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Auto Tuning Of Analog Circuit Using PI Controller In SMPS

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Abstract

Consumer and portable electronics like microwave oven, refrigerator, smoke detector, washing machine etc., requires 12v to 1.5v DC-DC converter. To regulate the output voltage and current of the converters, controllers are required. Auto-tuned controllers modify system parameters and accordingly adjust to the required mode of operation. This work aims at the design of digital auto-tuning and fast-response voltage-mode controllers for low-power DC-DC switched-mode power supplies. The auto-tuning of controllers used in low-power SMPS improves the dynamic characteristics as well as power processing efficiency. The auto-tuning technique is carried out by inserting non-linear block in the analog control loop to generate controlled oscillations in the output voltage. The non-linear block is used to suppress the oscillation and to produce the delay. In order to obtain required output voltage when input voltage is not constant, auto-tuned PI controller is used. The design specification is for 12v to 1.5v using buck converter. The design and implementation is carried out using MATLAB.

Index Terms — current controller; DC-DC converter; non-linear block; Integral gain; PI controller; Proportional gain.

1. Introduction

DC-DC converters are power electronic circuits that convert a constant dc voltage to a desired voltage level. There are different types of conversion methods such as electronic, linear, switched mode, magnetic, capacitive are available. When there is a change of DC electrical power from one voltage level to another is needed these electronic devices are used. Digital control of switch mode power supplies (SMPS) is more and more used because of the increased computational capabilities and of the reduced cost of the devices available on the market [1].

DC-DC converters belong to the category of SMPS. The various types of voltage regulators, used in Linear Power Supplies (LPS), consists of dissipative regulator, as they have control element, usually a transistor which dissipates power equally to the voltage difference between an unregulated input voltage and a fixed supply voltage multiplied by the current flowing through it. Low-power switched-mode power supplies provide well regulated voltage and/or current for numerous electronic devices. The applications include miniature battery-powered devices, computers, telecommunication systems, consumer electronics, automotive and avionics electronics, lighting applications and other equipment that consumes power ranging from a fraction of watt to several hundreds of watts.

Most of the SMPS uses Pulse Width Modulation (PWM) to control the average value of the output voltage. Output voltage decreases when the load on the system increases. The power switch which feeds the primary of the step-down transformer is controlled by the PWM oscillator.

With the revolution of integration technology, it is possible to fabricate powerful microprocessors with large number of transistors on chip, resulting in higher power demand. On the other hand, to maintain/reduce the overall power consumption, the output voltage level of the microprocessor keeps dropping [2].

Modern switch-mode power supplies used in computers, laptops, and portable consumer electronics require fast transient response to minimize the size and cost of the power stage components. The key advantage of using fast dynamic control techniques is that they allow significant reduction of passive components (i.e., output capacitor) that are difficult to integrate on-chip, resulting in overall reduction of the cost and size of those electronic devices [3].

Compared to the previously used linear supplies, SMPS have much higher power processing efficiency, which often exceeds 90%, smaller dimensions, and can be implemented at a lower cost. A voltage controlled SMPS consists of two main parts: a power stage, i.e.

switching converter, and a controller. The power stage has several semiconductor devices operating as power switches and an LC filter network.

A nonlinear and time-varying system, a boost converter exhibits a right half - plane zero that is dependent on load resistance [4]. As a result, the linear controller could not perform satisfactorily when subjected to large load disturbance. In addition, the linear controller may experience difficulty in handling rapid input voltage reference change.

Optimal tuning of proportional-integral-derivative (PID) controller parameters is necessary for the satisfactory operation of automatic voltage regulator (AVR) system [5]. Since the fractional-order systems model is complex and the fractional-order controller requires more tuning parameters than that of integer-order controller, the tuning parameters method of fractional-order PID controller is difficult to obtain.

In SMPS, a controller is required for output voltage or current regulation. Processing of power from a fraction of watt to several hundred watts is possible in low power SMPS. The digital controllers have recently emerged as alternatives to the predominately used analog systems. This is because of the better power management capability, design portability and the potential for implementing advanced control techniques which is most difficult to realize with analog hardware.

