U.P.B. Sci. Bull., Series C, Vol. 68, No. 4, 2006

BOOST CIRCUIT CONTROL IN TRANSIENT CONDITIONS

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Lucrarea îşi propune să abordeze câteva aspecte legate de modelarea şi comanda circuitului "boost". Deoarece este bazat pe un dispozitiv de comutaţie, simularea numerică este cel mai eficient mijloc pentru analiza funcţionării. Este prezentat un algoritm implementat în limbaj MathCad, bazat pe o singură ecuaţie recursivă vectorială. Regimul tranzitoriu analizat indică fenomene inerţiale, care pun probleme în cazul unei comenzi rapide. Pentru mărirea performanţelor este propus un mod de comandă incrementală, bazată pe anumite funcţii indicator, cu caracter energetic. Pe baza acestora se poate stabili o dependenţă liniară între parametrul de comandă şi cel de ieşire. Astfel poate fi asigurată stabilitatea circuitului şi promtitudinea comenzii

The paper purpose is to approach some aspects concerning the modeling and the control of the "boost" circuit. Because it is based on a switching device, the numerical simulation is the most efficient mean for the operation analysis. It is presented a MathCAD language implemented algorithm, based on a single recursive vectorial equation. The transient regime, that is analyzed, yields inertial phenomena, which make problems when a high speed of operation is necessary. In order to increase the performances, it is proposed an incremental control mode, based on certain indicator functions, having an energetic character. Using them, it can be stated a linear dependence between the output and the control parameter. Thus may be ensuring the stability and the speed of operation.

Keywords: boost circuit, numerical simulation, nonlinear analysis.

Introduction

The Boost circuit has, from one point of view, similar characteristics as the resonant circuits. It enables to obtain real time controlled output voltages. The output voltage characteristics are the minimum, the maximum and the mean value. These are correlated with the circuit components' values, the output impedance and the switching time durations. For a given configuration the output voltage is dependent only on the time control parameters.

This paper is focused on the Boost circuit optimization. To solve this problem the circuit operation must be analyzed. A good possibility is the numerical simulation for different control and operation parameters. The main

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purpose is to define some indicators and criteria that are useful for the control function determination, for an optimal operation. In order to obtain numerical results, a MathCAD language implementation is used.

1. The theory of operation

Here is considered a Boost circuit diagram showed in Fig.1. This contains the L inductance, the R_1 resistance, the K switch, the D diode, the C capacity, and the output resistive impedance R_2. In this case the R_1 resistor represents the cumulative equivalent resistance corresponding to the output supply impedance and to the resistive component of the inductor.

In a virtual mode, the Boost circuit scheme may be analyzed considering two interacting sections. The first ("the primary circuit") contains the input supply, the R_1 resistance and the inductance L. The second ("the secondary circuit") contains the semiconductor diode D, the C capacitor and the output resistive impedance. The switch K is used in common in the both circuits and controls their operation.

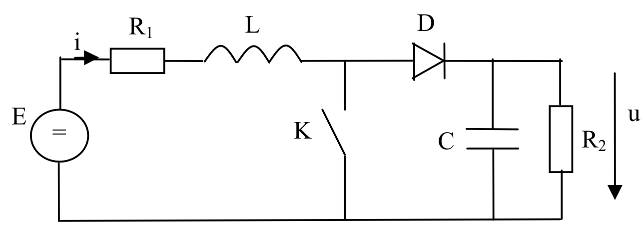

Fig.1. The basic scheme of the Boost circuit.

Although the Boost circuit has a simple configuration, its operation makes some problems, due to the relation between the variation of the output voltage parameters and the K switch control mode. The time durations corresponding to the "on" state and "off" state of the K switch determines in a nonlinear manner the output signal characteristics, as the variation frequency, the minimum, the maximum and the mean value. The problem is to command the K switch action, so to obtain the desired parameters.

