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Evaluation and Optimization of Power Electronic Converters using Advanced Computer Aided Engineering Techniques

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ABSTRACT

Computer aided engineering (CAE) is a systematic approach to develop a better product/application with maximum possible options and minimum transition time. This paper presents a comprehensive feasibility analysis of various CAE techniques for evaluation and optimization of power electronic converters and systems. Different CAE methods for analysis, design, and performance improvement are classified. In addition, their advantages compared to the conventional workbench experimental methods are explained in detail and through examples.

Keywords: AC/DC rectifiers, computer aided engineering, DC-AC power conversion, DC-DC power conversion, optimization.

1. Introduction

Industrial environment of power electronic engineering has become far more competitive today than ever before. Developing products that can sustain the competition is the prime requirement in the industry. To develop a new idea or make improvements in performance of present power electronic applications, one should have the tools to implement the best product in the market as fast as possible, as cheap the product as possible, as perfect as possible, and obviously as much profitable as possible.

However, before a decade or so, there had not been many tools available for power electronic applications due to their inherent non-linearity and time-dependability. This is where knowledge of computer aided engineering (CAE) plays a vital role[1]-[7].

In this paper, we classify and present CAE techniques in three major steps, which are computer aided analysis (CAA), computer aided design (CAD), and computer aided optimization (CAO). These steps allow engineers to consider and check the practical aspects that could never been possible with traditional workbench experiments.

CAA step involves the mathematical modeling of power electronic systems such as switching power supplies. CAD step has three subsections: process level simulations, design level simulations, and system level simulations.

Using a process analyzer/simulator, the performance and response of particular part or the complete product will be evaluated. TCAD and ECAD are among the process simulation tools that will be presented for this step[8]. In the last step of CAO, different possible options for each and every part of the system are investigated in order to improve the performance and reduce the costs.

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Suitability of these steps through different techniques as well as their advantages and limitations for power electronic applications will be presented as well.

2. Computer Aided Analysis

This step involves the mathematical modeling of power electronic converters. This includes development of differential equations for each and every part/section of the complete application/system and analyzing the performance of the complete system using mathematical tools available such as MATLAB, MATHCAD, and MAPPLE. This will approve the idea of developing a new application or the improvement in the existing one theoretically. In fact, this step involves computer formulation of system equations. There are mainly three methods employed for this; they are nodal, hybrid, and state variables. The nodal method is used in various circuit analyses. However, many power electronic applications involve current loops and affected by the variations in current. This is where nodal analyses fail. Hybrid analysis tools involve both current and voltage loops and both appear as unknowns in the equations characterizing the power electronic system. This method can handle many nonlinear elements of all types. Yet, almost all power electronic systems contain essentially power semiconductor switches, which are often modeled as the elements having only two states, a low impedance state when conducting and a high impedance state when not conducting. Power electronic systems, therefore, tend to favor state equation method of the formulation of system equations. In general, a power electronic system can be described in state space form as the following.

$$\begin{aligned}\frac{d}{dt}[X]&=[A][X]+[B][U] \\ [Y]&=[C][X]+[D][U]\end{aligned} \tag{1}$$

Where, [U] = n x 1 vector representing the n inputs,
[Y] = n x 1 vector representing the n outputs,
[X] = n x 1 vector representing a set of n independent auxiliary variables,
[A], [B], [C], [D] = constant real matrices called state equation matrices of appropriate dimensions, where A is always square matrix.

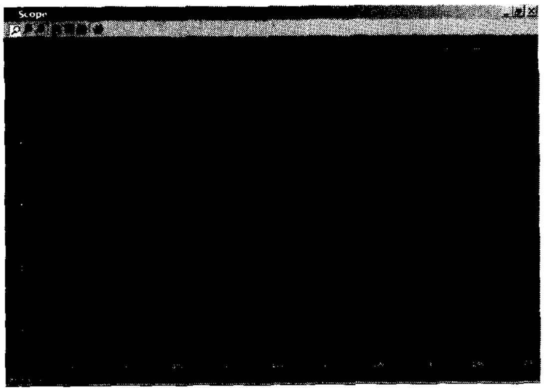


Fig. 1. Typical MATLAB/Simulink simulation result, output voltage of a Flyback converter.

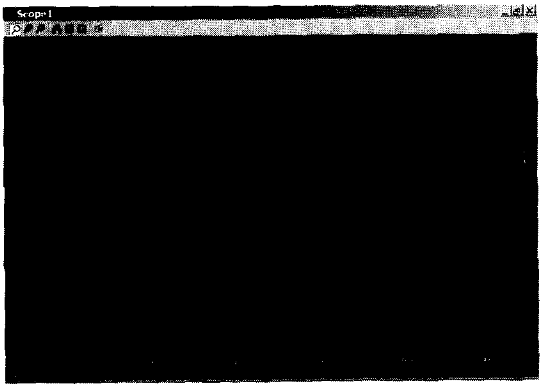


Fig. 2. Typical MATLAB/Simulink simulation result, inductor current of a Flyback converter.

(1) is a set of first order differential equations mostly coupled and usually referred as state space equation. The main advantage of the state variable method is the simplicity with which it can be manipulated by many numerical methods of analyses. Not only that, the state variable method can be extended without much difficulty to deal with nonlinear networks, which is the general case.

These simulations can be performed by MATLAB / Simulink. MATLAB provides excellent facility of programming for mathematical modeling of not only power stages, but also the control strategies. There is also facility of interface between Simulink and MATLAB. Thus, the part that is not available in Simulink can easily be added by characterizing it in the MATALB program. Simulink also has the facility of power system toolbox, which can be integrated with the MATLAB programming with workspace interfacing. By doing so, it is possible to visualize the effects of dynamic changes in various converter circuit parameters. Fig. 1 and Fig. 2 depict two typical simulation results from MATLAB/Simulink for a Flyback converter.

