Investigation of Power Quality Analysis of Three-Phase Inverter Topologies for Renewable Energy Systems

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Abstract

Today's, renewable energy systems are extending day by day and becoming more and more popular. Most of renewable resources are wind turbines, fuel cells and solar cells. Due to increasing to integration these renewable energy systems (RES), effect of RESs on quality of electric power are increasing day by day. Inverter is one of main component of these renewable energy systems. Inverters are becoming popular with spread of the use of RES. Inverter is main component of RESs which converting direct current to alternating current; for these reasons, Inverter main part of RESs which related to power quality and inverter design are important for quality of electric power. This project aims designing different three-phase inverter topologies for using RESs with different circuit topology at different load condition and give analyze of their characteristic in terms of current waveform and comparing DC injection, total harmonic distortion and individual harmonics with help of PSIM and MATLAB Simulink.

1. Introduction

ENERGY can be defined as ability of work in a system or object. Energy word derives from energon in ancient Greek. En means interior and ergon means work and from there it means creation of work inside. Energy can be different form such as heat energy, light energy from sun, chemical energy, nuclear energy, mechanical energy, and electrical energy. Throughout history, popular energy type was changed. Until recent times humanity struggle convert other energy types into mechanical energy. Todays, electrical energy is popular instead of mechanical energy. In this age, the most needed energy type is electrical energy.

Energy resources can be classified into 2 main categories; renewable and non-renewable or with other names conventional energy resources. Theoretically renewable energy sources are unlimited and can be used continuously and repeatedly. Wind turbines, fuel cells and solar cells, nuclear energy and hydroelectric energy are examples of renewable energy resources. Non-renewable or with other names conventional energy resources are limited and non-recurrent energy in a short time interval. Gasoline, coal, natural gas and fuel oil are common used examples of non-renewable energy resources. Theoretically, all energy resources are renewable but some energy resources renewal time up to thousands years such as coal, natural gas etc. For this reason this energy resources called as non-renewable or conventional energy resources. Despite decreasing of popularity of conventional resources which are limited, 80% of energy generation from conventional energy resources [1].

There is so many disadvantageous of using conventional energy resources. Using conventional resources produces greenhouse gases and such as CO_2, CH_4 etc.[2]. %25 of greenhouses gas generates from electricity and heat production [3].Greenhouse gases causes increasing global temperature, climate changing and vital changing on all ecosystem in long run. RESs are very clean compared to conventional sources. Due to being limited and harmful effects to environment of conventional sources, RESs popularity is increasing more and more and so many governments, foundations supports using RESs instead of conventional sources.

Inverter is main component for many RESs such as solar cells, fuel cells, wind turbines and combination of RESs or with other names hybrid systems. Today's trend is very popular with the combined use of photovoltaic systems (PV) and wind turbine systems [4]. Inverters are crucial equipment especially hybrid systems due to integrating properties. Inverter becomes important with increasing integration of new RESs day by day for transmission and distribution system. Power quality is major problem for all power system and getting more complex integrating linear and non-linear loads. Inverter is one of main component of RESs which affect power quality directly due to D.C-. A.C. converting. Due to increasing number of inverters integrated line, inverters play important role of power quality. . This paper provide investigation of power quality analysis such as DC bias, total demand distortion and individual harmonics for different three-phase inverter topologies as off-grid condition with renewable energy sources such as wind turbines, fuel cells and solar cells, which shows the characteristics of D.C. voltage sources and different control methodology at different resistive load condition such as 25%, 50%, 75%, 100% and comparing result with help of PSIM and Matlab Simulink software.