The Boost circuit operation is a cyclical (periodical) one. Each cycle may be partitioned in two phases (partial operation cycles). In the first phase the K switch is considered in the "on" state. Thus, the direct current input voltage supply determines a current flowing only in the L inductance. This generates a reactive energy accumulation stored in the self magnetic field. So, this process can be considered as an accumulation one and will be referred in the following as the first phase (sequence) of the whole operating cycle. On the other hand, during this sequence, the capacity C is isolated from the input supply and is discharging on the load resistance R_2. It results that, if the accumulation phase duration increases, the inductive stored energy increases as well, but on the other hand, the output voltage values may reach lower values because a longer discharging duration affects the capacity. It is clear that, in an extreme situation, when this phase has a very long duration, the inductance current will guide towards a constant value, fixed by the R_1 resistance value. So, the dissipated power in R_1 becomes dominant, while the inductance energy remains constant.

In the second operation phase the K switch is in the “off” state. In this sequence the magnetic energy stored in the inductance is evacuated towards the output circuit. The output power delivery is supported, both, by the capacity and the primary circuit resources. Thus, the second stage duration defines the charging time of the capacity. The charging current is maintained, only if, the diode is direct polarized. Thus, an increasing of the second cycle duration over this limit is useless.

From the arguments stated above, it may be observed that the choice of the two phase durations must depend on the desired output parameters and on the circuit component values. It must be emphasized their nonlinear dependence character. An optimum situation is not obvious and may be defined as a compromise, because the simultaneous optimization of several parameters may be impossible. Thus, for example, the maximization of the voltage amplitude, for a given output resistance may cause an increasing of the distance between the maximum and minimum values.

It must be observed that the boost circuit efficiency, from the energetically point of view is correlated with the output performances. So, a non-maximal value of the output voltage may be caused by a too long duration of the accumulation phase. In this case, an excessive power is dissipated in the primary circuit.

On the other hand, if during the second operation sequence, the whole inductance stored energy is evacuated in the capacitor, the energetically efficiency is better. But if, on reverse, at the end of the second sequence the inductance current is not zero, it means that a permanent current component flow anytime through the R_1 resistance, causing a supplementary power dissipation in the primary circuit, lowering the efficiency. However, it is possible to obtain higher values for the output voltage if the accumulation phase begins with a nonzero current in the inductance. In this manner the inductance energy becomes higher.

Is interesting that, in every operation sequence, the limit values reached by different parameters are dependent, one hand, on the cycle duration, and on the other hand, on the initial condition specific for the sequence starting. This phenomenon has, as consequence, a certain inertial behavior, during the time evolution, when a parameter is sudden changed. It results that, for a given time moment, it can’t be defined an apriori optimal control command.

The most accessible indicator, useful to determine the control is the output voltage. But because the inertial effects, even an interactive continue relation, between the output and the control signal, may be unsatisfactory for an efficient fast and stable behavior.

The paper presents a strategy, based on two computed indicators functions, enabling to identify the stable operation state of the circuit, and on the other hand, to control the future evolution of the circuit, when a transient regime appears. By these, it can be found the optimum regime and the control criteria, useful when we try to reach this situation.

The principle of the Boost circuit operation is based on the energy transfer from the inductance to the capacitor. When a steady state is present, after a complete operation cycle, containing the two stages specified above, the physical phenomena must repeat identically. Thus, the energy variation located in the inductance and in the capacitor must have a cyclical character.

When a transient regime takes place, the limits of the energy variation are continuously changing, having an inertial behavior related to the control signal evolution, until a new equilibrium is reached.

2. The mathematical model

The Boost circuit simulation is achieved by solving the corresponding differential equations. But, because of the K switch action, the circuit configuration is changing during its time evolution. Thus the equation form is different for each type of evolution sequence, depending on the state of the K switch. In order to obtain a first order differential system with a unique solution, there are chosen, as unknown functions, the inductance current and the capacitor voltage. In the following relations the time dependence is implied. This choice is very useful for a variable configuration circuit modeling, because when the scheme is changing, the energy stored in the reactive elements must be conserved. It results that, at each transition, the continuity of the inductance current and the capacitor voltage must be guaranteed.

