy+h-a-q) (sx-1-q) (sy+h-a-q);...
(sx-q-1) (sy+h-a-q) (sx-q-1) (sy+a+q);...
(sx+a+q) (sy+a+q) (sx+a+1+q) (sy+a+q);...%Copper winding right
(sx+a+1+q) (sy+a+q) (sx+a+1+q) (sy+a+h-q);...
(sx+a+1+q) (sy+a+h-q) (sx+a+q) (sy+a+h-q);...
(sx+a+q) (sy+a+h-q) (sx+a+q) (sy+a+q)
]);
J = step(shapeInserter, Q, polygon);
imshow(J);

%Gives text information in figure
position = [sx+x+50 300; sx+x+150 300; sx+x+250 300;...
sx+x+350 300; sx+x+450 300; sx+x+500 300]; % [x y]
value = [X H W R PriceCu PriceFe];
RGB = insertText(J,position,value);
Inr = (['Iteration nr: ', num2str(i)]);
imshow(RGB, title(Inr));
end
end

%Code below draw shape of inductor of chosen iteration i!!!!
if automatic == 0 %Only executes one drawing at iteration i
i=16;
figure
ShapeInserter = vision.ShapeInserter('Shape','Lines');
Q = imread('Second.tif');
sx=0.8;
sy=0.3;
a = history.x(i,1);
d = history.x(i,2);
l = history.x(i,3);
N = history.x(i,4);
R = history.x(i,5);
h = history.x(i,6);
g = history.x(i,7);

X = 2.1*l+2*a;
H = h+2*a;
W = 2*l+d;
q = 0.007;

```

APPENDIX B - MATLAB CODE

```

polygon = int32(200*[sx sy (sx+x-1) sy;...
    (sx+x-1) sy (sx+x-1) (sy+0.5*h-0.5*g);...
    (sx+x-1) (sy+0.5*h-0.5*g) (sx+a+1.1*l) (sy+0.5*h-0.5*g);...
    (sx+a+1.1*l) (sy+0.5*h-0.5*g) (sx+a+1.1*l) (sy+a);...
    (sx+a+1.1*l) (sy+a) (sx+a) (sy+a);...
    (sx+a) (sy+a) (sx+a) (sy+a+h);...
    (sx+a) (sy+a+h) (sx+a+1.1*l) (sy+a+h);...
    (sx+a+1.1*l) (sy+a+h) (sx+a+1.1*l) (sy+0.5*h+0.5*g);...
    (sx+a+1.1*l) (sy+0.5*h+0.5*g) (sx+x-1) (sy+0.5*h+0.5*g);...
    (sx+x-1) (sy+0.5*h+0.5*g) (sx+x-1) (sy+h);...
    (sx+x-1) (sy+h) sx (sy+h);...
    sx (sy+h) sx sy;...
    (sx-l-q) (sy+a+q) (sx-q) (sy+a+q);... %Copper winding left
    (sx-q) (sy+a+q) (sx-q) (sy+h-a-q);...
    (sx-q) (sy+h-a-q) (sx-l-q) (sy+h-a-q);...
    (sx-q-l) (sy+h-a-q) (sx-q-l) (sy+a+q);...
    (sx+a+q) (sy+a+q) (sx+a+l+q) (sy+a+q);...%Copper winding right
    (sx+a+l+q) (sy+a+q) (sx+a+l+q) (sy+a+h-q);...
    (sx+a+l+q) (sy+a+h-q) (sx+a+q) (sy+a+h-q);...
    (sx+a+q) (sy+a+h-q) (sx+a+q) (sy+a+q)
    ]);
J = step(shapeInserter, Q, polygon);
imshow(J);

position = [sx+x+50 300; sx+x+150 300; sx+x+250 300;...
    sx+x+350 300; sx+x+450 300; sx+x+500 300]; % [x y]
value = [X H W R PriceCu PriceFe];
RGB = insertText(J,position,value);
Inr = (['Iteration nr: ', num2str(i)]);
imshow(RGB), title(Inr);
end

```

Matlab code for converter optimization

Main Script

```

%Main script for Buck Converter optimization, Constraints =
%BuckConstraints.m and Objective Function = BuckFunction.m

clear all
global ETonN EToffN EDoFFN VinN IoutN rTcond VDcond...
      VTcond Vout Iout DT PriceE1 PriceAssemb1mod...
      PriceIGBT rDcond VolIGBT1mod history searchdir totVOV

%history and searchdir saves values for each iteration
history.x = [];
history.fval = [];
searchdir = [];

%Choice of transistor, T1 = 600V, T2 = 1200V, T3 = 1700V, T4 = 3300V
totVOV = 0.3;
T = 4;
if(T==1)%SKM145GB066D
    ETonN = 0.0085;           %[ETon]
    EToffN = 0.0055;         %[EToff]
    EDoFFN = 0.0035;         %[Err]
    rTcond = 0.0079;         %[Calculated from graph]
    VDcond = 0.8;           %[Calculated from graph]
    VTcond = 0.6;           %[Calculated from graph]
    rDcond = 0.005;         %[Calculated from graph]
    VinN = 300;             %[Vcc]
    IoutN = 150;            %[IcN]
    PriceIGBT = 82.17;
    VolIGBT1mod = 0.000095880;
    VinUb = 600/1.4;        %Upper bound
end
if(T==2)%SKM150GBR12T4
    ETonN = 0.0192;           %[ETon]
    EToffN = 0.0158;         %[EToff]
    EDoFFN = 0.013;         %[Err]
    rTcond = 0.01;          %[Calculated from graph]
    VDcond = 1;             %[Calculated from graph]
    VTcond = 0.9;          %[Calculated from graph]
    rDcond = 0.0091;        %[Calculated from graph]
    VinN = 600;             %[Vcc]
    IoutN = 150;            %[IcN]
    PriceIGBT = 109;
    VolIGBT1mod = 0.000095880;
    VinUb = 1200/1.4;      %Upper bound
end
if(T==3)%SKM400GB176D
    ETonN = 0.170;           %[ETon]
    EToffN = 0.118;         %[EToff]
    EDoFFN = 0.078;         %[Err]
    rTcond = 0.0056;        %[Calculated from graph]
    VDcond = 0.9;          %[Calculated from graph]
    VTcond = 1;             %[Calculated from graph]

```


APPENDIX B - MATLAB CODE

```

rdcond = 0.0032;           %[Calculated from graph]
vinN = 1200;               %[Vcc]
IoutN = 300;               %[IcN]
PriceIGBT = 237.09;
VolIGBTlmod = 0.00019925528;
vinUb = 1700/1.4;         %Upper bound
end
if(T==4)%FF200R33KF2C
    ETonN = 0.365;         %[Eon]
    EToffN = 0.255;        %[Eoff]
    EDoffN = 0.255;        %[Erec]
    rTcond = 0.0125;       %[Calculated from graph]
    VDcond = 1.3;          %[Calculated from graph]
    VTcond = 1.9;          %[Calculated from graph]
    rDcond = 0.0152;       %[Calculated from graph]
    vinN = 1800;           %[Vce]
    IoutN = 200;           %[ICnom]
    PriceIGBT = 748.71;
    VolIGBTlmod = 0.000320908;
    vinUb = 3300/1.4;     %Upper bound
end

%Choice of the Electricity price
E1L = 0.1; %Normal
E1M = 0.15;
E1H = 0.25;

%Choice of the Assembly price
InstL = 0;
InstM = 3000; %Normal
InstH = 5000;

%Constant values
vout = 2000;               %Output voltage
Iout = 100;                %Output current
DT = 0.9;                  %Dutycycle of transistor
PriceE1 = E1L;             %Price of electricity
PriceAsemblmod = InstM;    %Price of instalation, 1 module assembling cost

%The design variables, [fsw Vin N] DeltaILmax Deltavmax]
lb = [0.01 0 1 0 0];       %Lower bounds for [fsw Vin N]
ub = [20000 vinUb inf 15 1000]; %Upper bounds for [fsw Vin N]
startPoint = [10000 200 2 0.5 0.5]; %Start points for [fsw Vin N]
A = [];
b = [];
Aeq = [];
beq = [];

```

APPENDIX B - MATLAB CODE

```

%Optimization algorithm
options = optimoptions(@fmincon,'OutputFcn',@outfun, 'Algorithm', 'sqp');
problem = createOptimProblem('fmincon', 'objective',...
    @BuckFunction, 'nonlcon', @BuckConstraints, 'x0', startPoint, ...
    'lb', lb, 'ub', ub, 'options', options);
gs = GlobalSearch;
[x,fg,exitflag,output,solutions] = run(gs,problem);

% All code below is for displaying in the commandwindow and is not
% important for the optimization!!!!!!
printCW = 1;
if(printCW == 1)
    fsw = x(1);
    Vin = x(2);
    N = x(3);
    DeltaILmax = x(4);
    DeltaVmax = x(5);

    Ltot=Vin/(4*DeltaILmax)*1/(N*fsw);
    Ctot=DeltaILmax/(8*DeltaVmax)*1/(N*fsw);
    L1mod = Ltot/N;

    %Losses
    %Switching losses
    PTON1mod = ETonN/(Vin*N*IoutN)*Vin*Iout*fsw;
    PTOFF1mod = EToffN/(Vin*N*IoutN)*Vin*Iout*fsw;
    PTCOND1mod = (Iout)^2*rTcond*DT+Iout*VTcond*DT;
    PDCOND1mod = (Iout)^2*rDcond*(1-DT) + VDcond*Iout*(1-DT);
    PDoff1mod = EDOFFN/(Vin*N*IoutN)*Vin*Iout*fsw;

    ConvLossesNmod = N*(PTON1mod + PTOFF1mod + PTCOND1mod ...
        + PDCOND1mod + PDoff1mod);

    %Cost of L, C, T and D and operational cost of switch
    CostLNmod = N*(41.09*1/2*L1mod*Iout^2);
    CostC = 32.1*(1/2*Ctot*Vout^2);
    CostIGBTNmod = N*(PriceIGBT);
    CostInstalNmod = N*(PriceAsemblmod);
    OperationalCostNmod = ConvLossesNmod*(10^-3)*5500*25*PriceE1;

    TotalCost = OperationalCostNmod + CostLNmod + CostC ...
        + CostIGBTNmod + CostInstalNmod;

    VolL1mod = 0.00007749*(1/2*L1mod*Iout^2);
    VolCNmod = 0.00005950*(1/2*Ctot*Vout^2);

    VOLTOT = N*VolL1mod + VolCNmod + N*VolIGBT1mod; %Totalvol N modules
    disp('----- ')
    disp(output.message)
    TRANS = ['IGBT model used in optimization: ', num2str(T)];
    disp(TRANS)
    disp('-----Calculated values-----')
    freq = ['fsw = ', num2str(fsw), ' Hertz'];
    disp(freq)

```

```

Viin = ['Vin = ', num2str(Vin), ' V'];
disp(Viin)
Number = ['Modules = ', num2str(N), ' nr of modules'];
disp(Number)
Vut = 0.9*Vin*N;
Vuut = ['Vout = ', num2str(Vut), ' V'];
disp(Vuut)
INDUC = ['value of L (total) = ', num2str(Ltot),', value of L = ' ...
        , num2str(L1mod), ' Henry'];
disp(INDUC)
CAPAC = ['value of C = ', num2str(Ctot), ' Farad'];
disp(CAPAC)
Totvol = ['TotalVolume = ', num2str(Voltot),': Volume C = ', ...
        num2str(VolCNmod), ', Volume of L (total) = ', ...
        num2str(VolL1mod*N), ', Volume N IGBT = ', ...
        num2str(N*VolIGBT1mod), ' [m3]'];
disp(Totvol)
LOSSES = ['Losses N module; Pcond = ', ...
        num2str(N*(PDcond1mod+PTcond1mod)),', Pswitching = ', ...
        num2str(N*(PTon1mod+PToff1mod+PDoff1mod)), ' [w]'];
disp(LOSSES)
LOSSESNMOD = ['Total losses N modules = ', ...
        num2str(ConvLossesNmod), ' W'];
disp(LOSSESNMOD)
COSTOP = ['Operational Cost N modules = ', ...
        num2str(OperationalCostNmod), ' W'];
disp(COSTOP)
COSTCAP = ['Capital Cost N modules = '...
        ,num2str(CostLNmod+CostIGBTNmod+CostC+CostInstalNmod),...
        ',: CostL = ', num2str(CostLNmod), ', CostIGBT = ', ...
        num2str(CostIGBTNmod), ', CostC = ', num2str(CostC), ...
        ', CostInstal = ', num2str(CostInstalNmod), ' [euro]'];
disp(COSTCAP)
TOTALCOST = ['Total cost N modules = ', num2str(TotalCost), ' euro'];
disp(TOTALCOST)
MAKINGSPACE= [' '];
disp(MAKINGSPACE)
end

```

Objective function

```

%Objective Function script for Buck Converter optimization, main script is
%MainBuck.m
function TotalCost= BuckFunction(x)

global ETONN ETOFFN EDOFFN VinN IoutN rTcond VDcond...
VTcond DT PriceE1 Vout PriceAsemb1mod Iout...
PriceIGBT rDcond

%Design variables [fsw Vin N]
fsw = x(1);
Vin = x(2);
N = x(3);
DeltaILmax = x(4);
DeltaVmax = x(5);

%Calculation of L and C
Ltot=Vin/(4*DeltaILmax)*1/(N*fsw); %L total for N modules
Ctot=DeltaILmax/(8*DeltaVmax)*1/(N*fsw); %C total
L1mod = Ltot/N; %L for 1 module

%Converter losses
PTon1mod = ETONN/(VinN*IoutN)*Vin*Iout*fsw; %Trans on losses 1 module
PToff1mod = ETOFFN/(VinN*IoutN)*Vin*Iout*fsw; %Trans off losses 1 module
PTcond1mod = (Iout)^2*rTcond*DT+Iout*VTcond*DT; %Trans cond losses 1 module
PDoff1mod = EDOFFN/(VinN*IoutN)*Vin*Iout*fsw; %Diode on losses 1 module
PDcond1mod = (Iout)^2*rDcond*(1-DT) + VDcond*Iout*(1-DT) ;
%Diode cond losses 1 module

%Converter losses N modules
ConvLossesNmod = N*(PTon1mod + PToff1mod + PTcond1mod ...
+ PDcond1mod + PDoff1mod);

%Cost of L, C, T and D and operational cost of switch
CostLNmod = N*(41.09*1/2*L1mod*Iout^2); %Cost for N modules
CostC = 32.1*(1/2*Ctot*Vout^2); %Cost for capacitance
CostIGBTNmod = N*(PriceIGBT);
CostInstalNmod = N*(PriceAsemb1mod); %Installation price for N modules
OperationalCostNmod = ConvLossesNmod*(10^-3)*5500*25*PriceE1;

