

Simulation of DC-DC Converter-Fed BLDC Motor Drive for PFC using PI-Fuzzy Methods

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Abstract: *This paper presents a power factor corrected (PFC) bridgeless (BL) buck–boost converter-fed brushless direct current (BLDC) motor drive as a cost-effective solution for low-power applications. An approach of speed control of the BLDC motor by controlling the dc link voltage of the voltage source inverter (VSI) is used with a single voltage sensor. This facilitates the operation of VSI at fundamental frequency switching by using the electronic commutation of the BLDC motor which offers reduced switching losses. A BL configuration of the buck–boost converter is proposed which offers the elimination of the diode bridge rectifier, thus reducing the conduction losses associated with it. A PFC BL buck–boost converter with Fuzzy logic control (FLC) is designed to operate in discontinuous inductor current mode (DICM) to provide an inherent PFC at ac mains. The performance of the proposed drive is evaluated over a wide range of speed control and varying supply voltages (universal ac mains at 90–265 V) with improved power quality at ac mains. The obtained power quality indices are within the acceptable limits of international power quality standards such as the IEC 61000-3-2. The performance of the proposed drive is simulated in MATLAB/Simulink environment.*

Index Terms: *Bridgeless (BL) buck–boost converter, brushless direct current (BLDC) motor, discontinuous inductor current mode (DICM), power factor corrected (PFC), power quality.*

I. INTRODUCTION

EFFICIENCY and cost are the major concerns in the development of low-power motor drives targeting household applications such as fans, water pumps, blowers, mixers, etc. [1], [2]. The use of the brushless direct current (BLDC) motor in these applications is becoming very common due to features of high efficiency, high flux density per unit volume, low maintenance requirements, and low electromagnetic-interference problems [1]. These BLDC motors are not limited to household applications, but these are suitable for other applications such as medical equipment, transportation, HVAC, motion control, and many industrial tools [2]–[4]. A BLDC motor has three phase windings on the stator and permanent magnets on the rotor [5], [6]. The BLDC motor is also known as an electronically commutated motor because an electronic commutation based on rotor position is used rather than a mechanical commutation which has disadvantages like sparking and wear and tear of brushes and commutator assembly [5].

Power quality problems have become important issues to be considered due to the recommended limits of harmonics in supply current by various international power quality standards such as the International Electro technical Commission (IEC) 61000-3-2 [7]. For class-A equipment (< 600 W, 16 A per phase) which includes household equipment, IEC 61000-3-2 restricts the harmonic current of different order such that the total harmonic distortion (THD) of the supply current should be below 19% [7]. A BLDC motor when fed by a diode bridge rectifier (DBR) with a high value of dc link capacitor draws peaky current which can lead to a THD of supply current of the order of 65% and power factor as low as 0.8 [8]. Hence, a DBR followed by a power factor corrected (PFC) converter is utilized for improving the power quality at ac mains. Many topologies of the single-stage PFC converter are reported in the literature which has gained importance because of high efficiency as compared to two-stage PFC converters due to low component count and a single switch for dc link voltage control and PFC Operation [9], [10].

The choice of mode of operation of a PFC converter is a critical issue because it directly affects the cost and rating of the components used in the PFC converter. The continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are the two modes of operation in which a PFC converter is designed to operate [9], [10]. In CCM, the current in the inductor or the voltage across the intermediate capacitor remains continuous, but it requires the sensing of two voltages (dc link voltage and supply voltage) and input side current for PFC operation, which is not cost-effective. On the other hand, DCM requires a single voltage sensor

for dc link voltage control, and inherent PFC is achieved at the ac mains, but at the cost of higher stresses on the PFC converter switch; hence, DCM is preferred for low-power applications [9], [10].

