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Simulation of Single Stage Inverter with High Voltage Gain for Distributed Energy Resources Using PSIM

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Abstract*— *This paper presents the simulation of high voltage gain single stage inverter for distributed energy resources using PSIM software. In this, a Cuk derived circuit is integrated with Fly back auxiliary circuit to achieve high voltage gain. Here the capacitors of Flyback and Cuk circuits are paralleled for charging and connected in series for discharging. Due to capacitive voltage dividing, DC side switch voltage stress is reduced and losses are also reduced, hence gain can be increased. Simulation results are given to show the merits of the inverter.

Index Terms*— *Distributed energy resources (DER), Cuk derived voltage source inverter, Flyback auxiliary circuit, high voltage gain, PSIM

I. INTRODUCTION

In today's world, distributed energy resources have come to light because of the increasing concern about energy demand and environmental aspects like global warming. Distributed energy resources (DER) generate electricity from small energy resources like solar and wind. Distributed generation (DG) allows collection of energy from many sources and may give lower environmental impacts and improved security of supply. DG systems are used to deliver electrical power to utility grid [5] or used as standalone power supplies in remote areas [7]. Solar cells, fuel cells, batteries and ultra capacitors are all low voltage DC source, hence a high voltage DC-AC conversion is essential and many DC/AC converters have been proposed.

The resulting efficiency of a two stage or a multistage converter will be degraded because of its complexity and high cost [3]. We can also use a DG unit with shunt active power filter capabilities but the integration of power quality features increases the overall current and cost [2]. Photovoltaic modules are connected into single phase grid connected inverter. But the use of electrolytic capacitors increases reliability which further increases cost [4]. Sepic, cuk or zeta derived DC/AC converters are also proposed. Here the control of AC and DC parts of converter circuit is integrated to achieve ideal characteristic of single stage three phase Sepic AC/DC rectifier. Boost mode is used and maximum output power at reasonable cost is limited [6]. However only very few existing DC/AC converter can achieve high voltage while maintain rather good efficiency [1]. In this paper, a high voltage gain single stage inverter for distributed energy resources has been proposed. Here a cuk derived circuit is integrated with flyback auxiliary circuit to achieve high voltage gain. Capacitors of the flyback and cuk circuit are paralleled for charging and connected in series for discharging. The DC side switch voltage stress is reduced due to capacitive voltage dividing and low voltage rating devices can be used to further reduce both switching and conduction losses to increase conversion efficiency. This inverter achieves high voltage gain and suitable for DER applications

II. SINGLE STAGE INVERTER

In this Inverter, Cuk derived voltage source inverter is integrated with Flyback auxiliary circuit [1] to achieve high voltage gain. The output capacitor of the fly back circuit is placed in series with the secondary side capacitor of Cuk converter. Also, through this capacitor voltage divider, the voltage stress of DC side switch will be reduced significantly. From fig.1.there is one DC side switch Q and four AC side switches QA, QB, Qa and Qb. The capacitors of cuk and flyback circuits are paralleled for charging and connected in series for discharging [7]. Due to capacitor voltage dividing, DC side switch voltage stress is reduced. V_S denote the input voltage, L_b denote the input boost inductor. C_P and C_S represents the Primary and secondary capacitors. C_f is the energy storing capacitor. Two diodes D_S and D_f. L_O, C_O and R represent the output inductor, output capacitor and resistor respectively. L_k and L_m denote leakage inductance and magnetizing inductance respectively. The low influence of coupling coefficient α of flyback circuit renders inverter design flexible and easy. The cuk converter can step up or step down the output voltage by controlling the duty cycle of the switch.

