Turkish Journal of Electrical Engineering and Computer Sciences

Volume 22 | Number 2 Article 8

1-1-2014

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SHENBAGA LAKSHMI

SREE RENGA RAJA

Recommended Citation

LAKSHMI, SHENBAGA and RAJA, SREE RENGA (2014) "Observer-based controller for current mode control of an interleaved boost converter," *Turkish Journal of Electrical Engineering and Computer Sciences*: Vol. 22: No. 2, Article 8. https://doi.org/10.3906/elk-1201-97
Available at: https://journals.tubitak.gov.tr/elektrik/vol22/iss2/8

Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2014) 22: 341 – 352

doi:10.3906/elk-1201-97

Observer-based controller for current mode control of an interleaved boost converter

Shenbaga LAKSHMI[1,*], **Sree Renga RAJA**[2]
[1]Department of Electrical and Electronics Engineering, TRP Engineering College (SRM Group) Tiruchirappalli, Tamil Nadu, India
[2]Department of Electrical and Electronics Engineering, Anna University of Technology, Tiruchirapalli, Tamil Nadu, India

Received: 27.01.2012 • **Accepted:** 01.12.2012 • **Published Online:** 17.01.2014 • **Printed:** 14.02.2014

Abstract: A state feedback control method for an interleaved boost power converter is designed, which, in turn, can achieve interleaved current sharing among parallel-connected converters. The state feedback control in the continuous time domain is derived using the pole placement technique and linear quadratic optimal method. The load estimator is designed by deriving a full-order state observer to ensure the robustness and optimality of the state feedback control and an observer-based controller (control law plus full-order state observer) is designed using the separation principle. The adopted control strategies achieve effective output voltage regulation, good dynamic stability, and reject disturbances. Extensive simulation is carried out and the results are illustrated.

Key words: Control law, full-order state observer, interleaved boost converter, pole placement, Riccati matrix, separation principle

1. 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 photovoltaic arrays. Among the basic DC-DC converters, boost converters are more significant and have several advantages, such as simple construction, step-up conversion ratio, and higher efficiency and performance. In high-power applications, it is often required to associate converters in series or in parallel due to the unavailability of a single device to withstand the voltage stress or current stress. In particular, for higher current ratings, an interleaved boost converter is the best choice, since a fraction of the input current flows through the switches [1].

Interleaved boost converters consist of N-paralleled boost converters. The main advantages are: 1) the input current ripple is reduced, 2) the inductor size is reduced, 3) the current rating of the semiconductors are reduced, 4) good current sharing is achieved among the converter modules, 5) the I^2R losses and inductor AC losses are reduced, 6) easier system maintenance and expansion is obtained, and g) increased system reliability is achieved. The main challenge in the field of power electronics is emphasized more in the control aspects of the DC-DC converters. The control approach requires effective modeling and a thorough analysis of the converters. In conventional design approaches, control problems are more complex and topology-dependent [2].

Many studies have been developed for the control of interleaved boost converters. Some of them are discussed here. A digital state feedback control using the pole placement technique was proposed for a

*Correspondence: lakshmi_amrith@yahoomail.com

synchronous buck-boost converter in [3]. This paper mainly focused on the current sharing among the converter modules during the transition from one mode to another mode. It did not show the performance parameters of the converters in terms of the output voltage, settling time, rise time, maximum peak overshoot, or any undershoots.

The stabilization of input series and output parallel-connected converters were discussed in [4]. This method uses a single outer loop to generate a reference. It is quite disadvantageous when compared with a 2-loop system, and especially when it is employed for boost converters, lots of disturbances will be generated.

The modeling and control of a DC-DC multilevel boost converter using the differential geometry theory was proposed in [5], where a state feedback matrix was derived to achieve stability using both reduced-order and full-order models. Improved performances were obtained but the unmeasurable variables were not taken into consideration. In practice, all of the variables that are assumed cannot be measured; hence, there is a need for deriving a load estimator, which performs estimation in terms of the unmeasurable variables, thereby minimizing the error. Load estimation is done particularly to ensure the robustness of the state feedback control.

The observer controller for 3 basic buck, boost, and buck-boost converter topologies was proposed using the passivity-based nonlinear design in [6]. The obtained output showed overshoots and undershoots that were undesirable.

Many of the conventional control methods employing current loops use peak current mode control, which is highly detrimental due to its higher noise sensitivity. In general, a small value of precision resistor is required for current sensing. This may produce noise, thereby leading to the false firing of the power transistor when it is employed in the converters for practical applications. In many industrial applications, a decrease in the sensor number is more important. A cost-effective sensor is required. A feasible solution is obtained using a well-known observer control.