The conventional PFC scheme of the BLDC motor drive utilizes a pulse width-modulated voltage source inverter (PWM-VSI) for speed control with a constant dc link voltage. This offers higher switching losses in VSI as the switching losses increase as a square function of switching frequency. As the speed of the BLDC motor is directly proportional to the applied dc link voltage, hence, the speed control is achieved by the variable dc link voltage of VSI. This allows the fundamental frequency switching of VSI (i.e., electronic commutation) and offers reduced switching losses. Singh and Singh [11] have proposed a buck–boost converter feeding a BLDC motor based on the concept of constant dc link voltage and PWM-VSI for speed control which has high switching losses. A single-ended primary-inductance converter (SEPIC)-based BLDC motor drive has been proposed by For further improvement in efficiency, bridgeless (BL) converters are used which allow the elimination of DBR in the front end [13]–[21]. A buck–boost converter configuration is best suited among various BL converter topologies for applications requiring a wide range of dc link voltage control (i.e., bucking and boosting mode). Jang and Jovanovich [13] and Huber et al. [14] have presented BL buck and boost converters, respectively.

These can provide the voltage buck [13] or voltage boost [14], [15] which limits the operating range of dc link voltage control. Wei et al. [16] have proposed a BL buck–boost converter but use three switches which is not a cost-effective solution. A new family of BL SEPIC and Cuk converters has been reported in the literature [17]–[21] but requires a large number of components and has losses associated with it.

This paper presents a Fuzzy based PFC - BL buck–boost converter-fed BLDC motor drive with variable dc link voltage of VSI for improved power quality at ac mains with reduced components.

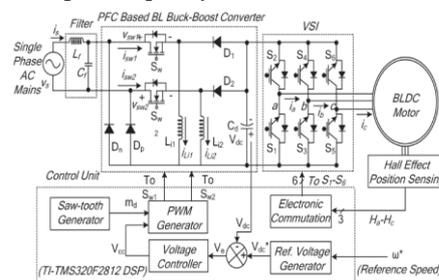


Fig. 1. Proposed BLDC motor drive with front-end BL buck–boost converter.

II. PROPOSED PFC BL BUCK–BOOST CONVERTER-FED BLDC MOTOR DRIVE

Fig. 1 shows the proposed BL buck–boost converter-based VSI-fed BLDC motor drives. The parameters of the BL buck–boost converter are designed such that it operates in discontinuous inductor current mode (DICM) to achieve an inherent power factor correction at ac mains. The speed control

Table I: Comparative Analysis Of Proposed BI Buck–Boost Converter With Existing Topologies

Configuration	No. of Devices					$\frac{1}{2}$ Period Cond.	Suitability
	S_w	D	L	C	Total		
BL-Buck [13]	2	4	2	2	10	5	No
BL-Boost [14]	2	2	1	1	6	4	No
BL-Boost [15]	2	2	1	2	7	7	No
BL-Buck-Boost [16]	3	4	1	3	11	8	Yes
BL-Cuk T-1 [17, 18]	2	3	3	3	11	7	Yes
BL-Cuk T-2 [17, 18]	2	2	3	4	11	11	Yes
BL-Cuk T-3 [17, 18]	2	4	4	3	13	7	Yes
BL-Cuk [19]	2	3	3	2	10	8	Yes
BL-SEPIC [20]	2	3	1*	3	9	7	Yes
BL-SEPIC [21]	2	3	2	2	9	7	Yes
Proposed	2	4	2	1	9	5	Yes

*- Coupled Inductor

of BLDC motor is achieved by the dc link voltage control of VSI using a BL buck–boost converter. This reduces the switching losses in VSI due to the low frequency operation of VSI for the electronic commutation of the BLDC motor.

The performance of the proposed drive is evaluated for a wide range of speed control with improved power quality at ac mains. Moreover, the effect of supply voltage variation at universal ac mains is also studied to demonstrate the performance of the drive in practical supply conditions. Voltage and current stresses on the

PFC converter switch are also evaluated for determining the switch rating and heat sink design. Finally, a hardware implementation of the proposed BLDC motor drive is carried out to demonstrate the feasibility of the proposed drive over a wide range of speed control with improved power quality at ac mains.

A brief comparison of various configurations reported in the literature is tabulated in Table I. The comparison is carried out on the basis of the total number of components (switch—Sw, diode—D, inductor—L, and capacitor—C) and total number of components conducting during each half cycle of supply voltage. The BL buck [13] and boost [14], [15] converter configurations are not suitable for the required application due to the requirement of high voltage conversion ratio. The proposed configuration of the BL buck–boost converter has the minimum number of components and least number of conduction devices during each half cycle of supply voltage which governs the choice of the BL buck–boost converter for this application.