%Objective function
TotalCost = OperationalCostNmod + CostLNmod + CostC ...
+ CostIGBTNmod + CostInstalNmod;
end

```

Constraints

```

%Constraints script for Buck Converter optimization,
%main script is MainBuck.m
function [c, ceq] = BuckConstraints(x)

global vout Iout volIGBT1mod totVOV %DeltaILmax DeltaVmax

%Design variables
fsw = x(1);
vin = x(2);
N = x(3);
DeltaILmax = x(4);
DeltaVmax = x(5);

%Equality constraints
ceq(1) = 0.9*vin*N-vout;%VoutMax=0.9*vin*N
%ceq(2) = N-2;      %Constraint when wanting to bound number of modules

%Calculation of L and C
Ltot=vin/(4*DeltaILmax)*1/(N*fsw);
Ctot=DeltaILmax/(8*DeltaVmax)*1/(N*fsw);

%Calculation of volumes of L and C. volumes of TD are given in mainscript
volL1mod = 0.00007749*(1/2*Ltot/N*Iout^2);      %volume N inductors
volCNmod = 0.00005950*(1/2*Ctot*vout^2);      %volume of C

%Inequality constraints
c(1) = N*volL1mod + volCNmod + N*volIGBT1mod - totVOV; %Totalvolume <= totVov
c(2) = DeltaILmax - 0.1*Iout;
c(3) = DeltaVmax - 0.01*vout;
end

```

C

APPENDIX C - DATASHEETS

SKM 145GB066D



SEMITRANS[®] 2

Trench IGBT Modules

SKM 145GB066D

Features

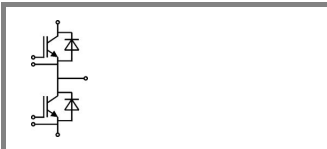
- Trench = Trenchgate technology
- $V_{CE(sat)}$ with positive temperature coefficient
- High short circuit capability, self limiting to $6 \times I_C$

Typical Applications*

- AC inverter Drives
- UPS
- Electronic welders

Remarks

- Case temperature limited to $T_c = 125^\circ\text{C}$ max, recomb. $T_{op} = -40 \dots +150^\circ\text{C}$, product rel. results valid for $T_j \leq 150^\circ\text{C}$
- SC data: $t_p \leq 6\mu\text{s}$; $V_{GE} \leq 15\text{V}$; $T_j = 150^\circ\text{C}$; $V_{cc} \leq 360\text{V}$, use of soft R_G necessary!
- Take care of over-voltage caused by stray induct.



GB

Absolute Maximum Ratings		$T_{case} = 25^\circ\text{C}$, unless otherwise specified		
Symbol	Conditions	Values	Units	
IGBT				
V_{CES}	$T_j = 25^\circ\text{C}$	600	V	
I_C	$T_j = 175^\circ\text{C}$	195	A	
	$T_c = 25^\circ\text{C}$ $T_c = 80^\circ\text{C}$	150	A	
I_{CRM}	$I_{CRM} = 2 \times I_{Cnom}$	300	A	
V_{GES}		± 20	V	
t_{psc}	$V_{CC} = 360\text{V}$; $V_{GE} \leq 15\text{V}$; $T_j = 150^\circ\text{C}$ $V_{CES} < 600\text{V}$	6	μs	
Inverse Diode				
I_F	$T_j = 175^\circ\text{C}$	$T_c = 25^\circ\text{C}$	150	A
		$T_c = 80^\circ\text{C}$	100	A
I_{FRM}	$I_{FRM} = 2 \times I_{Fnom}$	300	A	
I_{FSM}	$t_p = 10\text{ms}$; sin. $T_j = 175^\circ\text{C}$	880	A	
Module				
$I_{j(RMS)}$		200	A	
T_{vj}		-40 ... +175	$^\circ\text{C}$	
T_{stg}		-40 ... +125	$^\circ\text{C}$	
V_{isol}	AC, 1 min.	4000	V	

Characteristics		$T_{case} = 25^\circ\text{C}$, unless otherwise specified			
Symbol	Conditions	min.	typ.	max.	Units
IGBT					
$V_{GE(th)}$	$V_{GE} = V_{CE}$; $I_C = 2,4\text{mA}$	5	5,8	6,5	V
I_{CES}	$V_{GE} = 0\text{V}$; $V_{CE} = V_{CES}$ $T_j = 25^\circ\text{C}$		0,08	0,25	mA
V_{CE0}		$T_j = 25^\circ\text{C}$	0,9	1	V
		$T_j = 150^\circ\text{C}$	0,85	0,9	V
r_{CE}	$V_{GE} = 15\text{V}$	$T_j = 25^\circ\text{C}$	3,7	6	$\text{m}\Omega$
		$T_j = 150^\circ\text{C}$	5,7	8	$\text{m}\Omega$
$V_{CE(sat)}$	$I_{Cnom} = 150\text{A}$; $V_{GE} = 15\text{V}$	$T_j = 25^\circ\text{C}_{chiplev.}$	1,45	1,9	V
		$T_j = 150^\circ\text{C}_{chiplev.}$	1,7	2,1	V
C_{ies}	$V_{CE} = 25\text{V}$; $V_{GE} = 0\text{V}$ $f = 1\text{MHz}$		9,25		nF
C_{oes}			0,6		nF
C_{res}			0,28		nF
Q_G	$V_{GE} = -8\text{V} \dots +15\text{V}$		1100		nC
R_{Gint}	$T_j = ^\circ\text{C}$		2		Ω
$t_{d(on)}$	$R_{Gon} = 4,3\Omega$	$V_{CC} = 300\text{V}$ $I_C = 150\text{A}$ $T_j = 150^\circ\text{C}$ $V_{GE} = -8/+15\text{V}$	150		ns
			52		ns
E_{on}			8,5		mJ
$t_{d(off)}$	$R_{Goff} = 4,3\Omega$		490		ns
			46		ns
E_{off}			5,5		mJ
$R_{th(j-c)}$	per IGBT			0,3	K/W

SKM 145GB066D



SEMITRANS[®] 2

Trench IGBT Modules

SKM 145GB066D

Features

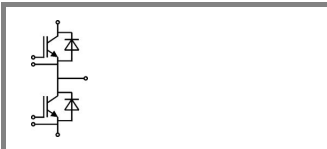
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- $V_{CE(sat)}$ with positive temperature coefficient
- High short circuit capability, self limiting to $6 \times I_C$

Typical Applications*

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- UPS
- Electronic welders

Remarks

- Case temperature limited to $T_C = 125^\circ\text{C}$ max, recomb. $T_{op} = -40 \dots +150^\circ\text{C}$, product rel. results valid for $T_j \leq 150^\circ\text{C}$
- SC data: $t_p \leq 6\mu\text{s}$; $V_{GE} \leq 15\text{V}$; $T_j = 150^\circ\text{C}$; $V_{cc} \leq 360\text{V}$, use of soft R_G necessary!
- Take care of over-voltage caused by stray induct.



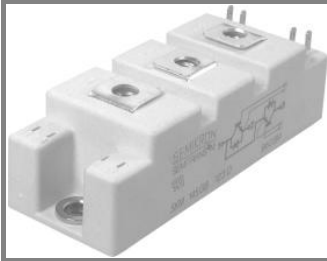
GB

Characteristics						
Symbol	Conditions	min.	typ.	max.	Units	
Inverse Diode						
$V_F = V_{EC}$	$I_{Fnom} = 150\text{ A}; V_{GE} = 0\text{ V}$		$T_j = 25^\circ\text{C}_{chiplev.}$	1,4	1,6	V
			$T_j = 150^\circ\text{C}_{chiplev.}$			V
V_{FO}			$T_j = 25^\circ\text{C}$	0,95	1	V
r_F			$T_j = 25^\circ\text{C}$	3	4	mΩ
I_{RRM}	$I_F = 150\text{ A}$		$T_j = 150^\circ\text{C}$	90		A
Q_{rr}	$di/dt = 2100\text{ A}/\mu\text{s}$			20		μC
E_{rr}	$V_{GE} = -8\text{ V}; V_{CC} = 300\text{ V}$			3,5		mJ
$R_{th(j-c)D}$	per diode				0,5	K/W
Module						
L_{CE}					30	nH
R_{CC+EE}	res., terminal-chip		$T_{case} = 25^\circ\text{C}$	0,75		mΩ
			$T_{case} = 125^\circ\text{C}$	1		mΩ
$R_{th(c-s)}$	per module				0,05	K/W
M_s	to heat sink M6			3	5	Nm
M_t	to terminals M5			2,5	5	Nm
w					150	g

This is an electrostatic discharge sensitive device (ESDS), international standard IEC 60747-1, Chapter IX.

* The specifications of our components may not be considered as an assurance of component characteristics. Components have to be tested for the respective application. Adjustments may be necessary. The use of SEMIKRON products in life support appliances and systems is subject to prior specification and written approval by SEMIKRON. We therefore strongly recommend prior consultation of our personal.

SKM 145GB066D



SEMITRANS[®] 2

