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# Optimal design of DC/DC converters for automotive applications based on Monte Carlo search method

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ABSTRACT

DC-DC converter devices are broadly applied in usages such as computer secondary power supplies, automobiles auxiliary power supplies and medical instruments. This research work analysis computer-aided optimization technique of dc/dc converters instruments, with a focus on converter instruments for dual-voltage automotive electrical systems. A new CAD optimization method based on Monte Carlo search methods is suggested which permits the draft space to be speedy searched in an automated fashion and the most optimal drafts and design ways to be detected. The optimization technique also permits the effects of oscillation in draft features on the charge, weight, and bulk of an optimized converter instrument to be readily determined. An archetype converter device designed by the mentioned optimization method is tested and compared to a converter device drafted by traditional means.



## 1. Introduction

Many industrial usages essential power from variable DC voltage sources. DC-DC converters convert fixed DC input voltage to a variable DC output voltage for application in such cases. DC-DC converters are furthermore applied as interface between DC systems of several voltage values.

Load in automobiles has been growing speedy for several decades, and is starting to exceed the actual capacity of nowadays electrical systems. To site this wrangle, it is extensively agreed that a dual-voltage system is the future evolutionary step for automotive electrical systems. High power loads will be moved to a new high-voltage terminal, while incandescent lighting, electronics, and other loads that benefit from a lower voltage will remain on the currently-used low voltage terminal (Kassakian et al., 1996; Jeyappragash et al., 1996).

One extensively-considered approach for applying a dyadic-voltage level electrical system is shown in Fig. 1. A high-voltage alternator generates the high-voltage level terminal, while the low-voltage level terminal is generated from the high-voltage level terminal using a dc/dc converter. The converter controls the flow of energy between the two buses, and can be used to regulate the energy balance between the high level and low-voltage level batteries. In the case where a bidirectional converter device is applied, either battery may be applied to recharge the other if it becomes depleted. These benefits make the dc/dc converter-based system the very favorite of exist options from an operation view.

DC to DC converters are important in portable electronic instruments such as cellular phones and laptop computers, which are supplied with power from batteries primarily. Such electronic devices often contain several sub-circuits, each with its own voltage level requirement different from that supplied by the battery or an external supply (sometimes higher or lower than the supply voltage). Additionally, the battery voltage declines as its stored energy is drained. Switched DC to DC converters offer a method to increase voltage from a partially lowered battery voltage thereby saving space instead of using multiple batteries to accomplish the same thing.

Most DC to DC converters also regulate the output voltage. Some exceptions include high-efficiency LED power sources, which are a kind of DC to DC converter that regulates the current through the LEDs, and simple charge pumps which double or triple the output voltage.

DC to DC converters developed to maximize the energy harvest for photovoltaic systems and for wind turbines are called power optimizers.

The computer-aided optimization base approach is suggested in this research study. A new CAD soft computing technique is suggested which permits the draft space to be rapidly searched in an automated fashion and the very optimal drafts and design methods to be detected. Furthermore, it permits the effects of oscillation in the draft properties on the toll, weight, and volume of an optimized converter to be readily determined, an attribute of specific value to the electrical system designer and industrial makers. In second section of this paper, a brief review of CAD methods that applied for optimization in power electronic is done. Third section of this article, provides scheme of optimization technique and details of it. Computer simulation results and obtained results is shown in section four of this research work, and finally section five conclude the paper.

## 2. Optimization concept

Computer-aided engineering (CAE) is the broad usage of computer software to aid in engineering analysis tasks. It includes Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), Multibody dynamics (MBD), and optimization. Software tools that have been developed to support these activities are considered CAE tools. CAE tools are being used, for example, to analyze the robustness and performance of components and assemblies. The term encompasses simulation,

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validation, and optimization of products and manufacturing tools. In the future, CAE systems will be major providers of information to help support design teams in decision making. In regard to information networks, CAE systems are individually considered a single node on a total information network and each node may interact with other nodes on the network. CAE systems can provide support to businesses. This is achieved by the use of reference architectures and their ability to place information views on the business process. Reference architecture is the basis from which information model, especially product and manufacturing models. The term CAE has also been used by some in the past to describe the use of computer technology within engineering in a broader sense than just engineering analysis. It was in this context that the term was coined by Jason Lemon, founder of SDRC in the late 1970s. This definition is however better known today by the terms CAx and PLM.

