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Design and implementation of an observer controller for a buck converter

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Abstract: An observer controller for a buck converter is presented. A state feedback gain matrix is derived in order to achieve the stability of the converter and to ensure the robustness of the controller. A load estimator is designed to estimate the unmeasurable variables and to obtain the zero output voltage error. A pulse-width modulation scheme is adopted to obtain the output voltage regulation. In order to improve the transitory response and dynamic constancy of the converter, the controller parameters are designed based on the current mode control. The design is evaluated and verified using MATLAB/Simulink. An experimental set-up is done to evaluate the controller platform.

Key words: Buck converter, control law, LabVIEW, load estimator, observer controller, state feedback matrix

1. Introduction

DC-DC converters are widely used in personal computers, computer peripherals, communication systems, medical electronics, and adapters of consumer electronic devices to provide the required level of DC voltages [1]. The switched-mode power supplies that are used for telecommunication and computer systems require a high switching frequency, high efficiency, high power density, small size, low weight, low voltage stress, and low component count [2]. The feedback loops are designed in order to obtain the stability of the converter system. Due to issues such as component deprivation or input voltage changes, conventional designs may lead to the degradation of the closed-loop performance, resulting in poor dynamic stability due to a change in the operating point [3]. This leads to the design of a robust controller that achieves good dynamic performance.

Among DC-DC converters, the buck converter plays a vital role. In portable consumer electronics, buck converters are used the most. A buck converter is the simplest one, requiring only 1 switch, and is more than 90% efficient. In low-power DC-DC converters, overload protection, increased efficiency, and improved dynamic response are obtained by current sensing or measurement. The measurement methods are generally the voltage drop method and observer-based method. In the voltage drop method, the major drawback is that it decreases the efficiency and requires an amplifier with a wide bandwidth, which is very difficult to implement [4]. Hence, there is a need for the design of an observer controller.

The control techniques implemented through pulse-width modulation can be categorized into voltage-mode control or current-mode control. Current-mode control is advantageous over voltage-mode control because the system responds quickly to the disturbances [5]. However, this technique suffers from an inherent instability

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and subharmonic oscillations at constant frequency operation; hence, a dynamic compensation has to be designed. The major constraint in the design of control based on the frequency domain is the presence of a zero in the right-hand side of the plane in many of the averaged models. The average value of the inductor current is inversely proportional to the location of this zero; therefore, any increase in the value of the inductor current may reallocate this zero to the lower frequency side of the right-hand side of the plane. This results in considerable phase lags, thereby restraining the existing bandwidth for a constant operation of the converter [6]. This enables the design to be carried out in the time domain.

The main control objective in the design of a controller for a buck converter is to impel the semiconductor switch with switching pulses that make the system able to track the desired reference value of the given voltage at the output. The output voltage regulation should be maintained consistently, regardless of the deviation in the load or in the input voltage. Furthermore, the limitations in the design of the controller result from the duty cycle, which is circumscribed between 0 and 1. This problem can be solved by modeling the buck converter using the state-space averaging technique [7]. Using this technique, the converter can be described by a single equation, approximately, over a number of switching cycles. The averaged model makes the simulation and control design much faster.

The main objective of this work is to design a robust compensator based on the observer approach that overcomes the above-mentioned problems. The design is based on the time domain, in which converter specifications such as the rise time, settling time, maximum peak overshoot, and steady state error are met. The modeling of the buck converter is done using the state-space averaging method and the observer controller is designed using the pole placement technique and separation principle. MATLAB/Simulink is used to perform the simulation. The experimental set-up is carried out using LabVIEW program as a controller platform and a convenient USB data acquisition (DAQ) gadget, the results of which are illustrated. The subsequent sections are organized as follows: Section 2 gives the design of a buck converter, Section 3 discusses the modeling, Sections 4 and 5 explain the design of the state feedback matrix and the observer controller, Sections 6 and 7 give the simulation and experimental results, and, finally, the conclusion is given in Section 8.

