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Discrete prediction controller for DC-DC converter

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ABSTRACT. A discrete controller is designed for low power dc-dc switched mode power supplies. The approach is based on time domain and the control loop continuously and concurrently tunes the compensator parameters to meet the converter specifications. A digital state feedback control combined with the load estimator provides a complete compensation, which further improves the dynamic performance of the closed loop system. Simulation of digitally controlled Buck converter is performed with MATLAB/Simulink. Experimental results are given to demonstrate the effectiveness of the controller using LabVIEW with a data acquisition card (model DAQ Pad - 6009).

Keywords: buck converter, digital state feedback, pole placement, prediction observer, separation principle.

Controlador de previsão discreta para conversor DC-DC

RESUMO. Um controlador discreto foi desenhado para o fornecimento DC-DC de baixa energia. Baseia-se em domínio temporal e o recebimento de resposta controlador sintoniza continua e correntemente os parâmetros de compensador para se adequar às especificações de conversão. Um controle digital de resposta, combinado com o estimador de carga, proporciona a compensação completa, o qual melhora o desempenho dinâmico do sistema fechado de recebimento de resposta. A simulação do controlador digital é executada por MATLAB/Simulink. Os resultados do experimento demonstram a eficácia do controlador pelo LabVIEW com o cartão de dados (modelo DAQ Pad-6009).

Palavras-chave: conversor abaixador, resposta digital, colocação de pólo, observador de previsão, princípio de separação.

Introduction

DC-DC converters are widely used in many applications such as distributed power supply systems, power factor improvement, harmonic elimination, fuel cell applications and photo voltaic arrays. In power electronic systems, the switched mode dc-dc converters are very popular due to their light weight, compact, more power density, fast dynamics, higher efficiency and smaller size. Therefore they are extensively used in personal computers, computer peripherals, communication, medical electronics and adapters of consumer electronic devices to provide different level of voltages (CHANDER et al., 2011).

Especially in portable consumer electronics Buck converters play a vital role. Buck converter is very simple in construction and highly efficient. The main challenge in the field of Power Electronics is emphasized more on the control aspects of the dc-dc converters. The control approach requires effective modeling and a thorough analysis of the converters. The switching power converters in general are non-linear and time invariant. The major disadvantage of the Buck converter is its dependence on large passive components. In conventional analog design approaches, control problems are more complex and topology dependent (LEUNG et al., 1991). The major disadvantages include: (i) difficulty in adjusting; (ii) system alteration and higher functions are difficult; (iii) low reliability and (iv) sensitivity to noise. Thus Buck converters cannot be analyzed by directly implementing the conventional method, thereby leading to the implementation of digital compensators. In low power dc-dc converters, the overload protection, increased efficiency and improved dynamic response are obtained by current sensing or measurement. The measurement methods are generally voltage drop method and observer-based method. In voltage drop method, the major drawback is that it decreases the efficiency and requires a wide bandwidth amplifier which is very difficult to implement (LUKIC et al., 2008). Hence the observer plays a vital role in current sensing leading to the design of Observer controller for the dc-dc converters.

In recent years digital controller for power switching converters are being popular due to several advantages such as advanced control strategies, low sensitivity to variations, robustness to ageing and environmental changes, noise immunity and ease of programming. In digital approach, the two areas which find significance in the research are (i) the Digital Pulse Width Modulation (DPWM) signals are generated with highest resolution in order to obtain high accuracy in required output voltage; (ii) the digital control algorithms are being developed to fully utilize the features of the controller (GUO et al., 2009).

In this paper, high resolution DPWM signals are generated keeping the system clock frequency low to provide the state feedback control. The main control objective in the design of controller for the dc-dc converters is to drive the semiconductor switch with a duty cycle so that the dc component of the output voltage is equal to the reference. The regulation should be maintained constant despite variations in the load or in the input voltage. Furthermore, the constraints in the design of controller results due to the duty cycle which is bounded between zero and one.

This problem may be solved by modeling the dc-dc converters using state space averaging technique (GEYER et al., 2008). By using this technique, the converter may 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 prediction observer, which overcomes the above mentioned problems. The design is based on time domain in which the converter specifications such as rise time, settling time, maximum peak overshoot and steady state error are met. The dc-dc converters are modeled using state space averaging technique and the discrete observer controller is designed using pole placement technique and separation principle. MATLAB/Simulink is used to perform simulation. The experimental set up has been carried out using LabVIEW program with portable USB DAQ device whose results are illustrated. The sections are organized as follows: Section I gives the design of buck converter; Section II discusses the modeling; Sections III and IV explain the design of digital state feedback matrix and the Prediction Observer controller; Sections V and VI give the simulation and experimental results; finally conclusion and references are given in sections VII and VIII respectively.

