"Optimization of PWM Strategy for Single Phase Inverter and Its Hardware Realization"

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ABSTRACT: *This system is used to generate the optimal pulse width modulated (PWM) signal for single phase inverter using MATLAB. PWM signals are generally used in motor control application, power electronics and solid-state electric energy conversion. In this system, I am going to generate the optimal PWM with help of MATLAB which reduces the total harmonic distortion. This system uses two PWM patterns, three pulses PWM and five pulses PWM pattern. For obtaining the optimal PWM different conditions are undertaken, case 1 is middle pulse having constant center time & constant pulse width, side pulses having constant pulse Width changing center of side pulses. Case 2 is having [*W_m *(width of middle pulse) +*W_s *(width of side pulses)] width constant, center of all pulses also constant, but changing width of middle pulse and side pulse in proportion such a way that [*W_s*(side pulses) + (a/2)], [*W_m *(middle)-(a)] where 'a' is constant.*

That generated MATLAB code gives switching times of optimal PWM waveform. For testing the THD practically FPGA board with inverter circuitry is used. PWM signals are generated on FPGA board using switching times of optimal PWM waveform. That signal is applied to inverter circuit which work efficiently with lowest THD.

Keywords—pulse width modulation (PWM), single-phase inverter, optimal PWM, total harmonic distortion (THD).

I. INTRODUCTION

The inverters based on the PWM technology are more advantageous than the conventional inverter. The use of PWM strategy for inverter is advantageous because it gives a steady output voltage irrespective of the load. The output of practical inverters contains harmonics and the quality of an inverter is normally evaluated in terms of total harmonic distortion (THD). Inverters are generally used in consumer electronics and industrial applications to get a variable alternating current output from direct current input. The gain of the inverter can be changed using various techniques like a Pulse-Width Modulation technique. This inverter gain variation provides an efficient control drive for alternating current applications. The output waveform of an ideal inverter is a sinusoidal in nature but we don't get this type of output for practical inverter. The output of practical inverter is discontinuous and contains harmonics. This discontinuous operation is not desirable for the practical applications due to its problems such as extra power losses.

Operating the power switches at low frequency level we can limit the switching loss at the high power level. For that within fundamental period only a few switching actions may take place. To achieve the best modulation value, optimizing the waveform based on optimal value for each switching time is important.

Harmonic elimination technique is generally used technique to generate optimal PWM method. This method is used to eliminate the some low order harmonics completely. Technique used for harmonic elimination is complex and totally related to solving the nonlinear equation using the effective method. In this method the equations are formed to calculate the value of different switching angle of inverter. To get the equation some low-order harmonics are set to zero and remaining fundamental amplitude are set to the specified value, this result in the formation of system having N nonlinear equations. The required optimal PWM patterns can be obtained by solving these nonlinear equations.

Different off line pulse-width techniques

1. Conventional pulse-width-modulation techniques
2. Single pulse width modulation control
3. Uniform pulse width modulation technique
4. Sinusoidal pulse width modulation technique
5. The Selected Harmonic Elimination (SHE)

The Selected Harmonic Elimination is used to reduce current ripple and to eliminate low order harmonics, it is also used to decrease the inverter switching losses and produce improved quality output voltage. Various techniques are there to control the inverter power switches, among them commonly used control technique for the inverter is the optimal PWM technique. As a result of great research in this area during the past two decades, methods like as Newton-Raphson method, symmetric polynomial based method and methods based on genetic algorithm have been suggested to achieve the optimal switching strategy. However, optimal switching techniques based on above methods are very challenging to solve online in real-time control, as mathematical model consists of a set of nonlinear equations at various modulation depths and therefore it have multiple solutions. For obtain the solutions for the above methods use of the computer offline is best option as the calculations are difficult and time consuming than getting solution by a Digital Signal Processor in real time. Results obtained offline are stored in memory locations therefore offline methods need large memory.

The online implementation is possible by using the interpolation technique and lookup tables. The problems in achieving optimal switching strategies in real-time is generally recognized and significant research efforts have been investigated to overcome the drawbacks of offline method. The generally used online methods are,

1. Space Vector Modulation
2. Curve Fitting Technique (CFT)

II. PROPOSED ALGORITHM

In this system, the main units are the optimal PWM generator, single phase inverter circuit and FPGA controller.