Trench IGBT Modules

SKM 145GB066D

Features

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- Take care of over-voltage caused by stray induct.



GB

Zth		Symbol	Conditions	Values	Units
Z^{th(j-c)I}					
$R_{\theta j-c}$			i = 1	220	mk/W
$R_{\theta j-c}$			i = 2	60	mk/W
$R_{\theta j-c}$			i = 3	16,5	mk/W
$R_{\theta j-c}$			i = 4	3,5	mk/W
$\tau_{\theta j-c}$			i = 1	0,0447	s
$\tau_{\theta j-c}$			i = 2	0,0223	s
$\tau_{\theta j-c}$			i = 3	0,0015	s
$\tau_{\theta j-c}$			i = 4	0,0002	s
Z^{th(j-c)D}					
$R_{\theta j-c}$			i = 1	330	mk/W
$R_{\theta j-c}$			i = 2	137	mk/W
$R_{\theta j-c}$			i = 3	28	mk/W
$R_{\theta j-c}$			i = 4	5	mk/W
$\tau_{\theta j-c}$			i = 1	0,05	s
$\tau_{\theta j-c}$			i = 2	0,0129	s
$\tau_{\theta j-c}$			i = 3	0,002	s
$\tau_{\theta j-c}$			i = 4	0,0002	s

SKM 145GB066D

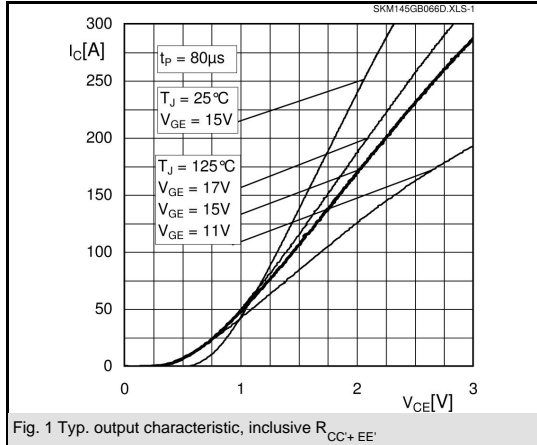


Fig. 1 Typ. output characteristic, inclusive R_{CC+EE}

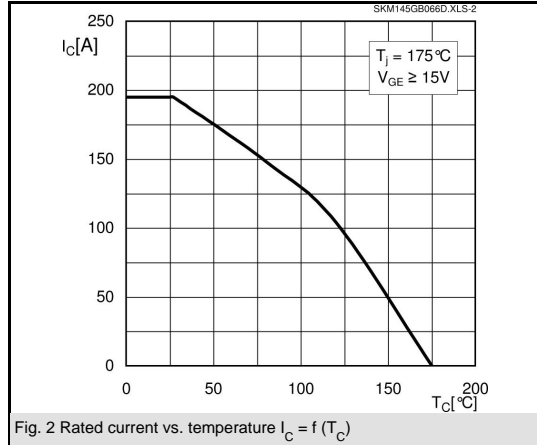


Fig. 2 Rated current vs. temperature $I_C = f(T_C)$

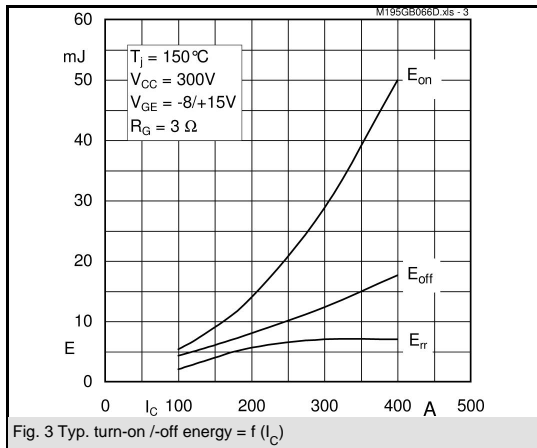


Fig. 3 Typ. turn-on /-off energy = $f(I_C)$

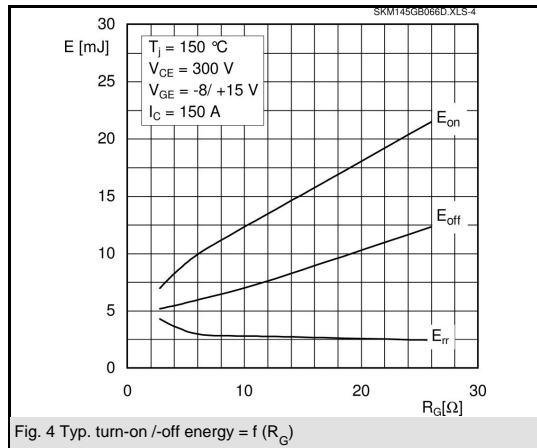


Fig. 4 Typ. turn-on /-off energy = $f(R_G)$

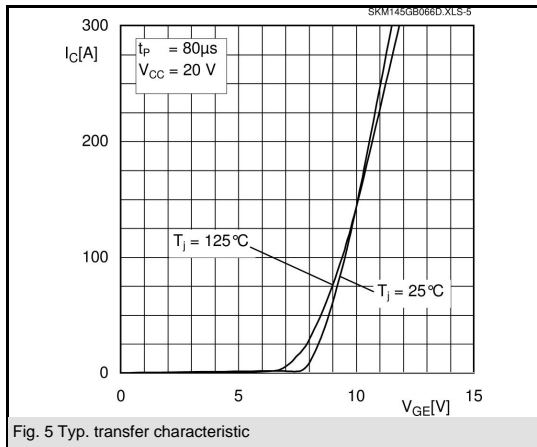


Fig. 5 Typ. transfer characteristic

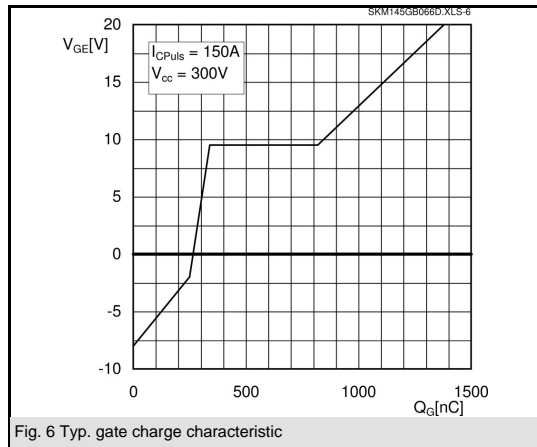
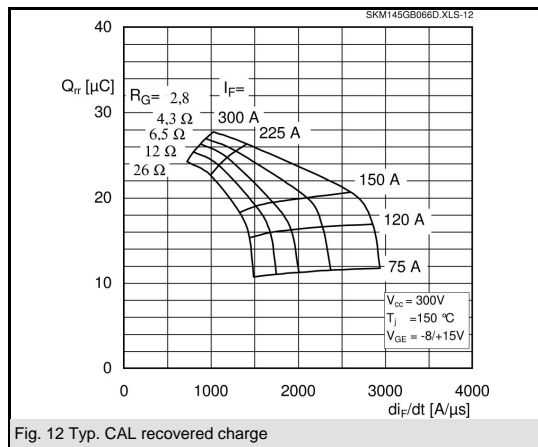
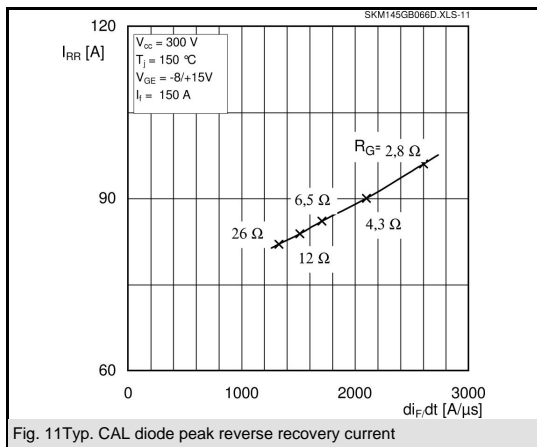
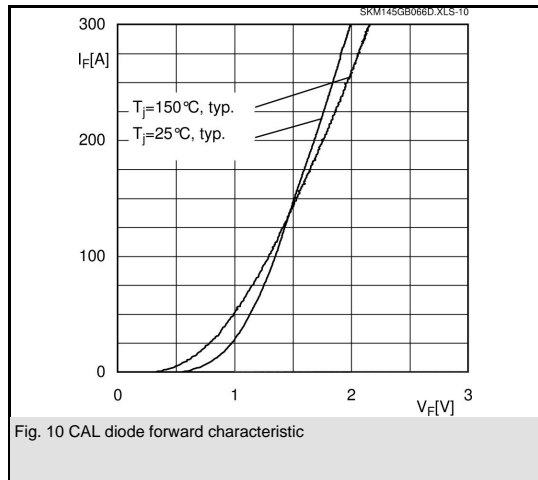
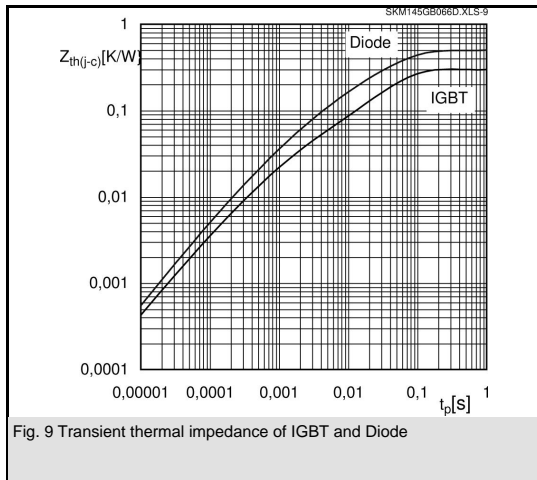
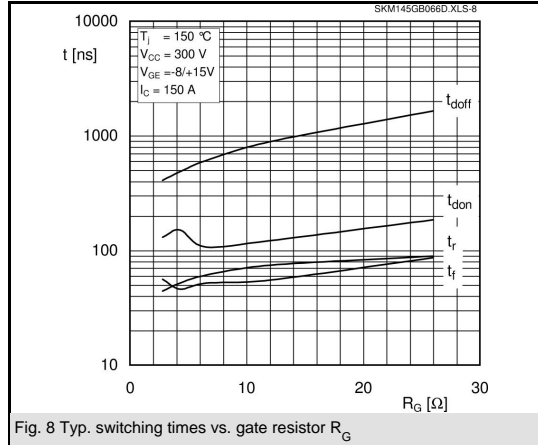
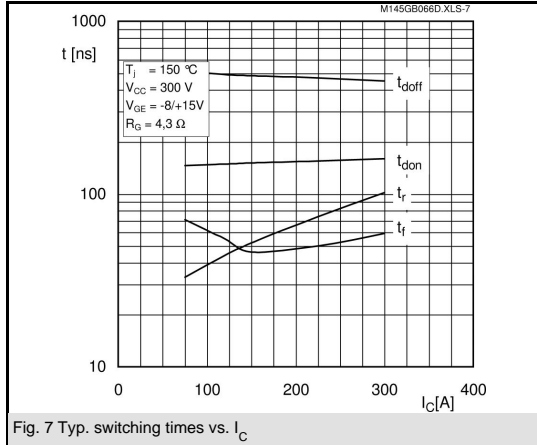


Fig. 6 Typ. gate charge characteristic

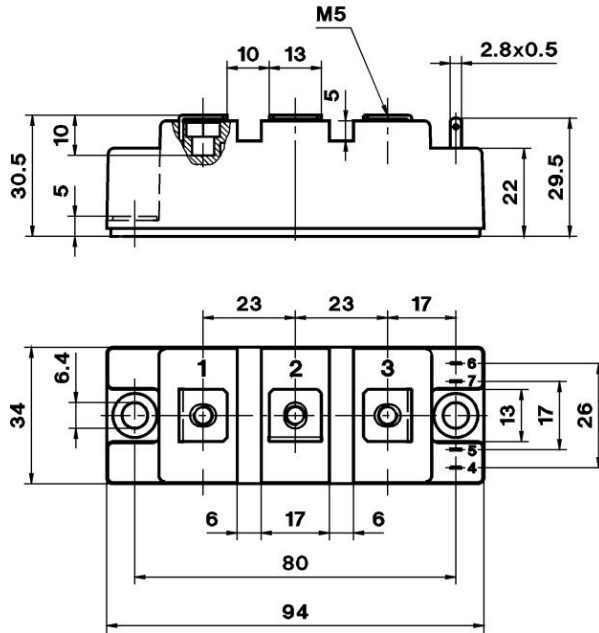
SKM 145GB066D



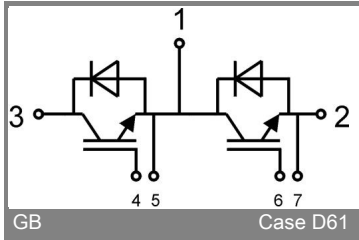
SKM 145GB066D

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CASED61



Case D 61



SKM 150GB12T4



SEMITRANS® 2

IGBT4 Modules

- SKM 150GB12T4
- SKM 150GAL12T4
- SKM 150GAR12T4

Features

- IGBT4 = 4. Generation IGBT
- V_{CEsat} with positive temperature coefficient
- High short circuit capability, self limiting to $6 \times I_{CNOM}$
- Soft switching 4 Generation CAL diode (CAL4)

Typical Applications

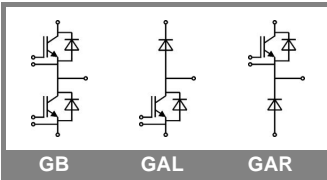
- AC inverter drives
- UPS
- Electronic welders at f_{sw} up to 20 kHz

Remarks

- Case temperature limited to $T_c = 125^\circ\text{C}$ max, recomb. $T_{op} = -40 \dots +150^\circ\text{C}$, product rel. results valid for $T_j \leq 150^\circ$

Absolute Maximum Ratings		$T_c = 25^\circ\text{C}$, unless otherwise specified		
Symbol	Conditions	Values	Units	
IGBT				
V_{CES}	$T_j = 25^\circ\text{C}$	1200	V	
I_C	$T_j = 175^\circ\text{C}$	230	A	
	$T_{case} = 25^\circ\text{C}$ $T_{case} = 80^\circ\text{C}$	180	A	
I_{CRM}	$I_{CRM} = 3 \times I_{CNOM}$	450	A	
V_{GES}		± 20	V	
t_{psc}	$V_{CC} = 800\text{ V}; V_{GE} \leq 15\text{ V}; T_j = 150^\circ\text{C}$ $V_{CES} < 1200\text{ V}$	10	μs	
Inverse Diode				
I_F	$T_j = 175^\circ\text{C}$	$T_{case} = 25^\circ\text{C}$	190	A
		$T_{case} = 80^\circ\text{C}$	140	A
I_{FRM}	$I_{FRM} = 3 \times I_{FNOM}$	450	A	
I_{FSM}	$t_p = 10\text{ ms}; \text{sin.}$ $T_j = 175^\circ\text{C}$	900	A	
Module				
$I_{L(RMS)}$		200	A	
T_{vj}		$-40 \dots +175$	$^\circ\text{C}$	
T_{stg}		$-40 \dots +125$	$^\circ\text{C}$	
V_{isol}	AC, 1 min.	4000	V	

Characteristics		$T_c = 25^\circ\text{C}$, unless otherwise specified			
Symbol	Conditions	min.	typ.	max.	Units
IGBT					
$V_{GE(th)}$	$V_{GE} = V_{CE}; I_C = 6\text{ mA}$	5	5,8	6,5	V
I_{CES}	$V_{GE} = 0\text{ V}; V_{CE} = V_{CES}$ $T_j = 25^\circ\text{C}$			0,3	mA
V_{CE0}		$T_j = 25^\circ\text{C}$	0,8	0,9	V
		$T_j = 150^\circ\text{C}$	0,7	0,8	V
r_{CE}	$V_{GE} = 15\text{ V}$	$T_j = 25^\circ\text{C}$	6,7	7,3	$\text{m}\Omega$
		$T_j = 150^\circ\text{C}$	10	10,7	$\text{m}\Omega$
$V_{CE(sat)}$	$I_{Cnom} = 150\text{ A}; V_{GE} = 15\text{ V}$	$T_j = 25^\circ\text{C}_{chiplev.}$	1,8	2	V
		$T_j = 150^\circ\text{C}_{chiplev.}$	2,2	2,4	V
C_{ies}	$V_{CE} = 25; V_{GE} = 0\text{ V}$ $f = 1\text{ MHz}$		9,3		nF
C_{oes}			0,58		nF
C_{res}			0,51		nF
Q_G	$V_{GE} = -8\text{ V} / +15\text{ V}$		850		nC
R_{Gint}	$T_j = 25^\circ\text{C}$		5		Ω
$t_{d(on)}$	$R_{Gon} = 1\ \Omega$ $di/dt = 3400\text{ A}/\mu\text{s}$	$V_{CC} = 600\text{ V}$ $I_C = 150\text{ A}$		180	ns
			$T_j = 150^\circ\text{C}$	42	ns
E_{on}	$R_{Goff} = 1\ \Omega$ $di/dt = 1750\text{ A}/\mu\text{s}$	$T_j = 150^\circ\text{C}$ $V_{GE} \leq -8\text{ V}$		19,2	mJ
$t_{d(off)}$				410	ns
t_f				72	ns
E_{off}			15,8		mJ
$R_{th(j-c)}$	per IGBT			0,19	K/W



SKM 150GB12T4



SEMITRANS[®] 2

IGBT4 Modules

SKM 150GB12T4

SKM 150GAL12T4

SKM 150GAR12T4

Features

- IGBT4 = 4. Generation IGBT
- V_{CEsat} with positive temperature coefficient
- High short circuit capability, self limiting to $6 \times I_{CNOM}$
- Soft switching 4 Generation CAL diode (CAL4)

Typical Applications

- AC inverter drives
- UPS
- Electronic welders at f_{sw} up to 20 kHz

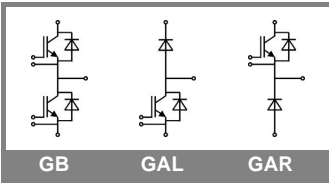
Remarks

- Case temperature limited to $T_c = 125^\circ\text{C}$ max, recomm. $T_{op} = -40 \dots +150^\circ\text{C}$, product rel. results valid for $T_j \leq 150^\circ$

Characteristics						
Symbol	Conditions	min.	typ.	max.	Units	
Inverse Diode						
$V_F = V_{EC}$	$I_{Fnom} = 150 \text{ A}; V_{GE} = 0 \text{ V}$		$T_j = 25^\circ\text{C}_{chiplev.}$	2,15	2,45	V
			$T_j = 150^\circ\text{C}_{chiplev.}$	2,05	2,4	V
V_{F0}			$T_j = 25^\circ\text{C}$	1,3	1,5	V
			$T_j = 150^\circ\text{C}$	0,9	1,1	V
r_F			$T_j = 25^\circ\text{C}$	5,7	6,3	mΩ
			$T_j = 150^\circ\text{C}$	7,7	8,7	mΩ
I_{RRM}	$I_F = 150 \text{ A}$		$T_j = 150^\circ\text{C}$	120		A
Q_{rr}	$di/dt = 3100 \text{ A}/\mu\text{s}$			31,3		μC
E_{rr}				13		mJ
$R_{th(j-c)}$	per diode				0,31	K/W
Freewheeling Diode						
$V_F = V_{EC}$	$I_{Fnom} = \text{A}; V_{GE} = \text{V}$		$T_j = ^\circ\text{C}_{chiplev.}$			V
V_{F0}			$T_j = ^\circ\text{C}$			V
r_F			$T_j = ^\circ\text{C}$			V
I_{RRM}	$I_F = \text{A}$		$T_j = ^\circ\text{C}$			A
