Pakistan Journal of Science, 71 (4 Suppl.): 2019, Page 36-41
ISSN: 2411-0930

ADVANCE CONTROL TECHNIQUE FOR CONTROLLING THE GAIN AND MINIMIZING LOW FREQUENCY RIPPLES OF SWITCHED INDUCTOR Z-SOURCE INVERTER

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ABSTRACT: In this paper simple boost, max boost control, and max constant boost control are three approaches proposed for switched inductor Z-source inverter topology. If we consider practical design of maximum boost control technique, we can say that gain can be altered for given modulation index and it can also reduce the voltage stress. Max constant boost control is introduced to overcome low frequency ripples which are linked with capacitor voltage and inductor current. These techniques show the relationship between voltage gain versus modulation index, voltage stress versus voltage gain and stress ratio versus voltage gain. These switching strategies are analyzed in detail and also proved by simulations.

Keywords: SL-ZSI, low frequency ripples, Modulation Index, Voltage gain, Voltage stresses.

INTRODUCTION

Electricity plays vital role for the sake of lighten and running our industries and factories respectively. With the passage of time there is huge increase in population and the demand of electricity increases day by day and there is shortage of electricity. Alternately, non-RE (renewable energy resources) based power plants including coal and combine cycle emits poisoned gases which cause of global warming. Due to global warming. Even though the use of backup energy sources like generators has also many disadvantages, such as high operation and maintenance costs and also causes air pollution by the emission of carbon dioxide (Yang *et al.* 2008; Dursun, 2012). Due to all these drawbacks the trend is shifted towards biomass, solar system, fuel cell and wind which are environment friendly renewable energy sources (Sahan *et al.*, 2010). Inherited power from RE like PV panel is in Dc form and we need AC supply in our homes so conversions from DC to AC is needed. Power electronics facts devices perform these tasks like VSI and CSI (Dursun, *et al.*, (2013), but they suffer from power conversions in 2-stage, which results in more component requirements, losses and more complex control. The VSI having lesser output Ac voltage than that of input DC voltage which leads to the power conversions in 2-stage, due to the requirement of an extra dc-dc boost converter (Kalinci *et al.*, 2015). Furthermore, both the upper and lower devices of phase leg can never be Turned ON otherwise S.T problem would occur which can damage the machines. To overcome these aforementioned limitations z-source inverter (Boxwell, 2010) is proposed which dominated over VSI to use the S.T state, to improve the voltage. There will be no extra boost converter required so single stage conversion take place. Other Z-source topologies have been introduced (Errabelli and Mutschler, 2011), which minimize the total number of components improves the system reliability. Among all power electronics devices, ZSI have become prominent due to their features and broad area of applications. Quasi Z-source inverter (Ellabban and Abu-Rub, 2016) have advantages over Z- source inverter, QZSI draws continuous input current and have less component Vstress. Most importantly, Qzsi shows high theoretical gains while in real scenario, gains are restricted due to less modulation index and high Vstress on components which leads to low power qualities and utilities are facing major power quality problems. Few changes have been made in the circuit of QZSI to increase the boosting limit (Hiendro *et al.*, 2013). C switching and L switching structure has been introduced (Peng, 1999; Yang *et al.*, 2010). To improve the boost factor, switched inductor Z-source inverter has been developed (Errabelli and Mutschler, 2011).

But the main disadvantage of using M.B.C is that the low frequency ripples associated with both inductor current and capacitor voltage has been produced which will badly affect the output voltage. In this paper, to minimize these low frequency ripples which are associated with the current of inductor and voltage of capacitor, we will implement MBC on SL-Z source inverter and voltage gain also improved.

MATERIALS AND METHODS

As shown in Fig. 1, the given SL Z source inverter (F. Z. Peng, (2003)) has 4 inductors named as L1, L2, L3, L4. 2 capacitors C1, C2 and 6 Diodes D1, D2, D3, D4, D5, D6. The operation of Top cell SL is done by combining the components as of L1-L3-D1-D3-D5 and the operation of lower SL cell is done by L2-L3-D2-D4-D6. Energy is stored and transferred from capacitor to dc bus of main circuit by both of these cells. This is done under switching action of main circuit.

Operational principles: The active and passive switch, named as S and D0 respectively, are introduced in order to simulate the actions of S.T state for both top and bottom arms. So, the states of introduced impedance network are divided into two further states, S.T and N.S.T.

