Recognition of Dynamic Patterns in DC-DC Switching Converters

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Abstract—**Techniques for analyzing the dynamic patterns of power flow in high frequency dc-dc switching converters are developed. Emphasis is placed on exploring methods for developing reduced order instantaneous and averaged models of power electronic circuits for simulation, analysis, and control design. Tools from selective modal analysis are used to develop the dynamic pattern recognition algorithm, which facilitates the classification of circuit modules.**

I. INTRODUCTION

Background

A SWITCHING converter displays linear and nonlinear processes, often occurring on widely varying time scales at a variety of power levels. The switching action induces discontinuities in the state space descriptions of switching converters; these discontinuities impede the direct application of standard methods for linear circuit analysis. There is a remarkable lack of automated tools for the modular analysis and design of complete switching converters. For instance, it would be desirable to have an automatic way of recognizing from a schematic those portions or modules of a converter that should be retained in an averaging analysis of the power stage. Even general tools such as simulation packages typically require case by case analysis when applied to switching power supplies.

One feature that makes power supply design tractable is modularity. Each module (snubber, clamp, power stage, etc.) is added with the intent of creating or repairing certain dynamics in the power supply. Of course, the different modules all interact, frequently through parasitic elements. These interactions strongly influence the design and physical construction of each module. Analysis and selection of appropriate modules is typically accomplished through expert judgement and intuition.

Contributions of this Paper

The dynamic pattern recognition (DPR) algorithm developed in this paper is a tool that facilitates the automated classification and identification of power supply modules. DPR opens the door to computerized expert assistance early in the power supply design process. The algorithm described in this paper is intended for the analysis of high frequency switching converters derived from the canonical switching cell [1], e.g., the buck, boost, and flyback converters.

This algorithm and a variety of other tools, including a basic circuit simulator, are implemented in the *C* language program PENDANT (Power ElectroNics Design and ANalysis Tool), developed by the authors for this research. In addition, PENDANT provides a convenient, graphics-based interface that allows the user to analyze a power supply by simply drawing the circuit schematic. The DPR algorithm presently implemented in PENDANT is not meant to be an end-all tool, but is rather a demonstration of the potential of dynamic pattern recognition in power electronics.

Outline

We begin in Section II with a brief review of participation factors, a mathematical tool borrowed from selective modal analysis (SMA), [2]–[5], and used extensively in DPR. The use of participation factors is illustrated with a simple circuit example, a buck-boost converter with turn-off snubber. This example serves as a point of departure for developing the concept of dynamic patterns.

Section III introduces the notion of a dynamic pattern and develops relevant notation and terminology. Section IV then illustrates how dynamic patterns are used in PENDANT to identify circuit modules and to develop useful instantaneous and averaged models for simulation, analysis, and control design. The validity of PENDANT's DPR algorithm is confirmed in Section V by comparing PENDANT's predictions to data recorded from hardware. Finally, Section VI concludes with a discussion of potential applications of DPR.

II. PARTICIPATION FACTORS AND DPR

Participation factors are part of a set of mathematical tools developed for SMA. In short, they are dimensionless scalars whose relative magnitudes indicate the extent to which a state is involved in a mode. Participations have found a wide range of application and, as [2] points out, uses are likely to be found in new settings. Space limitations permit only a brief description of participation factors and a review of their use, presented in this section. For more on participations and the other tools provided by SMA, see [2]–[5].

Consider the linear, time invariant description of a switching power supply in a given switch configuration. The system may be described in state space form where $\mathbf{x}$ represents a complete vector of n state variable (inductor currents and capacitor voltages) present in the circuit and A is the $n \times n$ system matrix relating $\mathbf{x}$ to $d\mathbf{x}/dt$:

$$\frac{d\mathbf{x}}{dt} = A\mathbf{x} + B\mathbf{u}.$$

The variable $\mathbf{u}$ represents a vector of source terms and the matrix B governs the impact of these sources on the derivative $d\mathbf{x}/dt$.

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For a model of a physical power supply, A typically has n distinct eigenvalues and a complete set of n corresponding independent right eigenvectors; this is assumed here. Let the ith eigenvalue be represented by λ_i and the corresponding right and left eigenvectors be $\boldsymbol{v}_i$ and $\boldsymbol{w}_i$, respectively. Also, let v_{ij} denote the jth scalar entry of $\boldsymbol{v}_i$ and w_{ij} denote the jth scalar entry of $\boldsymbol{w}_i$. (Choose the normalization $\Sigma w_{ij} v_{ij} = 1$.)

