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Three level solar inverter for stand-alone power systems: Simulation and practical realization

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Abstract. Providing electrical energy for oil and gas extraction sites can be a real challenge especially for a large oil and gas company like Sonatrach. Solar energy can be great solution for this issue. This study presents an efficient way to convert electrical energy from DC to AC using a modulation strategy called selective harmonic elimination; this method will be used to optimize the performance of a three level solar inverter for standalone power system. Harmonic pollution is a very common problem in the field of power electronics, this problem can cause multiple problems for power converters and electrical devices and also reduce their lifespan, the (SHEPWM) modulation strategy allows the elimination of low order harmonics and also control the amplitude of the fundamental component of the output voltage spectrum. Simulation and experimental results are presented in this work.

Keywords: *Solar inverter, Harmonic elimination, Energy efficiency, Stand-alone power systems*

1. Introduction

The global demand for energy is expected to increase significantly over the upcoming two hundred years, this increase will pose a major challenge for oil and gas companies such as ExxonMobil, Chevron, and Sonatrach .Oil production and refining process consume a lot of energy. Oil and gas fields are often located far away from cities and towns, so getting essential resources and necessary equipments to the sites present a big problem. Using solar energy in production sites will solve some of the logistical problems.

Energy efficiency is a very important issue in the field of power electronics, modern solar power systems and converters (DC/DC or DC/AC) destined for professional use must meet high efficiency and protection standards and also must generate high quality electrical power to ensure the proper functioning of the electrical devices on site.

The harmonic content in an AC voltage waveform generated by an inverter can affect significantly the performance of AC machines. For example harmonics can raise the temperature of an AC motor which decreases the lifetime of the insulation and consequently the lifetime of the motor itself. One way to fight this problem is by choosing the right modulation strategy.

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Several modulation strategies have been proposed and studied for the control of multilevel inverters such as Sinusoidal Pulse width modulation (SPWM) [1] and space vector pulse width modulation (SVPWM) [2]. A more efficient method called selective harmonic elimination pulse width modulation (SHE-PWM) [3] is also used; the method offers a lot of advantages such as operating the inverters switching devices at a low frequency which extends the lifetime of the switching devices. The main disadvantage of this method is that a set of non-linear equations must be solved to obtain the optimal switching angles to apply this strategy.

The optimal firing (switching) angles are computed by solving a set of nonlinear equation that represents the desired waveform. Multiple algorithms have been used to solve the optimal switching problem for multilevel inverters such as Genetic Algorithm [4], Differential Evolution [5] and Particle swarm optimization [6] but these algorithms are hard to program and they can take a long time to solve the equations. Newton-Raphson algorithm can be used to solve the optimal switching problem, it is really easy to program and it can solve the nonlinear equations in few seconds.

This study presents the use of a simple H bridge configuration controlled by N-R based selective harmonic elimination for solar application. The next section will present briefly the Selective harmonic elimination for multilevel inverters and the Newton-Raphson algorithm. The last section presents the obtained simulation and experimental results.

2. Selective harmonic elimination for solar inverter

Standalone solar power system is an off grid electrical supply system. An as shown in figure 1 the system consists of an arrangement of several components including solar panels, batteries and charge controllers, and also inverters which are the parts responsible for changing the electric current from DC to AC.

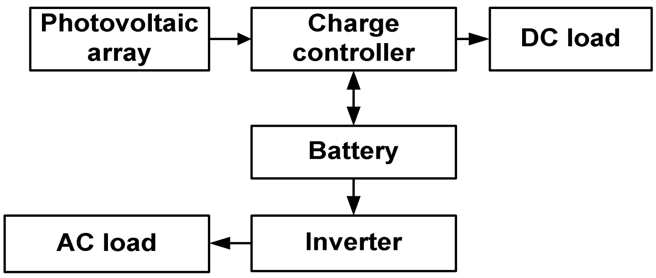

Figure 1: Standalone solar power system

The configuration of the inverter chosen in this study is presented in figure 2 which consists of four switching elements assembled in an H-bridge configuration, this configuration can generate up to three voltage levels. The converter is powered by a direct current source.

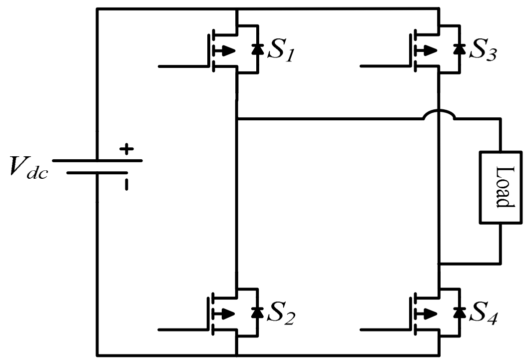

Figure 2: The proposed three level solar inverter

The performance of an inverter using any modulation strategy is rated according to the harmonics in the generated voltage waveform. In order to control the fundamental voltage and eliminate low order harmonics the proposed inverter must generate a waveform similar to figure 3. The figure shows a three level voltage waveform with three switching angles θ_1, θ_2 and θ_3.