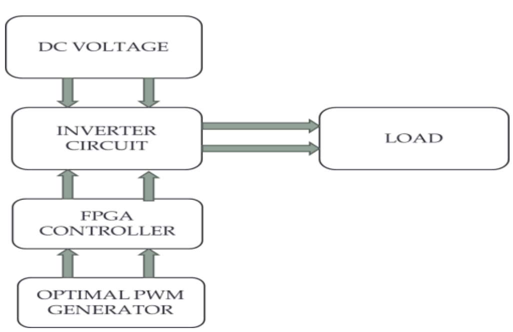

Fig.1 Proposed block diagram

A. Optimal PWM generator

The main objective of this system is to generate the optimal PWM waveform so that it has small total harmonic distortion value and apply this PWM waveform to the switching circuit of single phase inverter circuit

For generation of optimal PWM, the MATLAB software is used. A PWM waveform have a series of positive and negative pulses of constant amplitude but with variable switching instances as depicted in Fig. 2. A typical goal is to generate a train of pulses such that the fundamental component of the resulting waveform has a specified frequency and amplitude (e.g., for a constant speed control of an induction motor). From high residual harmonics that are difficult to control and from limitations in their applicability. A method that theoretically offers the highest quality of the output waveform is the so-called programmed or optimal PWM.

If the shape is symmetric in the PWM waveform then only the odd harmonics exist. Assuming that the PWM waveform is chopped times per half a cycle, the Fourier coefficients of odd harmonics are given by

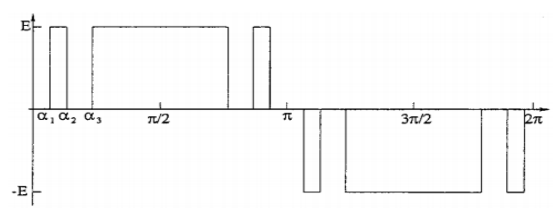

Fig.2 Three pulse PWM waveform.

$$Bn = \frac{4Vs}{n\pi}\left[1 + \sum_{k=1}^{m}(-1)^k \cos(n\alpha_k)\right]$$

By proper value of firing angle α1, α2…… we can change the shape of pulse and so reduce the THD value.

B. FPGA controller

FPGA controllers are very useful in fast prototype making and testing purpose as it is easily reconfigurable. Altera cyclone IV FPGA board is used for hardware realization.

Using switching time of optimal PWM waveform, the VHDL Code is generated. That code is used to generate the optimal PWM waveform on the FPGA board. Altera FPGA board with quartus software is used to generate PWM waveforms. These PWM waveforms are then applied to the switching devices of single phase inverter circuit.

C. Inverter circuit

A single phase bridge voltage source inverter is shown in Fig,4. It consists of four choppers. Voltage Vs gets across the load when the transistor Q1 and Q3 are conducting and voltage across the load is –Vs when the transistor Q3 and Q4 in turned on.

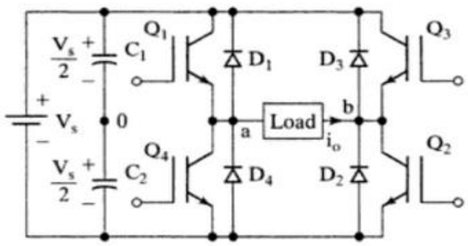

Fig.4 Full bridge inverter circuit

Gate signal applied to the transistor is the PWM waveform signal. PWM waveform applied to transistor Q1 and Q2 are same, and PWM signal applied to transistor Q3 and Q4 are same and 180^0 out of phase with the PWM signal applied to transistor Q1 andQ3.applying optimal PWM gate signal we reduce the total harmonic distortion of output signal.

III. Experiment and Result

1. SIMULATION RESULT

For simulation of system the software likes SIMULINK and PSIM are useful. At initial stage PSIM software is used for the simulation of single phase full bridge inverter. Fig.3 is the simulation window, in this window the circuit of full bridge inverter is created and its output is observed.

