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Photovoltaic (PV) Panel to Transformer-Less Inverter Topology: A Review Paper

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ABSTRACT

Environmental friendly energy system is going to develop compared to convectional primary energy due to energy security problems. As the cost of solar energy is zero, the demand of solar energy is gradually increased in different purposes such as electricity, cooling and so on. Moreover, in the energy market, Photovoltaic (PV) inverters bear a very important role due to cost and efficiency. Hence, Transformer (TRX)-less inverter system is part and parcel where possible to reduce the overall system cost, size with high efficiency. In this review paper, different TRX-less inverter topologies are focused with the different switching conditions and the process of Leakage Current Reduction (LCR). Here is shown the basic concept of PV panel, flow chart according to the review papers, different leakage current paths and the mitigation processes.

1. Introduction

A Photovoltaic (PV) panel is made of semiconductor devices fabricated such that it produces electricity when sunlight falls on it. The PV cells are integrated to form solar panels, which could also be used for producing hot water as well. A series connection of Photovoltaic (PV) cells in a solar panel gives voltage in the range of 10V to 30V with 50W power rating with current of several amperes. A further series connection of such modules in series can lead to generating as high a voltage as 150V. However, the main limitation in solar power generation is low power efficiency which partly is due to the use of many power electronic devices in series [1]. The PV panels are used stand alone or even connected to grid; in both of the cases, power conditioning and regulation are the core components [2]. In the case of grid tied solar generation, inverters become the second core components to be used; inverter may be transformer-based or transformer-less. However, in both cases, it does very good performance and expected outcome. PV panel actually works to manage DC current that actually converted to AC through inverter, although the main concentration is clean the environment as much as possible [3, 4]. To do so, transformer is highly needed to make the system proper handed. Where the PV panel is used as for DC signal achieving, but other side of the system is connected to grid that used for AC signal [5]. The use of photovoltaic panel for power generation is becoming larger in number and use due to these panels' affordable prices, hence day by day the capacity and popularity of using PV panel increases almost exponentially [4, 6-8]. It can be more empathized if the temperature and dust of PV panel is reduced [9-12]. A model circuit representing a PV cell is as shown in Fig. 1.1, where I is overall current, I_{PH} is the photo-generated current, Rs is panel series resistance and Rsh is the panel parallel (shunt) resistance [13].

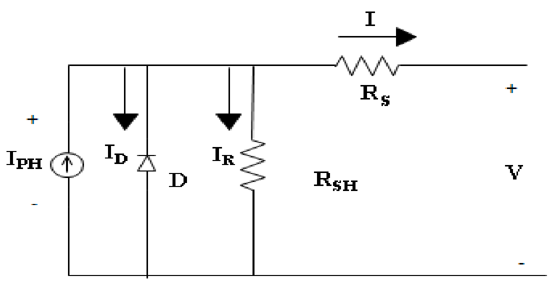

Figure 1.1. Photovoltaic (PV) Cell equivalent circuit [13]

In photovoltaic panels the ouput depends on temparatures, load conditions as well as various irradiance which are very important for maximum power point tracking (MPPT) that can be found by I-V charactaristics and V-P curves. Meanwhile, in above circuit diagram, maximum power depends on output achieving voltage and current where the output current is exponantially developed with junction thermal voltage V_t, that shown through below equation.

$$I = I_{PH} - I_0 \left(e^{\frac{V+I_R}{n_s V_t}} - 1\right) - \frac{V+I_{R_S}}{R_{SH}} \quad \text{and where} \quad V_t = \frac{AKT_{stc}}{q}$$

Where A= diode quality factor (ideally), K= Boltzmann's constant, q= the charge of the electron, ns=the number of cells, T_{stc}=standard test constand (stc) temparature in kelvin. I_o= dark saturation current in STC. In Fig. 1.2 below is shown the I-V and P-V charactaristics under given light irradiance level at which it gives Isc under short-circuit condition while Voc is the output voltage when the pannel is open. Maximum power at P_{max} is indicated at current I_{MP}, and voltage V_{MP} respectively.

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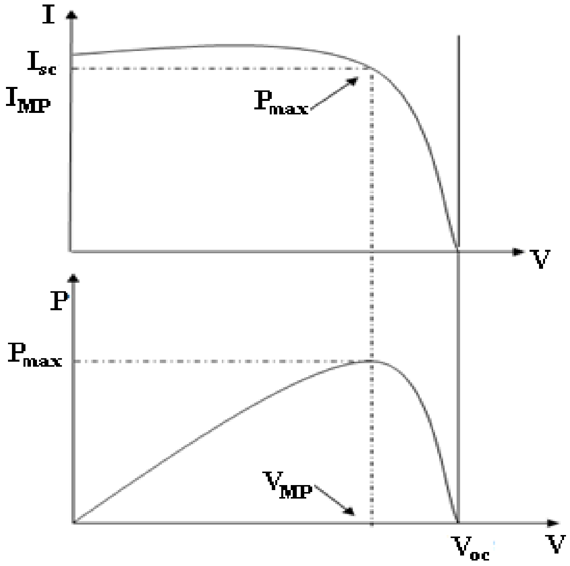

Figure 1.2. I-V characteristics and P-V curve and maximum power achieving point [14].

