UDC 621.314 https://doi.org/10.20998/2074-272X.2022.5.06

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Single phase transformerless inverter for grid connected photovoltaic system with reduced leakage current

Introduction. *Transformerless inverters are of vital importance in the field of grid connected solar photovoltaic systems offering higher efficiency than the conventional one. i.e., using transformer. General grid connected inverters are constituting of transformers requires more area besides the loss in them.* ***Problem***. *Eliminating transformers can cause leakage current due to the variation of common mode voltage which in turn due to parasitic capacitance effect. Research literature in transformerless inverters has addressed the problems of common mode leakage current issues by offering the study of different inverter topologies like H4, H5, H6 and HERIC etc. utilizing variety of modulation strategies like unipolar, bipolar pulse width modulations.* ***Goal***. *The paper significantly presents a new transformerless inverter topology, analyzes common mode voltage and leakage current behavior of the system. The simulation is carried out for comparing the leakage current profiles with other transformerless inverter topologies in literature.* ***Novelty***. *This paper gives an impression of the efficient transformerless inverter for grid connected photovoltaic system.* ***Results***. *The various inverter topologies full bridge with different pulse width modulation techniques are analyzed and to determine the common mode voltages and leakage currents.* References 13, tables 2, figures 17.

Key words: **transformerless inverter, leakage current, photovoltaic system.**

Вступ. *Безтрансформаторні інвертори мають життєво важливе значення в області сонячних фотоелектричних систем, підключених до мережі, та забезпечують більш високу ефективність, ніж звичайні, завдяки трансформатору. Підключені до загальної мережі інвертори, які складаються з трансформаторів, потребують більшої площі через втрати у них.* ***Проблема***. *Усунення трансформаторів може спричинити струм витоку через зміну синфазної напруги через вплив паразитної ємності. Дослідницька література з безтрансформаторних інверторів присвячена проблемам синфазних струмів витоку, пропонуючи дослідження різних топологій інверторів, таких як H4, H5, H6, HERIC та ін., з використанням різних стратегій модуляції, таких як уніполярна, біполярна широтно-імпульсна.* ***Мета***. *У статті докладно подано нову топологію безтрансформаторного інвертора, проаналізовано поведінку синфазної напруги та струму витоку в системі. Моделювання проводиться для порівняння профілів струму витоку з іншими топологіями безтрансформаторних інверторів, описаних у літературі.* ***Новизна***. *Ця стаття містить ефективний безтрансформаторний інвертор для фотоелектричної системи, підключеної до мережі.* ***Результати***. *Проаналізовано різні топології інверторів з повним мостом та різними методами широтно-імпульсної модуляції, а також визначено синфазну напругу та струми витоку.* Бібл. 13, табл. 2, рис. 17.

Ключові слова: **безтрансформаторний інвертор, струм витоку, фотогальванічна система.**

Introduction. Fossil fuels are getting depleted over past few years. Renewable energy sources are facing a huge demand despite the rise in energy requirements of the world. Photovoltaic (PV) generation is the highest among all the renewable energy sources due to its simplicity and little or no maintenance. PV systems are of two types of standalone, and grid connected. Grid connected PV system has been widely in commercial use due to its modularity in scaling and ease in its energy conversion process. As per a study by council on energy, environment and water, India set a goal of raising 450 GW to reach by the year 2030 [1]. Conventional grid connected inverters will use a transformer which will provide galvanic isolation. It can be a low or power frequency transformer on ac side of the inverter i.e., grid side, or a high frequency transformer is used on DC side of the inverter. Transformer will increase the size of the inverter and will cause loss in transformer by which efficiency of the inverter would be reduced. By eliminating the transformer galvanic isolation will not be available.

It causes leakage currents from PV panel to ground due to the parasitic capacitance effect between PV panel and ground. The range of parasitic capacitance will be 7 nF/kW to 220 nF/kW. As shown in Table 1 the leakage currents are indicated against the time within which circuit must be isolated. However, protection equipment will be engaged to protect the circuit from leakage currents [2].