Q_{rr}						μC
E_{rr}						mJ
	per diode					K/W
Module						
L_{CE}				20	30	nH
R_{CC+EE}	res., terminal-chip		$T_{case} = 25^\circ\text{C}$		0,75	mΩ
			$T_{case} = 125^\circ\text{C}$		1	mΩ
$R_{th(c-s)}$	per module				0,05	K/W
M_s	to heat sink M6			3	5	Nm
M_t	to terminals M5			2,5	5	Nm
w					160	g

This is an electrostatic discharge sensitive device (ESDS), international standard IEC 60747-1, Chapter IX.

This technical information specifies semiconductor devices but promises no characteristics. No warranty or guarantee expressed or implied is made regarding delivery, performance or suitability.



SKM 150GB12T4

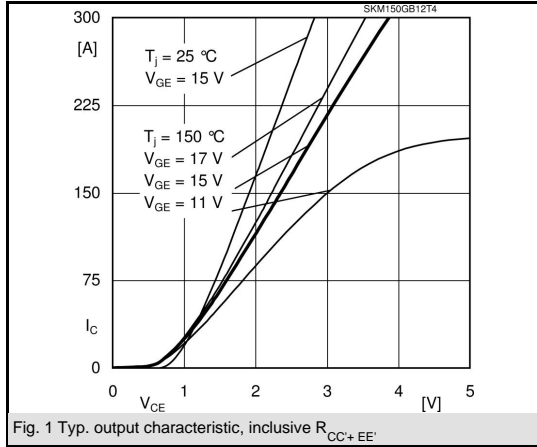


Fig. 1 Typ. output characteristic, inclusive R_{CC+EE}

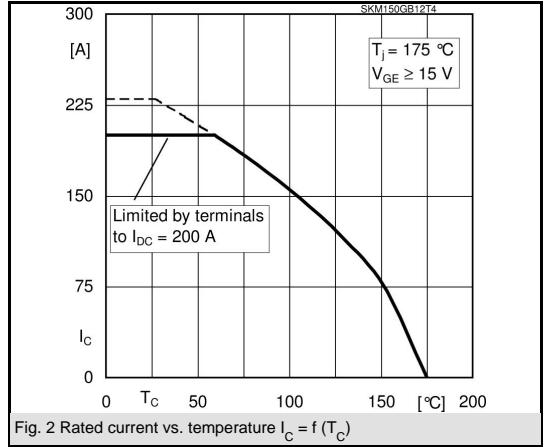


Fig. 2 Rated current vs. temperature $I_c = f(T_c)$

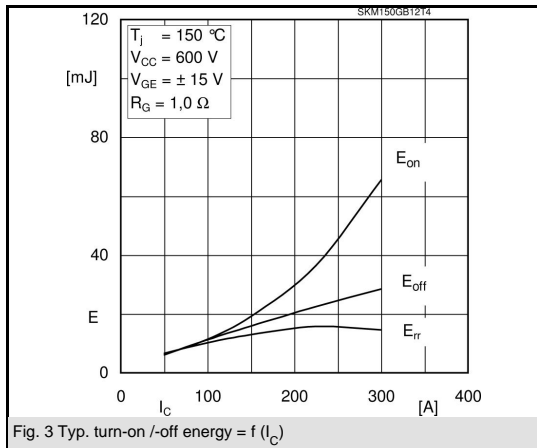


Fig. 3 Typ. turn-on /-off energy = $f(I_c)$

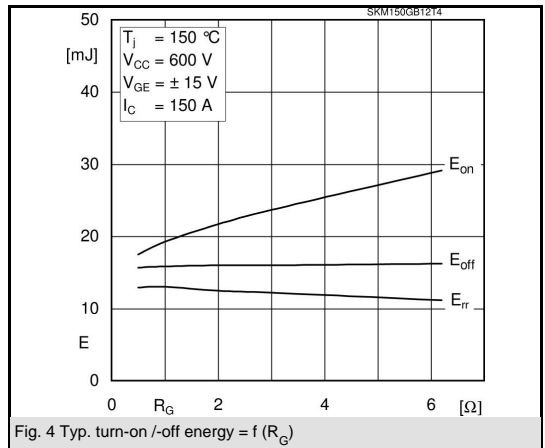


Fig. 4 Typ. turn-on /-off energy = $f(R_G)$

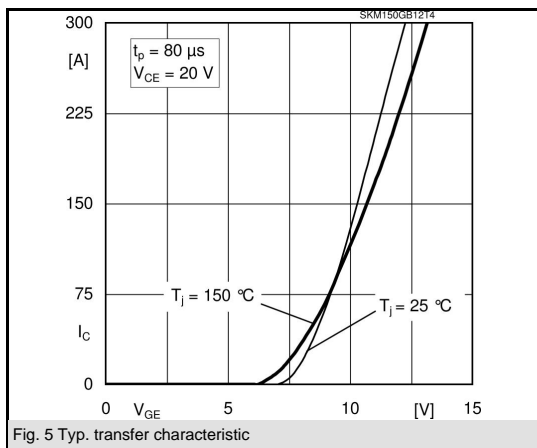


Fig. 5 Typ. transfer characteristic

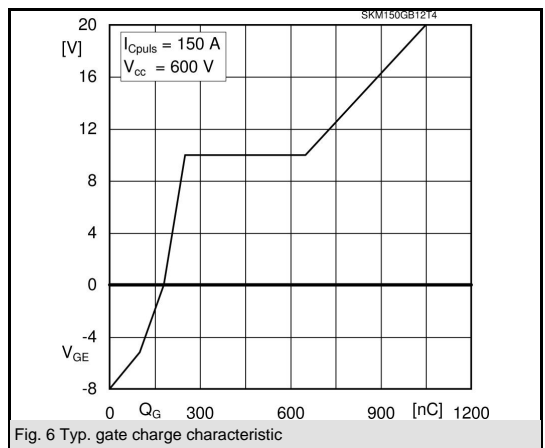
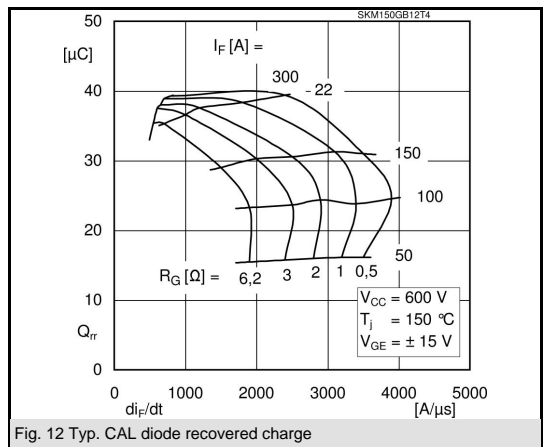
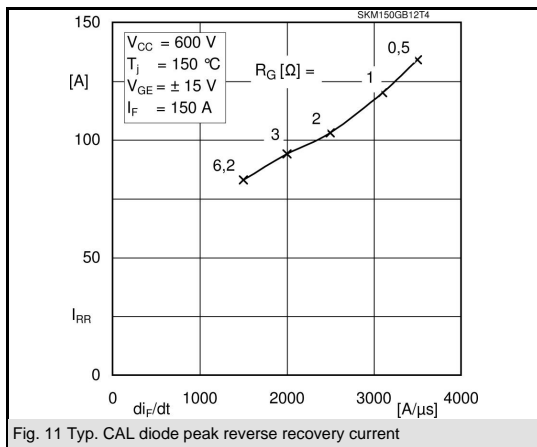
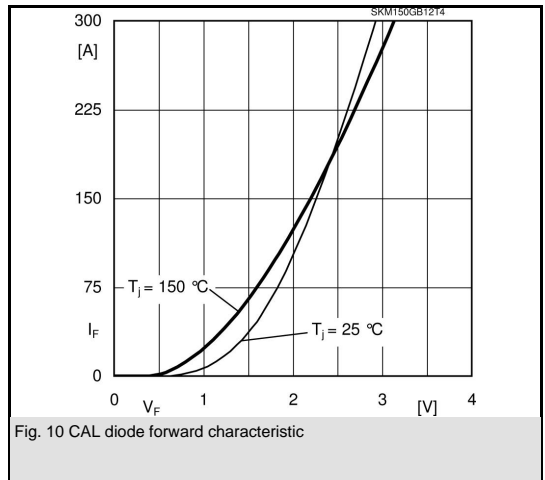
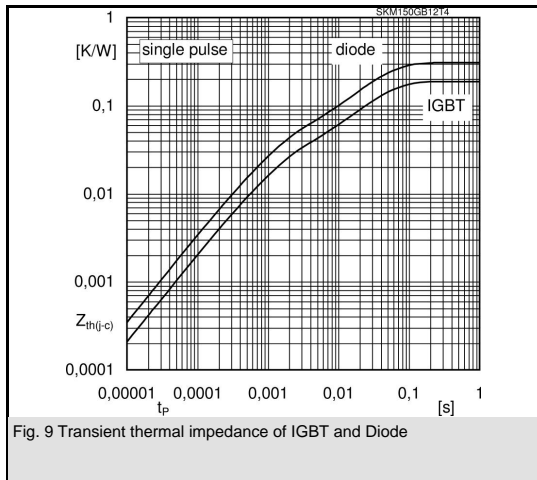
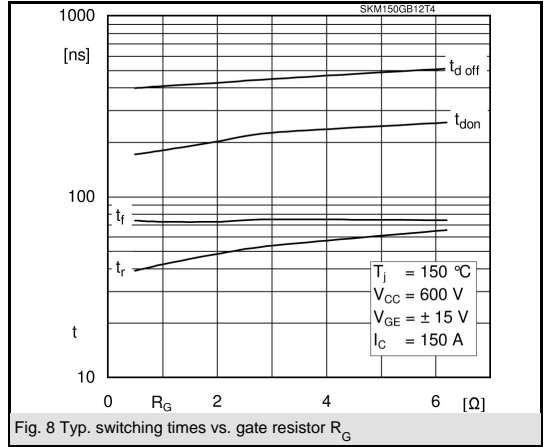
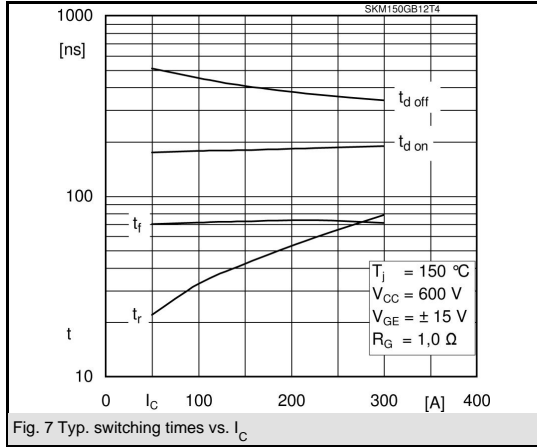


Fig. 6 Typ. gate charge characteristic

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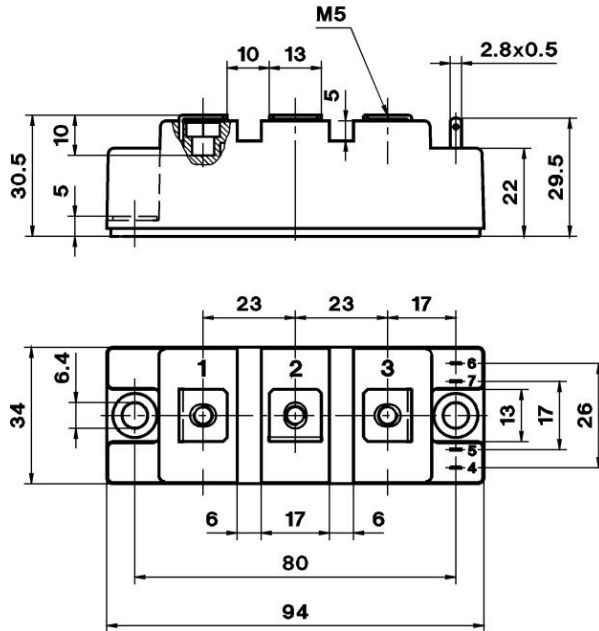


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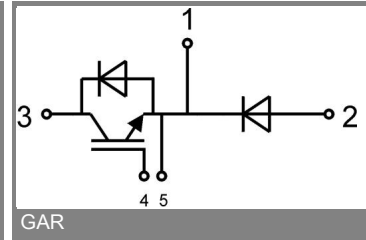
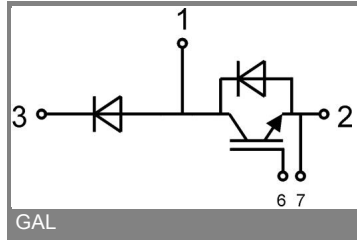
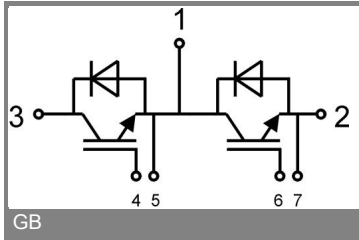
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CASED61

no. E 63 532



Case D61



SKM 400GB176D



SEMITRANS® 3

Trench IGBT Modules

SKM 400GB176D

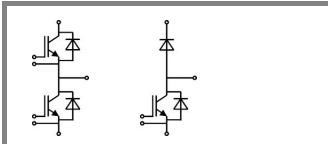
SKM 400GAL176D

Features

- Homogeneous Si
- Trench = Trenchgate technology
- $V_{CE(sat)}$ with positive temperature coefficient
- High short circuit capability, self limiting to $6 \times I_C$

Typical Applications*

- AC inverter drives
- mains 575 - 750 V AC
- Public transport (auxiliary syst.)
- Wind power



GB GAL

Absolute Maximum Ratings		$T_{case} = 25^\circ C$, unless otherwise specified		
Symbol	Conditions	Values	Units	
IGBT				
V_{CES}	$T_j = 25^\circ C$	1700	V	
I_C	$T_j = 150^\circ C$	$T_c = 25^\circ C$	430	A
		$T_c = 80^\circ C$	310	A
I_{CRM}	$I_{CRM} = 2 \times I_{Cnom}$	600	A	
V_{GES}		± 20	V	
t_{psc}	$V_{CC} = 1200 V; V_{GE} \leq 20 V; T_j = 125^\circ C$ $V_{CES} < 1700 V$	10	μs	
Inverse Diode				
I_F	$T_j = 150^\circ C$	$T_c = 25^\circ C$	440	A
		$T_c = 80^\circ C$	300	A
I_{FRM}	$I_{FRM} = 2 \times I_{Fnom}$	600	A	
I_{FSM}	$t_p = 10 ms; sin.$	$T_j = 150^\circ C$	2200	A
Freewheeling Diode				
I_F	$T_j = 150^\circ C$	$T_{case} = 25^\circ C$	440	A
		$T_{case} = 80^\circ C$	300	A
I_{FRM}	$I_{FRM} = 2 \times I_{Fnom}$	600	A	
I_{FSM}	$t_p = 10 ms; sin.$	$T_j = 150^\circ C$	2200	A
Module				
$I_{(RMS)}$		500	A	
T_{vj}		- 40 ... + 150	$^\circ C$	
T_{stg}		- 40 ... + 125	$^\circ C$	
V_{isol}	AC, 1 min.	4000	V	

Characteristics		$T_{case} = 25^\circ C$, unless otherwise specified			
Symbol	Conditions	min.	typ.	max.	Units
IGBT					
$V_{GE(th)}$	$V_{GE} = V_{CE}; I_C = 12 mA$	5,2	5,8	6,4	V
I_{CES}	$V_{GE} = 0 V, V_{CE} = V_{CES}$			4	mA
V_{CE0}		$T_j = 25^\circ C$	1	1,2	V
		$T_j = 125^\circ C$	0,9	1,1	V
r_{CE}	$V_{GE} = 15 V$	$T_j = 25^\circ C$	3,3	4,2	m Ω
		$T_j = 125^\circ C$	5,2	6	m Ω
$V_{CE(sat)}$	$I_{Cnom} = 300 A, V_{GE} = 15 V$	$T_j = 25^\circ C_{chiplev.}$	2	2,4	V
		$T_j = 125^\circ C_{chiplev.}$	2,45	2,9	V
C_{ies}	$V_{CE} = 25, V_{GE} = 0 V$	$f = 1 MHz$	19,8		nF
C_{oes}			1,1		nF
C_{res}			0,88		nF
Q_G	$V_{GE} = -8V...+15V$	2500		nC	
$t_{d(on)}$	$R_{Gon} = 4 \Omega$	$V_{CC} = 1200V$ $I_C = 300A$	330		ns
			$T_j = 125^\circ C$	55	ns
t_r	$R_{Goff} = 4 \Omega$	$V_{GE} = \pm 15V$	170		mJ
			$T_j = 125^\circ C$	880	ns
$t_{d(off)}$			145		ns
			$T_j = 125^\circ C$	118	mJ
$R_{th(j-c)}$	per IGBT	0,075		K/W	

SKM 400GB176D



SEMITRANS[®] 3

Trench IGBT Modules

SKM 400GB176D

SKM 400GAL176D

Features

- Homogeneous Si
- Trench = Trenchgate technology
- $V_{CE(sat)}$ with positive temperature coefficient
- High short circuit capability, self limiting to $6 \times I_C$

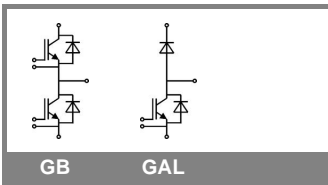
Typical Applications*

- AC inverter drives
- mains 575 - 750 V AC
- Public transport (auxiliary syst.)
- Wind power

Characteristics					
Symbol	Conditions	min.	typ.	max.	Units
Inverse Diode					
$V_F = V_{EC}$	$I_{Fnom} = 300 \text{ A}; V_{GE} = 0 \text{ V}$	$T_j = 25 \text{ }^\circ\text{C}_{chiplev.}$	1,7	1,9	V
		$T_j = 125 \text{ }^\circ\text{C}_{chiplev.}$	1,8	2	V
V_{F0}		$T_j = 25 \text{ }^\circ\text{C}$	1,2	1,4	V
		$T_j = 125 \text{ }^\circ\text{C}$	0,9	1,1	V
r_F		$T_j = 25 \text{ }^\circ\text{C}$	1,7	1,7	mΩ
		$T_j = 125 \text{ }^\circ\text{C}$	3	3	mΩ
I_{RRM}	$I_F = 300 \text{ A}$	$T_j = 125 \text{ }^\circ\text{C}$	418		A
Q_{rr}	$di/dt = 5800 \text{ A}/\mu\text{s}$		117		μC
E_{rr}	$V_{GE} = -15 \text{ V}; V_{CC} = 1200 \text{ V}$		78		mJ
$R_{th(j-c)D}$	per diode			0,125	K/W
FWD					
$V_F = V_{EC}$	$I_{Fnom} = 300 \text{ A}; V_{GE} = 0 \text{ V}$	$T_j = 25 \text{ }^\circ\text{C}_{chiplev.}$	1,7	1,9	V
		$T_j = 125 \text{ }^\circ\text{C}_{chiplev.}$	1,8	2	V
V_{F0}		$T_j = 25 \text{ }^\circ\text{C}$	1,2	1,4	V
		$T_j = 125 \text{ }^\circ\text{C}$	0,9	1,1	V
r_F		$T_j = 25 \text{ }^\circ\text{C}$	1,7	1,7	V
		$T_j = 125 \text{ }^\circ\text{C}$	3	3	V
I_{RRM}	$I_F = 300 \text{ A}$	$T_j = 125 \text{ }^\circ\text{C}$	418		A
Q_{rr}	$di/dt = 5800 \text{ A}/\mu\text{s}$		117		μC
E_{rr}	$V_{GE} = -15 \text{ V}; V_{CC} = 1200 \text{ V}$		78		mJ
$R_{th(j-c)FD}$	per diode			0,125	K/W
Module					
L_{CE}			15	20	nH
R_{CC+EE}	res., terminal-chip	$T_{case} = 25 \text{ }^\circ\text{C}$	0,35		mΩ
