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Research Article

A Comparative Study between H5 and HERIC Transformer-Less Inverters for PV Standalone System

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Abstract

This paper presents a comparative study between H5, HERIC transformer-less inverters when they are utilized in PV system feeding a standalone load. Pulse width modulation and selective harmonic elimination techniques are applied for each inverter. The comparison between the inverters is carried out based on inverter conduction losses, filter size and PV leakage current. A dc-dc boost chopper is used to raise the PV-array voltage to a suitable value to meet load requirements. The boost converter is controlled through the incremental inductance maximum power point tracker which is utilized to maximize the power delivered from the PV-array.

Keywords: *PV system, H5 and HERIC inverter, incremental inductance*

1. Introduction

Recently renewable energy generated from clean and environmentally friendly sources has become one of the most major challenges. Among renewable energy sources, PV systems attract more attention because of the large quantity and sustainability of solar energy. PV sources can be connected to electric grid or they can deliver energy to standalone loads. Usually a dc-dc boost converter is required to raise the output voltage of the PV-array to a suitable level to meet the requirements of the electric grid or standalone loads. The relation between the PV output current and voltage is nonlinear. Therefore the maximum power extracted from the PV system can be achieved under particular voltage condition. Consequently maximum power point trackers (MPPT) are utilized to achieve the maximum power delivered from the PV system (T. M. Chung *et al*, 2016; A. Safari *et al*, 2011; T. Halder *et al* 2016). The MPPT adjusts the operation of the boost converter in such a way that the output voltage of the PV-array always follows the value corresponding to the maximum power point. The boost converter delivers the solar energy from the PV-array to the electric grid or standalone loads through dc-ac inverters. Conventional H-bridge inverters causes a path of leakage current from the PV to ground (through parasitic capacitance) and it must be minimized to certain values according to standards. Transformer-less inverters overcome this problem. The main idea of transformer-less inverters is to disconnect the PV from the grid or loads during freewheeling periods thus cutting the path of leakage current. Several topologies of transformer-less inverters are introduced in the literature (F. T. K. Suan *et al*, 2011; H. Xiao *et al*, 2010; G. Rizzoli *et al*, 2016; R. Gonzalez *et al* 2007). This paper presents a comparative study between two common used transformer-less inverters; H5 and High Efficiency and Reliable Inverter Concept (HERIC). The two inverters are employed in a PV system delivering energy to a standalone load. Sinusoidal pulse width modulation (SPWM) and selective harmonic elimination (SHE) techniques are applied for each inverter as an output voltage modulation technique. The comparison between the inverters is based on three criteria; inverter conduction losses, LCL filter size and leakage current of PV system. The PV output voltage is raised to a suitable level to meet the load requirements using dc-dc boost converter. Incremental inductance maximum power point tracker is applied to control the boost converter in such a way that the PV operates at an output voltage corresponding to PV maximum power.

The paper is organized as follows. Section 2 presents the principle of operation of H5 and HERIC inverters and inverter modulation techniques. Section 3 introduces the modeling of PV and analysis of incremental inductance MPPT. Section 4 presents simulation results of the whole system. Comparison of the two inverters are presented in section 5.

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2. Principle of operation of transformer-less inverters

The following sections presents the principle of operation of H5 and HERIC inverters.

2.1 Principle of operation of HERIC inverter

HERIC transformer-less inverter consists of conventional H-bridge inverter in addition to two switches S_5 and S_6 as shown in Fig. 1 . The switches S_5 and S_6 are connected in a reversed manner. The additional switches with their antiparallel diodes disconnect the PV-array from the load during periods of zero output voltage of the inverter. There are four modes of operation during each cycle as follows:

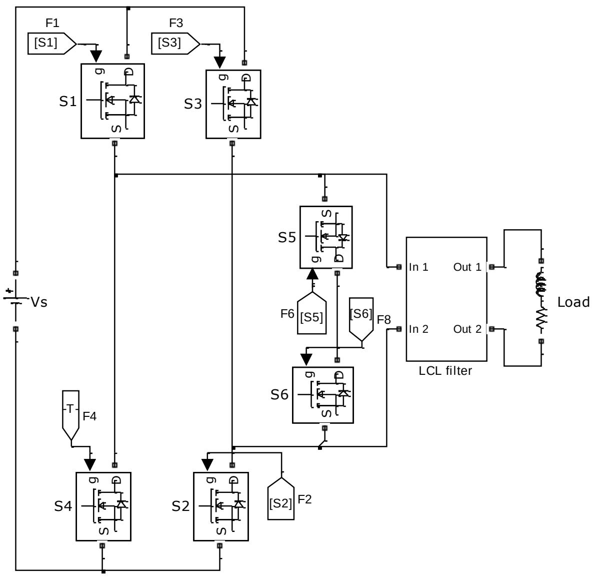

Fig. 1 HERIC inverter

Positive active mode 1: in this mode, the energy is delivered from PV-array to the load. The inverter has a positive level output voltage equals V_s. The switches S_1 and S_2 are in the 'ON' state while the other four switches are in the 'OFF' state.

Zero level voltage 1: during this mode, the PV-array is disconnected from the load. Switch S_6 and antiparallel diode D_{S5} conduct together creating a freewheeling path. The path of the freewheeling current is S_6-D_{S5}-filter-load-S_6. This mode occurs during periods of zero inverter output voltage in the positive half cycle.

Negative active mode 1: in this mode, the energy is delivered from PV-array to the load. The inverter has a negative level output voltage equals -V_s. The switches S_3 and S_4 are in the 'ON' state while the other four switches are in the 'OFF' state.

Zero level voltage 2: during this mode, the PV-array is disconnected from the load. Switch S_5 and antiparallel diode D_{S6} conduct together creating a freewheeling path. The path of the freewheeling current is S_5-D_{S6}-filter-load-S_5. This mode occurs during periods of zero inverter output voltage in the negative half cycle.

The control signals of the six switches are shown in Fig. 2. It is noted that two switches are conducting during each active mode.

2.2 Principle of operation of H5 inverter

H5 transformer-less inverter consists of conventional H-bridge inverter in addition to only extra switch S_5 as shown in Fig. 3. Although only one switch is added, this switch conducts during the two active modes.

Therefore, three switches are always 'ON' in the active modes thus the conduction losses increase. The principle of operation of H5 inverter is as follows:

Positive active mode 1: This mode is similar to that in HERIC inverter. The only difference is conducting S_5 besides S_1 and S_2

Zero level voltage 1: during this mode, the PV-array is disconnected from the load. Switch S_1 and antiparallel diode D_{S3} conduct together creating a freewheeling path. The path of the freewheeling current is D_{S3}-S_1- filter-load-D_{S3}. This mode occurs during periods of zero inverter output voltage in the positive half cycle.

Negative active mode 1: This mode is similar to that in HERIC inverter. The only difference is conducting S_5 besides S_3 and S_4

Zero level voltage 2: during this mode, the PV-array is disconnected from the load. Switch S_3 and antiparallel diode D_{S1} conduct together creating a freewheeling path. The path of the freewheeling current is D_{S1}-S_3- filter-load-D_{S1}. This mode occurs during periods of zero inverter output voltage in the positive half cycle.

The control signals of the five switches are shown in Fig. 4. Disconnecting the PV-array in the freewheeling modes in HERIC and H5 inverters results in significant reduction in leakage current from the PV-array to ground.