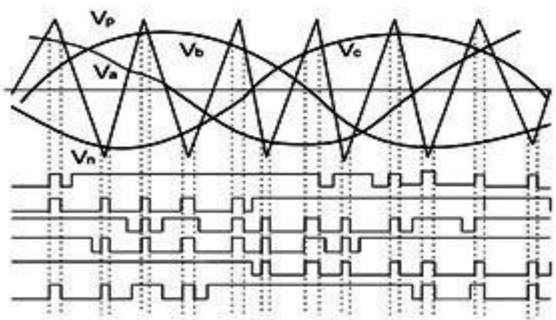

Figure-1: SL-ZSI (Switched inductor Z-source inverter)

Shoot-Through-State: During this state, switch S is ON while D0 and Din are OFF. For the top cell of SL, the diodes D1 and D2 are turned ON, while Diode D3 is turned OFF. Inductors L1 and L3 are in parallel with capacitor C1 and get charged by it. For the lower cell of SL, diodes D4 and D5 are turned ON while diode D6 is turned OFF. Inductors L2 and L4 are connected in parallel with capacitor C2 and charged by it. This state is similar to the zero state which is due to the S.T actions of both top and bottom arms. It has been observed that both SL cells do the function of absorbing the energy stored in capacitors.

Non-shoot-through-State: During this state, switch S, is turned ON while D0, and Sin are turned OFF. For upper cell of SL diodes D2 and D3 are turned OFF while D5 is turned ON. Inductors L1 and L2 are in series and the energy stored is passed to the circuit. For the lower cell of SL, diodes D4 and D5 are turned ON while D6 is turned OFF. Inductor L3 is in series with L4. The stored energy is introduced to the circuit. To add the energy taken by C1 and C2 in the S.T state, through the lower cell of SL, Vin charges C1 and through the upper cell of SL, Vin charges C. So, the boost factor for SL-ZSI can be expressed as

$$B = \frac{1+Dsh}{1-3D} \qquad (1)$$

where Dsh is the STDR. As explained in [27] the K of inverter can be described as

$$K = \frac{Vo}{Vdc} = MB \qquad (2)$$

where Vo is the output voltage, N is the modulation index and B is boost factor which is calculated by using (1) and (2)

$$B = \frac{1+Dsh}{1-3Dsh}*\mathrm{N} \qquad (3)$$

Simple boost control (SBC): A modulation scheme name SBC is utilised to overcome the shoot trough duty ratios as discussed in (S. M. Dehghan et al (2010). Figure 2 depicts the SBC that consists of straight line equal to or greater than peak of 3-phase reference signal to explain the S.T duty. When carrier signal is higher or lower than Vp and Vn signals respectively, S.T state happens in case of carrier signal is higher or lower than Vp and Vn signals respectively. D.R for S.B.C is 1−N. This equation shows that there is inverse relation between DR and N, DR falls with increase in N. DR=0, when N=1 so STDR is restricted to 1−N.

$$D = 1 - N \qquad (4)$$

In Fig.4 the maximum possible K across the given N is shown by the curve named as SBC. In the systems where large amount of K is needed, a small N is used. This causes Vstress on the switching components. We can calculate gain of S.B.C method by using (3) and (4).

$$K = 2N - N_2$$
$$= 3N - 2 \qquad (5)$$

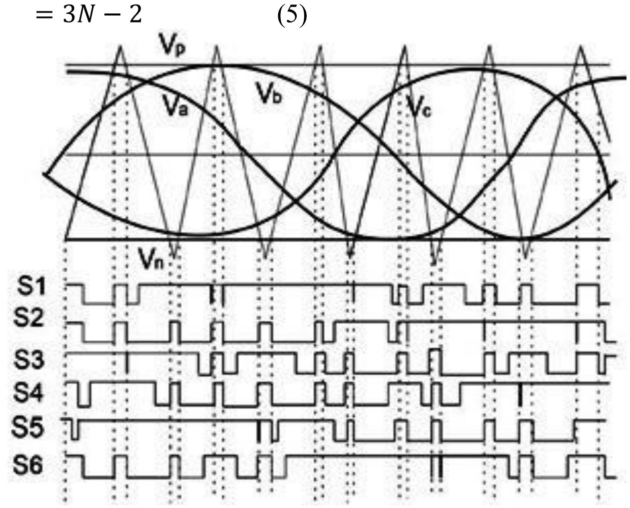

Figure-2: Switching technique for simple boost control

By using (5), the maximum value of N at which the required K is possible,

$$N = \frac{2-3K+\sqrt{9K^2-4K+4}}{2} \qquad (6)$$

As shown in (S. M. Dehghan et al (2010), the Vstress over switches is,

$$V_{stress=BV_{out}} \qquad (7)$$

Vstress on the switches for S.B.C technique can be calculated by using (6) and (7) as $V_{stress,}$