2. Inverter

An inverter is equipment which converts D.C. to A.C. Frequency, voltage, current and other parameters can be adjusted independently to desired level. Inverter definition for IEEE dictionary; inverter, is an electronic device or circuitry that changes direct current (DC) to alternating current (AC) [5]. There is no producing in inverter; inverter should be provided with a D.C source such as battery or solar cells etc. Inverters can be classified according to output level: 2-level and multilevel. The concept of multilevel inverters has been introduced since 1975.The term multilevel began with the three-level inverter [6]. Todays, semi-conductors are used for switching equipment such as MOSFET, IGBT etc. and there are many different circuit connections. There are so many inverter circuit topologies with combined parameters. There are many different classification of inverter: current and voltage source according to controlled source; single and 3-phase according to number of phase;

multilevel and 2-level according to inverter waveform; single dc source, multiple dc source according to dc supply number; neutral point clamp, flying capacitor, cascaded H bridge etc. according to circuit connection schema. Also, there are many controlling techniques for switching semiconductors such as pulse width modulation (PWM), sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHE-PWM), space vector modulation (SVM), and others. Inverters can be categorized different properties such as controlled type, switching method and output waveform etc. as indicated above but it can be classified extensively into 3 main categories according to output waveform as: Square wave, modified square wave and true sine wave inverter.

2.1. Square Wave

This inverter type is the simplest and the cheapest form in these categories. Output waveform is simple square wave. Output waveform compared to modified square wave and true sine wave inverter is shown in Fig 1. Switching semiconductors is the simplest for this type of inverter but it can use limited application due to containing harmonics.

2.2. Modified Square Wave

Output of modified square wave or with other named quasi-sinusoidal inverter is so like square wave inverter. There is a least an extra step in output waveform. Output waveform of modified square wave inverter is shown in Fig 1. Voltage sits 0 volts for a short time before changing polarity. Through this property, inverter can be avoided shoot-through. A modified square wave inverter output contains more harmonic than sinusoidal wave inverter but it contains fewer harmonics than square wave inverter. The inverter is compatible more application than square wave. Some applications may not work such as clocks, timers, A.C motors etc. but some devices works better than other types of inverter such as air conditioner in terms of efficiency.

2.2. True sine wave inverter

True sine wave inverter or with other names pure sine wave inverter output is more likely to sine wave; with other words output of true sine wave inverter is so similar to grid waveform. Only this type of inverter can be used grid connected with other words on-grid inverter. Noise of waveform is so less, it means the less harmonic content is shown compared to other inverter types is in Fig 1. There are some benefits for using true sine wave inverter or as other named pure sine wave inverter [7]. Most of electrical and electronic equipment's are designing for the sine wave so this type of inverter is available for nearly all equipment. Some electronic equipment does not provide nominal power without sine wave such as variable motor, refrigerator, microwave etc.; so this equipment does not work or works noisier.

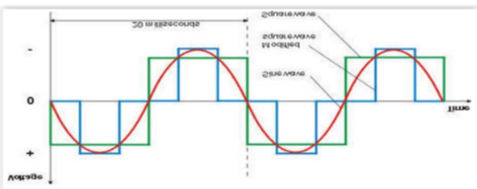

Fig 1. Comparing output waveform of Inverters at 50Hz

3. Methodology Modeling and Simulation

Effects of inverters on power quality are increasing day by day as indicated below. Due to these reasons, this paper 3 different 3-phase circuit design and investigated: 3-phase H-bridge 2 level inverter as manually controller with PSIM, 3-phase H-bridge 2 level inverter with phase locked loop (PLL) controller with MATLAB and 3-phase 3-level cascaded H-bridge inverter with help of PSIM as off grid. Aim of this paper is comparing control effect on power quality comparing both controlling, non-controlling 2- level and cascaded 3-level H-bridge topologies at different loading level. MOSFET transistors are used for all topology and internal resistance (R_{on}) is determined 1 ohm according to desired voltage and current level and literature researches. Sinusoidal pulse width modulation (SPWM) was used for switching MOSFETS. SPWM which is through comparing a low power sine wave reference with a high frequency triangular wave which named carrier waveform. This PWM signal was used to control switches.LC filter is used as low pass filter for filtering output waveform of inverter due to reducing harmonics content and keeps between standards such as IEEE 1547.2003. As mentioned previous section, waveform from grid is similar pure sine wave and many of devices designed for sine wave. Due to this reason, LC filter specifications must be determined properly for eliminated harmonics also cut-off frequency should be determined properly such that most of the low order harmonics is eliminated. For ideal A.C sine wave, there is not voltage distortion despite different load condition or non-linear load, the output impedance of the inverter must be kept zero. As a result of this, the capacitance value should be maximized and the inductance value should be minimized at the selected cut-off frequency of the low-pass filter. For all inverter topology, same L and C values is used for comparing power quality of inverter and L and C values are changed for reducing THD and kept the THD in limits. Basically cut-off frequency of LC filter is [8]:

$$f_0 = \frac{1}{2\pi\sqrt[2]{LC}} \qquad (1)$$

where L and C value of inductance capacitance. It is common that the filter components are determined at the set of a small capacitance and a large inductance and consequently the output impedance of the inverter is so high. For all circuit L is determined 8 mH and C is determined 3.16 μF for cut-off frequency 1000Hz.