Table 1

Leakage currents against the time

Leakage current	Time
$i > 300$ mA	300 ms
$\Delta i > 30$ mA	300 ms
$\Delta i > 60$ mA	150 ms
$\Delta i > 150$ mA	40 ms

It is expected to break the circuit within 0.3 s if the leakage current exceeds 300 mA and a sudden change in the current must be within the range of prescribed limits and it also advisable to monitor grid frequency for the reliable and stable grid. The reduction in leakage currents can be achieved either by incorporating the hardware changes i.e., different inverter topologies or software manipulations i.e., different pulse width modulation (PWM) techniques. Basic half bridge inverter produces a constant common mode voltage resulting zero leakage current. But the output voltage 50 % of the output voltage given by full bridge inverter for the same input voltage [3].

The full bridge inverter with bipolar switching technique will give constant common mode voltage results zero leakage current. Unipolar PWM with full bridge inverter will cause leakage currents though it has higher conversion efficiency. Based on isolating DC side to ac side, different inverter configurations are broadly classified into two types. First that uses switches to isolate on DC side and the second using switches on AC side [4]. The variation in capacitor voltage will cause larger change in leakage currents. Figure 1 indicates an inverter connected to PV on DC side and is connected to grid on ac side. Figure 2 shows some of transformerless inverter topologies.

Common mode voltage Avoiding transformer in grid connected PV systems will result in common mode leakage currents which are caused because of variable common mode voltage that is given by (1) i.e. average of the voltages of mid points of respective legs of an inverter with respect to negative of DC bus point as shown in Fig. 3:

$$V_{Common\ mode} = (V_{AN} + V_{BN})/2, \qquad (1)$$

where V_{AN} is the voltage at midpoint of the first leg of the single-phase inverter with respect to neutral point; V_{BN} is the voltage at midpoint of second leg of the single-phase inverter with respect to neutral point.

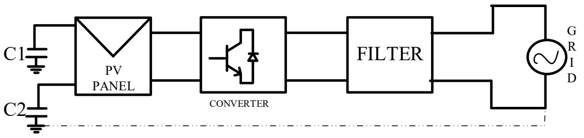

Fig. 1. Schematic of transformerless inverter

Main aim is to reduce the ripples in common mode voltage and achieve constant voltage such that leakage current limited to very small value

$$V_{Common\ mode} = (V_{AN} + V_{BN} + V_{CN})/3, \qquad (2)$$

where V_{AN}, V_{BN} and V_{CN} are the inverter leg midpoint voltages with respect to negative of DC bus.

Equation (2) shows common mode voltage of a three phase inverter circuit.

Transformerelss inverter topologies The widely used common mode topologies are H4, H5, H6, HERIC (Highly Efficient and Reliable Inverter Concept) as shown in Fig. 2. H5 inverter topology is adding a switch on DC side to a basic full bridge inverter, H6 topology is formed by incorporating two switches on DC side of full bridge [5]. H5 inverter shown in Fig. 2,*a* configuration is formed by adding one extra switch on DC side of the full bridge inverter with one capacitor on DC side. The use of this type of transformerless inverter circuit is limited due to the variable common mode voltage resulting considerable magnitude of leakage current, besides it gives good performance under resistive loads. Figure 2,*b* indicates HERIC is framed by explicitly adding extra leg of switches on ac side of the inverter. It will isolate the PV from grid on ac side unlike H5 inverter which disconnects the circuit on PV side [6] H6 inverter circuit is two DC link capacitors.

