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Simulation of Modified Aalborg Inverter with Single Power Supply for Grid Connectivity and for Renewable Energy Application

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***Abstract*—This paper aimed at presenting a topology for a two stage dc/ac inverter which is suitable for grid connection of renewable energy sources. The main advantage of this inverter is that it combines the operation of both CSI and VSI. Here no separate converter is required for this inverter. Hence the efficiency of the whole system becomes high. The main advantage is that only one power stage works at high frequency to achieve minimum switching loss. The conventional Aalborg inverter is realized using a dual supply and suitable for a range of 150V to 350V of input dc voltage. This range of voltage may not be available from renewable energy source. Here single power supply is used in which input voltage can vary from 40V. The evaluation of this topology is done through simulation results.**

***Index Terms*— MatlAB Simulink; Current Source Inverter (CSI); Voltage Source Inverter (VSI).**

I. INTRODUCTION

Nowadays, energy crisis is the major issue which the world faces today. The power resources are being extinct due to large power demand. An alternative for the power resources are renewable energy such as photovoltaic cell, wind energy, tidal energy etc. The demand for renewable energy is becoming popular. Inverters can be mainly categorized as CSI and VSI where VSI is dominant over CSI in grid tied application. This is because CSI must have a large inductor as a storage element and to keep the current constant for proper modulation while VSI does not require this. The main challenge for CSI is to decrease the total dc link inductance and then the efficiency can be improved. Various inverter topologies are available and the problem is with the switching losses because all the power stage operates at high frequencies. This can cause the system to be less efficient. This issue can be solved by operating only one power stage at high frequency.

In renewable energy system input voltage to the converter may vary greatly due to the change in environmental conditions. In order to transfer this type of energy to the grid we require a two stage or three stage converters. Fig.1 shows the conventional PV system where a separate dc-dc converter is added in the front end of the dc-ac inverter. This is a two stage inverter where the input voltage should be boosted before feeding it to the inverter. Both the power stage works at high frequency. If all the power stages works at high frequency then this will affect the overall efficiency of the system by increasing the switching loss.

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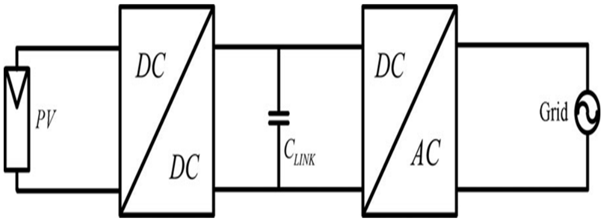


Fig. 1. Conventional two stage PV inverter

Many inverters were proposed for the grid connection. A transformer less single phase non isolated inverter for ac module application is proposed for in [2]. This is suitable for both grid connection and solar pane requirements. But it is a two stage topology and requires higher cost and complex control. An active non-linear modulation technique to reduce lo order harmonics in CSI is presented in [3]. This paper also deals with the reduction of dc inductance value. A Z source inverter is proposed in [4] which overcome the technical limitations of VSI and CSI. It acts as a buck boost inverter hence the need for a two stage inverter is reduced. A dual mode time sharing cascaded sinusoidal inverter is proposed in [5]. It consist of a time sharing buck type current fed converter and time sharing sinusoidal pulse modulated full bridge inverter. But the switching frequency of this inverter is high compared to the conventional ones. A boost- buck converter based PV inverter is proposed in [6], where boost cascaded with a buck converter is designed.

In this paper a new modified Aalborg half bridge inverter is proposed with a single power source in which input voltage can vary from 40V onwards. The operating principle is explained for both positive and negative half cycle. Both the half cycles works in symmetry. The major attraction for this inverter is that it can works as both CSI and VSI. The control loops for the inverter is designed separately for both buck and boost control. The main advantage of this with the conventional is that it can operate with large range of input voltages and efficiency can be improved further.

This paper is organized as follows. Section II describes the existing models of grid tied inverters. Section III composed of the working and principle of operation of Aalborg inverter. Section IV deals with the modified Aalborg inverter circuit and its advantages. Section V explains the control loop of the proposed inverter. Section VI shows the simulation results followed by conclusion in section VI.

II. EXISTING SYSTEMS

Various inverter topologies are available to connect with the grid connected system. Mostly used ones are VSI and CSI.