Input voltage is determined 700V for uncontrolled and controlled full-bridge topology and 450 V for cascaded H-bridge each bridge. All topology output power determined as phase 10 kW so all inverter topology has 30 kW power All topology analyzed at 25%, 50%, 75% and 100% resistive load condition so all topologies analyzed at power 2.5 kW, 5 kW, 7.5 kW and 10 kW resistive load condition as phase. Resistive load is used for all power level. Load resistance value is changed for the purpose of desired power.

For all inverters output voltage as phase is determined 220 V and frequency is determined 50 Hz. Voltage level adjusted according to loading level with modulation index for controlled topology m is adjusted by controller. Modulation Index is defined as [9]:

$$m = \frac{Vsine}{Vcarrier} \qquad (2)$$

SPWM is a PWM method of carried-based PWM method. 2 signals are compared with a comparator and obtained signal was used as gating pulses. For SPWM techniques there are multiple numbers of output pulse per half cycle and pulses are of different width. When sinusoidal wave has magnitude higher than the triangular wave, the comparator output is high, otherwise it is low. Generating SPWM is shown in fig 2.

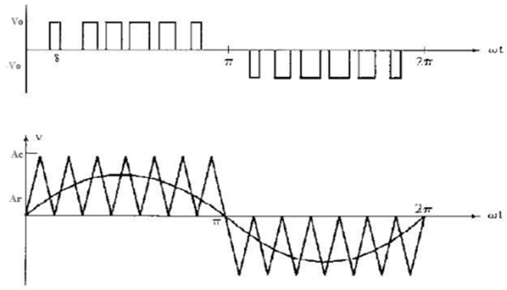

Fig 2. Sinusoidal pulse width modulation and gate pulses

Carrier frequency is same and determined 2000 Hz for all topology, when carrier frequency increases, wave is much more similar the pure wave but at high frequency carrier waveform losses will increases. Todays, with development of power electronic switching frequency is up to 10 kHz. Consequently, literature review and previous research and application is considered and carrier frequency is determined 2000 Hz for all topology due to comparison. Fast Fourier Transform (FFT) which is basically converting signal from time domain to frequency domain and total harmonic distortion (THD) which is used for power quality issue. The sinusoidal waves which outside the fundamental wave are called "harmonic". These distorted waves are called "non-sinusoidal waves and sum of up to proper harmonics is named THD is shown in formulas 3.There is extension for PSIM and MATLAB for calculation of FFT and THD.

$$\%THD=\frac{\sqrt{\sum_{n=1}^{\infty} {V_n}^2}}{V_f} * 100 \quad (3)$$

3.1. 3-phase H-bridge 2-level SPWM inverter

3-phase Full-bridge inverter or in other words universal bridge is modeled with MOSFETs in PSIM. There is 3 leg and 6 MOSFETs in circuit the switches of any leg of the inverter cannot be switched on simultaneously because this would result in a short circuit across the dc link voltage supply. . 2-level SPWM is produced with compare a 3 sine wave and a carrier signal. Phase angle of carrier signals are 0^0,-120^o, and - 240^o , there is phase shifting between carrier signals. Resistances are adjusted for loading. Circuit schema is shown in Fig 3.

