Improving the Power Capacity and Reducing Harmonic Distortion with Triangle Signals

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ABSTRACT: *To change the DC output to the AC output, we use inverters. The modulation produces pure signals that help in the right pulse. We aim to improve the power capacity and also reduce the harmonic distortion using PWM techniques. We have generated the total harmonic distortion analysis of the new waveform with correct solution using triangle signals. For conducting simulation experiments, we have used the single phase of the complete bridge DC/AC inverter.*

Keywords: DC/AC Inverter, Pulse Width Modulation (PWM), Total Harmonic Distortion (THD)

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1. Introduction

Power inverters are circuits that changes direct current (DC) to alternating current (AC) [1]. The converted AC can be at any required voltage and frequency with the use of corresponding transformers, switching, and control circuits. They are standard used as: a) grid tie with order to inject electricity into the electric power distribution system; b) stand-alone power sources for home appliances and small industries; c) drivers for asynchronous motors in industry and automotive; etc. Inverters are realized as solid-state devices without moving parts. With high energy efficiency and fast time response, inverters have possibility to convert any DC to any AC voltage.

The main drawbacks of inverters relate to involving harmonic distortion into a generated output signal. Distortions in a form of noise have negative impact on correct operation of other equipment connected as energy consumer to the inverter. Having this in mind, it is imperative to design inverter with low total harmonic distortion at the output. This hot problem was considered in literature for a long time [2, 3, 4]. However, a comparative analysis which deals with optimal choice of PWM parameters with order to achieve trade-off among THD, energy efficiency, switching frequency, cost was not considered in overall.

In this paper, THD analysis for three types of modulation signals (sawtooth, inverted sawtooth, and triangle) of constant frequency is given. According to the obtained results, it can be concluded that triangle shape is the best choice as generator of PWM signal for driving the inverter. In addition, Simulink model of DC/AC inverter is developed, thanks to which it is possible to define optimal working parameters (DC input voltage, switching frequency, AC output voltage, output frequency).

This paper is structured as follows: Section II deals with power inverter structures that is based on MOSFET (Metal Oxide Semiconductor Field Effect Transistor) or IGBT (Insulated Gate Bipolar Transistor). Global structure of singlephase full-bridge inverter topology is presented. Section 3 explains the application of PWM technique for control of switching inverters in order to generate pure sine wave. Section 4 defines PWM parameters that have impact on increasing the power efficiency of a system. Simulation results which relate to output signal quality are given in Section 5. Section 6 summarizes the conclusions.

2. Power Inverters Structures

Power switches are basic building blocks of static inverters. During the past two decades inverter topologies have changed from large thyristor-equipped grid-connected inverters to smaller IGBT or MOSFET-equipped ones [5]. MOSFETs and IGBTs are good candidates for implementation of switching devices in DC to AC converters. IGBT characterizes output switching and conduction features of bipolar transistor but is voltage-controlled like MOSFET. IGBT has simpler driving circuits with respect to other power switching devices which lead to high-power application. It has the advantages of highcurrent handling capability and the ease of control. The disadvantages of IGBT are comparatively large current tail and nobody drain diode [6]. Design choice between IGBTs and MOSFETs is application-specific in term of cost, size, switching speed, energy losses and thermal requirements [5]. Bearing in mind the fact that by replacing power MOSFETs with IGBTs the efficiency is improved and cost is reduced, we will consider inverter topology based on IGBTs.

There are many ways to achieve inverter function. Voltagesource inverters (VSIs) are widely used in industrial applications because they behave as voltage sources [5]. Single-phase VSI can be realized as half-bridge and fullbridge circuit. The full-bridge inverter consists of two halfbridge legs, as shown in Figure 1. Both switches S1+ and S1 in the first leg, (or S2+ and S2- in the second leg) cannot be on simultaneously with order to avoid short circuit between the DC power supply voltage and common point (ground). The modulating technique should ensure that either the top or the bottom switch of each leg is on at any instant. Maximal value of the AC output voltage is equal to the DC source value, V_{DC}, which is twice that the obtained value with half-bridge VSI circuit.

