A 2-D Nonlinear FEA Tool Embedded in Matlab/Simulink Surrounding for Application of Electromagnetic Field Analysis in Power Converters

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***Abstract*-This paper presents a 2-D nonlinear finite element analysis (FEA) tool embedded in Matlab/Simulink surrounding for the application of electromagnetic field analysis in power converters. Comparing with other FEA tools such as ANSYS and ANSOFT, as different control arithmetic has been realized in Matlab/Simulink surrounding, the significant advance by using the FEA tool embedded in Matlab/Simulink surrounding is that the field analysis can be more easily interfaced with the external control arithmetic. Considering that the characteristics of most field analyses in power converters which are static electromagnetic equipments, not only the general application procedure of the 2-D FEA tool is introduced, but also some improvements for strengthening its function is proposed. As an example, the proposed model is implemented for the performance analysis of a flyback switching AC-DC converter. By running the proposed model in Simulink surrounding, several performances can be obtained efficiently.**

I. INTRODUCTION

With the development of modern electronic equipments, more and more power converters are produced. In most off-line power converters, there is generally a transformer used for the isolation between the input and output. Under the influence of the saturation and nonlinearity of magnetic materials, the nonlinear finite element analysis (FEA) has often been used to obtain the accurate performance of electromagnetic equipment [1], and many FEA tools have been programmed.

As a control system, a typical converter is constituted by both the transformer and its feeding control circuit. However, because most FEA tools are programmed in general languages such as C and FORTRAN, or are supported by commercial softwares such as ANSOFT and ANSYS, the field analysis and the analysis of control system often belong to two different software systems. This brings some difficulties in the analysis.

Considering that the control arithmetic can be realized in the Matlab/Simulink surrounding easily, and an FEA tool can also be embedded in the Simulink, the analysis results obtained from the FEA tool embedded in Matlab/Simulink surrounding would be very convenient to be transferred to the control system block, which can also be realized in Simulink [2]. Although the function of FEA tool is weak that only static 2-D nonlinear FEA analysis can be processed, to most power converters as a static electromagnetic equipment, its function may be sufficient. For that, in this paper, based on the introduction of the general application procedure of the 2-D FEA tool, some improvements for strengthening its function is presented. As an example, the proposed model is implemented for the performance analysis of a flyback switching AC-DC converter, and several performances are obtained efficiently.

II. FINITE ELEMENT FORMULATION

A. Basic Field Equations

The general equations for a soft magnetic material can be expressed as

$$\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M}) = \mu_0(1+\mathbf{M}/\mathbf{H})\mathbf{H} = \mu_0\mu_{\mathrm{r}}\mathbf{H} \tag{1}$$

$$\mu_{\mathrm{r}} = 1+\frac{\mathbf{M}}{\mathbf{H}} \tag{2}$$

where **B** is the magnetic flux density, **M** the magnetization with respect to the magnetic field strength, **H**, μ_0 the permeability of air, and μ_r the relative permeability of the magnetic material, which is the function of the magnetization and magnetic field strength and can be decided by the Preisach model directly.

According to the Maxwell equations, one has

$$\nabla\times\mathbf{H} = \mathbf{J_0} \tag{3}$$

where $\mathbf{J_0}$ is the current density.

The magnetic flux density **B** can be expressed as the circulation of a magnetic potential vector **A**:

$$\mathbf{B} = \nabla\times\mathbf{A} \tag{4}$$

Based on (1)-(4), the governing equation is given by

$$\nabla\times\left(\frac{\nabla\times\mathbf{A}}{\mu_0\mu_r}\right) = \mathbf{J} \tag{5}$$

For the 2-D case, this is reduced to

$$\nabla\cdot\left(\frac{\nabla\mathbf{A}}{\mu_0\mu_r}\right) = \mathbf{J}_0 \tag{6}$$

or

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu_r}\frac{\partial \mathbf{A}_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu_r}\frac{\partial \mathbf{A}_z}{\partial y}\right)=\mu_0 \mathbf{J}_z \quad (7)$$

where $\mathbf{A}_z$ is the axial component of the magnetic vector potential, and $\mathbf{J}_z$ is the current density in the axial direction.