The participation factor for state x_j in mode λ_i is defined to be

$$p_{ij} = w_{ij} v_{ij}. \tag{1}$$

The term v_{ij} indicates the activity of the jth state in the ith mode, while the term w_{ij} gives the weight of the contribution of this activity. The magnitude of the dimensionless factor p_{ij} corresponds to the relative contribution of the jth state to the ith mode. The experience (with large power system models in particular) reported in [2]–[5] suggests that participation factors constitute a sound basis for associating state variables with the modes in which they are most involved.

As an illustration of the use of participation factors, consider the buck-boost converter shown in Fig. 1. This circuit is a simplified version of a converter that will be examined more thoroughly later in this paper. The switching frequency is 46 kHz. The power stage consists of L_1 and C_1 and the controllable switch is protected by a turn-off snubber which contains C_2. The 0.5-Ω resistor in series with L_1 is used to provide a current sense for the controller circuit (not shown in Fig. 1).

Two switch configurations or topologies that describe the interesting behavior of the turn-off snubber will be examined here. The first, Topology 1, occurs when the controllable switch and the catch diode are open and the snubber diode is forward biased. During this interval when the controllable switch has just opened, the turn-off snubber limits the rate of voltage rise across the controllable switch by providing a shunt path for the load current until the catch diode turns on.

The system matrix of the state space description which describes Topology 1 has three eigenvalues, shown in Table I. The magnitudes of the state participations for each of these eigenvalues are listed in Table II. Eigenvalue λ_1 governs a simple, first order decay process. From the participation factor magnitudes listed in Table II, the state variable which contributes most to this mode is V_1, the voltage across C_1. The complex conjugate pair of eigenvalues, λ_2 and λ_3, correspond to a relatively fast, lightly damped ringing. Table II indicates that the significantly participating states are V_2 and I_1, corresponding respectively to the voltage across C_2 and the current in L_1.

The second topology, Topology 2, occurs when the controllable switch is closed and the two diodes are reverse biased. During Topology 2, the snubber capacitor is clearing for the next switch opening. The eigenvalues for Topology 2 are listed in Table III and the state participation magnitudes are presented in Table IV.

The state participation magnitudes for λ_1 indicate that this mode governs the ramping up of the inductor current I_1. Similarly, it is evident from the participation factors that λ_2 governs the relatively slow discharge of C_1 through the load resistance and λ_3 governs the relatively fast discharge of the snubber capacitor C_2.

In the next section, participation factors are used to develop the notion of a dynamic pattern; the turn-off snubber analyzed in this section will provide a useful example for understanding dynamic patterns.

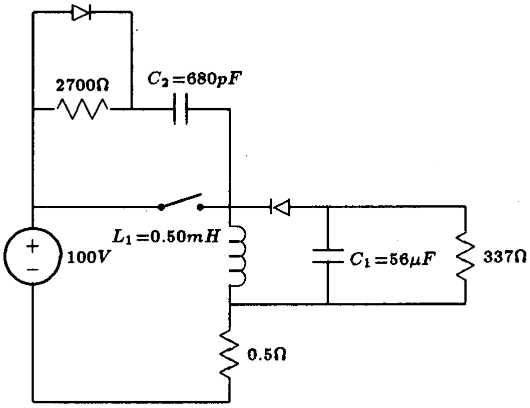


Fig. 1. Buck-boost converter with turn-off snubber.

TABLE I
EIGENVALUES FOR TOPOLOGY 1

Eigenvalues
$\lambda_1 = -53.0$
$\lambda_2 = -601 + j1.71 \times 10^6$
$\lambda_3 = -601 - j1.71 \times 10^6$

TABLE II
PARTICIPATION MAGNITUDES FOR TOPOLOGY 1

State Variable	Participations		
	λ_1	λ_2	λ_3
V_1	1.00	0.00	0.00
V_2	0.00	0.50	0.50
I_1	0.00	0.50	0.50

TABLE III
EIGENVALUES FOR TOPOLOGY 2

Eigenvalues
$\lambda_1 = -1.00 \times 10^3$
$\lambda_2 = -53.0$
$\lambda_3 = -5.45 \times 10^5$

TABLE IV
PARTICIPATION MAGNITUDES FOR TOPOLOGY 2

State Variable	Participations		
	λ_1	λ_2	λ_3
V_1	0.00	1.00	0.00
V_2	0.00	0.00	1.00
I_1	1.00	0.00	0.00

III. DYNAMIC PATTERNS

The fundamental assumption in the DPR process is that the different structures in a switching converter have fairly unique, characteristic dynamic behavior in the circuit. This assumption is heuristic and not amenable to rigorous proof. Nevertheless, our experience in this research indicates that the different structures in a switching converter can be associated with systematically recognizable patterns of eigenvalues.