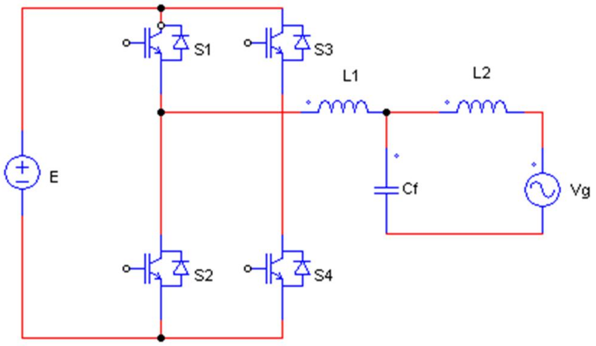


Fig. 2. Single phase grid tied VSI

Fig 2 shows a typical VSI with an LCL filter at the end [1]. It is understood that VSI is a step down or a buck type inverter. So that this type of inverter is used in application where the amplitude of input voltage should be higher than the grid voltage.

Fig 3 shows the typical connection of CSI to the grid tied system [1]. CSI is basically a step up or boost inverter and it is only used in the cases where the amplitude of the input voltage is lower than the grid voltage.

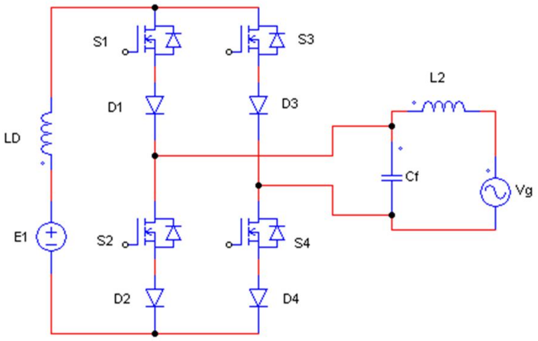


Fig. 3. Single phase grid tied CSI

Usually the output from a renewable source such as PV may vary in a big range so this CSI or VSI cannot be directly connected to the grid. For connecting this we need an additional dc-dc converter in front of inverter so that input voltage can meet the grid requirement. But it is a less efficient method because both stage works at high frequency. To overcome this disadvantage a new type of inverter was proposed known as Z-source inverter (ZSI). This combines the character of both CSI and VSI i.e. it can act as step up and step down inverter as required. The schematic of this inverter is shown in Fig 4.

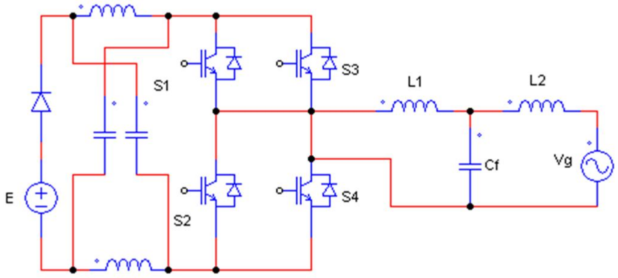


Fig. 4. Single phase grid tied ZSI

The problem with ZSI is that it consists of two additional inductors in the power loop and this leads to high conduction power loss. Apart from this there are chances for over filtering to take part in the buck mode that is when input voltage is high. This proves that the efficiency of ZSI is not high compared with other inverters.

III. CONVENTIONAL AALBORG INVERTER

Aalborg university in Denmark and hence the name Aalborg inverter. The schematic layout of an Aalborg inverter is shown in Fig 5.

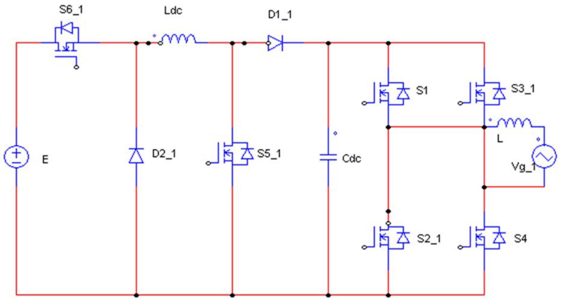


Fig. 5. Full bridge Aalborg inverter

Fig 5 shows the full bridge Aalborg inverter, which has two stages and output stage works at line frequency and only one power stage works at high frequency. Total inductance in the loop is low so conduction power loss is reduced. Proper working of this inverter is explained through a half bridge Aalborg inverter. This inverter works in both buck and boost mode according to value of input voltage. If the amplitude of the input voltage is greater than the grid voltage then it works as a buck converter or VSI and if the amplitude of the input voltage is lower than the grid voltage then it operates as boost converter or CSI. The principle of operation is explained in two modes.