		$T_{case} = 125 \text{ }^\circ\text{C}$	0,5		mΩ
$R_{th(c-s)}$	per module			0,038	K/W
M_s	to heat sink M6	3	5		Nm
M_t	to terminals M6	2,5	5		Nm
w				325	g

This is an electrostatic discharge sensitive device (ESDS), international standard IEC 60747-1, Chapter IX.

* The specifications of our components may not be considered as an assurance of component characteristics. Components have to be tested for the respective application. Adjustments may be necessary. The use of SEMIKRON products in life support appliances and systems is subject to prior specification and written approval by SEMIKRON. We therefore strongly recommend prior consultation of our personal.



SKM 400GB176D



SEMITRANS[®] 3

Trench IGBT Modules

SKM 400GB176D

SKM 400GAL176D

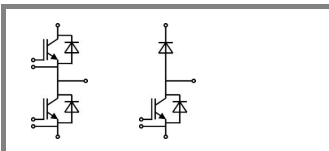
Features

- Homogeneous Si
- Trench = Trenchgate technology
- $V_{CE(sat)}$ with positive temperature coefficient
- High short circuit capability, self limiting to $6 \times I_C$

Typical Applications*

- AC inverter drives
- mains 575 - 750 V AC
- Public transport (auxiliary syst.)
- Wind power

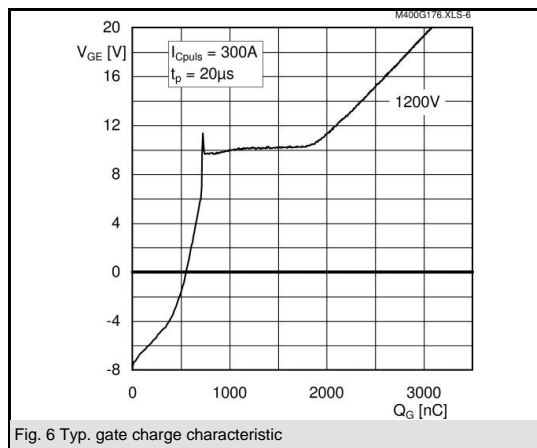
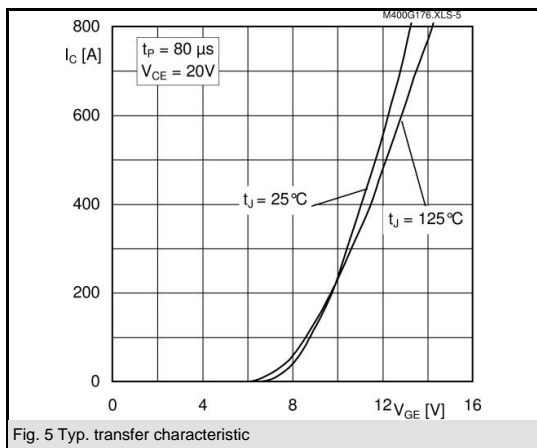
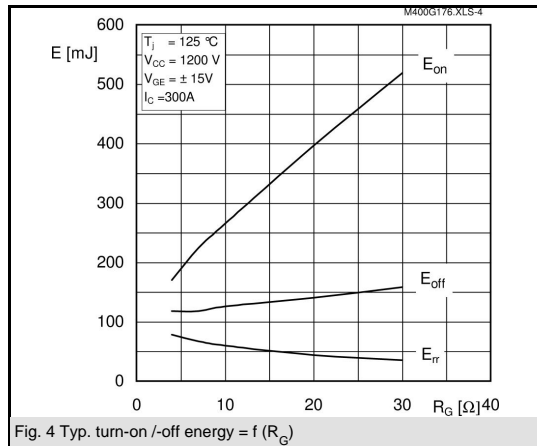
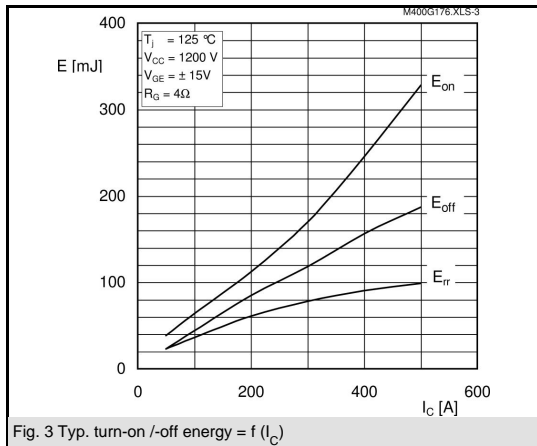
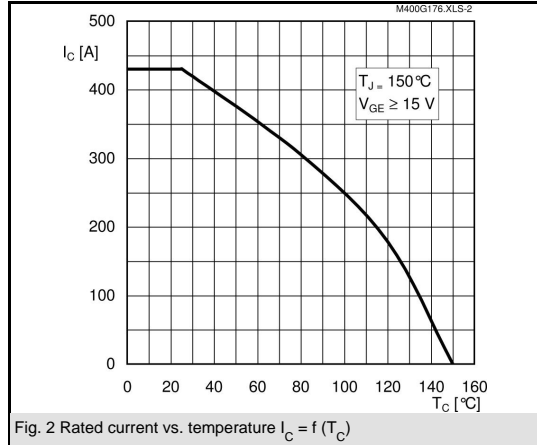
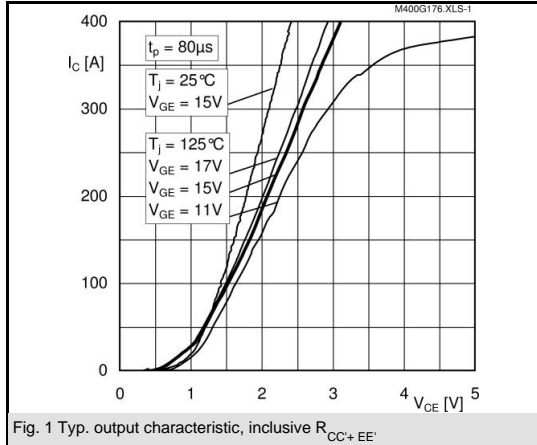
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Z^{th(j-c)}	R_i	i = 1	52	mk/W
	R_i	i = 2	18	mk/W
	R_i	i = 3	4,6	mk/W
	R_i	i = 4	0,4	mk/W
	tau_i	i = 1	0,0569	s
	tau_i	i = 2	0,0122	s
	tau_i	i = 3	0,002	s
	tau_i	i = 4	0,02	s
Z^{th(j-c)D}	R_i	i = 1	85	mk/W
	R_i	i = 2	28	mk/W
	R_i	i = 3	10,5	mk/W
	R_i	i = 4	1,5	mk/W
	tau_i	i = 1	0,054	s
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	tau_i	i = 4	0,0002	s



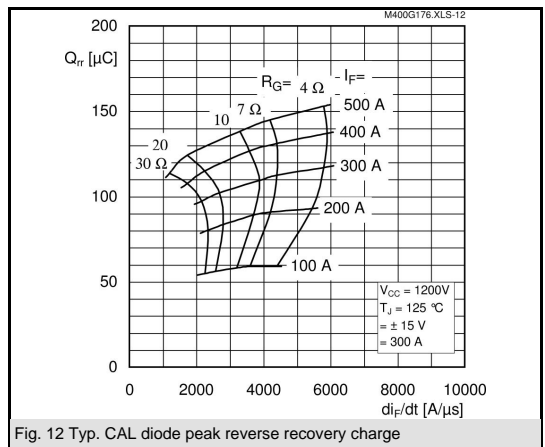
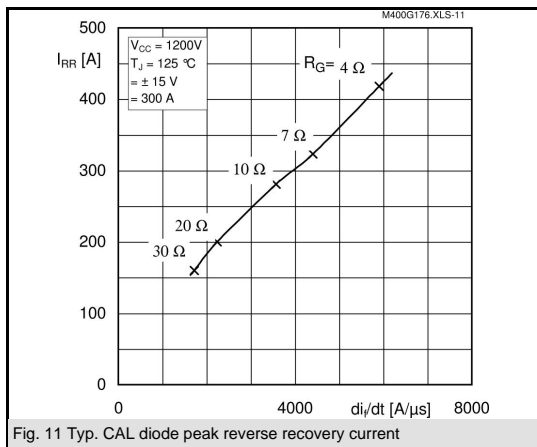
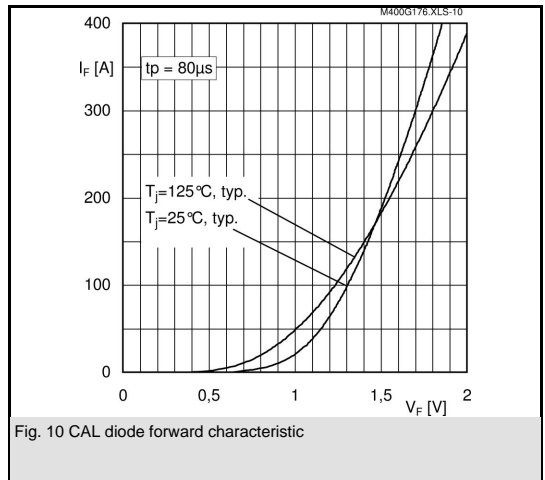
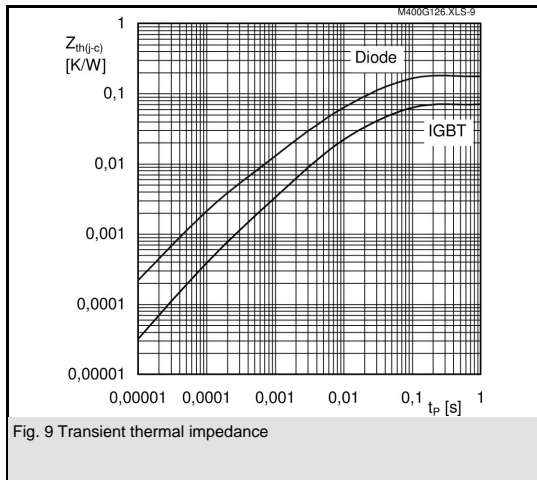
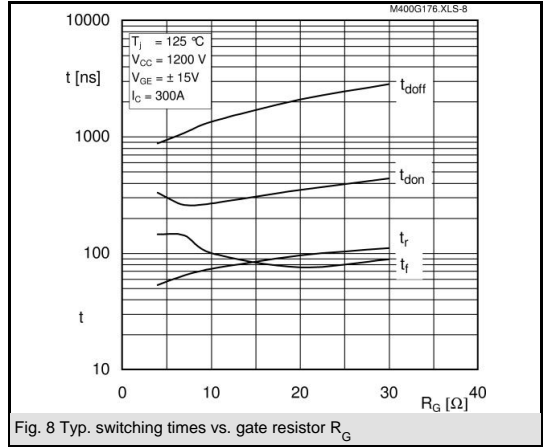
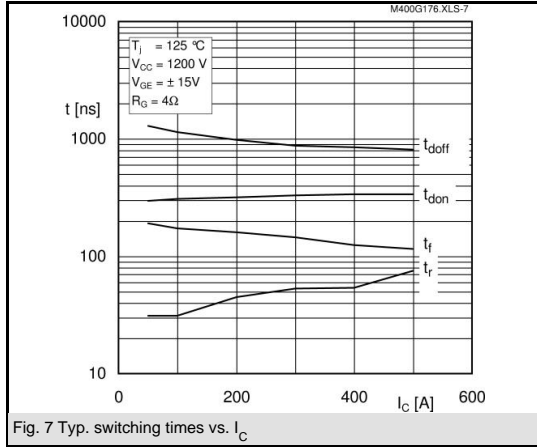
GB

GAL

SKM 400GB176D



SKM 400GB176D

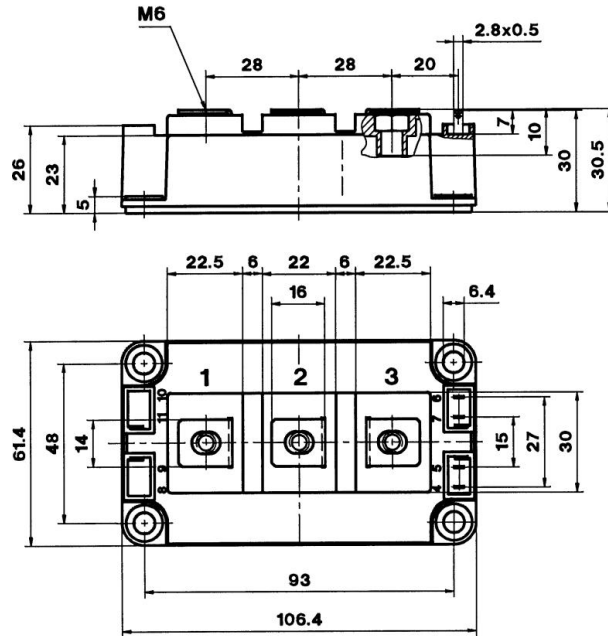


SKM 400GB176D

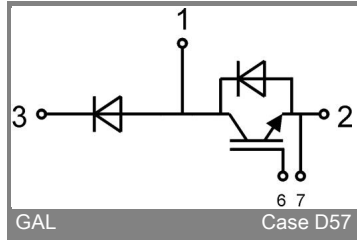
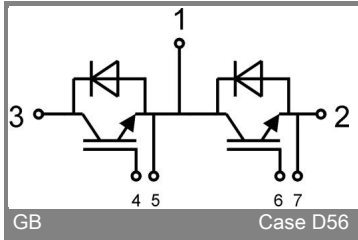
UL Recognized


CASED56


File no. 63 532




Case D 56



Technische Information / Technical Information				
IGBT-Module IGBT-modules <h1 style="text-align: center;">FF200R33KF2C</h1>				
IGBT, Wechselrichter / IGBT, Inverter Höchstzulässige Werte / Maximum Rated Values		Vorläufige Daten Preliminary Data		
Kollektor-Emitter-Sperrspannung Collector-emitter voltage	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = -25^{\circ}\text{C}$	V_{CES}	3300 3300	V
Kollektor-Dauergleichstrom Continuous DC collector current	$T_C = 80^{\circ}\text{C}, T_{vj\max} = 150^{\circ}\text{C}$ $T_C = 25^{\circ}\text{C}, T_{vj\max} = 150^{\circ}\text{C}$	$I_{C, nom}$ I_C	200 330	A A
Periodischer Kollektor-Spitzenstrom Repetitive peak collector current	$t_p = 1\text{ ms}$	I_{CRM}	400	A
Gesamt-Verlustleistung Total power dissipation	$T_C = 25^{\circ}\text{C}, T_{vj\max} = 150$	P_{tot}	2,20	kW
Gate-Emitter-Spitzenspannung Gate-emitter peak voltage		V_{GES}	+/-20	V
Charakteristische Werte / Characteristic Values		min. typ. max.		
Kollektor-Emitter-Sättigungsspannung Collector-emitter saturation voltage	$I_C = 200\text{ A}, V_{GE} = 15\text{ V}$ $I_C = 200\text{ A}, V_{GE} = 15\text{ V}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	$V_{CE\text{ sat}}$	3,40 4,30 4,25 5,00 V V
Gate-Schwellenspannung Gate threshold voltage	$I_C = 20,0\text{ mA}, V_{CE} = V_{GE}, T_{vj} = 25^{\circ}\text{C}$		V_{GEth}	4,2 5,1 6,0 V
Gateladung Gate charge	$V_{GE} = -15\text{ V} \dots +15\text{ V}, V_{CE} = 1800\text{V}$		Q_G	4,00 μC
Interner Gatewiderstand Internal gate resistor	$T_{vj} = 25^{\circ}\text{C}$		R_{Gint}	2,5 Ω
Eingangskapazität Input capacitance	$f = 1\text{ MHz}, T_{vj} = 25^{\circ}\text{C}, V_{CE} = 25\text{ V}, V_{GE} = 0\text{ V}$		C_{ies}	25,0 nF
Rückwirkungskapazität Reverse transfer capacitance	$f = 1\text{ MHz}, T_{vj} = 25^{\circ}\text{C}, V_{CE} = 25\text{ V}, V_{GE} = 0\text{ V}$		C_{res}	1,40 nF
Kollektor-Emitter-Reststrom Collector-emitter cut-off current	$V_{CE} = 3300\text{ V}, V_{GE} = 0\text{ V}, T_{vj} = 25^{\circ}\text{C}$		I_{CES}	5,0 mA
Gate-Emitter-Reststrom Gate-emitter leakage current	$V_{CE} = 0\text{ V}, V_{GE} = 20\text{ V}, T_{vj} = 25^{\circ}\text{C}$		I_{GES}	400 nA
Einschaltverzögerungszeit, induktive Last Turn-on delay time, inductive load	$I_C = 200\text{ A}, V_{CE} = 1800\text{ V}$ $V_{GE} = \pm 15\text{ V}$ $R_{Gon} = 5,6\ \Omega, C_{GE} = 33,0\text{ nF}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	t_{don}	0,28 0,28 μs μs
Anstiegszeit, induktive Last Rise time, inductive load	$I_C = 200\text{ A}, V_{CE} = 1800\text{ V}$ $V_{GE} = \pm 15\text{ V}$ $R_{Gon} = 5,6\ \Omega, C_{GE} = 33,0\text{ nF}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	t_r	0,18 0,20 μs μs
Abschaltverzögerungszeit, induktive Last Turn-off delay time, inductive load	$I_C = 200\text{ A}, V_{CE} = 1800\text{ V}$ $V_{GE} = \pm 15\text{ V}$ $R_{Goff} = 7,5\ \Omega, C_{GE} = 33,0\text{ nF}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	t_{doff}	1,55 1,70 μs μs
Fallzeit, induktive Last Fall time, inductive load	$I_C = 200\text{ A}, V_{CE} = 1800\text{ V}$ $V_{GE} = \pm 15\text{ V}$ $R_{Goff} = 7,5\ \Omega, C_{GE} = 33,0\text{ nF}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	t_f	0,20 0,20 μs μs
Einschaltverlustenergie pro Puls Turn-on energy loss per pulse	$I_C = 200\text{ A}, V_{CE} = 1800\text{ V}, L_S = 70\text{ nH}$ $V_{GE} = \pm 15\text{ V}$ $R_{Gon} = 5,6\ \Omega, C_{GE} = 33,0\text{ nF}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	E_{on}	235 365 mJ mJ
Abschaltverlustenergie pro Puls Turn-off energy loss per pulse	$I_C = 200\text{ A}, V_{CE} = 1800\text{ V}, L_S = 70\text{ nH}$ $V_{GE} = \pm 15\text{ V}$ $R_{Goff} = 7,5\ \Omega, C_{GE} = 33,0\text{ nF}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	E_{off}	215 255 mJ mJ