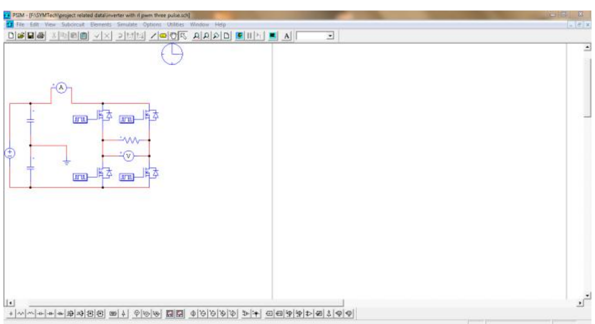

Fig.3 PSIM simulation window

Fig.4 is the AC output voltage generated by the inverter, which is controlled by the gate signal i.e. optimal PWM waveform applied to gate of switching devices.

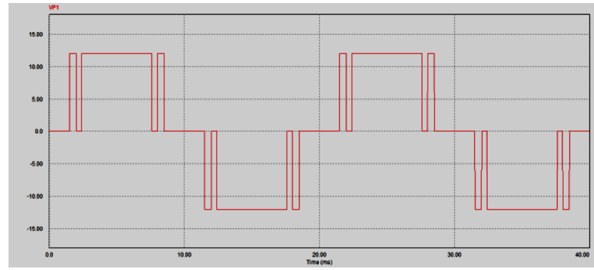

Fig.4 PSIM -PWM waveform window

The FFT of Fig.4 is shown in Fig.5, the value of individual harmonics are measured and used for calculation of the total harmonic distortion.

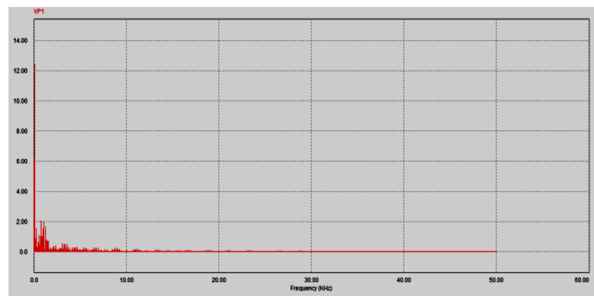

Fig.5 PSIM simulation FFT window

HORMONIC REDUCTION

To find out the total harmonic distortion, we have to calculate the Fourier series coeff. of the output voltage.

$$V_O = \sum_{n=1,3,5..}^{\infty} \sin(nwt)$$

Where,

With unipolar voltage notches, coefficient Bn is given by

$$Bn = \frac{4Vs}{\pi}\left[\int_0^{\alpha1} \sin nwt\, d(wt) - \int_{\alpha1}^{\alpha2} \sin nwt\, d(wt) + \int_{\alpha2}^{\frac{\pi}{2}} \sin nwt\, d(wt)\right]$$

$$= \frac{4Vs}{\pi}\left[\frac{1 - 2cosn\alpha1 + 2cosn\alpha2}{n}\right]$$

Equation can be extended to m notches per quarter wave,

$$Bn = \frac{4Vs}{n\pi}\left[1 + 2\sum_{k=1}^{m}(-1)^k cos(n\alpha_k)\right]$$

n=1, 3, 5….. And $\alpha_1 < \alpha_2 \ldots < \alpha_k < \frac{\pi}{2}$

With unipolar voltage notches, coefficient Bn is given by,

$$Bn = \frac{4Vs}{\pi}[\int_0^{\alpha 1} sin\ nwt\ d(wt) + \int_{\alpha 2}^{\frac{\pi}{2}} sin\ nwt\ d(wt)]$$

$$= \frac{4Vs}{\pi}\left[\frac{1 - cosn\alpha 1 + cosn\alpha 2}{n}\right]$$

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n=1, 3, 5….. And $\alpha_1 < \alpha_2 \ldots < \alpha_k < \frac{\pi}{2}$

Total harmonic distortion is calculated as,

$$THD = \frac{1}{v_{o1}}\left(\sum_{n=2,3,\ldots}^{\infty} v^2{}_{on}\right)^{1/2}$$

Three pulse PWM:

For f=50 Hz, period=0.02 second

Case 1: Middle pulse having constant center time & constant pulse width, side pulses having constant pulse Width changing center of side pulses.