$$V_{stress} = \frac{2K}{2-3K+\sqrt{9K^2-4K+4}} \qquad (8)$$

Through SBC switching technique, we can also calculate the ratio of Vstress to Equivalent dc Voltage. Equivalent dc Voltage is the least value of dc voltage required to generate output voltage. It is denoted by GVdc (P. C. Loh,et al (2010). This ratio shows the cost that SL-ZS inverter has to pay to get to voltage boost.

By using (7) and (8), ratio of Vstress to Equivalent dc Voltage can be obtained as $\frac{\text{Vstress}}{\text{Gvdc}}$

$$\frac{\text{Vstress}}{\text{Gvdc}} = \frac{2K}{2-3K+\sqrt{9K^2-4K+4}} \qquad (9)$$

In Fig. 6, the very high stress ratio for SBC is shown by the curve. The main disadvantage of using this switching method is that the Vstress on the switches is too high which ultimately affects the gained voltage.

Maximum boost switching scheme: In SBC of SL-ZSI, the switching devices have higher value of Vstress. To decrease Vstress over switching devices for specific value of K is very important for SL-ZSI. We should take D.R to maximum value and boost factor to the minimum value in order to get the desired value of K. Due to this, M.B switching technique is introduced (P. C. Loh,et al (2010), which is a switching technique almost identical to the PWM control technique. But the difference is that it keeps all six active states unchanged and change each of the zero sate into SH. Implementation of M.B.C technique and PWM control scheme on SL-ZSI, is shown in Figure below. When triangular carrier signal is greater than reference curve Vp or lower than Vn, Shoot-through will occur.

$$D_{sh} = \frac{2\pi-3\sqrt{3}N}{2\pi} \qquad (10)$$

A larger operating area as compared to S.B.C technique, so provides larger N for required K, which as a result decreases the Vstress on the switching devices. From (3) and (10), we can calculate gain for this control method as,

$$K = \frac{2N-N_2}{3N-2} \qquad (11)$$

From (11), The maximum N that can produce required K,

$$N = \frac{-K\sqrt{3}-4\pi+\sqrt{(243K^2-24\sqrt{3}\pi K+16\pi^2)}}{6\sqrt{3}K} \qquad (12)$$

By using (7) and (12), the Vstress over the switches can be calculated as,

$$V_{stress} = \frac{2\sqrt{3}}{-3K\sqrt{3}+4+\sqrt{(27K^2-8\sqrt{3}K+16)}} \qquad (13)$$

If we compare to SBC technique, Vstress over the switches is very low in suggested switching technique, which results to produce high K. stress ratio has been also defined in simple boost and for maximum boost strategy it is calculated as by using (7) and (13)

$$\frac{V_{stress}}{KV_{dc}} = \frac{6\sqrt{3}K}{-3K\sqrt{3}+4+\sqrt{(243K^2-24\sqrt{3}\pi K+16\pi^2)}} \qquad (14)$$

The proposed method has relatively lower stress ratio in comparison with S.B.C. But the major drawback of this technique is that all the zero states are changed into S.T. Since the S.T changes at six times the inverter frequency, due to this changing voltage and current ripples are introduced because of passive components like inductor and capacitor respectively.