The control of DC-DC converters is mainly aimed at obtaining the desired output voltage regulation. The typical control strategy that is used in many applications is current mode control. In current mode control, 2 control loops are provided. The outer loop is slower, in which the output voltage is compared with a reference signal, which in turn forms a reference to the inner loop. The inner loop is much faster, which forces the inductor current to reach the reference value, provided by the outer voltage loop. This control approach is mainly used in boost converters, which suffer from an undesirable nonminimum phase response [7]. This undesirable effect is suppressed by including the inductor current and the output voltage signal y, which enters in the performance index [8].

The control aspect in implementing the interleaved boost converter mainly focuses on 2 major drawbacks: 1) when operating in continuous conduction mode current, unbalances due to intrinsic device parameter variations occur, which is quite critical; and 2) there is complexity in the circuit. This paper is aimed at presenting a feasible solution for the above-mentioned control problems existing in interleaved boost converters. The control approach is based on deriving a control law defined as $u = -kx(t)$, where k is the state feedback matrix and x(t) is the state vector. The proposed observer controller is designed in 2 steps:

(i) The appropriate observer poles are chosen and the controller is designed by combining the state feedback matrix and observer poles using the separation principle. The main advantage of this principle is that the designs of the state feedback matrix and the observer can be carried out independently, and when both are used concurrently, the roots remain unchanged.

(ii) The state feedback matrix is optimized by deriving the Riccati matrix, and using the same observer poles chosen in step 1, a linear quadratic optimal regulator (LQR) is designed.

The designed observer controller for the interleaved boost converter results in excellent output voltage regulation, improved dynamic response, robustness, rejection of disturbances, high efficiency with much less settling time (in the range of milliseconds), and good current sharing among the converter modules.

2. Modeling of the interleaved boost converter

The schematic diagram of the interleaved boost converter is shown in Figure 1, where Vg is the input voltage, L_1 and L_2 are magnetizing inductances, S_1 and S_2 are semiconductor switches, D_1 and D_2 are diodes, C is an output capacitor, and R is a load resistance.

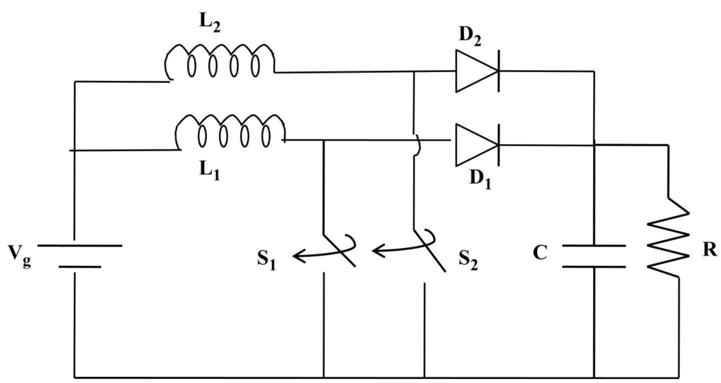

Figure 1. Schematic diagram of the interleaved boost converter.

The converter is modeled using the state-space averaging method, which is highly significant for this kind of converter since pulse-width modulation (PWM) converters are a special type of nonlinear system, which is switched in between 2 or more nonlinear circuits depending upon the duty ratios. Furthermore, the control signals include not only the independent voltages and currents, but also the duty ratios [9].

As a general case, the state space averaging method for 2 switched basic PWM converters is discussed now. The inductance currents and capacitance voltages are state variables and the matrix form of the equation is as follows:

$$\dot{X} = A_1 x + B_1 u, \tag{1}$$

$$\dot{X} = A_2 x + B_2 u, \tag{2}$$

where x is a state variable vector, u is a source vector, and A_1, B_1, A_2, and B_2 are the system matrices. The significance of the state space averaging technique lies in replacing the above 2 sets of state equations with a single equivalent set, described as follows:

$$\dot{X} = Ax + Bu. \tag{3}$$

The A and B matrices are the weighted averages of the actual matrices describing the switched system, given by the following equations:

$$A \equiv dA_1 + (1-d)A_2, \tag{4}$$

$$B \equiv dB_1 + (1-d)B_2, \tag{5}$$

where d is the duty cycle ratio. Based on the above discussion, the state model of the interleaved boost converter is derived and is discussed now.

The mode of operation is assumed as a continuous conduction mode, in which only a part of the energy is delivered to the load. In recent studies, the continuous current mode was mainly considered, since higher power densities are possible only with this mode of operation. However, the main disadvantage in going for the continuous current mode of operation is the inherent stability problems caused due to the right-half plane zero in the converter transfer function. This can easily be solved by the proposed pole placement technique.

