Power Conversion Modeling Methodology Based on Building Block Models

L. Laguna, R. Prieto, J.A. Oliver, J.A. Cobos
Universidad Politécnica de Madrid
Centro de Electrónica Industrial (CEI)
Madrid, SPAIN.
e-mail: cei@upm.es

H. Visairo
Systems Research Center, Mexico
Intel Corporation
Guadalajara, MEXICO
e-mail: horacio.visairo-cruz@intel.com

P. Kumar
Circuits and Systems Research
Intel Corporation
Hillsboro, U.S.
e-mail: pavan.kumar@intel.com

***Abstract* – Power systems modeling tools used to analyze static and dynamic characteristics usually rely on detailed and complex models, thus taking a long simulation time. Due to the acceleration of time to market of today's computing platforms, it is required to arrive at feasible solution options in a short amount of time to meet cost and time targets. Specifically, the areas of power conversion and power management traditionally rely on experimental verification and are lacking in computer design methodologies. In this paper, a modeling methodology based on fundamental building block models for power delivery systems is presented to address the aspects of energy efficiency optimization, area occupied by the power delivery solution and the cost associated with power conversion.**

***Index Terms* – DC-DC power conversion, genetic algorithms, optimization methods, power system modeling.**

I. Introduction

Design of computing platforms requires fast physics simulation tools to accurately analyze system behavior while making quick trade-off analysis of important parameters that impact the entire platform in terms of energy efficiency, size and cost. Long simulation times of today's modeling and simulation tools based on complex models could represent an issue at the initial stage of the design since designers are required to quickly arrive at practical solution options to significantly reduce the time and cost associated to a new product development. Therefore, a design methodology based on fast physics models, which involves the interaction and influence among the different technology areas, is required to accelerate time to market of new products by finding the best solution in the shortest time.

Designing an electronic device when considering all the previously mentioned factors is not an easy task given the fact that prototyping capabilities for such devices are limited due to cost and time constraints. In order to solve this problem, computer simulation plays a key role.

There is a need to develop new design and simulation tools intended to make trade-off analysis of power conversion systems when considering design factors such as power conversion losses, size and cost. Such tools could be used to directly provide the power delivery solution of a computing platform with minimum iterative experimentation. The main capabilities a new design trade-off methodology must cover are:

- Analysis of wide range of possibilities and identification of most viable solutions.
- Trade-off analysis of power conversion efficiency and estimation of area and cost of the entire power delivery solution.
- Consideration of thermal effects.

This paper describes a new design methodology for the development of a tool to specifically address the challenges outlined previously in the power delivery and distribution area. Some of the key elements of this methodology are:

- Follows a top-down design approach to handle large size systems.
- Uses artificial intelligence techniques to find feasible power delivery architectures.
- Provides a mechanism to evaluate the performance (in terms of power conversion losses, size and cost) of the proposed architectures in a short time.
- Provides an optimization framework (using evolutionary and stochastic techniques) to define the best power delivery architecture and its components for each application.

II. Power Delivery, Distribution and Design Tool (PD3T)

Proposed methodology consists of a set of modules developed to accomplish all the tasks involved in the design of power conversion systems. The general structure of the design tool with its main modules is shown in Fig. 1.

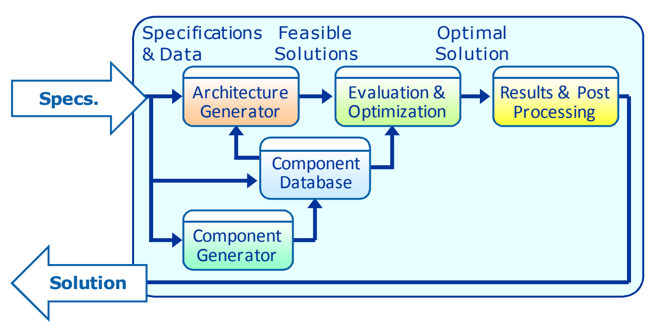

Fig. 1. General structure of PD3T modeling tool

Example of input specifications are: energy source characteristics such as input voltage range, battery capacity, etc.; load specifications such as voltage rails domain, maximum load power, etc.; and design constraints and boundary conditions such as maximization of battery life, area and cost constraints, etc. The output of the system is a set of solution candidates for building the power delivery architecture with a detailed description of voltage regulator (VR) technologies and performance evaluation.