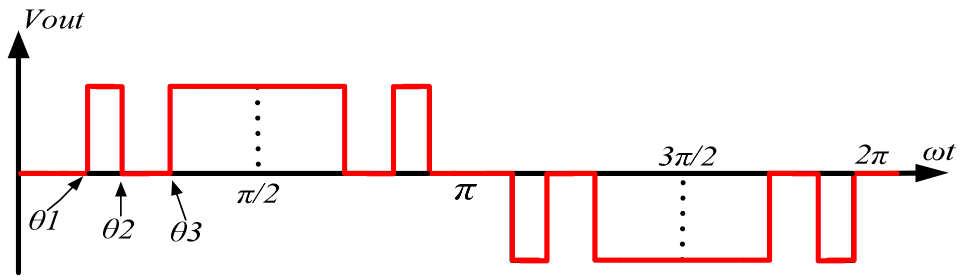

Figure 3: Generalized three level waveform with multiple switching angles.

Fourier series expansion of the generalized three level waveform output waveform of the single-phase multilevel converter shown in Fig. 1 can be expressed as follows:

$$V(\omega t) = \sum_{n=1,3,5,\ldots}^{\infty} \left[\frac{4V_{dc}}{n\pi} \sum_{i=1}^{p} (-1)^{i+1} \cos(n\theta_i)\right] \sin(n\omega t) \tag{1}$$

Where n is rank of harmonics, n =1,3,5,… ,and p =(N-1)/2 is the number of switching angles per quarter waveform., and θ_i is the i^{th} switching angle, and N is the number of voltage levels per half waveform. The optimal switching angles θ_1, θ_2 *and* θ_3 can be determined by solving the following system of non-linear equations:

$$\begin{cases} \cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) = r\pi/4 \\ \cos(3\theta_1) + \cos(3\theta_2) + \cos(3\theta_3) = 0 \\ \cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) = 0 \end{cases} \tag{2}$$

θ_1, θ_2 and θ_3 are the angles to be optimized and they must satisfy the following condition:

$$0 < \theta_1 < \theta_2 < \theta_3 < \pi/2 \tag{3}$$

Equation (2) can be written as

$$F(\theta) \ = B(r\pi/4) \tag{4}$$

where

$$F(\theta) = \begin{bmatrix} \cos(\theta_1) & -\cos(\theta_2) & \cos(\theta_3) \\ \cos(3\theta_1) & -\cos(3\theta_2) & \cos(3\theta_3) \\ \cos(5\theta_1) & -\cos(5\theta_2) & \cos(5\theta_3) \end{bmatrix} \tag{5}$$

and

$$B(r) = \begin{bmatrix} r\pi/4 \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

One method to solve the system expressed in equation (4) is by using an iterative method such as the Newton Raphson.

The Newton Raphson method is used to compute the switching angles θ_1, θ_2 and θ_3 for the system given by equation (4). And as mentioned before those switching angles they must satisfy the condition expressed in (3) and also produce the desired fundamental voltage with the 3rd and the 5th harmonic components eliminated for any given value of *r*.

The application of Newton Raphson method for selective harmonic elimination problem can be summarized in these few steps:

1. Set the initial values of θ_1, θ_2 and θ_3 with: $0 < \theta_1 < \theta_2 < \theta_3 < \pi/2$. And also set the initial value of *r*.
2. Compute $F(\theta)$ presented in (5) and $B(r)$ presented in (6) and also compute the jacobian matrix $J(\theta)$ where

$$J(\theta) = [\frac{dF}{d\theta}] = \begin{bmatrix} -\sin(\theta_1) & \sin(\theta_2) & -\sin(\theta_3) \\ -3\sin(3\theta_1) & 3\sin(3\theta_2) & -3\sin(3\theta_3) \\ -5\sin(5\theta_1) & 5\sin(5\theta_2) & -5\sin(5\theta_3) \end{bmatrix} \tag{7}$$

3. Compute $d\theta$ using the following relation :

$$d\theta = INV\left[\frac{dF}{d\theta}\right](B - F) \quad (8)$$

4. Update the values of θ using the following relation

$$\theta^{k+1} = \theta^k + d\theta^k \quad (9)$$

Where k is the current iteration

5. Repeat steps (2) to (4) for a number of iterations (k) to reach an acceptable error value $d\theta$.
6. Save the current values of θ
7. Increment the value of r with a fixed step size.
8. Repeat steps (2) to (7) until the maximum value of r is reached.

