Modelling of Interleaved Buck Converter with Observer Controller for More Electric Aircraft Applications

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***Abstract*— More electric aircraft technology is the current emerging technology for aerospace industry and taking new face to the possibility of all electric aircraft technology. The challenge is to solve the limitations of existing system like high maintenance cost, bulkier, elevated gas emissions, etc. These can be overcome by incorporating advanced power electronic converters. Converters are needed to convert aircraft grid voltages either ac to dc or dc to dc. In this paper interleaved buck converter is implemented with observer controller for more electric aircraft applications. For high power applications it is required to combine the converters either in series or parallel and this can be achieved by using interleaved buck converter. An observer based controller is designed which diminishes the deprivation of the performances caused due to non-ideal conditions of the aircraft power system. A state feedback control is designed to attain the stability of the system and a load estimator is designed to ensure the robustness of the state feedback control. The proposed controller can withstand the conditions against parameter divergence and has higher efficiency. Extensive simulations are carried out using MATLAB/Simulink. Simulation results elucidate that the proposed converter with observer controller tracks the reference voltage irrespective of the system dynamics.**

Keywords—More Electric Aircraft; DC-DC converter; 230Vvariable frequency AC systems; Full Order State Observer; Interleaved Buck Converter; Pole Placement; Riccati Matrix; Separation Principle.

I. INTRODUCTION

With the technological development in aircraft industry during 21st century passenger density is increased to a greater extent. Environmental issues related to greenhouse gas emission in the transportation are a major threat which needs primary attention to be paid especially on aviation industry [1]. It opened the doorway for the development of environmental friendly airplanes. In addition to this another challenges to be overcome by the future aircrafts are optimized aircraft performance, lesser operating and maintenance expenses, improved transportation reliability [2].

In recent decade More Electric Aircraft (MEA) was introduced in which the conventional secondary power sources such as hydraulic, pneumatic and mechanical systems are replaced by electrical systems. MEA possesses several advantages such as better power transmission efficiency, less fuel consumption and more reliable. The recent developments in high performance power electronic converters are the primary motivation for the technology of MEA [1, 2].

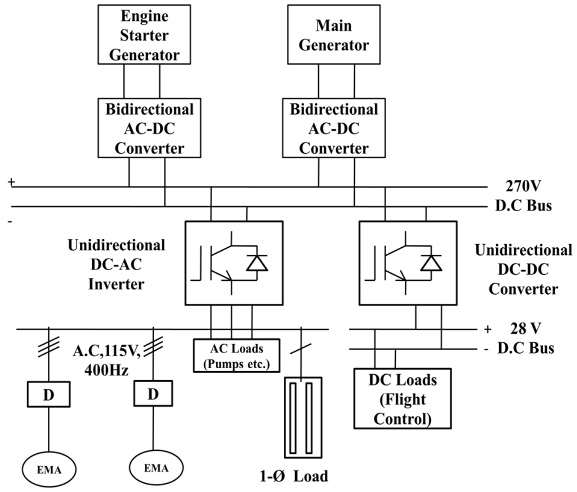

Fig. 1. Power system architechture of a More Electric Aircraft.

Aircraft electrical system standards include 115V AC at 400Hz for large loads like electro-mechanical actuators (EMA) in large civilian aircraft, 28V DC supply for small loads and also for small aircrafts and 270V DC supply for military aircraft [11, 12].

Switched mode dc-dc converters are generally proficient power electronic systems that convert an unregulated dc input voltage into a regulated dc output voltage. Switched mode power supplies on comparison with the linear power supplies are lesser in dimension, more competent and include elevated power density. Amongst the fundamental categories of dc-dc converters buck converters are extensively utilized in portable consumer electronics [3]. In high power applications, it is frequently needed to combine the converters in series or in parallel since there is no single device to resist voltage stress or current stress [10].