2. Design of the buck converter

The circuit diagram of the buck converter is specified in Figure 1.

The converters convert an unregulated DC supply into a regulated DC voltage. The buck converter comprises an inductor L, a capacitor C, a semiconductor switch, and a diode. V_S denotes the input voltage and R denotes the load resistance [8]. The coil nonlinearities and the noise, which are caused mainly by the oscillations of stray inductors and parasitic capacitors at each of the switching instants, are neglected. The switch is assumed as ideal [9]. The buck converter design details are discussed below.

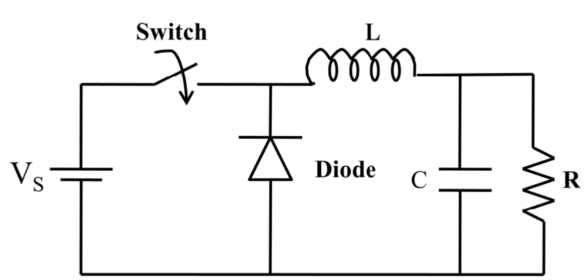

Figure 1. Schematic diagram of the buck converter.

The output voltage of the buck converter is always less than the input voltage and is given by:

$$V_O = dV_S, \tag{1}$$

where $d = \frac{T_{on}}{T}$ is the duty cycle ratio, T_{on} is the 'on' time of the semiconductor switch, and T is the switching period. To ensure the continuous current mode of conduction, the selected value of inductance should be greater than the critical value of the inductance L_C, which acts as a boundary condition for the continuous and discontinuous current modes of the operations.

The critical value of inductance is given by:

$$L_C = (1-d)\frac{R}{2f_S}, \tag{2}$$

where f_S is the switching frequency.

The inductor value must be chosen by considering the fact that the magnitude of the ripple current in the output capacitor, as well as the load current, is determined by the appropriate inductor value. Hence, normally a ripple current of 10% to 20% of the average output current is assumed for the design to achieve good performance of the converter. The value of the inductor is determined by:

$$\Delta I_L = \frac{V_S T d(1-d)}{L}, \tag{3}$$

where T is the time period.

The capacitor value is determined by assuming the output voltage ripple as 1% to 2% of the output voltage. The capacitor value is determined by:

$$\Delta V = \Delta I_L \times \frac{1}{8 f_S C}. \tag{4}$$

The following are the parameters considered for design: V_S = 48 V, V_O = 12 V, f_S = 100 kHz, L = 720 μH, C = 8.667 $\times$ 10^{-7} F, and R = 14.4 Ω.

3. Modeling of the buck converter

The state space analysis for the converter is carried out. The unique feature of this method is that the design can be carried out for a class of inputs, such as the impulse, step, or sinusoidal function, in which the initial conditions are also incorporated. This technique is expedient to use but it presents a low frequency estimate of the accurate dynamics, where the discontinuous results initiated by the switching are disregarded [8]. The state space analysis is discussed below.

The switch is turned on and off by a sequence of pulses with a constant switching frequency, f_S [10,11]. The state vector for this converter is defined as $x(t) = \begin{bmatrix} i_l(t) \\ V_c(t) \end{bmatrix}$, where $i_l(t)$ is the current through the inductor and $V_C(t)$ is the voltage across the capacitor. For the given duty cycle $d(k)$ for the kth period, the systems are illustrated by the following set of state-space equations in the continuous time domain:

$$\dot{x}(t) = A_1 x(t) + B_1 V_S(t), s = 1$$

$$x\dot{(t)} = A_2 x\,(t) + B_2 V_S\,(t)\,, s = 0, \tag{5}$$

where $s = 1$ represents the condition at which the switch is conducting and $s = 0$ represents the 'off' condition of the switch. Matrices A_1, A_2, B_1, and B_2 for the buck converter are given by:

$$A_1 = A_2 = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix}, \tag{6}$$

$$B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, \tag{7}$$

and

$$B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \tag{8}$$

The output voltage V_O (t) across the load is expressed as:

$$V_O\,(t) = \begin{bmatrix} 0 & 1 \end{bmatrix} x(t) \tag{9}$$

4. Control scheme for the DC-DC converter

The control structure for the converter is shown in Figure 2 [12]. If all of the states are accurately measured at all times, is possible to implement a linear control law, which is defined as $u = -kx\,(t)$, where k is the state feedback gain matrix. The ultimate idea in designing the control law is to ensure that the output voltage tracks the reference voltage against the parameter variations with little overshoot and a faster settling time. The root locus of the buck converter is drawn and the desired poles are placed for designing the state feedback matrix. The state feedback matrix achieves the stability of the system, which further improves the dynamic performance.

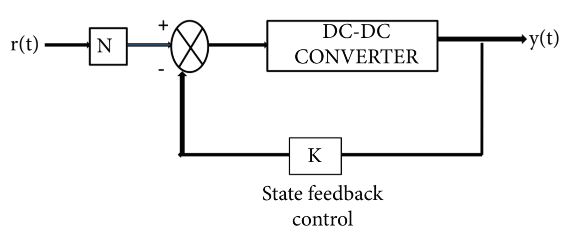

Figure 2. Control scheme with state feedback control.

The necessary condition for the arbitrary pole placement is that the system should be absolutely state controllable. The state feedback matrix reduces the chattering of the input when the system attains its steady state and further variations in the duty cycle. The system with the control law is defined as:

$$x\,\dot{(t)} = (A - Bk)\,x(t). \tag{10}$$

The system under consideration is completely state controllable; hence, all of the eigenvalues of *(A – Bk)* are placed in the left half of the s-plane, causing the system to become asymptotically stable.

The buck converter under consideration is of the second order and the desired poles can be easily placed by assuming the following converter specifications:

$$\left.\begin{array}{r}\text{Settling time } \approx \frac{4}{\zeta\omega_n} < 1ms \\ \text{Maximum peak overshoot } \approx 100e^{-\zeta\pi\sqrt{1-\zeta^2}} \leq 1\%\end{array}\right\} \quad (11)$$

where ζ is the damping ratio and ω_n is the natural frequency of oscillation of the system [13].

From the desired pole locations, the characteristic equation of the converter is given by:

$$\Delta = s^2 + 2\zeta\omega_n s + \omega_n^2. \quad (12)$$

The state feedback gain matrix is designed as $k_1 = 1.0881$ and $k_2 = 0.05$.

Figure 3 shows the step output tracked by the converter; hence, the required dynamics are achieved for the given time-domain specifications.

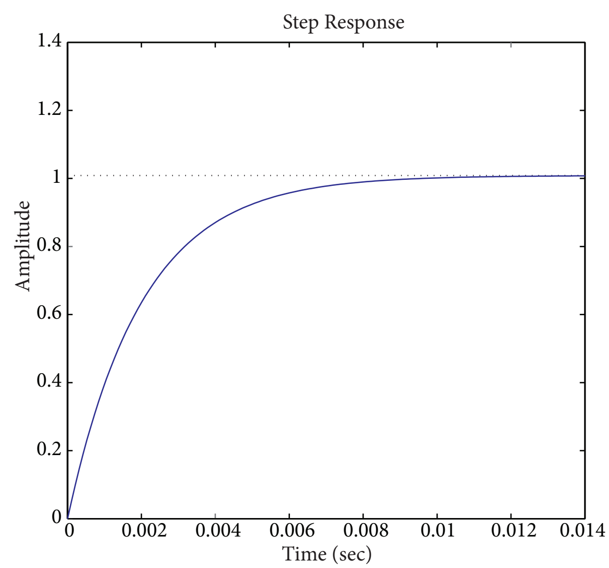

Figure 3. Step response for the buck converter.