The AC output waveform is made up of discrete values with fast transitions instead smooth ones, since it is synthesized from a DC input by closing and opening the switches in an appropriate sequence. The AC output voltage is usually non-sinusoidal, staircase (stepped) wave and has a high harmonic content. The main causes of harmonic distortion are the following: modulation algorithm, dead times and voltage drops across the switches [4]. Although AC output voltage waveform is not pure sinusoidal as expected, its fundamental component (50 Hz) behaves as such. This behavior should be ensured by selecting modulating technique that controls the amount of time and the sequence used to switch the power switches on and off in appropriate way [5].

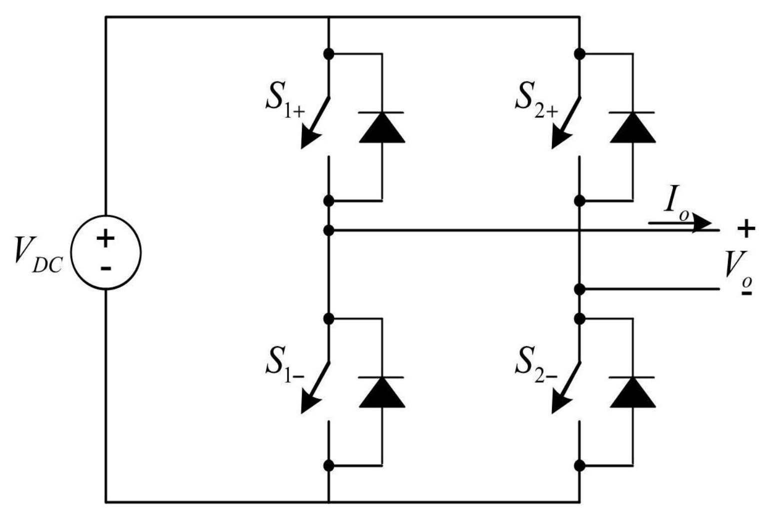

Figure 1. Single-phase full-bridge inverter

The DC/AC inverters with pure sine wave output are used for powering electronic devices with more accuracy and less power loss because they introduce minimal amount of harmonics and have high efficiency. Inverter with sinusoidal AC output characterizes controllable magnitude, frequency, and phase. During the design of this inverter it is necessary to fulfill the following requirements: high quality waveforms, low harmonic distortion, low switching frequency, low energy losses, and high efficiency.

3. PWM Technique

As mentioned earlier, it is needed to define the on- and offstates of the switches for both legs of a VSI with order to ensure that the AC output voltage, V_o, follows a given sinusoidal waveform on a continuous basis. The pulse width modulation (PWM) technique can fulfill this requirement. Real switches do not turn on or off instantly, so that it is necessary to provide correct switching times. PWM signal controls the top and bottom switches of a leg by comparing a modulating signal (desired AC output voltage) with a carrier signal (for example, triangular waveform). The duty cycle of a generated waveform is modulated such that its average voltage corresponds to pure sine wave. The widths of the voltage pulses, over the output cycle, vary in a sinusoidal manner. A series of on and off pulses, that repeats, supplies the analog load. The on time is a time during which the DC supply is applied to a load, and the off-time is the period during the supply is switched off [7]. After that, an LC filter can be used for refinement of PWM signal that will closer approximate a sine wave.

There are two types of switching schemes for PWM, unipolar and bipolar. In unipolar switching scheme, the output is switched from either high to zero or low to zero, rather than between high and low as in bipolar switching. Unipolar PWM requires half the switching frequency than required by bipolar PWM.

Various PWM techniques have been developed thanks to improvements in the field of VLSI ICs, which related to the power electronics [8]. However, there is no unique PWM method that represents the best choice for all applications.

3.1. Inverter performance

Ideal electrical power system is characterized with constant frequency and specified value of the output voltage. In practice, there are harmonic components which involve deviations in a perfect sine wave. Accordingly, performance of the inverter is usually assessed on basis of harmonic content of its output voltage. Distortion can be determined from a spectrum of the output signal. Performance measures that quantify distortion due to undesirable harmonics are needed to be involved. Total harmonic distortion (THD) is an appropriate measure that is used to determine the level of harmonics into the output voltage and current waveforms, and to provide useful information concerning the impact of different modulation strategies to the generated output [2].

In general, THD is defined as ratio of the sum of the powers of all harmonic components to the power of the fundamental. Accordingly, the harmonic content of voltage or current waveforms is compared to its fundamental harmonic component, and $THD_{v,i}$ is given as:

$$THD_{v,i} = \sqrt{\sum_{n=2}^{\infty} H_{on}^2} \Big/ H_{o1}$$

where $H_{on}=\{V_{on} \text{ or } I_{on}\}$ is the value of the n-th harmonic component of the voltage or current waveform, and $H_{o1}=\{V_{o1} \text{ or } I_{o1}\}$ is the value of the fundamental component of the voltage or current waveform.

