An Inverter with Coupled Inductor

John Ninan, Jasna S.B

Abstract— **Energy demand is increasing day by day. To meet this renewable energy sources have to be incorporated. Renewable energy sources like PV cells, fuel cells produce DC voltage. For house hold purpose and industrial purpose this DC voltage has to be converted into AC voltage. For this power electronic inverters are used. Multilevel inverters has got wide spread acceptance as it can synthesis almost sinusoidal wave form. This paper deals with a single phase multilevel inverter which can produce a five level AC output voltage from a single DC source. The operation mechanism of this inverter is analyzed in detail. Simulation as well as the prototype shows the feasibility of the paper.**

Index Terms—**Coupled inductor, Multilevel inverter, Power converter, Pulse width modulation.**

I. INTRODUCTION

Multilevel inverters have changed the face of medium and high voltage drives. The most popular single phase multilevel topologies are the diode-clamped, capacitor clamped and cascaded types [1]- [4]. There exist many other topologies. So multilevel inverter topologies can be classified into two types: Type I and Type II. Type I uses multiple DC voltage sources and Type II uses multiple (split or clamping) DC voltage capacitors [5]. As the level increases, the required number of DC sources also increases in Type I. This made the use of Type I a limited one. Type II is limited mainly by the balancing of the capacitor voltages. So the most desirable topology may be, a multilevel inverter with single source and no split capacitor.

Multilevel inverters with coupled inductors need only one source besides split capacitors are not required. For the inverter with coupled inductor, a three limb coupled inductor is the most desirable one; however coupled inductor with high inductance value is not preferred [6]. The analysis of the coupled-inductor designs in [7] suggests that reducing the target inductance of the coupled inductor could improve the overall balance of losses in the coupled inductor, with only a minor increase in ripple current. The number of voltage levels can be increased by using a split-wound coupled inductor within each inverter-leg and using interleaved pwm switching of the upper and lower switches [8]. The coupled inductor provides excellent protection against dc-rail shoot-through conditions.

Manuscript received Aug, 2014.

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II. FIVE LEVEL INVERTER TOPOLGY

The inverter used in this paper can synthesis an AC voltage with five levels from a single DC source. Besides in this inverter, no voltage split capacitors are used.

Fig. 1 shows the circuit of the single-phase five level inverter. 2E is the dc-link voltage and L_1 and L_2 are the coupled inductors. The mutual inductance of the two inductors is M and the output terminals of this inverter are 1 and 2.

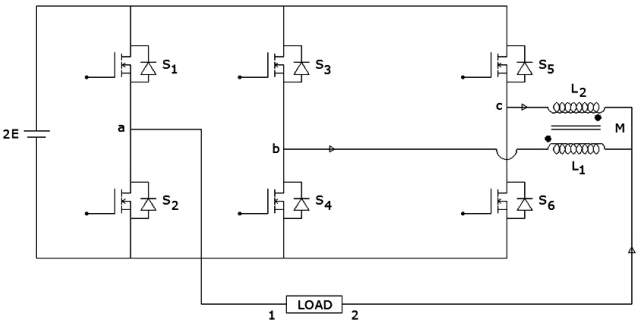

Fig. 1: Single-phase five-level inverter

A. Switching States for Five Level Output Voltage

The power switches in one arm are assumed to switch complementarily. For an instant switch S_1 is ON then the switch S_2 must made OFF and vice versa. Similarly in case of S_3, S4 and S_5, S6. The details of the switching state is given in the below table.

TABLE I: Switching states for five-level output voltage

S_1	S_3	S_5	u_{12}
1	0	0	+2E
1	0	1	+E
1	1	0	+E
1	1	1	0
0	0	0	0
0	0	1	-E
0	1	0	-E
0	1	1	-2E

The number "1" is used to denote the ON state of one switch and "0" will be used to denote the OFF state. There are mainly four switching states in this inverter circuit. In each

ISSN: 2278 – 7798

case one of the upper switches or a combination of the upper switches is made ON and similarly on the bottom switches. The assumption taken for explaining the cases are the inductance L_1, L_2 of the coupled inductor are equal and the leakage inductance, L_k is zero.

