ANALYSIS OF THE BOOSTER DC TO DC CONVERTER WITH FEEDBACK

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***Abstract* — The field effect power transistors are used in many applications in electromechanical systems. Control of the field effect power transistors requires isolated 5V control signals and isolated 12V DC sources. The first problem is resolved by using optical pairs: light emitting diodes with phototransistors. The second problem can be resolved by using impulse voltage sources. The primary coil of a transformer is connected to the battery by a transistor switch. In the first period of operation of this voltage source, the energy is stored in the magnetic field of transformer's inductance. In the second period, the energy is delivered to the output voltage source. Energy is delivered from the secondary transformer's coil to the output capacitor through a diode. As a rule, one separate voltage source has a small power, that is why one impulse voltage source can have the necessary number of isolated output voltage sources, i.e., 3, 6, 9, 12, etc So, we can design an impulse DC to DC voltage source with multiple isolated output voltage sources.**

By changing the charge time of the inductor, we can control the output voltage by using negative feedback proportional to the output voltage and / or a current. In the report, different variants of impulse voltage sources are considered, with analog base elements and on the base of microprocessors. Analyses operation of these impulse voltage sources enable us to determine the period (frequency) of internal operation with ordered maximum transformer efficiency values.

The concept of controlled impulse voltage sources is very important because these sources are very simple. They are reliable and have high level of electrical isolation.

***Index Terms* — Control system, Field effect transistors, Power electronics, Transient response.**

INTRODUCTION

One of the drive circuits for MOSFET transistors is shown in Figure1. In this driver, there are three elements: an optic-coupler (diode D1 and transistor Q1), isolated DC voltage source V1, and resistor R1. The optic-coupler and isolated DC voltage source are employed to provide electrical isolation between logic level 5V signals and drive level 12V signals. When the input signal is zero, the transistor Q1 is turned off and MOSFET terminal gate is connected to the MOSFET terminal source.

MOSFET M1 is turned off. When the input signal is 5V, the transistor Q1 is on, connecting the 12V voltage source to the gate terminal of MOSFET M1. Transistor M1 turns on. The discussed drive becomes very simple if there is a simple DC voltage source

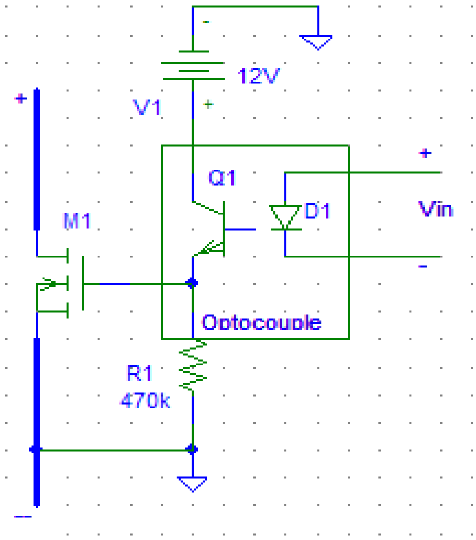

Figure 1. Drive circuit for a MOSFET

DC TO DC CONVERTER'S CONFIGURATION

Figure 2 shows a DC to DC voltage converter with a transformer and four switches. The transformer can have several secondary output coils. The load in Figure 2 is connected to a secondary coil. We can consider the load as an isolated DC voltage source. The DC voltage source includes a rectifier and a filter. The switches U1, U2, U3, and U4 in Figure 2 are transistors.

During one half period (the converter operation) switches U1 and U4 are on and U2 and U3 are off. In the next half of the period operation, U1 and U4 are off and U2 and U3 are on. When switches U1 and U4 are on and switches U2 and U3 are off, the current flows from the +DC voltage source to: switch U1, the transformer primary coil, switch U2, and back to the voltage source. In the second half period, current flows in the primary coil in the opposite direction. In this converter, partial energy stores in the magnetic field of the transformer inductance and another part transforms to the load.