The DPR algorithm uses three basic quantities to determine the role of a state variable and thereby identify an associated module: 1) the relative amount of energy storage in the module; 2) the speed (with respect to the switching frequency) of energy flow between the module and neighboring elements; and 3) the number and identity of states participating in each possible interaction. The values of these three fundamental indicators exhibited by a module throughout a cycle of its operation tend to cluster into a distinct group. We refer to such a grouping as a dynamic pattern. Before elaborating further on the DPR algorithm, it will be helpful to more precisely define the three basic quantities that constitute a dynamic pattern.

Relative Energy Storage

The relative energy storage capacity for a component (inductor or capacitor) is determined by comparing its value to that of the largest inductor or capacitor in the circuit, as appropriate. Based on this comparison, the component is assigned one of five rough energy storage ranges: VERY LOW, LOW, MEDIUM, HIGH, and PRIMARY.

PRIMARY elements have values equal to the largest appropriate energy storage element in the circuit. For example, in the circuit in Fig. 1, both C_1 and L_1 have PRIMARY capacities. Elements classified as having VERY LOW capacity have values less than one percent of the appropriate PRIMARY component. LOW elements fall in the range between one percent and five percent. MEDIUM elements have values that are in the range between five and 50 percent of the appropriate PRIMARY value. HIGH elements are those with values greater than 50 percent that are not PRIMARY.

The simple turn-off snubber module analyzed in the last section contains only one state variable component, the snubber capacitor C_2. All of the energy stored in this capacitor by the snubbing action is completely dissipated every cycle in Topology 2. Hence, it is desirable to keep the size of C_2 as small as possible to avoid substantial loss. The energy capacity of a snubber capacitor is therefore typically found to be VERY LOW. Examining the relative values of C_1 and C_2, this is clearly the case for the circuit in Fig. 1.

Speed of Energy Flow

For a given switch configuration, the speed of energy flow is determined by finding the magnitude of the eigenvalue(s) in which the module's states participate substantially. If the magnitude is large compared to the switching frequency, the eigenvalue is categorized as FAST. Otherwise, the eigenvalue is SLOW.

If DPR is to be used as the basis for developing design tools, some numerical means of classifying FAST and SLOW eigenvalues must be found. One of the goals of this work is to develop automatable techniques for producing and validating instantaneous and averaged models. We therefore identify what FAST and SLOW should be in the context of these two classes of models. The instantaneous models are used primarily for detailed simulation at time scales finer than the switching period, while the averaged models are valuable in simulation, analysis, and control design.

A condition for an averaged model to be valid is that each eigenvalue λ_i present in the system matrices that are averaged together satisfies the condition

$$|\lambda_i T| \ll 1 \tag{2}$$

where T is the switching period. Additional checks are needed to rigorously ensure the validity of an averaged model; however, (2) often provides a reasonable first measure of a proposed model [6]. In fact, the critical reduced order modeling that must typically precede averaging is generally performed ad hoc. Formal checks are rarely computed.

In the context of averaged models, one obvious candidate criterion for distinguishing FAST and SLOW eigenvalues is to insist that all SLOW eigenvalues satisfy the equation $|\lambda_i| < R$ where R is a value significantly less than the switching frequency. An illustration of the location of the SLOW and FAST eigenvalues based on this criterion is shown in Fig. 2. Developing models for averaging, however, is not our only concern.

For many simulation algorithms the step size must be small enough to determine switch transitions accurately. Therefore many steps are taken every switch period. Hence, for purposes of simulating the basic power conversion function, one would normally only consider discarding modules whose associated eigenvalues had magnitudes significantly larger than the switching frequency. This suggests a much larger magnitude range for SLOW eigenvalues than in the case of averaging. In the simulation context, SLOW eigenvalues are those that satisfy the criterion $|\lambda_i| < R$ where R is a value at least on the order of the switching frequency and probably larger.