Interleaved buck converters comprise of N number of buck converters connected in parallel. The main benefits are: (i) current ripple at the input side is low (ii) size of the passive components employed can be reduced (iii) there will be a reduction in current rating of the switches (iv) good current sharing will exist among the two converters connected in parallel (v) there will be very less loss due to heat dissipation in the passive elements (vi) Maintaining and expanding the system for other applications are quite easy (vii) consistency of the system is very high. The major problem faced by the researchers is to control the output of the dc-dc converter for the desired output voltage regulation and its stability. The converter has to be modelled effectively and a detailed investigation has to be carried out. When the converters are designed using a conventional technique, the control system becomes further complex and it fluctuates with each topology. [13].

General dc-dc converters are time variant, non-linear dynamic systems. The non-linear characteristics of the dc-dc converters occur primarily because of power semiconductor devices and passive components. One intrinsic drawback of buck converter is its dependence on large passive components like inductors and capacitors [4]. The main objective of this work is to design a powerful closed loop system based on observer approach which overcomes the above mentioned problems. Effective time domain analysis has been carried out and the desired performance parameters of the interleaved Buck converter such as rise time, settling time, maximum peak overshoot and steady state error are met [5]. The mathematical modelling of interleaved buck converter is obtained using state space averaging technique and the observer controller is designed using pole placement technique and separation principle. MATLAB/Simulink is used to perform the simulation. The Observer Controller thus designed for the Interleaved Buck converter results in excellent output voltage regulation, improved dynamic response, robust, rejects the disturbances, highly efficient with much lesser settling time in the range of millisecond and superior current partaking amongst the interleaved sections.

This paper is organized as follows. Modelling of Interleaved Buck Converter is presented in section 2. Design of observer controller for the converter is discussed in Section 3. Simulation results for the proposed converter is discussed in Section 4, and finally the conclusions are drawn in Section 5.

II. MODELING OF INTERLEAVED BUCK CONVERTER

A. Design

The elementary structure of Interleaved Buck converter is shown in fig.1. Here the input voltage is DC, L1 and L2 are magnetizing inductances, S1 and S2 are power switches, D1 and D2 are diodes, C is an output capacitor.

B. Selection of Inductor

Designing the inductor value for the interleaved converter is very much important in order to obtain higher efficiency of the dc-dc converter system and also for the transitory response of the converter modules. The inductor is principally decided based on the value of the tolerable inductor ripple [13].

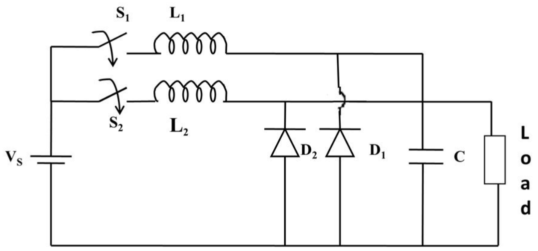

Fig. 2. Schematic Diagram of Interleaved Buck Converter.

The load current amplitude and switching frequency also play a major role in the inductor selection [6]. Hence the inductor values are designed in such a way that the inductor ripple current should be presumed a larger value as 40% of the maximum current flowing throughout the individual channel [6, 7]. As the two phases of interleaved buck converter vary in phase by 180°, the inductor current ripple in both sections of the converter rescind each other and thus permits the flow of a small current ripple through the capacitor connected across the load [7]. The output current ripple frequency is increased by two fold and consequently results in the necessity of lesser output capacitor value for similar ripple voltage requisite. During the time interval from T_{on} to T, it is assumed that the switch S_1 is in off position and the switch S_2 is in on position. Consequently inductor current in the Buck converter phase 1 decreases whereas the current in phase 2 increases in that way permitting smaller current ripple to flow through the output capacitor. The output ripple current is given by,

$$\Delta I_0 = \frac{2V_0(1-d)T}{L}\frac{|1-2d|}{|1-2d|+1} \tag{1}$$

Where ΔIo is the inductor ripple current, d is the duty cycle, T is the time period and L is the inductor. Here it is assumed as L1=L2. Substitution of the essential values in equation (1) furnishes the appropriate value of the inductor.