The power stage parameters are estimated by the controller, i.e. capacitance of the output, resistive load, frequency and damping factor by examining the amplitude and frequency by introducing the limit cycle oscillations purposefully. Accordingly, a digital PID compensator is automatically redesigned and the power stage is adapted to provide good dynamic response and high power processing efficiency.

The PI controller is tuned to obtain constant output voltage. The current controller is used to generate pulses in the switches.

2. Basic scheme of auto-tuning

The buck converter is commonly used in circuits that steps down the voltage level from the input voltage according to the requirement. It has the advantages of simplicity and low cost.

The proposed auto-tuning method for buck-converter using PI controller and non-linear block is shown in Fig. 1. The auto-tuning controllers can monitor or estimate system parameters and accordingly adjust their own mode of operation to improve dynamic performance, overall system efficiency, as well as reliability. For example, in “mission-critical” power systems such as those in aircrafts, satellites, and medical applications, they can perform real-time “state-of-health monitoring” where component degradation/aging and other possible sources of failures are detected and a preventive action is taken in advance. Furthermore, the auto-tuning system can be used for the development of universal “plug and play” digital controllers. The main challenge in implementing auto-tuning controllers for low-power SMPS is hardware complexity.

Existing auto-tuning systems used in large-scale systems are not suitable for the targeted applications.

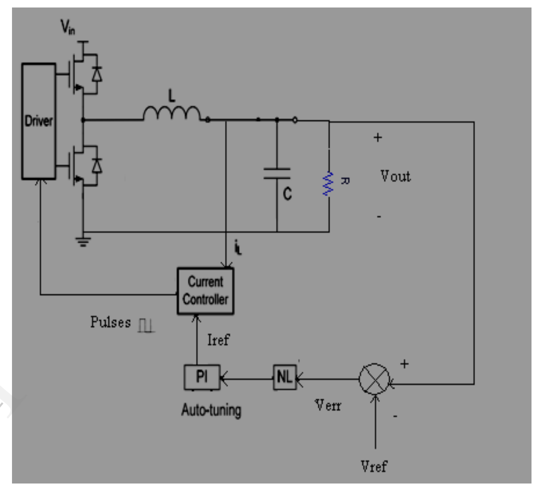

Fig. 1 Scheme of auto-tuning method using buck-converter

Usually, they use hardware whose complexity and power consumption exceed that of a complete low power dc-dc converter. This is mostly due to the use of powerful microprocessors, required to implement complex auto-tuning algorithms.

The PID controller is the most common way of solving practical control problem. Due to its simplicity and excellent if not, performance in many different applications, PID controllers are used in most of 95% closed-loop industrial applications. It is tuned by operators without giving extensive background in controls, unlike many other modern controllers that are much more complex but often provide only marginal improvement. In fact, most PID controllers are tuned on-site. Although all the theories in ME475 to design the controller are learned, the lengthy calculations for an initial guess of PID parameters can often be circumvented if a few useful tuning rules are known. This is especially useful when the system is unknown.

The recent work on the auto-tuning method is based on the digital controller [6-10] for implementing the programmable controller easily. Some of the digital controllers are also available in market with reference to the high frequency DC-DC converters.

The basic scheme comprises of DC-DC buck converter, current controller, PI controller, non-linear block. The simulation is carried out without using the driver circuit as shown in Fig. 1. Pulse generator generates pulses to the 2 switches. The current through the inductor and the error current from the PI controller is given to the current controller. The current mode technique is used in the current controller to switch ON and switch OFF the MOSFETS. So that, the compensated voltage is added and output voltage is obtained with less ripples and stable.

3. Design and procedure

3.1 BUCK-converter design

In the basic scheme firstly buck-converter is designed. The converter is designed for 12v to 1.5v as shown in Fig. 2.