3. Computer Aided Design

This section has three subsections: (i) process level simulations, (ii) design level simulations, and (iii) system level simulations. From the theoretical knowledge, decide which topology is best suited for specific application and do the theoretical feasibility analysis with mathematical tools, as mentioned in previous section. Once that done, it is clear that which components are required to develop specific product or application.

With process analyzer/simulator, it is possible to check the performance or response of particular part or the complete product. Analysis of individual part, i.e., diodes, energy storage elements, transformer, other switching semiconductor devices, is very important, as it decides what will be the characteristics of that element once it will come out of the process. TCAD and ECAD are few of the process simulation tools that can be used for this step.

Once parts' characteristics are approval, it is possible to develop the design of each section of the complete application or product, i.e., filter, converter, and controller, and can check all the required characteristics in all the possible operating modes. It is even possible that with advance CAE tools to check the worst case or a case which is unusual or rare, but not impossible, without wasting time and money on actual experiment with circuits and costly parts for different operating conditions. Spices, Saber, Simplorer, ICAP are few of them. Each has their specialty and unique feature in circuit design and simulation. Knowledge of them can result in extensive design analysis.

Integration is the only task remained after developing each section of the product. This integration will result in complete system or product. Now, with the use of system level simulation tools, it is advisable to check the complete system performance in all the possible scenarios that could happen to the product. It is also possible to check the behavior of each and every section and part of the system after integration and check whether they give the same characteristics or they get changed in due course of operation due to the integration. At this stage, if any undesired behavior is observed, it is good that it is observed well before the product goes for final production or experimental testing. This could save both time and money. Cadence and Silvaco are among the suppliers of the tools available for system level simulations. Many of the other tools mentioned in this paper are also equally well suited for system level simulations.

Following is the examples of how CAE tools can be useful for power electronics. Here, as an example, switched mode power supply (SMPS) design is considered.

3.1 Design of Input Stage

Principle function of the input stage in SMPS is to convert an AC supply to DC supply in order to provide power to DC-DC converter. Requirements or characteristics of this input stage in SMPS design can be stated as (i) the maximum ripple of its DC output voltage must be within allowable range accepted by the DC-DC converter, (ii) input inrush current must be limited to a safe value, so that it will not damage the circuit, and (iii) conducted interference that gets into the AC mains should be minimize to satisfy various regulations such as FCC and VDE.

(i) Input filter capacitor value is limited by size, cost, and ripple requirements. Given the ripple requirements, design and optimization is possible with CAD tools such as Spice and PSIM.

$f = 1/T$ = AC mains frequency

V_{AC}(min.) = minimum allowable AC mains voltages (rms values)

P = output of rectifying circuit

C = required filtering capacitor

r = allowable ripple in percentage

From the theory of energy balance, we have

$$\frac{T}{2}P = \frac{1}{2}C(\Delta Vc)^2 \tag{2}$$

$$\frac{T}{2}P = \frac{1}{2}C(Vc\max - Vc\min)^2 \tag{3}$$

Solving above equation for C will give,

$$C = \frac{TP}{(Vrms(\min) - (1 - r)Vrms(\min))^2} \tag{4}$$

If the switching regulator is to be designed for universal application, it would be very helpful to check different operating conditions with CAD tool. As shown in Fig. 3, above filter design can be carried out with the use of SIMPLORER. This software provides all the facilities for modeling any power electronic converter. It has added advantage of modeling power electronic drives. The limitation with this software is limited flexibility with control schemes. SIMPLORER provides the benefit of implementing the same phenomenon with different approach with circuit implementation of Simulink-type block representation or SIMPLORER inbuilt deferential equation setup (DES).

Fig. 4 is for designing input rectifier just before the DC-DC converter stage with ICAP. This software provides very good flexibility in vendor supplying actual semiconductor component. For example, it is possible to use Motorola supplied PWM converters, TI supplied control ICs, and semiconductors supplied from ON semiconductor. This software also provides all the facility to model power stage of power electronic applications. However, it has some limitations on user defined control strategies. It is possible to import/export models from/to PSpice. It is also possible to design layout in ICAP.

(ii) Large potential difference between input line voltage and capacitor voltage causes large inrush current when switch is made 'ON'. Another small switch with parallel resistance (like Triac) can be put in series with the input stage, which has very low drop. When the capacitor gets fully charged, switch is made "ON" and current is limited by the parallel resistance and after that, resistance is taken out by making the switch "ON". Here, you can also check which are different types of switches available for this sort of explicit purpose and what should be the rating, keeping all operating conditions in mind.

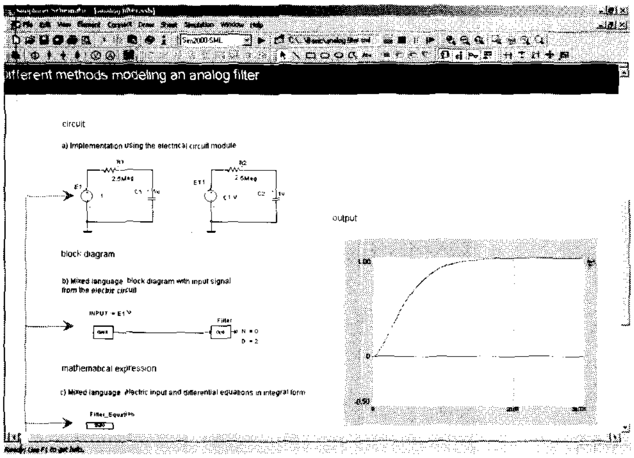
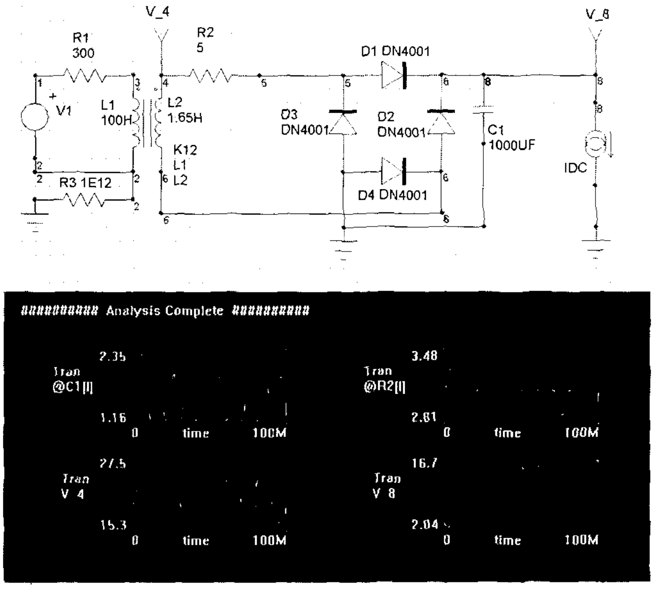


Fig. 3. Typical filter design with SIMPLORER.