C. Selection of Capacitor

The exact capacitance value, the Equivalent Series Resistance (ESR) and Equivalent Series Inductance (ESL) are the main parameters that should be considered for the design of the capacitor value. It is essential to consider the above said parameters since these will adversely affect the transient response of the converter, influences the ripple voltage and also affects the stability of the system [13]. The capacitor value can be obtained by the estimating the output ripple voltage by using the following equation.

$$\Delta V_0 = \frac{\Delta I_0 T}{8mC} + \Delta I_0 \times ESR \tag{2}$$

Where m is number of phase, C is the capacitor and ΔVo is peak-peak ripple voltage on the capacitive components of C and the second term ΔI_ox ESR represents the ripple voltage developed across the ESR of the output capacitor.

The output ripple current and voltage will become zero, when the duty cycle ratio equals the critical value and it is defined as,

$$d_{critical} = \frac{i}{m}, i = 1,2,\cdots\cdots m-1 \tag{3}$$

Accordingly after assuming appropriate values for the peak to peak ripple voltage, the capacitor value can be obtained by substituting in the equation (2).

D. Modelling of the Proposed Converter

The converter is modelled using state space averaging method. State space averaging method is highly preferred method of the interleaved Buck converter since it is basically a time variant ,non-linear system. Moreover it mainly depends on the duty cycle ratio for switching in between either on or off non linear states. In addition to that the duty cycle ratio is included in the control structure.

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

$$\left.\begin{aligned} \dot{X} &= A_1x + B_1u \\ \dot{X} &= A_2x + B_2u \end{aligned}\right\} \tag{4}$$

Where x is a state variable vector, u is a source vector, A1, B1, A2, B2 are the system matrices respectively [9]. The importance of this technique reclines in reinstating the above mentioned state equations by a single equivalent set described as follows,

$$\dot{X} = Ax + Bu \tag{5}$$

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

$$\left.\begin{aligned} A &\equiv dA_1 + (1-d)A_2 \\ B &\equiv dB_1 + (1-d)B_2 \end{aligned}\right\} \tag{6}$$

Where d is the duty cycle ratio. Based on the above discussion, state model of Interleaved Buck converter is derived and is discussed now.

Mode of operation is assumed as continuous conduction mode in which, only a part of the energy is delivered to the load. In recent researches, continuous current mode is mainly considered since higher power densities are possible only with this mode of operation. But the main disadvantage in going for continuous current mode of operation is the inherent stability problems caused due to the right-half plane zero in converter transfer function. This can easily be solved by the proposed pole placement technique [10].

Fig. 2 represents the schematic diagram of interleaved buck converter. During continuous conduction mode of operation , diodes D1 and D2 are always in complementary state with the switches S1 and S2 respectively, that is when S1 is on, D1 is off and vice versa. Similarly when S2 is on, D2 is off and vice versa. Accordingly four modes of switching states are possible and corresponding state equations are explained as follows:

Mode1: S1 and S2 are on

$$\dot{X} = A_1x + B_1V_g \tag{7}$$

$$x = \begin{bmatrix} i_1 \\ i_2 \\ V_C \end{bmatrix} \tag{8}$$

Where i1 and i2 are currents flowing through the inductances L1 and L2 respectively and VC is the capacitance voltage.

Mode 2: S1 is on and S2 is off

$$\dot{X} = A_2x + B_2V_g \tag{9}$$

Mode 3: S1 is off and S2 is on

$$\dot{X} = A_3x + B_3V_g \tag{10}$$

Mode 4: S1 and S2 are off

$$\dot{X} = A_4x + B_4V_g \tag{11}$$

Where,

$$A_1 = A_2 = A_3 = A_4 = \begin{bmatrix} 0 & 0 & \frac{-1}{L_1} \\ 0 & 0 & \frac{-1}{L_2} \\ \frac{1}{C} & \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \tag{12}$$

$$B_1 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix} \tag{13}$$

$$B_2 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix} \tag{14}$$

$$B_3 = \begin{bmatrix} 0 \\ \frac{1}{L_2} \\ 0 \end{bmatrix} \tag{15}$$

$$B_4 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{16}$$

The average state model takes the form described as follows:

$$\dot{X} = [A][X] + [B][U] \tag{17}$$

Where,

$$[A] = A_1d_1 + A_2d_2 + A_3d_3 + A_4d_4$$

$$[B] = B_1d_1 + B_2d_2 + B_3d_3 + B_4d_4$$

and the duty cycle ratio is given by

$$d_1 + d_2 + d_3 + d_4 = 1.$$

The output equation is defined as follows,

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ V_C \end{bmatrix} \tag{18}$$

The design of observer controller for the proposed converter is discussed in the following section.