4. Problem Definition

The power system based on a voltage controlled voltage source inverter is presented in Figure 2. As it is given in Figure 2, the proposed system uses an inverter as interface circuit which connects the DC source to local loads and/or utility grid. Primary function of grid connected inverter is to supply active power to load and grid in accordance with grid connection standards. Requirements concerning grid standard involve reactive power compensation, harmonic minimization produced by the nonlinear loads, and correct synchronization with aim to achieve power factor, $PF = 1$.

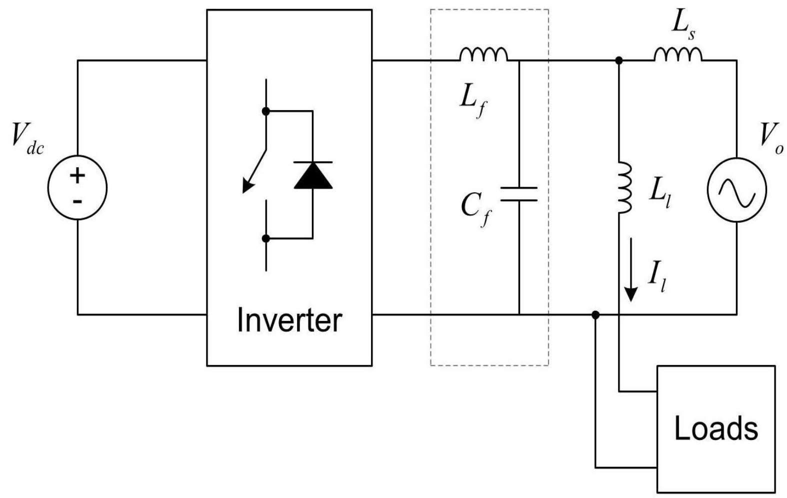

Figure 2. Power system

With order to study the effects of a system to the load and to the electrical distribution network, we will consider development of an appropriate model. This model is based on high voltage DC/AC inverter in full-bridge topology with IGBT realization.

Implementation of sine-wave PWM output requires a sinusoidal reference (modulating) signal, *r* (*t*), which correspond to the desired fundamental component of the voltage waveform, and a high frequency carrier signal, *c* (*t*), which control the switching frequency [9].

The binary PWM output can be represented as $b_{PWM}(t) = \text{sgn}\left[r(t) - c(t)\right]$, where 'sgn' is sign function. Constant frequency PWM can use the next three types of carrier signals: a) Sawtooth carrier (trailing-edge modulation); b) Inverted sawtooth carrier (leading-edge modulation); and c) Triangle carrier (double-edge modulation).

Our objective is to find optimal PWM technique that will enable generation of pure sine-wave signal and will give the best results in terms of reduction of harmonic distortion and efficiency increase. With order to determine this we use the following two parameters:

1. Amplitude modulation ratio, m_a, defined as reference carrier $m_a = V_{reference} / V_{carrier}$

2. Frequency modulation ratio, m_f, given as carrier reference $m_f = f_{carrier} / f_{reference}$.

5. Simulation Results

With aim to find suitable PWM technique for sinusoidal signal generation, FFT analysis was performed for the mentioned three types of carrier signals. Working parameters used in analysis process were the following: *DC* source $V_{DC} = 400V$, output voltage $V_o = 320V$, frequency modulation ratio $m_f = 21$, sinusoidal reference signal frequency $f_{reference} = 50Hz$. FFT analysis is performed using MATLAB/Simulink environment. The results of simulation are presented in Figure 3 show that the best design choice of producing PWM signal is achieved by comparing the reference sine-wave with triangle wave. This PWM eliminates most of the harmonics and presents a preferred method for bipolar switching control of DC/AC inverters.