Modules shown in Fig. 1 are described as follows:

- **Component generator**: This block is used to simplify the development of the VR models to be stored in a database. It helps to capture the behavior of the VR and to write the VR building blocks.
- **Component database**: It stores the models of all the VR technologies to be used by the tool.
- **Architecture generator**: Based on the models included in the database, this block searches for multiple ways to interconnect these components and creates architectures that satisfy the design specifications.
- **Evaluation/Optimization block**: Using the created architectures and the components in the database, this block evaluates the performance of all the combinations that are feasible to be built. When the optimization function is enabled, the result is a set of the best solutions in terms of power conversion losses, size and cost according to the design criteria.
- **Post Processing block**: This block is used to sort, classify and handle the solutions provided by the tool.

A. Modeling Approach

Conventional modeling and simulation tools used in power conversion systems are usually time consuming due to the use of complex models. For example, finite elements models are very accurate at the expense of long simulation times. Also, time domain models of power systems are usually slow due to the switching nature of the voltage regulator. Furthermore, simulation time can be exponentially increased when the number of options to analyze is very large, thus making necessary the use of effective, intelligent algorithms. Designers have to look for the best option among a large number of VRs or power components available from manufacturers (e.g. optimal VR module or individual power component for a specific application). In order to reduce a large number of options to a set of practical solutions that can be feasible to implement, it is necessary to use adequate evaluation techniques and simplified models.

Proposed modeling approach is a top-down scheme, therefore, only the effects that have a significant impact on the calculation performed are included. The fundamental blocks found in power delivery systems that affect the performance in terms of power conversion losses, size and cost are: VR technology, energy source and load pattern. Other elements like protections and filters are considered as part of the VR block.

In order to calculate the energy efficiency and battery life it is necessary to define a loss model for every block of the power system. In the case of the converters, the behavioral modeling approach presented in [1] is used. This modeling approach has the advantage that it is not necessary to know details about the converter; the model can be obtained from various sources based on the datasheets, experiments, simulations or analysis. To develop the loss model it is necessary to capture the power loss curve (at least) as a function of the load current. Equation (1) represents the simplified behavior of a converter, where the losses function can be approximated by a polynomial function or a lookup table.

$$v_{in} \cdot i_{in} = v_{out} \cdot i_{out} + Losses(i_{out}) \quad (1)$$

where v_{in}, v_{out}, i_{in}, and i_{out} are input voltage, output voltage, input current and output current, respectively; and $Losses(i_o)$ is a polynomial expression of the VR power losses.

Fig. 2 shows the power loss function of a real DC-DC converter approximated by a second order polynomial function.

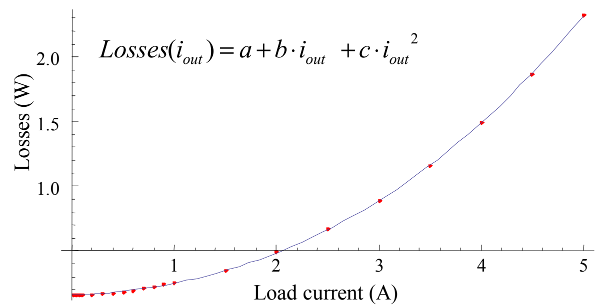

Fig. 2. Approximation of a power loss curve by a polynomial function

Behavioral modeling approach is also used for batteries and loads. In order to properly model the system, the load current behavior is considered (e.g. load current variations during the system operating time). Once the power losses are calculated, the battery capacity is used for calculation of system run-time.

The models used by the design methodology are stored in an HDL format similar to VHDL-AMS [2] or Verilog-AMS [3]. This representation has many advantages in terms of flexibility, which is widely addressed in [2].

B. Evaluation mechanism and optimization framework

As stated before, in commercial applications the three main performance metrics to design a power delivery system for a given electronic device are: energy efficiency (losses), size and cost. Priority of these metrics is defined according to the application. For example in laptop computers and cell phones the size and battery life are more critical than in desktop computers; but on the other hand, mobile devices tend to be more expensive. Therefore it is very important to make a proper selection of the components that will be used.