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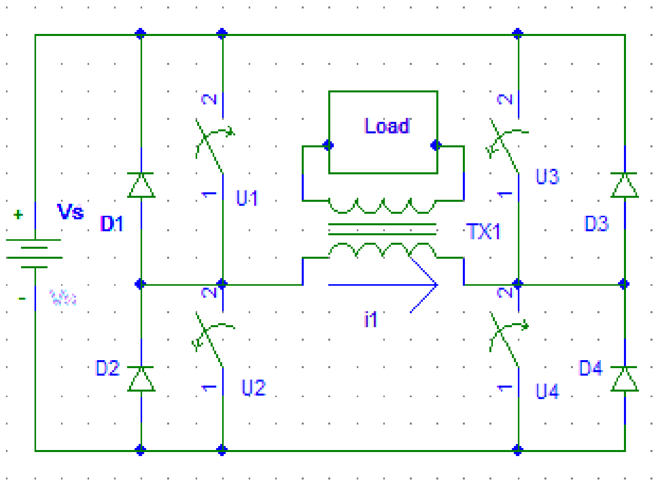

Figure 2. DC to DC Converter with transformer and four switches

Energy stored in the inductor is less than energy transformed to the load in nominal mode. Energy transformed to the load is equal to zero in idle mode. In the idle mode of converter operation, the coefficient of the efficiency equals zero. The maximum converter efficiency is approached at approximately seventy percent of maximum load. Energy stores in the magnetic field and returns back to voltage source twice during one period of operation. Figure 3 shows an impulse DC to DC converter. The converter includes one switch and one transformer. The secondary transformer coil is connected to the one-half rectifier D1, filter C1, and the load. The operation of this circuit starts when switch U1 is on (see Figure 3 (a)). The secondary coil of the transformer is disconnected from the load by diode D1, which is reverse biased by induced voltage in the secondary coil. When voltage source Vs is connected to the primary transformer coil, the energy stored in the magnetic flux of the transformer is determined by the equation

$$W = L\,(i2) / 2 \qquad (1)$$

Where: W is the energy, L is the inductance and, i is the primary coil current.

When switch U1 is off (see Fig. 3(b)), energy stored in the magnetic field transferred to the load.

We see that the second converter is simpler because it contains fewer components. The transformer in the second converter has a different mode of operation. Transformers do not transform energy to the load when they store energy. If we would like to transfer the same amount of energy from the voltage source to the load, the number of primary coil turns should be less than in the first case. The value of the transformer current is determined by the equation