For the PENDANT DPR algorithm, we have (somewhat arbitrarily) chosen $R = 1/T$. That is, SLOW eigenvalues are those that satisfy the criterion

$$|\lambda_i T| \leq 1.0.$$

This condition can be conveniently written in terms of $\omega = 2\pi/T$, the angular switching frequency:

$$|\lambda_i| \leq \frac{\omega}{2\pi}. \tag{3}$$

The set of SLOW eigenvalues found by sorting with (3) will definitely include all of the eigenvalues suitable for incorporation in an averaged model. Some eigenvalues not suitable for inclusion in an averaged model, but acceptable for a simulation model, may also be labeled as SLOW. Additional checks may be used to distill the SLOWest eigenvalues from the remaining SLOW eigenvalues. Finally, this criterion may label as FAST some eigenvalues that are actually SLOW for simulation; typically, the modules associated with these eigenvalues do not have a large role in power conversion. A MEDIUM speed category might be useful in some situations.

Number and Identity of Participating States

The third and last numerical indicator used in the PENDANT DPR algorithm is the number of state variables that participate significantly in the various FAST and SLOW modes of interest. The DPR algorithm in PENDANT computes participations for each eigenvalue. PENDANT then manipulates the participations to determine, based on prescribed tolerances, which states participate significantly in each mode. A type classification for each mode is made based on the number of state variables participating in the mode: Isolated (ISOL) for a single-state-variable participation (e.g., RC decay), coupled (CPLD) for a two-

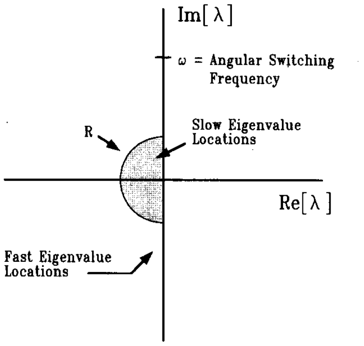


Fig. 2. Location of the SLOW and FAST eigenvalues in the complex plane.

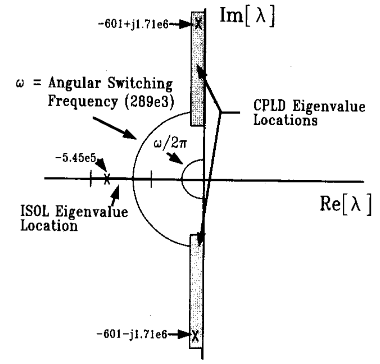


Fig. 3. Typical locations for eigenvalues of a turn-off snubber.

state-variable interaction (e.g., *LC* ringing), and multiply coupled (MCPLD) for significant participation of more than two state variables.

For example, the turn-off snubber capacitor in the circuit in Fig. 1 participates in two distinct sets of eigenvalues during a cycle of operation. These are a FAST, CPLD pair of eigenvalues in Topology 1 and a FAST, ISOL eigenvalue in Topology 2. In general, the eigenvalues in which a turn-off snubber capacitor participates will typically fall somewhere in the shaded regions of the complex plane indicated in Fig. 3. For comparison, the eigenvalue locations for the turn-off snubber capacitor in Fig. 1 are also shown in Fig. 3.

Comments

Since each module interacts with other modules, the dynamic pattern for a particular module may contain eigenvalues that have significant participations from more state variables than are present in the module. This is apparent from Fig. 3. A dynamic pattern is associated directly with a particular module, not with the state variables in the module. Further, dynamic patterns are typically only meaningful for describing modules in the circuit context in which the modules are designed to operate. A dynamic pattern captures the essence of a module's structure and its intended interaction with other modules; minor topological changes that preserve the behavior of the original module also preserve the original dynamic pattern.

The use of dynamic patterns to determine the role of a module is the essence of DPR. DPR identifies a module by first determining its dynamic pattern and then matching its dynamic pattern to one in a library of known dynamic patterns. Also, DPR can make recommendations concerning instantaneous and averaged models by using basic rules about converter design to categorize the various dynamic patterns exhibited by a power supply.