5. Design of the observer controller

The load estimation is done by deriving the observer gain matrix in order to ensure the robustness of the control law. The observer is designed using the same pole placement procedure. The major benefit of this method is the simple design procedure, and thus better dynamic performance is obtained. In order for the complexity to be avoided, the load deviations are dealt with using state feedback control and a Kalman-like filter is added as an outer loop featuring a correcting integral action. It is desirable that the response of the system be much faster since the observer tends to act upon the error of the system. As a rule of thumb, the desired observer location is made by having the following assumption:

natural frequency of oscillation (observer controller) $\approx$ 2 to 5 times that of the natural frequency of oscillation of the system [12].

Now the dynamic equation of the system with the full-order state observer is denoted as:

$$\dot{x(t)} = (A - Bk)\,x\,(t) + Bk_1 r, \quad (13)$$

where k_1 is the element of the state feedback matrix and r is the step input. The dynamic equation describing the state observer is given by:

$$\tilde{x}(t) = (A - k_e C)\tilde{x} + Bu(t) + k_e y(t), \tag{14}$$

where k_e is the observer gain matrix.

Using the separation principle, a dynamic compensator can be obtained by combining the control law and the observer poles. The main advantage of this principle is that the design of the control law and observer can be carried out independently, and when both are used concurrently, the roots remain unchanged. The observer controller thus designed for the buck converter is discussed below.

The transfer function of the observer controller for the buck converter for a continuous time system is obtained as follows:

$$\frac{U(s)}{-Y(s)} = \frac{-3.624 \times 10^3 s + 4.22 \times 10^{10}}{s^2 + 2.113 \times 10^5 s + 4.467 \times 10^{10}}. \tag{15}$$

It is obvious from Figure 4 that the output thus obtained for this converter shows a much lower settling time and no overshoots or undershoots, with zero steady-state error.

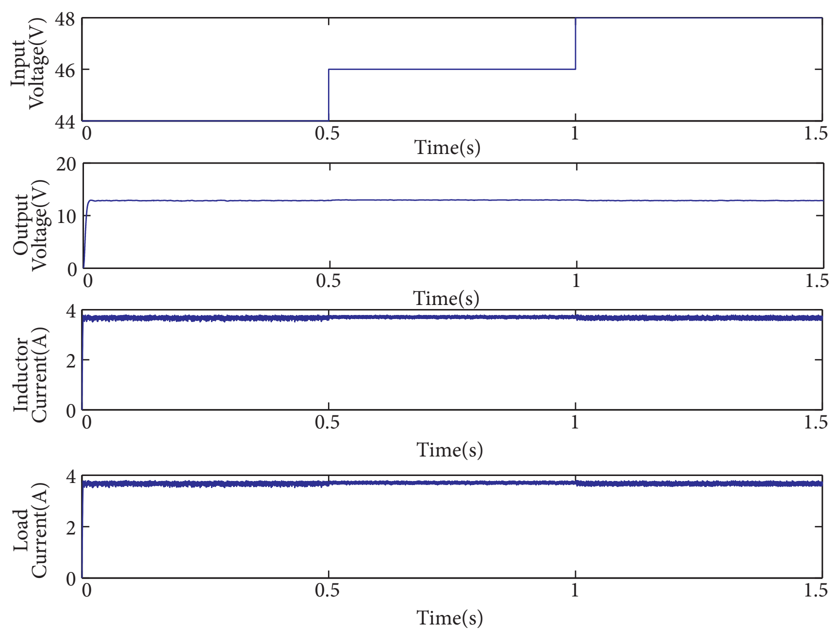

Figure 4. Simulated results for the buck converter.