During the continuous conduction mode of operation, diodes D_1 and D_2 are always in a complementary state with switches S_1 and S_2, respectively; that is, when S_1 is on, D_1 is off, and vice versa. Similarly, when S_2 is on, D_2 is off, and vice versa. Accordingly, 4 modes of switching states are possible and the corresponding state equations are explained as follows:

Mode 1: S_1 and S_2 are on:

$$\dot{X} = A_1 x + B_1 V_g, \tag{6}$$

$$x = \begin{bmatrix} i_1 \\ i_2 \\ V_C \end{bmatrix}, \tag{7}$$

where i_1 and i_2 are currents flowing through inductances L_1 and L_2, respectively, and V_C is the capacitance voltage.

Mode 2: S_1 is on and S_2 is off:

$$\dot{X} = A_2 x + B_2 V_g. \tag{8}$$

Mode 3: S_1 is off and S_2 is on:

$$\dot{X} = A_3 x + B_3 V_g. \tag{9}$$

Mode 4: S_1 and S_2 are off:

$$\dot{X} = A_4 x + B_4 V_g, \tag{10}$$

where:

$$A_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix}, \tag{11}$$

$$A_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{L_1} \\ 0 & \frac{1}{C} & \frac{-1}{RC} \end{bmatrix}, \tag{12}$$

$$A_3 = \begin{bmatrix} 0 & 0 & \frac{-1}{L_1} \\ 0 & 0 & 0 \\ \frac{1}{C} & 0 & \frac{-1}{RC} \end{bmatrix}, \tag{13}$$

$$A_4 = \begin{bmatrix} 0 & 0 & \frac{-1}{L_1} \\ 0 & 0 & \frac{-1}{L_2} \\ \frac{1}{C} & \frac{1}{C} & \frac{-1}{RC} \end{bmatrix}, \tag{14}$$

$$B_1 = B_2 = B_3 = B_4 = \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix}. \tag{15}$$

The average state model takes the form described as follows:

$$\dot{X} = [\ A\ ][\ X\ ] + [\ B\ ][\ U\ ], \tag{16}$$

where $\left[\begin{array}{c} A \end{array} \right] = A_1 d_1 + A_2 d_2 + A_3 d_3 + A_4 d_4$, $\left[\begin{array}{c} B \end{array} \right] = B_1 d_1 + B_2 d_2 + B_3 d_3 + B_4 d_4$, and $\left[\begin{array}{c} U \end{array} \right] = V_g$, and the duty cycle ratio is given by $d_1 + d_2 + d_3 + d_4 = 1$ [10]. The output equation is defined as follows:

$$y = \left[\begin{array}{ccc} 0 & 0 & 1 \end{array} \right] \left[\begin{array}{c} i_1 \\ i_2 \\ V_C \end{array} \right]. \tag{17}$$

3. Robust design of the state feedback matrix

3.1. Pole placement technique

The robust design comprises the derivation of the state feedback gain matrix based on a control law defined as $u = -kx(t)$ for the converter under consideration. The required steady-state value of the controlled output variable y is a constant reference input r, which is taken as the unit step input. The design is carried out using the values shown in Table 1. The root locus of an interleaved boost converter is drawn, from which the desired closed-loop poles are chosen. The poles are arbitrarily placed in the s-plane in such a way that the output variable y tracks any of the references r, which is considered as a step function in this case.

Table 1. Circuit parameters of an interleaved boost converter.

No.	Circuit parameters	Values
1	Switching frequency	20 kHz
2	Input voltage	24 V
3	Inductance L_1	72 μH
4	Inductance L_2	72 μH
5	Capacitance C	217 μF
6	Load resistance	23 Ω

The necessary condition for arbitrary pole placement is that the system should be completely state controllable. When all of the state variables are assumed to be accurately measured at all times, then the implementation of a linear control law is possible, which is defined as $u = -kx\,(t)$ With this state feedback control law, the state equations of the system under consideration take the following form:

$$\dot{x(t)} = (A - Bk)\, x(t). \tag{18}$$

Now, the system under consideration is of the third order and the desired poles can be easily placed by assuming the following converter specifications:

$$Settling\, time \approx \frac{4}{\zeta\omega_n} < 1ms$$

$$Maximum\, Peak\, Overshoot \approx 100e^{-\zeta\pi\sqrt{1-\zeta^2}} \leq 1\%. \tag{19}$$

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

$$\Delta\ = s^2 + 2\zeta\omega_n s + \omega_n^2. \tag{20}$$

The third root is considered as at least 6 times the value of $(-\zeta\omega_n)$. The control scheme for the interleaved boost converter is shown in Figure 2.