III. OPERATING PRINCIPLE OF PFC BL BUCK–BOOST CONVERTER

The operation of the PFC BL buck–boost converter is classified into two parts which include the operation during the positive and negative half cycles of supply voltage and during the complete switching cycle.

A. Operation during Positive and Negative Half Cycles of Supply Voltage

In the proposed scheme of the BL buck–boost converter, switches Sw1 and Sw2 operate for the positive and negative half cycles of the supply voltage, respectively. During the positive half cycle of the supply voltage, switch Sw1, inductor Li1, and diodes D1 and Dp are operated to transfer energy to dc link capacitor Cd as shown in Fig. 2(a)–(c). Similarly, for the negative half cycle of the supply voltage, switch Sw2, inductor Li2, and diodes D2 and Dn conduct as shown in Fig. 3(a)–(c). In the DICM operation of the BL buck–boost converter, the current in inductor Li becomes discontinuous for certain duration in a switching period. Fig. 2(d) shows the waveforms of different parameters during the positive and negative half cycles of supply voltage.

B. Operation During Complete Switching Cycle

Three modes of operation during a complete switching cycle are discussed for the positive half cycle of supply voltage as shown hereinafter.

Mode I: In this mode, switch Sw1 conducts to charge the inductor Li1; hence, an inductor current i_{Li1} increases in this mode as shown in Fig. 2(a). Diode Dp completes the input side circuitry, whereas the dc link capacitor Cd is discharged by the VSI-fed BLDC motor as shown in Fig. 3(d).

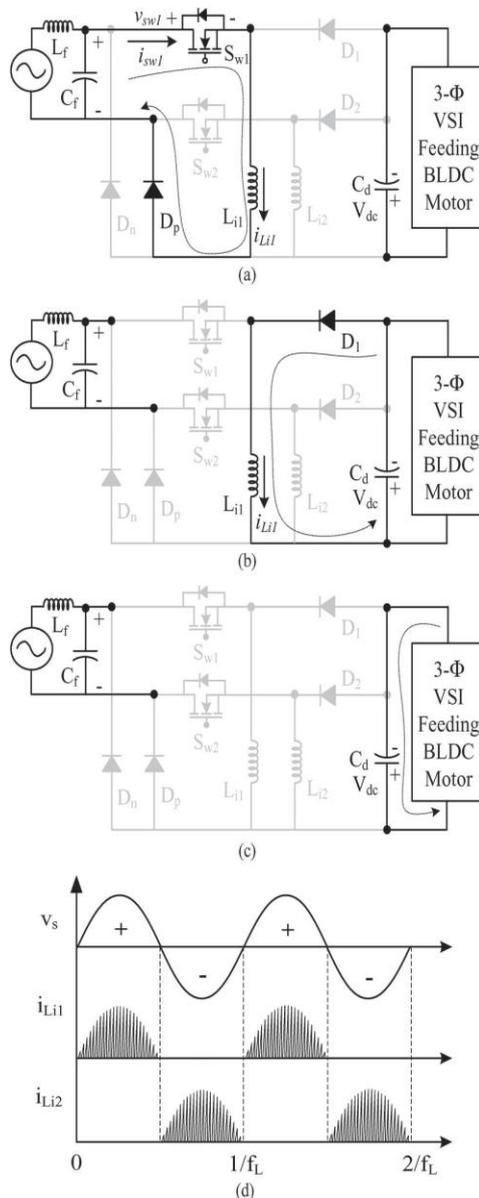


Fig. 2. Operation of the proposed converter in different modes (a)–(c) for a positive half cycles of supply voltage and (d) the associated waveforms. (a) Mode I. (b) Mode II. (c) Mode III. (d) Waveforms for positive and negative half cycles of supply voltage.

Mode II: As shown in Fig. 2(b), in this mode of operation, switch Sw1 is turned off, and the stored energy in inductor Li1 is transferred to dc link capacitor Cd until the inductor is completely discharged. The current in inductor Li1 reduces and reaches zero as shown in Fig. 3(d).

Mode III: In this mode, inductor Li1 enters discontinuous conduction, i.e., no energy is left in the inductor; hence, current i_{Li1} becomes zero for the rest of the switching period. As shown in Fig. 2(c), none of the switch or diode is conducting in this mode, and dc link capacitor Cd supplies energy to the load; hence, voltage Vdc across dc link capacitor Cd starts decreasing. The operation is repeated when switch Sw1 is turned on again after a complete switching cycle.

