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Leakage Current Mitigation in Transformer-less Photovoltaic Inverter Systems for Mining Equipment

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Abstract: Challenging task of leakage current in photovoltaic converter is dealt for the application of portable mining electrical equipment. Inductive load and earth leakage causes distortion in the performance of the equipment in the transformer-less photovoltaic inverter systems. This leakage current introduce electromagnetic interference with neighboring circuits. The basic six device B6 type voltage source inverter is widely used for photovoltaic inverter systems, but leakage current is not addressed. H7 and H8 with additional switching device topologies reduces the leakage current problem and control strategy detects zero voltage states for reduction in switching losses. The proposed concept minimizes the leakage current due to inductance of RL loads, in general and specifically for mining equipment. Simulations study was carried out using MATLAB simulation software. Experimental were also carried out in real time, results showed that, reduced leakage current and total harmonic distortion in the output voltage and current waveforms. The elimination of the transformer and loading effects were analyzed for mining equipment having 1 kW Photovoltaic inverter system.

Keywords: Photovoltaic system, Leakage current, Transformer-less inverter, Total harmonic distortion.

Abbreviations:

PV	*Photovoltaic*
PWM	*Pulsewidth modulation*
C-PWM	*Continuous pulsewidth modulation*
SV-PWM	*Space vector- pulsewidth modulation*
AZS-PWM	*Active zero state - Pulse width modulation*
NS-PWM	*Near state - pulsewidth modulation*
RS-PWM	*Remote state - pulsewidth modulation*
D-PWM	*Discontinuous - pulsewidth modulation*
MD-PDM	*Modified discontinuous - pulsewidth modulation*
RCMV-PWM	*Reduced common mode voltage- pulse width modulation*
THD	*Total harmonic distortion*

I. INTRODUCTION

The emerging use of diesel engines in mining produces CO_2 emissions as well as sound pollution. It leads to inconvenience to the workers in the mines.

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Technological advancements in renewable energy systems is the motivation to explore its utilization in various applications.
Solar is one of the major renewable energy source which is reliable in continuity of supply.
It has manyadvantages like inexhaustible, available for free, green energy and good potential in a country like India [1].
B6 inverters (i.e. inverters with six power electronic devices) are more popularly used in the early days for PV applications with a transformer for isolation purpose, which adds more cost and weight to the system. It also have many power stages which effects the efficiency of the system. Common mode leakage current is the main constraint to the elimination of transformer in the PV inverter systems but it reduces the complexity, size and cost.
The balancing capacitance and fictitious capacitance arising across the PV panel causes the leakage current. This leakage current have the impact on efficiency of the PV system and introduce unwanted signals at the output, increases harmonic distortion. It also induce spurious signals through electromagnetic interference. It demands a mechanism to minimize the leakage charge per time in PV inverter systems.
H7 & H8 PV inverter can reduce leakage current, improve efficiency and improve the output power quality for grid connected systems. Several topologies and control techniques were proposed recently to overcome the difficulty of leakage current. H5 and H6 topologies are proposed originally for single phase PV inverters [2] and same is extended for H7 and H8 topologies respectively for three phase PV systems.
Various traditional PWM techniques are available for the control of inverter, targeting the reduced leakage current and THD. Namely, C-PWM, SV-PWM, D-PWM, not suitable to reduce leakage charge per time in transformer-less PV inverters [3]. Use of additional switches with zero state switching or control of fluctuations in PV panel voltage is key pointto reduce leakage current [4].
The major mining applications includes lighting, hand held mining apparatus, mine water pumps, ventilation systems and drilling jumbos, should facilitate with a power supply, having less harmonics. In surface mines, power supply problems are solved to a greater extentwith latest power electronic converters and renewable energy systems. As an example a drilling machine with transformer-less PV inverter is easy to carry and handle in surface mines, where technicians are required to cover wide area in a day. In this paper, H8 PV system with RL load was analyzed for mining equipment applications. Leakage current is reduced to less than 350 mA which is very less when compared to traditional B6 type inverter.

The results are reviewed and compared among various possible loads in the mining applications.

