Design of Robust H_2 controller of DC-DC SEPIC converter

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***Abstract*: This paper presents an optimal design of robust H_2 controller for DC-DC single ended primary inductance converter (SEPIC) operating in continuous conduction mode (CCM). The converter is modelled using state space averaging method and the closed loop system is obtained by properly tuning the weight function of proposed H_2 controller and implemented using Matlab/Simulink software. To study the performance of the proposed H_2 controller the closed loop parameter under step change in the input voltage is analyzed with the presence of uncertain noise in the output end of the converter. The steady state and transient performance of the proposed controller is compared with the conventional Z-N tuned Proportional–Integral (PI) controller. The results obtained reveals that the steady state performances such as IAE and ISE, and the transient performances such as settling time, rise time, peak overshoot and steady state error are greatly reduced for the proposed robust controller compared to the conventional Z-N tuned PI controller. Moreover, the stability of the proffered converter with H_2 controller is analyzed using Nyquist method of stability.**

Keywords: SEPIC converter; continuous conduction mode; H_2 control; Nyquist Stability.

I. INTRODUCTION

The single-ended primary-inductor converter (SEPIC) is a DC-DC converter, most widely used for various applications namely power factor correction, renewable energy power generation like photovoltaic system, DC motor and LED lighting. Moreover, the converter possess the following advantages namely reduced output voltage ripple, high efficiency, high transfer gain, low input current ripple and operates in continuous conduction mode [1]. Many researchers work on topology to reduce the stress in the components, in [1] author proposes the parallel – operated SEPIC converters for sharing the load using coupled inductor and in [2] a non-isolated bidirectional soft switching based SEPIC/ZETA converter were used to reduce the ripples in the output current. In addition, various topologies such as non-isolated, isolated and partially isolated topology for multiport converters were used for renewable power applications [3].

On the other side, researchers are also focusing on modelling and control of converters which enhances the performance of converter such as efficiency, voltage regulations by operating the converter in closed loop with proper design of controllers under various conditions. The controller improves the stability, robustness, dynamic and chaos behaviour, faster response in presence of disturbances and wide range of operating points [4]. The SEPIC converter with fuzzy logic controller [5-6], fuzzy tuned PI controller [6], neural network based PI controller [7] and modified PID controller [8] were used for improving the dynamic performance of the converter and in [6] a small signal model of converter were developed to design the LQR controller for improving the performance and reducing the sensitivity to disturbances and the results were compared with the conventional PID controller. Moreover, DC-DC converters offer solution to improve the power quality of the three phase by improving the power factor of the system [9]. Furthermore, DC-DC converters namely buck, boost, buck-boost, cuk, fly back and SEPIC converters are most widely used in renewable power generation like PV generation to improve the performance of the panel [7]. A robust control strategy were developed using sliding mode controller for effective tracking control of drives [10]. Robust H_2 control methods were used to stabilize the plant or process not only for its nominal parameter values, but also if the system parameters varies with the worst case of disturbance and offers the advantages of low overshoot, short settling time and disturbance rejection [11]. The design of robust H_2 controller for DC-DC boost converter was designed for nominal and uncertain parameter value in [12].

This paper proposes the design of robust H2 controller for a DC-DC SEPIC converter operating in continuous conduction mode (CCM) for effective set point tracking even in the presence of uncertainties. The paper is organized as follows: Section II describes the mathematical analysis of SEPIC converter with design parameter calculations. Section III presents the design of conventional and robust H_2 control techniques are represented. Section IV discusses about the simulation results of proposed controller with conventional PI controller. Finally, the conclusion is made in Section V.

II. MATHEMATICAL ANALYSIS OF SEPIC CONVERTER

A DC-DC SEPIC converter is a traditional buck-boost converter which operates in a continuous conduction mode (CCM) by proper turning on of MOSFET switch. It exchanges the energy from capacitor to inductor and vice versa to convert from one form of voltage to other form. The converter operates in two modes of operation: ON-state and OFF-state mode.