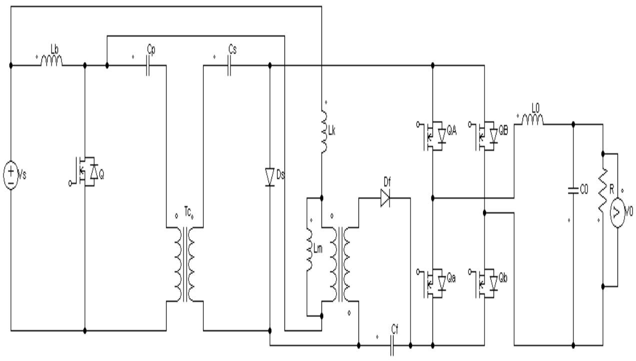

Fig. 1 Circuit diagram of Single stage inverter

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$$\alpha = \frac{L_m}{L_k + L_m} \qquad (1)$$

The inverter boosts its input voltage to DC link voltage by controlling the duty cycle of the DC side switch. The figure.2 below shows the modulation scheme of the inverter.

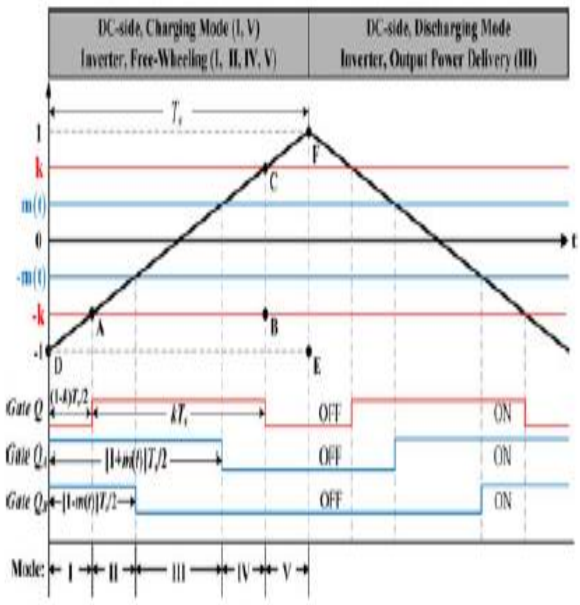

Fig. 2 Modulation Scheme of the Inverter

III. OPERATING PRINCIPLE OF SINGLE STAGE INVERTER

There are five modes of operation. The five modes are explained briefly.

Mode I: Switches *QA and QB* are turned ON. *Q, Qa, Qb* are turned OFF. D_S and D_f are forward biased. Energy stored in boost inductor L_b and leakage inductance L_k is released to capacitors in primary and secondary sides of transformer T_C. Then input power is delivered to secondary side through T_f to charge C_f. Output power is supplied from output filter.

Mode II: Switches *Q, QA* and *QB* are turned ON. Switches *Qa*, and *Qb* are turned OFF. D_S are D_f are reverse biased. Magnetizing inductor L_m and input boost inductor L_b are charge by V_S. At the same time, output power is still supplied from output filter.

Mode III: Switches *Q, QA* and *Qb* are turned ON and *Qa* and *QB* are turned OFF. Diodes D_S and D_f are reverse biased. Current through L_b and L_m increase to store energy in boost inductor L_b and magnetizing inductor L_m. Capacitors C_S and C_f are connected in series to give DC- link voltage ($V_{bus}= V_{CS}+V_{Cf}+N_C V_{CP}$) to deliver energy through switches *QA* and *Qb* to externally connected AC load.

Mode IV: Switches *Q, Qa* and *Qb* are turned ON and *QA* and *QB* are turned OFF. D_S and D_f are reversed biased. Input boost inductor L_b and magnetizing inductor L_m are charged by V_S. Mean while AC side of the inverter enters into freewheeling operation mode and output power is supplied from output filter.

Mode V: Switches Qa and Qb are turned ON and Q, QA and QB are turned OFF. D_S and D_f are forward biased. Energy stored in boost inductor L_b and leakage inductance L_k is released to capacitors C_P and C_S. At the same time, input power is delivered to secondary side through T_f to charge C_f and the AC side of the inverter remains in freewheeling mode and output power is still supplied from output filter.

The key waveforms of the single stage inverter are shown in Fig.3.