II. LEAKAGE CURRENT

Leakage current problems are popularly minimized using transformer less PV inverters. This topology gives galvanic isolation (i.e. isolation of load and source by DC/ AC coupling) between PV system and the load [5]. The equivalent circuit for leakage current due to common mode voltage (V_{CM}) and PV capacitance (C_{PV}) is shown in Figure 1. This leakage current discharges the PV Panel and reduces the efficiency of the system. Figure 2 shows the circuit for modelling the leakage current for B6 PV system. The leakage current can be derived from equivalent circuit and can be extracted from Kirchhoff's law given in Equation (1)

$$I_{leakage} = C_{PV} \frac{dV_{CM}(t)}{dt} \qquad (1)$$

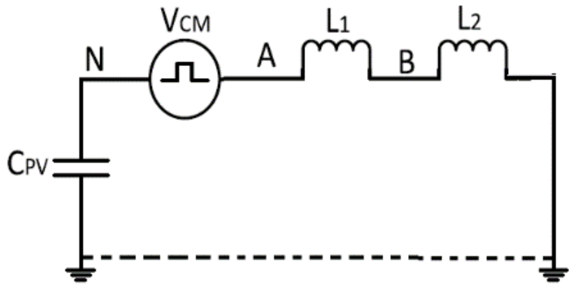

Fig. 1 Equivalent circuit to analyze leakage current

III. PROPOSED H7 AND H8 TOPOLOGY FOR MINING EQUIPMENT REALIZED WITH RL LOAD

The proposed H7 and H8 confutations are shown in Figure 3 and 4 respectively. With devices from S_1 to S_6 forms the basic B6 inverter. Addition of S_7 results in H7 configuration and addition of S_7& S_8 results in H8 configuration. With the removal of transformer only, the leakage current problem arise. Galvanic isolation is obtained by these additional devices S_7 and S_8. Leakage current can be made zero during freewheeling periods in case of RL or RLE loads with DC/ AC decoupling. Various PWM techniques are tried by the researchers in the earlier. These PWM techniques mostly differed based on production of zero vector and reference vector. Two opposing active vectors are used to produce zero vector in AZS-PWM and three triangular vectors are used to produce zero vector in NS-PWM. Group of odd/even vectors are used to produce desired voltage vector, in RS-PWM. RS-PWM only focus on leakage current but neglects the overall performance of the PV inverter. RCMV-PWM technique is used to reduceminimize common mode voltage and leakages charge per time without using zero vectors. But the elimination of zero vectors introduce the issue of voltage linearity, and harmonic distortion. Conventional SV-PWM and D-PWM provides good performance, simplicity, reduced switching losses and harmonics. And the voltage vector are shown in Figure 5.

The common mode voltage of a three phase inverter is expressed as (2) [20, 21].

$$V_{CM} = \frac{V_{an} + V_{bn} + V_{cn}}{3} \quad (2)$$

The common mode voltage for different switching states are mentioned in Table I. Pulse patterns for various PV inverter systems PWM techniques are clearly mention in [1].

In this study, the inverter was controlled by MD-PWM technique (a pulse patterns is a combination of NS-PWM and RS-PWM/ AZSPWM). This technique is applied toreduce the leakage current, without sacrificing the overall performance. Basic D-PWM proved to be best for voltage linearity, harmonics reduction and switching losses. But it causes the leakage charge per time and ripples in the output current. Although galvanic isolation is possible both with DC & AC decoupling, AC decoupling results better performance with reduction in switching losses [2]. Galvanic isolation reduces leakage current up to some extent only and further reduction can be obtained by common mode voltage clamping. Optimal clamping performance is obtained by zero state rectifier voltage switching not shown in the structure for simplicity.