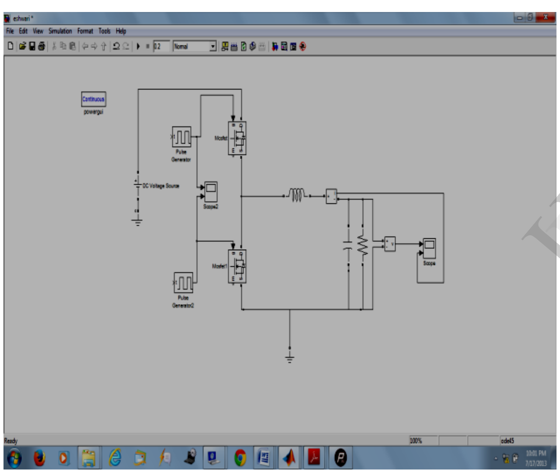

Fig. 2 Buck-converter design using MATLAB

Analysis of the buck converter begins by making these assumptions:

1. The circuit is operating in the steady state.
2. The inductor current is continuous (always positive)
3. The capacitor is very large, and the output voltage is held constant at voltage Vo. This restriction will be relaxed later to show the effects of finite capacitance.
4. The switching period is T; the switch is closed for time DT and open for time (1-D) T
5. The components are ideal.

Circuit design and implementation is shown below.

Design parameters:

Vin=12v, Vout=1.5v,

Switching frequency (f) =500k hz,

R=100 ohm, L=87.5 mH, C=0.5 µF,

Amplitude=1v, Pulse width=12.5%.

$D=\frac{Vo}{Vin} = 12.5\%$

$L=\frac{(1-D)R}{2f} = 87.5\ \mu H$

$C=\frac{(1-D)Vo}{8VrLf^2} = 0.5\ \mu F$

Vr= 1% of Vo = 0.015

The pulse generator is used to generate the pulses to the buck-converter as shown in Fig. 2. The pulse generator is designed in such a way that when top switch is ON bottom switch is OFF and vice versa with a delay of 1 ms.

3.2 Current controller design

The current controller in Fig. 1 is designed using the block shown in Fig. 3. The current controller produces triggering pulses to switches by comparing inductor current and the reference current. In the varying load and input voltage conditions, the DC-DC converter must give dc regulated output voltage. The component values changes with respect to time, temperature, and pressure. In order to keep output voltage constant a closed loop system with the negative feedback is necessary.

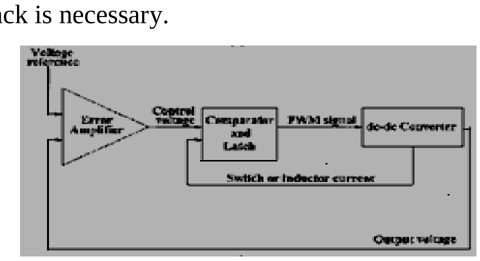

Fig. 3 Current mode-control scheme

In the current-mode control scheme shown in Fig. 3, the converter output voltage is sensed and it is compared with the reference voltage and the comparator produces error signal. The control voltage is produced by the error amplifier, which is compared with the constant-amplitude saw tooth waveform [11]. The comparator produces a PWM signal that is fed to drivers of controllable switches in the dc-dc converter [12]. The duty ratio of the PWM signal depends on the value of the control voltage. Also the frequency of the PWM signal generated is same as the frequency of the saw tooth waveform. An inner control loop feeds back an inductor current signal, and this current signal, converted into its voltage analog, is compared to the control voltage.

3.3 Tuning the PI controller

PID controller is the most common controller used in auto tuning method because of its simplicity. In most of the system derivative action is eliminated because with derivative action is that an ideal derivative has very high gain for high frequency signals. This means that high frequency measurement noise will generate large variations of the control signal. So by eliminating derivative action only proportion and integral actions [13] are tuned.

There are many ways to tune a PID controller. Traditional control techniques based on modeling and design can be used, but there are also special methods for direct tuning based on simple process experiments.

3.3.1 Ziegler-Nichols' Tuning Method

These are the two methods commonly used for tuning the controller. This method was developed by Zeigler and Nichols in the year 1940.