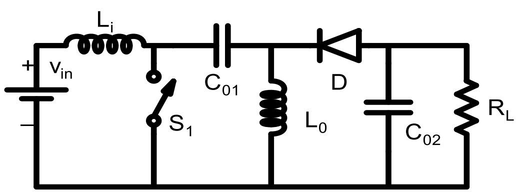

Fig.1. SEPIC converter

A. ON-state

Fig.2. depicts the ON state mode (S=1) of the converter with input voltage Vi supplying the inductor L1 and capacitor supplying the energy L2 with diode D reverse bi-as. In this mode, the inductor L1 and L2 stores the energy and the capacitor C1 and C2 discharge the energy to inductor L2 and load R respectively.

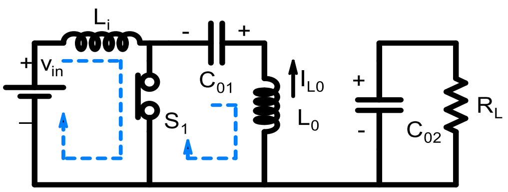

Fig.2. ON state of SEPIC converter

The on-state of converter state-space equation are given by,

State space equations:

$$\dot{X} = AX + Bu \tag{1}$$

$$Y = CX + Du \tag{2}$$

$$\begin{bmatrix} (di_{Li}/dt) \\ \left(\frac{dI_{L0}}{dt}\right) \\ \left(\frac{dV_{CT}}{dt}\right) \\ \left(\frac{dV_{C0}}{dt}\right) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_0} & 0 \\ 0 & -\frac{1}{C_T} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{RC_0} \end{bmatrix} \begin{bmatrix} i_{Li} \\ i_{L0} \\ V_{CT} \\ V_{C0} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_i} \\ 0 \\ 0 \\ 0 \end{bmatrix} [V_{in}] \tag{3}$$

B. OFF state

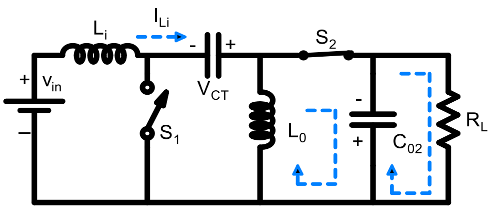

Fig.3. OFF state circuit diagram of SEPIC converter

Fig.3 depicts the off state mode of the converter. In this mode, the capacitor C1 charges by inductor L1 and which in turn charges L2 during the on-mode, both L1 and L2 delivers power to load in this mode and whose state-space equations are given by

$$\begin{bmatrix} (di_{Li}/dt) \\ \left(\frac{dI_{L0}}{dt}\right) \\ (dV_{CT}/dt) \\ (dV_{C0}/dt) \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1/L_i & -1/L_i \\ 0 & 0 & 0 & -1/L_i \\ 1/C_T & 0 & 0 & 0 \\ 1/C_0 & 1/C_0 & 0 & -1/RC_0 \end{bmatrix} \begin{bmatrix} i_{Li} \\ i_{L0} \\ V_{CT} \\ V_{C0} \end{bmatrix} + \begin{bmatrix} 1/L_i \\ 0 \\ 0 \\ 0 \end{bmatrix} [V_{in}] \tag{4}$$

Output equation:

$$Y = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{Li} \\ i_{L0} \\ V_{CT} \\ V_{C0} \end{bmatrix} + u\begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

Here A_1, B_1 represents the state matrix, input matrix for the switch in ON condition and A_2, B_2 represents the state matrix, input matrix for the switch in OFF condition. Using the equations (1) - (5) and by applying the following formulas, the state matrix (A), input matrix (B), output matrix(C) are computed.