Here, N represents the scalar feedforward gain. As is evident from Figure 3, the designed state feedback gain matrix tracks the reference step input very well, which proves that the system is completely stable.

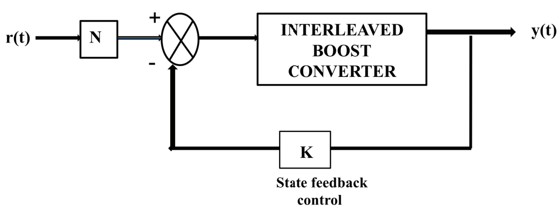

Figure 2. Control scheme for the continuous time system.

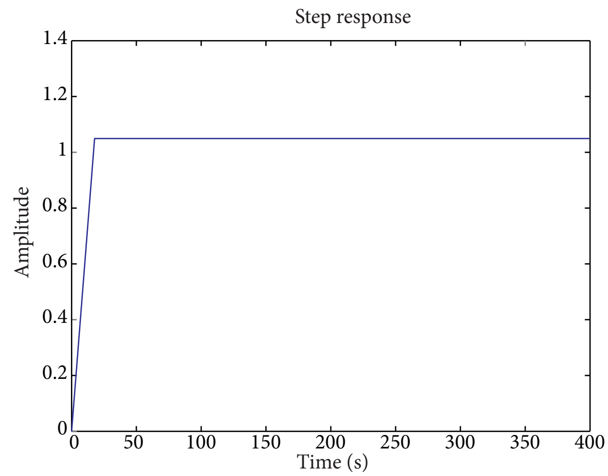

Figure 3. Step response of the interleaved boost converter with state feedback control.

3.2. LQR method

It is necessary to determine the state feedback gain matrix optimally in order to obtain tight output regulation and it is highly insensitive to system parameter variations or external disturbances. The optimal solution is obtained by choosing the appropriate performance index. The desired closed-loop poles can be chosen such that the poles are closer to the desired locations by the linear optimal control theory. The designed optimal controller diminishes the sensitivity to plant parameter deviations. The optimal regulator problems determine the state feedback matrix k for obtaining the optimal control law given by $u(t) = -kx(t)$.

The main objective is to minimize the performance index, which is defined as follows:

$$J = \frac{1}{2}\int_{0}^{\infty} \left(x^T * Qx + u^T * Ru\right) dt. \tag{21}$$

Here, Q and R are the positive definite Hermitian symmetric matrix. The design of the control scheme is carried out in the following 2 steps:

1. The positive definite Riccati matrix P is determined, which should satisfy the reduced Riccati matrix equation given by:

$$A^T * P + PA - PBR^{-1}B^T * P + Q = 0. \tag{22}$$

   For the appropriate P value, (A – Bk) should be asymptotically stable.

2. Substitution of the Riccati matrix in the equation described below results in the optimal k value.

$$k = -R^{-1}B^T * P \tag{23}$$

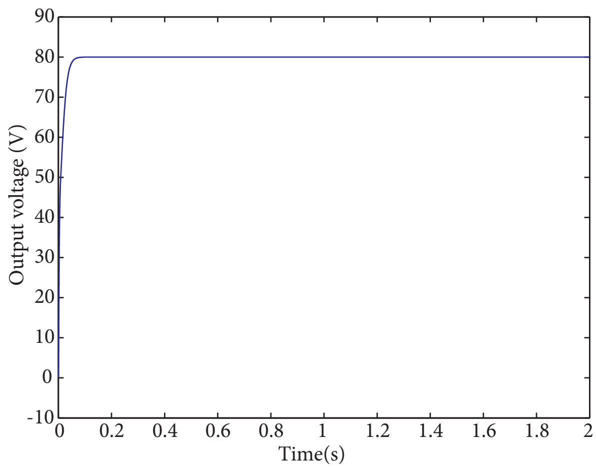

Figure 4. Output of the interleaved boost converter with the full-order observer controller.

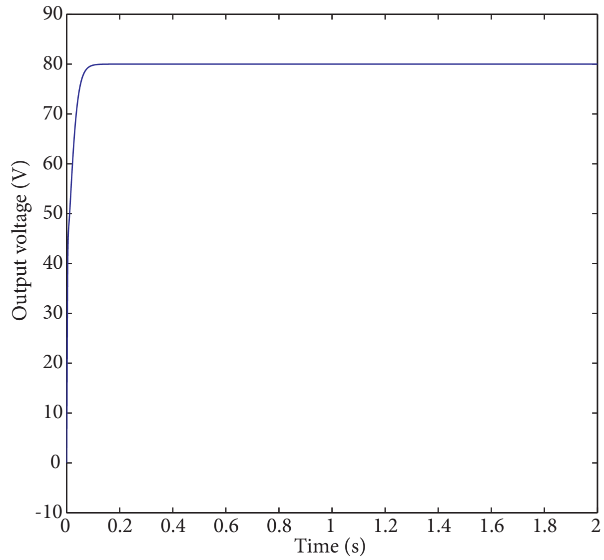

Figure 5. Output of the interleaved boost converter with the LQR.