3. Simulation and experimental results

In order to prove the theoretical predictions and to test the effectiveness of the proposed algorithm, the control method and the mathematical model of the proposed inverter were developed and simulated using MATLAB scientific programming environment; the optimization program was executed on a computer with Intel(R) Core(TM) i3 CPU@ 2.13GHz Processor and 4GB of RAM, the optimization algorithm takes 4.994 seconds to complete the computation process.

An H-Bridge module was built to validate the results obtained from the simulation process; Irf640 MOSFETS were used as switching devices for the proposed inverter, 4N25 optocouplers were used to protect the microcontroller used in this experiment, Siglent SDS 1000 oscilloscope with FFT capability was used to preview the voltage waveforms and to perform FFT analysis. Figure 3 shows the experimental setup used in this study.

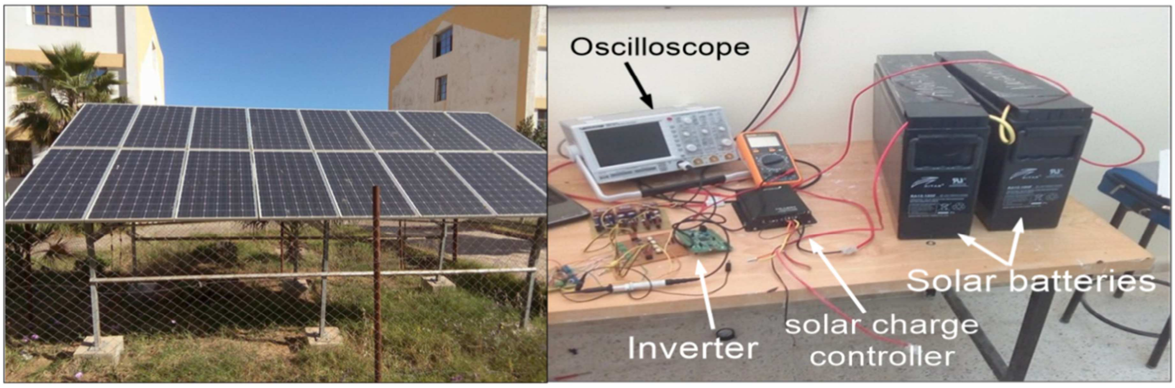

Figure 3: Solar panels (left) and experimental setup used in this study (right)

To choose the set of switching angles with the lowest total harmonic distortion (*THD*), the generated solutions from the *NR* algorithm are examined for their corresponding *THD* using this equation:

$$THD(\%) = \frac{\sum_{n=3,5,7,\dots}^{\infty} H_n{}^2}{H_1} \times 100 \quad (10)$$

Where H_n is the amplitude of a harmonic of rank n and H_1 is the amplitude of the fundamental component. The left side of Figure.4 shows the generated switching angles for the three level inverter versus the modulation index *r*. The modulation index varies from 0 to 1.06 with a step size of 0.01. The right side of figure.4 presents the corresponding total harmonic distortion for each set of solutions and it can be clearly seen that the lowest harmonic content corresponds to r = 1.05 with a *THD* of 44.28%. So the values (in degrees) of the switching angles with lowest *THD* are: $\theta_1 = 20.08°$, $\theta_2 = 33.04°$ and $\theta_3 = 43.63°$.

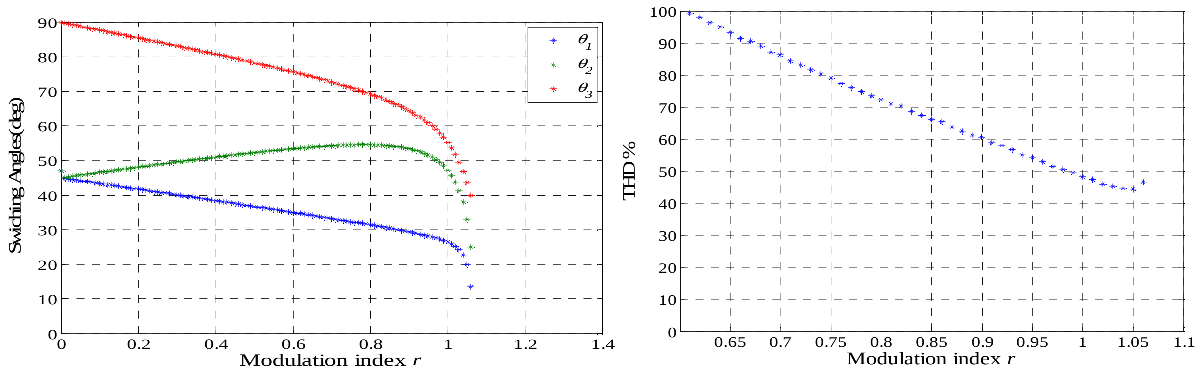

Figure 4: Switching angles VS Modulation index r (Left), THD VS Modulation index r (Right)

Figure 5 presents simulation (on the left) and experimental (on the right) results of the output voltage waveform for switching angle values of: θ_1=20.08°, θ_2 =33.04° and θ_3=43.63°. and it can be clearly seen that simulation and experimental waveforms are identical.