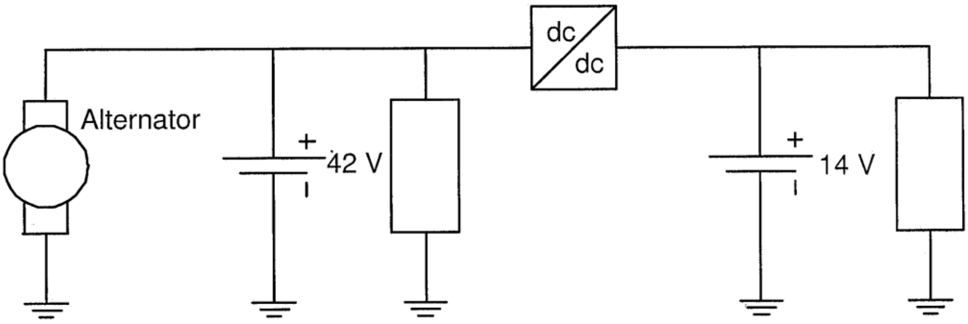


**Fig. 1.** Dual-voltage automotive electrical system.

Computer-aided design (CAD) is the use of computer systems to assist in the creation, modification, analysis, or optimization of a design (Achiammal and Kayalvizhi, 2014). CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing. CAD output is often in the form of electronic files for print, machining, or other manufacturing operations. Computer-aided design is used in many fields. Its use in designing electronic systems is known as electronic design automation, or EDA. In mechanical design it is known as mechanical design automation (MDA) or computer-aided drafting (CAD), which includes the process of creating a technical drawing with the use of computer software.

There has been many performed research works on soft computing and CAD application in power electronic systems and issues. Jeyappragash et al. (1996) suggested that optimization routine is coupled with a circuit simulator to find variables for a power converter filter. The objective function to be minimized is a predetermined function of the filter inductance, capacitance, and output voltage oscillation. The circuit simulator ACSL is used to forecast the variation operation of a draft, as a deterministic outer loop explores for the target function minimum.

Gezgin et al. (1997) proposed the new method to control the behavior of joint optimization of converter structure. The structural objective of the optimization is defined in condition of converter losses or efficiency, which are based on simplified closed-form computations (Reatt, 1994), as the control charge is based on a formulation of the control struggle and operation. The researchers use this technique to the draft of a buck converter, where the plant draft variables are the converter inductance and capacitance, with other plant variables are constant. A main taint to this method is that it requires a very complex equations of case study. Some other applications and examples are presented in Blaabjerg and Pedersen (1997).

### 2.1. Monte Carlo method

Monte Carlo methods (or Monte Carlo experiments) are a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results; typically one runs simulations many times over in order to obtain the distribution of an unknown probabilistic entity. The name comes from the resemblance of the technique to the act of playing and recording results in a real gambling casino. They are often used in physical and mathematical problems and are most useful when it is difficult or impossible to obtain a closed-form expression, or unfeasible to apply a deterministic algorithm. Monte Carlo methods are mainly used in three distinct problem classes: optimization, numerical integration and generation of draws from a probability distribution.

In physics-related problems, Monte Carlo methods are quite useful for simulating systems with many coupled degrees of freedom, such as fluids, disordered materials, strongly coupled solids, and cellular structures (see cellular Potts model). Other examples include modeling phenomena with significant uncertainty in inputs such as the calculation of risk in business and, in math, evaluation of multidimensional definite integrals with complicated boundary conditions. In application to space and oil exploration problems, Monte Carlo–based predictions of failure, cost overruns and schedule overruns are routinely better than human intuition or alternative "soft" methods (Anderson, 1986).

The modern version of the Monte Carlo method was invented in the late 1940s by Stanislaw Ulam, while he was working on nuclear weapons projects at the Los Alamos National Laboratory. It was named by Nicholas Metropolis, after the Monte Carlo Casino, where Ulam's uncle often gambled (Kassakian et al., 1996). Immediately after Ulam's breakthrough, John von Neumann understood its importance and programmed the ENIAC computer to carry out Monte Carlo calculations.

Monte Carlo methods vary, but tend to follow a particular pattern:

1. Define a domain of possible inputs.
2. Generate inputs randomly from a probability distribution over the domain.
3. Perform a deterministic computation on the inputs.
4. Aggregate the results.

In this procedure the domain of inputs is the square that circumscribes our circle. We generate random inputs by scattering grains over the square then perform a computation on each input (test whether it falls within the circle). Finally, we aggregate the results to obtain our final result, the approximation of π.