Case-1 (+2E): In this case, the required output voltage level is +2E. To achieve this upper switch S_1 is turned ON along with the lower switches S_4 and S_6 are turned ON. The equivalent circuit becomes Fig. 2

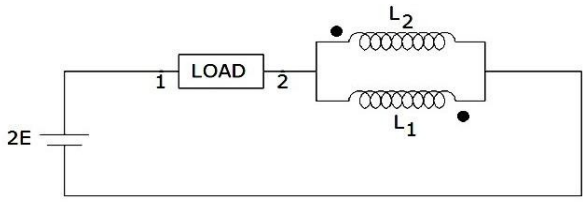

Fig. 2: Equivalent circuit of case1

The inductors are parallel and opposing. So the net or equivalent inductance is

$$\frac{L_1 L_2 M^2}{L_1 + L_2 + 2M} \quad (1)$$

The inductance of the coupled inductor can be expressed as the sum of mutual inductance and the leakage inductance. By considering the assumption it can be stated as $L_1 = L_2 =$ (mutual inductance + leakage inductance) $= M + L_k$. By substituting this in the above equation, the net equivalent inductance become

$$\frac{L_k}{2}$$

(2)

So the net equivalent circuit become Fig. 3.

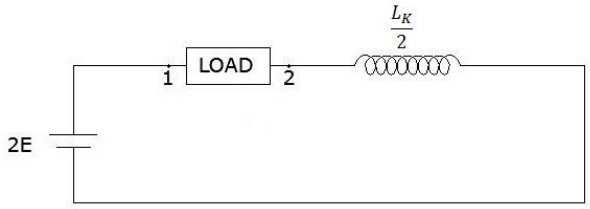

Fig. 3: Net equivalent circuit of case1

The leakage inductance, L_k is assumed to be zero. So +2E voltage across the load.

Case-2 (+E): In this case, the required output voltage level is +E. To achieve this there are two options. Option-1 with upper switches S_1, S_5 are turned ON along with lower switch S_4 is turned ON. Option-2 with upper switch S_1, S_3 are turned ON along with lower switch S_6 is turned ON. The equivalent circuit becomes Fig. 4.

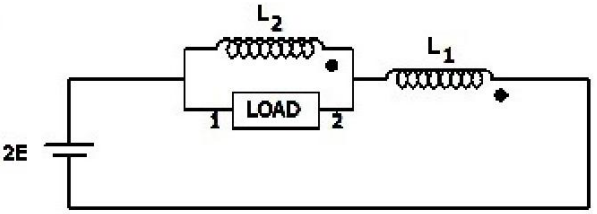

Fig. 4: Equivalent circuit of case2

Now apply Thevenin theorem. Thevenin voltage is given by the Fig. 6. The inductors share the applied voltage equally. So voltage across L_2 is +E. Thevenin impedance is given by the Fig. 7. Inductors are parallel and opposing. So the net inductance is given by

$$\frac{L_k}{2}$$

(3)

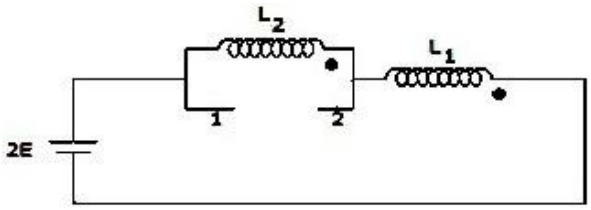

Fig. 5: Load is removed from the equivalent circuit of case-2

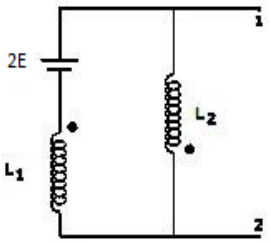

Fig. 6: Thevenin voltage of case-2

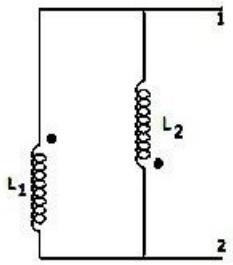

Fig. 7: Thevenin impedance of case-2

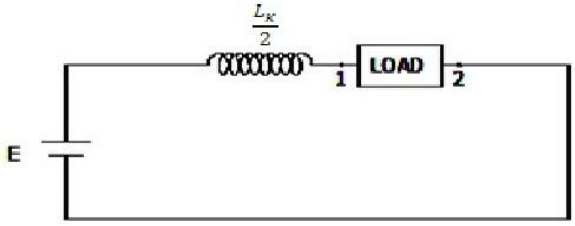

Fig. 8: Thevenin equivalent circuit of case-2

The Thevenin circuit is given by the Fig. 8. The leakage inductance, L_k is assumed to be zero. So +E voltage across the load.