Design of Buck converter

The schematic model of Buck converter is shown in Figure 1.

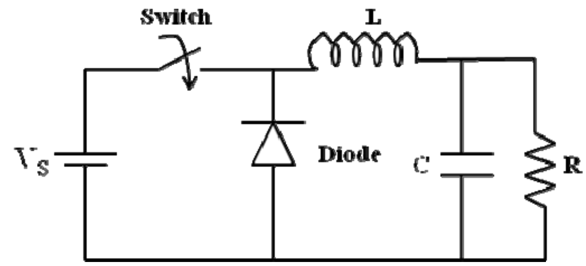

Figure 1. Schematic diagram of Buck converter.

The converters convert an unregulated dc supply into regulated dc voltage to a variable load. 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. The coil non linearities and the noise which are caused mainly due to the oscillations of stray inductors and parasitic capacitors at each switching instants are neglected. The switch is assumed as ideal (LEUNG et al., 1991). The design of the converter is now discussed. The output voltage of the Buck converter is always less than the input voltage and is given by,

$$V_0 = dV_s \tag{1}$$

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 continuous and discontinuous current mode of operations.

The critical value of inductance is given by,

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

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 inductor is determined by

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

where:

T is the time period.

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

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

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

Modeling of Buck converter

The dc-dc converter is modeled using state space averaging technique. The unique feature of this method is that the design can be carried out for a class of inputs such as impulse, step or sinusoidal function in which the initial conditions are also incorporated. Although this technique is convenient to use, it offers a low frequency approximation of the true dynamics where the discontinuous effect introduced by the switching is ignored (MARIETHOZ et al., 2010). The state space analysis is discussed below.

The switch is driven by a pulse sequence with a constant switching frequency, f_S. 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 inductor current and $V_C(t)$ is the capacitor voltage. For the given duty cycle d(k) for the kth period, the systems are described by the following set of affine continuous time state space equations,

$$\begin{aligned} \dot{x}(t) &= A_1 x(t) + B_1 V_S(t), = 1 \\ \dot{x}(t) &= A_2 x(t) + B_2 V_S(t), = 0 \end{aligned} \tag{5}$$

where:

s = 1 represents the condition at which the switch is conducting and s = 0 represents the off-condition of the switch. The 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

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

V_O (t) across the load is expressed as,

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

The continuous state equations are discretized in order that the prediction observer controller has to be designed. It is considered that the discrete system is the same as that of the continuous system, except that the system is sampled with a sampling time, which is assumed as 1μs. The state space solution is transformed into a sampled system as given by using the relation t = kT, where T is the sampling time. With the analog coefficient matrices, discrete counter parts are obtained by using the following relationship,

$$G = e^{AT} \tag{10}$$

$$H = \int_{\tau=0}^{T} e^{A\tau} d\tau B \tag{11}$$

$$C_d = C \tag{12}$$

$$D_d = D \tag{13}$$

where:

G, H, C_d and D_d are the coefficient matrices for discrete systems.

The dynamics of the Buck converter for discrete time system is obtained as follows,

$$G = \begin{bmatrix} 0{,}9999 & -0{,}00138 \\ 0{,}1148 & 0{,}9919 \end{bmatrix} \tag{14}$$

$$H = \begin{bmatrix} 0{,}000347 \\ 1{,}995 \text{ x } 10^{-5} \end{bmatrix} \tag{15}$$

Design of robust digital state feedback control using pole placement technique

The main objective is to choose the state feedback gain matrix based on control law given by

u = -$kx(k)$ for the systems under consideration, defined by their respective state equations. The desired steady state value of the controlled variable 'y' is a constant reference input 'r', which is taken as a unit step input. The root locus of Buck converter under consideration is drawn from which the desired closed loop poles were chosen for the design of the state feedback gain matrix of the converter. The necessary and sufficient condition for arbitrary pole placement of the system is that the system should be completely controllable and it will be very much simpler to find the state feedback gain matrix when the state equations are in the controllable canonical form (JONG et al., 2009).