6. Simulation results

The design and performance of the buck converter are accomplished in continuous conduction mode and simulated using MATLAB/Simulink. The ultimate aim is to achieve a robust controller in spite of uncertainty and large load disturbances. The converter specifications under consideration are the rise time, settling time, maximum peak overshoot, and steady-state error, which are shown in Table 1. The results thus obtained are in concurrence with the mathematical calculations. The simulation is also carried out by varying the load, not limited to the R load, and it is illustrated in Table 2. It is evident from Table 2 that the controller tracks the reference voltage in spite of the load variations. The output of the buck converter shows some steady-state error, which is of appreciable order. The output voltage, load current, and inductor current are obtained by varying the input voltage as 44 V, 46 V, and 48 V, respectively, and are shown in the Figure 4. For all of the variations, the controller is robust enough in tracking the reference voltage. It is evident that the controller improves the dynamic performance of the system irrespective of the variations in the input voltages and load values.

Table 1. Performance parameters of the buck converter.

Parameters	Values
Settling time (s)	0.015
Peak overshoot (%)	0
Steady state error (V)	0.05
Rise time (s)	0.0125
Output ripple voltage (V)	0

Table 2. Output response for the load variations.

Buck converter				
R (Ω)	L (μH)	E (V)	Reference voltage (V)	Output voltage (V)
3.6	-	-	12	12.05
15	-	-	12	12.02
9	10	-	12	12
9	35	-	12	12.05
20	10	10	12	12.03
9	20	6	12	12

7. Hardware implementation

7.1. LabVIEW package

The buck converter with the observer controller is implemented using LabVIEW as a controller platform. LabVIEW is primarily used as a platform for implementing any closed-loop system and it can be used for the improvement of a control system. It is extensively used for analyzing projects experimentally with a shorter duration due to its programming flexibility along with integrated tools designed especially for testing, measurements, and control. The key feature of LabVIEW is that it extensively supports accessing the instrumentation hardware. Drivers and abstraction layers are provided for almost all types of instruments. The buses are also accessible for addition. The abstraction layers and drivers act as graphical nodes and enable effective communication with the hardware devices, thereby offering standard software interfaces [14].

This software is used to build up the virtual instrumentation, which comprises the front panel and a functional block diagram. The front panel shown in Figure 5 is mainly used for user interactions. It is through the front panel that the desired transfer function of the observer controller is entered, as well as the corresponding parameters of the closed-loop control, and hence the restructured condition of the system is obtained. The block diagram, data acquisition, transfer function, and signal generation are built using the functional block diagram, as shown in Figure 6. It provides wide varieties of small icons to perform the desired task. The LabVIEW package provides many libraries with a large number of tasks for data acquirement, signal production, arithmetical and statistical analysis, signal conditioning, and investigation, along with many graphical interface elements. These features make it superior when compared with other development environments.

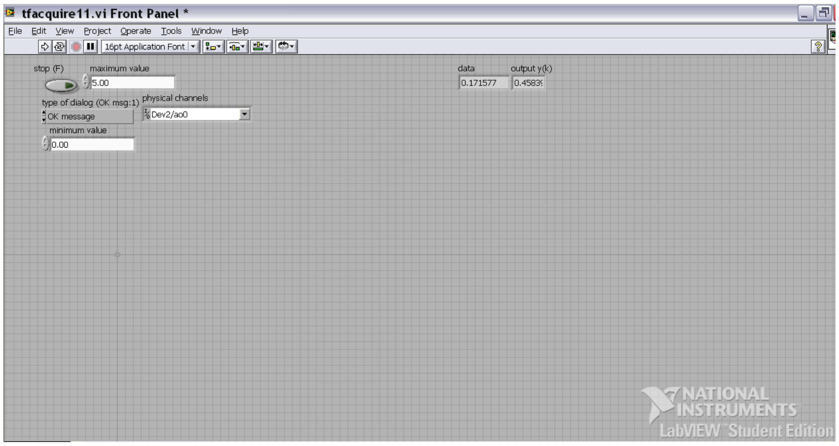

Figure 5. Front panel.