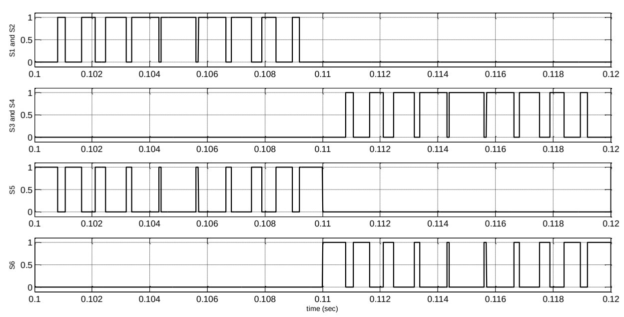

Fig. 2 Control signals of HERIC inverter

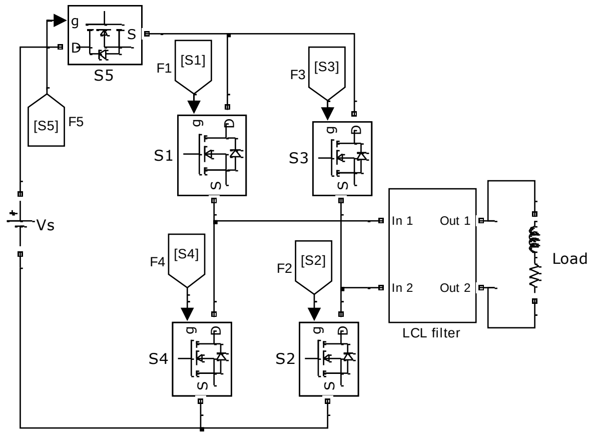

Fig. 3 H5 inverter

2.2 Sinusoidal pulse width modulation

Sinusoidal pulse width modulation (SPWM) inverters are considered as the most popular technique used for dc-ac inverters. As well-known in this technique, a sine-wave signal having the required fundamental frequency "f_s" is compared with a triangular wave having a frequency "f_c". The relative levels of the sinusoidal and carrier waves determine the pulse widths of the control signals for the inverter switches (M. H. Rashid, 2007). Harmonics in the output voltage when applying SPWM is reduced due to multi switching and output is approximately sine wave so filter size and cost is reduced.

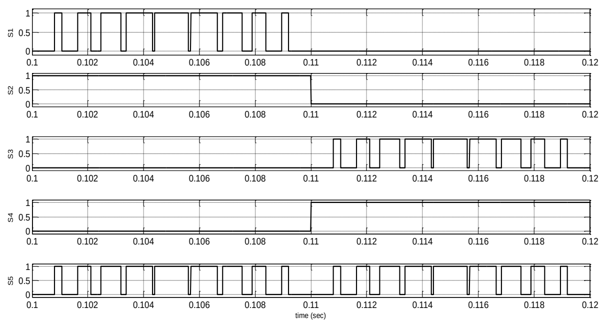

Fig. 4 Control signals of H5 inverter

2.4 Selective harmonic elimination

In selective harmonic elimination (SHE) technique, the inverter switches are switched on and off at specified angles to eliminate certain selected low order harmonics. The switching angles are utilized to generate the control signals of the inverter switches. These switching angles are determined by solving nonlinear equations called "transcendental equations" depending on the number of low order harmonics to be cancelled (Essam Hendawi, 2015). The switching frequency of the inverter switches is low and as a result the switching losses are very small when compared to SPWM. To eliminate harmonics of higher order than the selected orders, the size of the required filter is larger than that with SPWM.

3. PV arrays and MPPT algorithm

Fig.. 5 presents the overall system. The one diode circuit consisting of a current source, parallel diode series resistance and parallel resistance is used to model the PV array.

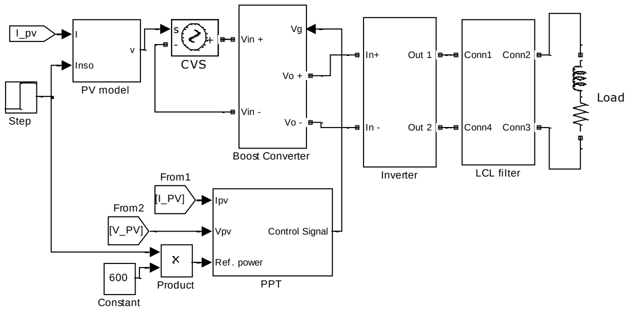

Fig. 5 PV system for standalone load

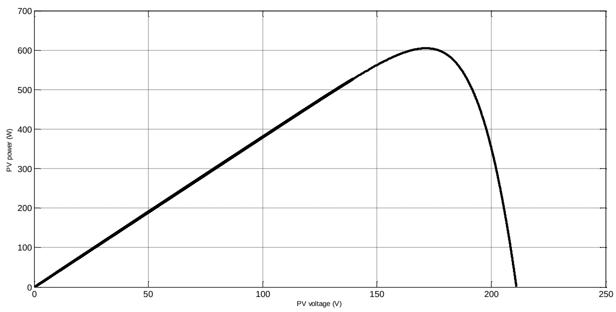

Fig. 6 P-V characteristic

The P-V characteristic of the PV panels is shown in Fig. 6. The equations describing the model is well-known in the literature (D. Bonkoungou *et al*, 2013; V. Tamrakar *et al*, 2015). PV panels are connected in series or parallel to raise the total output voltage and current. However, the level of the output voltage is still under the required value and therefore a dc-dc boost converter is employed to raise the output voltage to meet the load requirements. The incremental conductance MPPT is used to control the boost converter so that the output voltage of the PV array has a value corresponding to maximum power value.