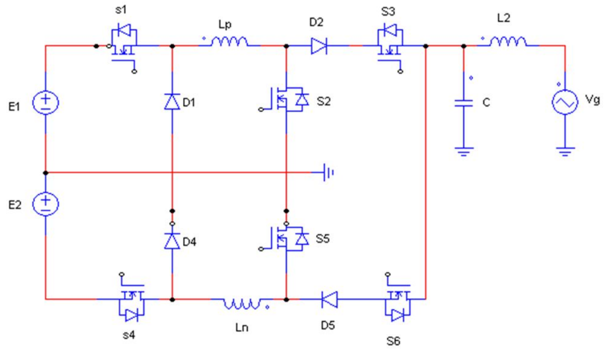


Fig. 6. Half bridge Aalborg inverter

A. Mode 1: E_1 or E_2 greater than V_g

This is the case when the input voltage is greater than or equal to the grid voltage. There are two cases during one cycle of grid voltage i.e. positive half cycle and negative half cycle. During the positive half cycle E_1 provides total supply for the circuit.

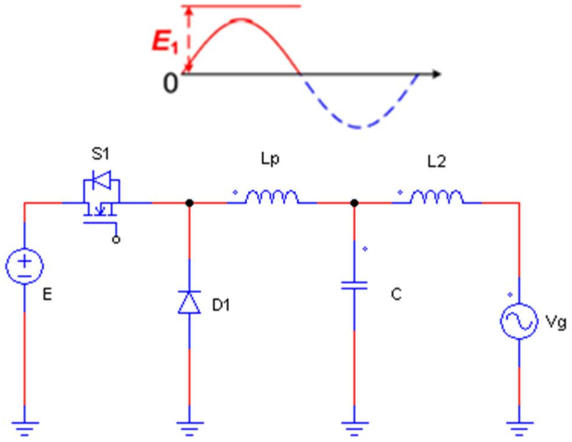
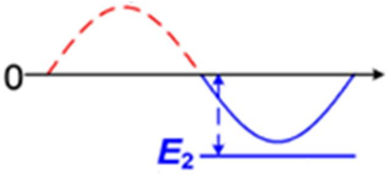


Fig.7. Equivalent circuit when E_1 or $E_2 > Vg$

In this mode switches S_3 is ON, S_2 is OFF and S_1 operates at high frequency to obtain a perfect sinusoidal grid current. From the Fig.7 it is clear that the inverter act as a pure buck converter with an LCL filter at the end. This filter is capable of satisfying the harmonic requirements of the grid. Similarly is the case in negative period of grid voltage which is shown in Fig. 8.



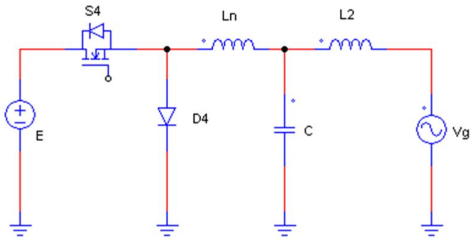


Fig. 8. Equivalent circuit during negative half cycle

In this mode E_2 supplies the total energy for the circuit. This mode comes into action when the amplitude of input voltage is higher than the grid voltage. Here switches S_6 is ON, S_5 is OFF and S_4 works at high frequency. This works as pure VSI with LCL filter at the end.

B. Mode 2: Mode 1: E_1 or E_2 less than V_g

If the amplitude of input voltage is less than the grid voltage then the inverter should operate as boost inverter. Here the control becomes little complex because inverter should perform the operation of both buck and boost according to the input voltage. The time sequence is split into six intervals. Time sequence during positive half cycle is shown in Fig 9.

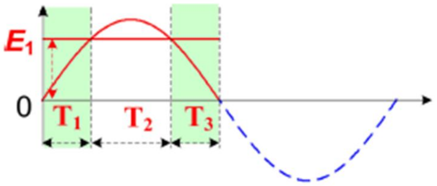


Fig. 9. Working sequence when E1 or E2 less than Vg

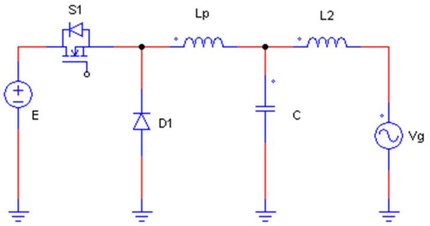


Fig. 10. Equivalent circuit during T1 and T3

During T_1 and T_3 the input voltage E_1 is greater than grid voltage, so this should act as a pure VSI. Hence the switch S_3 is ON, S_4 works at high frequency and all other switches are in OFF condition.