By applying Galerkin's weighted residual approach to (6), the system matrix can be obtained as

$$[\mathrm{K}]\cdot\{\mathrm{A}\}=\{\mathrm{F}\} \quad (8)$$

where

$$\begin{cases} K_{ij}=\int_\Omega \frac{1}{u_r}(\nabla N_i\cdot\nabla N_j)\cdot d\Omega \\ F_i=\int_\Omega (N_i\mu_0 J_z)\cdot d\Omega \end{cases}, \quad (9)$$

and N_i is a shape function.

Considering that the energy method has high accuracy, by using (8) and (9), the flux densities in two consecutive time steps can be obtained. Then the differential inductance of the primary winding in the transformer can be calculated by

$$\begin{cases} L_p=L(i^k)=\frac{d\psi^k}{di^k}=\frac{\psi^k-\psi^{k-1}}{i^k-i^{k-1}} \\ \psi^k=2W_k/i^k \end{cases} \quad (10)$$

where ψ is the flux linkage of the primary winding of the transformer, i the current flowing through the primary winding, W the energy stored in the transformer, and the upper scripts (k) and (k-1) refer to the kth and (k-1)th steps, respectively.

B. FEA Tool in Matlab/Simulink Surrounding [3]

In Matlab environment, there is a partial differential equation (PDE) toolbox. The core of the PDE toolbox is a PDE solver that uses the finite element method (FEM) for problems defined on bounded domains in the plane. The toolbox can solve four kinds of PDE equations: elliptic equation, parabolic equation, hyperbolic system, and eigenvalue equation. The magnetostatic field equation of (6) belongs to the elliptic equation. The toolbox provides a user-friendly interface between the computing environment of MATLAB and the technical procedures of the FEM.

The technical procedures of the FEM shown in Fig.1 are divided into seven steps including: (1) Geometry description; (2) Boundary conditions; (3) Mesh generation; (4) PDE coefficients; (5) Solve parameters; (6) Plot flags and user data strings; and (7) Solve PDE. In Fig. 1, the rectangles stand for functions and ellipses give data represented by matrices or M-files. Arrows indicate data necessary for the functions. As there is a definite direction in this diagram, one can cut it by presenting the needed data sets, and then continue downward.