$$i * N = H * l \qquad (2)$$

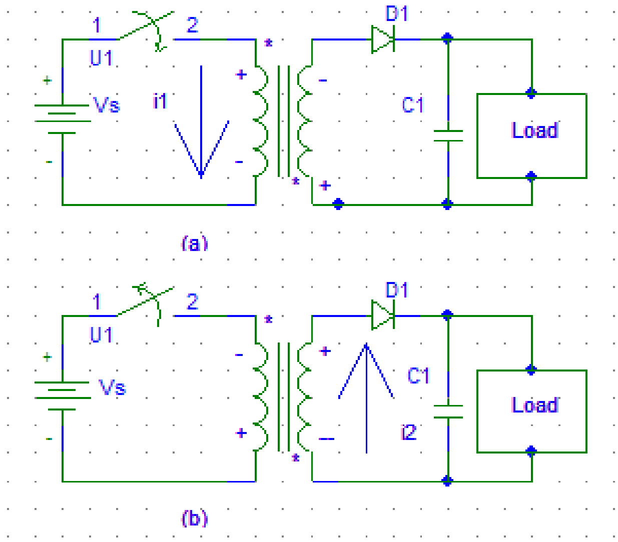

Figure 3. The impulse DC to DC converter with transformer and one switch

Where: N is the number of primary coil turns, H is the magnetic field intensity, and l is the mean length of the magnetic path. If two transformers have the same H and l, the current can be increased by reducing the number of turns. For transferring the same power, the primary coil’s cross-sectional area should have the same value. That means that in the second case, the amount of copper in transformer will be reduced. In the first case, the iron is better utilized, because it is magnetized in two directions. The choice of the converter is determined by the purpose of practical converter application. The impulse DC to DC converter is more preferable for MOSFET control circuits. Figure 4 shows a DC to DC impulse converter with nine output isolated DC voltage sources. The circuit converts the 5V DC input to multiple 12V DC outputs or the one 12V DC input to multiple 12V DC outputs. The main advantage of this circuit is very simple construction. The operation amplifier serves to generate rectangular output voltage. For this purpose, negative feedback (R5, C2) and positive feedback (R3, R4) are used. The voltage divider (R1, R2) in parallel with the capacitor divider (C1, C2), and virtual ground creates two polarity voltage sources for amplifier operation. The primary transformer coil is connected to the primary DC voltage source through transistor Q1. The transistor Q1 is controlled by the rectangular voltage which is produced by the operation amplifier U1. The secondary coils of the transformer create nine output DC (12VDC) voltage sources. All output voltage sources are identical. For example, the first voltage source includes the secondary coil, diode D1, zener diode D4, and capacitor C4. The zener diode keeps output voltage on the level of 12 volts and operates as a simple voltage controller. The number of output voltage sources can be increased. It depends on the electrical and physical parameters of the transformer. When we design impulse DC to DC impulse converters, the important thing is to select values of time to turn on and to turn off the transistor Q1. That means that the period of operation and the on/off time values of the primary coil determine the efficiency of the transformer. We will consider this problem from the standpoint of transformer effectiveness

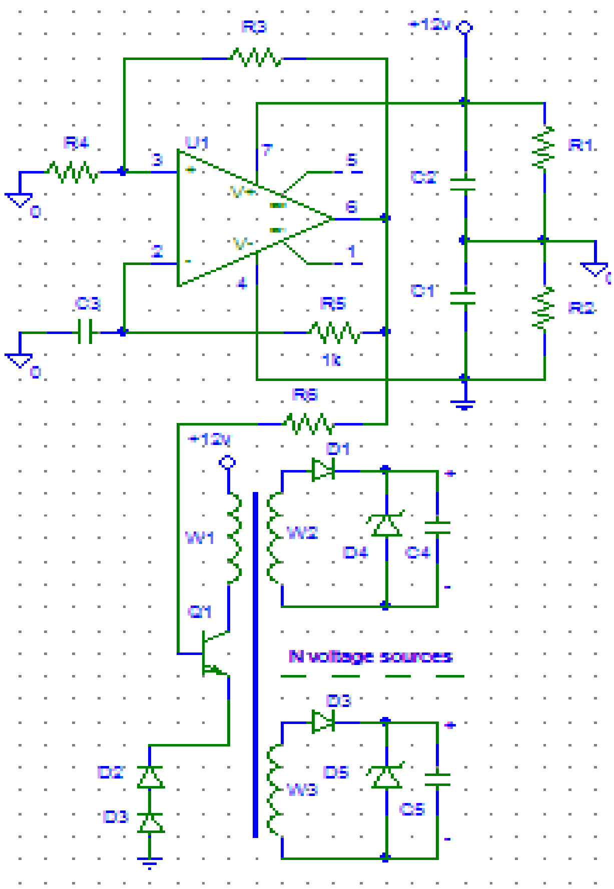

Figure 4. Impulse DC to DC converter with nine output isolated DC voltage sources

ANALYSIS OF OPERATION THE IMPULSE DC TO DC CONVERTER

This analysis has three main objectives: 1.To determine the interval needed for charging the transformer inductance. 2 To determine the primary coil efficiency of the transformer as a function of the charge interval. 3. To determine the period of the converter operation. Figure 5 shows the equivalent circuit of the converter in the first interval operation.