4. Design and implementation of the full-order observer controller

The observer is designed using the same pole placement technique, mainly to estimate the unmeasurable variables. It is desirable that the response of the observer should be faster than the response of the system, since the observer tends to act upon the error of the system. The necessary condition for the observer design is that the system should be completely state-controllable. By rule of thumb, the desired observer locations are made with the following assumption:

The natural frequency of oscillation (observer controller) is approximately equal to 2–5 times that of the natural frequency of oscillation of the system. Now, the dynamic equation of the system with a full-order state observer takes the following form:

$$\dot{x}\,(t) = (A - Bk)\,x\,(t) + \; Bk_1, \tag{24}$$

where k_1 is the element of the state feedback gain matrix and r is the step input. The dynamic equation describing the state observer (continuous time system) takes the following form:

$$\tilde{x}\,(t) = (A - k_e C)\,\tilde{x} + Bu\,(t) + k_e y(t), \tag{25}$$

where k_e is the observer gain matrix [11].

Now, the transfer function of the observer controller (control law plus full-order observer) obtained by the pole placement method is as follows:

$$\frac{-U(s)}{Y(s)} = \frac{2.496 \times 10^7 s^2 - 2.174 \times 10^{10} s + 632}{s^3 + 1.204 \times 10^6 s^2 + 2.63 \times 10^{11} s - 6.657}. \tag{26}$$

The output voltage obtained for the interleaved boost converter with the observer controller is shown in Figure 4. It is evident that the settling time is much lower (in the range of milliseconds), no overshoots or undershoots are seen, and the steady-state error is 0.

The transfer function obtained for the interleaved boost converter with the LQR (optimal control law plus full-order observer) is as follows:

$$\frac{-U(s)}{Y(s)} = \frac{2.459 \times 10^{7}s^{2} - 1.567 \times 10^{10}s + 255.6}{s^{3} + 1.203 \times 10^{6}s^{2} + 2.626 \times 10^{11}s + 2.65}. \tag{27}$$

It is obvious from Figure 5 that the output voltage obtained for the converter shows good dynamic performance without steady-state error and undershoots or overshoots, and it settles down much faster.

5. Simulation results and discussion

The design and performance of the interleaved boost converter is 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 2. The obtained results are in concurrence with the mathematical calculations. The simulation is also carried out by varying the load, not limiting it to R load, and this is illustrated in Table 3. The simulation is also carried out by varying the input voltage, and the corresponding output voltage, inductor currents, and load currents are shown in Figures 6 and 7 for the pole placement and LQR methods, respectively. The input voltage is changed to ±2 V with respect to the input 24-V DC supply. From time 0 s to 0.4 s, the input voltage is maintained at 24 V, and at 0.4 s, it is changed to 22 V, until 0.8 s, where the input voltage remains at 22 V. The voltage is also changed to 24 V and 26 V at 0.8 s and 1.2 s, respectively. Despite such variations, the controller is robust and efficient enough to track the reference of 75 V for both of the methods, as is evident from Figures 6 and 7. The overshoots and undershoots are seen, which are very minimum, of the order of 2%. Inductors L1 and L2 have good current sharing between them. The current shows very reduced ripples.