Table1: Table for case 1

1st side Pulse		Middle pulse		3rd Pulse		THD
Centre (ms)	Width(W1)(Sec)	Centre(ms)	Width (W2)(sec)	Centre(ms)	Width (W3)(sec)	
0.85	0.002	5	0.0036	9.15	0.002	81.81
0.95	0.002	5	0.0036	9.05	0.002	81.45
1.05	0.002	5	0.0036	8.95	0.002	79.72
1.15	0.002	5	0.0036	8.85	0.002	76.32
1.25	0.002	5	0.0036	8.75	0.002	71.42
1.35	0.002	5	0.0036	8.65	0.002	65.28
1.45	0.002	5	0.0036	8.55	0.002	58.46
1.55	0.002	5	0.0036	8.45	0.002	51.72
1.65	0.002	5	0.0036	8.35	0.002	45.67
1.75	0.002	5	0.0036	8.25	0.002	40.53
1.85	0.002	5	0.0036	8.15	0.002	36.14
1.95	0.002	5	0.0036	8.05	0.002	32.19
2.05	0.002	5	0.0036	7.95	0.002	28.59
2.15	0.002	5	0.0036	7.85	0.002	25.79

case 2: having W1+W2+W3 time constant, center of three pulses also constant, W1+(a/2),W3+(a/2),W2-(a) where 'a' is constant.

W1: LHS side pulse width, W2: middle pulse width, W3=RHS side pulse width.

ON time =62%

Table 2: For Wc1=1.25*10^-3, Wc2=5*10^-3, Wc3=8.75*10^-3

W1	W2	W3	THD
0.0005	0.0052	0.0005	37.94
0.0006	0.0050	0.0006	42.99
0.0007	0.0048	0.0007	45.36
0.0008	0.0046	0.0008	49.73

Table 3: For Wc1=1.5*10^-3, Wc2=5*10^-3,Wc3=8.5*10^-3

W1	W2	W3	THD
0.0005	0.0052	0.0005	26.45
0.0006	0.0050	0.0006	31.36
0.0007	0.0048	0.0007	36.23
0.0008	0.0046	0.0008	42.12

Five pulse PWM

Table 4: For Wc1=1.75*10^-3, Wc2=5*10^-3, Wc3=8.25*10^-3

W1	W2	W3	THD
0.0005	0.0052	0.0005	18.30
0.0006	0.0050	0.0006	20.81
0.0007	0.0048	0.0007	26.06
0.0008	0.0046	0.0008	34.12

Table 5: For Wc1=2*10^-3, Wc2=5*10^-3, Wc3=8*10^-3

W1	W2	W3	THD
0.0005	0.0052	0.0005	24.17
0.0006	0.0050	0.0006	23.14
0.0007	0.0048	0.0007	24.01
0.0008	0.0046	0.0008	28.54

Case 1: Middle pulse having constant center time & constant pulse width, side pulses having constant pulse Width and changing center of side pulses.

Table6: Table for case 1

1st Pulse		2nd Pulse		3rd Pulse		4th pulse		5th Pulse		THD
Centre (ms)	Width (ms)	Centre (ms)	Width (ms)	Centre (ms)	Width (sec)	Centre (ms)	Width (ms)	Centre (ms)	Width (ms)	
0.85	0.45	1.85	0.45	5	0.005	8.15	0.45	9.15	0.45	25.85
0.90	0.45	1.90	0.45	5	0.005	8.10	0.45	9.10	0.45	23.05
0.95	0.45	1.95	0.45	5	0.005	8.05	0.45	9.05	0.45	20.34
1	0.45	2	0.45	5	0.005	8	0.45	9	0.45	17.91
1.05	0.45	2.05	0.45	5	0.005	7.95	0.45	8.95	0.45	16.02
1.10	0.45	2.10	0.45	5	0.005	7.90	0.45	8.90	0.45	14.92
1.15	0.45	2.15	0.45	5	0.005	7.85	0.45	8.85	0.45	14.71
1.20	0.45	2.20	0.45	5	0.005	7.80	0.45	8.80	0.45	15.28
1.25	0.45	2.25	0.45	5	0.005	7.75	0.45	8.75	0.45	16.38
1.30	0.45	2.30	0.45	5	0.005	7.70	0.45	8.70	0.45	17.71
1.35	0.45	2.35	0.45	5	0.005	7.65	0.45	8.65	0.45	19.05
1.40	0.45	2.40	0.45	5	0.005	7.60	0.45	8.60	0.45	20.27
1.45	0.45	2.45	0.45	5	0.005	7.55	0.45	8.55	0.45	21.23
1.50	0.45	2.50	0.45	5	0.005	7.50	0.45	8.50	0.45	22.21

case 2: having W1+W2+W3 time constant, center of three pulses also constant, W1+(a/2),W3+(a/2),W2-(a) where 'a' is constant.