The current is described by the differential equation:

$$\frac{di}{dt}+\frac{R}{L}i=\frac{V}{R} \qquad (3)$$

Where R and L are the coil resistance and inductance and V is a voltage.

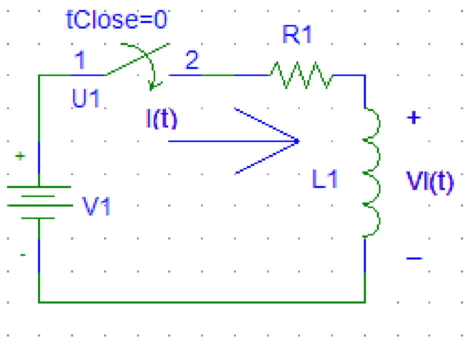

Figure 5. Equivalent circuit of the converter in the first interval operation

The solution of equation (3) is

$$i=\frac{V}{R}(1- e^{-\frac{t}{\tau}}) \qquad (4)$$

Where $\tau = L / R$ is the time constant.

The energy stored in the magnetic field with inductance L is

$$W_L = L\frac{i^2}{2} \qquad (5)$$

The stored energy divided over one period converter operation determines the average power

$$P_L=W_L / T \qquad (6)$$

Figure 6 shows the power stored in the magnetic field as a function of a charge interval. The converter operation period in (6) is taken to equal a double charge interval. The primary coil parameters are:

R=0.079 Ohms, L=122 μH, V=15 V (7)

The maximum power transferred to the inductance magnetic field occurs when the charge time is equal to 1.2 times the time constant

The energy dissipated in the resistor is determined by the equation

$$W_R=\int_0^t p_R dt=\int_0^t i^2 R dt=\int_0^t \frac{v^2}{R}(1-e^{-\frac{t}{\tau}})^2 dt \qquad (8)$$

Energy dissipated in the resistor is determined by equation:

$$W_R=\frac{v^2}{R}(t+2\tau * e^{-\frac{t}{\tau}}-2\tau-\frac{\tau}{2}e^{-\frac{2t}{\tau}}+\frac{\tau}{2}) \qquad (9)$$

The coefficient of efficiency of storage energy in the magnetic field is determined by expression:

$$\eta=\frac{W_L}{W_R+W_L} \qquad (10)$$

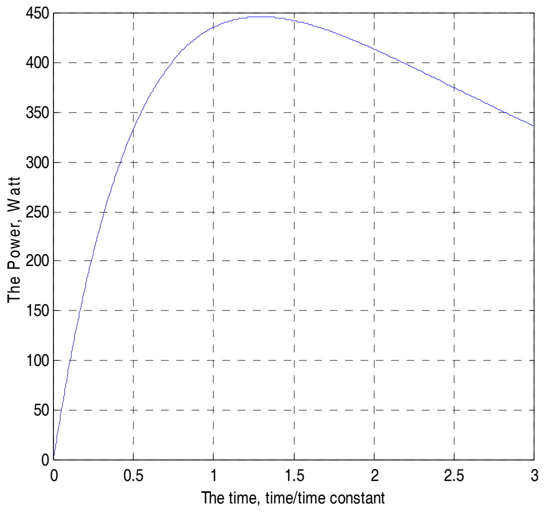

Figure 6. Power stored in the inductor as a function of charge time

Figure 7 shows the energy stored in the transformer inductance, energy dissipated in the resistor of the primary coil, and the efficiency of the primary coil as a function of charge time. The charge time is shown in reference to a time constant. The coefficient of efficiency curve appears as an exponential function. The transformer efficiency is close to maximum (100%) when the charge time of the inductance is close to zero. At the t=1.2 x time constant, the coefficient of efficiency is fifty percent. At this time, maximum power is stored in inductance (see Figure 6). It is very important to evaluate the value of maximum power. The value of current at t=1.2 * time constant equals:

$$I_{Pmax} = 0.7 * V / R \tag{11}$$

The value of maximum power stored in the inductor can be determined by the expression:

$$Pmax = (L / 2 * (0.7)^2 (V / R)^2) / (1.2*L / R)$$

$$Pmax = 0.102* V 2 / R = 0.102 * Psc$$

Where Psc=V2 / R is DC short circuit power in primary coil.