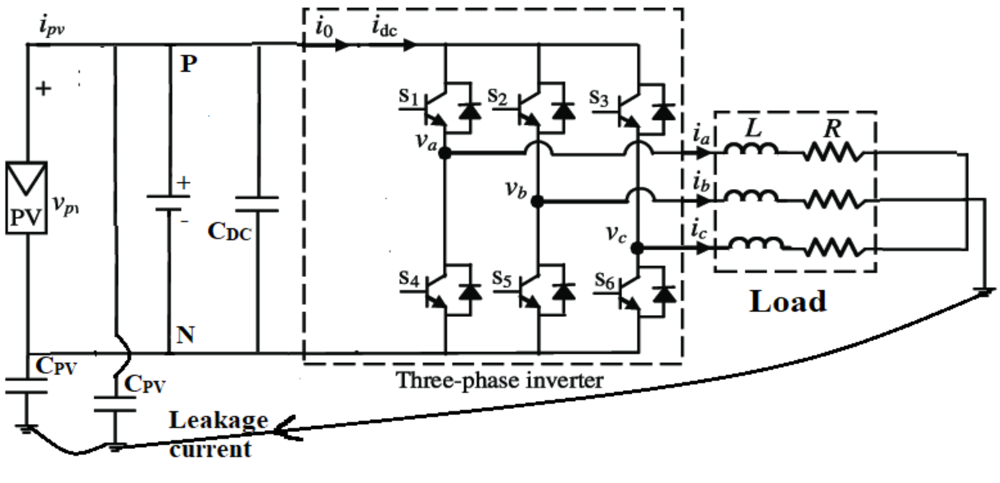

Fig. 2 Transformer-less B6 photovoltaic inverter with RL load

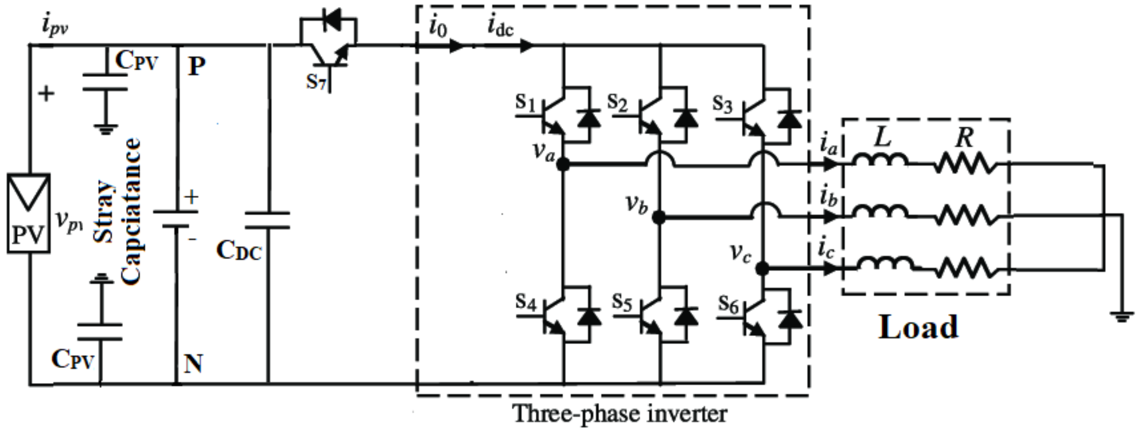

Fig. 3 Transformer-less H7 photovoltaic inverter with RL load

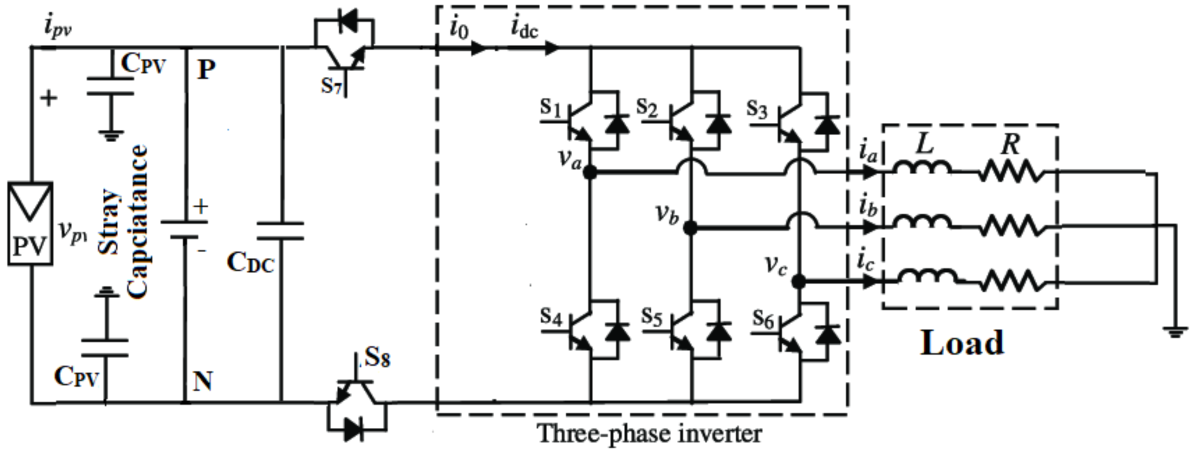

Fig. 4 Transformer-less H8 photovoltaic inverter with RL load

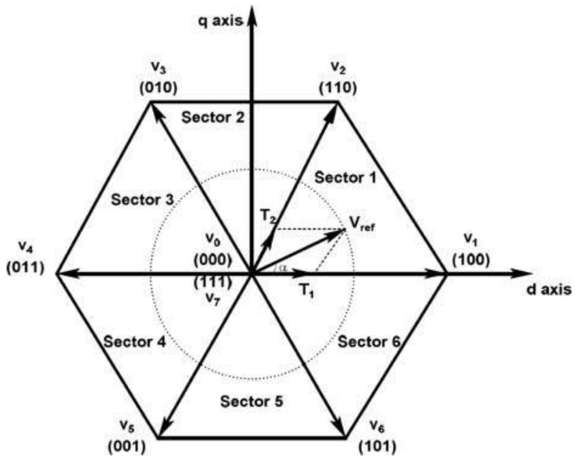

Fig. 5 State space representation of voltage vectors [6]

Table ICommon mode voltages for inverter switching states

Switching state ($S_1S_2S_3$)	Voltage vector	Common mode voltage
100	V_1	$\frac{V_{dc}}{3}$
110	V_2	$\frac{2V_{dc}}{3}$
010	V_3	$\frac{V_{dc}}{3}$
011	V_4	$\frac{2V_{dc}}{3}$
001	V_5	$\frac{V_{dc}}{3}$
101	V_6	$\frac{2V_{dc}}{3}$
111	V_7	$\frac{V_{dc}}{3}$

D-PWM performs well with transformer type PV applications in view of losses and THD, but it yields high leakage current and voltage ripples. MD-PWM is used to overcome such problems. Inverter switching states are controlled like normal inverter for the desired voltage. S_7 and/or S_8 are controlled to reduce leakage current. It uses all active and null state vectors to produce desired output voltage as listed in Table I. Null state vector can be obtained V_7 state. If V_1, V_2….V_7 states are indicated by 1, 2….7 then sector switching pattern for the Figure 5 is tabulated in Table II. Pulse pattern of D-PWM and MD-PWM only differs in null vector implementation in regions 2, 4 & 6. D-PWM locks the common mode voltage between $\frac{V_{dc}}{3}$ & V_{dc} in sectors 1, 3 & 5.

Where as in sectors 2, 4, & 6 it locked between $\frac{V_{dc}}{3}$ & $\frac{2V_{dc}}{3}$.

Null vector of V_0 influence the output voltage profile and reduces current ripples.

Table II Inverter switching pattern for each switching state

Sector Number	Switching pattern
1	72127
2	23732
3	74347
4	45754
5	76567
6	61716

IV. SIMULATION OF MD-PWM SOLAR PV SYSTEM

Simulation was implemented according the circuit diagrams shown in Figure 3 and 4. The simulation was carried out using MATLAB simulation software. Inclusion of S_7 forms H7 configuration. Leakage current flows during freewheeling period between load and PV panel during null state of 0 & 7. To stop this leakage current between load and PV panel, $S_7$is included in conventional basic B6 inverter. Proper control of this additional switch with the proposed MD-PWM can reduce the leakage current.