Now, during the interval T_2 the amplitude of input voltage is lower than that of the grid voltage, so the inverter should operate as a boost converter. The equivalent circuit in this mode is shown in the Fig.11.

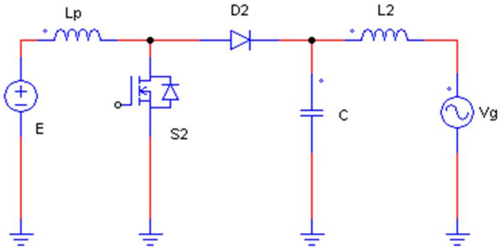


Fig.11. Equivalent circuit of time interval T_2

In this interval switches S_1 and S_3 are ON and S_2 operates at high frequency. From the circuit it is clear that the inverter acts as pure CSI with a CL filter at the end.

In the negative half cycle the operation is similar and time sequence is shown in Fig. 12.

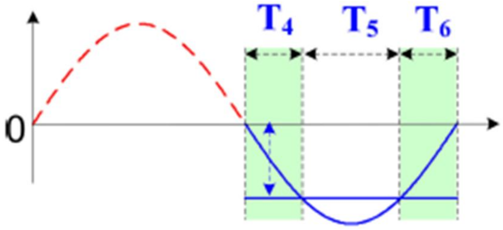


Fig. 12. Working sequence of negative half cycle during Mode 2

During T4 and T6, input voltage is lower than the grid voltage so it should act as buck converter. The equivalent circuit is shown in Fig. 13.

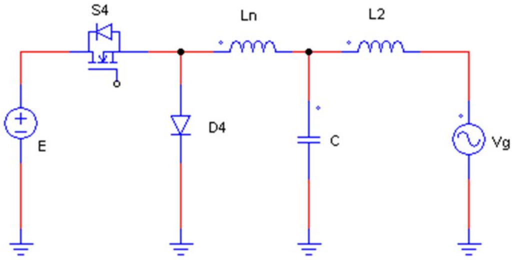


Fig.13. Equivalent circuit during T_4 and T_6

From this figure it is clear that it is pure VSI connected to the grid with an LCL filter. Switch S_6 is ON and S_4 works at high frequency, rest of the switches are OFF.

During T_5, the input voltage is lower than the grid voltage. And the inverter should operate as a CSI. Fig. 14 shows the equivalent circuit during the time interval T_5 and it is a pure CSI with CL filter connected to the grid. Here three switches are in ON condition. S_4 and S_6 is ON, S_5 works at high frequency.

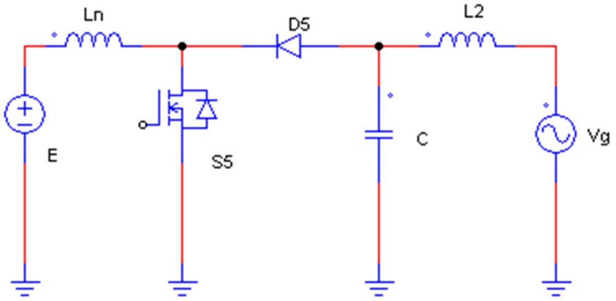


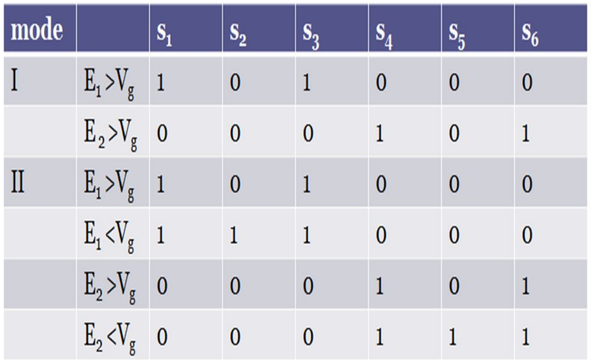
Fig.14. Equivalent circuit during T_5

From the previous analysis it is understood that in all modes only one switch operate at high frequency and improves the efficiency by reducing the switching loss.