In the first operation cycle, the K switch is closed and the scheme is virtually divided in two separate circuits. The L inductance is connected exclusive to the supply voltage source, through the R_1 resistance. The capacitor circuit is not supplied and is discharging through the R_2 resistance. Using the first and the second Kirchhoff theorems, the following equations can be obtained:

$$R_1 \cdot i + L\frac{di}{dt} = E \tag{1}$$

$$C\frac{du}{dt} = \frac{1}{R_2}u \tag{2}$$

In the second operation sequence, the K switch is open, obtaining a single connected circuit. Applying the same theorems, it results:

$$R_1 \cdot i + L\frac{di}{dt} + u = E \tag{3}$$

$$i = C\frac{du}{dt} + \frac{1}{R_2}u \tag{4}$$

If we separate in the left side the differential terms, the standard form can be obtained. For the both operation sequences, a couple of differential equation systems are valid. For the first operation cycle we have:

$$L\frac{di}{dt} = -R_1 \cdot i + E \tag{5}$$

$$C\frac{du}{dt} = \frac{1}{R_2}u \tag{6}$$

For the second operation sequence we have:

$$L\frac{di}{dt} = -R_1 \cdot i - u + E \tag{7}$$

$$C\frac{du}{dt} = i - \frac{1}{R_2}u \tag{8}$$

If, for a given first order differential equation system, we use the vectorial representation form, the following condensed notation may be used:

$$\frac{dv}{dt} = F(t,v) \tag{9}$$

where $v = v(t)$ is an unknown time dependent vectorial function and *F(t,v)* is a vectorial operator. From the geometrical point of view, this operator represents the *v(t)* slope variation during the evolution.

If it is the case of a nonlinear problem, the *F(t,v)* operator may be dependent on the time moment and on the instantaneous value of the unknown function. When a step by step, numerical procedure is used, the *F(t,v)* expression must be changing during the numerical process, respecting of course, the continuity restrictions.

Depending on the instantaneous circuit configuration, the *F(t,v)* operator takes different forms. In our case, corresponding to the K switch states, the following expressions are used for the *F(t,v)*:

$$G(t,v) := \begin{bmatrix} -\dfrac{R_1}{L} & 0 \\ 0 & -\dfrac{1}{R_2 \cdot C} \end{bmatrix} \cdot \begin{bmatrix} v_0 \\ v_1 \end{bmatrix} + \begin{bmatrix} \dfrac{E}{L} \\ 0 \end{bmatrix} \tag{10}$$

$$H(t,v) := \begin{bmatrix} -\dfrac{R_1}{L} & -\dfrac{1}{L} \\ \dfrac{1}{C} & -\dfrac{1}{R_2 \cdot C} \end{bmatrix} \cdot \begin{bmatrix} v_0 \\ v_1 \end{bmatrix} + \begin{bmatrix} \dfrac{E}{L} \\ 0 \end{bmatrix} \tag{11}$$

For the numerical solving purpose there are used the Runge-Kutta, four order method, and the MathCAD program. This program contains specific procedures dedicated for the differential equations solving. However, in this case we have a variable configuration problem and the differential equation form must be changed during the numerical solving procedure. For this goal, an explicit solving method is considered. Used as a mathematical expression interpreter, the MathCAD program requires that the reciprocal interconnected variables in a computing process are contained in a single relation. This may be preceded by symbolical function definitions or index variable definitions.

Because it is the case of a differential equation system the solution must have a vectorial representation. Its numerical approximation needs a recursive computing process. The unknown functions are obtained step by step, corresponding to the evolution time moments. Thus, the numerical procedure must be represented as a single recursive equation, implying an indexed vector solution, denoted by $v^{<k>}$. The *k* index is corresponding to the k evolution moment. The current function *i(t)* is given by the first vector component, denoted by $[v^{<k>}]_0$, and the voltage function *u(t)* is given by the second vector component, denoted by $[v^{<k>}]_1$.

The circuit modifying action during the time evolution uses a conditional statement, having the syntax: if(condition,expresion1,expresion2). This returns the first expression value, when the condition is satisfied and the second expression value in the other case.