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########## Analysis Complete ##########

      2.35                                   3.48
Tran                                    Tran
@C1[I]                                  @R2[I]

      1.16                                   2.81
          0      time      100M                  0      time      100M

      27.5                                   16.7
 Tran                                    Tran
 V 4                                     V 8

      15.3                                   2.04
          0      time      100M                  0      time      100M
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Fig. 4. Typical rectifier design in ICAP.

(iii) Switching activity at high frequency causes both conducted and radiated interference. Input stage of the power supply is the most common path for conducted interference. Coupled inductors and capacitors between rectifier and AC mains can solve this problem at great extent. L1 and L2 are connected in such a way that each other cancel magnetic effect from AC mains. Leakage inductance of L1 and L2 can be used to reject differential mode interference, as L1 and L2 are explicitly for common mode conducted interference. Choices for L1, L2, C1, C2, C3, and C4 empirically,

L1 & L2 = 2 to 50mH
C1 & C2 = 0.1 to 1uF
C3 & C4 = 2200pF to 0.033uF

Depending on the specific requirements, all of these values are determined. Operating frequency of the switching regulator, output voltage, and load variations, all will play critical role in determining the values of all the components at the input stage. Simulation with available CAD tool will definitely be necessary to check the performance and effect in different operating conditions (even when component value changes due to aging effect). At the input stage, steady state AC simulation is very much useful to predict frequency response characteristics of complete input filter and other individual components. Transient simulation is helpful in predicting current and voltage shoot-ups on input side when switch is made "ON" or "OFF".

3.2 Selection of Converter Topology

Selection of converter topology for a switching power supply depends on various aspects. Important of them are as follows.

Requirement of transformer isolation between input and output.

Requirement of multiple outputs.

Output power required.

Desired operating frequency or efficiency.

Special requirements like unity power factor.

Fig. 5 and Fig. 6 depict modeling of typical Forward and Push-pull converters with PSIM and ICAP, respectively.

3.3 Inductor Design

Primary requirement of inductor in a switching power supply is required inductance at specified current without magnetic and temperature saturation. Size and cost are always issues for any component or application and same with the inductor in SMPS. From the basics of electromagnetism,

$$\begin{aligned} L\frac{dI}{dt} &= N\frac{d\Phi}{dt} \\ LdI &= Nd\Phi \qquad (5) \\ LI &= N\Phi \end{aligned}$$

$$LI = NAcB \qquad (6)$$

where, L = required inductance

I = specified current

N = number of turns

Ac = cross sectional area of magnetic core

B = flux density of inductor.

At the same time, current density in the winding is the maximum ampere-turns (AT) for a given winding area; thus

$$\begin{aligned} NI_{rms} &= JK_uA_w \\ \therefore N &= \frac{JK_uA_w}{I_{rms}} \end{aligned} \qquad (7)$$

where, J= maximum allowed current density of winding material

K_u = utilization factor of winding

A_w = winding area.

From equations (5)-(7), we can write

$$A_cA_w = \frac{LI_{\max}I_{rms}}{K_uJB_{\max}} \qquad (8)$$

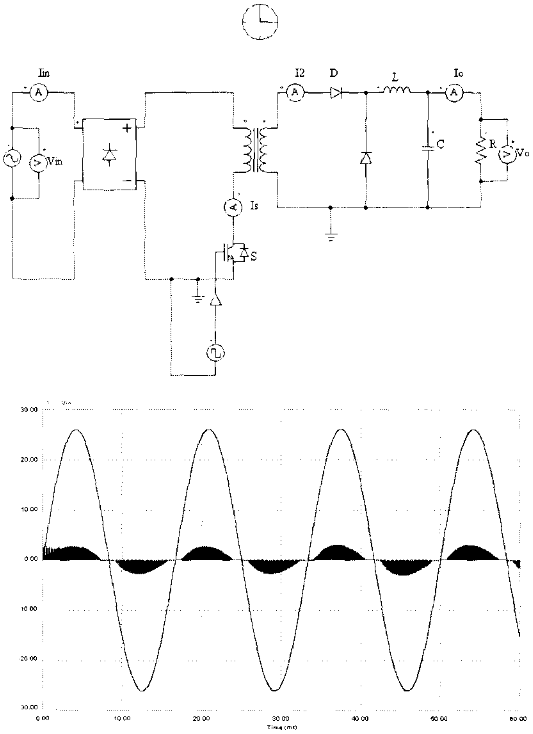


Fig. 5. Typical modeling of Forward converter with PSIM.