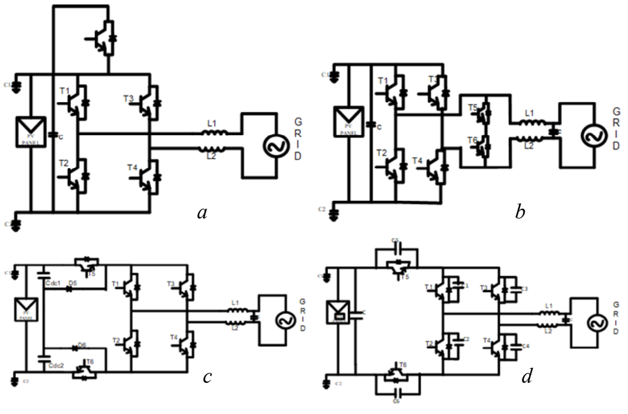

Fig. 2. *a* – H5 inverter topology; *b* – HERIC inverter topology; *c* – H6 inverter topology; *d* – improved H6 inverter topology

The power dissipation in this type of inverter is smaller compared to H5 circuit [7]. In H6 inverter circuit switching scheme will be unique to the switches position and it is not complementary to the other switches. Because of the usage of diodes reverse operation of the diodes will cause reverse recovery time delay. Common mode can be made invariable with the help of the capacitances across each device as shown in Fig. 2,*d*. As the circuit contains capacitors and inductors resonance in the circuit will occur for common mode voltage. Though capacitances at the junction would cause oscillations and the effect of stary capacitances on the board may also have an influence [8-13]. The mentioned circuit topologies in Fig. 2 indicate transformerless inverter topologies for handling common mode voltage, leakage current of the system and isolating DC (i.e. PV) from grid.

Proposed T2D4 inverter topology The proposed T2D4 inverter topology shown in Fig. 3 uses 4 diodes in upper half of the circuit and 2 IGBTs in lower half of the circuit. The respective diodes acts in forward mode and will act as freewheeling diodes during which IGBT switches are in on and off position respectively. The switches are operated at high frequency and their operation is complementary. The operating principle mentioned in terms of phases in the next section of the paper.

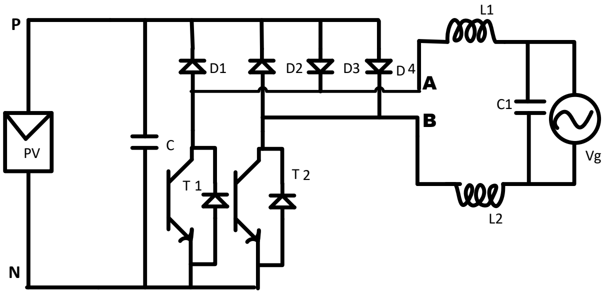

Fig. 3. T2D4 inverter topology

Operating phases of the circuit.

Phase 1. During positive half cycle the switch T2 is turned on and the current flows in the direction P–D3–L1–Grid–L2–T2–N yielding a voltage $V_{AN} = V_{PV}$ and common mode voltage is $0.5V_{PV}$.

Phase 2. T2 is switched off during freewheeling action and the current closes its path via diodes D2, instead of T2 and the current paths will be as follows D2–D3–L1–Grid–L2–D2 so that $V_{AN} = V_{BN} = V_{PV}$, $V_{AB} = 0$ and $V_{CM} = 0.5V_{PV}$.

Phase 3. In this phase of negative half of grid current flows via P–D4–L2–Grid–L1–T1–N. Switch T1 is switched on during this phase, so $V_{AN} = 0$, $V_{BN} = V_{PV}$, $V_{AB} = V_{PV}$ and $V_{CM} = 0.5V_{PV}$.

Phase 4. In this phase D1, D4 will be in forward biased and form freewheeling path so that current through the grid held constant isolating PV from the inverter via the path D1–D4–L2–Grid–L1–D1, so $V_{AN} = V_{BN} = V_{PV}$, $V_{AB} = 0$ and $V_{CM} = 0.5V_{PV}$.

In T2D4 inverter topology the 2 switches T1, T2 are switched alternately at grid frequency and the diodes are conducted during freewheeling period. However, diodes D3 and D4 will be conducted during the turn on period of T1, T2 respectively [9, 10]

Control scheme. Figure 4 shows control flow of grid connected transformerless inverter which is fed with PV at the input side. The gate pulses to the inverter are fed from PWM pulses that are generated from $\alpha\beta$ to dq transformation. The d axis current is controlled by the reference input as shown in Fig. 4.

Perturb and observe MPPT is being used to track the peak power point in PV.