If the grains are not uniformly distributed, then our approximation will be poor. Secondly, there should be a large number of inputs. The approximation is generally poor if only a few grains are randomly dropped into the whole square. On average, the approximation improves as more grains are dropped.

Monte Carlo methods are especially useful for simulating phenomena with significant uncertainty in inputs and systems with a large number of coupled degrees of freedom. Areas of application include: Physical sciences, Engineering, Computational biology, Computer graphics, applied statistics, artificial intelligence for games, design and visuals, finance and business and etc. (Baeurle, 2009; Davenport, 1992).

## 3. Proposed method

To site the problem of optimizing converter structure for the automotive usage, we have suggested an intelligent CAD system that is significantly different from those introduced in last decade and other works. The applied algorithm searches the converter optimal design space to detect the converter draft or set of designs that fully minimizes a fitness function that is a weighted sum of member bulk, weight, and charge.

To do an optimization procedure, the draft properties should primary be set, consist the power rating, ambient temperature constraints, input and output voltage boundaries, and input and output electromagnetic interference (EMI) features. The human user must has complete control over the region of the draft space to be searched. Draft parameters considered by the program consist a collection of power stage architect, the number of interleaved power stages, switching frequency, inductor oscillation ratio, EMI filter structure, and passive member choosing.

A hybrid of a Monte Carlo algorithm and an expert system is applied to select all the members essential for the converter device. In the Monte Carlo technique applied, the program chooses random initial candidates in the human-assigned design range, and designs converters that meet the favorite features based on these initial nominates.

The proposed method include five basic parts, as shown in Fig. 2. These parts are the control loop section, the design algorithm section, the device models section, the database section, and the applier interface section (Neugebauer, 1999).

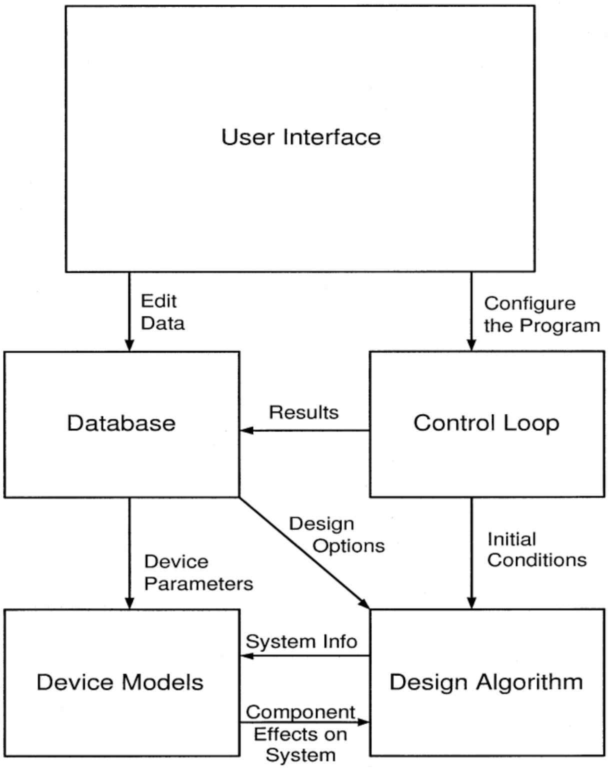


**Fig. 2.** Structure of the optimization program.

The proposed method guarantee that each model saved are valid; if a model proves to be invalid at any point the model algorithm stops and the control loop section will generate new model variables.

There are several vital kinds of datasets applied in the CAD program. Configuration data collection store the parameters applied to define the design space and set design properties. The results data collection store the parts applied and pertinent information about any valid converter found during the design space search. The human interface has a number of functions. It permits one to modify the features of all the sections in the dataset, to set up the converter properties and design space, and to look the optimized designs and other information generated by the programmed algorithm or proposed method.

For example, consider the subroutine applied to draft the converter power stage inductors. The routine takes as input the favor inductance and operating bound and utilizes the dataset of exist inductor cores and their properties. The initial step in the draft is to discover the number of turns required and the resulting flux density that will be induced in the core of system. The second stage is to define the wire size value. The program verifies that this wire size value will result in a maximum current density, $J_{\max}$, of less $3000\,A/in^2$ (approximately $465\,A/cm^2$ in the wire).