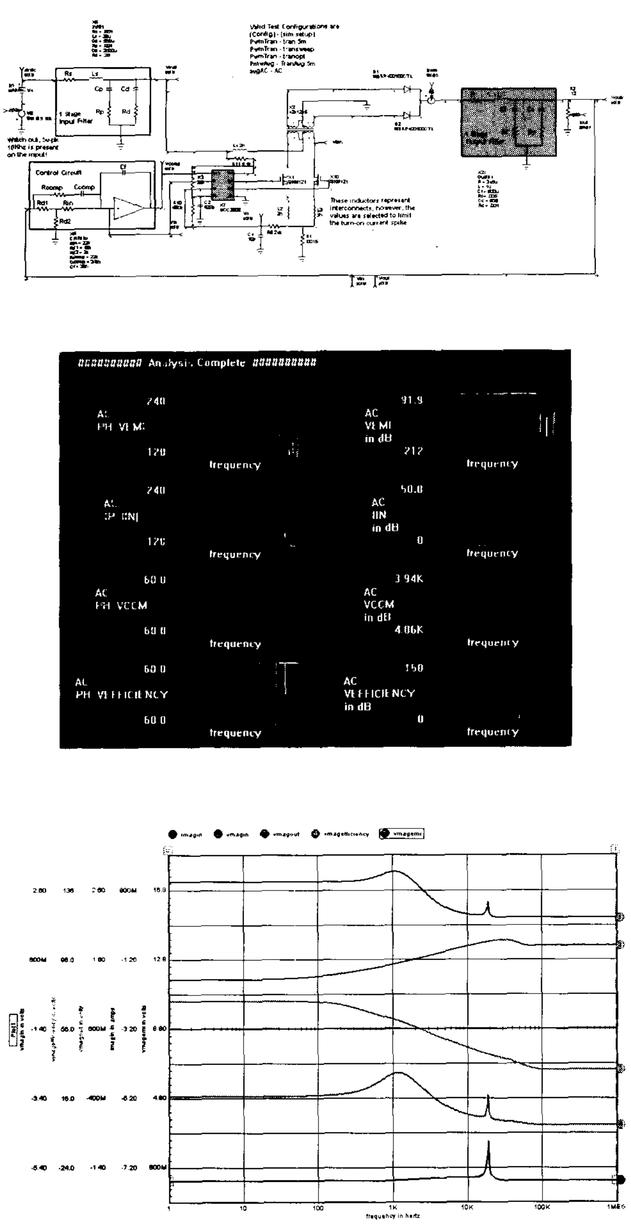


Fig. 6. Typical modeling of Push-pull converter with ICAP.

Above equation gives the constraint on size of the inductor. Now, to achieve required performance out of the inductor, two controls are available: *Ac* and *Aw*. Depending on the requirement, trade-off between them can be made. Result of variations in *Ac* and *Aw* can be observed multiple times with the use of CAD tools for magnetic component design like PEmag and Maxwell. In addition, specific requirements of inductors can be examined and designed by CAD tools. Specific inductor for given current density can be optimized. For inductors using magnetic cores with high μ_r , an air gap is often required to limit the magnetic flux density to the value of *Bmax* at the rated value of peak current *Ipeak*. If no air gap is provided, the magnetic core may go into the saturation.

$$L = \frac{\mu_0 N^2 A_c}{l_g}$$
$$\therefore l_g = \frac{\mu_0 N^2 A_c}{L} \tag{9}$$

This gives the design criteria for length of the air gap. Variation in this parameter may affect the performance of the inductor and, thus, complete application. Advanced CAD tools for magnetic systems can be employed to check the effects of variations of air gap on the performance of the inductor. It is also possible with PEmag to check which core and winding is best suited for a typical application (see Fig. 7). Furthermore, it is possible to check temperature variations in the magnetic elements.

If *Bmax* is sufficiently below saturation level and switching frequency is sufficiently low, then temperature is assumed to be in acceptable range. However, if that is not the case, temperature rise in conductor limits both cross sectional area of the conductor and winding area of the core. Design and size of the inductor is pre-dominantly decided by the copper losses only if operating frequency is low (below 40-50kHz). However, at higher frequencies, core losses (eddy current and hysteresis) are high and affect the design of the inductor.

3.4 Transformer Design

As mentioned in the last section, at high frequencies, the hysterisis and eddy current losses become significant. The core losses is given by