TABLE 1: Tuning values of P, I, D

PID Type	K_p	$T_i = K_p/K_i$	$T_d = K_d/K_p$
P	$\frac{T}{L}$	∞	0
PI	$0.9\frac{T}{L}$	$\frac{L}{0.3}$	0
PID	$1.2\frac{T}{L}$	$2L$	$0.5L$

By using values in the Table-1 proportional and integral values are set. And also by using reaction curve method the system oscillation is checked. Ziegler and Nichols conducts numerous experiments and proposed rules for determining values of Kp , Ki and Kd based on the frequency or step response[14] of the system. It is not applicable to system with neither integrator nor dominant complex-conjugate poles, whose unit-step response resemble an S-shaped curve with no overshoot. The S-shaped curve is called the reaction curve. The tangent line is drawn to the S-shaped curve and by using values of L and T critical gain is calculated as shown in Fig. 4.

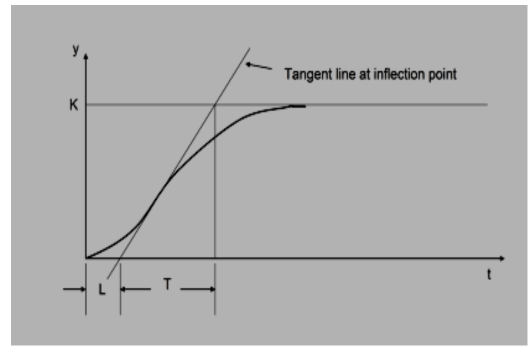

Fig. 4 Reaction curve method

PI controller parameter values using tuning method:
System oscillates when,
L=0.075, T=0.0083,

$$Kp = \frac{T}{L} * 0.9 = 0.1$$

$$Ki = \frac{0.3 * Kp}{L} = 0.4$$

The tuning is carried out with and without non-linear block. PI controller is tuned manually using Ziegler-Nichols method and the complete buck converter circuit with PI controller and without non-linear block is shown in Fig. 5.

The non-linear block is used to suppress the oscillation and to produce delay. The PI controller is the most commonly used controller used in auto-tuning method as the derivative action is eliminated here as it comprises of high frequency signals. Auto-tuning is carried out with the non-linear block as shown in Fig. 6. The value of Emax and Emin (reference error values) are 0.1 and -0.1 respectively are used to generate non-linear characteristic.

The error reference values and measured error are given to the comparator. The logic is created by comparing the errors and it is given to a AND gate. The logical output created by AND gate is given to the D-flip flop which will give the pulses as output.

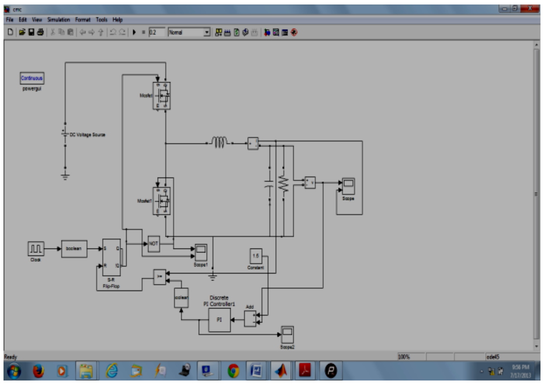

Fig. 5 PI controller without non-linear block

The pulses generated by the D flip-flop are given to switches S1 and S2. The top switch S1 is turned ON when the delay is absent and the current mode controller is activated. Under the presence of delay and ripples, the bottom switch S2 is turned ON. The min and max error limits are compared and the result is given as an input to auto-tuning block. The proportional and integral controller is automatically tuned to suit the situation.

The PI controller is designed as shown in Fig. 7. The Ki is connected with integrator block and Kp with zero order hold block.

The output of PI auto tuning block and the inductor current are given to the comparator. The output of the comparator is given to the reset pin of SR-flip-flop. The pulses with the switching frequency are given to set pin. The output of SR-FLIP-FLOP is given to power switches.