IV. PENDANT

The dynamic pattern recognition algorithm implemented in PENDANT is primarily intended to assist with the development of models for simulation and averaging. To verify a circuit model for simulation or averaging, it is not necessary to specifically identify the types of modules in the circuit. It is sufficient to simply locate modules that have dynamic patterns with unacceptably FAST eigenvalues. However, to demonstrate the technique of matching dynamic patterns to identify modules, PENDANT will identify several common modules including the turn-off snubber and the voltage clamp. While the PENDANT DPR algorithm described here is both useful for the important tasks of developing models for simulation and averaging and also generally illustrative of the DPR concept, the potential uses of DPR are even more numerous.

In the setting of high frequency canonical cell switching converters, the association between state variables and modules is very strong. That is, a superficial consideration of a component is frequently sufficient to guess the general type of module of which the component is a part. For example, an inductor with a large relative energy storage capacity is probably a part of some SLOW module like a power stage. A capacitor with a small relative storage capacity is likely to be a member of a FAST module like a turn-off snubber or a voltage clamp.

Hence, as a first step in identifying circuit modules and making recommendations about models for simulation or averaging, PENDANT begins by broadly classifying modules using two easily obtained pieces of information. The first is the relative energy storage capacity for all of the inductors and capacitors in the circuit. The second is the collection of eigenvalues exhibited in the rest state topology with all switches (diodes and controllable switches) turned off. Of course, some of these eigenvalues will never appear in the actual dynamic patterns of the modules and are thus meaningless; others, e.g., some simple *RC* decays, may be more useful.

Using the relative energy storage capacities and the rest state eigenanalysis, PENDANT makes a first cut determination of the importance of each state variable for simulation and for averaging. At this early level, no distinction is made between elements to be kept for simulation and averaging—this initial analysis simply provides a rough, probable-but-not-definite, three tier categorization: KEEP, DISCARD, or UNKNOWN.

The next step is to verify these preliminary classifications and, in the process, to both differentiate the state variables needed for simulation from those needed for simulation and averaging, and also to identify any familiar modules. PENDANT's approach is to examine the dynamics associated with each state variable as the converter cycles through its various topologies, looking for evidence to determine if the initial classifications are reasonable.

To determine the dynamic patterns exhibited by the different modules in the circuit, PENDANT needs some way of flexing the converter model, i.e., activating switches in physically meaningful combinations, to see what patterns of eigenvalues are present. Of course, there is no way for PENDANT to know *a priori* which of the converter topologies are physically meaningful. Typically, it would be very inefficient or impossible to simulate the full circuit to find the appropriate topologies. Instead, PENDANT exploits another heuristic rule.

Clearly, the zeroth topology with all switches off is nearly always a legitimate topology, since it describes the circuit in the rest state. PENDANT examines small deviations from this topology by turning on one switch at a time. In a switching power supply, the physical layout as well as the abstract schematic are critical in determining the electrical design intent [9]. Since one key design goal is to minimize or control the effect of parasitics, it is a good assumption that a state variable or module of state variables will be designed to interact predominantly with its nearest neighboring elements in other modules. So, one of two situations is likely. A module will exhibit its primary dynamic pattern either regardless of topology, as in the case of a linear multi-stage input filter, or when its local switch is turned on, allowing it to interact with its neighboring components.

As each topology with a single switch turned on is examined, the eigenvalues are recorded. Also, the eigenvalue types, speeds, and the specific state participations are determined and recorded. Presumably, encapsulated within the collective set of dynamic information for all of these one-switch topologies are all or most of the dynamic patterns exhibited by the modules in the circuit.

PENDANT sifts through this dynamic information to find evidence to confirm or deny its initial classifications. This second classification step is performed on two levels. On the first level, models are developed for simulation and averaging. Later, specific modules are identified.

The collected dynamic information for each state variable is examined. PENDANT challenges the initial classifications first for UNKNOWN elements, then for KEEP elements, and finally for DISCARD elements. Space limitations prevent a detailed discussion of the PENDANT search techniques and the heuristics involved. An example may, however, serve to illustrate the technique.

The small snubber capacitor C_2 in Fig. 1 will have been initially classified as a DISCARD element. PENDANT does not expect that a DISCARD element will ever participate in a SLOW, CPLD charging interaction with a suspected KEEP element. If a DISCARD element did participate in such an interaction, this could indicate that the module associated with the element was diverting significant power from the power stage or a similar, high power module, an unexpected role for an element with a small relative energy storage capacity. In this case, the element would be reclassified as UNKNOWN for simulation. On the other hand, if the suspected DISCARD element only participates in FAST interactions, it would remain classified as DISCARD for simulation. Generally, DISCARD elements have relatively low energy storage capacities and participate in at least some FAST dynamics. Hence, elements initially classified as DISCARD always remain so for averaging.