Such model study is useful in understanding the non-linear behavioural performance of PV cells which could be useful in extracting maximum power from the photovoltaic arrays. In addition, Grid connected inverter is nowadays highly popular to get high range of power point over the system where the maximum points are developed through analog maximum or normal point tracking methods [15, 16]. Previously isolation transformer-based topology had highly populated, although the main predicament is size, cost and efficiency [7, 17]. In contrast, to recover these problems, the best solution would be used no transformer-based topology for both cases single phase and three phase [3]. As for getting tiny weight, low cost and high efficiency system no transformer topology is the best solution where the galvanic isolation is not included, the main problem can be seen that is common mode leakage issue which is actually the reason of reducing the efficiency and increasing the loss [3, 18, 19].

In this review paper is focused about the PV panel and connection of this PV panel with different transformer less inverter topologies. Moreover, the switching techniques of different topologies have been discussed. Working principle of various PV-transformer-less inverter topologies and how the leakage current is occurred in the overall system. Different places of occurring leakage current in the system and the importance of mitigating leakage current.

2.Different Topologies of no-transformer technique

Paralleled-buck topology has been shown in Figure 2.1 which is consisted with four switches with two extra diodes. The basic concept of the two paralleled-buck converters is operated according to the polarity of grid voltage. According to the polarity of grid voltage, all switches independently operate with the high or grid frequency. In the positive half-cycle, the switch S4 is turned on and the switches S2 and S3 are turned off. The switch S1 is switched with the high-frequency. In the negative half-cycle, the switch S3 is turned on and the switches S1 and S4 are turned off. The switch S3 is switched with the high-frequency. Voltage in between A and B terminal is the three-voltage levels including the zero-output-voltage state which leads to lower core losses and prevents the reactive power exchange during the freewheeling operation. Moreover, this scheme has low leakage current and EMI.

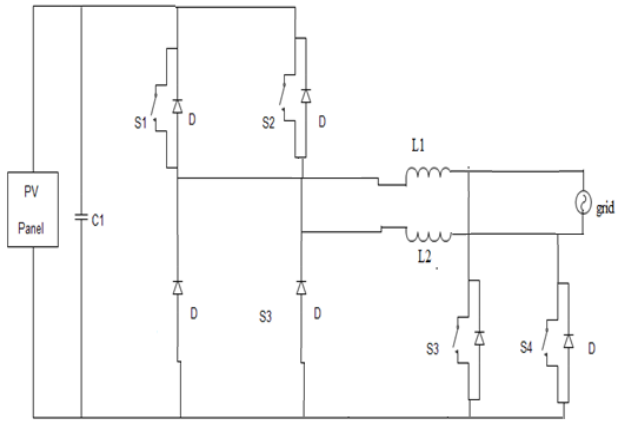

Figure 2.1. Paralleled-buck TRX-less Inverter [20]

In figure 2.2 is the oH5 topology which is an extension of H5 topology is presented in figure 2.4. For oH5 topology is added an extra switch (S6) with the H5 topology for clamping the CM voltage at the half of input voltage.

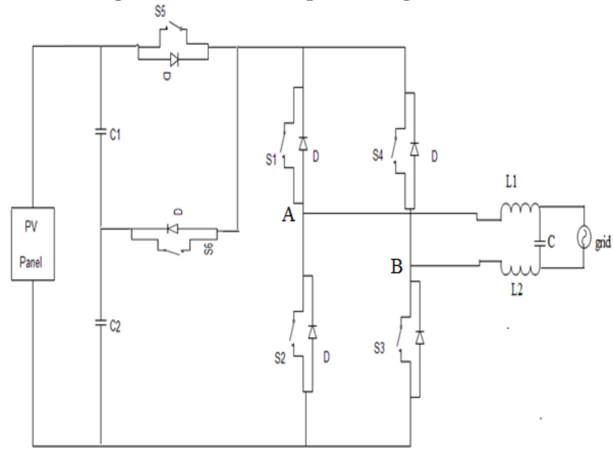

Figure 2.2. oH5 topology [21]

In Figure 2.3 has been proposed a topology with two switches freewheeling branch with one bi-directional switch and four diodes called H-bridge zero voltage rectifier (HB-ZVR) topology. Also, another diode has been added for better eliminating the leakage current. The clamping function of this topology has been done using that diode which allows one-directional clamping.