$$A = A_1 d + A_2 (1-d) \tag{6}$$

$$B = B_1 d + B_2 (1-d) \tag{7}$$

$$C = C_1 d + C_2 (1-d) \tag{8}$$

C. Design Parameters Of Converter

The converter operating in the CCM is designed with the design parameters as follows: switching frequency f_s is 100 kHz, Inductor L_1 and L_2 is 30mH, Capacitors C_1 is 150μF and C_2 is 50μF, load resistance R is 100Ω, duty ratio d is 0.8, Input voltage V_{in} is 100V. The state space equation parameters A, B, C and D are obtained by substituting the design parameters in equation (3) and (4)

$$A = \begin{bmatrix} 0 & 0 & -17 & -17 \\ 0 & 0 & 17 & -17 \\ 3333 & 10000 & 0 & 0 \\ 10000 & 10000 & 0 & -200 \end{bmatrix} \tag{9}$$

$$B = \begin{bmatrix} 33.33 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{10}$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

$$D = 0 \tag{12}$$

The transfer function of the converter is given by

$$TF = C[sI - A]^{-1}B + D \tag{13}$$

The output transfer function G(s) of the proposed system is

$$G(s) = \left\{\frac{3.333e5s^2+7.407e10}{s^4+200s^3+5.556e5s^2+4.444e7s+7.407e10}\right\} \tag{14}$$

III. CONTROL STRATEGY

This section presents the design of controller for DC-DC SEPIC converter to regulate the output voltage and effective set point tracking of the output voltage with presence of disturbances. This section discuss about proposed H_2 controller and the conventional Z-N method of tuning of PI controller.

A. *Z-N tuned PI controller*

A PI controller was used to regulate the output voltage sensed by the sensor and compared with the reference set voltage using the comparator. The error output from the comparator are processed by the PI controller tuned based Ziegler–Nichols method of tuning with the ultimate gain Kcr = 2.1903 and ultimate period Pcr = 9.5e-03 secs. By this technique, the values of K_p and K_i are found to be 0.986 and 368.9 respectively. The parameters in Table 1 are K_p is proportional gain, K_i is integral gain, T_i is reset time $=K_p/K_i$, K_d is the derivative gain and T_d is rate time or derivative time.

B. *H_2 controller*

This section describes the design of H2 controller for DC-DC SEPIC converter and whose generalised standard form is shown in Fig.4. In Fig.4 G represents the plant transfer function, K is the controller, w is the external input, z is the error signal, u is the control input and y represents the observed output [11].

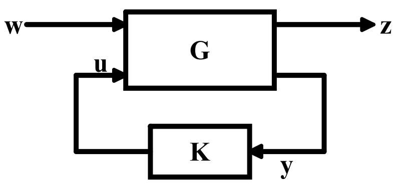

Fig.4 Generalized form of H_2 controller

The augmented system model P(s) for designing the optimal H_2 controller F(s) is given by

$$P(s) = \begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix} \tag{15}$$

The augmented state space of the system is given below,

$$\dot{x}(t) = A\dot{x}(t) + B_1 w(t) + B_2 u(t) \tag{16}$$

$$z(t) = C_1 x(t) + D_{12} u(t) \tag{17}$$

$$y(t) = C_2 x(t) + D_{21} w(t) + D_{22} u(t) \tag{18}$$

Such that the H_2-norm of the linear fractional transformation $T_{y1u1}(s)$,

$$\left\|T_{y1u1}(s)\right\|_2 = \|P_{12}(s) + P_{12}(s)[I - F(s)P_{22}(s)]^{-1} F(s) P_{21}(s)\|_2 < 1 \quad . \tag{19}$$

The H_2-norm for a SISO system can be expressed as

$$\min_{F(s)} \left\|T_{y1u1}\right\|_2 = \min_{F(s)} \sqrt{\frac{1}{\pi}\int_0^{\infty} T_{y1u1}(-j\omega) T_{y1u1}(j\omega) d\omega} \tag{20}$$