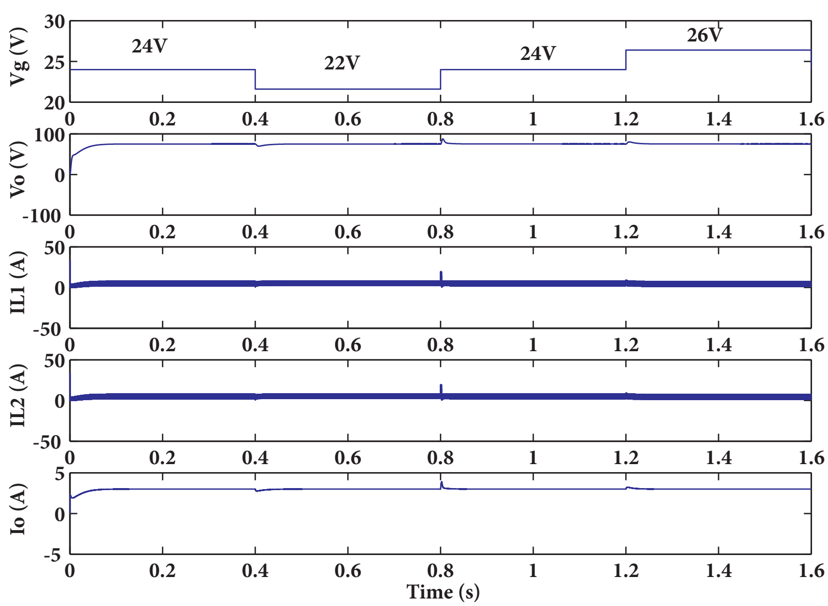

Figure 6. Output responses with the input voltage variations (pole placement method): input voltage (Vg), output voltage (Vo), inductor current 1 (IL1), inductor current 2 (IL2), and load current (Io).

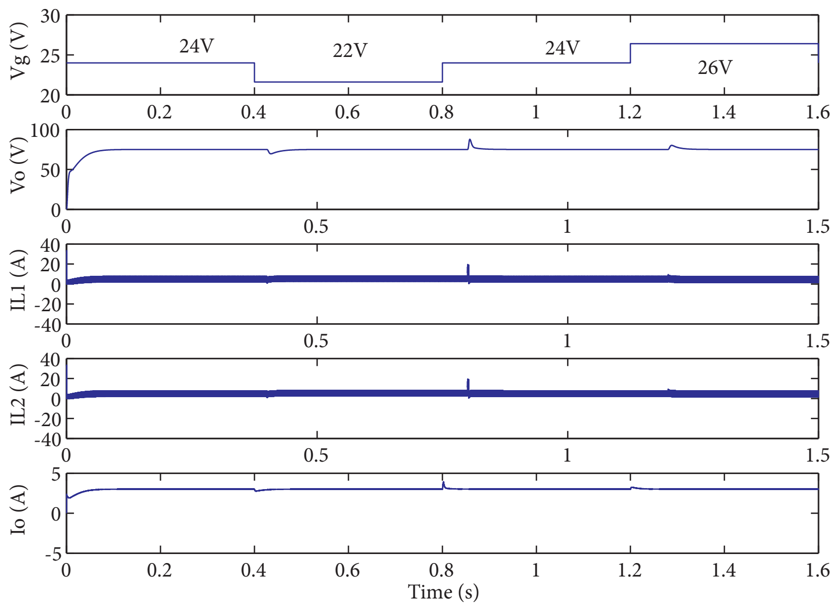

Figure 7. Output responses with the input voltage variations (LQR method) : input voltage (Vg), output voltage (Vo), inductor current 1 (IL1), inductor current 2 (IL2), and load current (Io).

Table 2. Comparison of the performance parameters of the interleaved boost converter.

No.	Controller	Settling time (s)	Peak overshoot (%)	Steady-state error (V)	Rise time (s)	Output ripple voltage (V)
1	Observer controller	0.15	0	0	0.075	0
2	Linear quadratic optimal regulator	0.005	0	0	0.001	0

Table 3. Output response of the interleaved boost converter for the load variations.

R (Ω)	L (mH)	E (V)	Reference Voltage (V)	Output Voltage (V)
10	-	-	60	60
15	-	-	60	60
23	-	-	60	60
10	50	-	60	60
15	100	-	60	60
23	100	-	60	60
30	50	5	60	60
23	100	10	60	60
15	100	15	60	60
10	100	20	60	60

In order for the dynamic performance to be ensured, both methods show tight output regulation with much less settling time and no steady-state errors without any undershoots or overshoots, which is illustrated in Figure 8 for a particular value of input voltage, 24 V. It is evident that the optimal solution for the obtained control law shows improved results when compared with the pole placement method in terms of the performance specifications, as listed in Table 2.

Simulations are carried out in 2 modes. In mode 1, the inductances are chosen as $L_1 = L_2$, and in mode 2, the inductances are chosen as $L_2 = 2L_1$. The added advantage is that the efficiency is higher even with high input to output ratios. From Table 4 it is very well understood that the control scheme offers robust control and good current sharing among the converters. Figure 9 shows the efficiency as a function of output load current and it is seen that the state feedback control method achieves higher efficiency for a wide range of load variations; the maximum efficiency achieved is 95.63% at a 176-W load condition.