The winding power loss for the inductor, consist skin section and proximity section impact, is calculated by the models introduced by Carsten (1986). The inductor current will be computed as follow:

$$P_{wire} = \sum_n I_{n,rms}^2 . R_{n,wire}. \tag{1}$$

More details regarding the parameters and variables can be found by Carsten (1986). The skin depth, is computed as follow:

$$\delta_n = \sqrt{\frac{2.\rho_{Cu}}{2.\pi.n.f_{sw}.\mu_{Cu}}}, \tag{2}$$

here n, $\rho_{Cu}$ and $\mu_{Cu}$ are the number of each harmonic, the resistivity and permeability factor of copper material. Also we have:

$$X_n = \left(\frac{\pi}{4}\right)^{3/4} . \frac{d^{3/2}}{L^{1/2}} . \frac{1}{\delta_n}. \tag{3}$$

The effective resistance of the wire at the *n*th harmonic is calculated as follow:

$$\mathrm{R_n} = \left(M_n + \frac{m^2-1}{3} . D_n\right) . R_{dc}, \tag{4}$$

here *m* is the number of layers of windings that used and we will have:

$$\mathrm{M_n} = \mathrm{Re}\left\{\frac{(X_n+j.X_n).\cosh(X_n+j.X_n)}{\sinh(X_n+j.X_n)}\right\}, \tag{5}$$

$$D_\mathrm{n} = \mathrm{Re}\left\{\frac{2(X_n+j.X_n).\sinh(0.5(X_n+j.X_n))}{\cosh(0.5(X_n+j.X_n))}\right\}. \tag{6}$$

To compute core power loss, the ac flux swing in the core is computed as a sinusoid form and the core power loss is computed by the actual Steinmetz pattern (Reinert et al., 2001).

$$\mathrm{P_{core}} = C_M f^{\alpha} B_{ac}^{\beta} V_{core}. \tag{7}$$

### 3.1. Program validation

One example of trials evaluate of the proposed models is shown in Table 1.

## 4. Simulation results

In order to evaluate the use of the suggested method for these purposes, we use example results for the (component) volume optimization of dc/dc converters meeting the properties on Table 2.

**Table 1**
Comparison of inductor core and heat temperature rises of an experimental prototype to those predicted by the optimization program.

| Component | Measured temperature rise | Calculated temperature rise |
|---|---|---|
| Converter inductor | 13.3°$C$ | 13.3°$C$ |
| Heat sink | 13.3°$C$ | 13.3°$C$ |

Values are for a specific converter operating at 500 W in 25°$C$ambient temperature; predictions and measurements at rated power and ambient temperature (1000W, 105°$C$)would be higher.

**Table 2**
Design specification for a power converter in a dual-voltage automotive electrical system.

| | |
|---|---|
| High-side voltage range | 33-53 V |
| Low-side voltage range | 11-16 V |
| Power rating | 1000 W |
| ambient temperature | 105°$C$ |
| EMI specification | SAEJ 1113/41 class 1 |

### 4.1. Searching of design trends

Fig. 3 shows how the parts volume of a volume-optimized converter varies with power rating. To achieve this data value, the Monte Carlo was applied to identify the minimum volume design for converters rated at 250, 500, 750, and 1000W (with other specifications as per Table 2). The volume representation can be formulated as follow:

$$Volume(cm^3) \approx 0.18.Power(W) + 29.88.$$

Remaining design essentials also have a strong impact on the optimized converter draft. These features may be larger more easily defined by the suggested CAD technique than is possible by traditional means.

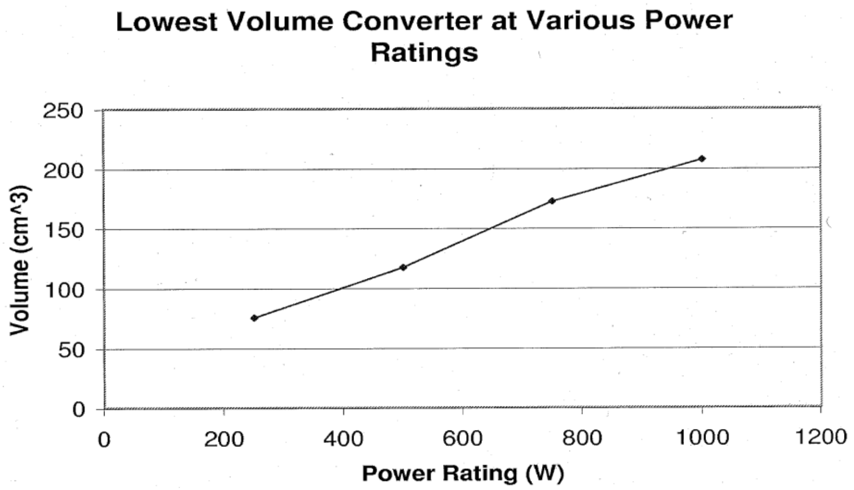


**Fig. 3**. Relationship between the component volume of the volume-optimized converter and its power rating.

The relationship among the volume of a volume-optimized converter and its respective power rating is dependent to the ambient temperature features. Fig. 4 illustrates this temperature dependence.