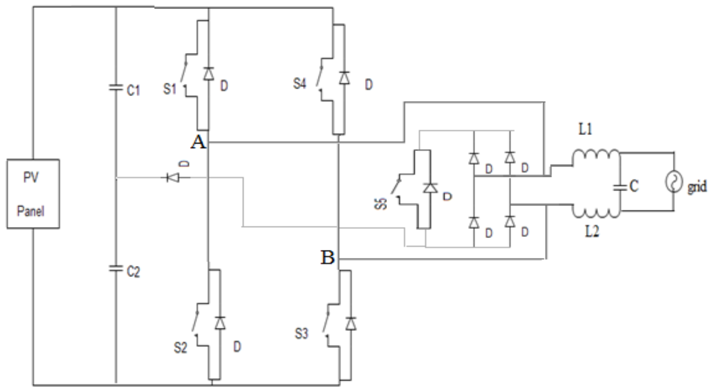

Figure 2.3.HB-ZVR topology [21]

Transformer-less photovoltaic (PV) panel is well known for high efficiency and low size and cost [5, 22]. However, it gives rise to the possibility of current flow between inverter and ground that actually is reason of power losses and that of the Electromagnetic Interference (EMI), current harmonics and as well as safety concerns. In order to enhance the efficiency in [23] is proposed a new topology where they used MOSFETs as a switches in H5, H6 and Dual-paralleled-buck inverters configurations. There are six switches used with three diodes in their proposed technique showing the function of the circuit diagram in active and freewheeling stage during the positive and negative half cycles that has been shown in fig. 2.4. As we know that efficiency is partly affected by the leakage current, hence power losses are shown in the case of proposed topology in H5, H6 and Double Paralleled Buck inverter configurations for 20 kHz frequency. The power efficiency achieved stands at around 99.3% and 98.8% for 20 kHz and 40 kHz switching frequencies respectively. The H5 configuration is shown in Figure 2.4 where five switches has presented and in between these five switches is used a switch S5 for enabling DC passed onto inverter whereas rest of the switches are used for inverter control purposes.

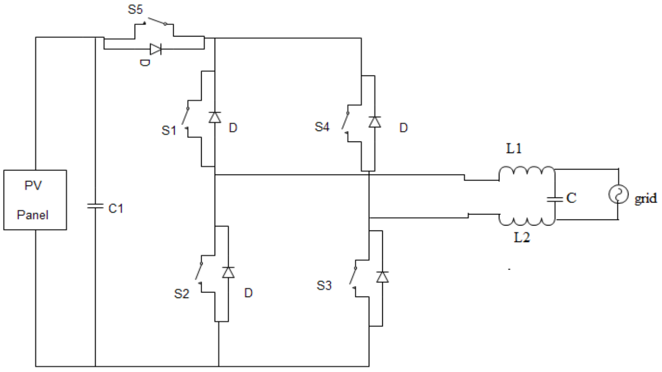

Figure 2.4. H5 type topology [23].

Both H5 and HERIC are very high range of power efficiency-based cost-effective converters. In paper [22] is proposed the same topology with additional improvement by adding two step-down converters compared to those of a single-phase transformer-less inverters. The switches are low frequency, and so it is easy to obtain a higher efficiency as well as reliability as the number of semiconductor devices is reduced with simple configuration to implement. Moreover, here are shown the different circuits for analyzing the single phase transformer-less PV inverter topologies for high efficiency such as Karschny, Heric (fig. 2.7) extended input-voltage in H5 topology by connecting Free-wheeling diodes for combating the phenomenon of fly-back spikes generation, and the effect of duty cycle is verified. In this paper, as shown in Figure 2.5, the circuit is made from four switches connected is different manner. The switches S1 and S2 are used for letting DC passed while the remaining two switches are connected with a filter shunted with resistance R.

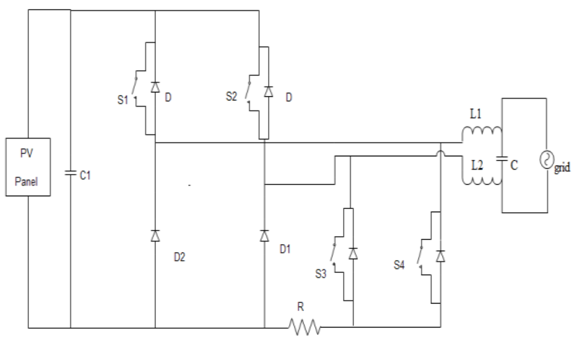

Figure 2.5. Step down converter based transformer-less topology [22].