Conventional Aalborg inverter has the advantage of low switching losses by operating only one switch at high frequency. It can operate both as CSI and VSI so there is no need of any separate converter.

Conventional Aalborg inverter is designed such that the input dc voltage is assumed to vary from 150V to 300V. This inverter is mainly designed for the application of renewable energy source to the grid. But in practice high voltage range of 150V to 300V cannot be obtained from renewable energy sources, so an additional converter may be required most of the time. Then Aalborg inverter is designed with a dual supply, but realizing this in hardware is difficult.

TABLE I. SWITCHING TABLE



mode		S_1	S_2	S_3	S_4	S_5	S_6
I	$E_1>V_g$	1	0	1	0	0	0
	$E_2>V_g$	0	0	0	1	0	1
II	$E_1>V_g$	1	0	1	0	0	0
	$E_1<V_g$	1	1	1	0	0	0
	$E_2>V_g$	0	0	0	1	0	1
	$E_2<V_g$	0	0	0	1	1	1

IV. MODIFIED AALBORG INVERTER

To overcome the disadvantages of the conventional Aalborg inverter a separate supply circuit is designed. Modified Aalborg inverter is designed in a way which has only one power supply. This single power supply circuit is split into two voltages with equal amplitude and acts as dual supply. These voltages can be treated as E_1 and E_2 in the conventional Aalborg inverter. Thus the working of modified circuit remains the same as that of the conventional inverter.

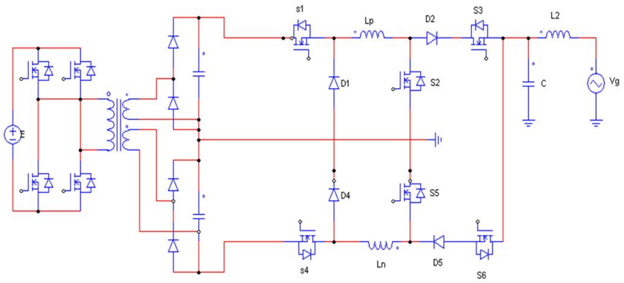


Fig. 15. Circuit diagram of Modified Aalborg inverter

Fig.15 shows the schematic circuit of the modified Aalborg inverter consisting of only one power supply. The single power supply is divided into two separate dc sources using a simple push-pull circuit. The input voltage of this modified circuit can vary from 40V onwards. This input voltage can be boosted to thrice its value by changing the turn's ratio of the transformer. Therefore dual voltage of equal amplitude is obtained and it is equal to the working range voltage of conventional Aalborg inverter. This modified circuit is well suited for the application of renewable energy resources. For example output voltage from photovoltaic panel can vary according to the temperature conditions. At times it provides only low voltage such as 40V etc. For this PV panel to be connected to the grid modified Aalborg inverter is well suitable.

V. CONTROL LOOP

For controlling the buck and boost switches in both half cycles a separate control method have been designed [8]. The control circuit is shown in Fig. 16.

The input signals to the control loops include the input dc voltages E_1 and E_2, the grid voltage Vg and the inductor currents i_{lp} and i_{ln}. The control loop works by comparing the dc voltage and the grid voltage.

If the input voltage is higher than the grid voltage then the buck control loop works. In buck control loop boost switches will be OFF. The reference current is derived as

$$Iref_{buck} = \frac{|v_g(t)|}{R_f}$$

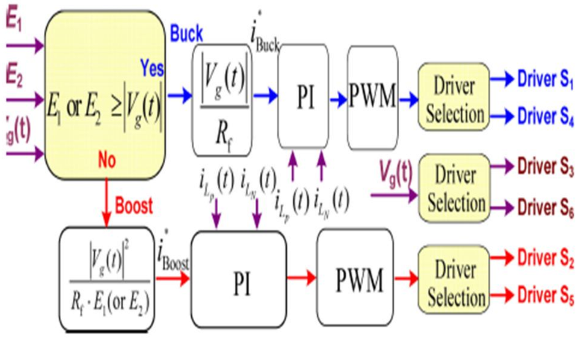


Fig. 16. Control diagram

where R_f is the equivalent resistor. This reference current is given to PI controller. This PI controller checks for the steady state error between reference current and the inductor current. This error is further provided to PWM generator which produces the necessary PWM to drive the buck switches S_1 and S_4. Similar is the case in boost control loop.