Harmonic amplitudes are functions of parameter m_a. Normalized Fourier coefficients, V_{on} / V_{DC}, for bipolar PWM signal are given in Table 1. The spectrum of the output signal contains components located at multiples of carrier frequency and around them (sidebands type), and are defined as

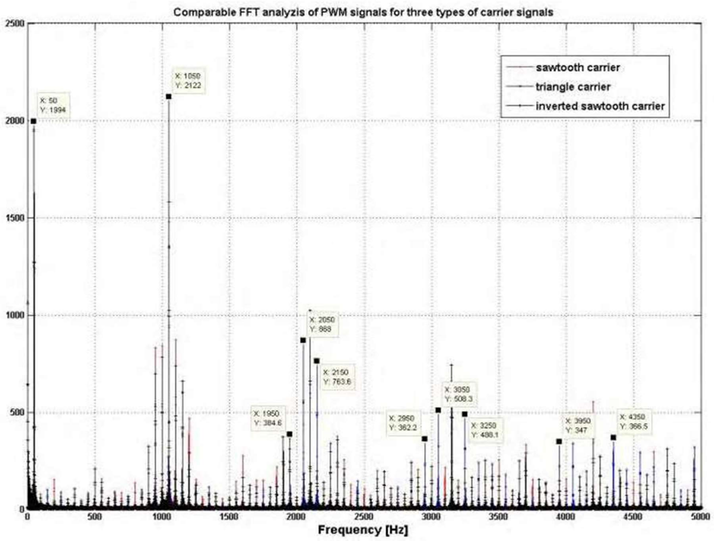

Figure 3. Comparable FFT analyzis of PWM signals for three types of carrier signals

$$f_{k-th} = k\, f_{carrier} \pm 2\, f_{refrence} \qquad k = 1, 2, 3, \ldots$$

m_a	1	0.9	0.8	0.7
$n = 1$	1.00	0.90	0.80	0.70
$n = m_f$	0.60	0.71	0.82	0.92
$n = m_f \pm 2$	0.32	0.27	0.22	0.17

Table 1. Normalized fourier coefficients for bipolar PWM

Table 2 reports the results which relate to THD values of voltage waveform which is generated using bipolar PWM by full bridge inverter without load. The THD is evaluated using Matlab tool for different values of parameters m_a and m_f.

m_a		1	0.9	0.8	0.7
m_f	15	1.0355	1.1890	1.3186	1.9053
	17	0.9045	1.2061	1.2965	1.5529
	19	0.9528	1.2260	1.3128	1.6546
	21	0.9405	1.2081	1.3883	1.5885
	23	0.9176	1.1181	1.1938	1.6979

Table 2. THD values of voltage waveform

The main goal is to generate an output voltage of 220V @50Hz for off-grid and grid-tie systems. Therefore, it is necessary to consider existence of RL type load, and its impact to THDi value. We assume that the internal resistance of the electrical distribution network is $R \approx 1\Omega$ and its serial inductance $L = 5\,mH$. DC source voltage value is $V_{DC} = 400V$. According to Tables 1 and 2 and the required amplitude modulation ratio $m_a = 220\sqrt{2}/400 = 0.7778 \approx 0.8$, it is possible to calculate THD_i.

Voltage, impedance and current values on the harmonics that are defined by parameter n, are presented in Table 3.

n	$f_n[Hz]$	$V_n[V]$	$Z_n[\Omega]$	$I_n[A]$
1	50	320	1.86	167.10
19	950	88	29.86	2.9469
21	1050	328	33.00	9.4280
23	1150	88	36.14	2.44

Table 3. Fourier series quantities for the bipolar PWM inverter

Based on the values given in the Table 3, the THD_i is

$$THD_i = \sqrt{\sum_{n=2}^{\infty} I_n^2} \Big/ I_1 = 0.06089 \approx 6.1\%$$

This result (for $m_j = 21$) presents an approximate value since it is consequence of truncating the Fourier series. In spite of that, this value can be accepted because the amplitude values of the remaining harmonics generally decrease with increasing the number of harmonic, n, i.e. their impact on THD_i is negligible.

The results of the previous analysis can be used as input parameters for Matlab/Simulink tool. The conducted analysis should take into account the actual parameters of the switch implemented as IGBT.

Simulink model of the single phase full bridge inverter is presented in Figure 4. As switches IGBT SPW20N60C3 components are used. These components are the part of inverter in the High Voltage Solar Inverter DC-AC Kit [10]. Parameters of the IGBT used in the simulation are:

$V_{DS} = 650V$, $I_d = 20.7A$, $R_{DS}(on) = 0.19\ \Omega$, R_S=100 $k\Omega$, and $C_S = 1\ nF$.

