Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Environmental Sciences 17 (2013) 519 – 528
Procedia Environmental Sciences

The 3rd International Conference on Sustainable Future for Human Security
SUSTAIN 2012

Elimination of harmonics in photovoltaic seven-level inverter with Newton-Raphson optimization

Krismadinata[a]*, Nasrudin Abd Rahim[a], Hew Wooi Ping[a], Jeyraj Selvaraj[a]

[a]University of Malaya Power Energy Dedicated Advanced Centre (UMPEDAC)
Level 4 Wisma R&D University of Malaya Kuala Lumpur 599990 Malaysia

Abstract

This paper describes a strategy to optimize the switching angle of a modified H-bridge single-phase seven-level inverter for stand-alone photovoltaic (PV) system. The inverter comprises a conventional H-bridge inverter and two bidirectional switches. It can generate seven-level output voltage level, namely +Vdc, +2/3Vdc, +1/3Vdc, 0, -1/3Vdc, -2/3Vdc and -Vdc. Optimized Harmonic Elimination Stepped Waveform (OHESW) technique was employed to improve the output waveform quality. Newton-Raphson method is engaged to solve the transcendental equations from OHESW technique which produces all possible solutions with any random initial guess. Among which sets, the one producing the least output-voltage THD was chosen. Computation resulting from the optimized switching angle was simulated. A small-scale laboratory prototype was built and tested. Its results indicated the proposed method's effectiveness and the application feasibility of the fundamental frequency switching.

Selection and peer-review under responsibility of SUSTAIN conference's committee and supported by Kyoto University; (OPIR), (GCOE-ES), (GCOE-HSE), (CSEAS), (RISH), (GCOE-ARS) and (GSS) as co-hosts.

Keywords: multilevel inverter; Newton-Rapson ; OHESW; photovoltaic

1. Introduction

Owing to deregulation and privatized electricity supply, many countries in the world prefer solar (or photovoltaic, i.e., PV) and wind energy for green power. Solar energy has received the most attention

* E-mail address: krismadinata@um.edu.my .

Selection and peer-review under responsibility of SUSTAIN conference's committee and supported by Kyoto University; (OPIR), (GCOE-ES), (GCOE-HSE), (CSEAS), (RISH), (GCOE-ARS) and (GSS) as co-hosts.
doi:10.1016/j.proenv.2013.02.067

because it appears to be one of the better solutions to environmental problems. Also, PV is scalable from very small to very large and easy to integrate into existing power converters [1].

An inverter is needed to convert PV's DC power to AC because most electric loads are AC. Multilevel inverters have been attracting attention for their high-voltage operation capability, high efficiency and low electromagnetic interference (EMI)[2]. Various topologies for multilevel inverters have been proposed over the years. Common ones are diode-clamped, flying capacitor or multicell, cascaded H-bridge and multilevel, modified H-bridge [1-12].

The modified H-bridge topology is significantly advantageous over others; fewer power switches, fewer anti parallel diodes, power diodes and fewer capacitors in inverters of the same number of levels. It has a conventional H-bridge inverter and bidirectional switches.

Multilevel inverter's efficiency parameters, such as switching losses and harmonic reduction, principally depend on its modulation strategies, which can be classified according to the switching frequency used. Multilevel inverter control techniques are based on fundamental and high switching frequencies.

Selective Harmonic Elimination (SHE) technique with optimized harmonic elimination stepped waveform for low switching frequency is very suitable for a multilevel inverter circuit. It can eliminate some specific harmonic components.

Optimized switching angles are computed by solving transcendental equation from non-linear equation SHE-OHESW technique. Solution methods for non-linear transcendental equations have been reported. Optimization technique based on Genetic Algorithm (GA) is proposed for computation of the switching angles for a seven-level inverter [3,4]. Transcendental equations converted into polynomial equations are then solved via the method of resultants from the elimination theory proposed in [5]. Neural network has been investigated by [6,7]. Newton-Raphson method can be used to solve the non-linear equations of OHESW technique [8-11].

This paper reports the development of a novel modified-H-bridge single-phase multilevel inverter with two diode-embedded bidirectional switches for PV-system application. The inverter has seven output-voltage values: zero, one third positive, two thirds positive, full positive, one third negative, two thirds negative, and full negative, of the dc supply. Its switching angle optimization via OHESW technique with Newton-Raphson method is also presented.