In Figure 2.6 is shown the Karschny inverter topology made from five switches based topology where inductor is connected in middle of S1 and S2 switches and D1 is connected in between S5 and S1 while D2 is allied in between S4 and S2.

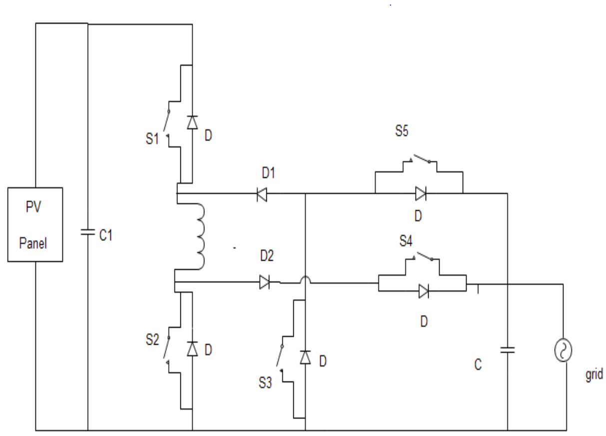

Figure 2.6. Karschny inverter topology [22].

In the case of low input voltage using only bridge-based inverter topology, one has to use many stages of DC-DC boost to bring it to some usable voltage level. In [24] is suggested topologies with additional components of inductances used with two switches S5 and S6 for Heric topology (fig. 2.7). This is simulated and verified achieving AC signal from the inverter whereas two extra switches for Hybrid bridge topology (fig. 2.8) are added with middle of the inverter having two diodes in series with the inverter.

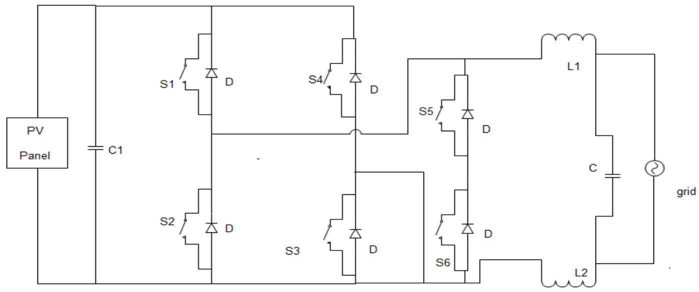

Figure 2.7. HERIC type topology [24].

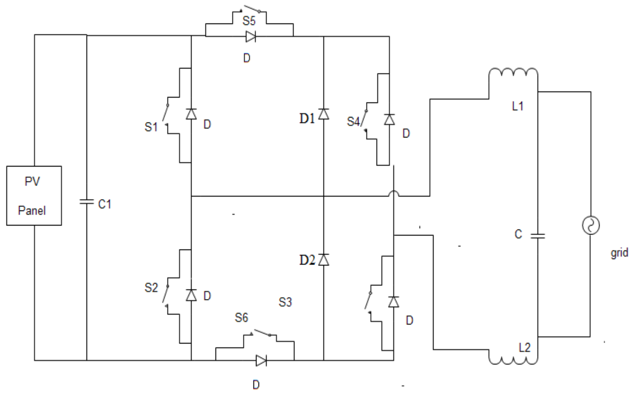

Figure 2.8. Hybrid bridge type topology [24].

Although having the benefits of the small size, high efficiency, reliability and low cost, transformer-less topologies are with the limitation of common-mode voltage development which leads to having three-fold increase in leakage current than using transformer-based topology of galvanic isolation benefits. To overcome these problems in [25] is proposed a new highly attributed buck-boost transformer-less topology. It is included with inductors coupled with the feature of stepping up or down the input voltage from PV panel. Buck and boost models with four steps are shown where is given the circuit diagram and brief discussion to explore the effect of duty cycle on its wave shapes. The experimental setup is given for verifying different wave shapes of voltage and current in buck and boost modes with different input voltages, showing thus an improved efficiency. In Fig. 2.9 below is shown the transformer-less PV inverter using buck-boost where the four switches S1, S2, S3, and S4 are connected with coupled inductor L1 and L2 and diodes D1, D2, D3, and D4 for providing electrical isolation, rest of the four switches are connected in grid format.

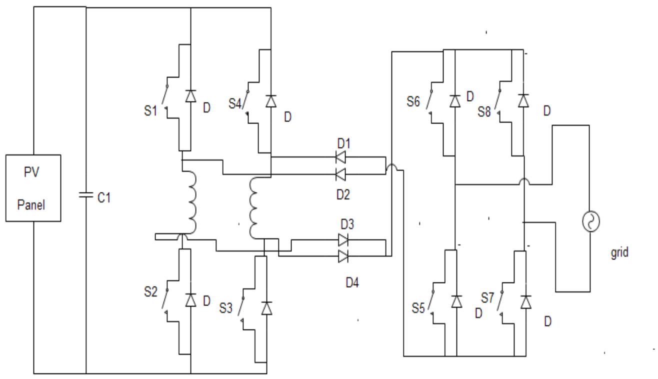

Figure 2.9. Transformer-less inverter using buck-boost [25].