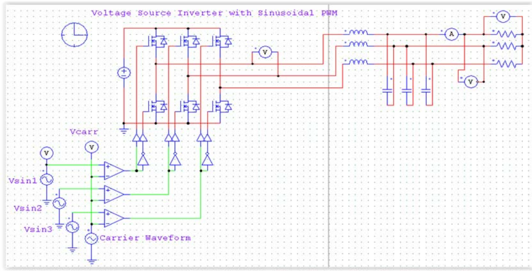

Fig 3. 3-Phase 2-level Full- Bridge Inverter

3.2. 3-phase 2-level controlled SPWM inverter

3-phase Full-bridge inverter or in other words universal bridge is modeled with MOSFETs in Simulink. Simulation of circuit diagram is shown Fig.4 and circuit parameters and properties of carrier signals as same as uncontrolled 2-level SPWM inverter in section 3.1. Amplitude of sine wave is changed due to voltage regulation automatically. Inverter circuit is controlled with PLL, abc to dq_0 transform and PI controller. For voltage control, voltage regulator block is used which is in Simulink library example. Reference signal amplitude so sine wave amplitude controlled by voltage regulator and phase voltage is always 220V**.**

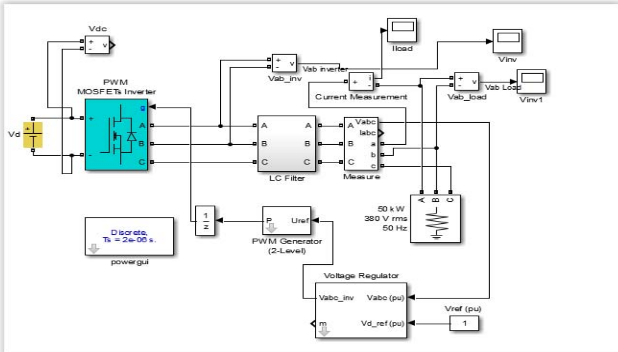

Fig 4. 3-Phase 2-level Controlled Full- Bridge Inverter

3.3. 3-phase 3-level cascade SPWM inverter

In this topology, simulated circuit designed as 3-phase 3-level cascade connection which used 3 H-bridge in PSIM software. Simulation of circuit diagram is shown fig 3.7 and carrier signal parameters are shown in Table 1. 3 different 3-level SPWM for each H-bridge is produced with compare a 3 sine wave and a 6 different carrier signal [10]. There is phase disposition and shifting between carrier waves. As mentioned 3-level single-phase topology, there should be 2 carrier signal for each phase and a sin wave. Phase-shifting on any two adjacent carrier waves is 180^o [11]. Amplitude of sine waves is changed due to voltage regulation for 3 H-bridge. As mentioned in circuit topologies, there is 3 H-bridge in 3-level 3-phase cascade inverter so there is 3 different input source is needed for this topology all input voltage is determined 350 V and output voltage and frequency is same as other 3-phase topologies respectively 220 V as phase and 50 Hz.

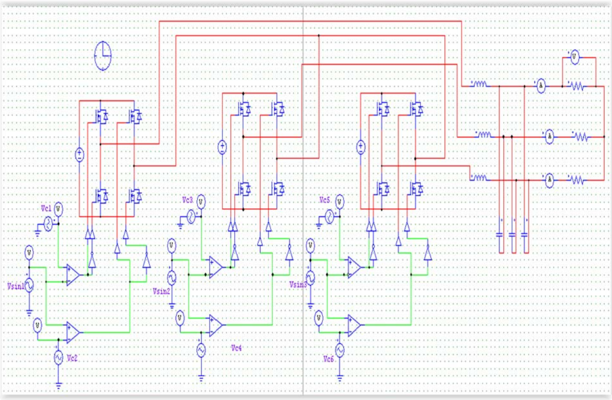

Fig 5. 3-Phase 3-level cascaded H-bridge inverter

Table 1. Carrier signals parameters

	Vc1	Vc2	Vc3	Vc4	Vc5	Vc6
Vpeak-peak	1	1	1	1	1	1
Frequency(Hz)	2000	2000	2000	2000	2000	2000
Duty Cycle	0,5	0,5	0,5	0,5	0,5	0,5
Dc offset	-1	0	-1	0	-1	0

4. Result and Comparison

Simulation results of topologies which is designed as 3-phases is mentioned in this part at %25, %50, %75, %100 loaded condition.