The calculation of the cost and size can be easily approximated by adding the value of the individual components of the architecture as shown in (2). It would be impractical trying to calculate a more accurate value of the size and cost because to know the actual size we need to know the final distribution of the components in the electronic device; that is why the used approach is considered a very fast and accurate enough calculation.

$$size = \sum blocksize_i \ , \ cost = \sum block\,cost_i \qquad (2)$$

Load behavior is a very important aspect to take into account in the calculation of power losses since most of mobile devices have power states at which the loads are turned on and off according to the usage model. It is estimated that most of the operating time of mobile devices is spent at low power consumption modes [4], thus making very important to account the VR light load efficiency when designing the power delivery solution. As a result, a proper selection of the components will depend on the information coming from the load pattern over the entire operating range.

As an example, Fig. 3 shows two power loss curves of two different VR technologies with the same power ratings. It can be seen that converter B has lower power losses in the light load region while converter A has lower losses in the heavy load side. Consequently, if the mobile device spends most of the time at low power states it could be better to select the converter B. To calculate the power losses including the effect of the load behavior, three approaches have been studied (Fig. 4): design at maximum load, design for a given load range, and design based on load probability distribution.

Due to the broad range of VR and power components manufacturers, a very large number of combinations can result when combining the components in the database and the architectures created by the architecture generator block, being impractical to analyze every single option. For example, if there are ten options for each of the converters of the very simplified power delivery architecture shown in Fig. 5, it will result in 100,000 combinations to analyze. In order to determine the best combination without analyzing the whole solution space, optimization methods like genetic algorithms [5], Harmony Search [6] or other heuristic and evolutionary methods should be used.

This problem is a multi-objective optimization problem with discrete variables, where each variable defines a set of converters with the same power rating but different characteristics. An objective function as shown in (3) can be used to find the best option, which corresponds to a weighted function in which the value of the weights are settled depending on the application.

$$Objective(size, cost, losses) = w_{size} \cdot size + w_{cost} \cdot cost + w_{losses} \cdot losses \qquad (3)$$

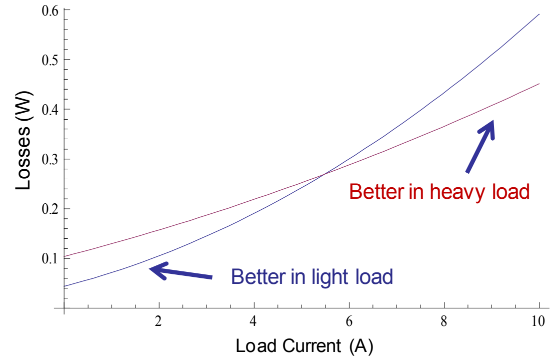

Fig. 3. Power loss curves of two different VR technologies with the same power ratings

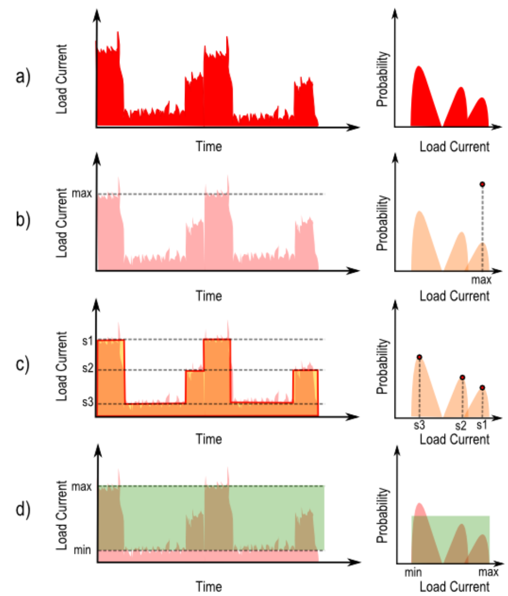

Fig. 4. a) Example of load current pattern. b) Design at maximum load current. c) Design based on load current probability distribution. d) Design based on a load current range.