Maximum constant boost switching scheme: To control these low frequency voltage and current ripples and to get maximum voltage boost, M.C.B.C (S. Yang, et al (2011)), is introduced, which is applied on SL-ZS inverter topology. The PWM switching technique is shown in Fig. 3. Vp and Vn are constant S.T envelopes used to control the S.T state. When carrier signal is higher than the Vp or lower than Vn, S.T will occur. Maximum S.T duty ratio that can be obtained from this control method is,

$$D_{sh} = \frac{1-\sqrt{3}N}{2} \qquad (15)$$

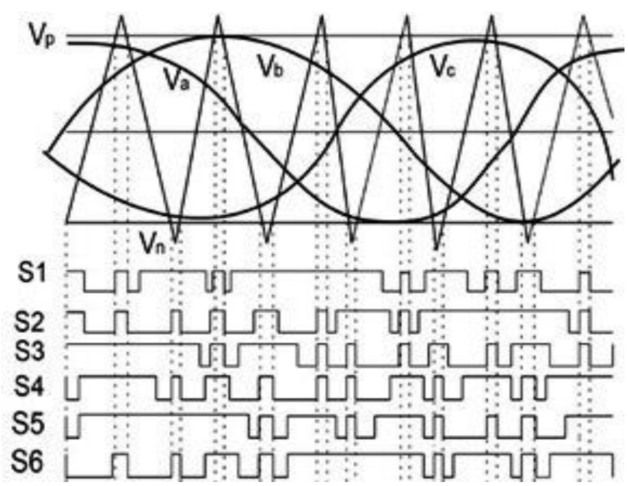

Figure-3: Switching technique for max constant boost control.