IV. DESIGN EQUATIONS

T_S is the switching period of DC side switch *Q*, *k* is the duty ratio of *Q* and m(t) is the modulation index of the AC side inverter. The turn ON period of switch is kT_S and the corresponding turn OFF period of *Q* is $(1-k)T_S$. Based on the previously mentioned operating modes, the voltage conversion ratio of the inverter can be calculated according to voltage second balance principle of inductors. The voltage second balance equation for inductor Lb becomes:

$$(V_S - v_{cp} - (\frac{v_{cs}}{N_c}))(1-k) + V_S(k-M) + V_S M = 0 \qquad (2)$$

$$V_S = (1-k)(v_{cp} + \frac{v_{cs}}{N_c}) \qquad (3)$$

Where *M* represents the peak value of modulation index m(t) of AC output reference. The voltage second balance equation for equivalent inductance *Lp* in the primary side of the isolated transformer is

$$\frac{v_{cs}(1-k)}{N_c} - v_{cp}(k-M) - v_{cp}M = 0 \qquad (4)$$

From this, we get

$$v_{cs} = \frac{k}{1-k} N_c v_{cp} \qquad (5)$$

From (3) and (4), voltage across capacitors C_P and C_S of the inverter can be obtained.

$$v_{cp} = V_S \qquad (6)$$

$$v_{cs} = \frac{k}{1-k} N_c V_S \qquad (7)$$

Voltage across the capacitor C_f is

$$v_{cf} = \frac{\alpha k}{1-k} N_f V_S \qquad (8)$$

From (6), (7) and (8)

$$V_0 = (\frac{1}{1-k} N_c + \frac{\alpha k}{1-k} N_f) M V_S \qquad (9)$$

Voltage conversion ratio or Gain G_V of the inverter is

$$G_v = \frac{V_0}{V_s} = (\frac{1}{1-k} N_c + \frac{\alpha k}{1-k} N_f) M \qquad (10)$$

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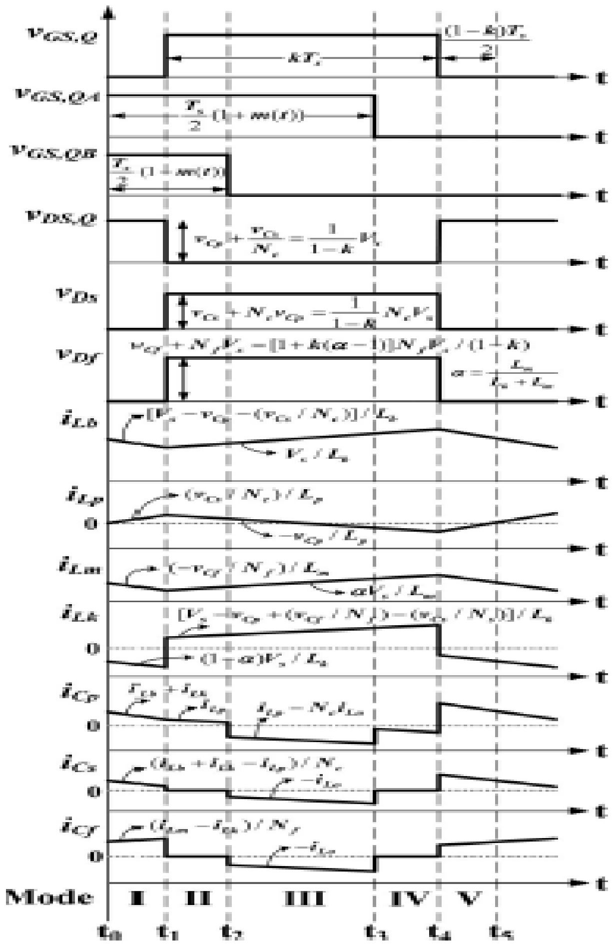

Fig. 3 Waveforms of single stage inverter

V. SIMULATION OF SINGLE STAGE INVERTER

The Single stage Inverter is simulated using PSIM software. We can use PSIM software version 9. Simulation results are shown to understand the merits of the inverter. Given below is the Table I of the circuit design parameters.