Maximum power does not depend on the time constant but depends on the converter operation period and the values of the output voltage and resistor. The best result can be achieved when the discharge interval is followed immediately by the charge interval. This mode of converter operation is possible by determining the moment of time when the discharge current is equal to zero. A microprocessor controller can solve this problem very well. If the discharge inductance interval is longer than the real interval for the current to decrease to zero, the value of maximum power decreases. Pulse Width Modulation (PWM) is natural for impulse DC to DC converters. Negative feedback can be used in this case to control output voltage. It is known that negative feedback, besides controlling voltage, decreases the time transient response as well. The interval discharge of the transformer inductance depends on the value of the real output voltage. If the output voltage is more than the nominal value, then the discharge time decreases. The nominal value of the output voltage is determined by the coefficient of transformation of the transformer. The period of converter operation is minimal when it is equal to the sum of the time charge and discharge of the inductance. In simple design converter cases, the period of operation is a selected constant. In this case, the time for discharge inductance is more than the real discharge time. It leads to a decrease in the maximum power value. If there is an opportunity to determine the discharge time when the secondary coil current decreases to zero, then the converter operation period will be minimized and the value of the power is maximized.

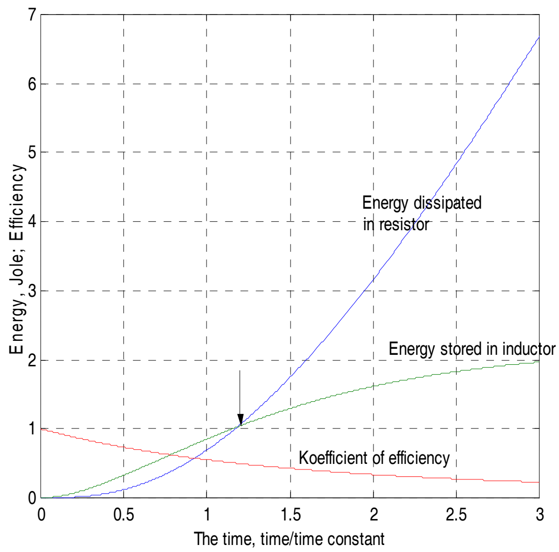

Figure 7. Energy dissipated in the resistor, energy stored in the inductor, and coefficient of efficiency as a function of the time/time constant

DYNAMIC PROPRTIES OF THE IMPULSE DC TO DC BUST CONVERTER WITH FEEDBACK

Figure 8 shows a simplified model of the impulse DC to DC converter. For simplification of the task, we will take in account: inductance of the transformer, primary and secondary coil resistances, diode, and capacitor, connected in parallel with load resistance. The operation time diagram of the simplified converter is shown in Figure 9. In the picture, the period converter operation is constant. We will start the converter operation description in interval (tn, t1) of the inductance charge. In this interval, diode D is off and the voltage of capacitor is described by the first order differential equation.