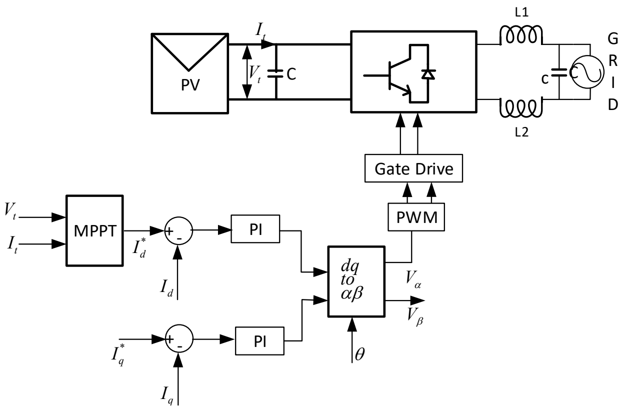

Fig. 4. Control structure for single phase transformerless inverter

Bipolar PWM technique is used to design a controller that controls the output voltage of the inverter following reference value set. A phase locked loop (PLL) gives the phase angle after it receives grid voltage as the input. PLL used to synchronize the output voltage of the inverter with grid voltage (Fig. 5).

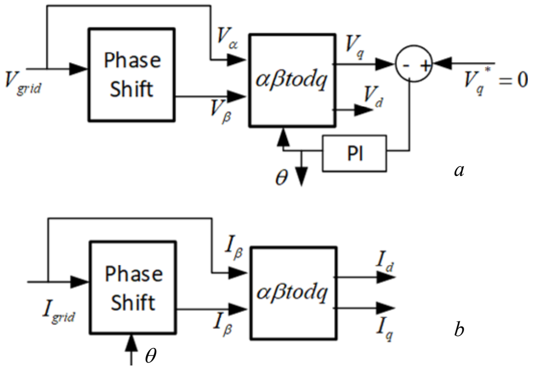

Fig. 5. *a* – PLL for measuring phase angle;
b – generation of I_d and I_q

Simulation results. MATLAB simulation is carried for analysing various inverter configurations and observe common mode voltage and leakage currents. The parameters to perform the simulation are shown in Table 2.

Table 2

Simulation parameters

Parameter	Values	Parameter	Values
DC bus voltage	400 V	Filter inductor	3.6 mH
Grid voltage	230 V	Rated power	3.6 kW
DC bus capacitor	1000 μF	Filter capacitor	3.1 μF

Bipolar PWM is the common method sinusoidal PWM in which a sinusoidal of supply frequency is compared with a high frequency carrier signal so that the resulting modulating signals are fed as gating signals to IGBTs of a H bridge inverter. It gives 2 levels of output voltage of the inverter $+V_{dc}$ and $-V_{dc}$. Bipolar PWM technique results in greater total harmonic distortion when compared to its counterpart i.e. unipolar PWM.

Unipolar PWM technique is pursued by considering two sinusoidal signals which are phase shifted by 180° are compared with a high frequency triangular waveform to obtain the gating signals to IGBTs of the inverter.

Figure 6 indicates bipolar PWM and Fig. 7 – unipolar PWM. Common mode voltage and leakage current using bipolar PWM is shown in Fig. 8, Fig. 9. Common ode voltage is constant when used bipolar PWM whereas it is varying when used unipolar PWM as shown in Fig. 10, Fig. 11.