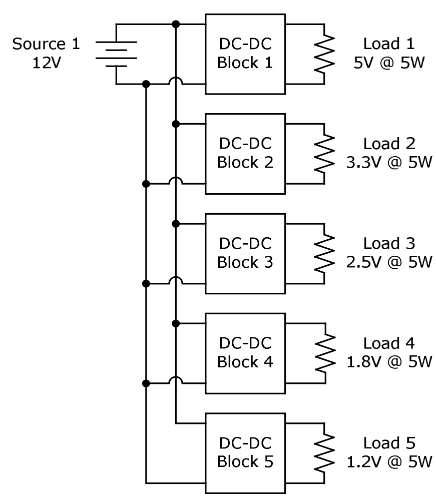

Fig. 5. Example of a power delivery architecture with five loads

III. Simulation and Experimental Results

In order to validate the proposed methodology, the electrical specifications given in Fig. 5 were taken as an example and a database with a total of 57 DC-DC converters from 3 different manufacturers was used to feed the tool.

Table I summarizes the DC-DC converters from 3 manufacturers, Power-One [7], Murata [8] and Lineage Power [9], used to perform the analysis with the input and output voltage ratios specified in the Table. Converters are used as VR building blocks to find all the possible power delivery architectures that meet the specifications. For this specific example (Fig. 5), there are 5 different voltage rails: 5V, 3.3V, 2.5V, 1.8V and 1.2V, obtained from a 12V input power source.

The first step is to use the component generator module to get the power loss curve of each of the converters with information available from datasheets. VR models are mainly defined in terms of the power loss curve, in a polynomial expression as shown in Fig. 2, and a set of properties that define the VR such as the maximum output power, operating frequency and a lumped model for transient response analysis.

Once the VR models are stored in the database, the architecture generator module takes the input specifications given by the user and, based on available models, looks for all the power delivery architectures that meet the electrical specifications. Depending on the characteristics of available converters, the number of possible interconnections can be very large. However, the user can define the criteria the tool will use to build the architectures such as the number of conversion stages that can be connected in cascade, the use of pre-regulators or specific converters for some of the voltage rails, etc., thus minimizing the solution space of feasible architectures.

TABLE I
DATABASE OF DC-DC CONVERTERS

Vin:	12V					5V				3.3V		
Vo:	5V	3.3V	2.5V	1.8V	1.2V	3.3V	2.5V	1.8V	1.2V	2.5V	1.8V	1.2V
YM12S05	✓	✓	✓	✓	✓							
YEV09T03		✓	✓		✓							
YM05S05						✓	✓	✓	✓			
MPDTH12050	✓	✓	✓	✓	✓							
MPDTH12060	✓	✓	✓	✓	✓							
MPDTH05050						✓	✓	✓	✓			
MPDTY201S								✓	✓		✓	✓
MPDTH03050										✓	✓	✓
MPDTY116S										✓		
MPDTY114S											✓	
MPDTY112S												✓
AXA005A0X-SRZ	✓	✓	✓	✓	✓							
ATA010A0X3-SRZ	✓	✓	✓	✓	✓							
AXH003A0X4-SRZ						✓	✓	✓	✓	✓	✓	✓
AXH005A0X-SRZ						✓	✓	✓	✓			

For this specific example, a total of 33 different architectures (i.e. different ways to interconnect the VRs) were found. Randomly selected, Fig. 6 shows only 6 of the architectures found, which provide specific characteristics in terms of the area and cost associated with the number and type of VRs available in the database. Since there is more than one option for each of the VR blocks shown in the architectures, a very large number of combinations can be found when considering all the possibilities. For the 33 architectures and the database with 57 converters, a solution space of 194,000 different combinations was found.