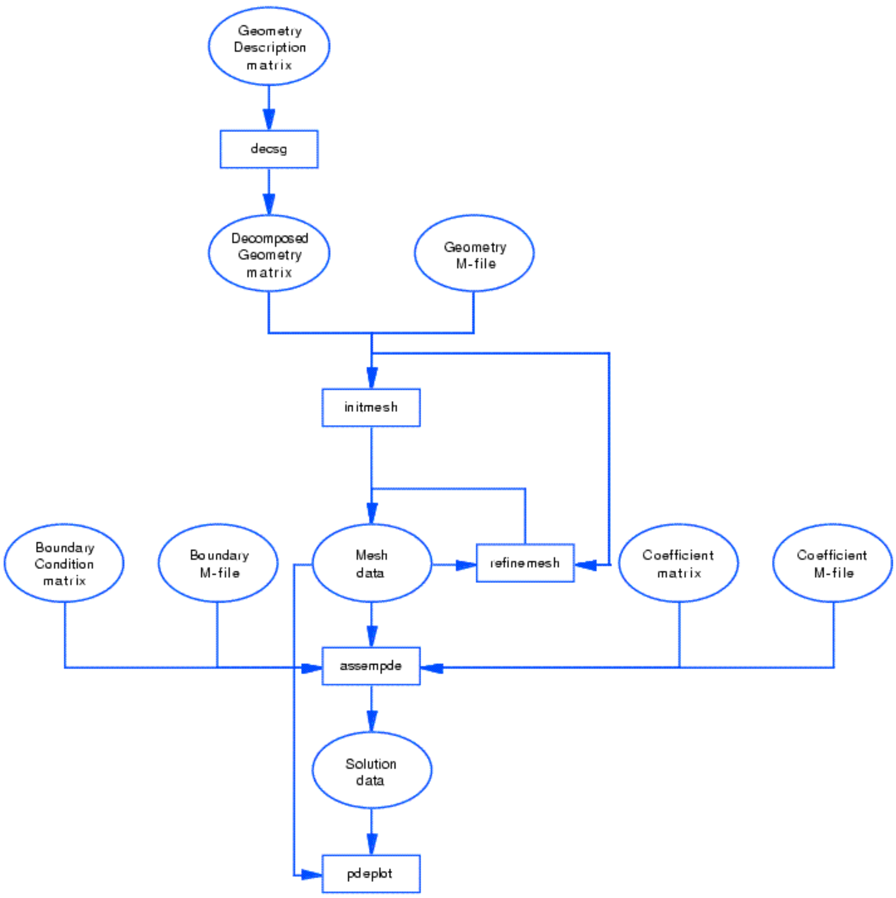


Fig. 1. Technical procedures of the FEM

C. Improvement of FEA Tool in Matlab/Simulink Surrounding

The PDE Toolbox is designed for both beginners and advanced users. It has the graphical user interface (GUI), which is a self-contained graphical environment for PDE solving. For common applications one can use the specific physical terms rather than abstract coefficients, and solving a PDE guides you through an example step by step. For the application in which some parameters such as geometry are often changed, this method by which all the modification must be done in its graphical environment appears to be discommodious.

According to the help document of the PDE tool, advanced applications are also possible by downloading the domain geometry, boundary conditions, and mesh description to the MATLAB workspace. From the command line (or M-files) one can call functions from the toolbox to do the hard work, e.g., generating meshes, discretizing the problem, performing interpolation, and plotting data on unstructured grids, etc., while retaining full control over the global numerical algorithm.

In this paper, by using experiment program, the PDE tool can be done with a sub-function which can be called by its main function. As some parameters are processed, the PDE tool can be set as global variables and transferred from the main function. This will increase the efficiency of the PDE tool calculation.

III. Nonlinear Inductance of Transformer Considering the Magnetic Saturation

In order to describe the proposed method easily, a flyback switching AC-DC converter with input voltages of 85-264 VAC/50Hz, rated output of 15 VDC/1.2 A, and switching frequency of 100 kHz is used as an example in this paper.

The design of the transformer is divided into two steps. Firstly, by using the accustomed analytical method, the initial parameters of the transformer are determined as shown in Table I. Then by using the FEA tool embedded in Matlab surrounding, the accurate parameters of the transformer are obtained. The FEA meshing is plotted in Fig. 2(a), and Fig. 2(b) shows the 2D magnetic force lines of an E25-transformer with air gap. Both the differential inductance and apparent inductance of transformer are shown in Fig. 2(c). In order to obtain the same inductance shown in Table I, the length of air gap has been changed to 0.15 mm.

TABLE I. Major Parameters of the Transformer in a Flyback Converter

No.	Parameter	Value
1	Magnetic Core type	EE-25
2	Magnetic material type	TDK PC40
3	Bobbin Type	EE-25 (8 pin)
4	Inductance of the primary winding, L	0.865 mH
5	Number of turns of windings, $n1$:$n2$:$n3$	58:12:9
6	Frequency of PWM, f	100 KHz
7	Length of air gap: l_g	0.168 mm
8	Maximal magnetic flux density, B_{max}	298.0 mT
9	Maximal PWM duty ratio, D_{max}	0.428