The above equation (20) is simplified and can be represented as below

$$\|H\|_{H_2} = \sqrt{tr\int_0^{\infty} h^T(t)h(t)dt} = \sqrt{\frac{1}{2\pi} tr \int_{-\infty}^{\infty} H(j\omega) H^T(-j\omega) d\omega} \tag{21}$$

The H_2 controller (K) for the proposed DC-DC SEPIC converter is designed using the Fig.5

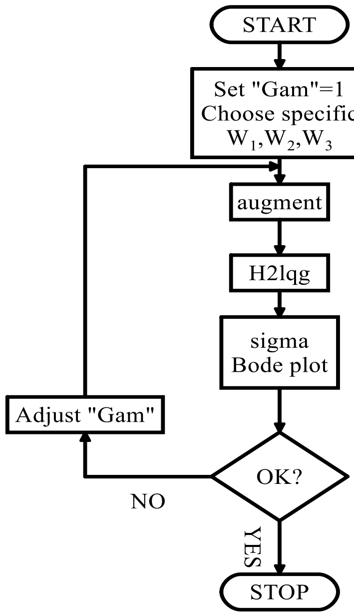

Fig.5. Flowchart for tuning of H_2 controller

The weight transfer function for optimal designing of controller is given by

$$W_1 = \frac{0.140s+660}{s+0.066} \tag{22}$$

$$W_2 = 1e-05 \tag{23}$$

The H_2 optimal controller transfer function (K) is found and it is given by

$$K = \frac{6.6e07s^4 + 1.32e10s^3 + 3.227e13s^2 + 5.749e15s + 1.017e18}{s^5 + 6.563e04s^4 + 2.154e09s^3 + 3.049e10s^2 + 9.956e14s + 6.571e13} \tag{24}$$

IV. RESULTS AND DISCUSSION

The simulations were carried in Matlab/Simulink using the transfer function model of the DC-DC SEPIC converter and the controllers namely PI and H_2 controller. Moreover, this section presents the performance comparison of proposed H_2 controller with the conventional Z-N tuned PI controller for step input voltage and change in the set point voltage to validate robustness of the controller.

A. *Steady state and transient analysis*

Fig.6 shows the step response of DC-DC SEPIC converter for the reference step input voltage of 400V. It is seen that the steady state error performances like ISE and IAE are reduced for the proposed controller as shown in Table 2. Table 3 represents the transient response characteristics such as % peak overshoot, rise time and settling time of H_2 and conventional PI controller. The results reveal that the transient response characteristics are reduced for the proposed H_2 controller than the conventional Z-N tuned PI controller. Moreover, the stability analysis of the proposed H_2 and the conventional PI controller were analysed using Nyquist method of stability as shown in Figs.7 and 8. It is inferred from the plot that the encirclement of the critical point (-1, 0) ensures the closed loop stability of DC-DC SEPIC converter using H_2 and PI controller and the closed loop system poles and zeros lies in the left half of s-plane.