Using the equivalent circuit of Figure 1, the common mode voltage is given by

$$V_{CM} = \frac{V_{an} + V_{bn} + V_{cn}}{3} = \frac{V_{dc}}{3} \qquad (3)$$

Equation (3) shows that common mode voltage is reduced by three times in H7 and H8 topology when compared to B6 inverter.

V. SIMULATION RESULTS

Figure 6 and 7 shows that the simulation waveforms output voltage, current and it's THD. From the Figure 6 and 7, it is clear that the load current is fairly sinusoidal with reduced harmonic content. They also shows that, the common mode voltage is found to be $\frac{V_{dc}}{3}$ for switching states 1,3& 5. And it is $\frac{2V_{dc}}{3}$ for the switching states 2, 4 & 6. Null state is obtained by switching ON all the upper group of switches.

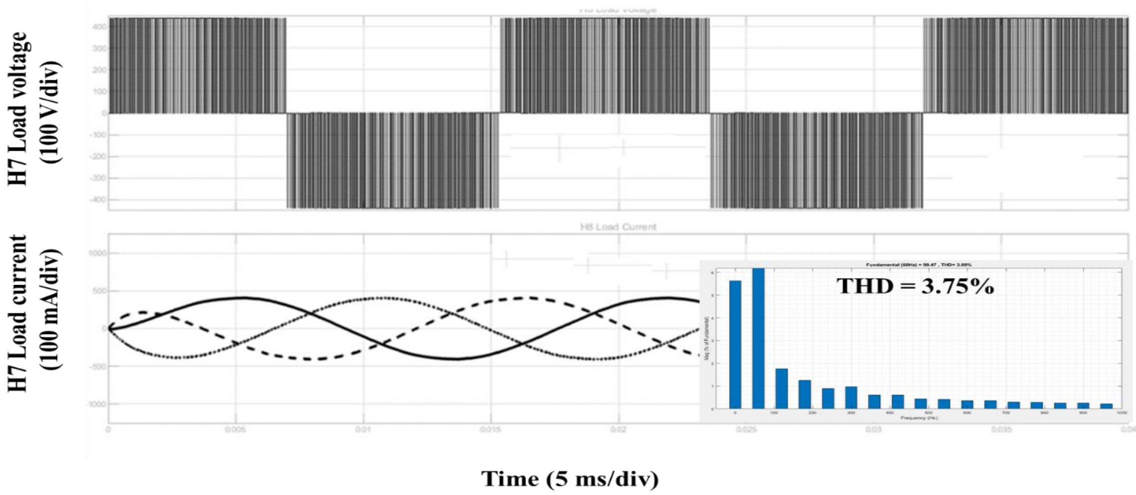

Fig. 6 Load voltage, current and THD with H7 photo voltaic inverter

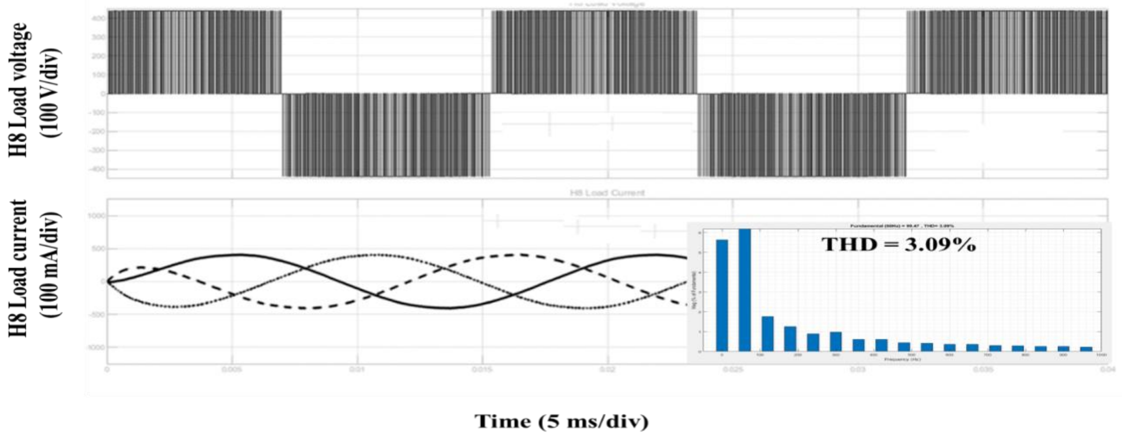

Fig. 7 Load voltage, current and THD with H8 photo voltaic inverter

The corresponding common mode voltage is $\frac{V_{dc}}{2}$. Zero switching state is avoided to reduce the leakage current as mentioned earlier.