If the input voltage is lower than the grid voltage the control becomes little complicated and an indirect current control loop is adopted. The reference current can be derived as

$$Iref_{boost} = \frac{|V_g(t)|^2}{R_f.\ E_1/E_2}$$

This reference current is given to the PI controller which checks the steady state error between reference current and inductor current. This error is processed to the PWM generator and produces necessary PWM to switch the boost switches S_2 and S_5.

Switches S_3 and S_6 are low frequency switches which is directly been switched from the reference grid voltage.

VI. SIMULATION

The validity of the modified Aalborg inverter is analyzed through simulation which is carried out in Mat lab Simulink. Simulation parameters are listed in the below table.

TABLE II. DESIGN PARAMETERS

Parameters	Unit
L2	600µH
C	2µF
L_p, L_n	600µH
Fs(s1,s2,s4,s5)	40 KHZ
Fs (s3,s6)	50 HZ

A. case 1

When the input voltage is higher than the grid voltage, that is E_1 and E_2 is equal to 400V. Simulation result is shown below. From Fig.17 it is seen that output voltage is obtained as a perfect sine wave with the same amplitude of grid voltage. Load current is also obtained as sine wave. So buck control loop is working in proper.

B. case 2

When input voltage is less than the grid voltage boost control loop should work correctly. This condition is analyzed by giving input voltage 40 V which is boosted to 150V.

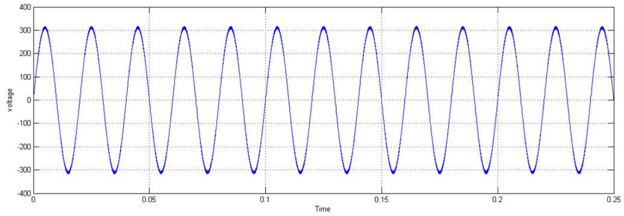


Fig 17. Load voltage when input voltage is 400V

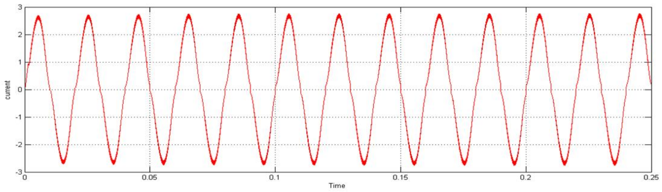


Fig. 18. Load current when input voltage is 400V

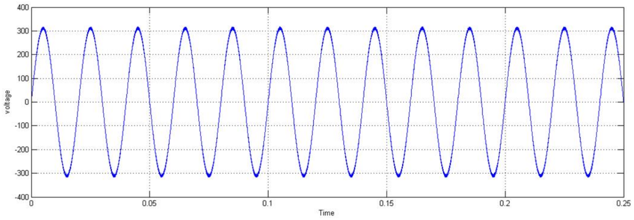


Fig. 19. Load voltage when E1 or E2 is 150V

It is observed from Fig. 19 that load voltage is sinusoidal with amplitude of 325V as that of the grid rms voltage even when the input voltage is lower than the grid voltage.

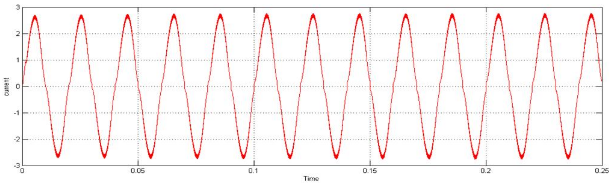


Fig. 20. Load current when E1 or E2 is 150V

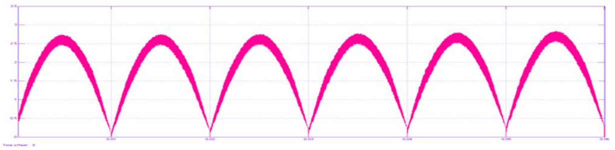


Fig. 21. Inductor current waveform

From the simulation results it is clear that the modified Aalborg inverter satisfies the requisites of the grid tied inverter.

VII. CONCLUSION

The proposed inverter works as CSI when the input voltage is less than the grid voltage and operates as VSI when the input voltage is higher than the grid voltage. This inverter is mainly suitable for renewable energy resources. The input dc voltage range can vary from 40V by making it to single supply by using a push pull circuit. Efficiency is higher because only one switch operates at higher frequency during a power stage.

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