2. Proposed PV inverter topology

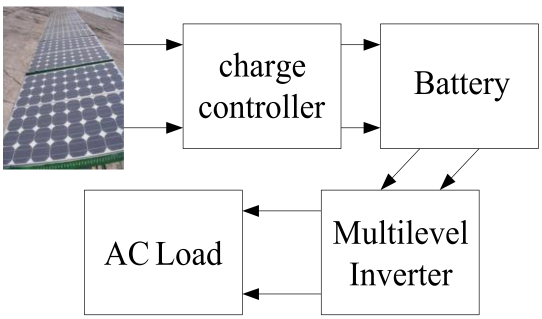

Fig. 1. Configuration of the proposed inverter in a PV system application

Fig. 1 is a PV system's configuration with the proposed multilevel inverter. The system comprises PV array, charge controller, battery, the proposed inverter, and AC load. The proposed single-phase seven-level PWM inverter comprises a single-phase conventional full-bridge inverter; two bidirectional switches and a capacitor voltage divider formed by C_1, C_2 and C_3 (see Fig. 2).

The states of operation switching for this inverter to generate seven output voltage levels (V_{dc}, $2/3V_{dc}$, $1/3V_{dc}$, 0, $-1/3V_{dc}$, $-2/3V_{dc}$ and $-V_{dc}$) is shown in Table 1.

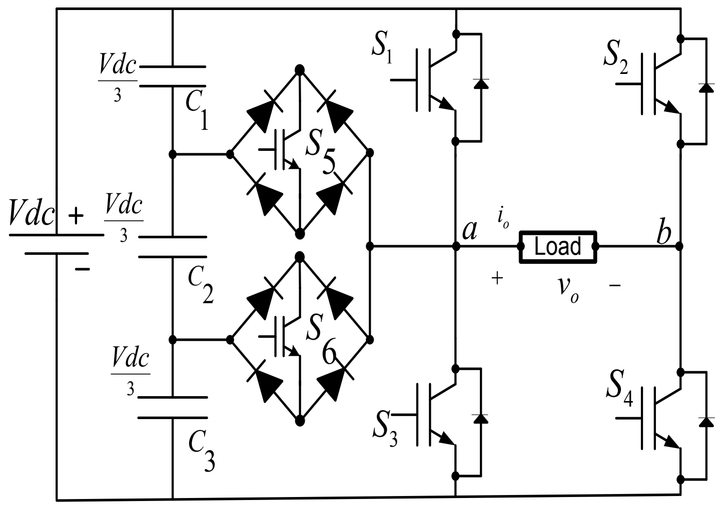

Fig. 2. Configuration of the proposed single-phase seven-level inverter

Table 1. Output voltage according to the switches on-off condition

v_0	S_1	S_2	S_3	S_4	S_5	S_6
V_{dc}	on	off	off	on	off	off
$2V_{dc}/3$	off	off	off	on	on	off
$V_{dc}/3$	off	off	off	on	off	on
0	off	off	on	on	off	off
0*	on	on	off	off	off	off
$-V_{dc}/3$	off	on	off	off	on	off
$-2V_{dc}/3$	off	on	off	off	off	on
$-V_{dc}$	off	on	on	off	off	off

3. OHESW technique

An inverter's performance, with any switching strategy, is generally accepted as relating to its output voltage's harmonic content. For a multilevel inverter, switching angles at fundamental frequency are obtained by solving selective harmonic elimination equations in such a way that the fundamental voltage is obtained as desired and specific lower order harmonics are eliminated.

Fig. 3 shows seven levels of output-voltage waveforms. Waveform for V_{a-b} is known as an odd-quarter waveform symmetric with 3 positive steps of equal magnitude each, i.e., $V_{dc}/3$. The Fourier series for a periodic function $v_0(\omega t)$ can be expressed as:

$$V_{a-b}(\omega t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t) \tag{1}$$