Pole Placement Technique is an effective one through which it is possible to stabilize a completely controllable system by arbitrarily choosing the closed loop poles. The main objective is to place the closed loop poles arbitrarily in z-plane of the buck converter in such a way that y(k) tracks any of the references r(k), which is considered as a step function in this case. The control scheme with digital state feedback is shown in Figure 2.

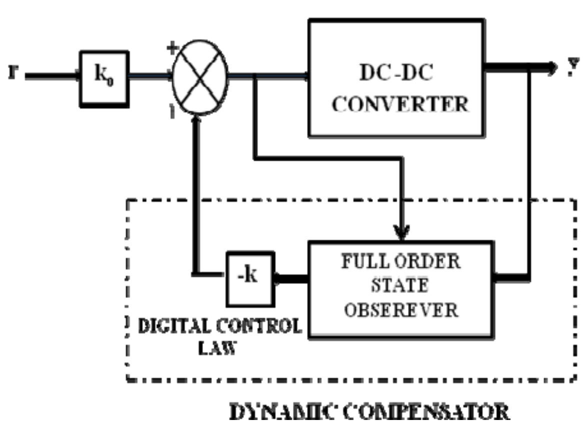

Figure 2. Control scheme with digital state feedback matrix.

Here k_o represents the adjustable gain.

For the state equations under analysis, if we assume that all the *n* state variables are accurately measured at all times, a linear control law may be implemented. It takes the form $u = -kx(k)$ for the discrete time systems. The dynamic equation of the discrete system with control law is defined as

$$\dot{x}(k) = (G - Hk)x(k) \quad (16)$$

With the necessary and sufficient condition that the system should be completely state controllable, if all the Eigen values of (G-Hk) are placed in the left half plane, the closed loop system thus considered is 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,

$$\text{Settling time} \approx \frac{4}{\zeta\omega_n} \leq 1ms$$
$$\text{Maximum peak overshoot} \approx 100e^{-\zeta\pi\sqrt{1-\zeta^2}} \leq 1\% \quad (17)$$

$$|z| = e^{-T\zeta\omega_n}$$
$$< z = \frac{2\pi\omega_d}{\omega_s} \quad (18)$$
$$\text{Sampling Time} \approx 1 \times 10^{-6} s$$

where:

ζ is the damping ratio and ω_n is the natural frequency of oscillation of the system.

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

$$\Delta = z^2 + 2\zeta\omega_{n^z} + \omega_n^z \quad (19)$$

The state feedback gain matrix is designed as k_1 = 1079 and k_2 = 861.

Figure 3 shows the step response tracked by the converter and hence the required dynamics are achieved for the given time domain specifications.

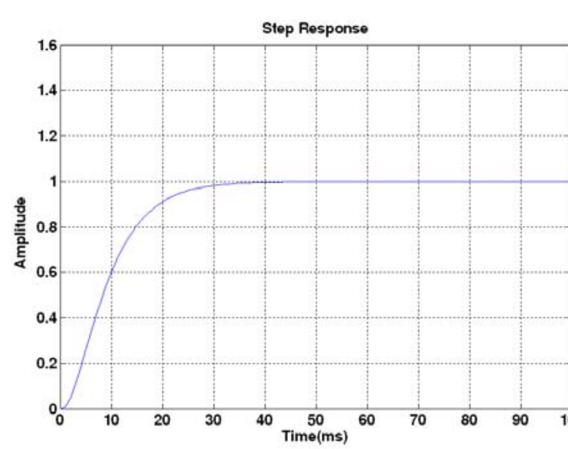

Figure 3. Step response of the Buck Converter.

Design and implementation of full order prediction observer controller

The control law thus designed is based on the assumption that all the state variables are available for feedback. Since all the states cannot be measured at all times, an estimation scheme employing full order observer is designed to replace the true states by their estimates in the control law. If the measurement of the portion of the states is given, then all the state variables may be reconstructed by the Prediction Observer. The dynamic equation describing the state estimation is defined as,

$$\hat{x}(k+1) = G\hat{x}(k) + Hu(k) + m(y(k) - C_d\hat{x}(k)) \quad (20)$$

where:

$\hat{x}$ is the estimate and m is an n x 1 real constant gain matrix. It is called Prediction Observer since the estimate $\hat{x}(k+1)$ is one sampling period ahead of the measurement y(k).The difference equation describing the behavior of the error is defined as

$$\tilde{x}(k+1) = (G - mC_d)\hat{x}(k) \quad (21)$$

where:

$\tilde{x} = x - \hat{x}$. The characteristic equation of the error is defined as

$$|zI - (G - mC_d)| = 0 \quad (22)$$

The desired characteristic equation is assumed as,

$$(z-\alpha_1)(z-\alpha_2)\ldots\ \ldots(z-\alpha_n) = 0 \quad (23)$$

The dynamic compensation may thus be provided to the discrete system under consideration by implementing the state feedback control law using an estimated state vector, thereby completing the design of Observer controller with the help of Separation Principle. The equation describing the Prediction Observer Controller is obtained by including the state feedback control in the Observer equation and is given by

$$\hat{x}(k+1) = (G - Hk - mC_d)\hat{x}(k) + my(k) \quad (24)$$

$$u(k) = -k\hat{x}(k) \quad (25)$$

The required elements of *m* are obtained by matching the coefficients of the equations (23) and (24).

The Prediction Observer Controller thus designed for the Buck converter is given by

$$G(z) = \frac{1772Z - 1637}{Z^2 - 1.118Z + 0.4533} \quad (26)$$

Thus, by Separation Principle, the digital control law and the state observer may be designed separately and yet used together to provide a robust dynamic compensation for the second order system under consideration.

Simulation results

The design and performance of Buck Converter is accomplished in continuous conduction mode 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 rise time, settling time, maximum peak overshoot and steady state error which are obtained as 0.005 s, 0.01 s, 0% and 0V. It is evident that the output voltage settles down at 0.01 s with a rise time of 0.005 s. No overshoots or undershoots are evident and the steady state error observed for load variations is very much less than 5%. The results thus obtained are in concurrence with the mathematical calculations. The simulation is also carried out by varying the load not limiting to R load. It is illustrated in Table 1.

It is evident from Table 1 that the controller tracks the reference voltage inspite of load variations. When the load resistance is varied as 1.44Ω, 2Ω and 5Ω, the Prediction Observer is efficient enough to track the output Voltages as 12, 12.10 and 12.44 V respectively for the reference Voltage of about 12 V. Again when the inductance of 10 and 100 μH are added to the load resistance of 1.44 and 14.4 Ω, the output voltage thus obtained is 12.5 and 12.6 V respectively. The steady state error thus observed is 4 and 5% respectively. The simulation is also carried out again using RLE load with a resistance of 2 Ω, inductance of 100 μH and an ideal dc voltage source of 6 V. Converter response is such that the controller is capable to work under all the load transients, thereby tracking the voltage as 12.01 V.

Table 1. Output Response for Load Variations.

BuckConverter				
R (Ω)	L (μH)	E (V)	Reference Voltage (V)	Output Voltage (V)
1.44	-	-	12	12.00
2	-	-	12	12.10
5	-	-	12	12.44
1.44	10e-6	-	12	12.50
14.4	100e-6	-	12	12.60
2	100e-6	6	12	12.01

Simulation is also carried out by varying the input voltage and the corresponding input voltage, output voltage, error, inductor current and load current are shown in Figure 4.

The input Voltage is first set as 44 V until 0.025 s and then varied from 44 to 46 V and again at 0.05 s, 46 V is varied to 48 V. The corresponding output response of the Buck converter shows tight output regulation. Undershoots and overshoots are not seen and the steady state error is also not apparent.

The error signal which is the difference between the output voltage and the reference voltage is almost zero and hence the controller is very much emphatic in tracking exactly the reference voltage of 12 V. The inductor current and the load current is also shown in the Figure 4, with no evidence of ripples.

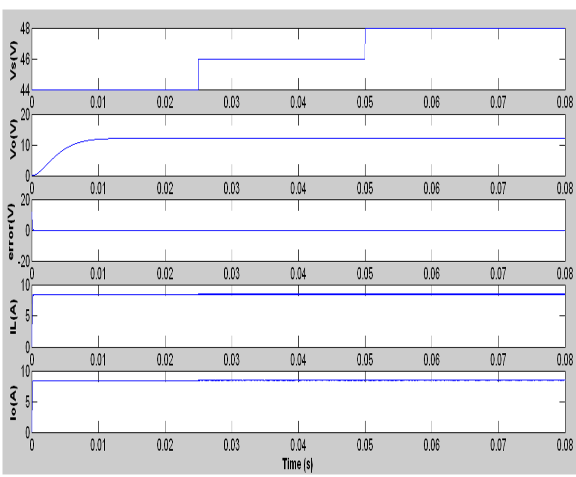

Figure 4. Output Response of the Buck Converter (Vs – Input Voltage, Vo – Output Voltage, IL – Inductor Current, Io – Load Current).