The normal model of the PV grid tied connected system is as simple as connection of PV panel to grid through filter and inverter and hence, its demand increases rapidly in commercial and residential structural way for every sector. On the other hand, different inverter topologies are helped to increase the power efficiency whereas the common mode voltage is developed. Beside the common mode voltage development and reducing leakage current issue, some topologies perform well, in this purposes, in paper [26] is proposed H6 topology (fig. 2.10) is actually high efficient and good experimental and simulated topology to get expected outcome. H6 topology has six switches and two diodes where these two diodes are connected as a cross couple of using two extra switches in the middle of the normal inverter. All of these six switches are used to get ac signal from the inverter where the diodes are helped to get it smoothly.

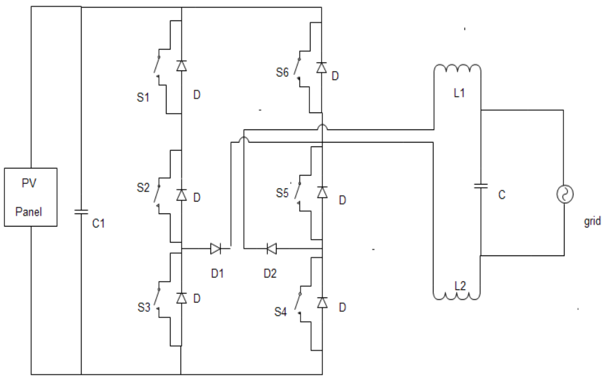

Figure 2.10. H6-type topology[26]

In the case of photovoltaic panel in transformer-less inverter topology, PWM is used for turning ON/OFF switches according to switching sequences needed and aimed at ultimately improving the power efficiency at better output wave-shapes. To analyze the effect of PWM, here is shown in fig. 2.11 [27] the modified form of PWM for doing the harmonic analysis with the required theoretical derived equations. Simulations are also done through PSIM software to show that the output from the H-bridge configuration is making use of Fourier analysis, load output voltage, inductor current and inductor current as well and all of these wave forms are done for modified unipolar PWM scheme. The total system losses, switching losses and other losses are not mentioned. Moreover, this unipolar Sinusoidal PWM and double PWM are reported in paper [28] where it suggests a novel topology with a filter, called electromagnetic compatibility (EMC) filter, meant to eliminate the effect of EMI from neighboring components. Here, four operational stages are shown and discussed for proposed topology with essential diagrams. Turn on/off the five switches of proposed topology using Unipolar and Double-frequency SPWM. Leakage current paths are shown and analyzed with calculation for mentioning four stages. The simulation results are verified with experimental which is giving all values in tabular form, as a result showed current stress S3, output current and grid voltage. Some of the portions are used in H5 topology to verify the common mode current that also shown in paper and current stresses are given in different capacitor ratios.

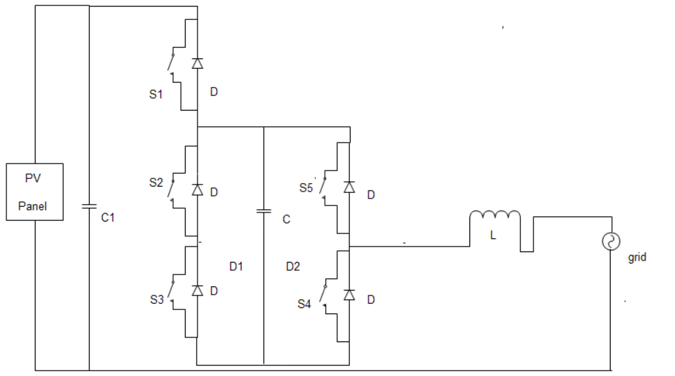

Figure 2.11. Four switches based inverter [27, 28]

Leakage current leads to increase in the EMI effects degrading the power quality as a result [29]. Here it studies a converter topology in PLECS simulation tool schematic. The leakage current is shown to be reduced by using unipolar PWM for specific values of inductances, capacitances and resistances. The common mode voltage, ground voltage and ground current are shown for full bridge converter. However, as reported that the ripple factor is proportional roughly to total harmonic distortion which is not detailed for analysis. To overcome the limitation of transformer-less topology, here in [19] is proposed a new topology with six switches where four switches are used for inverter and two are added before using inverter. Sinusoidal pulse width modulation (SPWM) wave form is used in simulation as well as in matching experimental results. As a result of SPWM, the power losses due to switching, core losses and copper losses are reduced with reduced current ripples.