For this control method, K can be calculated by using (3) and (15) as,

$$K = \frac{4N-\sqrt{3}N^2}{3\sqrt{3}N-4} \qquad (16)$$

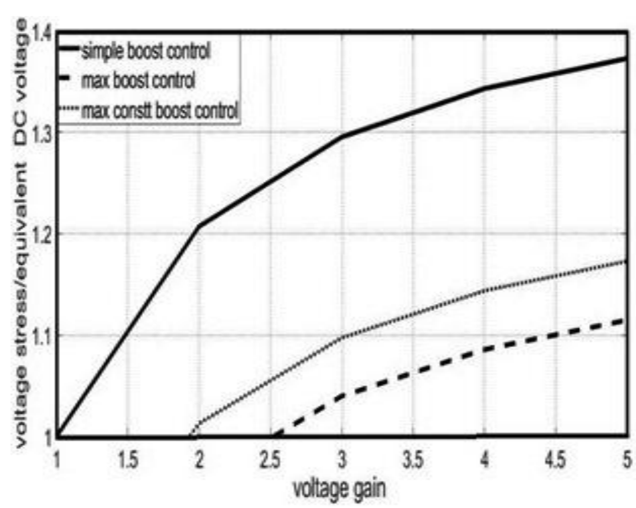

Figure-4: Stress in voltage versus Gain

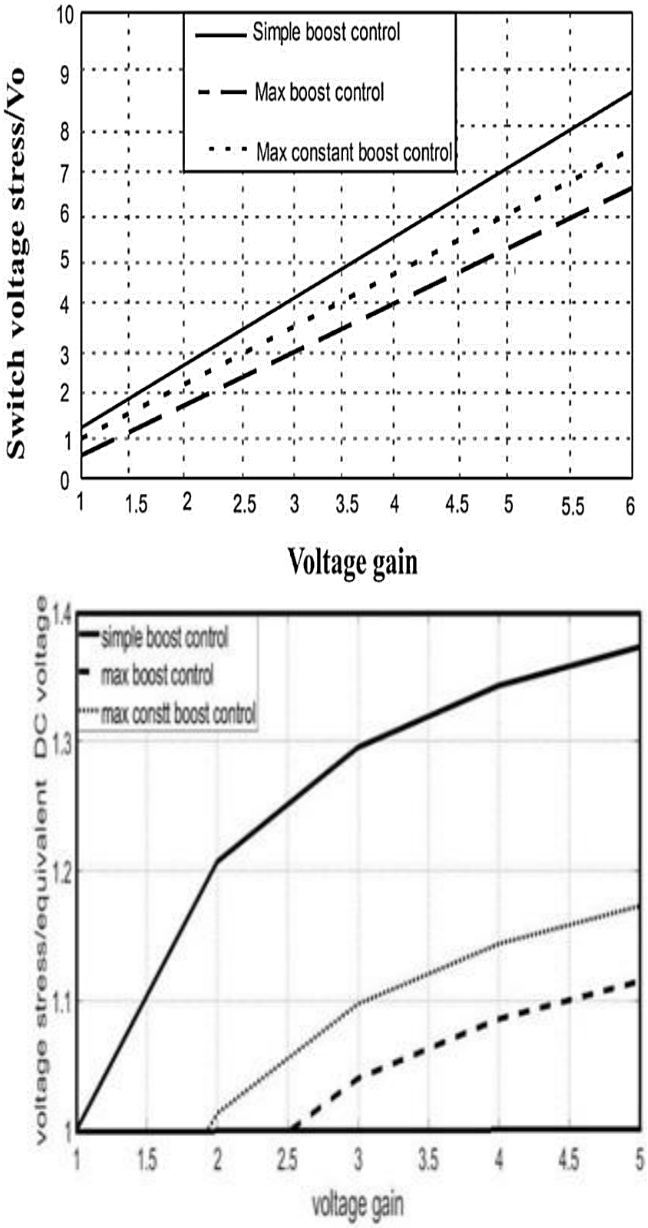

Figure-5: Stress ratio versus voltage gain

For M.B.C technique plot shown in Fig.4 is between K and N. The K becomes almost infinity as N(Modulation Index) goes to $\frac{\sqrt{3}}{3}$

From (16), for desired value of K, highest value of N is

$$N = \frac{-3K\sqrt{3}+4+\sqrt{(27K^2-8\sqrt{3}K+16)}}{2\sqrt{3}} \quad (17)$$

From (7) and (17), Vstress across the switches can be calculated as

$$V_{stress} = Aw_o = \frac{6\sqrt{3}K}{-9K\sqrt{3}-4\pi+\sqrt{(243K^2-24\sqrt{3}\pi K+16\pi^2)}} \quad (18)$$

VS on the switches M.C.B.C is shown in Fig 8. Curve show that the Vstress is smaller than the S.B.C and larger than the maximum boost control. By using (7) and (18), Stress Ratio (Vstress/Equivalent dc Voltage) can be shown as

$$\frac{V_{stress}}{KV_{dc}} = \frac{6\sqrt{3}K}{-3K\sqrt{3}+4+\sqrt{(243K^2-24\sqrt{3}\pi K+16\pi^2)}} \quad (19)$$

Figure 5 shows the comparison graph of all proposed switching techniques. As can be seen from figure that stress ratio for proposed technique is lesser than the S.B.C and greater than the M.B.C. Thus, the stress ratio for this control method is ideally 1. The main advantage of this technique is that there will be no low frequency ripples with related with the output.

RESULTS AND DISCUSSION

In order to confirm the results mentioned earlier, example of simulations for voltage inversion from 36V DC to 110V AC (rms) is given using the software SABER. It has been observed the ratio of voltage conversion should be as high as 8.64. This is tough for a classical Z-source inverter. So now we have to apply all of three techniques SBC, MBC and MCBC to the circuit. Major parameters for the circuit are as under:

1. SL Z-source impedance network with L1=L2=L3=L4-1mH and C1=C2= 800uF.
2. Output filter for 3-phase system, Lf = 1 mH, Cf = 22 μF;
3. The switching frequency is set as fs = 1/T = 10 kHz;
4. 3-phase resistive load, R = 10 Ω
5. Suppose that all the components are ideal.

Simple boost control: Using (11) and applying conditions of S.B.C, we have D=0.3 and N=0.7. From (8)-(11) we have B=13, K=9.1, Vdc=468V, VC1 = VC2 = 252 V and *VPn* = 163.8 V, Vpn = 115 V. It is convenient to apply control circuit by an analogue PWM circuit in the form of simulations because duty cycle of S.T state remains the same. Results of simulations from zero to steady state condition are shown in Fig. 6(a) and 6(b). Here firstly Vin is recorded and then Van, V_{dc} and finally VC. It has been observed that steady state response in simulations is same as that of theoretical analysis. The inductor current i.e IL id compared with current in shoot through state i.e I (shoot through). To shoot through is equal to sum of currents from all four inductors i.e. 4IL. Other than this, the ratio of voltage variations is very less (<0.5%).

If the values of D and N implemented to Z source inverter are same as the simulations, there will be a decrease in boost inversion ability. Here parameter is B=2.5 and K=1.75, which are very less than the suggested inverter values given in this paper. Similarly, in theory, V_{Pn} =63 V, i.e., only 44.6 V phase voltage is possible to be obtained at the ac side; so, it is very different from the specifications of original design.