$$Pc = \Delta B^{2.4}(K_h f + K_e f^2) \ \text{W/cm}^3$$

where, Pc = core losses

ΔB = peak to peak swing of magnetic flux density

K_h = Hysteresis loss co-efficient

K_e = eddy current loss co-efficient

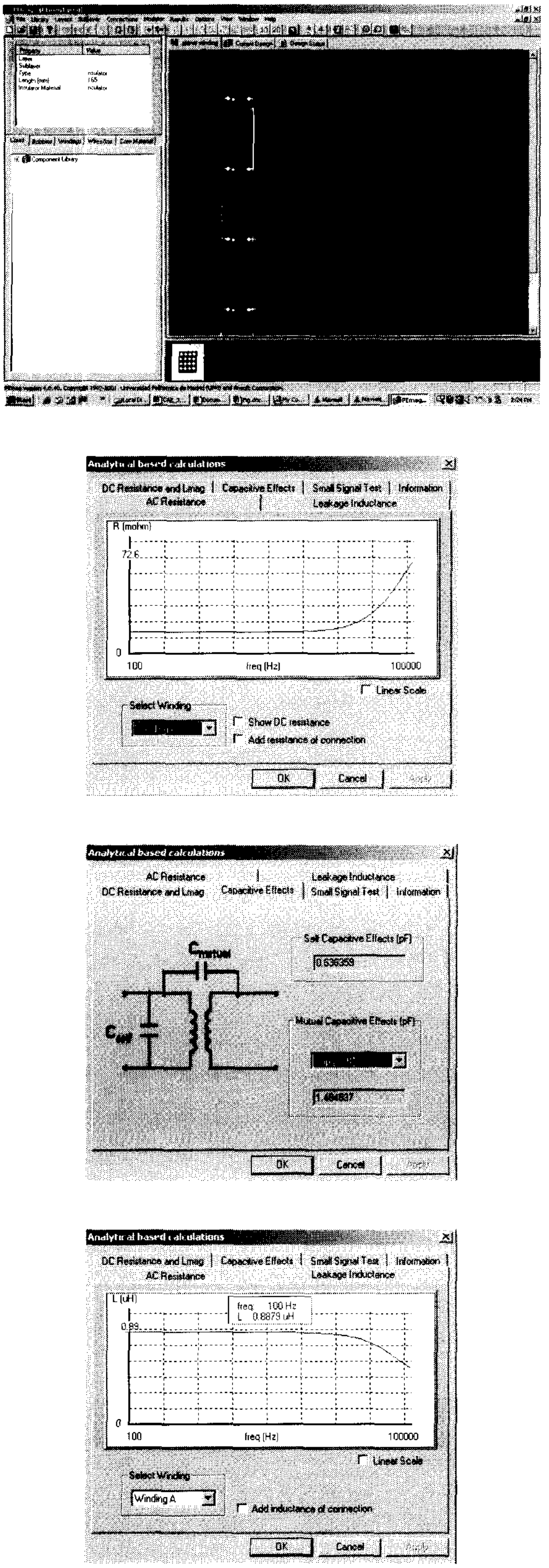


Fig. 7. Typical inductor design with PEmag.

In high frequency transformers, it is desirable that the core losses should be equal to the copper losses. Temperature rise due to losses can be written as,

$$\Delta T = P_c V_c R_{th} \tag{10}$$

where, Vc = volume of magnetic core

R_{th} = thermal resistance of the transformer

Pc = core losses

Empirically, Vc and Rth is given by

$V_c = 5.7(A_cA_w)^{0.68}$ degree cm^3

$R_{th} = 23(A_cA_w)^{-0.37}$ degree centigrade/W

$$\Delta T = \Delta B^{2.4}\left[K_h f + K_e f^2\right] \left[5.7(AcAw)^{0.68}\right] \left[28(AcAw)^{-0.37}\right]$$

$$\Delta B = \frac{\left[K_h f + K_e f^2\right]^{-0.4167}\left[(AcAw)\right]^{-0.1292}}{\Delta T} \tag{11}$$

Above equation gives the criteria of allowable variations in flux density for a given rise in temperature due to the core losses. For a given temperature rise, maximum current density can also be calculated. Based on all of the above equations, design of the transformer can be carried out.

Transformer design is one of the areas in which CAD tools can be used efficiently to help transformer designers. These tools accept user specified physical details of a transformer, such as type of the magnetic core, number of turns on each winding, and coupling co-efficient. PEmag (see Fig. 8) and Maxwell are few of them, which solely developed for magnetic component designs. Such computer programs provide an efficient and fast way of arriving at an optimum design idea.

3.5 Design of Output Filter

For the converters like Buck, Flyback, and Forward, which do not have any inductor in their basic topology, it is advisable to have an inductor at the output. The primary requirement of the output inductor in almost all the topologies is to maintain the continuous conduction irrespective of the variations in input conditions and load.

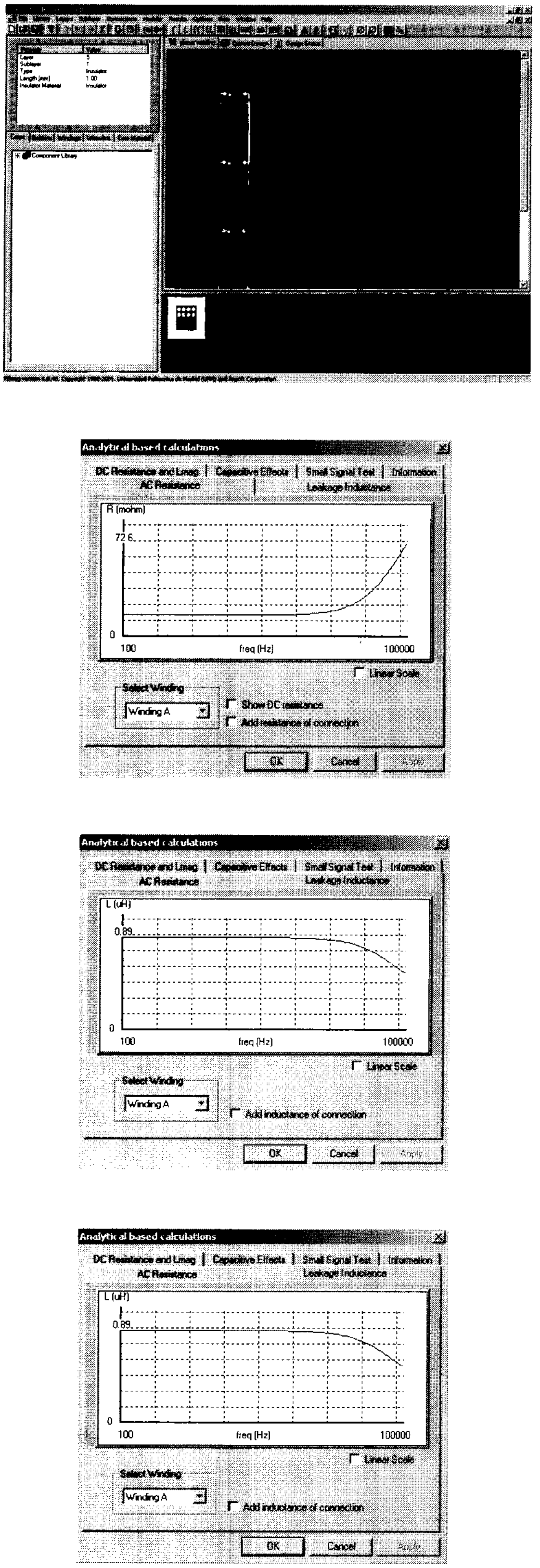


Fig. 8. Typical transformer design with PEMag.

Therefore, at the time of designing output inductor, this requirement should be considered. With the use of CAD tools for circuit level simulations, it is possible to estimate the performance of the overall application and state of the output inductor at the same time in different operating conditions.