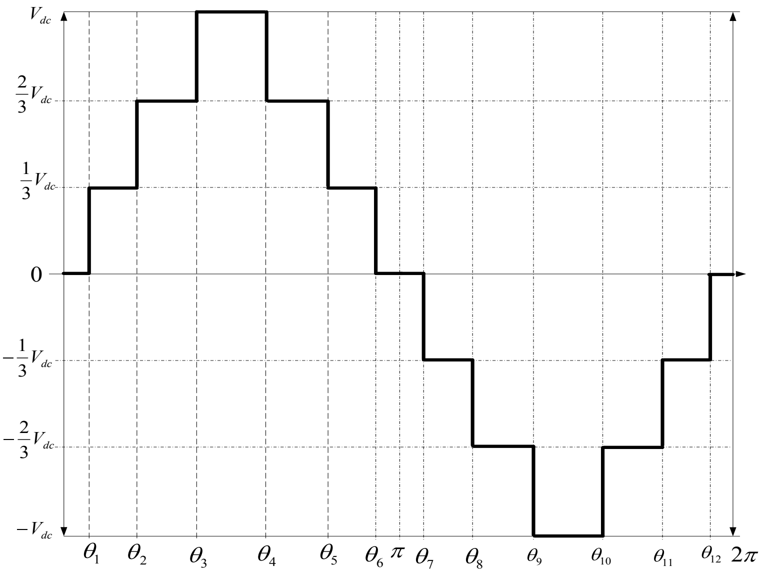

Fig. 3: Seven-level output voltage, V_{abb}. and switching angles

The Fourier series for odd functions contain only sine terms: $a_0 = 0$ and $a_n = 0$ for all *n*. The sine function is odd, the cosine function is not.

$$b_n = \begin{cases} \frac{4}{\pi}\int_0^{\frac{\pi}{2}} \sin(n\theta)\,d\theta & \text{for odd } n \\ 0 & \text{for even } n \end{cases} \tag{2}$$

$V_{a-b}(\omega t)$ can therefore be written as

$$V_{a-b}(\omega t) = \sum_{n=odd}^{\infty} b_n \sin(n\omega t) \tag{3}$$

where $\theta = \omega t$ $b_n = \frac{4}{\pi}\int_{\theta_1}^{\frac{\pi}{2}} V_{ab}(\theta)\sin(n\theta)d\theta$ (4)

$$b_n = \frac{4}{\pi}\int_{\theta_1}^{\frac{\pi}{2}} \frac{V_{dc}}{3}\sin(n\theta)d\theta + \int_{\theta_2}^{\frac{\pi}{2}} \frac{V_{dc}}{3}\sin(n\theta)d\theta + \int_{\theta_3}^{\frac{\pi}{2}} \frac{V_{dc}}{3}\sin(n\theta)d\theta$$

$$b_n = (V_{dc}/3)\frac{4}{n\pi}\left[\cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3)\right] \quad n = 1,3,5,7,\ldots \tag{5}$$

$$V_{ab}(\omega t) = (V_{dc}/3)\frac{4}{n\pi}\sum_{n=1,3,5\ldots}^{\infty}\left[\cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3)\right]\sin(n\omega t) \tag{6}$$

Note that the even harmonics all equal zero.

Equation (6) is the main equation of the proposed inverter; b_n is the amplitude of the harmonics order; θ_1, θ_2, and θ_3 are the switching angles to be optimized, and they must satisfy the following condition: $0 < \theta_1 < \theta_2 < \theta_3 < 90^0$. Ideally, for V_1 fundamental voltage desired, determination of switching angles θ_1, θ_2 and θ_3 is possible so that $V_{a\text{-}b}(\omega t) = V_1\sin(\omega t)$ and specific higher harmonics equal zero.

To control the peak value of the output voltage to be $V1$ and eliminate the 3rd and the 5th order harmonics, the resulting harmonic equations shall be:

$$b_1 = \frac{4V_{dc}}{3\pi}\left[\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3)\right] = V_1$$

$$b_3 = \frac{4V_{dc}}{9\pi}\left[\cos(3\theta_1) + \cos(3\theta_2) + \cos(3\theta_3)\right] = 0$$

$$b_5 = \frac{4V_{dc}}{15\pi}\left[\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3)\right] = 0 \tag{7}$$