On the second classification level, specific modules are identified. Once PENDANT has ascertained a state's classification, i.e., KEEP, DISCARD, or UNKNOWN, with reasonable certainty, it examines the eigenvalues in which the state variable participates, comparing them against a library of known dynamic patterns in that class. Our research indicates that when a match is found using this method, it is very likely to be correct [8].

The DPR algorithm is quite generally applicable and easily amended to include new module patterns. In the next section, a flyback converter is analyzed using PENDANT. Based on the PENDANT recommendations, a reduced order model for simulation is developed and simulated using the PENDANT circuit simulator. The results are compared with experimental data.

V. Experimental Results

The converter for study is a 25 W off-line flyback converter operating with discontinuous conduction. It has a 10-V main output winding (which powers a load resistance R_4) and another output winding used to provide both power and also an isolated voltage sense for the controller. The circuit is controlled by the Unitrode 3842 control chip and operates at a switching frequency of 46 kHz. This power supply was adapted from the circuit presented in [9].

To provide a meaningful DPR analysis, all components have been reflected across the output windings to the primary side of the transformer, leaving behind only the magnetizing inductance. Since storage capacity (as defined here) is a relative indicator of energy storage based strictly on the size of a component, the assignment of relative capacities must occur entirely on one side of the transformer to be meaningful. Reflecting the components across the ideal transformer does not change the natural frequencies in the circuit. Hence, the removal of the transformer is necessary to satisfy the assumptions and techniques used in PENDANT's DPR algorithm. Simulations of this converter will, of course, yield voltages and currents scaled by the transformer turns ratio. For easy comparison with the hardware data, the simulated results presented in this section have been scaled by the reverse transformer turns ratio. A schematic of the circuit appears in Fig. 4. The values for the components in Fig. 4 are given in Table V.

The PENDANT recommendation as to which variables to keep for simulation is shown in Fig. 5. The DPR algorithm has correctly classified capacitors C_1, C_2, and C_6 as members of modules that process relatively little power and are responsible for the introduction of FAST eigenvalues into the converter model. PENDANT reports that discarding the modules that contain these capacitors will speed up the simulation and result in negligible impact on the simulation accuracy. All of the other state variables are members of modules that have a sufficiently substantial role in power processing to demand inclusion in the simulation model. Additionally, the PENDANT DPR algorithm correctly identifies the modules that contain capacitors C_1 and C_2 as a voltage clamp and a turn-off snubber, respectively. To illustrate this, PENDANT's identification of capacitor C_2 is shown in Fig. 6.

A reduced order schematic with the modules containing C_1, C_2, and C_6 eliminated is shown in Fig. 7. The PENDANT simulation of the turn-on transient of the output capacitor voltage, i.e., the voltage across C_3, using the recommended reduced order model is shown as Curve 1 in Fig. 8. For comparison, the start-up transient of the output voltage of the real converter is shown as Curve 2 in Fig. 8. The actual data collected from the converter was median filtered [10] to remove spike noise without smearing the fundamental trajectory.

VI. Conclusion

There are many potential extensions of DPR. It seems likely that a computerized auto-router for power electronic circuit layout could now be developed. A program could be developed that first identifies modules in an ideal circuit schematic and then perturbs the modules by inserting different combinations

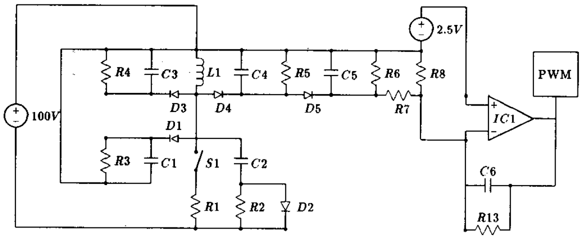
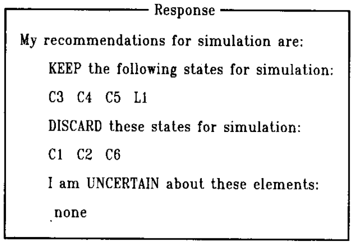


Fig. 4. Buck-boost converter for PENDANT analysis.