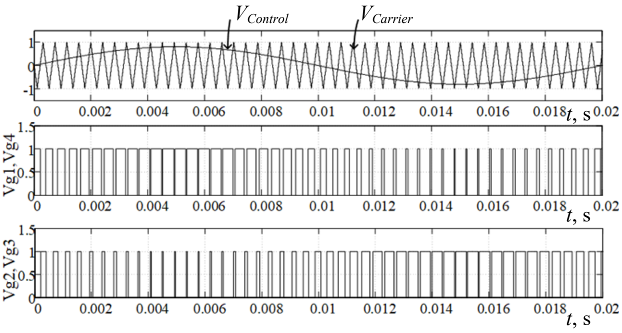

Fig. 6. Bipolar PWM

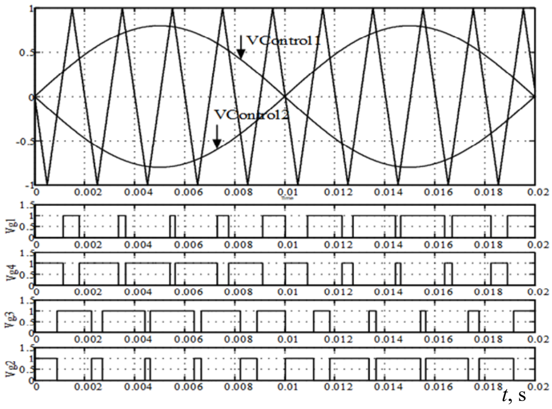

Fig. 7. Unipolar PWM

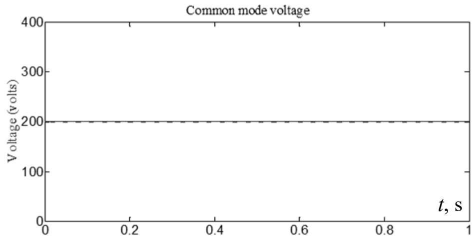

Fig. 8. Common mode voltage using bipolar PWM

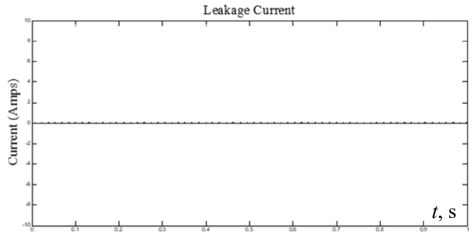

Fig. 9. Leakage current using bipolar PWM

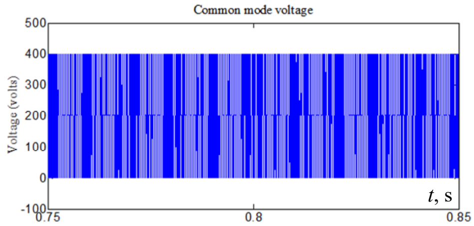

Fig. 10. Common mode voltage using unipolar PWM

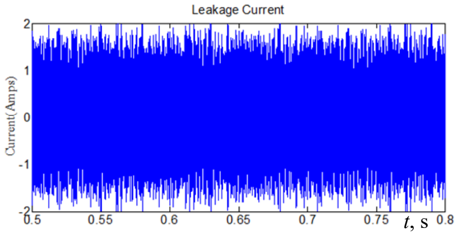

Fig. 11. Leakage current using unipolar of H bridge inverter

Common mode voltage and leakage currents of H5 inverter is shown in Fig. 12 and Fig. 13, indicating the leakage current is getting varied in terms of hundreds of milliamp.

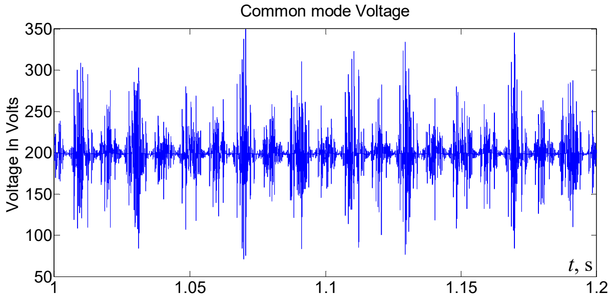

Fig. 12. Common mode voltage of H5 inverter

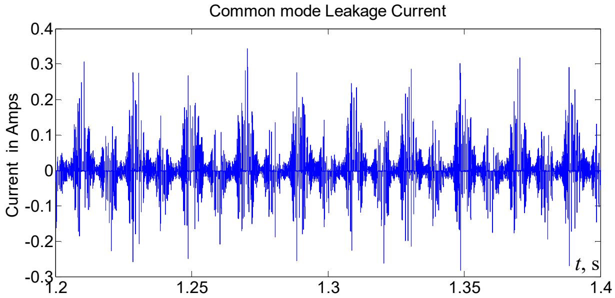

Fig. 13. Common mode leakage current of H5 inverter

The common mode voltage and leakage current of H6 inverter are shown in Fig. 14 and Fig. 15. It is observed that the variation in common mode voltage is small in H6 inverter when compared to H5 and H4 bridge inverter unipolar PWM.