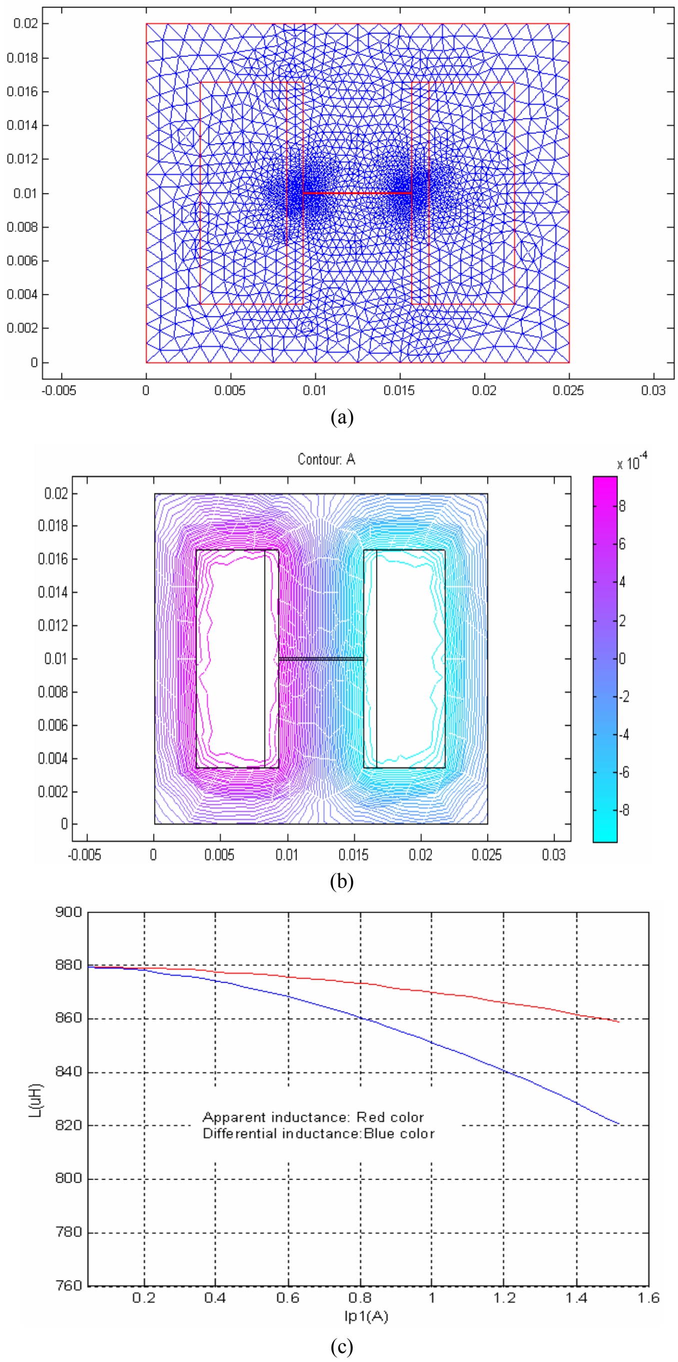


Fig. 2. Calculation of nonlinear inductance: (a) meshing plot, (b) magnetic force lines, and (c) apparent and differential inductances vs. primary current.

IV. Model Implementation

Fig. 3 illustrates the typical topology of a flyback AC-DC converter with peak current-controlled mode, where the dashed line connects control block to the main circuit, C_0 is the input filter capacitance, and R_0 is the parasitical resistance in the input circuit of the converter.

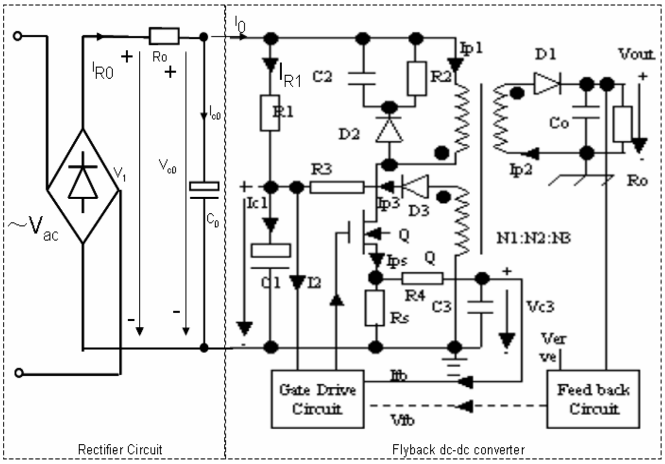


Fig. 3. Typical circuit of flyback AC to DC converter

A. *Modelling of the Flyback Switching AC-DC Converter*

Paper [2] has introduced a simulation model of flyback DC-DC converter in Matlab/Simulink surrounding. As the circuit of flyback AC-DC converter (Fig. 3) may be divided into two parts as shown in two dashed frames separately: one is the rectifier, and the other is the flyback DC-DC converter, the complete simulation model of flyback AC-DC converter can be obtained only by adding the model of rectifier circuit to that in [2], and it is shown in Fig. 4. The simulation model proposed in [2] is shown in the subsystem of flyback DC-DC converter and all the left parts constitute the model of the rectifier circuit. The two parts in Fig. 4 correspond to those in Fig. 3, and the same are the physical variables and electronic parts such as the resistor, R_0 and the output voltage of rectifier, V_1. The differential inductance of the transformer obtained from the PDE tool is put into a table which can be sampled by the simulation model through the method of lookup table.