TABLE V
COMPONENT VALUES FOR THE BUCK-BOOST CONVERTER

Resistors	Reactive Components
R_1 = .5 Ω	C_1 = 3300 pF
R_2 = 2700 Ω	C_2 = 680 pF
R_3 = 4700 Ω	C_3 = 55.95 μF
R_4 = 337 Ω	C_4 = 2.599 μF
R_5 = 1270 Ω	C_5 = 4.79 μF
R_6 = 24 kΩ	C_6 = 4.725 pF
R_7 = 402.04 kΩ	
R_8 = 99.45 kΩ	L_1 = 0.50 mH
R_{13} = 3.04704 MΩ	



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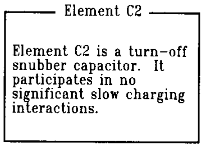
Response
My recommendations for simulation are:
   KEEP the following states for simulation:
   C3  C4  C5  L1
   DISCARD these states for simulation:
   C1  C2  C6
   I am UNCERTAIN about these elements:
   none
```

Fig. 5. PENDANT's suggestions for simulation.



```
Element C2
Element C2 is a turn-off
snubber capacitor.  It
participates in no
significant slow charging
interactions.
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Fig. 6. PENDANT's identification of C_2.

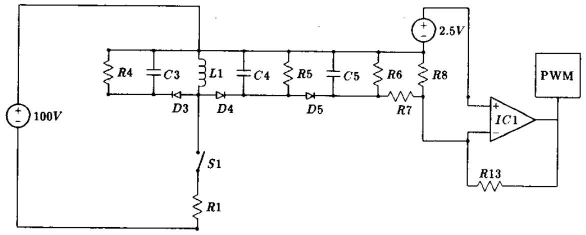

Fig. 7. Reduced order circuit schematic based on PENDANT's recommendations.

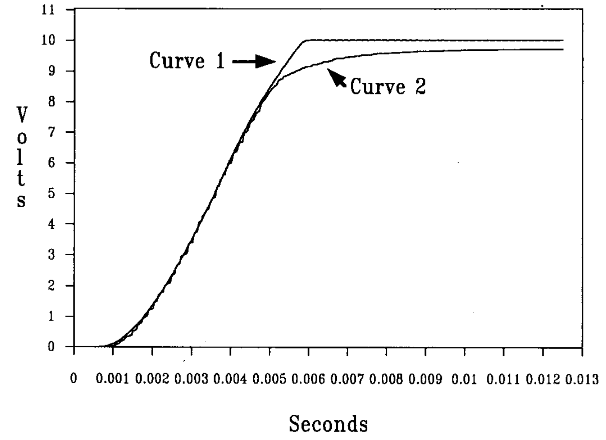

Fig. 8. Simulated and measured output voltage.

of parasitic elements. DPR could be used to examine the perturbed dynamic patterns and categorize the sensitivity of the various modules. An upper bound on the allowable magnitude of the parasitics could be determined by perturbing each module until it ceased to exhibit its dynamic pattern to within some predetermined degree. Based on this information, a suitable layout could be determined for good circuit performance.

In this paper, the application of DPR has been restricted to the canonical switching cell. However, DPR could certainly be used to identify dynamic patterns in other types of converters. The categorization procedures in the PENDANT DPR algorithm are steeped with rules appropriate for the canonical switching cell that would not be suitable for the identification of many of the new modules in other types of converters. For example, in a resonant converter, the dynamic pattern of the power stage will typically contain FAST eigenvalues. This condition is completely foreign to the canonical switching cell. To extend DPR to different converters, the general class of converters (e.g., resonant, canonical cell, quasi-resonant, etc.) must first be established so that appropriate pattern libraries and heuristics are employed.

Power electronic circuits contain a wealth of dynamics occurring on a wide variety of time scales and power levels. Techniques for analyzing switching converters typically require a detailed knowledge of the character of each module present in the circuit. Until now, designers of switching converters have often had to rely on intuition in the analysis of interacting modules. Dynamic pattern recognition seems to have a natural place in the automated identification and analysis of these modules and the converters that contain them.

ACKNOWLEDGMENT

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PENDANT uses subroutines from the EISPACK collection for eigenanalysis. It finds the state variable description of a circuit from a schematic description in netlist format using subroutines from KORNAP [11], [12].

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