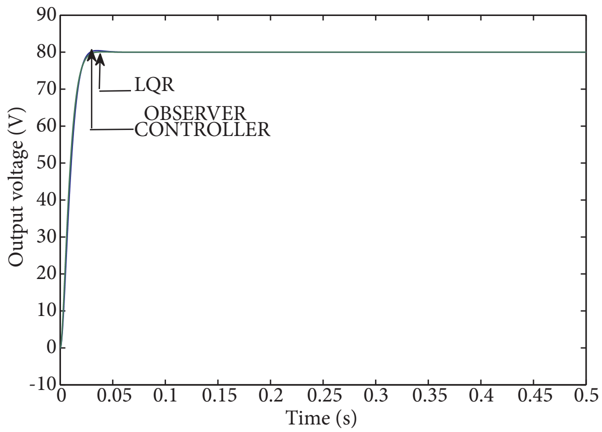

Figure 8. Comparison of the observer controller with the LQR.

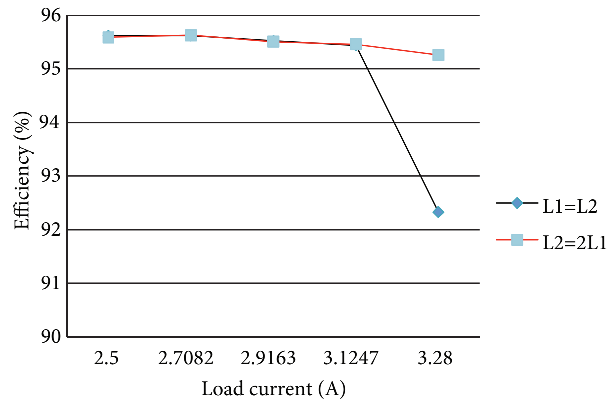

Figure 9. Efficiency of the interleaved boost converter.

The inductor currents and corresponding duty cycle ratios are shown in the Figures 10 and 11 for modes 1 and 2, respectively. It is evident from the current waveforms that the controller provides effective current sharing among the converter modules, irrespective of the values of the inductances.

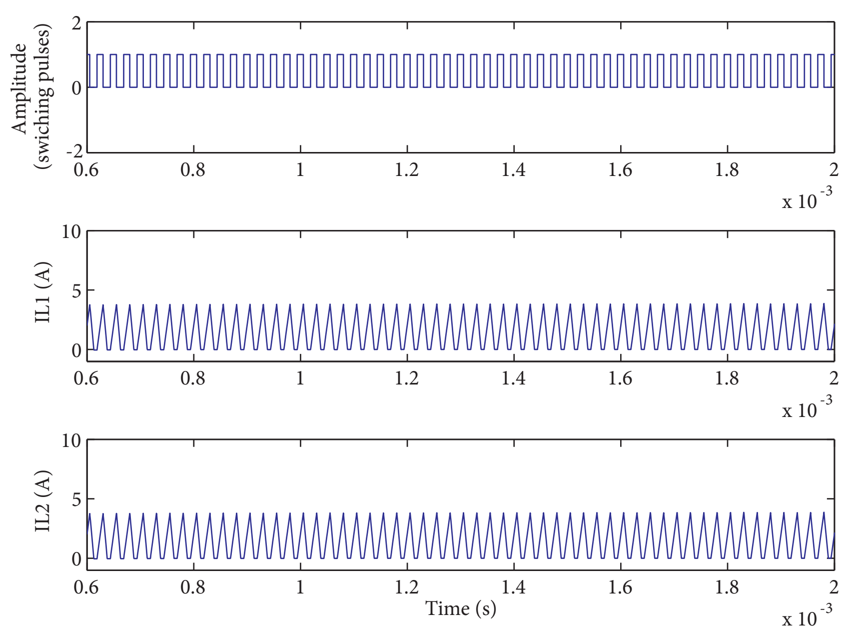

Figure 10. Inductor currents and duty ratio for mode 1.

Table 4. Performance calculations of the converter with the proposed control scheme.

Sl No.	Mode	Vref (V)	Vout (V)	I_L (A)	Iin (A)	Vin (V)	Pin (W)	Pout (W)	Efficiency (%)
1	1	60	60	2.5	6.5360	24	156.8640	150	95.62
	2			2.499	6.5360	24	156.864	149.94	95.59
2	1	65	65	2.708	7.6700	24	184.08	176.024	95.62
	2			2.708	7.6735	24	184.164	176.112	95.63
3	1	70	70	2.916	8.9034	24	213.6816	204.115	95.52
	2			2.916	8.9050	24	213.7200	204.129	95.51
4	1	75	75	3.124	10.23	24	245.52	234.33	95.44
	2			3.124	10.229	24	245.5008	234.345	95.46
5	1	80	80	3.28	11.652	24	279.648	258.202	92.33
	2			3.332	11.651	24	279.622	266.373	95.26