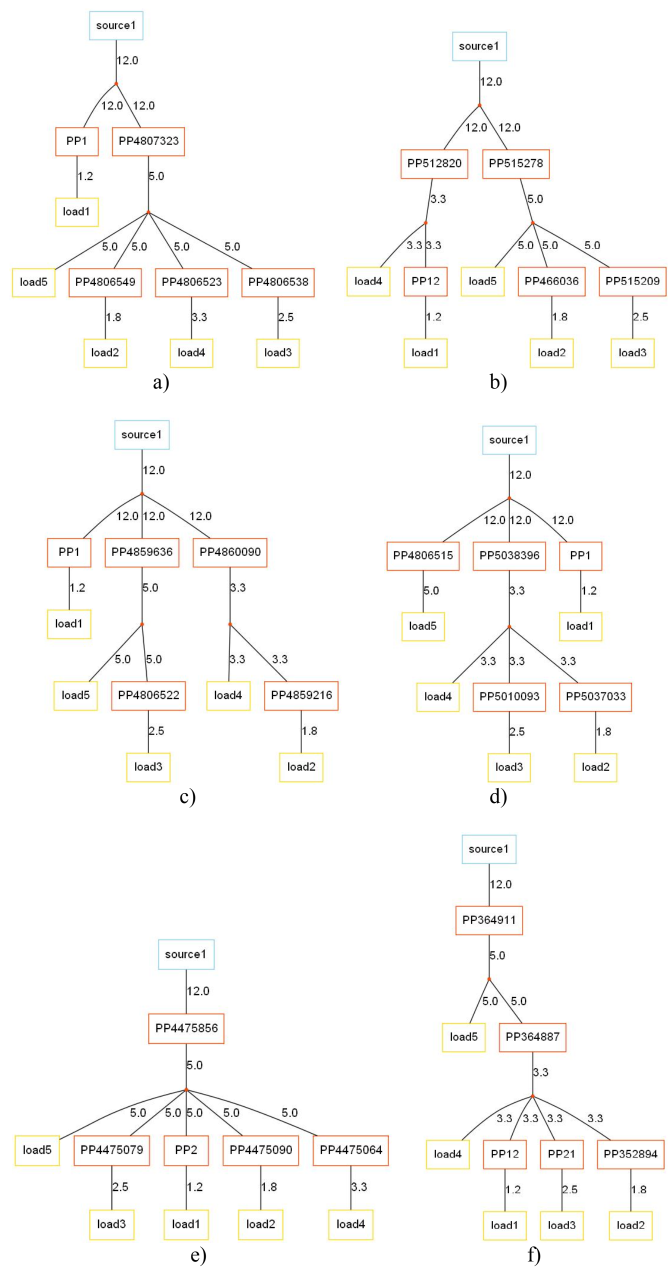

Fig. 6. Example of 6 power delivery architectures found with the tool

As it can be noted, architecture shown in Fig.6 a) makes use of a pre-regulator to provide an intermediate bus voltage of 5V at which, point-of-load converters are connected to obtain the low voltage rails (3.3V, 2.5V and 1.8V). The 1.2V rail, on the other hand, is obtained from a converter connected directly to the input source as it is usually done in low-voltage, high-current applications. A similar architecture can be seen in Fig. 6 e), which uses a pre-regulator to supply power to the rest of the converters. Tool helps the user to analyze which one is better based on the design criteria for a particular design (i.e. the one with the highest efficiency, the lowest cost, the lowest size or the one with the best trade-off).

Every single option of the 194,000 combinations in the solution space could be evaluated by doing brute force at the expense of several hours of simulation time, resulting impractical in most of the cases, especially at the early design stage. However, simulation time can be significantly reduced when using an evolutionary algorithm like Harmony Search, which requires a minimum number of iterations to find the most suitable solutions.

Fig. 7 shows the simulation results when using Harmony Search with 20,000 steps (~10% of the total solution space). Points in the graphs represent the best 74 options out of 194,000 in the solution space. Power losses were calculated at maximum load current for all the voltage rails.

Figures 7 b), c) and d) show the Pareto fronts for Cost[1] vs. Losses, Area vs. Losses, and Cost vs. Area, respectively. The 3 blue points labeled as A, B and C correspond to 3 options randomly selected to analyze their performance and decide which one is the best option based on design criteria.

From figures 7 b), c) and d), for example, it can be determined that option A is the best one in terms of losses. However, since it is the biggest and one of the most expensive options, the user might be interested in looking at smaller and cheaper options. Also, it can be noted in the same graphs that option B is the cheapest and smallest option but at the same time is the one with highest losses. As it can be seen in Table II, option C is the one which offers the best trade-off for losses, area and cost compared to options A and B.

In order to validate the computation of power losses of an entire architecture, options A, B and C were built with the actual converters specified in Table III. It is to be noted that not all the converters used to build the architectures are operating in the whole output current range.