Figure 6 presents simulation (on the left) and experimental (on the right) results of fast Fourier transform (FFT) of the generated three level waveform. Simulation and experimental results are identical and as expected it can be seen from the results that the targeted harmonics (3rd and 5th) were successfully eliminated.

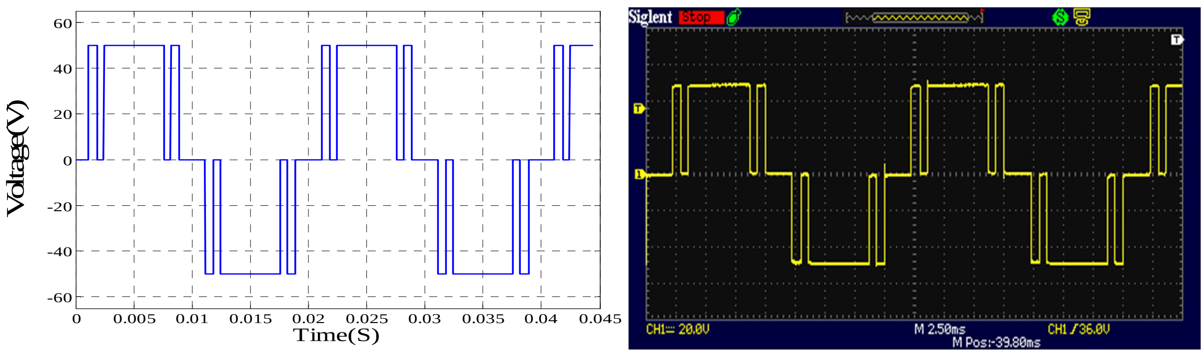

Figure 5: Output Voltage waveform for r=1.05: Simulation result (Left), Experimental result (Right)

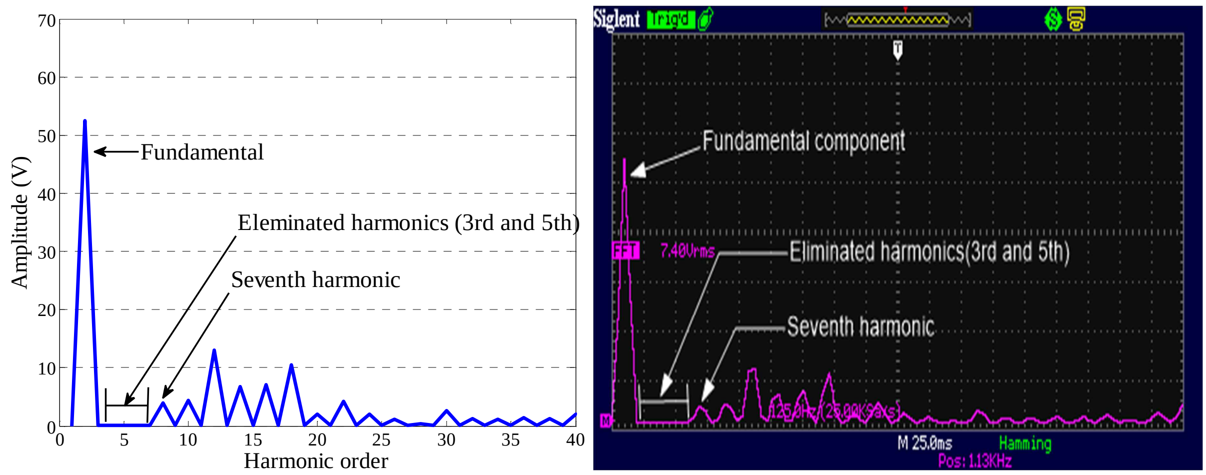

Figure 6: FFT analysis of the generated voltage waveform: Simulation result (Left) Experimental result (Right)

4. Conclusion

This paper demonstrated the ability of the selective harmonic elimination strategy for multilevel inverters of producing high quality voltage waveform with less harmonics and maintain the fundamental component at a desired value, and also the possibility of using the Newton-Raphson algorithm to solve the optimal switching problem for multilevel inverters. The SHEPWM would be a very efficient method to control solar DC to AC converters.

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