The fundamental voltage and the maximum obtainable voltage relate via the modulation index. Modulation index m_a is defined as the ratio of the fundamental output voltage V_1 to the maximum obtainable fundamental voltage V_{1max}. The maximum fundamental voltage is obtained when all the switching angles are zero, i.e., $V_{1max} = 4V_{dc}/3\pi$. The expression for m_a is, therefore, [4,11,12]:

$$m_a = \frac{\pi V_1}{4sV_{dc}} \tag{8}$$

where s is the number of switching angles, which also equals the number of DC sources.
Equation (7) can be written as:

$$[\cos(\theta_1)+\cos(\theta_2)+\cos(\theta_3)]=3m_a$$

$$[\cos(3\theta_1)+\cos(3\theta_2)+\cos(3\theta_3)]=0$$

$$[\cos(5\theta_1)+\cos(5\theta_2)+\cos(5\theta_3)]=0 \qquad (9)$$

Generally, equation (*9*) can be written as

$$F(\theta)=B(m_a) \qquad (10)$$

where

$$F(\theta)=\begin{bmatrix}\cos(\theta_1) & \cos(\theta_2) & \cos(\theta_3)\\ \cos(3\theta_1) & \cos(3\theta_2) & \cos(3\theta_3)\\ \cos(5\theta_1) & \cos(5\theta_2) & \cos(5\theta_3)\end{bmatrix}; \text{ and } \qquad B(m_a)=[3m_a \quad 0 \quad 0]^T$$

Equation (*9*) represents a system of three transcendental equations known as SHE-OHESW equations, in terms of three unknowns: θ_1, θ_2 and θ_3. For given values of m_a (from 0 to 1), complete and all possible solutions for (10) are required when they exist with minimum computational burden and complexity. One solution approach for sets of nonlinear transcendental equations (*9*) is by applying an iterative method such as the Newton–Raphson method [7-11].

To select the set generating the lowest harmonic distortion, the solution sets are examined for their corresponding total harmonic distortion. The computed THD in % is defined by:

$$THD(\%)=\frac{\sqrt{\sum_{n=2}^{\infty}V_n^2}}{V_1}x100\% \qquad (11)$$

4. Newton-Raphson method

The Newton-Raphson (N-R) method is one of the most widely used methods for root-finding. It can be easily generalized to the problem of finding solutions of a system of non-linear equations. This method has been applied in numeric analysis. It requires only one initial value.

The N-R method is to be implemented to compute the switching angles for the system given by equation (9). Switching angles in the range 0 to π/2 producing the desired fundamental voltage with the 3^{rd} and the 5^{th} harmonic components eliminated for a given modulation index are feasible solutions of equation (9).

In [11], the authors developed the N-R algorithm for cascade multilevel inverter; application to the proposed inverter is as follows:

1. Assume any random initial guess for the switching angles (say θ_0), such as, $0^0<\theta_1<\theta_2<<\theta_3<90^0$.
2. Set $m_a = 0$.
3. Calculate $F(\theta_0)$and $B(m_i)$ Jacobian $J(\theta_0)$
4. Compute correction $\Delta\theta_0$ during the iteration using relation, $\Delta\theta = J^{-1}(\theta_0)[B(m_a)-F(\theta_0)]$

5. Update the switching angles i.e. $\theta(k+1)=\theta(k)+\Delta\theta(k)$
6. Perform $\theta(k+1)=\cos^{-1}[abs(\cos(\theta(k+1)))]$ transformation to bring switching angles to feasible range.
7. Repeat steps (3) to (6) for sufficient number of iterations to attain error goal.
8. Increment m_a by a fixed step.
9. Repeat steps (2) to (8) for whole range of m_a.
10. Plot the switching angles as a function of m_a. Different solution sets would be obtained.
11. Take one solution set at a time and compute complete solution set for the range of m_a where it exits.

By following the above steps, all possible solution sets, when they exist, can be computed without any complex computation.

5. Computation results

For the proposed single-phase seven-level inverter, solution of three SHE-OHESW equations to get some numbers of switching angles is required.

As discussed, one switching angle is used to produce the fundamental voltage while the remaining two eliminates the 3rd and the 5th order harmonic components. Solutions computed with an arbitrary initial guess as m_a is incremented from 0 to 1 in steps of 0.01.

Figs. 4 and 5 show that the lowest harmonic content of the proposed seven-level inverter's output voltage is 11.85% where the modulation index is 0.813 and the switching angles are respectively 9.07^0, 28.52^0, and 55.05^0 for θ_1, θ_2 and θ_3. Note that not all m_a in the range have a solution, e.g., there are solutions in intervals: $m_a \in$ [0.550, 0.690] and [0.802, 0.818] only. Similarly, for $m_i \in$ [0, 0.549], [0.691, 0.801] and [0.819, 1], owing to iteration divergence, there are no solvable solutions.