The quality of electricity supply depends on power factor, harmonic distortion content, and dc components as well, but the main task is to reduce the common mode voltage current leakages for increased power efficiency. The switching sequence PWM is applied to two switches (S3 and S4) while S1 and S6 are always ON during the positive half cycle; similarly during the negative half cycle when S2 and S5 are always ON while S3 and S4 are operated by the PWM that has been shown in fig. 2.12. The operation of the circuit enables that at not instant in time, any voltage develops across points A and B, thus eliminating the development of common mode al-together [30].

Full wave inverter of unipolar sinusoidal pulse width modulation (SPWM) is a system which one has high frequency common mode voltage that is a boundary of a transformer-less photovoltaic topology which is connected with grid. However, this restriction is possible to overcome through using switches and capacitor with full bridge inverter. However, here using freewheeling diodes are helped to clamp the half input voltage in the time of freewheeling period which is equal to the high frequency common mode voltage, as a result of using those switches.

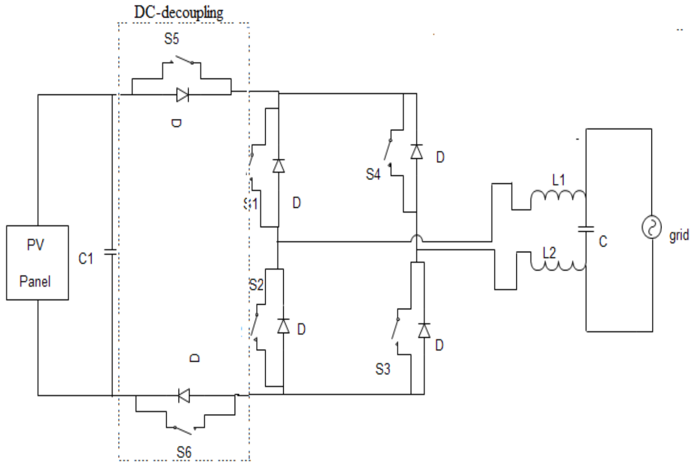

Figure 2.12. DC decoupling inverter topology [29, 30]

In paper [31], analysis the operation and clamping modes of proposed and existing transformer-less topologies is given in fig. 2.13 where also calculated the power losses. Hence, research shows the common mode voltage, current and ground current for different topologies such as Heric, H6 and H5 topology. Meanwhile, the differential -mode voltage (DMV), Detailed Common-mode voltage for H5 topology has been shown where also described the experimental waveform of capacitor divider for same topology as well as a result some advantages are come out from the describing paper. Moreover, the different leakage paths are shown on both sides of Photovoltaic (PV) panel, using filter as well before the grid. In the case of switches of this topology, S1, S2, S3 and S4 are used to transform the DC signal into AC whereas other two switches are used to pass the DC signal in active mode during the two halves cycles.

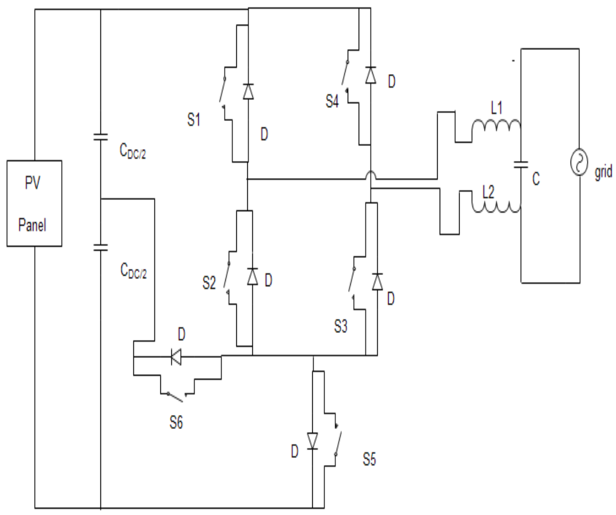

Figure 2.13. Optimized transformer less inverter [31].

In Fig. 2.14 is a transformer-less inverter topology where DC and AC decoupling are shown and DC decoupling is helped to pass the dc signal according to the switching command to inverter whereas AC decoupling is used to maintain the ac signal. Here actually shown seven switches and the switching simulations are done by using 50Hz and 10 kHz switching frequencies.