In full-bridge 2-level uncontrolled topology as mentioned in 3.1; THD is calculated as 3.56%, 3%, 2.56% and 2.27% at 25% 50% 75% and 100% load condition respectively. Harmonics is observed at around 2 kHz and 4 kHz because of switching frequency is 2 kHz. Harmonics around 2 kHz is change between 2.09-2.53%, 1.78-2.08%, 1.56-1.80%, and 1.35-1.53 % at 25% 50% 75% and 100% load condition respectively. Harmonics are observed around 4 kHz is between 0.1% and 0.8%, base is determined as fundamental component. DC component is observed 9.18*10-3, 3.8 *10-4, 6.7 *10-2 and 1.57*10-1 at 25%, 50%, 75%, and 100% load condition respectively.

In full-bridge 2-level controlled topology as mentioned in 3.2: THD is calculated as 3.67%, 3.06%, 2.57% and 2.25% at 25% 50% 75% and 100% load condition respectively. Harmonics is observed at around 2 kHz and 4 kHz because of switching frequency is 2 kHz. Harmonics around 2 kHz is change between 2.-2.55%, 1.8-2.0%, 1.6-1.8%, and 1.4-1.6 % at 25% 50% 75% and 100% load condition respectively. Harmonics are observed around 4 kHz is between 0.1% and 0.8%, base is determined as fundamental component. DC component is observed 9.4*10-3, 2 *10-4, 2 *10-2 and 1.8*10-2 at 25%, 50%, 75%, and 100% load condition respectively.

In cascaded H-bridge topology as mentioned in 3.3: THD is calculated as 3.48%, 2.83%, 2.21% and 1.78% at 25% 50% 75% and 100% load condition respectively. Harmonics is observed at around 2 kHz and 4 kHz because of switching frequency is 2 kHz. Harmonics around 2 kHz is change between 1.93-2.56%, 1.57-1.91%, 1.29-1.35%, and 0.9-1.12 % at 25% 50% 75% and 100% load condition respectively. Harmonics are observed around 4 kHz is between 0.05% and 0.1%, base is determined as fundamental component. DC component is observed 2.5*10- 3, 2 *10-2, 6.7 *10-2 and 1.52*10-1 at 25%, 50%, 75%, and 100% load condition respectively.

Inverter output forms is shown in Fig.6 and output waveform of load is shown in Fig.7 respectively uncontrolled H-bridge 2 level, controlled H-bridge 2-level, and cascaded H-bridge 3-level topology at full load condition.

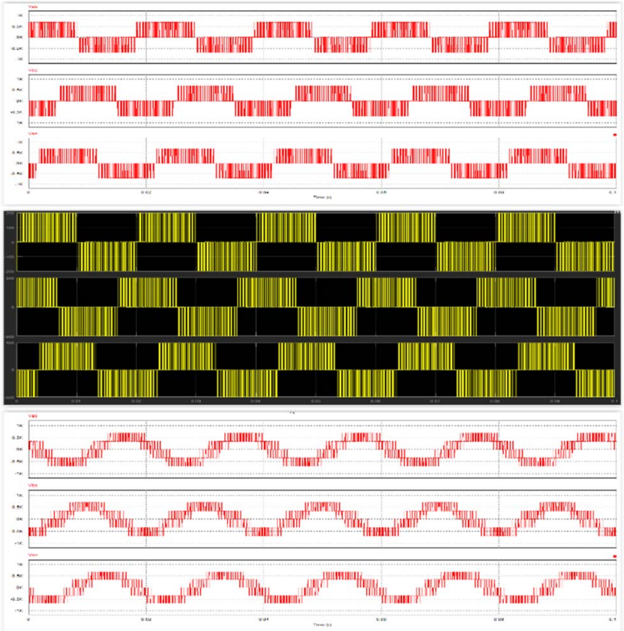

Fig 6. Output of inverters respectively uncontrolled and controlled full-bridge and cascaded H-bridge inverters