In switching regulators, the output capacitor plays a vital role. Primary requirement of the capacitor at the output of the SMPS is to keep the output voltage constant and to have a sufficiently small ESR to minimize the ripple voltage due to such resistance. By iterative simulations with different values of capacitors and ESRs, circuit performance can be easily checked. Aging effect on capacitor can also be simulated with advance CAD tools.

$$ESR \times \Delta I_o = \Delta V_o \tag{12}$$

Where, ΔI_o = Expected ripple current in filtering capacitor,

ΔV_o = Acceptable voltage ripple due to only ESR.

3.6 Modeling Switches

Almost all power electronic applications contain at least one semiconductor switch. Characteristics of these switches are very important. Depletion region, base temperature, junction temperature, and allowed base voltage and current are few of these characteristics. Satisfactory performance of complete power electronic application relies highly on proper operation and function of these switches. Thus, it is absolutely important to check how these semiconductor elements behave in different operating conditions. In the applications where more than one such switch is employed, it is desirable that they should have almost same characteristics if they follow the same type. Yet, it is very difficult to even manufacture semiconductor devices with exactly similar characteristics. Advanced CAD tools give flexibility of both modeling such semiconductor switches with all the parameters like junction capacitance, leakage capacitance, and inductance. It is also possible to have ready made models supplied from different vendors and check the same rated switches supplied from different vendors for a specific application in all the aspects.

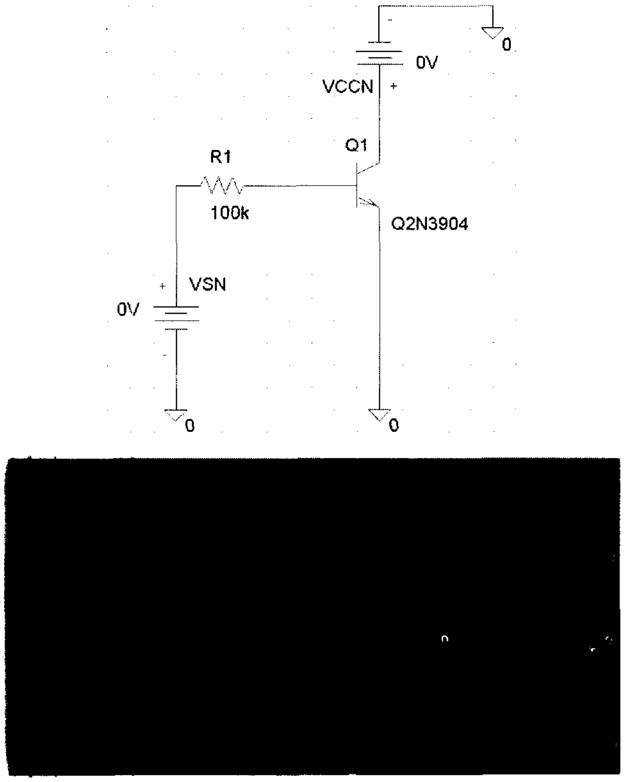


Fig. 9. Typical BJT characteristics and biasing from PSpice.

Simulation of Fig. 9 is carried out with PSpice. In fact, PSpice is very useful for semiconductor modeling and circuit layout. It is also possible to model any user-defined model of semiconductor and implement it in the circuit. This feature provides facility of defining the exact required characteristics from the semiconductor device for specific application, keeping all the possible circuit behaviors in mind.

SIMPLORER also provides good facility of modeling advanced semiconductor switches, i.e. IGBT and MOSFET. Fig. 10 shows bias characteristics obtained from the simulation carried out in SIMPLORER, design and optimization tool developed by Ansoft Corporation.

3.7 Controller Design

Controller design of a power electronic application is as important as all of the above parts of the complete application. MATLAB and Simulink are widely accepted tools to design controllers. Fig. 11 and Fig. 12 depict a typical controller design with other CAD tools available.

4. Computer Aided Optimization

With CAO techniques, it is possible to investigate what are the different possible options for each and every part of the system in the market from different vendors. Furthermore, the performance can be determined if one wants to change the parameter/value of the particular part or a section of the complete product. As mentioned earlier, it is possible to check all the worst scenarios that can happen to the product. However, it is not necessary that designing the best product result in maximum profit. It is also advisable to check what percentage if one do/don't design the product for all/some of these scenarios.