TABLE I. DESIGN PARAMETERS

Parameters	Part No.
Input voltage Vs	24V
Input Boost inductor Lb	300µH
Transformer (T_c & T_f)	1.Transformer T_c Turns ratio= 1:N_c, where N_c = 1.23 Leakage inductance L_k = 1.2Mh Magnetizing inductance, Lm = 800µH 2. Transformer T_f Turns ratio= 1:N_f, where N_f = 1.72 Leakage inductance Lk = 1.2µH Magnetizing inductance Lm = 500µH
Capacitors	Cp = 33µF/100VAC Cs & Cf = 560µF/200VDC C0 = 2.2µF
Output inductor	L0 = 1mH
Diodes D_s and D_f	15S2TH06FP
DC side switch Q	IXTQ30N60P
AC side switches QA,QB,Qa & Qb	IXFH120N20P
Switching frequency	20kHz
Duty cycle, k	0.8
Modulation index, M	0.75

We have to design a control circuit for DC side and AC side switches. The input to the DC side switch Q is a triangular waveform which is shown in fig.2 as the modulation scheme of the inverter. Fig. 6 shows the simulated circuit using PSIM software.

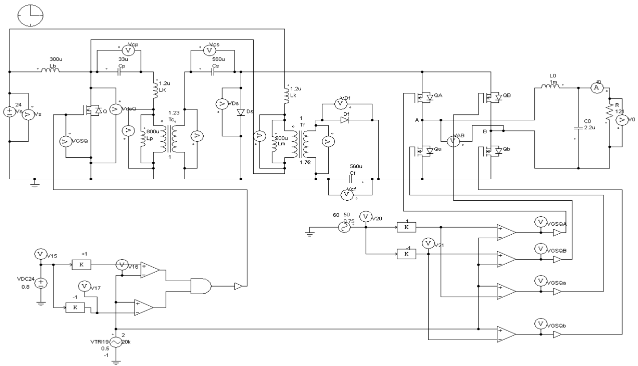

Fig. 6 Simulated diagram of single stage inverter PSIM

It can be seen that for an input voltage V_S = 24V, the 230V peak AC output voltage can be achieved with a duty cycle of 0.8 of the DC side switch and modulation index of 0.75. The maximum value of line voltage V_{AB} is about 314V. The DC side circuit can be seen as a boost function for boosting the low input voltage and the AC side circuit is used to invert a DC voltage to an AC output. We can control the voltage gain by changing the values of duty cycle *k* of the DC side switch and modulation index *M* of the AC side switches.