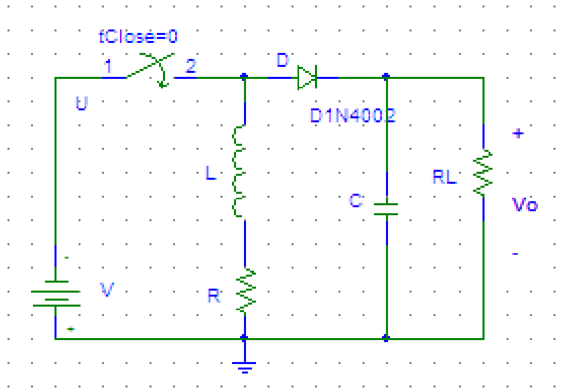

Figure 8. Simplified electrical model of the impulse converter

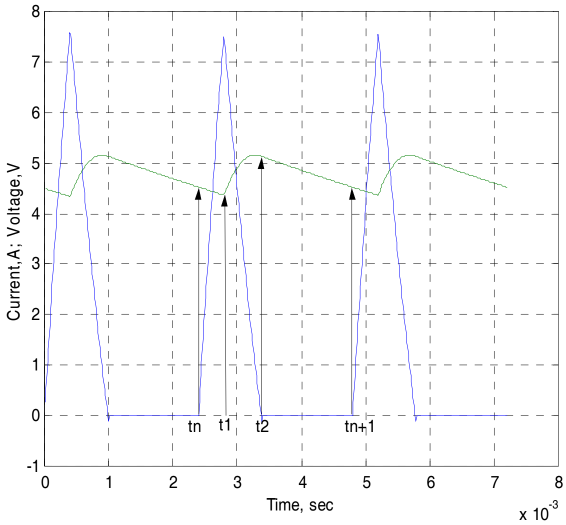

Figure 9. Time diagram of operation of a DC to DC converter

The initial condition of the capacitor is Vn. In this interval, the inductance connected to voltage source and current is described by the two independent first order differential equations. The initial condition for current is zero (in=0). Differential equations and solutions for this and other intervals are provided in the appendix. At the end of first interval we have

V1=f (Vn) and I1is the current when t=t1 (12)

The data in (12) will be the initial conditions for the same parameters in the second interval (t1, t2). In the interval, when inductance is discharged, the circuit is described by the two second order differential equations. At the end of interval we have:

V2 = f (I1,V1) and I2=0 (13)

The value of V2 is the initial condition for the solution of the first order differential equation describing the voltage of the capacitor in the next period (t2, tn+1). At the end of the period we will have:

Vn+1 = f (V2) (14)

The equations (14), (13), and (12) determine the first order non-linear difference equation

Vn+1 = F (Vn) (15)

This non-linear difference equation can be used for digital simulation of the converter and for linear approximation. For open loop digital systems, the interval t1 is fixed. By changing the value of t1 we can have different solutions for open loop systems. For closed loop systems we can calculate, at beginning of period, the value of interval t1 as follows:

t1= δ (VR - Vn) (16)

The linear approximation of difference equation (15) is described by the first order linear difference equation

ΔVn+1 = λ ΔVn (17)

The solution of the first order difference equation looks like this:

ΔVn= (λ) n (18)

Where n is the number of the period, λ is the root of the characteristic equation of the linear equation (17), ΔVn is the small difference between variable Vn and steady state value Vo

There are four different cases of this solution. If the value of the characteristic equation root is between one unit and zero, the solution is impulse-exponential. If the characteristic equation root is equal to zero, the time response is minimal (during one period of operation). If the characteristic equation root is negative but its absolute value is between zero and one unit, the transient response will oscillate with frequency equal to half the operation frequency. If the characteristic equation root (λ) is negative and the absolute value is more then one unit, then the transient response is unstable. Figures: 10, 11, 12, and 13 show transient responses in the converter with constant period of operation. These pictures illustrate all four dynamic cases.