The power delivered by the PV-array is:

$$P = V * I \tag{1}$$

Differentiating with respect to 'V'

$$\frac{dP}{dV} = V\frac{dI}{dV} + I \tag{2}$$

Investigating the P-V curve in Fig. 6 , At the point of maximum power, $\frac{dP}{dV} = \text{zero}$

$\frac{dP}{dV}$ is positive to the left of MPP and negative to the right of MPP

$\frac{dI}{dV} = -\frac{I}{V}$ at point of maximum power
$\frac{dI}{dV} < -\frac{I}{V}$ at the right to the point of maximum power
$\frac{dI}{dV} > -\frac{I}{V}$ at the left to the point of maximum power

The incremental inductance MPP algorithm always follows the maximum power point of the PV-array. Therefore, the algorithm controls the PV output voltage to be very close to the value corresponding to PV maximum power The output of the MPPT algorithm is the control signal of dc-dc boost converter.

Steps of incremental inductance algorithm is as follows:

1) Read the present values of PV output current and voltage then calculate the present PV output power.
2) Calculate increment of PV output power, voltage and current
   a. $\Delta P = P_{n+1} - P_n$
   b. $\Delta V = V_{n+1} - V_n$
   c. $\Delta I = I_{n+1} - I_n$
3) According to the sign of ΔP, ΔV and ΔI the duty cycle of the control signal of the boost converter is updated

4. Simulation results

The described system has been simulated using MATLAB/SIMULINK software program. The PV array parameters are: short circuit current = 3.8 A, open circuit voltage is 211 V and the maximum output power is 605 W and its corresponding voltage is 173 V. The boost converter has an inductance of 100 mH and a capacitor of 500 µF. Incremental inductance controls the boost converter by applying the described steps in section 3. Sinusoidal pulse width modulation (SPWM) and selective harmonics elimination (SHE) are applied for H5 and HERIC inverters. In case of SPWM, the frequency of the triangular wave 'f_c' is set at 5 kHz while the frequency of the fundamental wave 'f_s' is set at 50 Hz. In case of SHE, the switching angles are adjusted such that low order harmonics up to the 17th are fully eliminated. An LCL filter is utilized to eliminate other harmonics and consequently achieve pure sinusoidal voltage waveforms at the load. The load resistance and inductance are set at 51 Ω and 130 mH respectively.

Figures 7 and 8 shows the output voltage of the inverters when applying SPWM and SHE technique respectively. The high switching is clearly noticed in case of SPWM while low switching operation is noticed in case of SHE. Fig. 9 gives the load voltage and current when applying the two inverters at sun insolation level of 100%.

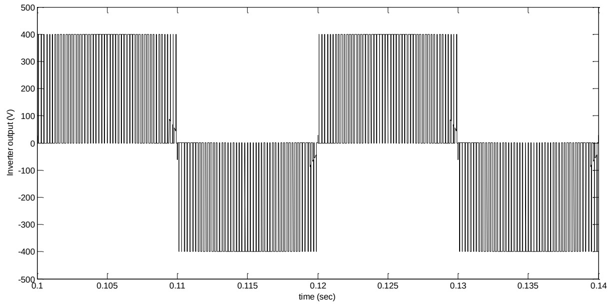

Fig. 7 Inverter output voltage (SPWM)

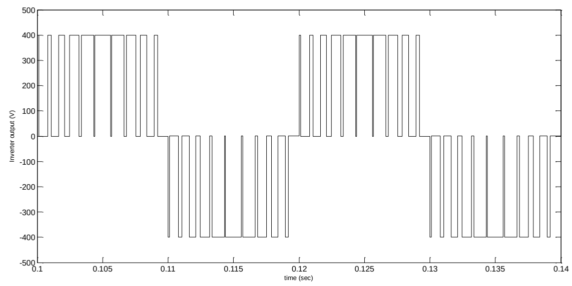

Fig. 8 Inverter output voltage (SHE)