Kurzschlußverhalten SC data	$V_{GE} \leq 15\text{ V}, V_{CC} = 2500\text{ V}$ $V_{CE\max} = V_{CES} - L_{SCE} \cdot di/dt$ $t_p \leq 10\ \mu\text{s}, T_{vj} = 125^{\circ}\text{C}$		I_{sc}	1000 A
Wärmewiderstand, Chip bis Gehäuse Thermal resistance, junction to case	pro IGBT / per IGBT		R_{thJC}	57,0 K/kW
Wärmewiderstand, Gehäuse bis Kühlkörper Thermal resistance, case to heatsink	pro IGBT / per IGBT $\lambda_{Paste} = 1\text{ W/(m}\cdot\text{K)} / \lambda_{grease} = 1\text{ W/(m}\cdot\text{K)}$		R_{thCH}	49,0 K/kW
Temperatur im Schaltbetrieb Temperature under switching conditions		$T_{vj\text{ op}}$	-40	125 $^{\circ}\text{C}$
prepared by: JB	date of publication: 2013-10-03			
approved by: CL	revision: 2.0			

Technische Information / Technical Information IGBT-Module IGBT-modules		FF200R33KF2C					
					Vorläufige Daten Preliminary Data		
Diode, Wechselrichter / Diode, Inverter Höchstzulässige Werte / Maximum Rated Values							
Periodische Spitzensperrspannung Repetitive peak reverse voltage	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = -25^{\circ}\text{C}$	V_{RRM}	3300 3300		V		
Dauergleichstrom Continuous DC forward current		I_F	200		A		
Periodischer Spitzenstrom Repetitive peak forward current	$t_p = 1 \text{ ms}$	I_{FRM}	400		A		
Grenzlastintegral I^2t - value	$V_R = 0 \text{ V}$, $t_p = 10 \text{ ms}$, $T_{vj} = 125^{\circ}\text{C}$	I^2t	14,0		kA^2s		
Spitzenverlustleistung Maximum power dissipation	$T_{vj} = 125^{\circ}\text{C}$	P_{RQM}	400		kW		
Mindesteinschaltdauer Minimum turn-on time		$t_{on \text{ min}}$	10,0		μs		
Charakteristische Werte / Characteristic Values							
				min.	typ.	max.	
Durchlassspannung Forward voltage	$I_F = 200 \text{ A}$, $V_{GE} = 0 \text{ V}$ $I_F = 200 \text{ A}$, $V_{GE} = 0 \text{ V}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	V_F		2,80 2,80	3,50 3,50	V V
Rückstromspitze Peak reverse recovery current	$I_F = 200 \text{ A}$, $-di_F/dt = 1100 \text{ A}/\mu\text{s}$ ($T_{vj}=125^{\circ}\text{C}$) $V_R = 1800 \text{ V}$ $V_{GE} = -15 \text{ V}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	I_{RM}		275 325		A A
Sperrverzögerungsladung Recovered charge	$I_F = 200 \text{ A}$, $-di_F/dt = 1100 \text{ A}/\mu\text{s}$ ($T_{vj}=125^{\circ}\text{C}$) $V_R = 1800 \text{ V}$ $V_{GE} = -15 \text{ V}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	Q_r		120 220		μC μC
Abschaltenergie pro Puls Reverse recovery energy	$I_F = 200 \text{ A}$, $-di_F/dt = 1100 \text{ A}/\mu\text{s}$ ($T_{vj}=125^{\circ}\text{C}$) $V_R = 1800 \text{ V}$ $V_{GE} = -15 \text{ V}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	E_{rec}		125 255		mJ mJ
Wärmewiderstand, Chip bis Gehäuse Thermal resistance, junction to case	pro Diode / per diode		R_{thJC}			110	K/kW
Wärmewiderstand, Gehäuse bis Kühlkörper Thermal resistance, case to heatsink	pro Diode / per diode $\lambda_{\text{Paste}} = 1 \text{ W}/(\text{m}\cdot\text{K})$ / $\lambda_{\text{grease}} = 1 \text{ W}/(\text{m}\cdot\text{K})$		R_{thCH}		93,0		K/kW
Temperatur im Schaltbetrieb Temperature under switching conditions			$T_{vj \text{ op}}$	-40		125	$^{\circ}\text{C}$
prepared by: JB		date of publication: 2013-10-03					
approved by: CL		revision: 2.0					

Technische Information / Technical Information IGBT-Module IGBT-modules				
FF200R33KF2C				
Vorläufige Daten Preliminary Data				
Modul / Module				
Isolations-Prüfspannung Isolation test voltage	RMS, f = 50 Hz, t = 1 min.	V _{ISOL}	6,0	kV
Teilentladungs-Aussetzspannung Partial discharge extinction voltage	RMS, f = 50 Hz, Q _{PD} ≤ 10 pC (acc. to IEC 1287)	V _{ISOL}	2,6	kV
Kollektor-Emitter-Gleichsperrspannung DC stability	T _{vj} = 25°C, 100 fit	V _{CE D}	1800	V
Material Modulgrundplatte Material of module baseplate			AlSiC	
Innere Isolation Internal isolation	Basisisolierung (Schutzklasse 1, EN61140) basic insulation (class 1, IEC 61140)		AlN	
Kriechstrecke Creepage distance	Kontakt - Kühlkörper / terminal to heatsink Kontakt - Kontakt / terminal to terminal		32,2 32,2	mm
Luftstrecke Clearance	Kontakt - Kühlkörper / terminal to heatsink Kontakt - Kontakt / terminal to terminal		19,1 19,1	mm
Vergleichszahl der Kriechwegbildung Comperative tracking index		CTI	> 400	
			min. typ. max.	
Wärmewiderstand, Gehäuse bis Kühlkörper Thermal resistance, case to heatsink	pro Modul / per module λ _{Paste} = 1 W/(m·K) / λ _{grease} = 1 W/(m·K)	R _{thCH}	16,0	K/kW
Modulstreuinduktivität Stray inductance module		L _{sCE}	58	nH
Modulleitungswiderstand, Anschlüsse - Chip Module lead resistance, terminals - chip	T _C = 25°C, pro Schalter / per switch	R _{CC+EE}	0,78	mΩ
Lagertemperatur Storage temperature		T _{slg}	-40	125 °C
Anzugsdrehmoment f. Modulmontage Mounting torque for modul mounting	Schraube M6 - Montage gem. gültiger Applikationsschrift Screw M6 - Mounting according to valid application note	M	4,25	- 5,75 Nm
Anzugsdrehmoment f. elektr. Anschlüsse Terminal connection torque	Schraube M5 - Montage gem. gültiger Applikationsschrift Screw M5 - Mounting according to valid application note	M	3,6	- 4,2 Nm
Gewicht Weight		G	500	g
prepared by: JB	date of publication: 2013-10-03			
approved by: CL	revision: 2.0			

Technische Information / Technical Information

IGBT-Module
IGBT-modules

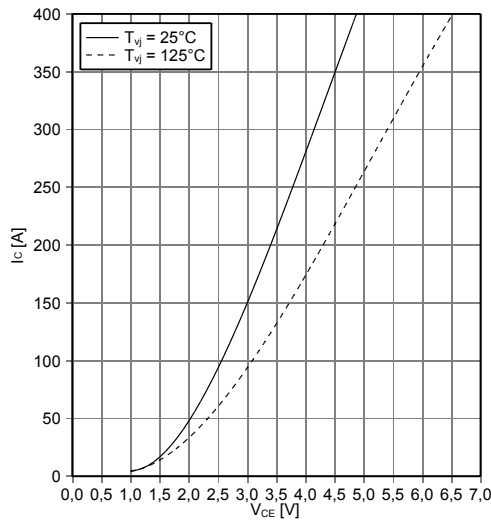
FF200R33KF2C



Vorläufige Daten
Preliminary Data

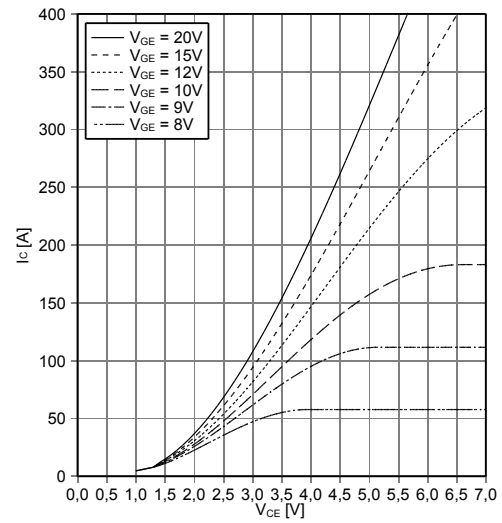
Ausgangskennlinie IGBT, Wechselrichter (typisch)
output characteristic IGBT, inverter (typical)

$I_c = f(V_{CE})$
 $V_{GE} = 15\text{ V}$



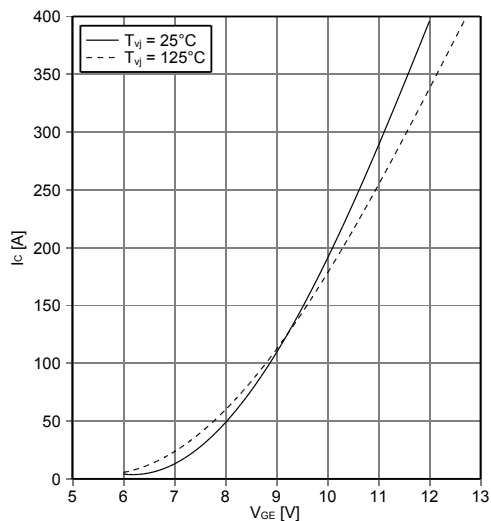
Ausgangskennlinienfeld IGBT, Wechselrichter (typisch)
output characteristic IGBT, inverter (typical)

$I_c = f(V_{CE})$
 $T_{vj} = 125^\circ\text{C}$



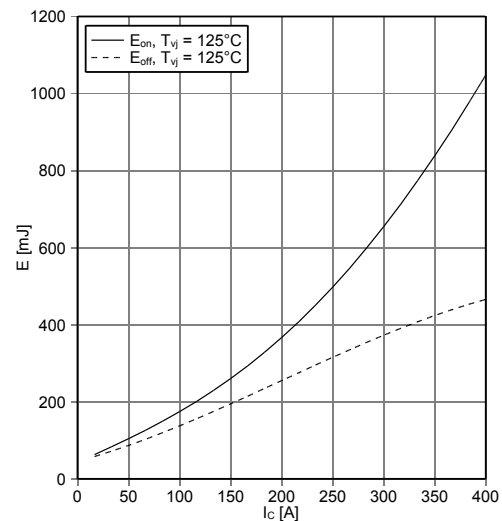