Hardware implementation

LabVIEW Package: The Buck converter with Observer Controller has been implemented using LabVIEW as a controller platform. LabVIEW (Laboratory Virtual Instrumentation Engineering Work Bench) is a system design platform and development environment for a visual programming language from National Instruments. It is a widely used software to implement the projects with a shorter duration, due to its programming flexibility combined with built-in tools designed especially for testing, measurements and control. The key feature of LabVIEW is that it extensively supports accessing the instrumentation hardware. It is provided with drivers and abstraction layers for almost all types of instruments. The buses are also available for inclusion. The abstraction layers and drivers act as graphical nodes and enable to communicate effectively with the hardware devices, thereby offering standard software interfaces (LEE et al., 2006).

The front panel shown in Figure 5 is mainly used for user interactions. It is through the front panel the desired transfer function of the observer controller is entered and the corresponding parameters of the controlled process and hence the updated status of the system are obtained.

The block diagram, data acquisition, transfer function and signal generation are built using the functional block diagram as shown in Figure 6.

Interfacing circuit: The NI DAQ Pad-6009 multifunction data acquisition (DAQ) devices provide plug and play connectivity via USB for acquiring, generating and data logging in a variety of portable applications. It is comprised of 8 analog inputs with referenced single ended signal coupling or 4 inputs with differential coupling, 2 analog outputs, 12 bits A/D and D/A converters and 32 bits counters.

There are 12 channels of digital input/output lines which may be used either as input or output. It eventually provides an excellent platform for the proposed observer controller. The prototype model of the Buck converter with Observer controller is shown in Figures 7 and 8, whilst Figure 9 shows the input voltage.

It is understood that the Observer controller works well and the LabVIEW provides the most feasible solution for the controller platform. To evaluate the performance, the reference values of 5 and 8 V are set so that output is obtained as 5.02 and 7.98 V respectively. The output obtained with 5 V reference value is illustrated in Figure 10. The steady state error thus observed is minimal, or rather, 0.02V, and the system settles down fast.

The acquisition of the error signal from the hardware takes place instantaneous as and when the program is run and at the same time the controlled signal from the LabVIEW package is also generated within a very short duration of time without any delay or time lag.

The experimental results thus obtained are in concurrence with the simulation results and mathematical calculations. Prototype model is developed using the following values: V_S = 10 V, V_O = 5 V, f_S = 20 kHz, L = 15 mH, C = 1 μF and R = 20 Ω.

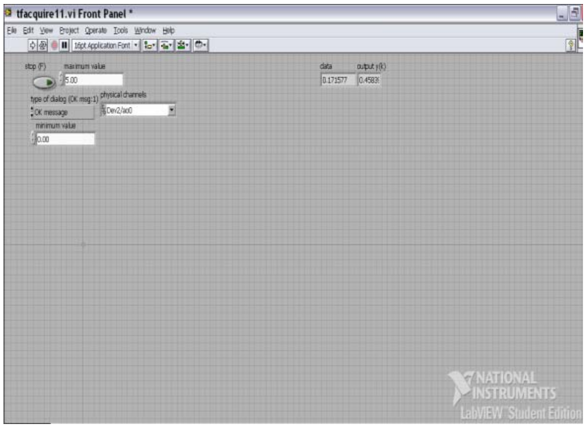

Figure 5. Front panel.

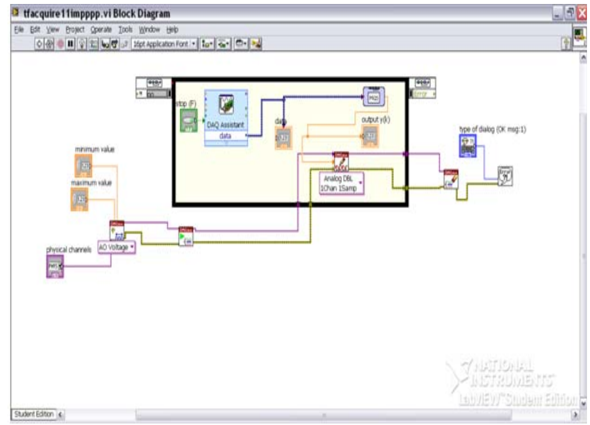

Figure 6. Block diagram.