III. OBSERVER CONTROLLER

Design of observer controller includes two steps such as the design of state feedback matrix and an observer gain matrix. The ultimate aim in designing the state feedback matrix is to make the converter to track the reference voltage and to attain a steady state value of the controlled reference variable. The root locus of an Interleaved Buck converter is drawn from which the desired closed loop poles are chosen. The necessary condition for arbitrary pole placement is that the system should be completely state controllable [8, 9]. When all the state variables are assumed to be accurately measured at all times, then implementation of a linear control law is achievable which is described as u=-$kx(t)$. With this state feedback control law, state equations of the system will take the following form:

$$\dot{x}(t) = (A - Bk)x(t) \tag{19}$$

Now the system under discussion is of third order and the desired poles can be effortlessly located by assuming the following converter specifications,

$$\left.\begin{aligned} Settlingtime &\approx \frac{4}{\zeta\omega_n} \leq 1ms \\ MaximumPeakOvershoot &\approx 100e^{-\zeta\,\Pi\sqrt{1-\zeta^2}} \leq 1 \end{aligned}\right\} \tag{20}$$

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

$$\Delta = s^2 + 2\zeta\omega_n s + \omega_n^2 \tag{21}$$

The third root is considered as at least six times the value of $(-\zeta\omega_n)$ Eigen values in general are assumed as σ1, σ 2, σ 3…. σ n. For Continuous time systems, the desired characteristic equation is defined as follows,

$$s^n + \xi_1 s^{n-1} + \ldots + \xi_{n-1}s + \xi_n = 0 \tag{22}$$

Thus the characteristic equation of the system along with state feedback matrix, k is given by,

$$\left| sI - T^{-1}AT + T^{-1}BkT \right| = 0 \tag{23}$$

Where Tm is the transformation matrix defined as,

$$T_m = MW \tag{24}$$

Where M is the controllability matrix given by,

$$M = \left[B \;\vdots\; AB \;\vdots\; \cdots \;\vdots\; A^{n-1}B \right] \tag{25}$$

$$\text{and } W = \begin{bmatrix} a_{n-1} & a_{n-2} & \cdots 1 \\ a_{n-2} & a_{n-3} & \cdots 0 \\ \vdots & \vdots & \vdots \end{bmatrix} \tag{26}$$

The equation (22) takes the same form as that of the characteristic equation of the system, when u=-kx is used as a control signal. Further simplification in the controllable canonical form the characteristic equation of the system attains the form as described as follows:

$$s^n + (a_1 + \delta_1)s^{n-1} + \cdots + (a_{n-1} + \delta_{n-1})s + (a_n + \delta_n) = 0 \tag{27}$$

By equating the like powers of s we can attain the state feedback matrix which acquires the following form;

$$k = [\delta_n \delta_{n-1} \ldots \delta_1]T^{-1} \tag{28}$$

The observer is designed using 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. Based on the thumb rule the appropriate observer design can be made by the assuming the following: Natural frequency of oscillation (Observer Controller) ≈ 2 to 5 times that of the Natural frequency of oscillation of the system. Now, dynamic equation of the system with full order state observer takes the following form,

$$\dot{x}(t) = (A - Bk)x(t) + Bk_1 \tag{29}$$

where k1 is the element of state feedback gain matrix and r is the step input. The dynamic equation describing state observer (continuous time system) takes the following form,

$$\tilde{x}(t) = (A - k_e C)\tilde{x} + Bu(t) + k_e y(t) \tag{30}$$

where k_e is observer gain matrix.