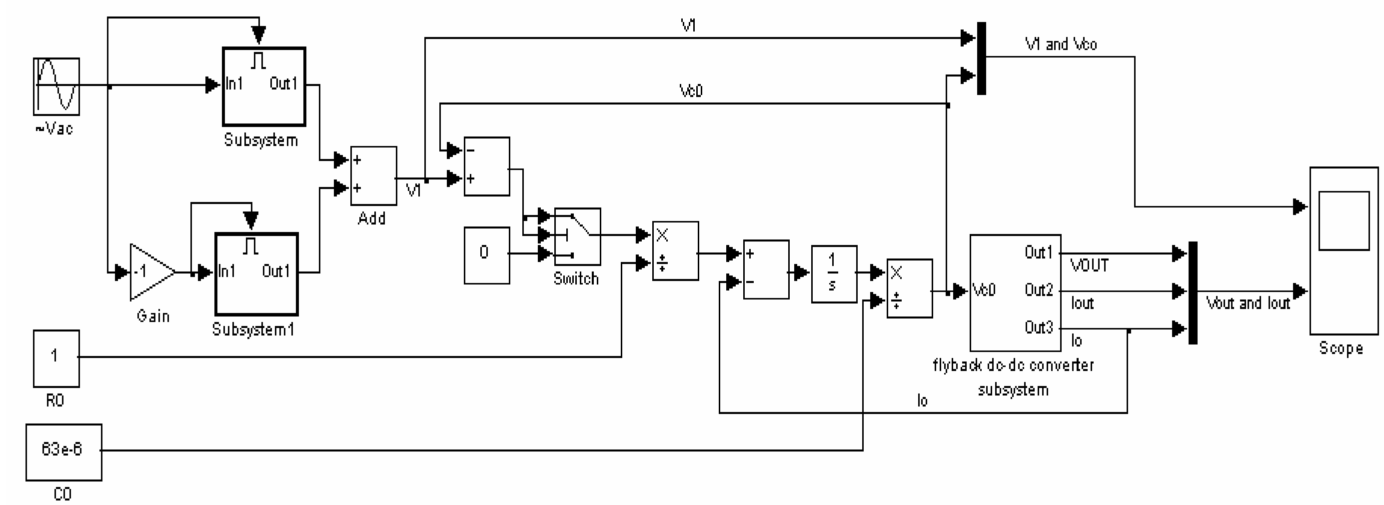
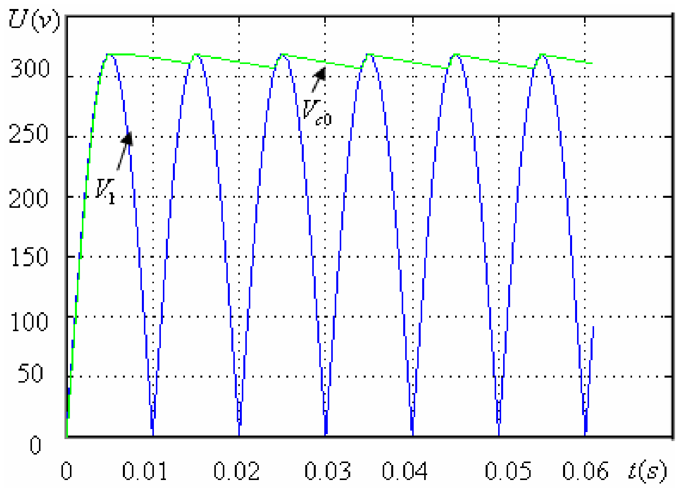


Fig. 4. Simulation model of flyback AC-DC converter

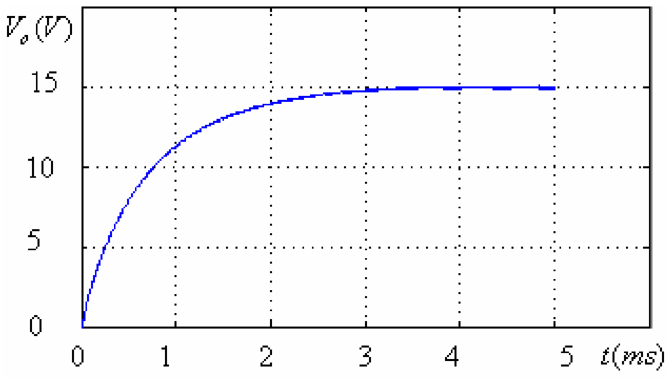
B. *Performance analysis*

Other key parameters of the converter include: $R1$=160 KΩ/1W, $C1$=10 uF/25 V, $C2$=63 μF/35 V, R_S=1.3 Ω, $R3$=1.2 KΩ, $C3$=100 pF, MOSFET: SSS6N60A, $R3$=0 Ω, D1: MUR1620, D2: UF4006, D3: 1N4148, $R2$=100 KΩ/1 W, $C2$=3.3 nF/1000 V, and C_o=1000 μF/25 V. All the left parameters of electronic parts in the flyback DC-DC converters are the same as those in [2].