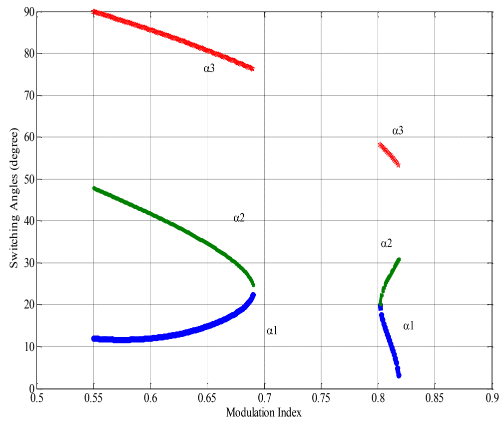

Fig. 4: Solution set computed with an arbitrary initial guess

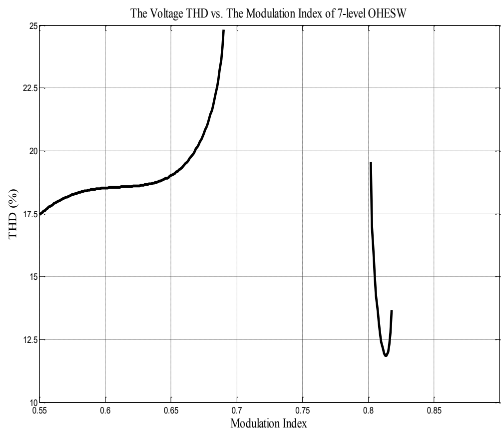

Fig. 5: Voltage THD versus modulation index

6. Simulation results

The first step in testing the proposed single-phase seven-level inverter was simulating it on software, i.e., Matlab/Simulink. The system's operation was simulated at low switching frequency.

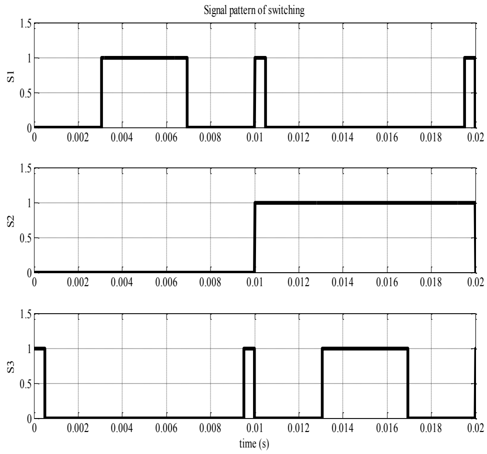

Fig. 6: Switching angles S_1-S_3 for $\theta_1 = 9.06^0$, $\theta_2 = 28.52^0$, and $\theta_3 = 55.05^0$

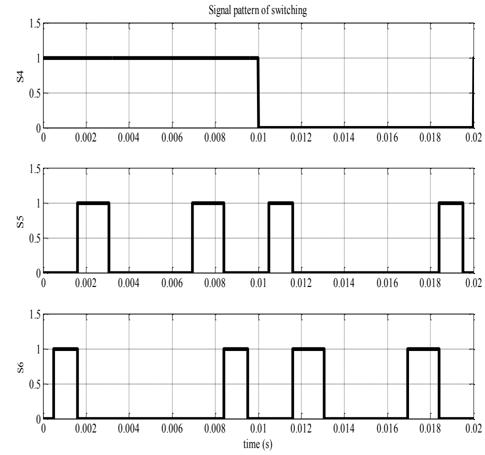

Fig. 7: Switching angles S_4-S_6 for $\theta_1 = 9.06^0$, $\theta_2 = 28.52^0$, and $\theta_3 = 55.05^0$

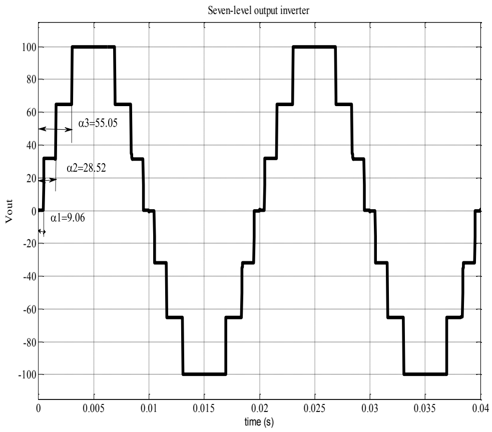

Fig. 8: Output voltage waveform for $\theta_1 = 9.06^0$, $\theta_2 = 28.52^0$, and $\theta_3 = 55.05^0$