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

$$\frac{-U(s)}{Y(s)} = \frac{-3.827\times10^{7}\,s^2 - 1.609\times10^{13}s - 6219}{s^3 + 2.824\times10^{6}s^2 + 5.336\times10^{12}s - 254.2} \tag{31}$$

The validity of designed observer controller and interleaved buck converter is tested with simulation study which is explained in the following section.

IV. SIMMULATION STUDY

In this section, the specifications of the circuit model are discussed. Subsequently, the design parameters are calculated for the given specifications. The simulation model prepared in MATLAB/Simulink is shown in Fig. 3.

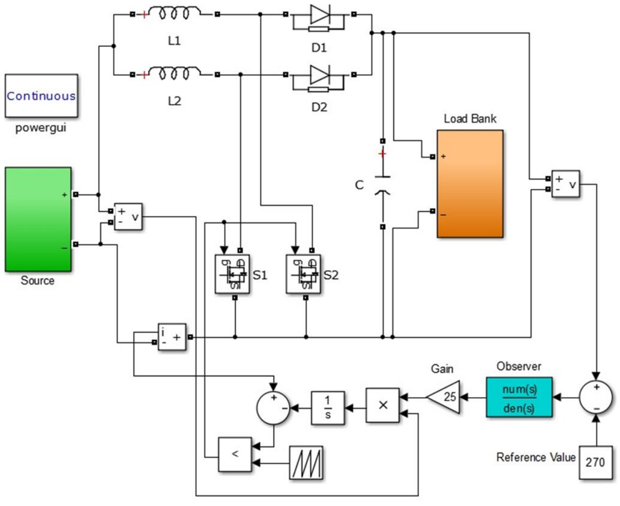

Fig. 3. Simulation Circuit of Interleaved Buck Converter.

The simulation results of the converter are illustrated to show the performance of the proposed converter with observer controller.

A. *Specifications of the Proposed Converter*

It is considered that the aircraft generator is producing a voltage of 230V with 10% variation in magnitude and variable frequency in the range of 360 to 800Hz. It is required to convert this into constant 270V DC for HVDC bus and 28V DC for small loads. One more requirement is that these voltages should not fluctuate with variation in load connected.

B. *Design Values of the Proposed Converter*

From the specifications considered above the values of various components used in converter configuration are calculated from the design part discussed in the previous sections. Table. I represent the design values for the proposed converter.

TABLE I. DESIGN VALUES OF THE PROPOSED CONVERTER

Design Parameters	
Inductances, L1=L2	720.288 µH
Capacitance, C	86.77 µF
Switching Frequency, f_s	100KHz

C. *Results*

Based on the design parameters shown in Table I, the proposed converter is simulated in MATLAB/Simulink. Extensive simulation has been done and the results thus obtained are shown in Fig. 4.

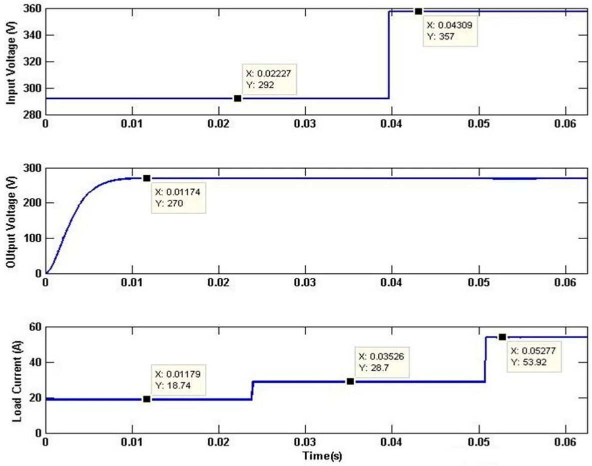

Fig. 4. Waveforms of input voltage, load current with variations and constant output voltage for 270V reference.

The Interleaved Buck converter performance parameters under consideration are rise time, settling time, maximum peak overshoot and steady state error which are shown in Table II. It is obvious that the Interleaved Buck converter with Observer controller designed using pole placement technique settles down at 0.01 s with a rise time of 0.006 s.The peak overshoot is of 1.4% which very well lies in the appreciable range. There are no output voltage ripples. In both the cases the steady state error is very minimum. The results thus obtained are in concurrence with the mathematical calculations. The simulation is also carried out by varying the load not limiting to resistive load and it is illustrated in Table II. The converter is robust enough to track the desired reference voltage irrespective of the load variations.