By replacing the above parameters into the model and running this model in MATLAB/Simulink surrounding, several performances are obtained as shown in Fig. 5. Under the input voltage of 220 V, Fig. 5(a) illustrates the output voltage of the rectifying circuit and the voltage across the input filter capacitor, C2, Figs. 5(b) and 5(c) show the output voltage and output current, Fig. 5(d) shows the current waveforms flowing through the primary winding of converter with the rated load, and Fig. 5(e) shows the input power of the converter with the rated load.



(a)



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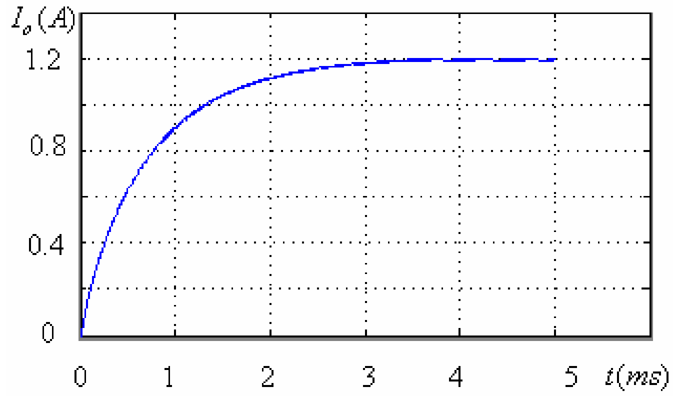
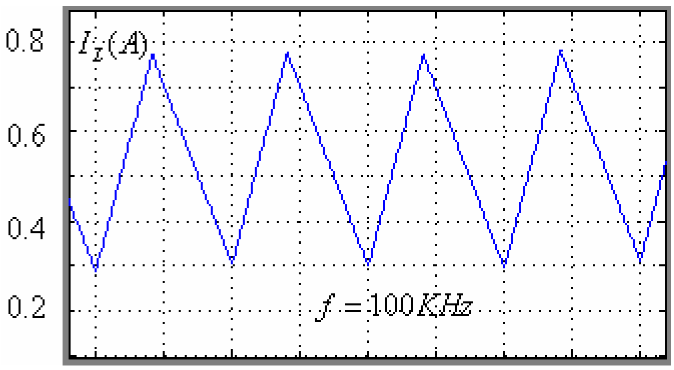
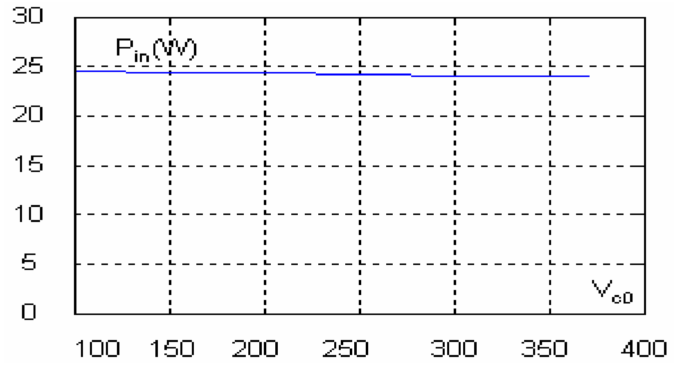


(c)



(d)



(e)

Fig. 5. Simulation results under the input voltage V_{ac}=220 V: (a).Output voltage of rectifier, V_I and the voltage across the capacitor, V_{c0}; (b) Output voltage, V_o; (c) Output current of flyback DC-DC converter, I_o; (d) Current waveforms flowing through the primary winding of converter with rated load; and (e) Input power of the converter with the rated load.

V. Conclusion

This paper presents the 2-D nonlinear finite element analysis (FEA) tool embedded in Matlab/Simulink surrounding for the application of electromagnetic field analysis in power converters. The significant advance of using the FEA tool embedded in Matlab/Simulink surrounding is that the field analysis can be easily interfaced with the external control arithmetic. The general application procedure of the 2-D FEA tool is introduced and some improvements for strengthening its function are presented. As an example, the performance of a flyback AC-DC converter is analyzed by a simulation model in Simulink surrounding, and several performances are obtained efficiently.

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