Maximum Boost Control: By using (13)-(15) and applying M.B.C condition, we have N=0.8477. So, we have D=0.2907, B=10.1, Gmax=8.66, Vdc=363.6V, Vc1=Vc2=200V, and Vpn=155.8V (i.e. Vpn=110V). Stress in this case is decreased than the stressed in other cases. SABER software is used to perform simulations and in order to generate changing duty cycle results of simulations from initial condition to steady state condition.

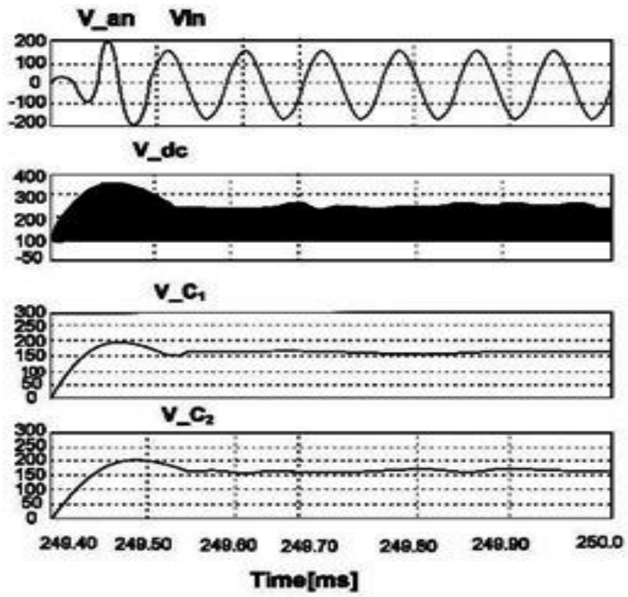

Figure-6(b): Simulation results for MCBC

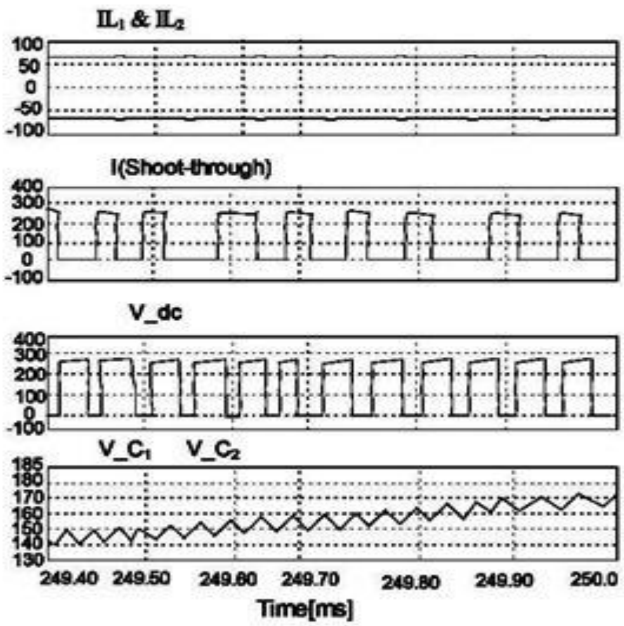

Figure-6(a): Simulation results for MCBC

Max constant boost control: Figure 6 depicts the MCBC simulation results. By applying MCBC condition, we have N=0.0.876. So, we have D=0.28, B= 10, Gmax=8.11, Vdc= 325.3V, VC1=VC2=180V, v̂pn = 140.2 V (i.e., Vpn = 105 V).

Voltage Stress in this case is relatively lower S.B.C and higher than M.B.C. SABER software is used to perform simulations and in order to generate changing duty cycle. As shown in Figure 12(a), low frequency ripples that are associated with capacitor voltage and inductor current of M.B.C are minimized. So, the output voltage has been improved.

Conclusion: This paper demonstrates the three control procedures to accomplish most extreme K for SL-ZSI. The procedure builds the shoot through time interim, so most extreme K is created for explicit N. Consequently, most extreme estimation of N is utilized to create any required K. M.B.C has been introducing which minimizes the voltage stress on the switching devices but it causes low frequency ripples. So, M.C.B.C has been introduced for SL-Z source inverter to overcome these low frequency ripples linked with the capacitor voltage and inductor current. This paper also shows the correlation of various control techniques has been appeared based on K against N, Vstress against K and stress proportion against K are researched in detail. Simulations were performed to confirm the control procedures and assessment.

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