Also, the leakage current in both configurations are found to be less than 350 mA. The performance isimproved in terms of quality of the load current. The load current THD is found to be 3.75 % with H7 configuration and it is 3.09 % with H8 configuration. This THD is around 6 % in convention photovoltaic inverter systems. The Harmonic analysis is depicted in Figure 7 & 8. The basic comparison of these topologies are compared with conventional photovoltaic inverter is shown in Table III.

Table III Comparative results of B6, H7 and H8

Parameter	B6	H7	H8
Leakage current	600 mA	350 mA	318 mA
THD	6.8%	3.75%	3.09%
Efficiency	94.5 %	94.14 %	94.05 %

VI. EXPERIMENTAL RESULTS

The proposed topology was implemented experimentally. The design data is given in Table IV. The experimental setup is shown in Figure 8. It includes PV module, DC to DC step up converter, stray capacitance, DC link inductance and capacitance, three phase inverter and switching module with a D-space kit. The MD-PWM gating pulses are generated using D-space interface with an adaptive model in the MATLAB.

Table IV Design data

Parameters	Rating
Power rating	1000 W
PV Module	500 V, 2 A
Switching frequency	20 kHz
Stray capacitance	0.05 μF
DC link capacitance	5 μF
Inverter Voltage	100 V
Load Inductance	0.8 mH
Load resistance	0.25 Ω

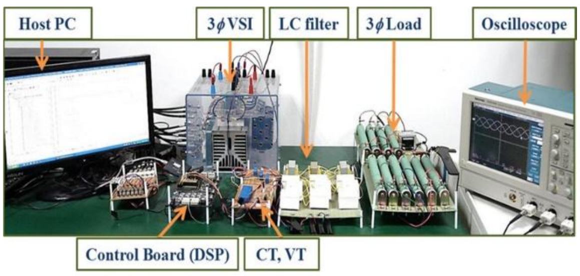

Figure 8Experimental setup

The leakage current is measured both for H7 and H8 inverters, found to be 350 mA and 320 mA respectively for the H7 and H8 inverter topologies. These values are almost matching with analyzed leakage currents through simulation. The leakage current patterns are shown in Figure 9 for H7 and H8 topologies.

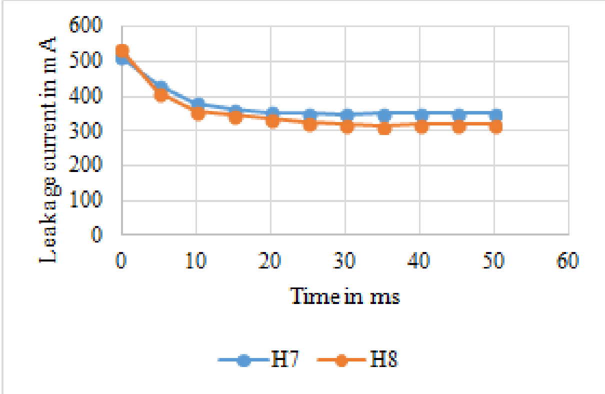

Fig. 9 Experimental leakage current patterns

The efficiency also calculated from the experimental set up. The efficiency is found to be around to be 94% in both cases without much difference between the two topologies.

VII. CONCLUSIONS

In this paper, H7 & H8 photovoltaic transformer-less inverter with MD-PWM is implemented for RL load. The same can be extended to portable equipment for mining industry. The difficulty of leakage current problem with conventional type PV inverters are solved to fair extent. Common mode voltage is clamped with zero state voltage switching. THD is found to be 3.75% and 3.09 % respectively in H7 and H8 configurations. The improved performance of the inverters can applicable to greater extent in mining applications.

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