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Case-3 (-E): In this case, the required output voltage level is -E. To achieve this there are two options. Option-1 with upper switch S_5 turned ON along with lower switches S_2, S_4 are turned ON. Option-2 with upper switch S_3 turned ON and lower switches S_2, S6 are turned ON. The equivalent circuit becomes Fig. 9. By applying Thevenin theorem as in the previous case, the Thevenin equivalent circuit is given as Fig. 10. The leakage inductance, L_k is assumed to be zero. So -E voltage across the load as the load is connected from 2 to 1.

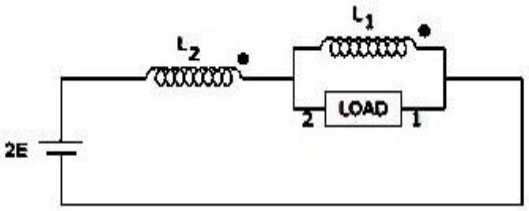

Fig. 9: Equivalent circuit of case3

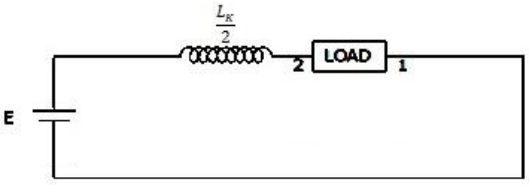

Fig. 10: Thevenin equivalent circuit of case-3

Case-4 (-2E): In this case, the required output voltage level is 2E. To achieve this, upper switches S_3, S_5 are turned ON along with the lower switch S_2 is turned ON. The equivalent circuit becomes Fig. 11.

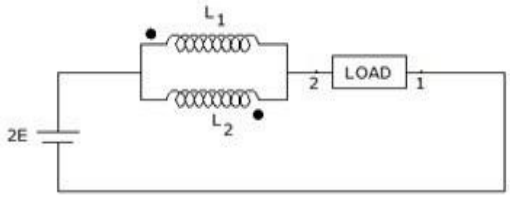

Fig. 11: Equivalent circuit of case4

The inductors are parallel and opposing. So the net or equivalent inductance is

$$\frac{L_1 L_2 M^2}{L_1 + L_2 + 2M} \quad (4)$$

As in case-1, by considering the assumption it can be stated as $L_1 = L_2 =$ (mutual inductance + leakage inductance) = M + L_k. By substituting this in the above equation, the net equivalent inductance become

$$\frac{L_k}{2} \quad (5)$$

So the net equivalent circuit become Fig. 12 The leakage inductance, L_k is assumed to be zero. So -2E voltage across the load as the load is connected from 2 to 1.

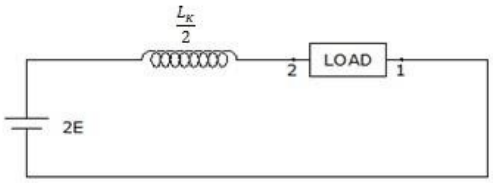

Fig. 12: Net equivalent circuit of case4

B. *Pluse Width Modulation*

By proper modulation the existence of the DC component in the output voltage can be reduced. The DC components in the output voltage result in large current, which may result in the failure of the inverter. By modulation the size and weight of the coupled inductor can be reduced.

III. SIMULATION RESULTS

To verify the validity of the paper, the circuit in this paper is simulated using MATLAB/Simulink tool. The inverter is tested with series connected RL load. A 70V DC source is given as the input. Gate signals to the switches are given according to the data given in the Table I. MATLAB simulation is given in the Fig. 13.

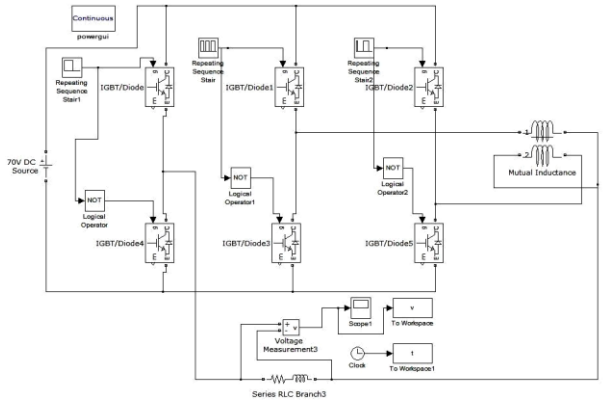

Fig. 13: Simulation of five level inverter with coupled inductor for R-L load

A five level AC voltage is obtained as the output with the input DC voltage as the maximum value. The frequency of the output wave form is 50Hz. Simulation result is given in the Fig 14.