Übertragungscharakteristik IGBT, Wechselrichter (typisch)
transfer characteristic IGBT, inverter (typical)

$I_c = f(V_{GE})$
 $V_{CE} = 20\text{ V}$



Schaltverluste IGBT, Wechselrichter (typisch)
switching losses IGBT, inverter (typical)

$E_{on} = f(I_c)$, $E_{off} = f(I_c)$
 $V_{GE} = \pm 15\text{ V}$, $R_{Gon} = 5.6\ \Omega$, $R_{Goff} = 7.5\ \Omega$, $V_{CE} = 1800\text{ V}$, $C_{GE} = 33\text{ nF}$



prepared by: JB	date of publication: 2013-10-03
approved by: CL	revision: 2.0

Technische Information / Technical Information

IGBT-Module
IGBT-modules

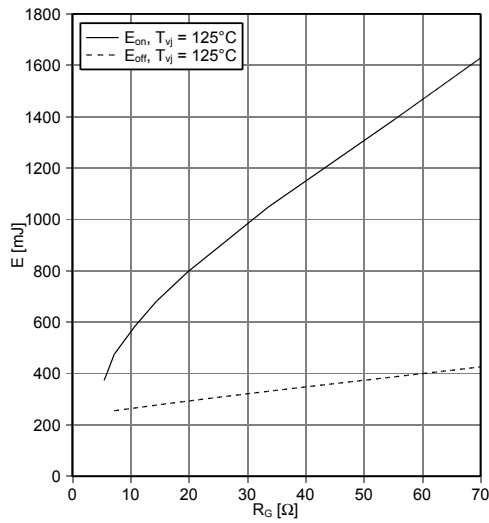
FF200R33KF2C



Vorläufige Daten
Preliminary Data

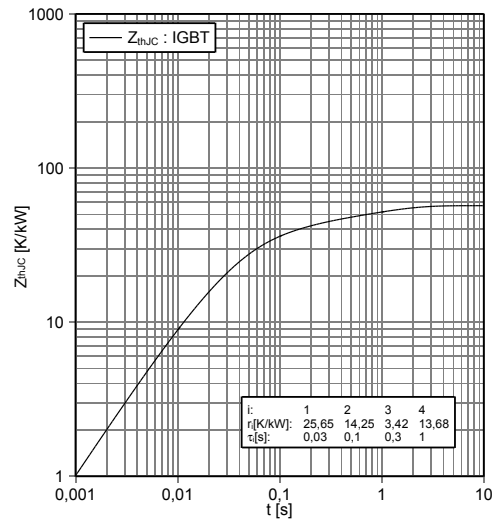
Schaltverluste IGBT, Wechselrichter (typisch)
switching losses IGBT, Inverter (typical)

$E_{on} = f(R_G)$, $E_{off} = f(R_G)$
 $V_{GE} = \pm 15\text{ V}$, $I_C = 200\text{ A}$, $V_{CE} = 1800\text{ V}$, $C_{GE} = 33\text{ nF}$



Transienter Wärmewiderstand IGBT, Wechselrichter
transient thermal impedance IGBT, Inverter

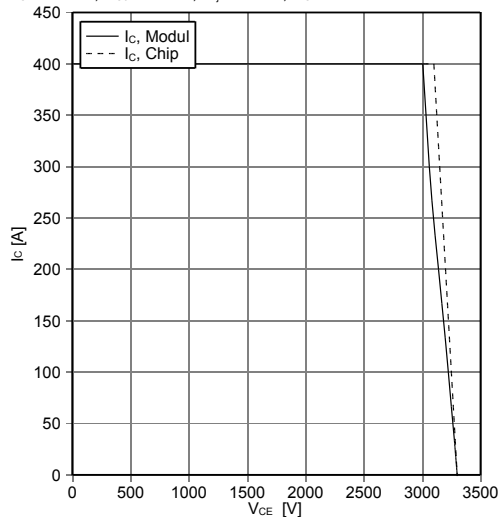
$Z_{thJC} = f(t)$



Sicherer Rückwärts-Arbeitsbereich IGBT, Wechselrichter
(RBSOA)

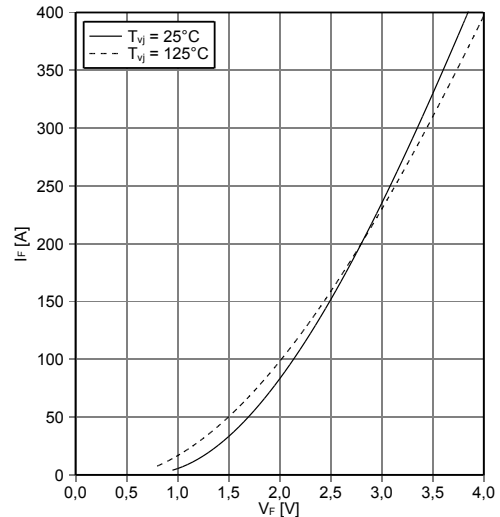
reverse bias safe operating area IGBT, Inverter (RBSOA)

$I_C = f(V_{CE})$
 $V_{GE} = \pm 15\text{ V}$, $R_{Goff} = 7.5\ \Omega$, $T_{vj} = 125^\circ\text{C}$, $C_{GE} = 33\text{ nF}$



Durchlasskennlinie der Diode, Wechselrichter (typisch)
forward characteristic of Diode, Inverter (typical)

$I_F = f(V_F)$



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Technische Information / Technical Information

IGBT-Module
IGBT-modules

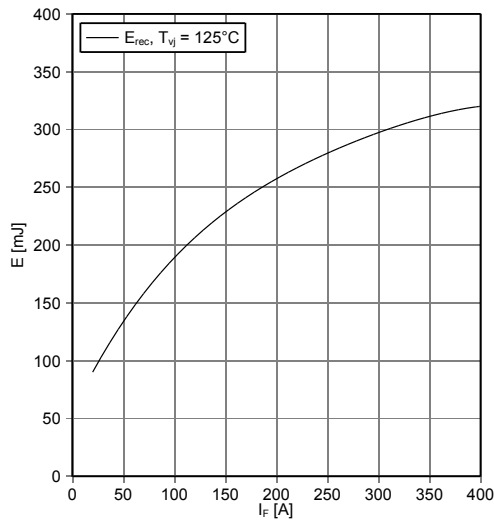
FF200R33KF2C



Vorläufige Daten
Preliminary Data

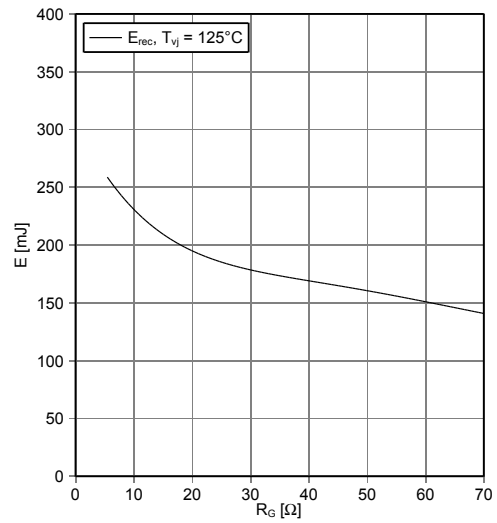
Schaltverluste Diode, Wechselrichter (typisch)
switching losses Diode, Inverter (typical)

$E_{rec} = f(I_F)$
 $R_{Gon} = 5.6 \Omega, V_{CE} = 1800 V$



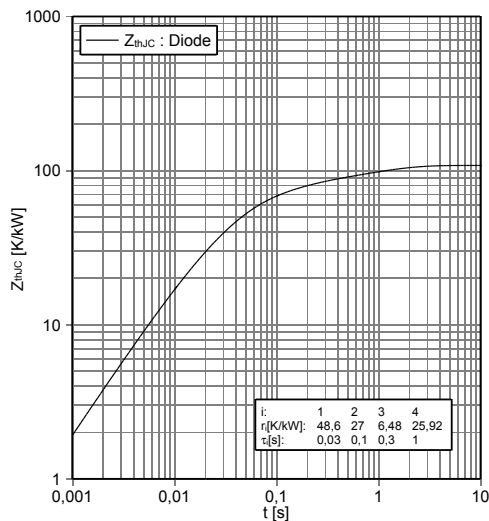
Schaltverluste Diode, Wechselrichter (typisch)
switching losses Diode, Inverter (typical)

$E_{rec} = f(R_G)$
 $I_F = 200 A, V_{CE} = 1800 V$



Transienter Wärmewiderstand Diode, Wechselrichter
transient thermal impedance Diode, Inverter

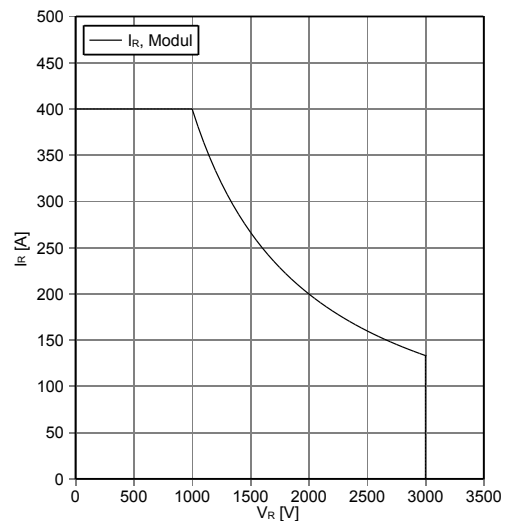
$Z_{thJC} = f(t)$



i:	1	2	3	4
r_i [K/kW]:	48,6	27	6,48	25,92
τ [s]:	0,03	0,1	0,3	1

Sicherer Arbeitsbereich Diode, Wechselrichter (SOA)
safe operation area Diode, Inverter (SOA)

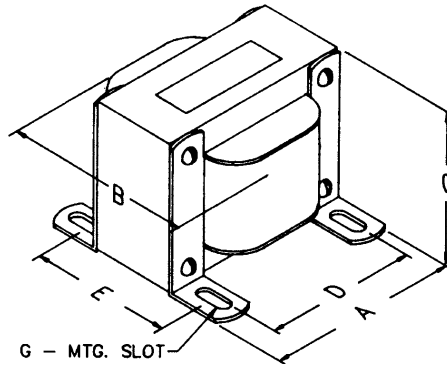
$I_R = f(V_R)$
 $T_{vj} = 125^\circ C$



prepared by: JB	date of publication: 2013-10-03
approved by: CL	revision: 2.0

D.C. Reactors (195 Series)

Chokes



HEAVY CURRENT REACTORS

- Open core & coil, 4-slot bracket mounting chokes.
- Tolerance of 15% on both inductance & resistance.
- Inductances measured at rated D.C. current.
- Connections are made to a screw terminal or heavy copper tabs with holes
- Perfect for high current power supply filtering.

Part No.	Inductance (Millihenries)	D.C. Current (Amps)	Resistance (Ohms)	Insulation Class	Dimensions (Inches)						Wt. Lbs.
					A	B	C	D	E	Mtg. - Slot (G)	
195B150	0.5	150	.0018	B	5.25	5.50	4.47	4.38	4.13	.28 x .56	26
195C20	1.0	20	.013	A	3.00	3.06	2.50	2.50	2.25	.20 x .38	3
195C30	1.0	30	.009	A	3.75	3.85	3.13	3.13	2.50	.20 x .38	6
195C50	1.0	50	.005	A	4.50	5.25	3.75	3.75	3.50	.20 x .38	14.5
195C75	1.0	75	.004	A	5.25	6.00	4.47	4.38	4.63	.28 x .56	23
195C100	1.0	100	.0036	B	5.25	6.50	4.47	4.38	5.13	.28 x .56	26
195E20	2.5	20	.022	A	3.75	4.20	3.13	3.13	2.75	.20 x .38	6.5
195E30	2.5	30	.013	A	4.50	5.25	3.75	3.75	3.50	.20 x .38	12.5
195E50	2.5	50	.008	A	5.25	6.00	4.47	4.38	4.63	.28 x .56	23.5
195E75	2.5	75	.008	B	6.00	6.63	5.16	5.00	4.88	.28 x .56	32.5
195E100	2.5	100	.006	B	9.00	9.75	7.50	7.00	6.00	.44 x .75	88
195G10	5	10	.040	A	3.75	3.60	3.13	3.13	2.25	.20 x .38	5.5
195G20	5	20	.025	A	4.50	4.75	3.75	3.75	3.00	.20 x .38	10.5
195G30	5	30	.023	A	5.25	5.00	4.47	4.38	3.63	.28 x .56	16
195G50	5	50	.021	B	7.50	6.50	6.25	6.00	4.50	.38 x .63	38
195G75	5	75	.01	B	9.00	9.50	7.76	7.00	7.00	.44 x .75	87
195J10	10	10	.07	A	3.75	4.35	3.13	3.13	3.00	.20 x .38	8
195J20	10	20	.045	A	5.25	5.00	4.47	4.38	3.63	.28 x .56	17.5
195J30	10	30	.037	A	6.00	7.50	5.00	5.00	5.88	.31 x .50	36
195J50	10	50	.023	B	9.00	9.75	7.50	7.00	6.25	.44 x .75	79
195M10	20	10	.013	A	4.50	4.75	3.75	3.75	3.00	.20 x .38	10.2
195M20	20	20	.075	A	6.00	7.50	5.00	5.00	5.88	.31 x .50	34
195M30	20	30	.045	B	6.00	7.63	5.16	5.00	5.88	.28 x .56	41
195P5	30	5	.23	A	3.75	4.20	3.13	3.13	2.75	.20 x .38	6.5
195P10	30	10	.17	A	4.50	5.25	3.75	3.75	3.50	.20 x .38	16
195P20	30	20	.13	B	5.25	6.91	4.47	4.38	5.54	.28 x .56	28
195R10	50	10	.165	A	5.25	5.50	4.47	4.38	4.13	.28 x .56	26
195R20	50	20	.13	B	9.00	8.25	7.50	7.00	5.75	.44 x .75	72
195T5	100	5	.64	A	4.50	5.25	3.75	3.75	3.50	.20 x .38	14
195T10	100	10	.42	B	7.50	6.00	6.25	6.00	4.25	.38 x .63	35



CANADA
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Basingstoke, UK 01256 812812

AUSTRALIA
Queenstown, Australia 61-8-8240-2244


MKV AC, MKV DC Capacitors
B25856
LSI Snubbing and Clamping
Features

- High dielectric strength
- High peak-current capability
- Extremely low inductance

Construction

- Self-healing
- Plastic dielectric
- Oil-impregnated tubular windings (no PCB)
- Metal-sprayed end faces ensure reliable contacting
- Fully insulated case
- Axial version

Terminals

- Internal thread M6 × 8 and M8 × 10
- Axial

Mounting

- On the terminals

Individual data sheets

Individual data sheets contain detailed specification incl. thermal data.
Upon request, these data sheets are available for each capacitor type.





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B25856

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Technical data

Standards		IEC 1071-1/2 EN 61071-1/2 VDE 0560 part 120 and 121
Dielectric dissipation factor	$\tan \delta_0$	2×10^{-4}
Capacitance tolerance		$\pm 10\%$