The waveforms have pure sine-shape as expected by applying the LCL filter. Fig. 10 illustrates the PV output voltage, PV output current and PV output power. The sun insolation level is initially set at 80% which is corresponding to a maximum PV power of about 484 W. At t = 0.5 sec, the sun insolation level is changed to 100%. It is obviously noticed that the incremental inductance MPPT always tracks the maximum power from the PV arrays.

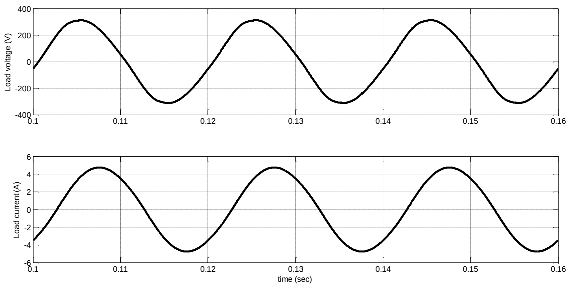

Fig. 9 Load voltage and current

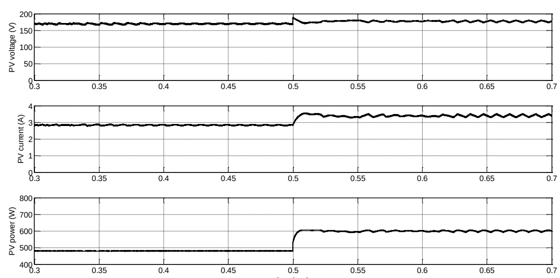

Fig. 10 PV output voltage, current and power

5. Comparison between HERIC and H5 inverters

The comparison between the two inverters is based on three criteria; conduction losses, size of the required filter and amount of leakage current.

5.1 Conduction losses

The dominant losses of power switches are the conduction losses. For simplicity, the switching losses are neglected. The conduction losses of each switch and its freewheeling diode is considered. The following equations calculate the average conduction losses of the switch (P_s) and the average conduction losses of the freewheeling diode (P_D)

$$P_s = \frac{1}{T} \int_0^T I_S^2 \, R_{ds} \, dt \tag{3}$$

$$P_D = \frac{1}{T} \int_0^T I_D \, V_D \, dt \tag{4}$$

where
I_S = Switch conduction current
I_D = Freewheeling diode forward current
R_{ds} = switch on resistance calculated from the MOSFET data sheet (IPW50R199CP) = 0.45 Ω
V_D = Diode forward voltage calculated from the MOSFET data sheet, 1.2V

Tables 1 and 2 give the average conduction losses of each switch, freewheeling diode conduction losses and total conduction losses for H5 and HERIC inverters respectively. Investigating the results in the tables, it can be noticed that the conduction losses with HERIC inverter is lower than that of H5 inverter although six switches are used in HERIC inverters. The reason is that during active modes S_5 always conducts in H5 inverter and as a results three switches always conduct in active modes. On the other hand, only two switches conducts in active modes with HERIC inverter. It is also noticed that the conduction losses when applying SHE is lower than conduction losses when applying SPWM for the two inverters.

Table 1 Average conduction losses of H5 inverter

Switch	Switch loss (W)		Diode	Diode loss (W)	
	SPWM	SHE		SPWM	SHE
S_1	1.42	1.1	D_1	0.44	0.28
S_2	1.0	0.9	D_2	Zero	zero
S_3	1.42	1.1	D_3	0.44	0.28
S_4	1.0	0.9	D_4	Zero	zero
S_5	2.0	1.8	D_5	Zero	zero
Total conduction losses (SPWM) = 7.72 W					
Total conduction losses (SHE) = 6.36 W					