Simulation results

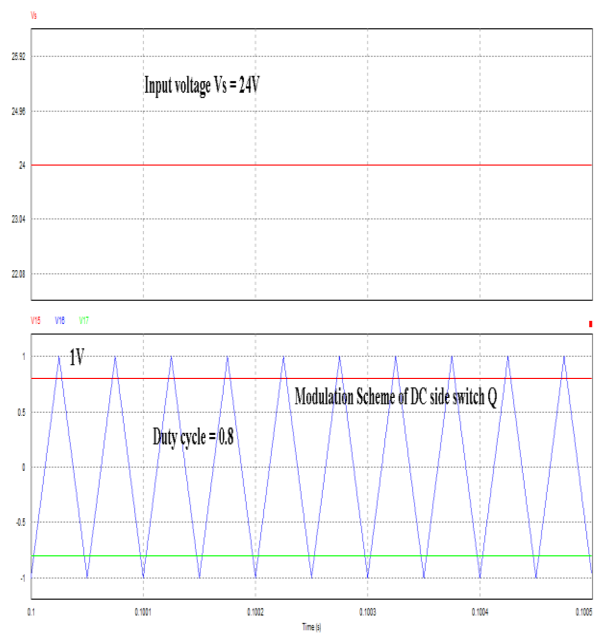

Fig.7 Waveforms of input voltage V_s and modulation scheme

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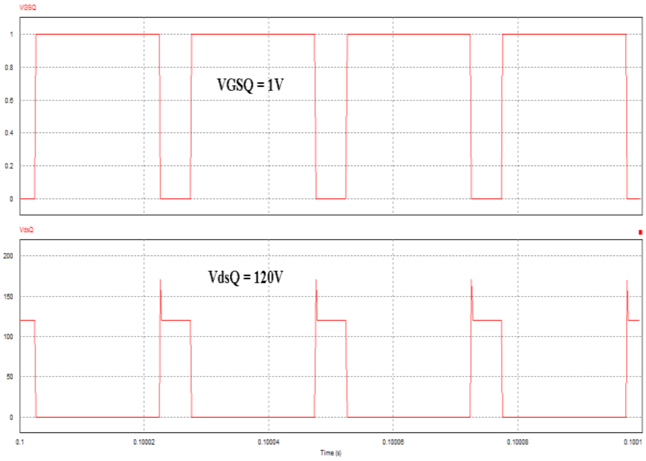