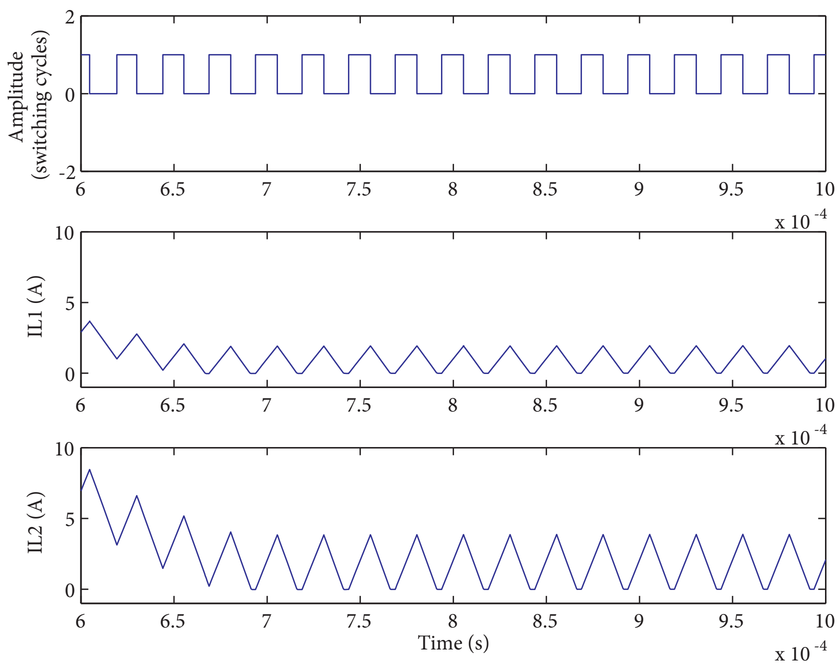

Figure 11. Inductor currents and duty ratio for mode 2.

6. Conclusion

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

References

[1] J.R. Pinheiro, H.A. Grundling, D.L.R. Vidor, J.E. Baggio, "Control strategy of an interleaved boost power factor correction converter", Power Electronics Specialist Conference, Vol. 1, pp. 137–142, 1999.

[2] H.F.F. Leung, K.S.P. Tam, C.K. Li, "The control of switching DC-DC converters - a general LQR problem", IEEE Transactions on Industrial Electronics, Vol. 38, pp. 65–71, 1991.

[3] H.S. Bae, J.H. Yang, J.H. Lee, B.H. Cho, "Digital state feedback current control using the pole placement technique", Journal of Power Electronics, Vol. 7, pp. 213–221, 2007.

[4] W.J. Kimball, T.J. Mossoba, T.P. Krein, "A stabilizing, high-performance controller for input series-output parallel converters", IEEE Transactions on Power Electronics, Vol. 23, pp. 1416–1427, 2008.

[5] J.C. Mayo-Maldonado, R. Salas-Cabrera, H. Cisneros-Villegas, M. Gomez-Garcia, E.N. Salas-Cabrera, R. Castillo-Gutierrez, O. Ruiz-Martinez, "Modeling and control of a DC-DC multilevel boost converter", Proceedings of the World Congress on Engineering and Computer Science, Vol. 2, 2010.

[6] N. Gonzalez-Fonseca, J. De Leon-Morales, J. Leyva-Ramos, "Observer-based controller for switch mode DC-DC converters", Proceedings of the 44th IEEE Conference on Decision and Control and European Control Conference, pp. 4773–4777, 2005.

[7] C.K. Tse, M. Di Bernardo, "Complex behavior in switching power converters", Proceedings of the IEEE, Vol. 90, pp. 768–781, 2002.

[8] S. Mariethoz, S. Almer, M. Baja, A.G. Beccuti, D. Patino, A. Wernrud, J. Buisson, H. Cormerais, H. Fujioka, T. Geyer, U.T. Jonsson, C.Y. Kao, M. Morari, G. Papafotiou, P. Riedinger, "Comparison of hybrid control techniques for buck and boost DC-DC converters", IEEE Transactions on Control Systems Technology, Vol. 18, pp. 1126–1145, 2010.

[9] R.D. Middlebrook, "Small-signal modeling of pulse-width modulated switched-mode power converters", Proceedings of the IEEE, Vol. 76, pp. 343–354, 1988.

[10] C. Sudhakarababu, M. Veerachary, "DSP based control of interleaved boost converter", Journal of Power Electronics, Vol. 5, pp. 180–189, 2005.

[11] M. Gopal, Digital Control and State Variables Methods Conventional and Intelligent Control Systems, New York, McGraw Hill, 2009.