The above represented equations take under consideration only the K switch action. However, our circuit contains one more switching device represented by the diode D. If this is considered an ideal one, the corresponding current is nonzero, only if, the diode is directly polarized. Thus, we need to include another condition, which forces a zero current value, when this attempts to reach a negative one. It results a numerical procedure represented by a recursive expression containing two nested conditional statements. In this manner the step by step numerical procedure is based on the following representation:

$$v^{<k+1>} := if\left(K(t_k) \neq 0, A(t,v), if\left(\left[v^{<k>}\right]_0 > 0, B(t,v), C(t,v)\right)\right) \quad (12)$$

Here, the following notations are used:

$v^{<k>}$ - the k component of the vector string;

K(t$_k$) – a binary function, having a unitary value when the t_k belong to the first operation sequence and a zero value for the other case;

A(t,u), B(t,u), C(t,u) – vectorial functions giving the computing expressions corresponding to the each circuit configuration for a given time moment.

3. The control strategy

The Boost circuit is supplied by a direct current voltage source. Its operation is based on a periodical energy pumping, using the inductance–capacitor tandem. The output voltage signal contains a continuous component superposed with a variable one. In this context, the output signal amplitude is defined as a maximal instantaneous level. When the load resistance is not very high, compared with the others impedances, the output voltage variations are important. For constant values of the inductance and the capacity these variations increase when the load resistance decreases.

The presented monitoring method is based on two defined indicator functions. These are used for the analysis of the energy variation located on the inductance and the load resistive device, for every accumulation cycle. In a discrete representation, for the instantaneous values of the two indicator functions, there are used the indexed variables denoted as WL_k and WR_k as following (where h denotes the computation time step).

$$WL_k := if\left(K(t_k) = 1, \frac{L \cdot (v_{0,k})^2}{2}, 0\right) \quad (13)$$

$$WR_k := if\left(K(t_k) = 1, WR_{k-1} + \frac{(v_{1,k})^2}{R_2} h, 0\right) \quad (14)$$

The first relation evaluates the instantaneous magnetic inductance energy and the other the load active transferred energy. The conditional expression is necessary to make a restriction referred only at the accumulation phase. During the other operation sequence the indicators values are reset.

The significance of the indicator functions' evolution is different.

During the first phase the inductance energy will grow. The output transferred energy will grow too, while the capacitor energy will decrease.

On the other hand, the variation of the *WL* function has two distinct parts. At the beginning, a sudden variation takes place, and after this, it continues with a near linear one. The first corresponds to the nonzero inductance current, which is present when the first sequence starts, after the end of the second phase.

During a steady state regime, the output energy variations must be compensated by the inductance energy variations. During the second phase, the inductance has two kinds of contributions. A part of the inductance energy is stored in the capacitor. Another part is used directly on the load resistance.

When the output energy variation is plotted, during the accumulation phase, only the capacitor stored energy contribution is observed, because in this sequence the primary circuit is isolated from the secondary circuit. It is interesting that in a steady state operation, for a given load resistance value, the ratio of the maximal values for the indicator functions remain the same.

In order to determine the transient regime particularities, it is taken under consideration a sudden change of the control timing, relative to the optimum situation, considering a lower, respectively a larger value. These both changes induce a decreasing of the amplitude of the output voltage, like in Fig.2.

The variations of the indicator functions WL_k and WR_k are plotted on the same graphic. To be clearer, the transition moment is marked on the graphics by a pointed line. The first case studies the effect of the increasing of the accumulation time (Fig.3) and the second the effect of the decreasing of the accumulation time (Fig.4).

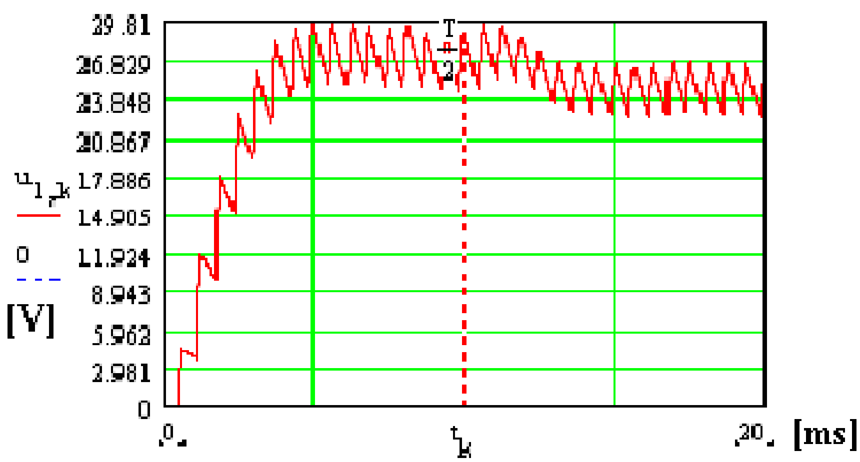

Fig.2. The transient output voltage variation.