Working parameters of the Discret PWM generator are: $f_{carrier}$=1050Hz, $f_{\sin}$=50Hz and $m_a = 0.8$.

Current waveform of the output signal generated by Simulink model is presented in Figure 5. According to Figure 5 we can conclude that for selected parameters $m_a = 0.8$, $m_f = 21$ and $THD_i = 6.1\%$, the generated current waveform corresponds to European standard IEC61727.

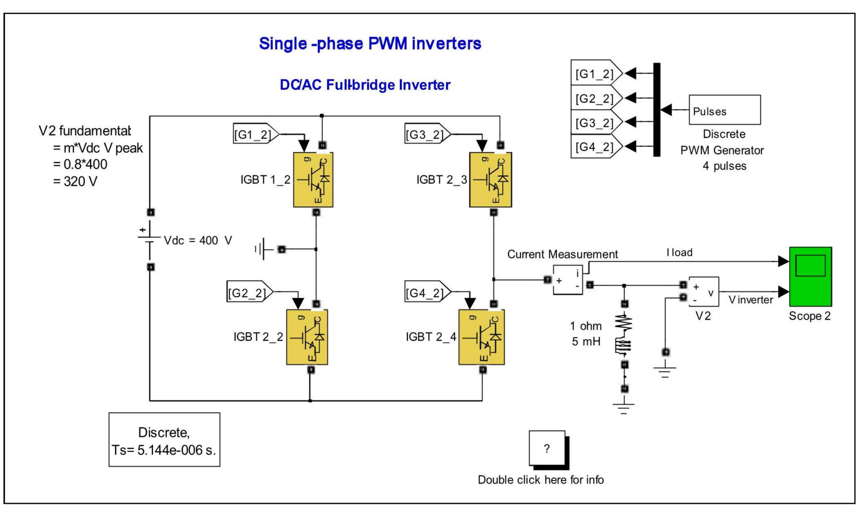

Figure 4. Simulink model for single phase full bridge inverter with load

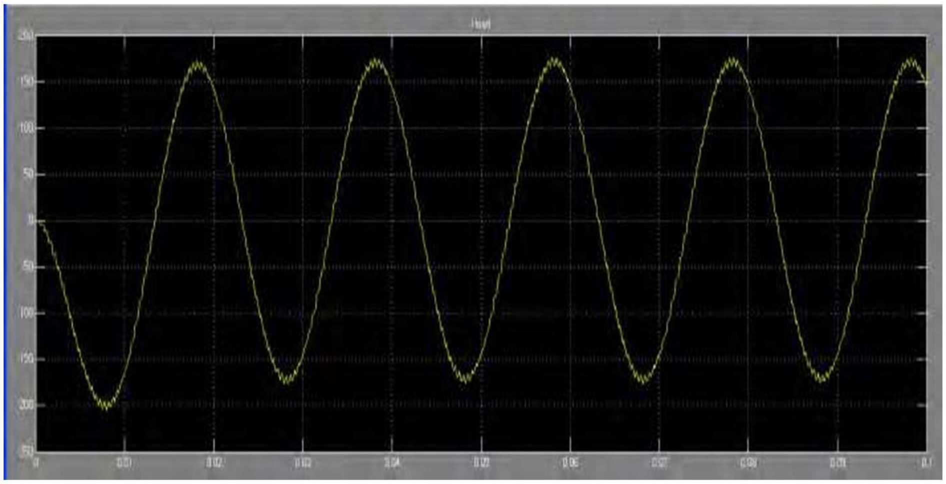

Figure 5. Current waveform of the output signal

By repeating the simulation for $m_f > 21$, the output current waveform becomes more smoothly, what indirectly suggests that the THD_i factor is lower. However, by increasing m_f the losses in switch elements increase too. Having this in mind, we can conclude that the choosen parameters, using this method, represent good design starting point for generating look-up table of the sine wave output signal.

6. Conclusion

Single phase full-bridge inverter, based on IGBTs as switching devices, is adopted in this paper. Spectrum analysis and THD values for PWM voltage waveform of three types of modulation signals (sawtooth, inverted sawtooth, and triangle) are presented. Triangle signal is selected as the method for PWM signal generation which is used for driving the inverter. Based on Simulink model working parameters of DC/AC inverter are confirmed as optimal solution for generating lookup table of the sine wave output signal.

Acknowledgement

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