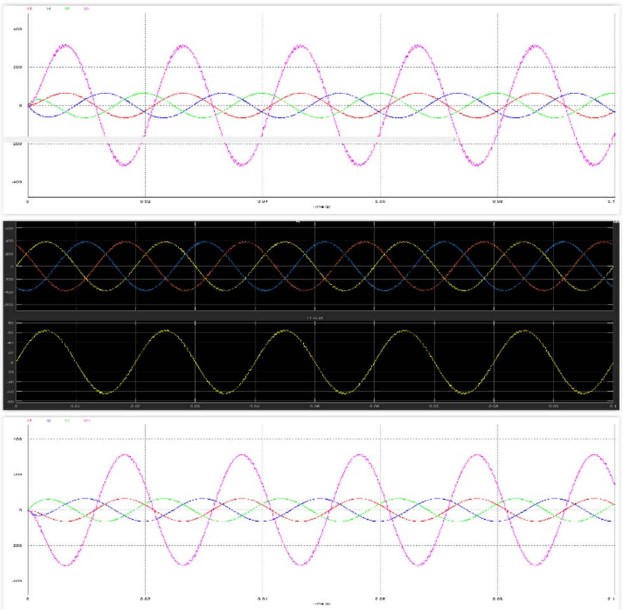

Fig 7. Voltage and Current waveform of load respectively uncontrolled and controlled full-bridge and cascaded H-bridge inverters

FFT analysis and individual harmonics result results is shown in Fig 8.

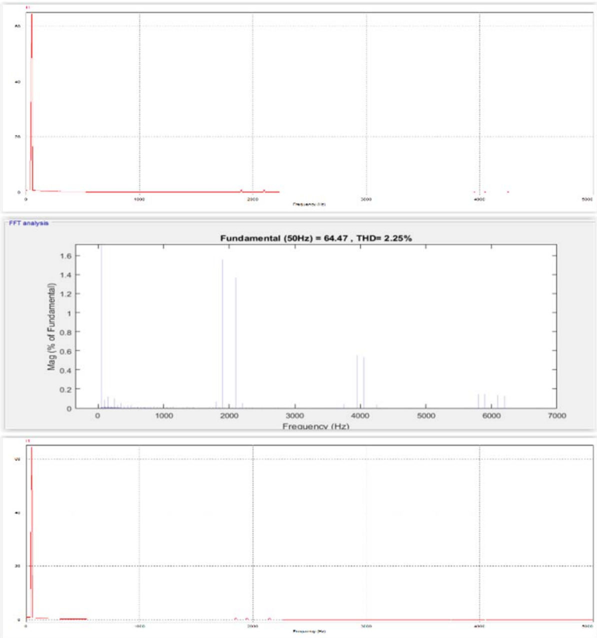

Fig 8. FFT analysis respectively uncontrolled and controlled full-bridge and cascaded H-bridge inverters at 100% loading

Table 2. THD of Inverters

Load	Full-bridge uncontrolled	Full -bridge controlled	Cascaded H-bridge
25%	3.56%	3.67%	3.48%
50%	3%	3.06%	2.83%
75%	2.56%	2.57%	2.21%
100%	2.27%	2.25%	1.78%

Table 3. DC injection of Inverters

Load	Full-bridge uncontrolled	Full -bridge controlled	Cascaded H-bridge
25%	0.057%	0.058%	0.016%
50%	0.0011%	0.006%	0.064%
75%	0.149%	%0.0421	0.14%
100%	0.244%	0.028%	0.23%

6. Conclusions

In this paper 3 different 3-phase inverters are designed, simulated and compared as power quality. The data obtained according to the results are as follows:

- ✓ Minimum THD is observed for 3-level cascaded inverter as expected.
- ✓ If level of output inverter increase, the output of inverter closes to sine wave and THD reduces However, when level of inverter increases, control topology is become more complex and switching are increases and cost of inverter increases. Another advantageous of CHB have been developed to use unequal dc bus voltage.
- ✓ DC injection for all topologies is acceptable and very low within certain limits
- ✓ THD of controlled topology is a little bit higher than uncontrolled topology due to oscillation of controller but results are so close and controlling effects can be neglect for power quality.
- ✓ Power of inverter is important for inverters. Minimum THD is observed at full-load condition and maximum THD is observed at 25% load condition for all topology. Power of inverter should 9be designed or selected according to desired system. If inverter works lower than its nominal power, THD is increases.
- ✓ All THD and DC bias parameters is within limits according to IEEE 1547.2003[12].

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