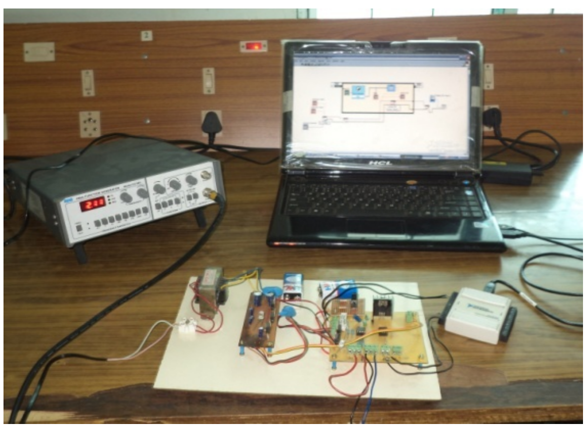

Figure 7. Experimental set up.

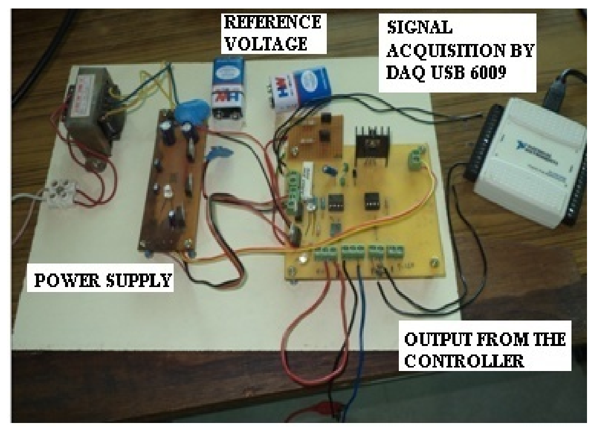

Figure 8. Indication of the set up.

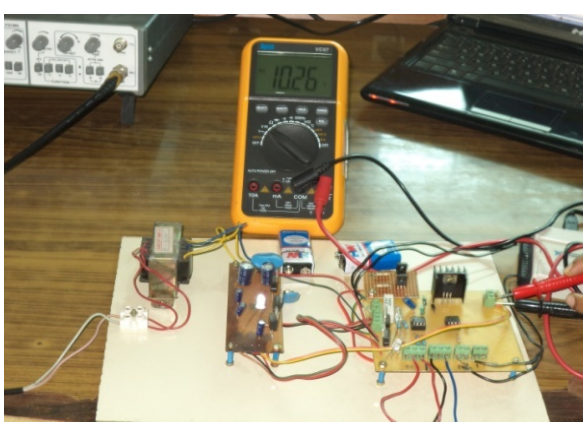

Figure 9. Input voltage.

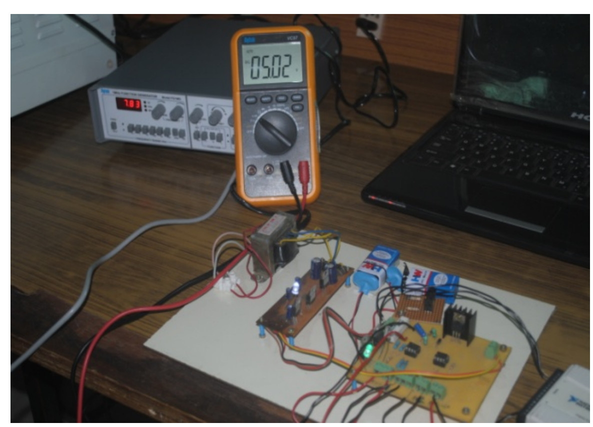

Figure 10. Output voltage obtained for the reference of 5V.

Conclusion

A state feedback control approach has been designed for the Buck converter in discrete time domain using pole placement technique and Separation Principle. The load estimator has been designed by deriving full order state prediction observer to ensure robust control for the converter.

The design is evaluated using LabVIEW as a control platform and the results are illustrated. The mathematical analysis, simulation study and the experimental study show that the Buck converter with Prediction Observer controller thus designed achieves tight output voltage regulation and good dynamic performances and higher efficiency.

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