TABLE II. PERFORMANCE PARAMETERS OF THR CONVERTER

Performance Parameters	
Settling Time (s)	0.01
Peak Overshoot (%)	1.4
Steady State Error(V)	0.35
Rise Time (s)	0.006
Output Ripple Voltage(V)	0

The simulation is carried out by varying the input voltage and load resistance simultaneously and the corresponding output voltage, inductor currents and load currents are observed and is shown in the Fig. 2 where the reference voltage is set as 270 V. The input voltage is set as 292V till 0.04s and it is varied as 357V and correspondingly the load resistance is varied as 14 Ω, 10 Ω and 5 Ω respectively at 0 s, 0.03 s and 0.06 s. The simulation is again repeated by setting the reference as 28V and the response is obtained for both input voltage and load variations and is illustrated in Fig. 3.

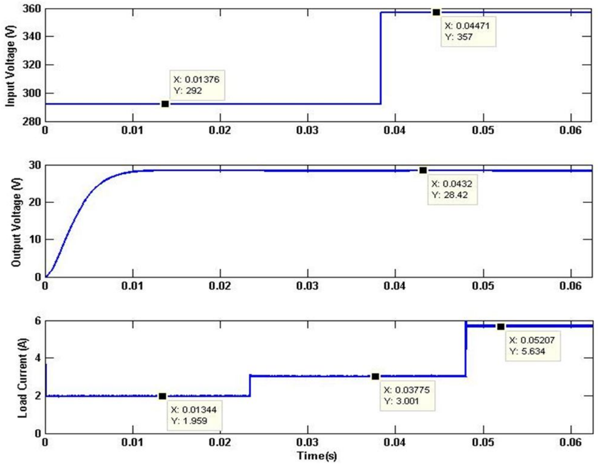

Fig. 5. Waveforms of input voltage, load current with variations and constant output voltage for 28V reference.

TABLE III. OUTPUT RESPONSE OF THE CONVERTER

Load Current (A)	**Reference Voltage (V)**	**Output Voltage (V)**
18.74	270	270.00
28.70	270	270.08
53.94	270	270.15
2.002	28	28.20
3.057	28	28.42
5.634	28	28.48

In spite of these input as well as load transients the interleaved buck converter with observer controller is capable of tracking the output voltage for the reference of about 270V and 28V which is very much essential for the MEA. It is also obvious that the parallel connected converters have good current sharing among them and the load current shows lesser ripple. This ensures the robustness of the controller. The inductor currents and corresponding duty cycle ratios are shown in the Fig. 6.

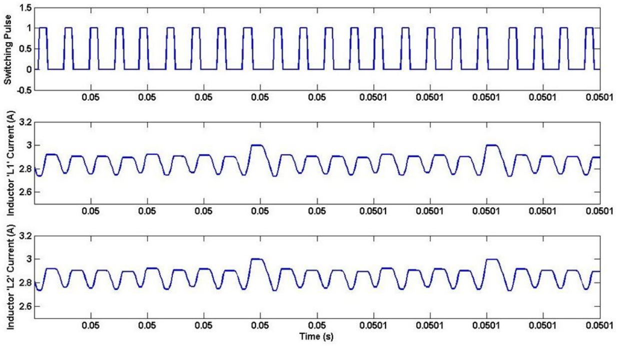

Fig. 6. Waveforms of inductor currents in relation to switching pulse.

It is evident from the current waveforms that the controller provides an effective current sharing among the converter modules irrespective of the value of the inductance.

V. CONCLUSIONS

A state feedback control approach has been designed for the Interleaved Buck converter in continuous time domain using pole placement technique for MEA. The load estimator has been designed by deriving full order state observer to guarantee robust and finest 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 simple root locus technique. The mathematical analysis and the simulation study shows that the controller thus designed achieves good current sharing among the converters, tight output voltage regulation and good dynamic performances and higher efficiency.

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