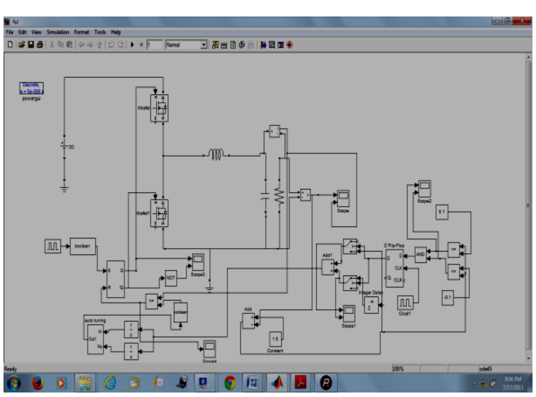

Fig. 6 Auto-tuning using non-linear block

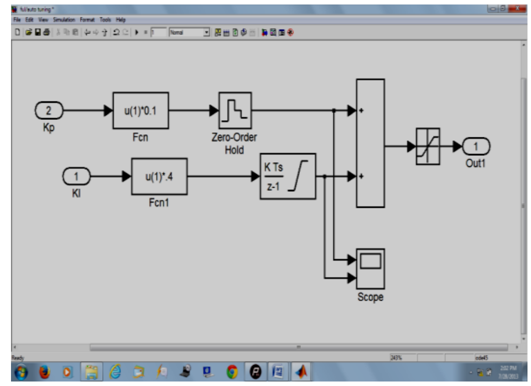

Fig. 7 PI controller design

4 Simulation results

The pulses are generated as when top switch is ON bottom switch is OFF and vice versa with a delay of 1 ms as shown in Fig. 8. Also the output voltage of 1.5 v and the inductor current obtained is shown in Fig. 9

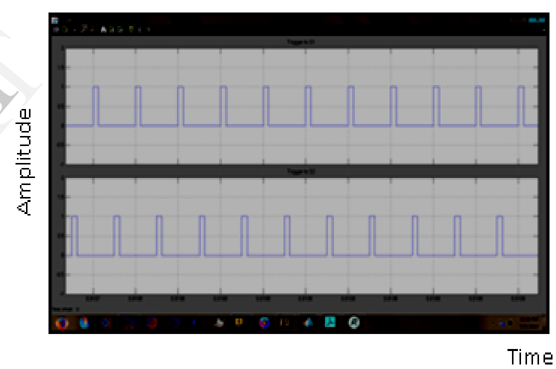

Fig. 8 PWM generation using pulse generator

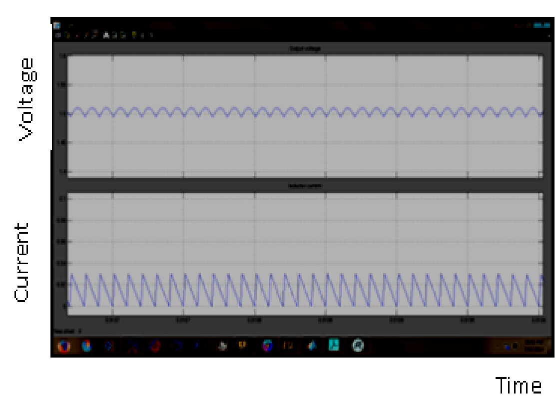

Fig.9 Output voltage and current of BUCK-converter

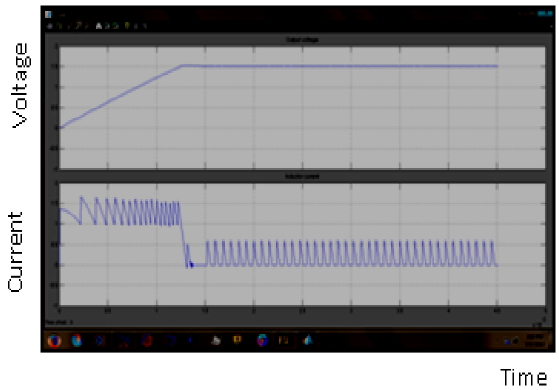

Fig. 10 Output voltage and inductor current with PI controller

The simulation result obtained is shown in Fig. 10. Initially output voltage increases to required value and it remains constant. The system oscillation is determined at this stage. The error current obtained across PI controller is shown in Fig. 11. The output current remains within the permissible limits.