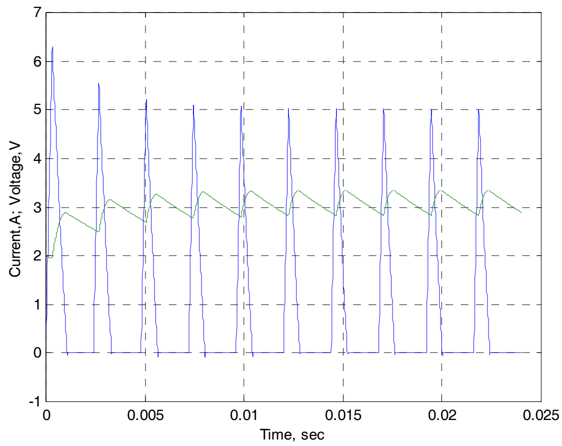

Figure 10. Transient response is impulse-exponential

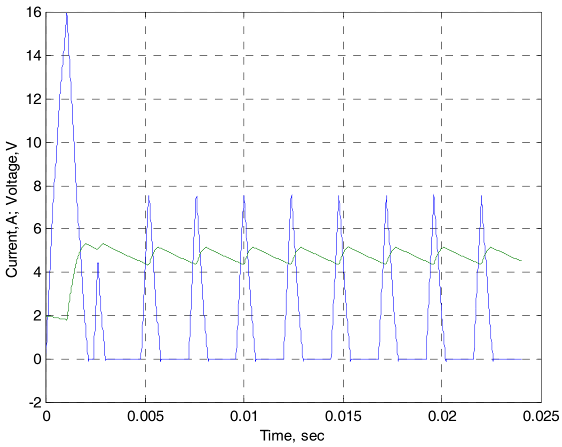

Figure 11. Transient response is minimal (during one period).

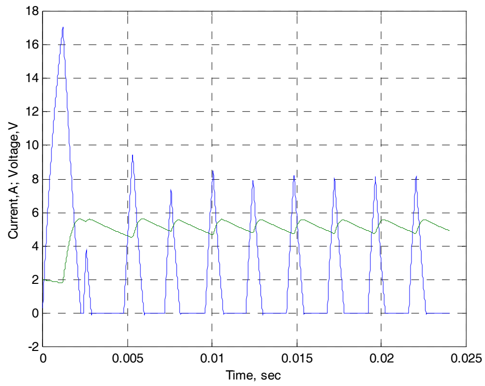

Figure 12. Transient response oscillates at half the operating frequency

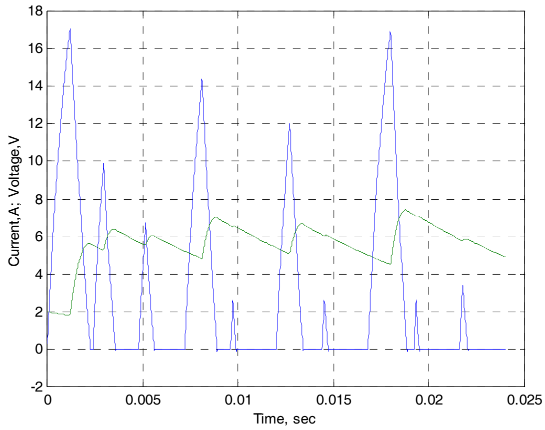

Figure 13. Transient response is unstable

Another simulation program was realized with a flexible (non constant) period of operation. The next period always starts when the inductance current decreases to zero.

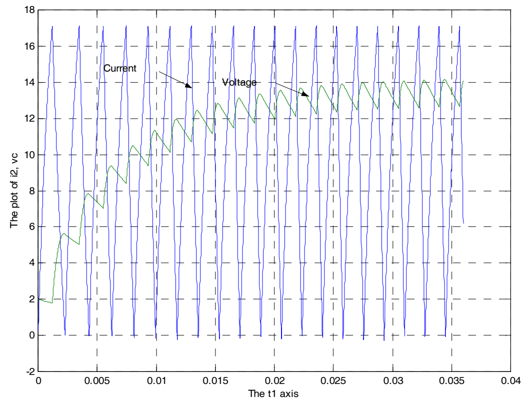

Figure 14. Transient responses in open loop system

Figures: 15, 16, 17, 18 illustrate the four different transient responses in a system with flexible (non constant) period