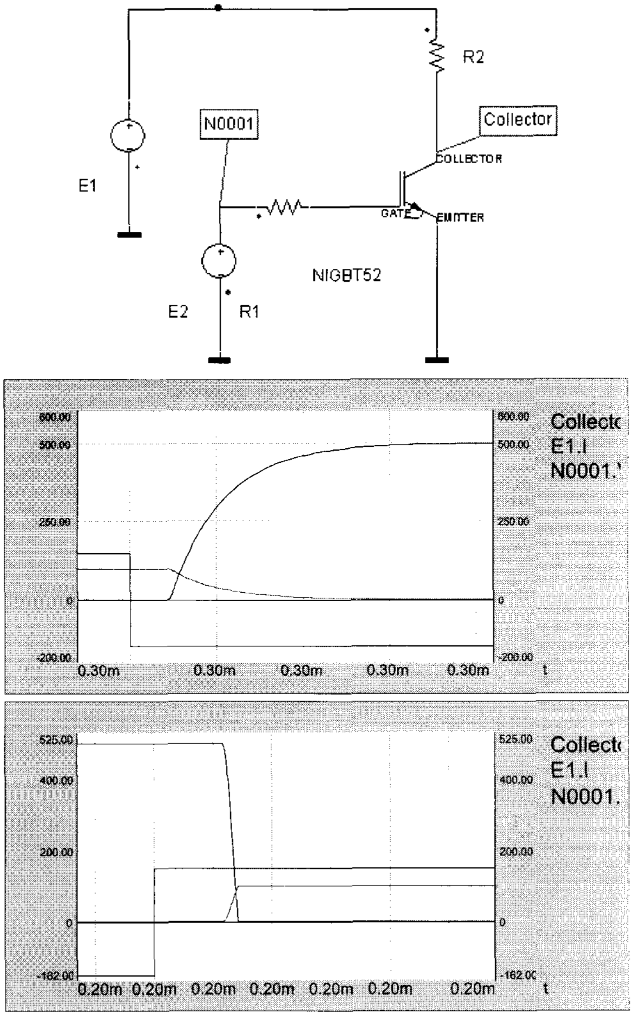
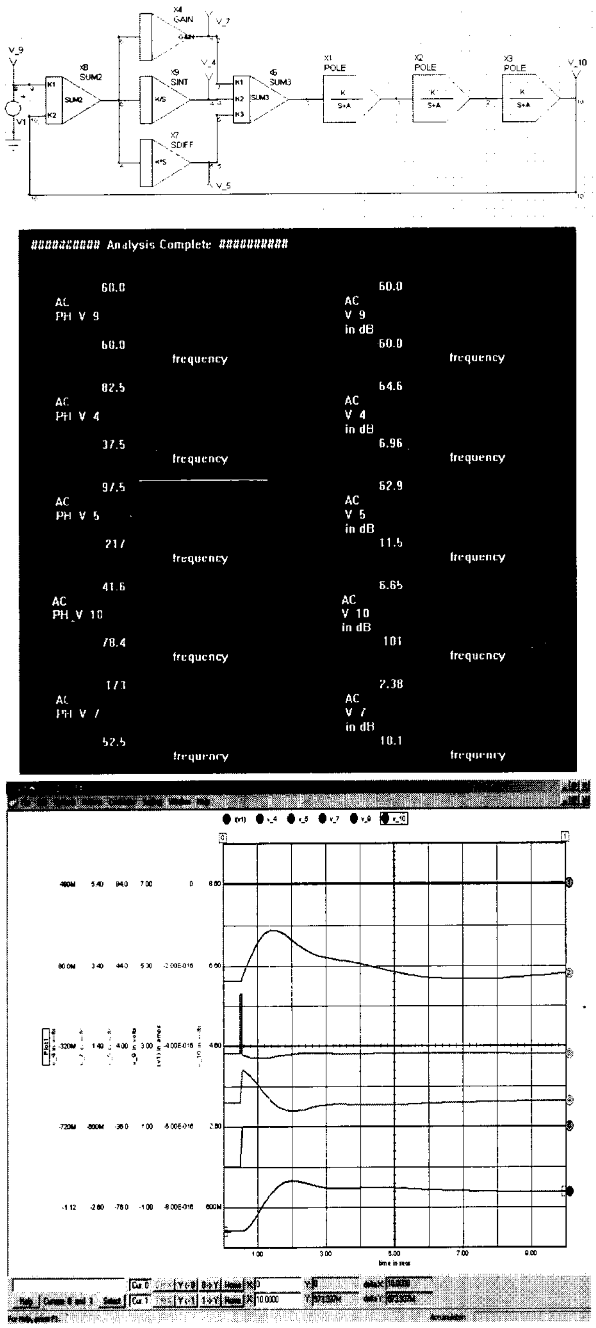


Fig. 10. Typical bias characteristics of IGBT carried out in SIMPLORER.

It is important here to define the term "optimization". We define optimization as equilibrium of product price and performance. With the use of combination of specific tools discussed above, it is possible to come up with this equilibrium in specified situation. For example, increase in the capacitance will reduce the ripples; yet, at the same time, it will increase the size and cost barrier. For inductor, it is the problem of leakage inductance and mutual interaction with other active components in the circuit.



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########## Analysis Complete ##########

        60.0                                  60.0
  AC                                     AC
  PH V 9                                 V 9
                                         in dB
        60.0                                  60.0
               frequency                              frequency

        82.5                                  64.6
  AC                                     AC
  PH V 4                                 V 4
                                         in dB
        37.5                                  6.96
               frequency                              frequency

        97.5                                  62.9
  AC                                     AC
  PH V 5                                 V 5
                                         in dB
        217                                   11.5
               frequency                              frequency

        41.6                                  6.65
  AC                                     AC
  PH_V 10                                V 10
                                         in dB
        78.4                                  101
               frequency                              frequency

        173                                   2.38
  AC                                     AC
  PH V 7                                 V 7
                                         in dB
        52.5                                  10.1
               frequency                              frequency
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Fig. 11. Typical PID controller with ICAP.

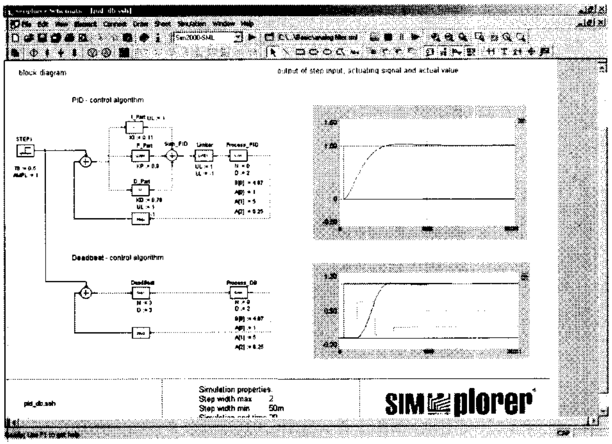


Fig. 12. Typical PI controller design with SIMPLORER.