TABLE II
SUMMARY OF CHARACTERISTICS OF 3 ARCHITECTURES

	Losses	Area	Cost
Option A	Best	Worst	Worst
Option B	Worst	Best	Best
Option C	Good	Very Good	Very Good

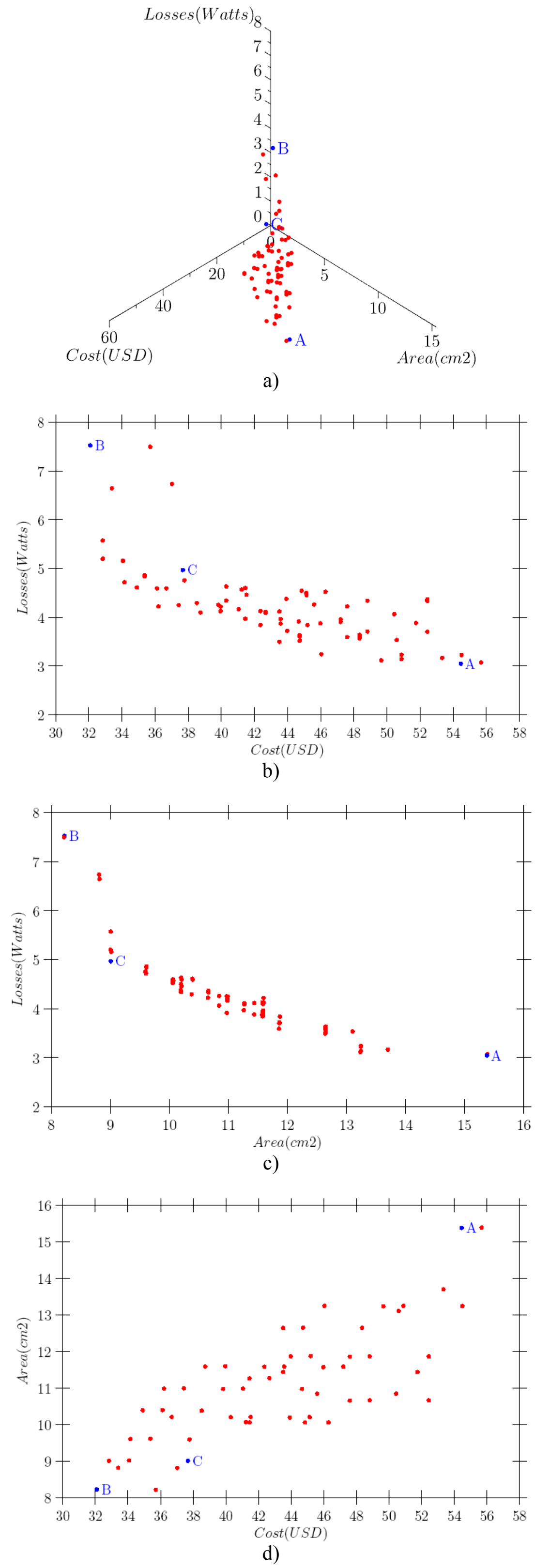

Fig. 7. Harmony Search simulation results: a) Parameters in 3D, b) Pareto front of Cost & Area, c) Pareto front of Area & Losses, d) Pareto front of Cost & Losses

[1] Relative cost for the entire architectures calculated with prices available from an on-line store.

TABLE III
SUMMARY OF CHARACTERISTICS OF 3 ARCHITECTURES

Vin-Vo	Option A	Option B	Option C
12V-5V	MPDTH12060	YM12S05	AXA005A0X-SRZ
12V-3.3V	N/A	YEV09T03	YEV09T03
12V-1.2V	ATA010A0X3-SRZ	N/A	YEV09T03
5V-3.3V	AXH003A0X4-SRZ	N/A	N/A
5V-2.5V	AXH003A0X4-SRZ	AXH003A0X4-SRZ	YM05S05
5V-1.8V	AXH003A0X4-SRZ	MPDTY201S	N/A
3.3V-1.8V	N/A	N/A	MPDTY201S
3.3V-1.2V	N/A	MPDTY201S	N/A

Fig. 8 shows the modeled power loss curves for options A, B and C in which a trade-off in terms of power conversion losses at light and heavy loads can be seen for options B and C. From Fig. 7 it was determined that option C has lower losses than option B when the calculation is done at maximum output power. At very light loads, however, it is to be noted from Fig. 8 that option B is better. As a result, the design should be done according to the load behavior, which in some cases will lead to a different solution.