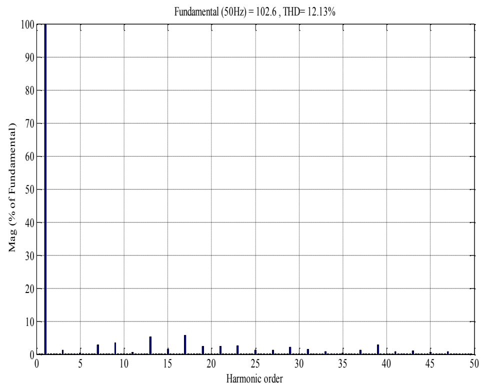

Fig. 9: Harmonic content output voltage waveform for $\theta_1 = 9.06^0$, $\theta_2 = 28.52^0$, and $\theta_3 = 55.05^0$

When the proposed multilevel inverter was simulated with switching angles $\theta_1 = 9.06^0$, $\theta_2 = 28.52^0$ and $\theta_3 = 55.05^{0,}$ as in Figs. 6 and 7, output voltage waveform, as in Fig. 8, would be obtained; its harmonic content (THD = 12.13%) is shown in Fig. 9.

7. Experiment results

To verify the validity of the proposed inverter, a prototype was designed and built. A 100V DC source was used as power supply, with m_a=0.813, $\theta_1 = 9.06^0$, $\theta_2 = 28.52^0$ and θ_3=55.05^{0,} as in Figs. 10 and 11. TMS320F2812 target board was used to generate the switching signal for the proposed inverter. Fig. 12 shows the experiment result for the output voltage waveform, which harmonic content (THD = 11.8%) is shown in Fig. 13.

Fig. 10: Switching angles S_1-S_3 for $\theta_1 = 9.06^0$, $\theta_2 = 28.52^0$, and $\theta_3 = 55.05^0$

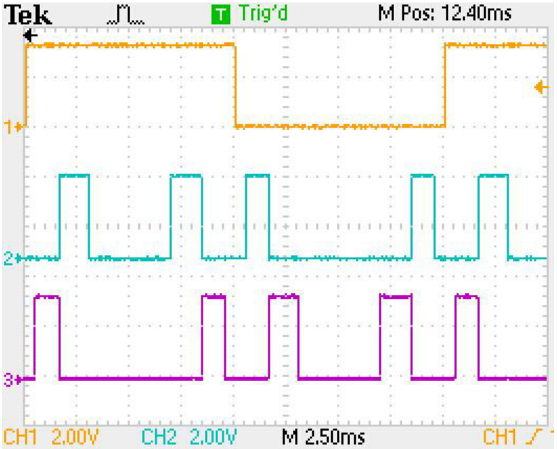

Fig. 11: Switching angles S_1-S_3 for $\theta_1 = 9.06^0$, $\theta_2 = 28.52^0$, and $\theta_3 = 55.05^0$

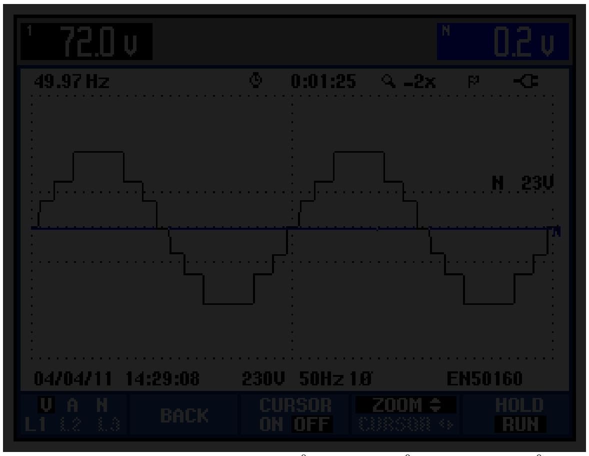

Fig. 12: Output voltage $\theta = 9.06^0$, $\theta_2 = 28.52^0$, and $\theta_3 = 55.05^0$