Max. repetitive rate of voltage rise	$(dv/dt)_{\max}$	$\frac{\hat{i}}{C}$
Max. non-repetitive rate of voltage rise	$(dv/dt)_s$	$\frac{I_s}{C}$
Climatic data:		
Min. operating temperature	T_{\min}	$-25\text{ }^\circ\text{C}$
Max. operating temperature	T_{\max}	$+85\text{ }^\circ\text{C}$
Average relative humidity		$\leq 95\%$
Failure quota	$\alpha_{\text{FQ}(\text{co})}$	300 failures per 10^9 component hours
Load duration	$t_{\text{LD}(\text{co})}$	100 000 h
Storage temperature limit	T_{stg}	$\leq 98\text{ mm diameter: } -55/+85\text{ }^\circ\text{C}$ $\geq 103\text{ mm diameter: } -30/+85\text{ }^\circ\text{C}$
IEC climatic category (IEC 68-1 and 2)		25/085/56
Test A, cold		$-25\text{ }^\circ\text{C}$
Test B, dry heat		$+85\text{ }^\circ\text{C}$
Test Ca, damp heat, steady state		56 days/ $40\text{ }^\circ\text{C}/93\%$ rel. humidity
Values after test Ca:		
Capacitance change	$\Delta C/C$	$\leq 1\%$
Insulation resistance	R_{ins}	$C_R \leq 1\text{ }\mu\text{F: } \geq 10000\text{ M}\Omega$
Self-discharge time constant $\tau =$	$R_{\text{ins}} \times C$	$C_R > 1\text{ }\mu\text{F: } \geq 10000\text{ s}$
Dissipation factor change	$\Delta \tan \delta$	$\leq 1 \times 10^{-4}$
Test data:		
Voltage test between terminals		
DC test voltage	V_{TT}	$1.5 \times V_R, 10\text{ s}$ ($V_R = \text{DC}$) $1.75 \times V_R, 10\text{ s}$ ($V_R = \text{AC}$)
AC test voltage (rms value)	V_{TT}	$1.25 \times V_R, 50\text{ Hz}, 10\text{ s}$ ($V_R = \text{AC}$)
Insulation resistance	R_{ins}	$C_R \leq 1\text{ }\mu\text{F: } \geq 10000\text{ M}\Omega$
Self-discharge time constant	$\tau = R_{\text{ins}} \times C$	$C_R > 1\text{ }\mu\text{F: } \geq 10000\text{ s}$
Dissipation factor (50 Hz)	$\tan \delta$	$\leq 3 \times 10^{-4}$

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3 09/05



MKV AC, MKV DC Capacitors **B25856**
LSI Snubbing and Clamping

Characteristics and ordering codes

$C_R^{1)}$	I_{max}	\hat{i}	I_s	R_S 20 °C	L_{self}	Dimensions $d \times l$	Fig.	Appr. weight	Ordering code
μF	A	A	A	m Ω	nH	mm		g	
$V_{RDC} = AC 1700 V$									
$V_R = AC 1400 V$									
$\hat{v} = 2000 V$					$v_s = 2900 V$				
					$V_{TT} = AC 1800 V, 10 s$				
0.2	30	200	500	3.1	<20	40 × 49	1	130	B25856K0204K003
0.47	80	470	1200	1.0	<20	68 × 49	1	300	B25856J0474K003
1	60	1400	3500	1.6	<20	53 × 59	1	200	B25856K0105K003
1.5	80	1400	3500	1.1	<20	68 × 68	2	500	B25856K0155K003
2	70	2000	5000	1.5	<20	68 × 79	2	550	B25856K0205K003
4	70	2400	6000	1.8	<20	73 × 100	2	700	B25856K0405K003
7.5	80	3000	7500	1.0	<20	93 × 100	2	1000	B25856K0755K003
15	80	3000	7500	2.0	<20	93 × 168	2	1600	B25856K0156K003
$V_{RDC} = AC 2000 V$									
$V_R = AC 1700 V$									
$\hat{v} = 2400 V$					$v_s = 3500 V$				
					$V_{TT} = AC 2200 V, 10 s$				
0.2	30	350	900	6.0	<20	40 × 59	1	150	B25856K4204K003
0.5	50	600	1500	1.1	<20	68 × 49	1	300	B25856K4504K013
1	50	1200	3000	2.4	<20	53 × 70	1	250	B25856K4105K003
2.5	80	3000	7500	1.0	<20	83 × 79	2	700	B25856K4255K003
7.5	80	4200	10500	1.4	<20	93 × 126	2	1250	B25856K4755K003
$V_{RDC} = AC 2500 V$									
$V_R = AC 2100 V$									
$\hat{v} = 3000 V$					$v_s = 4300 V$				
					$V_{TT} = AC 2700 V, 10 s$				
0.2	30	500	1200	6.1	<20	40 × 70	1	160	B25856K1204K003
1.5	80	3600	9000	0.9	<20	83 × 79	2	700	B25856K1155K003
2.5	80	3500	8800	1.3	<20	83 × 100	2	850	B25856K1255K003
5	80	5000	12500	1.5	<20	93 × 142	2	1400	B25856K1505K003
7.5	80	5000	13000	1.8	<20	98 × 173	2	1800	B25856K1755K003
10	80	6800	17000	1.4	<20	108 × 173	2	2200	B25856K1106K003

1) Other capacitance values upon request

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MKV AC, MKV DC Capacitors

B25856

LSI Snubbing and Clamping

Characteristics and ordering codes

$C_R^{1)}$	I_{max}	\hat{i}	I_s	R_S 20 °C	L_{self}	Dimensions $d \times l$	Fig.	Appr. weight	Ordering code
μF	A	A	A	m Ω	nH	mm		g	
$V_{RDC} = AC 3000 V$									
$V_R = AC 2500 V$									
$\hat{v} = 3600 V$									
$v_s = 5200 V$									
$V_{TT} = AC 3200 V, 10 s$									
0.5	70	2200	5500	1.9	<20	68 × 79	2	550	B25856K7504K013
1	80	3000	7500	1.1	<20	83 × 79	2	700	B25856K7105K003
1.5	80	4800	12000	0.7	<20	93 × 79	2	800	B25856K7155K013
2	80	3600	9000	1.3	<20	88 × 100	2	900	B25856K7205K003
2.5	80	4500	11000	1.0	<20	98 × 100	2	1100	B25856K7255K003
3	80	3600	9000	1.9	<10	88 × 142	2	1100	B25856J7305J003
3.5	80	4200	10500	1.7	<20	93 × 142	2	1400	B25856K7355K003
4	80	4800	12000	1.5	<20	98 × 142	2	1500	B25856K7405K003
5	80	6000	15000	1.2	<20	108 × 142	2	1800	B25856K7505K003
$V_{RDC} = AC 3300 V$									
$V_R = AC 2800 V$									
$\hat{v} = 4000 V$									
$v_s = 5800 V$									
$V_{TT} = AC 3500 V, 10 s$									
0.1	20	350	900	8.0	<20	40 × 70	1	160	B25856K3104K003
0.5	70	1800	4500	1.7	<20	73 × 79	2	600	B25856K3504K003
2.5	80	3500	8800	2.0	<20	88 × 142	2	1300	B25856K3255K003
$V_{RDC} = AC 4000 V$									
$V_R = AC 3400 V$									
$\hat{v} = 4800 V$									
$v_s = 7000 V$									
$V_{TT} = AC 4300 V, 10 s$									
0.2	50	1200	3000	2.6	<20	53 × 70	1	250	B25856K2204K003
0.5	80	3000	7500	1.1	<20	83 × 79	2	700	B25856K2504K003
1	80	3500	8800	1.3	<20	88 × 105	2	1000	B25856K2105K003
2	80	5000	12500	1.3	<20	98 × 126	2	1350	B25856K2205K003
2.5	80	3800	9400	2.3	<20	88 × 168	2	1500	B25856K2255K003
3	80	4500	11000	2.0	<20	98 × 168	2	1700	B25856K2305K003
4	80	6000	15000	1.5	<20	108 × 168	2	2100	B25856K2405K003

1) Other capacitance values upon request

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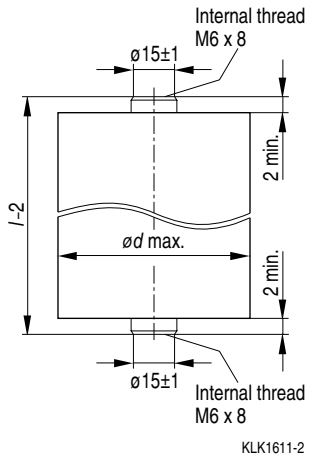


MKV AC, MKV DC Capacitors

B25856

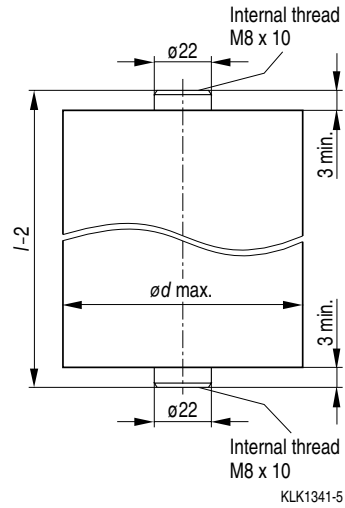
LSI Snubbing and Clamping

Dimensional drawing 1



$\varnothing d_{max} = 40 \dots 68 \text{ mm}$:
 Internal thread = M6 × 8
 Max. torque = 7 Nm

Dimensional drawing 2



$\varnothing d_{max} = 68 \dots 108 \text{ mm}$:
 Internal thread = M8 × 10
 Max. torque = 7 Nm

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6 09/05