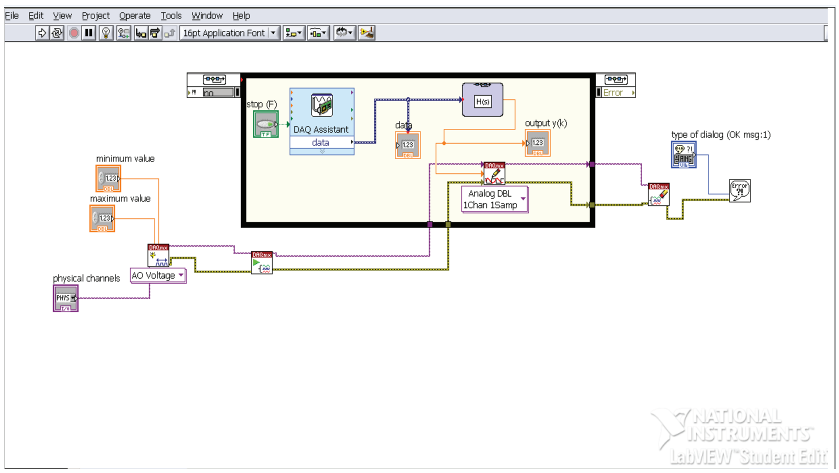

Figure 6. Block diagram.

7.2. Interfacing circuit

The NI DAQ Pad-6009 multifunction DAQ device is used. It can be easily connected via a USB port for data acquisition, generation, and data sorting in a wide range of convenient and portable applications. It comprises 8 analog inputs with referenced single-ended signal coupling or 4 inputs with differential coupling, 2 analog outputs, 12-bit A/D and D/A converters, and 32-bit counters. There are 12 channels of digital input/output lines that can be used either as input or output. It eventually offers a tremendous platform for the proposed observer controller. The DAQ pad 6009 is shown in Figure 7.

The prototype model of the buck converter with the observer controller is shown in Figure 8. The experimental prototype and the response of the buck converter with the observer controller are shown in Figures 9–13. It is understood that the observer controller works well and that LabVIEW provides the most feasible solution for the controller platform. To evaluate the performance, reference values of 5 V and 8 V are set, for which the output is obtained as 5.02 V and 7.98 V, respectively. The output obtained with the 5 V reference value is illustrated in Figure 11. The steady-state error thus observed is very minimal, of the order of 0.02 V, and the system settles down fast. The acquisition of the error signal from the hardware takes place instantaneously and when the program is run, and, at the same time, the controlled signal from the LabVIEW package is also generated within a much shorter duration of time without any delay or time lag. The experimental results thus obtained are in concurrence with the simulation results and mathematical calculations. The prototype model is developed using the values shown in Table 3.

Figure 7. NI DAQ Pad-6009.

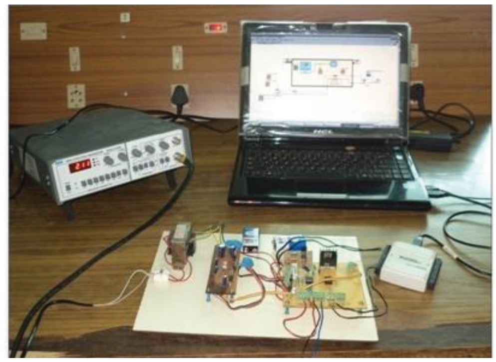

Figure 8. Experimental set-up.

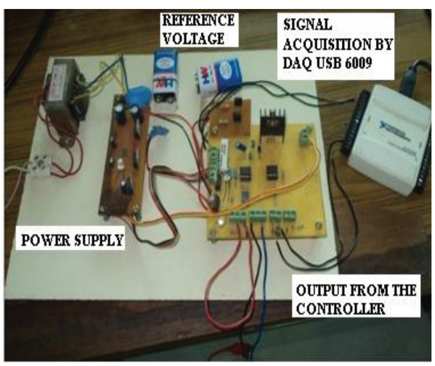

Figure 9. Indication of the set-up.