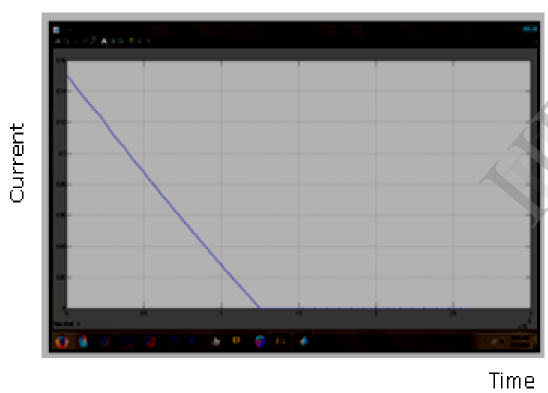

Fig. 11 Error current across PI controller

The results obtained in MATLAB with PI controller and non-linear block is shown in Fig. 12 and Fig. 13. Pulses are generated using the current controller such that when one switch is ON other is OFF and vice versa shown in Fig. 12.

The output voltage obtained of 1.5v is shown in Fig. 13 with less ripples and stable.

As shown in Fig. 14 values of Kp and Ki are initially increased and it is maintained constant to obtain required output voltage.

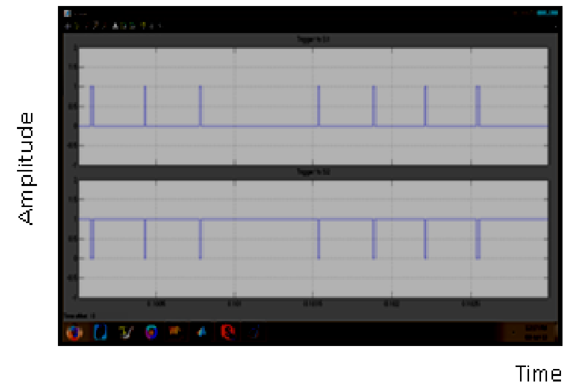

Fig. 12 PWM generation with non-linear block

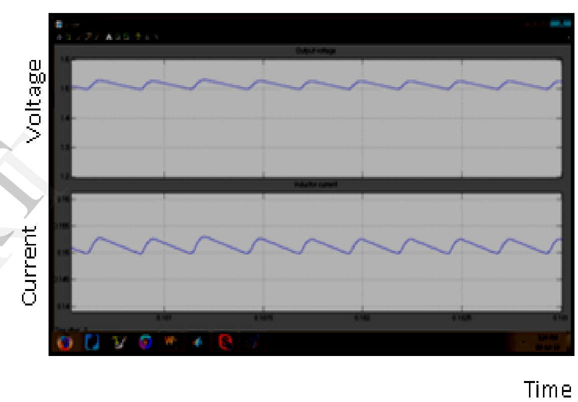

Fig. 13 Output voltage and current obtained with non-linear block

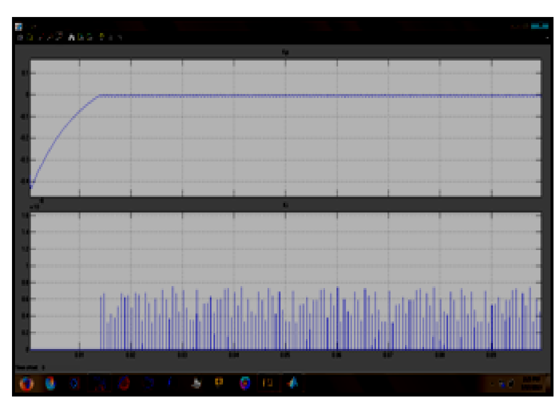

Fig. 14 Kp and Ki variation

5 Conclusion

The auto-tuning of the system is carried out using PI controller which is the most efficient way of tuning the system. PI controller is designed using the Zeigler-Nichols method and reaction curve method. Derivative action is not considered because; it has very high gain for high frequency signals. Non-linear block is used to suppress the oscillation and to produce delay. The output of the converter is maintained at 1.5v with an error limit of 0.1 for the range of 9v to 20v input voltage.

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