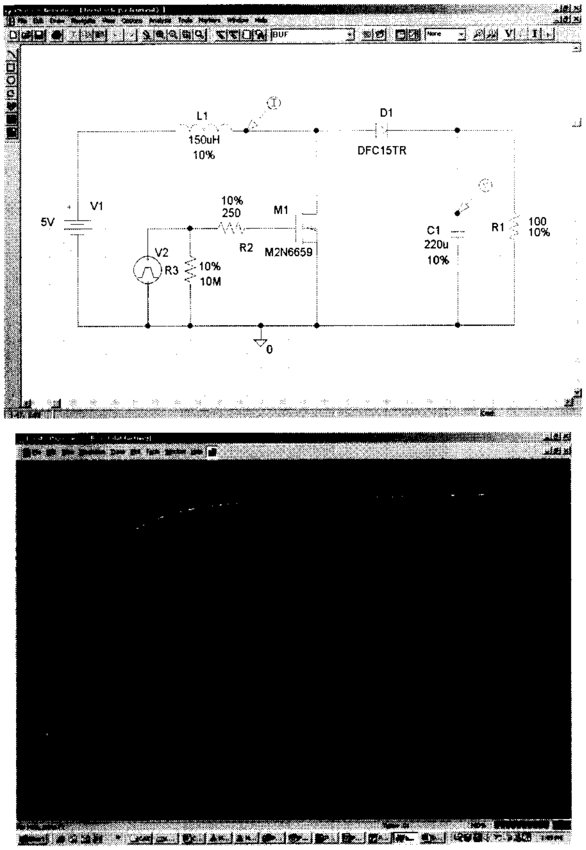


Fig. 13. Typical Monte Carlo analysis of Boost converter in PSpice.

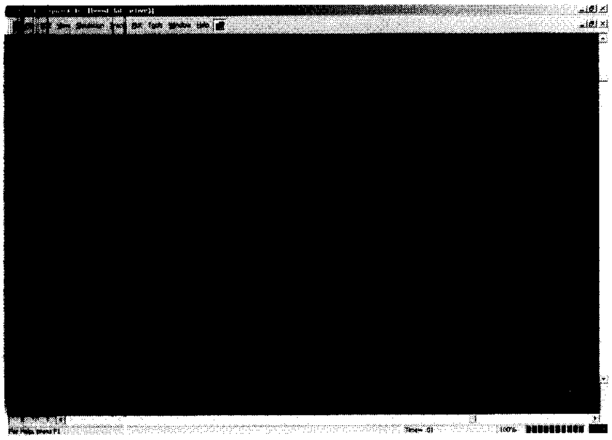


Fig. 14. Zoom view of the simulation in Fig. 13.

Parasitic elements of inductors, capacitors, and switches play important role in circuit performance. They are the function of both the circuit operating condition and the value of parent component. Thus, it is extremely difficult and time consuming to theoretically or analytically come up with the above mentioned equilibrium. But, with the CAE tools discussed above, it is possible. With the use of CAE tools, it is possible to carry out DC, AC, noise, Monte Carlo, worst case, and transient analysis of all the power electronic and digital circuits, as shown an example in Fig. 13 and Fig. 14.

Figs. 13 and Fig. 14 give the idea that by providing 10% tolerance to all the components in the power stage of a Boost converter, how the output voltage will change. Here, the simulation is carried out for open-loop control. For closed-loop control, the situation may change. This may affect the control strategy as well. Therefore, it is very useful to examine this possibility before finalizing the control strategy [9][10].

5. Conclusions

In this paper, steps involved in the design of power electronic converters such as switched mode power supplies have been discussed. It has been shown that, with the use of advanced computer aided engineering tools, it is possible to achieve more industry specific applications within shortest possible transition time. It has also been realized that with only traditional workbench and experimental techniques of design, it is not possible to achieve optimum design in limited time span, whereas computer aided engineering techniques are sufficient. Good technical and analytical skills as well as knowledge of the mentioned CAE methods go together and bring considerable advantages in power electronic industry.

References

[1] R. W. Michelet and W. D. Roehr, "Evaluation power supply designs with CAE models", in Proc. IEEE 4th Applied Power Electronics Conference and Exposition, Baltimore, MD, pp. 323~334, March 1989.

[2] G. Cross, "Power electronics computer aided engineering: an introduction", IEE Colloquium on Power Electronics and Computer Aided Engineering, London, UK, pp. 1/1~1/3, 1994.

[3] D. Schroder, "Modeling and CAE for power electronic topologies", in Proc. IEEE 1993 International Conference on Industrial Electronics, Control, and Instrumentation, Maui, HI, pp. 626~636, Nov. 1993.

[4] W. Qiang, J. Qi-Rong, H. Ying-Duo, X. Jian-Xin and B. Xiao-Feng, "Advanced modeling and control package for power system problems", in Proc. IEEE 1999 International Conference on Power Electronics and Drive Systems, pp. 696~701, July 1999.

[5] H. D. Venable, "Using CAE/CAT tools to evaluate power supply parasitics", in Proc. IEEE 4th Applied Power Electronics Conference and Exposition, Baltimore, MD, pp. 56~63, March 1989.

[6] G. Busatto, "Physical modeling of bipolar mode JFET for CAE/CAD simulation", IEEE Trans. on Power Electronics, Vol. 8, No. 4, pp. 368~375, Oct. 1993.

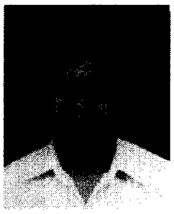
[7] C. M. Johnson, D. A. Hinchley and P. R. Palmer, "Accuracy and validation issues for the simulation of power semiconductor devices", in Proc. 5th European Conference on Power Electronics and Applications, Brighton, UK, pp. 118~124, 1993.

[8] R. Szczesny, K. Iwan and M. Ronkowski, "TCAD – A simulation package for power electronic systems", in Proc. 5th European Conference on Power Electronics and Applications, Brighton, UK, pp. 1~6, 1993.

[9] K. A. Nigim, "PC simulation of harmonics in power converters", in Proc. IEEE International Symposium on Industrial Electronics, Budapest, Hungary, pp. 311~315, June 1993.

[10] N. Froehleke, D. Hahm, H. Mundinger, H. Njiende, P. Wallmeier and H. Puder, "CAE-tool for optimizing

development of switched mode power supplies", in Proc. IEEE 16th Applied Power Electronics Conference and Exposition, Anaheim, CA, pp. 752~758, March 2001.



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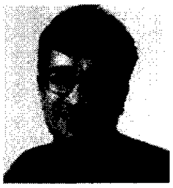

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