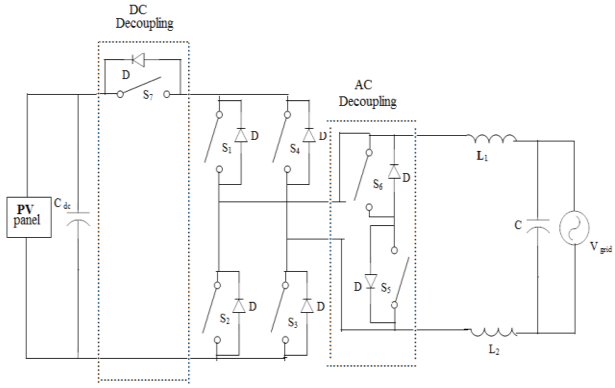

Figure 2.14. DC and AC decoupling included topology [23].

In above discussed the different topologies of PV-TRX-less inverter where easily can understand that all topologies are basically controlled by different types of switching in various way. Indeed from the above papers, achieving DC from PV panel is fluctuated DC where used the DC-DC converter for getting pure DC that can be converted to AC by Inverter where uses different switches for inverting process. Meanwhile, the achieving AC is not the accurate sine wave that can be made pure sine wave through filters. In below flow chart in figure 2.15, is the flow chart of overall getting result after reviewing papers.

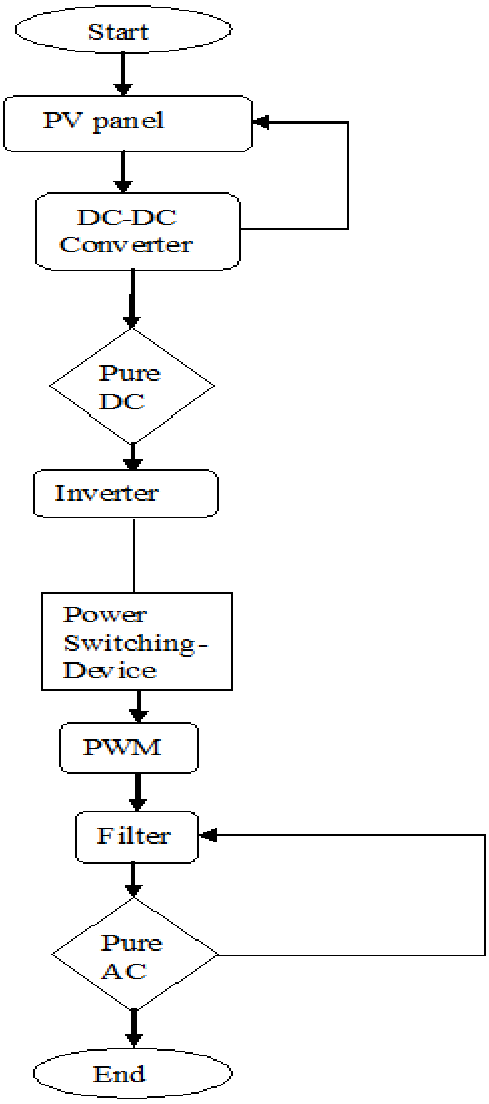

Figure 2.15. Flow chart of the reviewing work.

3. Leakage Current Paths and Issue

Electromagnetic compatibility (EMC) filters is used to describe the work/function of devices in a system of an electromagnetic environment and its filter helps to reduce the common mode problem from the system. However, this filter is included with different inverter topologies such as the full-bridge of the bipolar pulse width modulation (PWM) and half-bridge have been proposed for avoiding the common mode leakage issues where these topologies show some limitations which are overcome in [32] for giving high efficiency with require low input voltage. To do so, it uses EMC filter with inverter and using BJT switches with freewheeling diodes. However, the extra features of this work is in the form of two extra switches S_5 and S_6 with freewheeling diodes which is actually compared with normal full-bridge inverter with EMC filter where it uses unipolar PWM with 400V peak to peak voltage and 5 kHz switching frequency. The proposed topology shows better outcome in the case of inductor current, output voltage of the inverter, common mode voltage, measure efficiency and European efficiency. Moreover, the achieved efficiency is shown 97.4% where the European efficiency are varied between 97.16% and 95.2% with using input voltage range is in-between (350–800 V). In Fig.3.1 is given the block diagram of a circuit topology showing leakage current and the parasitic capacitor that actually has in between PV panel and ground.

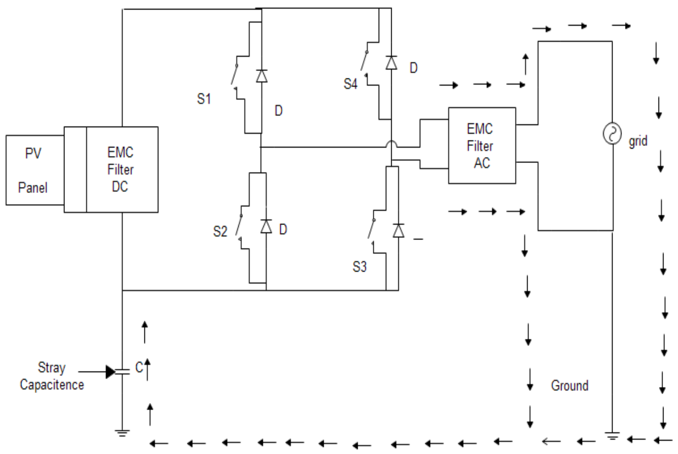

Figure 3.1. Current direction and parasitic capacitor are shown [32, 33].