A comparison of modeled and experimental power conversion efficiency for one of the architectures is shown in Fig. 9. As it can be noted, a maximum deviation of 3.2% is observed at maximum load current. Fig. 10 shows the picture of one of the actual architectures built with commercial VR modules.

IV. CONCLUSION

This paper presents a new design methodology for power delivery and distribution systems that has been completely adapted to fulfill the requirements in the design of commercial applications such as: analysis of many options, short time to market, top down design, and optimization in terms of power conversion losses, area and cost of electronic devices.

This methodology has been implemented in a tool that has been used to analyze thousands of combinations of power delivery architectures in a few minutes providing very accurate. The methodology makes intensive use of fields in computer science like artificial intelligence in order to create power delivery architectures and evolutionary algorithms to find the optimal selection of VR building blocks depending on the application.

Behavioral modeling techniques are used to obtain fast physics models with high level of abstraction of typical elements in power delivery systems such as VRs, loads and input sources.

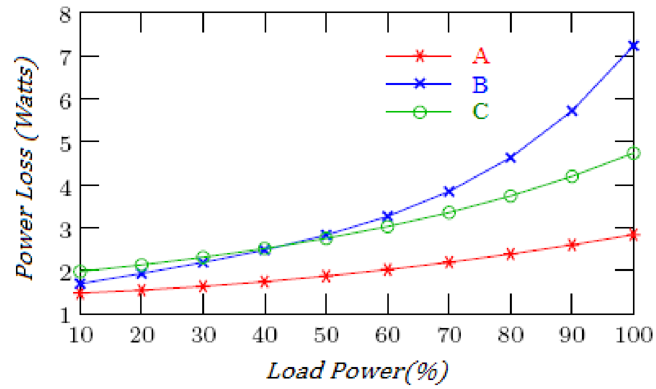

Fig. 8. Power loss curves for options A, B and C over the entire load power range for trade-off analysis at light and heavy loads

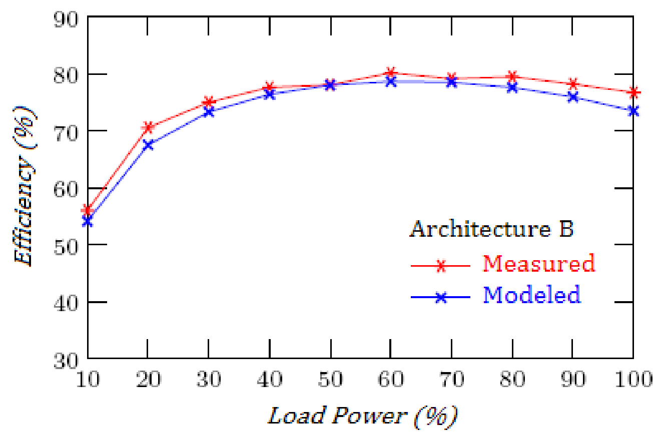

Fig. 9. Comparison of modeled and measured power conversion efficiency curves of option B

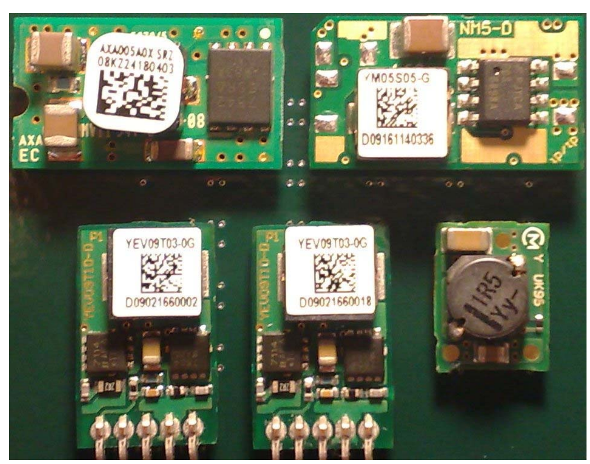

Fig. 10. Actual power architecture built with VR block modules

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