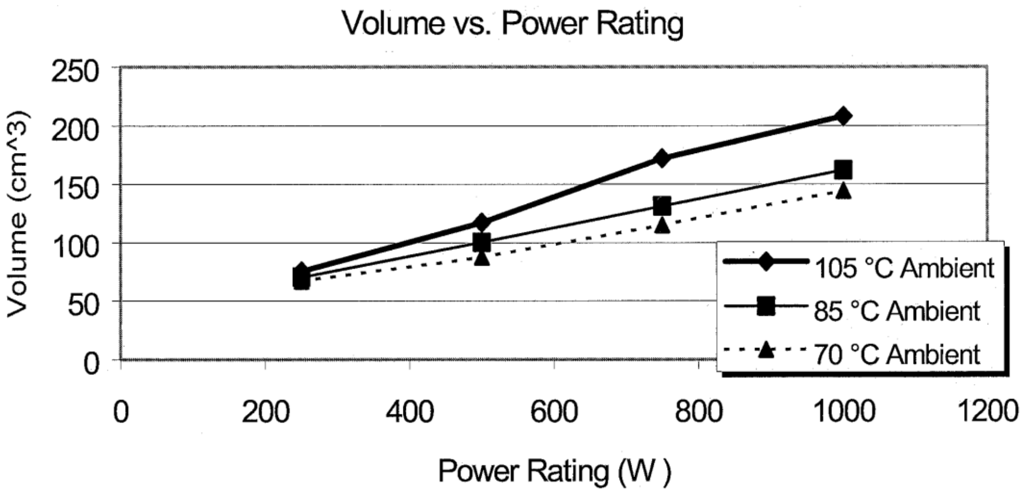


**Fig. 4.** Volume of the smallest converter at various power ratings for three different ambient temperatures.

### 4.2. Optimized converter design

Application of the optimization method was also searched for developing optimized converter designs. The first prototype converter was drafted with no the aid of the optimization ways, although the different subsystems were drafted toward low bulk and charge by many of the same models and drafts laws as applied in the optimization instruments. The second prototype converter was drafted by the CAD systems presented in this article, with a fitness function of minimum part bulk.

For the second prototype model, the optimization instrument was applied to detect the part bulk optimum converter design over the specified design space. Fig. 5 depicts an image of the optimized converter with the cover cancelled.

A comparison of the without optimization model and optimized model converters demonstrate that member volume is lower by a factor of six in the optimized converter as compared to the non-optimized converter.

Comparison of packaged converter volume shows that a smaller but still significant enhancement is obtained by the CAD approaches, as shown in Fig. 6.