An increase in leakage current induces harmonics on the grid side and makes the overall system unbalance, and as a result converter topology helps to overcome this problem because the amplitude as well as spectrum of leakage currents depend on it, at a time, switching condition also bring the vital role to reduce the leakage current. Here in [34] is used AC filter, resonant circuit and it is tried to measure the ground current for different conditions, hence, making a system where have inverter, low pass filter and connected to grid and here clearly showed that leakage current flowing at points to ground. Also, is shown different paths to show the inverter output, ground voltage and ground current when experimental setup was done that showed through oscilloscope. Meanwhile, using resonant circuit it has been shown and simulated with respect to frequency. It is used in NPC PV inverter to see the inverter output, ground voltage and leakage current as well. Although here may has no problem for using resonant frequency, however, they are not considered the switching losses and switching condition. In fig. 3.2 shows the ground current that flows in the system.

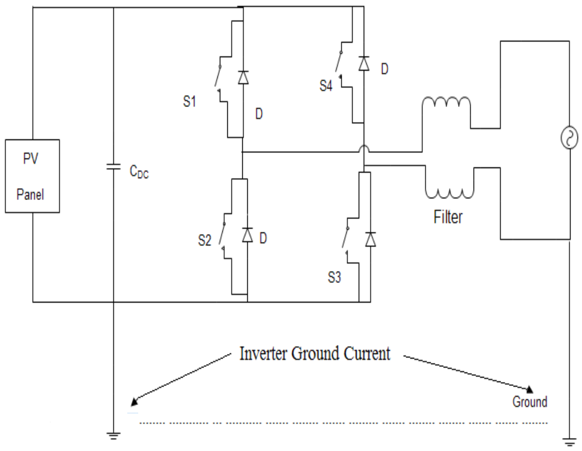

Figure 3.2. Ground current is around the system [34].

Highly populated renewable energy does recover from the power loss problem although are suggested enormous number of photovoltaic system with transformer-less topologies. The same objective is followed in paper [23] where the main target is aimed at increased power efficiency, as a result of which common mode leakage current is reduced. A new transformer-less topology had been proposed using the concept of AC Decoupling as well as DC Decoupling. Here is given simulation results verified by experimental results proving power efficiency of the overall system. Moreover, almost same work is done in paper [19, 23, 35] where the authors use a little bit approach.

4.Leakage Current mitigation:

Leakage Current reduction process is going to develop gradually through different inverter topologies such as three-level photovoltaic (PV) grid-connected inverter [36], four switches based [27], H5 [23], oH5[21], Optimized [31], DC decoupling [30], AC-DC decoupling [23], H6 [26], HERIC [24], HB-ZVR [21], Karschny [22] and so on. In all reviewing papers, the main observing part was Common Mode Voltage (CMV) where different techniques were used to verifying the system for reducing the leakage current that occurred in between PV- ground through parasitic capacitance. In the section 3 has been shown the current flowing way through the leakage path. Hence, filter bears the vital role for limiting the leakage current in the system. In all PV-TRX-less inverter topologies used LC based filters where it's helped to reduce highly the leakage current as well as achieve the accurate wave shape of output. Hence, efficiency is increased dramatically. On the other hand, switching is the most affordable and useful for Leakage Current Reduction (LCR). Here the most common solution for leakage current issues are switching condition and filtering process as well. In addition, Low Pass Filter (LPF) helps more in this issue with achieving high output voltage where all filters are not competent. In the case of switching condition, the best solution is Pulse Width Modulation (PWM) where have to design the PWM for LCR.

5. Conclusion

This review paper is discussed the different PV based TRX-less inverter topologies where all inverters are MOSFET switches based inverter. In the section 1 is about the PV panel for maximum power point tracking (MPPT). Importances of PV-TRX and PV-noTRX based inverter topologies. In the section 2, elaborate the switching processes for LCR with high efficiency gain of each PV-TRX-less inverter techniques. Furthermore, here shows the flow chart of overall process of achieving Alternative Current (AC) that has been gotten after reviewing the papers. In the next section shows the leakage current issues with different paths. Section 4 shows the mitigation technique and the solution process for LCR and the main solution is designing the PWM and LPF.

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