Similarly, for the negative half cycle of the supply voltage, switch Sw2, inductor Li2, and diodes Dn and D2 operate for voltage control and PFC operation.

IV. DESIGN OF PFC BL BUCK-BOOST CONVERTER

A PFC BL buck-boost converter is designed to operate in DICM such that the current in inductors L_{i1} and L_{i2} becomes discontinuous in a switching period. For a BLDC of power rating 251 W (complete specifications of the BLDC motor are given in the Appendix), a power converter of 350 W (P_o) is designed. For a supply voltage with an rms value of 220 V, the average voltage appearing at the input side is given as [24]

$$V_{in} = \frac{2\sqrt{2}V_s}{\pi} = \frac{2\sqrt{2} \times 220}{\pi} \approx 198 \text{ V.} \quad (1)$$

The relation governing the voltage conversion ratio for a buck-boost converter is given as [22]

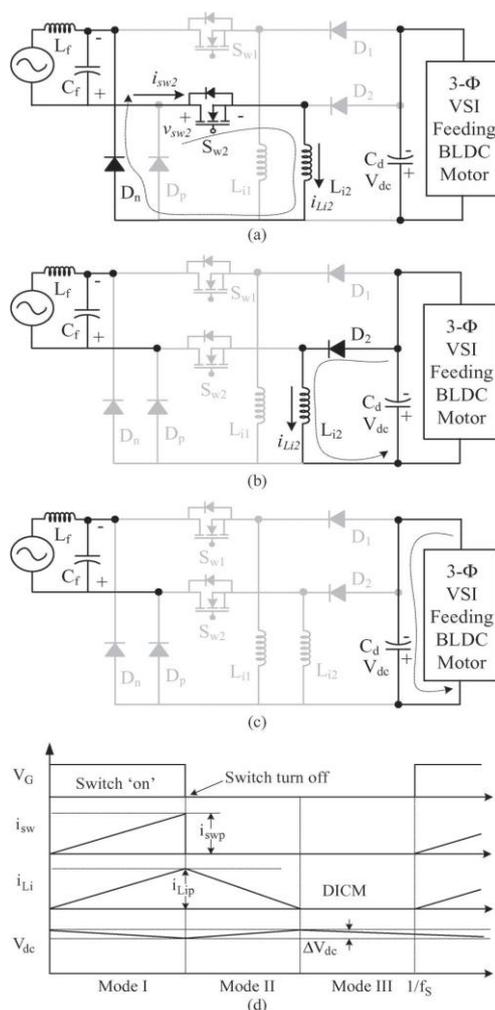


Fig. 3. Operation of the proposed converter in different modes (a)–(c) for a negative half cycles of supply voltage and (d) the associated waveforms. (a) Mode I. (b) Mode II. (c) Mode III. (d) Waveforms during complete switching cycle.

$$d = \frac{V_{dc}}{V_{dc} + V_{in}}. \quad (2)$$

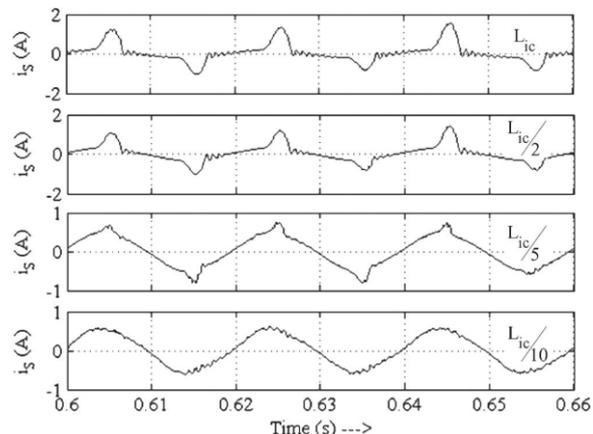


Fig. 4. Supply current at the rated load on BLDC motor for different values of input side inductors with supply voltage as 220 V and dc link voltage as 50 V.