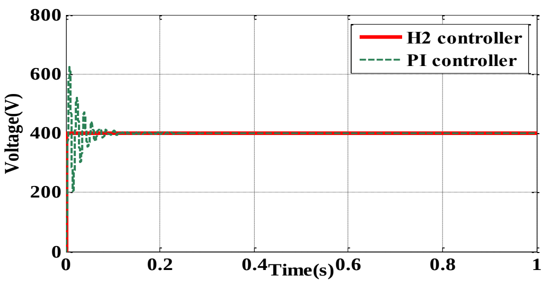

Fig.6. Controller response for step input

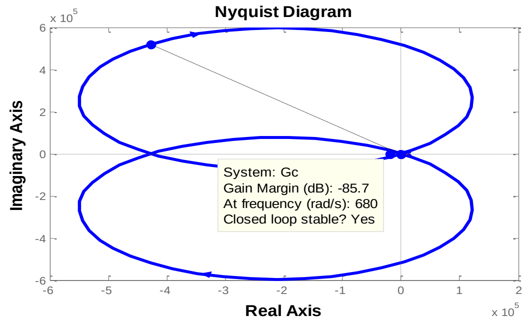

Fig.7. Nyquist plot of H_2 controller

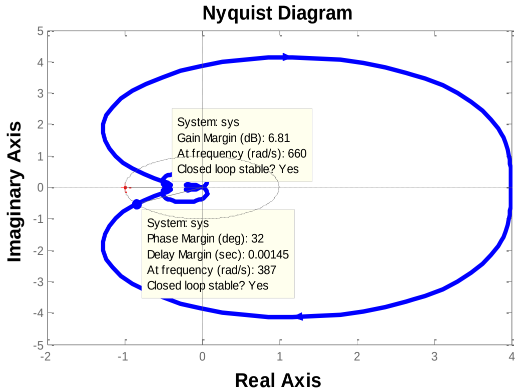

Fig.8. Nyquist plot of the PI controller

Table 1. Steady state error performance

Performance Indices	PI controller	H_2 controller
ISE	831.7	22.18
IAE	5.86	0.1627

Table 2. Transient performance

Transient Response parameters	PI controller	H_2 controller
Rise time	0.0031	4.6623e-4
Settling time	0.1037	8.6417e-4
Overshoot	56.1534	0.0047
Peak value	642.6136	400.0156

B. *Set point tracking:*

Set point tracking is the change in the operating conditions of the system such that the output is set to track the reference set voltage or trajectory. In this case, the reference set voltages are 400V, 360V, 500V and 200V for a time period of 0.5 seconds. Fig.9 and Fig.10 depicts the SEPIC converter response for change in the reference set voltage with the proposed H_2 and PI controller respectively. The results reveal that the proposed controller follows the set point voltage without any disturbance or peak overshoot/undershoot, but the conventional Z-N tuned PI controller has peak overshoot/undershoot during change in the set voltage.

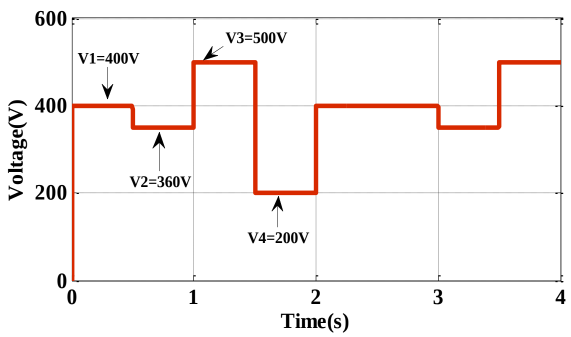

Fig.9. H_2 controller transient response for set point change

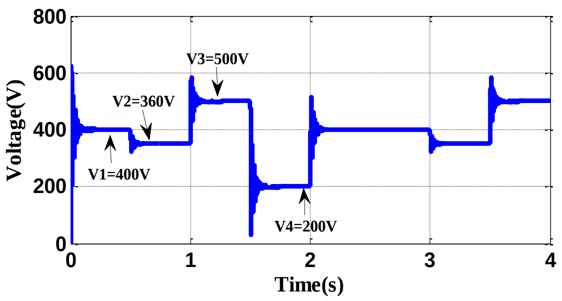

Fig.10. PID controller transient response for set point change

V. CONCLUSION

This paper has presented the design and analysis of robust H_2 controller applied to DC-DC SEPIC converter. The efficiency of the controller is validated with the effective set-point tracking for change in input voltage. Simulation results reveal that the proposed controller performance is superior to the conventional PI controller in the presence of disturbances. Moreover, the steady state performance such as IAE and ISE, and the transient response parameters such as rise time, settling time, %overshoot were greatly improved compared to the conventional Z-N tuned PI controller. The robustness of the proposed controller is validated using simulation, and the stability is made using Nyquist method of stability.

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