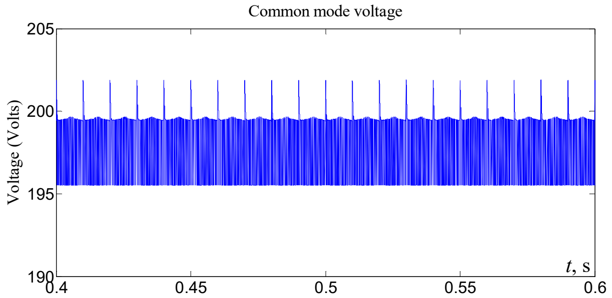

Fig. 14.Common mode voltage of H6 inverter

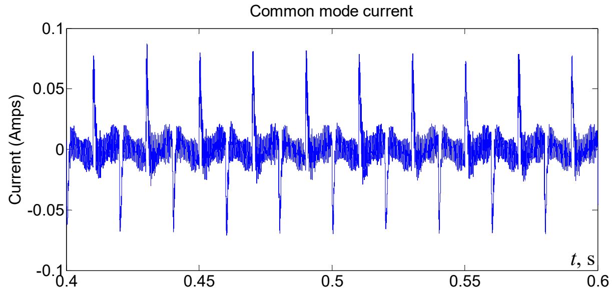

Fig. 15. Leakage current of H6 inverter

The main focus is on T2D4 inverter topology whose inverter common mode voltage and the leakage current profiles are compared with other Transformereless inverters. From Fig. 16 and Fig. 17, it is observed that T2D4 transformerless inverter topology found to give constant common mode voltage in zero or in the order of micro amps of leakage current so that H2D4 inverter found to be one of the efficient transformerless inverter. This indicates that the leakage current profile of T2D4 inverter offers superior leakage current profile.

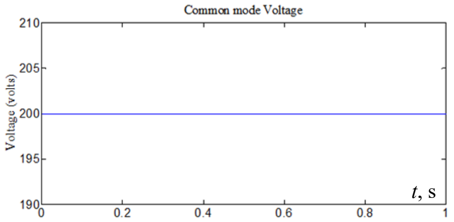

Fig. 16. Common mode voltage for T2D4 inverter

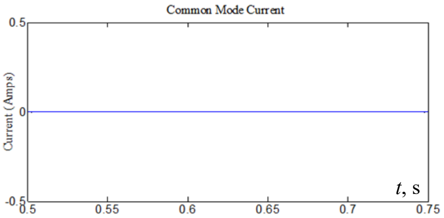

Fig. 17. Leakage current of T2D4 inverter

Conclusions.

The common mode voltage profile is the measure of efficiency of the inverter topology which describes the performance of the system. The various inverter topologies full bridge, H5, H6 and H2D4 with different pulse width modulation techniques are analyzed and to determine the common mode voltages and leakage currents.

The performance of the H2D4 inverter in terms of leakage current is found to be superior with constant common ode voltage of 200 V and leakage current in the order of nano Amps when compared to other inverter configurations. In addition to the inverter topologies discussed in the paper, there are various other configurations are also present in the literature for which evaluation is not pursued in this paper.

Conflict of interest. The authors declare that they have no conflicts of interest.

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Received 06.03.2022
Accepted 14.06.2022
Published 07.09.2022

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How to cite this article:
Janardhan G., Surendra Babu N.N.V., Srinivas G.N. Single phase transformerless inverter for grid connected photovoltaic system with reduced leakage current. *Electrical Engineering & Electromechanics*, 2022, no. 5, pp. 36-40. doi: https://doi.org/10.20998/2074-272X.2022.5.06