Fig.8 Waveforms of DC side MOSFET driving signal and switch voltage

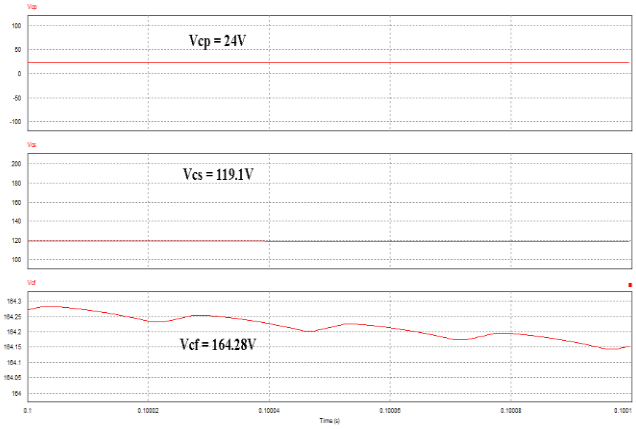

Fig.9 Waveforms of capacitor voltages

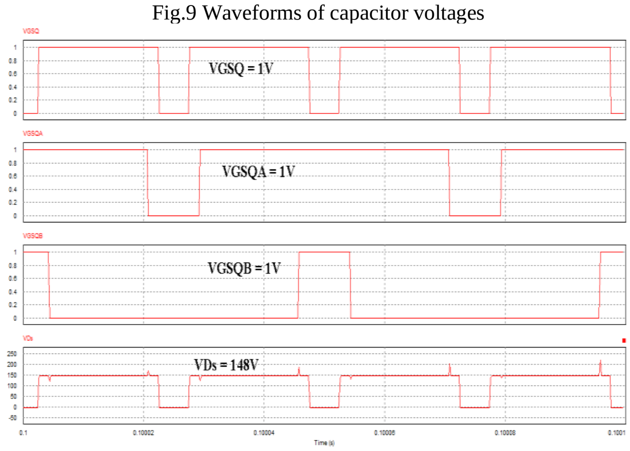

Fig.10 Waveforms of MOSFET driving signals and diode voltage V_{Ds}

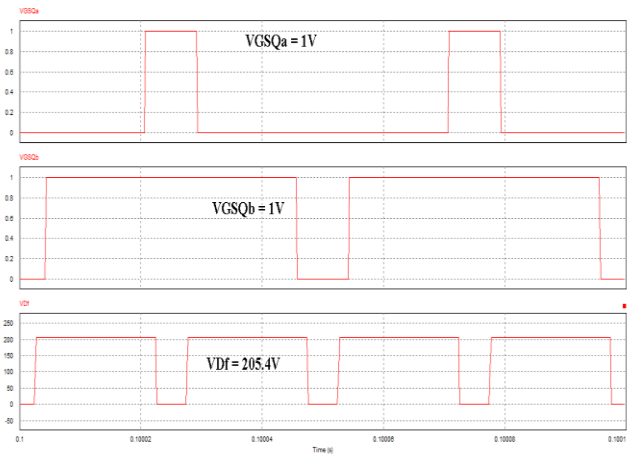

Fig.11 Waveforms of MOSFET driving signals and diode voltage V_{Df}

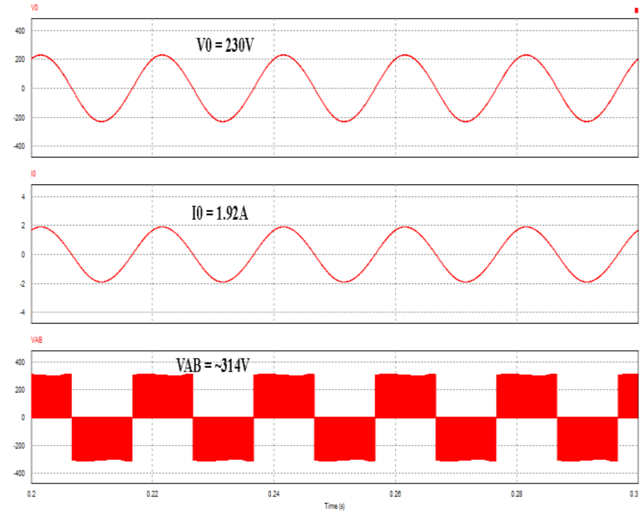

Fig.12 Waveforms of output voltage V_0, output current I_0 and line voltage V_{AB}

By understanding the modes of operation of the inverter, we can analyze the same in fig.10 and fig.11 waveforms. Voltages across the capacitor C_P are charged to 24V and voltages across the capacitor C_S are charged to 119.1V and that of C_f is charged to ~164.28V. Note that the voltage spikes in $VdsQ$, VD_S and VD_f in fig.8, fig.10 and fig.11 is due to leakage inductance of the power transformer T_f. An output voltage of 230V is obtained with an output current of 1.92A and line voltage V_{AB} about 314V. Both the capacitors C_P and C_S share most of the output voltage for reducing the voltage stress of the dc side active switches. Voltage stress by the bus voltage of the proposed inverter is given by

$$\frac{1}{N_c + \alpha k N_f} = 0.38\text{V} \qquad (11)$$

The voltage stress by the bus voltage of conventional circuit is given by

$$\frac{1}{N_c} = 0.81\text{V} \qquad (12)$$

From (11) and (12), we can see that the voltage stress is reduced in case of proposed inverter compared to that of conventional circuit. So when the voltage stress is reduced, losses are also reduced and hence efficiency of the inverter will be high and gain will be high. Increasing the values of k and M, the output voltage will increase and we can get an ac output above 230V. The AC output that we obtain can be connected to a grid. Gain of the inverter is calculated to be 9.7, which is more compared to that of conventional circuit with a gain of 3.75. Table II shows the voltage gain for the single stage inverter and a conventional circuit.

TABLE II. VOLTAGE GAIN OF DIFFERENT INVERTERS

Circuits	Voltage Gain
High voltage gain single stage inverter	$(\frac{1}{1-k} N_c + \frac{\alpha k}{1-k} N_f)M$

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Conventional Cuk derived single phase inverter	$\frac{M}{1-k}$

VI. CONCLUSIONS

A High voltage gain single stage inverter is designed for Distributed Energy Resources (DER) applications and simulated using PSIM software. Due to capacitive voltage dividing, DC side switch voltage is reduced. In other words efficiency will be high. For an input voltage of 24V, 230V output voltage is obtained and voltage stress is about 0.38V. Gain of the inverter is higher compared to the conventional circuit. Operating principle, design equations and simulation results are given to show the merits of the single stage inverter.

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