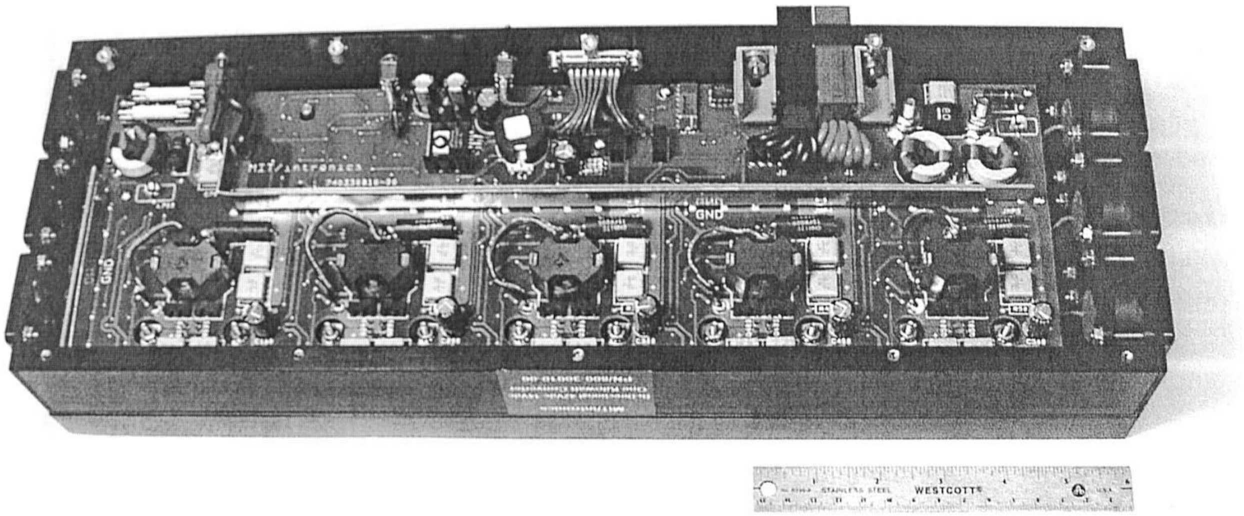


**Fig. 5.** Volume optimized bidirectional dc/dc converter.

The packaged volume of the non-optimized converter is a factor of 1.6 larger than that of the optimized converter ($6000cm^3$ as compared to $3700cm^3$). Care must be taken in comparing the packaged volume of the two converters. In addition to using more volumetrically-efficient capacitors as previously mentioned, the optimized converter also utilizes pcb-mount bus bars (to carry large currents without large trace areas), and makes more extensive use of surface mount control components. However, these volumetric advantages are largely offset by the volume cost of fully packaging the optimized converter for underhood automotive use. We conclude that—to first order—a comparison of the packaged volume of the two converters reflects the improvement that is achieved with the implemented optimization technique.

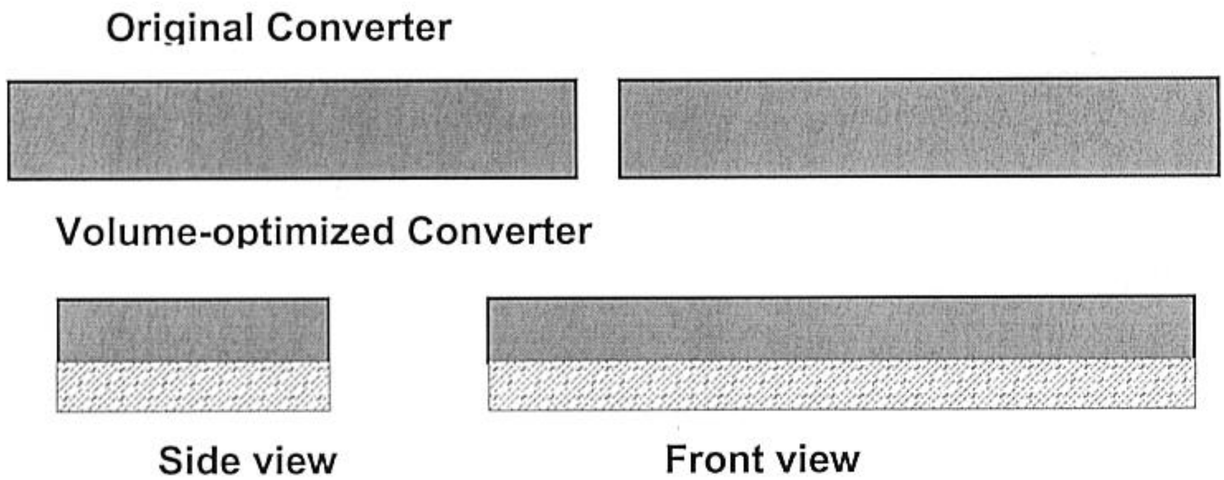


**Fig. 6.** Scaled comparison of the two prototype converters. The hashed section on the volume-optimized converter represents the heatsink needed if the converter is not mounted on an appropriate surface. The total packaged volume of the original converter is $6000cm^3$. The packaged volume of the volume-optimized converter is 2170 cm without the heatsink and $3700cm^3$ with it.

## 5. Conclusion

Power converters for binary-voltage automotive electrical systems will be manufactured in high production bulks under tight charge, size, and mass limits. To site the problem of drafting converters for this usage, this research article analyze intelligent CAD optimization method of dc/dc converters. A new CAD optimization approach based on Monte Carlo search methods is presented which permits the draft space to be rapidly explored in an automated fashion and the most optimal designs and design techniques to be detected. The program permits the impacts of oscillations in design features on the charge, weight, and volume of an optimized converter to be readily determined. This is of particular value to the automotive designer who must trade off the power converter design against system-level considerations. The approach is also valuable for developing highly optimized converter designs.

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