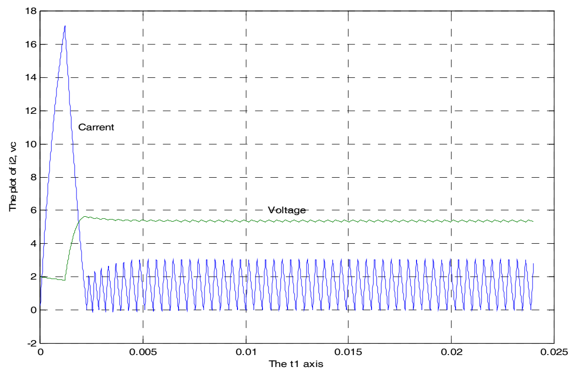

Figure 15. Transient response is impulse-exponential

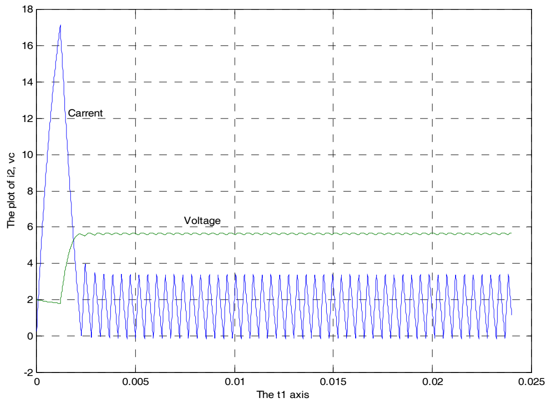

Figure 16. Transient response is minimal (during one period of operation).

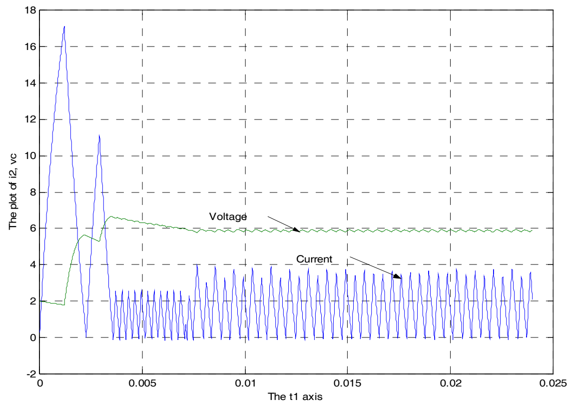

Figure 17. Transient response oscillates at half of the operating frequency

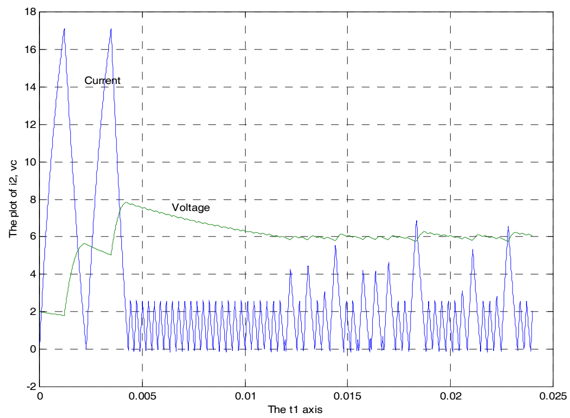

Figure 18.Transient response is unstable

CONCLUSION

1. Impulse voltage DC to DC converters (multi-source) have a simpler design and can be implemented for control of field effect power transistors.

2. Analyses of operation of impulse voltage sources enable one to select modes which maximize transformer power transfer and periods (frequency) of internal operation with ordered values of transformer efficiency.

3. DC to DC converters are more effective with flexible (non constant) periods of operation, when the period is determined by the sum of the inductance charge and discharge times.

4. Difference equations are very effective for analysis of the dynamic properties of the impulse converters

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