Table 2 Average conduction losses of HERIC inverter

Switch	Switch loss (W)		Diode	Diode loss (W)	
	SPWM	SHE		SPWM	SHE
S_1	1.0	0.9	D_1	Zero	zero
S_2	1.0	0.9	D_2	Zero	zero
S_3	1.0	0.9	D_3	Zero	zero
S_4	1.0	0.9	D_4	Zero	zero
S_5	0.41	0.23	D_5	0.44	0.28
S_6	0.41	0.23	D_6	0.44	0.28
Total conduction losses (SPWM) = 5.7 W					
Total conduction losses (SHE) = 4.62 W					

5.2 LCL filter size

A simple LCL filter is utilized to cancel the harmonics in the output voltage of the inverters. The values of capacitance and inductance for each case is listed in table 3. The values of filter capacitance are very close in all cases while the inductance value using SHE technique is nearly three times that in SPWM. The reason is that using SHE technique only eliminates selected low order harmonics.

5.3 Leakage current

Leakage current flows from the PV panel to the ground through a parasitic capacitance whose value is set at 60 nF for each case. Figures 11-14 gives the PV leakage current with the two inverters and when applying the two techniques of switching the inverters. All values of leakage currents are within the limit according to standard (VDE 0126-1-1-2006, 2008). The leakage current in case of HERIC inverters is lower than that when applying H5 inverter.

Table 3 LCL filter size of each inverter

Inverter type	Capacitance (μF)	Inductance (mH)
HERIC (SPWM)	40	12
HERIC (SHE)	35	35
H5 (SPWM)	40	12
H5 (SHE)	35	35

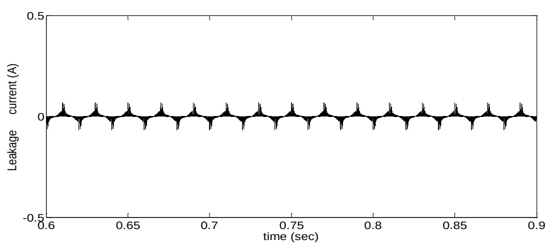

Fig. 11 PV leakage current with HERIC and SPWM

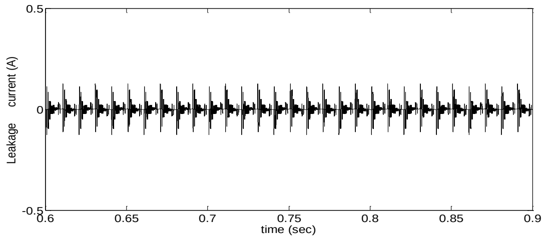

Fig. 12 PV leakage current with HERIC and SHE

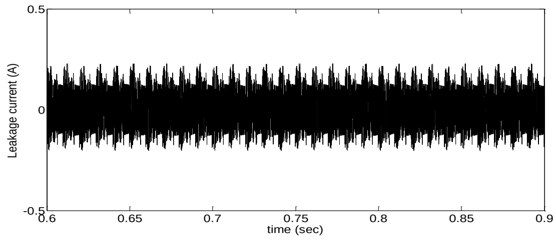

Fig. 13 PV leakage current with H5 and SPWM

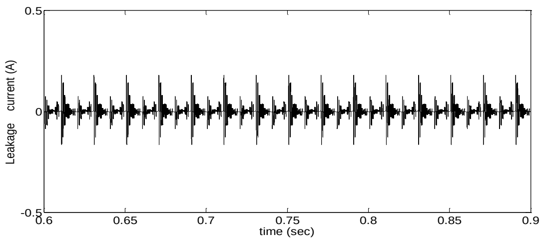

Fig. 14 PV leakage current with H5 and SHE

Conclusion

PV system feeding standalone load is proposed consisting of PV panels, dc-dc boost converter, incremental inductance MPPT, transformer-less inverter, LCL filter and R-L load. H5 and HERIC transformer-less inverters are utilized individually with the system. SPWM and SHE modulation techniques are applied when utilizing each inverter. The performance of the two inverters are compared based on conduction losses, LCL filter size and PV leakage current. H5 inverter exhibits higher conduction losses than HERIC inverter. The conduction losses with SHE is lower than that with SPWM. Filter capacitance has nearly the same value for all cases. Filter inductance with SHE is about three times its value with SPWM. The leakage currents are lower than the recommended limited values as in standard. The leakage current with HERIC is lower that with H5. Incremental inductance MPPT follows the maximum power point of the PV panels successfully.

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