ISSN: 2278 – 7798

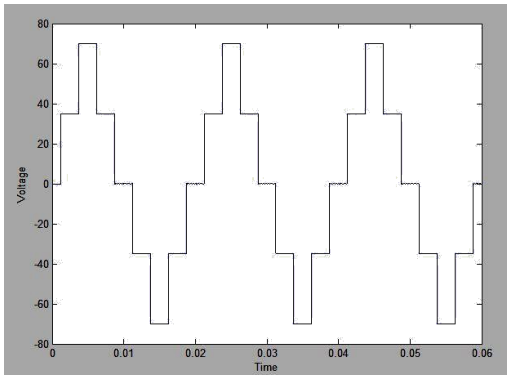

Fig. 14: Simulation result of five level inverter with coupled inductor for R-L load

IV. EXPERIMENTAL RESULTS

Hardware section consists of three parts; control circuit, drive circuit and power circuit. In the control circuit gate signals for the switches are generated according to the logic given in Table I. To produce pulse width modulated gate signal PIC18F4550 is used. Driver circuits are used to boost the gate signal to the required driving voltage of the switches. FAN7392 is used to drive the MOSFET. It is a monolithic high and low side gate drive IC that can drive the high speed MOSFETs. A single FAN7392 can handle two switches on the same arm. The power circuit consists of MOSFET IRF830 and the coupled inductor with mutual inductance of 1mH. The switching frequency is 7kHz. The output is taken across the load of 470ohm and 1.1mH. The input given to the hardware is 70V DC. A five level AC voltage with a peak of 70V is obtained as the output. The frequency of the output waveform is 50Hz. The Fig. 15 is the obtained output wave form. In general, from a single DC source, a five level AC voltage is obtained with the input DC voltage as the maximum value. Laboratory prototype of the five level inverter is shown in the Fig 16.

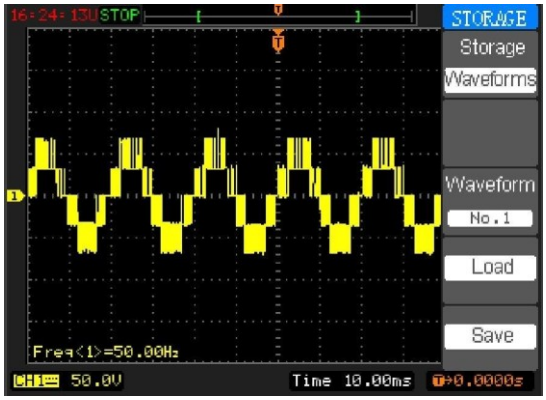

Fig. 15: 70V Five level AC output voltage

V. CONCLUSION

The inverter in the paper can synthesis a five level AC output voltage. Operation mechanism of this inverter was analyzed and the simulation is done using MATLAB/Simulink tool. It required only a single source to produce the five level output. Pulse width modulated gate signals are used in the prototype. Verification of the result shows the validity of the inverter.

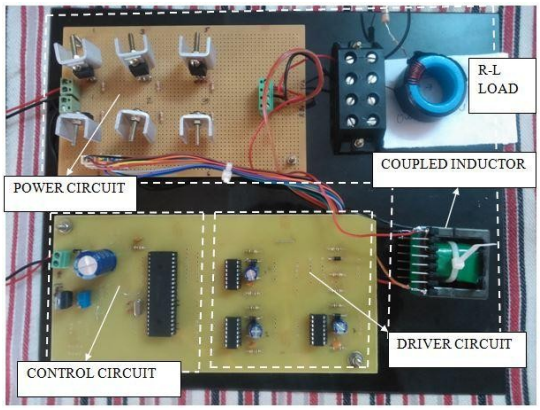

Fig. 16: Laboratory prototype of the single phase five level inverter

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ISSN: 2278 – 7798