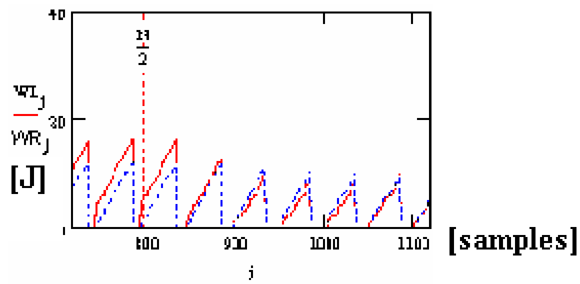

Fig.3. The indicator functions variation (decreasing duration).

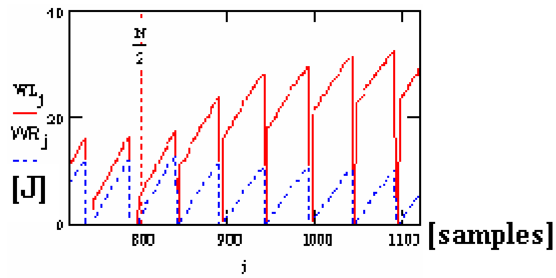

Fig.4. The indicator functions variation (increasing duration).

The numerical simulation yields that the output voltage has an inertial behavior against the timing control parameters' variation and the inductance energy maximum is directly dependent on the duration of the accumulation phase. This inertial behavior, which may be observed in Fig.3 and 4, creates some problems when an efficient control is necessary.

To obtain some desired output parameters, it is very important to find dependence between the observed output values and the switching control parameters. The operation of the boost circuit is based on two virtual operation sequences, concerning the energy transfer. In the first, the inductance stores magnetic energy. In the second, an important part of this is transferred to the capacitor and to the load. Thus a delay will appear and if a fast control loop is used, an instability phenomenon may arise. A solution is to use a slow control loop, based on an integrator circuit, but this is not an optimal choice.

In order to give a better solution to the problem a quasilinear dependence is searched. The input-output transferred energy must be conserved during a complete cycle. For some working operation conditions, as specified above, this has a pulsing character. The indicator functions give information about the energy quantities transferred at each cycle.

Analyzing the Fig.3 and Fig.4 diagrams it can be observed that, for each sequence, the shape of the waves is near linear, with a near constant slope and each operating regime is characterized by a quasiconstant difference between the *WL* and *WR* wave.

Thus, a new control strategy may take under consideration the offset between the linear fronts. Its magnitude may be memorized, depending to the output voltage, for a certain load value. The control timing must be set to satisfy this request.

Of course, we may wonder if the timing values, themselves, may use as control parameters. But, unfortunately this is impossible because the inertial behavior of the process and the indecidability of the sense of variation, when a differential control mode is adopted. Thus, a wrong choice of the timing parameters leads always to a decrease of the output voltage. But, we can't decide the correct sense of control variation.

It is interesting that, even at the beginning of each cycle, we can decide if the timing is optimal or not. There is a continuous dependence between the slope of *WR* and the starting value of *WL*.

Conclusions

The paper presents a numerical method dedicated to the boost circuit analysis. This is based on a nonlinear differential equation model and a MathCAD program implementation. On the other hand, a new control strategy is driven, based on two computed indicator functions. These give information about the energy transfer mode and are useful for the control of the timing parameters. Thus, the stability of the circuit during a transient operation is increased.

Using a digital signal processor the presented methods may be implemented. The numerical simulation gives an additional argument for the validity of the reasoning.

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