The proposed converter is designed for dc link voltage control from 50 V ($V_{dc \min}$) to 200 V ($V_{dc \max}$) with a nominal value ($V_{dc \text{ des}}$) of 100 V; hence, the minimum and the maximum duty ratio (d_{\min} and d_{\max}) corresponding to $V_{dc \min}$ and $V_{dc \max}$ are calculated as 0.2016 and 0.5025, respectively.

Design of Input Inductors (L_{i1} and L_{i2})

The value of inductance L_{ic1} , to operate in critical conduction mode in the buck–boost converter, is given as [23]

$$L_{ic1} = \frac{R(1-d)^2}{2f_s} \quad (3)$$

where R is the equivalent load resistance, d is the duty ratio, and f_s is the switching frequency. Now, the value of L_{ic1} is calculated at the worst duty ratio of d_{\min} such that the converter operates in DICM even at very low duty ratio. At minimum duty ratio, i.e., the BLDC motor operating at 50 V ($V_{dc \min}$), the power (P_{\min}) is given as 90 W (i.e., for constant torque, the load power is proportional to speed). Hence, from (4), the value of inductance $L_{ic \min}$ corresponding to $V_{dc \min}$ is calculated as

$$\begin{aligned} L_{ic \min} &= \frac{V_{dc \min}^2 (1-d_{\min})^2}{P_{\min} 2f_s} = \frac{50^2 (1-0.2016)^2}{90 \cdot 2 \times 20000} \\ &= 442.67 \mu\text{H}. \end{aligned} \quad (4)$$

The values of inductances L_{i1} and L_{i2} are taken less than 1/10th of the minimum critical value of inductance to ensure a deep DICM condition [24]. The analysis of supply current at minimum duty ratio (i.e., supply voltage as 220 V and dc link voltage as 50 V) is carried out for different values of the inductor (L_{i1} and L_{i2}). Fig. 4 shows the supply current at the input inductor's value as L_{ic} , $L_{ic}/2$, $L_{ic}/5$, and $L_{ic}/10$, respectively. The supply current at higher values of the input side inductor is highly distorted due to the inability of the converter to operate in DICM at peak values of supply voltages.

Hence, the values of inductors L_{i1} and L_{i2} are selected around 1/10th of the critical inductance and are taken as 35 μH . It reduces the size, cost, and weight of the PFC converter.

V. FUZZY CONTROLLER

Fuzzy logic uses fuzzy set theory, in which a variable is member of one or more sets, with a specified degree of membership. Fuzzy logic allow us to emulate the human reasoning process in computers, quantify imprecise information, make decision based on vague and in complete data, yet by applying a “defuzzification” process, arrive at definite conclusions.

The FLC mainly consists of three blocks

- **Fuzzification**
- **Inference**
- **Defuzzification**

RULES:

If input is NEGATIVE then output is POSITIVE

If input is ZERO then output is ZERO

If input is POSITIVE then output is NEGATIVE

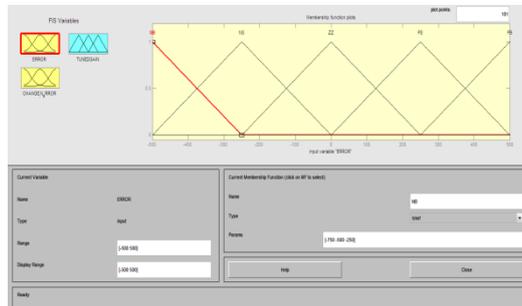


Fig..5 Fuzzy Inputs and Outputs

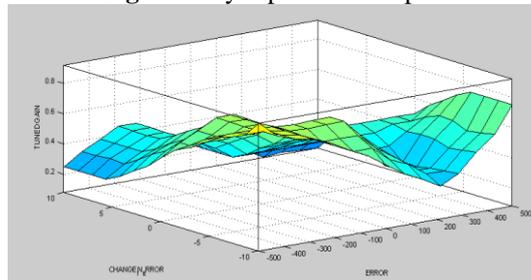


Figure 6 Surface of the Fuzzy logic controller

VI. SIMULATED PERFORMANCE OF PROPOSED BLDC MOTOR DRIVE

The performance of the proposed BLDC motor drive is simulated in MATLAB/Simulink environment using the SimPowerSystem toolbox. The performance evaluation of the proposed drive is categorized in terms of the performance of the BLDC motor and BL buck–boost converter and the achieved power quality indices obtained at ac mains. The parameters associated with the BLDC motor such as speed (N), electromagnetic torque (Te), and stator current (ia) are analyzed for the proper functioning of the BLDC motor. Parameters such as supply voltage (Vs), supply current (is), dc link voltage (Vdc), inductor’s currents (iLi1, iLi2), switch voltages (Vsw1, Vsw2), and switch currents (isw1, isw2) of the PFC BL buck–boost converter are evaluated to demonstrate its proper functioning.