W1: LHS side pulse, W2: middle pulse, W3=RHS side pulse

ON time =62%

Table 7: For Wc1=1.05*10^-3, Wc2=2.25*10^-3, Wc3=5*10^-3, Wc4=7.75*10^-3, Wc5=8.95*10^-3

W1	W2	W3	W4	W5	THD
0.0005	0.0005	0.0042	0.0005	0.0005	17.68
0.0006	0.0006	0.0038	0.0006	0.0006	24.43
0.0007	0.0007	0.0034	0.0007	0.0007	37.47
0.0008	0.0008	0.0030	0.0008	0.0008	52.91
0.0009	0.0009	0.0026	0.0009	0.0009	67.71
0.0010	0.0010	0.0022	0.0010	0.0010	80.18

Table 8: For Wc1=1.3*10^-3, Wc2=2.5*10^-3, Wc3=5*10^-3, Wc4=7.5*10^-3, Wc5=8.75*10^-3

W1	W2	W3	W4	W5	THD
0.0005	0.0005	0.0042	0.0005	0.0005	26.03
0.0006	0.0006	0.0038	0.0006	0.0006	24.49
0.0007	0.0007	0.0034	0.0007	0.0007	35.01
0.0008	0.0008	0.0030	0.0008	0.0008	52.73
0.0009	0.0009	0.0026	0.0009	0.0009	67.95
0.0010	0.0010	0.0022	0.0010	0.0010	77.3

Table 9: For Wc1=1.55*10^-3, Wc2=2.75*10^-3, Wc3=5*10^-3, Wc4=7.25*10^-3, Wc5=8.45*10^-3

W1	W2	W3	W4	W5	THD
0.0005	0.0005	0.0042	0.0005	0.0005	30.02
0.0006	0.0006	0.0038	0.0006	0.0006	25.08
0.0007	0.0007	0.0034	0.0007	0.0007	24.34
0.0008	0.0008	0.0030	0.0008	0.0008	35.58
0.0009	0.0009	0.0026	0.0009	0.0009	49.81
0.0010	0.0010	0.0022	0.0010	0.0010	60.58

Table 10: For Wc1=1.8*10^-3, Wc2=3*10^-3, Wc3=5*10^-3, Wc4=7*10^-3, Wc5=8.2*10^-3

W1	W2	W3	W4	W5	THD
0.0005	0.0005	0.0042	0.0005	0.0005	37.32
0.0006	0.0006	0.0038	0.0006	0.0006	34.96
0.0007	0.0007	0.0034	0.0007	0.0007	27
0.0008	0.0008	0.0030	0.0008	0.0008	21.82
0.0009	0.0009	0.0026	0.0009	0.0009	30.11
0.0010	0.0010	0.0022	0.0010	0.0010	42.68

HARDWARE RESULTS:

THD of single phase inverter is measured using the power DSO. This practical THD values are compared with the MATLAB results, which are shown in table no 11.

Fig.6 THD Measurmenton DSO

RESULT COMPARISION:

Vcc=20 volt, Fundamental freq. =50 Hz

For Wc1=1.75*10^-3, Wc2=5*10^-3,Wc3=8.25*10^-3

Table 11: comparison of THD results

Sr No.	System results (MATLAB)	SIMULATION Software (PSIM)	Practical result on DSO
1(w1=0.0005,w2=0.0052,w3=0.0005)	18.3	18.4	26.09
2(w1=0.0006,w2=0.0048,w3=0.0006)	20.2	20.5	29.5
3(w1=0.0007,w2=0.0046,w3=0.0007)	26.06	26.5	30.4

IV.CONCLUSION

This paper presents an idea of optimal PWM generation for single phase inverter. MATLAB program is used to generate PWM signals and calculate the total harmonic distortion of every PWM signal. Among all generated PWM signal, signal having lowest total harmonic distortion is selected and it is used as gate signal to drivethe FET pair of inverter and its complement is used to drive other pair of FET. In this way, by generating optimal PWM signal on software and using that optimal PWM on hardware circuit, the losses get minimized and improve system performance

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