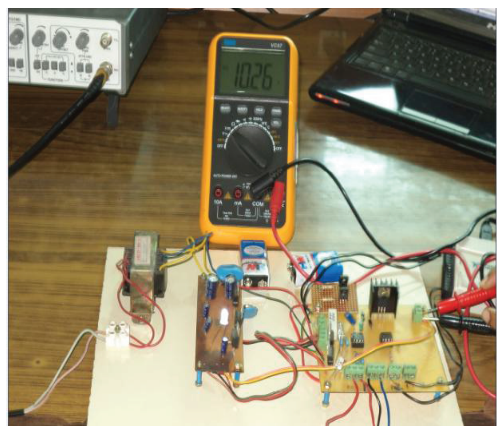

Figure 10. Input voltage.

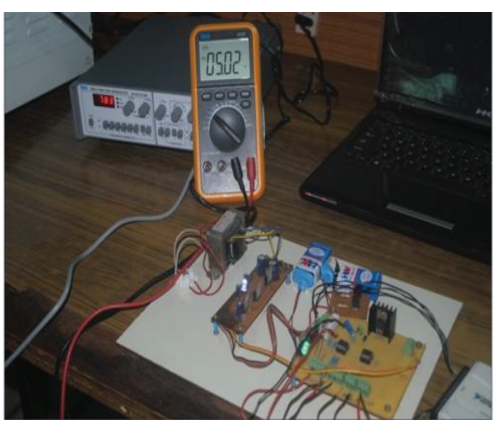

Figure 11. Output voltage (5 V reference).

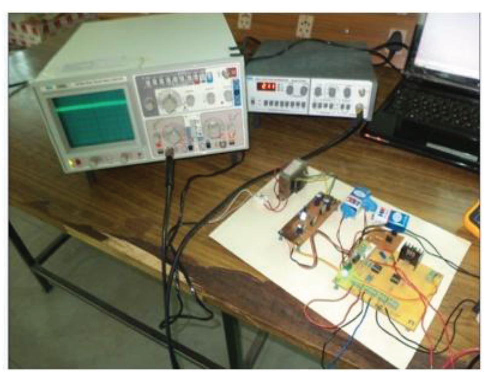

Figure 12. Output voltage measured using an oscilloscope (scale: y-axis: 5divX1V/div).

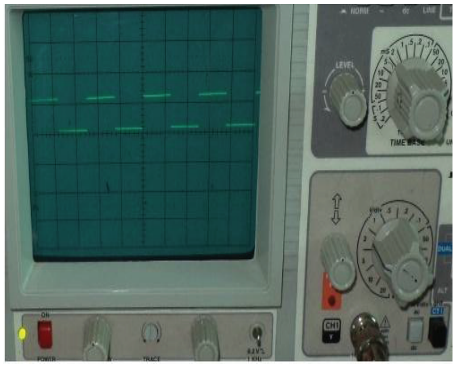

Figure 13. Gate pulse (scale: x-axis: 2.5divX20 μs/div = 20 kHz).

Table 3. Experimental values.

Description	Experimental values
L	15 mH
C	1 μF
R	20 Ω
V_S	10 V
f_S	20 kHz
D	1N4007
M	IRF840

8. Conclusion

A state feedback control approach has been designed for the buck converter in the continuous time domain using the pole placement technique and separation principle. The load estimator was designed by deriving a full-order state observer to ensure robust control for the converters. The separation principle allows the designing of a dynamic compensator, which looks very much like a classical compensator since the design is carried out using the simple root locus technique. The observer controller thus designed for the buck converter was implemented using LabVIEW as a control platform and the results were illustrated. The mathematical analysis, simulation study, and experimental study showed that the controller thus designed achieves tight output voltage regulation, good dynamic performances, and higher efficiency. This method is topology-independent and can also be extended for any of the applications such as power factor preregulation, photovoltaic cell, or speed control applications.

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