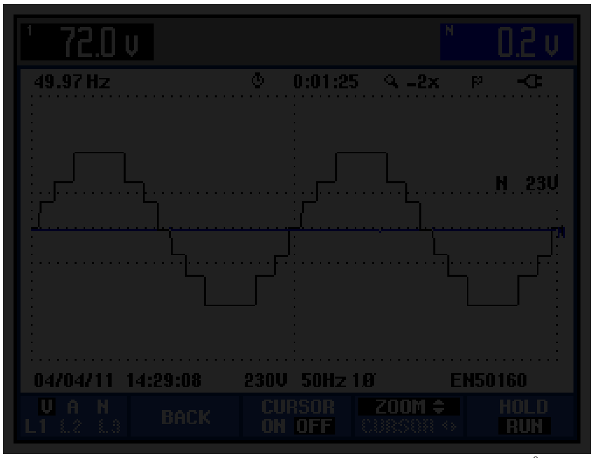

Fig. 13: Harmonic content output voltage waveform $\theta_1 = 9.06^0$, $\theta_2 = 28.52^0$, and $\theta_3 = 55.05^0$

8. Conclusion

A novel single-phase modified H-bridge seven-level inverter scheme for use in a stand-alone PV power generation system has been proposed. A fundamental frequency switching control algorithm for it has been developed. OHESW technique with Newton-Raphson method was used to solve the non-linear equations from the switching angles. The computed results were verified by simulation and experiment.

References

[1] J. Rodriguez, *et al.*, "Multilevel inverters: a survey of topologies, controls, and applications," *Industrial Electronics, IEEE Transactions on,* vol. 49, pp. 724-738, 2002.

[2] B. Ozpineci, *et al.*, "Harmonic optimization of multilevel converters using genetic algorithms," *Power Electronics Letters, IEEE,* vol. 3, pp. 92-95, 2005.

[3] P. M. Pandi and N. Devarajan, "Optimization of power quality in cascaded multilevel inverter-genetic algorithm approach," in *Computing Communication and Networking Technologies (ICCCNT), 2010 International Conference on*, 2010, pp. 1-7.

[4] J. N. Chiasson, *et al.*, "Elimination of harmonics in a multilevel converter using the theory of symmetric polynomials and resultants," *Control Systems Technology, IEEE Transactions on,* vol. 13, pp. 216-223, 2005.

[5] F. Filho, *et al.*, "Real time selective harmonic minimization for multilevel inverters connected to solar panels using Artificial Neural Network angle generation," in *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE*, 2010, pp. 594-598.

[6] I. Khoukha, *et al.*, "ANN control of nine level NPC voltage inverter based on selective harmonics elimination," in *Electrical Machines and Power Electronics, 2007. ACEMP '07. International Aegean Conference on*, 2007, pp. 587-591.

[7] S.-G. Song, *et al.*, "Multilevel inverter using cascaded 3-phase transformers with common-arm configuration," *Electric Power Systems Research,* vol. In Press, Corrected Proof.

[8] M. Honkala, *et al.*, "Improving the convergence of combined Newton-Raphson and Gauss-Newton multilevel iteration method," in *Circuits and Systems, 2002. ISCAS 2002. IEEE International Symposium on*, 2002, pp. II-229-II-232 vol.2.

[9] H. S. Patel and R. G. Hoft, "Generalized Techniques of Harmonic Elimination and Voltage Control in Thyristor Inverters: Part I--Harmonic Elimination," *Industry Applications, IEEE Transactions on,* vol. IA-9, pp. 310-317, 1973.

[10] L. M. Tolbert and T. G. Habetler, "Novel multilevel inverter carrier-based PWM method," *Industry Applications, IEEE Transactions on,* vol. 35, pp. 1098-1107, 1999.

[11] J. Kumar *et al.*, "Selective harmonic elimination Technique for a multilevel inverter," in *Fifteenth national Power SYstem Conference (NPSC) IIT Bombay*, 2008, pp. 608-613.

[12] K. El-Naggar and T. H. Abdelhamid, "Selective harmonic elimination of new family of multilevel inverters using genetic algorithms," *Energy Conversion and Management,* vol. 49, pp. 89-95, 2008.