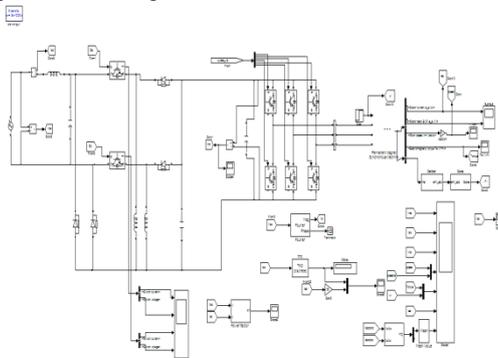
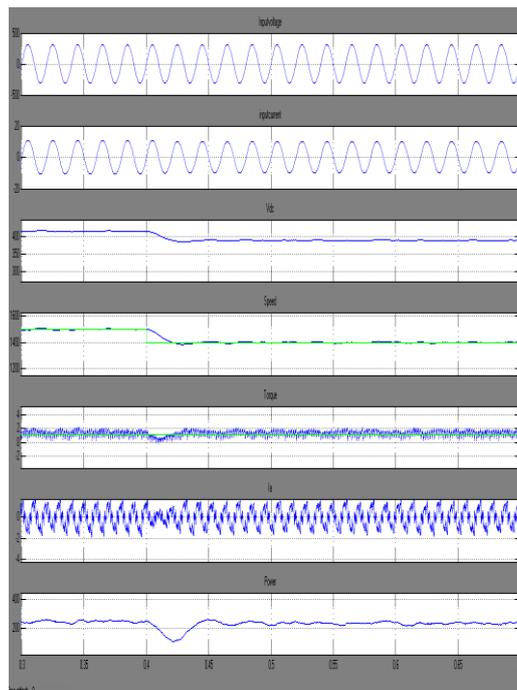


Figure 7 Matlab/Simulink model of the proposed method



(c)

Fig. 9 Dynamic performance of proposed BLDC motor drive during (a) starting, (b) speed control, and (c) supply voltage variation at rated conditions.

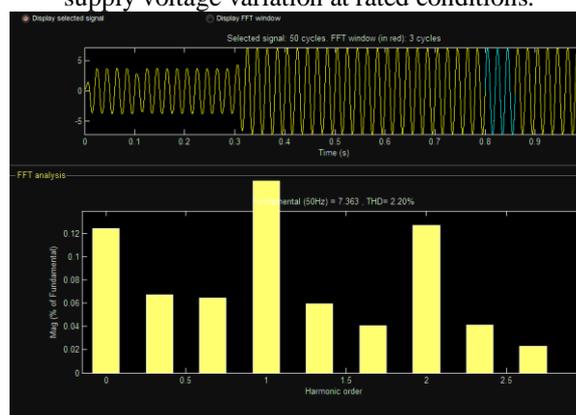


Fig.10 % of the Total Harmonic Distortion of Input current

VII. CONCLUSION

A PFC BL buck–boost converter-based VSI-fed BLDC motor drive has been proposed targeting low-power applications. A new method of speed control has been utilized by controlling the voltage at dc bus and operating the VSI at fundamental frequency for the electronic commutation of the BLDC motor for reducing the switching losses in VSI. The front-end BL buck–boost converter has been operated in DICM for achieving an inherent power factor correction at ac mains. A satisfactory performance has been achieved for speed control and supply voltage variation with power quality indices within the acceptable limits of IEC 61000-3-2. Moreover, voltage and current stresses on the fuzzy based PFC switch have been evaluated for determining the practical application of the proposed scheme. Finally, an experimental prototype of the proposed drive has been developed to validate the performance of the proposed BLDC motor drive under speed control with improved power quality at ac mains. The proposed scheme has shown satisfactory performance, and it is a recommended solution applicable to low-power BLDC motor drives.

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