A Multilevel Inverter for Grid-Connected Photovoltaic Systems Optimized by Genetic Algorithm

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ABSTRACT

This article introduces a grid-connected photovoltaic (PV) source combined with a multi-level inverter. A converter five-level neutral point (NPC) can be used to integrate the PV power into the power grid with minimum harmonic distortions and high power capacity. If the output voltage of the PV generator varies significantly with solar radiation, the output voltage of the ripple must be fixed. For this reason, a regulation loop was used. In this study, we used a classical PI regulator. It is difficult to determine the PI controller transaction values, so Genetic Algorithm was used to optimize the PI controller parameters. The Matlab/Simulink simulation results show the better performance and efficiency of the PI controller optimized by the GA, in comparison to the stand-alone PI controller, regarding stability and accuracy, and the reduction of Total Harmonic Distortions (THD) of the current injected into the grid for any difference in solar radiation.

Keywords-PV array; MPPT; inverter NPC; genetic algorithm

I. INTRODUCTION

Renewable energy is a developing sector in which many ongoing natural energy resources are utilized [1], solar energy being the most studied of them. Renewable energy in the coming years must meet, by 2020 and 2050, the 20% and 50% of the total demands, respectively [2].

The inverter is the core of a photovoltaic (PV) system. It converts the continuous current produced by the PV system into alternating current [3-6]. Disadvantages of the two-level PWM inverters are the high switching frequency, the many harmonics, and the large filters used [7]. The benefits of the multilevel converter are that it reduces the voltage of the apparatus, the exit wave of the staircase, and that it lowers the electromagnetic emissions. Multi-level converters know many industrial uses and high voltage and high output standards are necessary [8]. The topologies for multilevel inverters are: floating capacitor, loopback diode (NPC), and cascaded H-bridge inverter [9]. In the NPC inverter inlet, there is availability on the side of the bipolar common DC bus and it has the flexibility to add multiple PV panels in the system [10]. There is much interest in the NPC inverters topologies due to their low output current and low overall Total Harmonic Distortion (TDH) [11]. NPC supports a variety of classical sinusoidal modulation methods, such as multiple triangle sinusoidal modulation, vector modulation, and selective harmonic elimination [12]. Common strategies for controllers in voltage regulations include the widely used PI controllers due to their intrinsic simplicity and rapid dynamic response [13].

II. MULTILEVEL INVERTER FOR A GRID-CONNECTED PHOTOVOLTAIC SYSTEM

The proposed diagram shown in Figure 1 [10] consists of 4 main elements: a PV array, dc/dc buck converters, NPC inverter configuration, and an LC filter (filtering inductance and capacitors L_f, C_f are used to filter the current injected into the system).

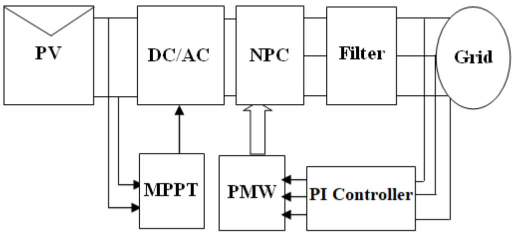

Fig. 1. The five-level inverter in grid-connected PV systems.

III. THE ARCHITECTURE OF THE DIODE-CLAMPED MULTI-LEVEL INVERTER

Authors in [1] proposed the neutral point converter for a variety of applications in 1981. A multi-level inverter structure was used in high and intermediate voltage conditions. The basic architecture for this inverter was addressed in [14-15]. NPC inverters are one of the most widely used PV systems. In [16], the system has significant advantages. The (n-1) capacitors required on the DC bus are part of the multilevel inverter and the required number of switches for each phase is 2(n-1). Moreover, there are 2*(n-2) diodes in each phase.

TABLE I. COMPONENT COUNT OF TRADITIONAL MLIS [24]

Topology components	Traditional MLIs		
	Diode clamped MLI	**Capacitor clamped MLI**	**Cascaded H-bridge MLI**
Main switches	2(n-1)	2(n-1)	2(n-1)
Main diodes	2(n-1)	2(n-1)	2(n-1)
Clamping diode	2(n-2)	0	0
Balancing capacitors	0	(n-2)	0
DC bus capacitors	n-1	0	0
DC sources	1	1	(n-1)/2

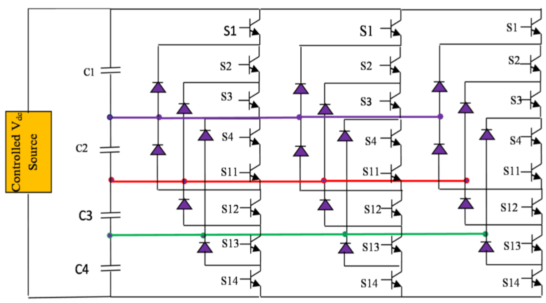

Fig. 2. The three-phase, five-level, diode-clamped inverter's schematic in Simulink.

IV. PHOTOVOLTAIC GENERATOR

The power available at the terminals of a cell is very low, it is therefore necessary to combine such cells in series and in parallel to obtain satisfactory power modules. This model consists of complex equations whose solution requires many (6) parameters. Another model has a single diode with 5 parameters (R_s, R_{sh}, I_{ph}, I_0, A), [18]:

$$I_{Ph} - I_0\left(e^{\frac{q}{nAKT}(V+R_s*I)} - 1\right) - \frac{V+R_s*I}{R_{sh}} \quad (1)$$

where I is the current delivered by the PV module, R_{sh} is ths shunt resistance, I_{ph} the photoelectrical current, I_0 the saturation current, R_s the series resistance, K is the Boltzmann's constant, and N is the coefficient of the diode ideality.

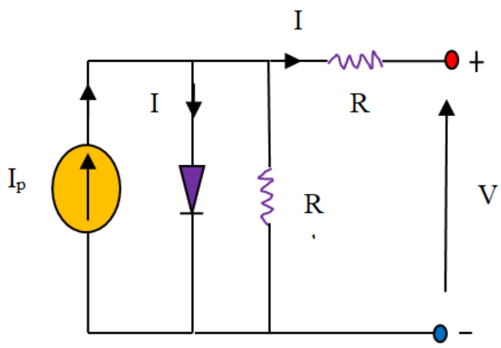

Fig. 3. Equivalent diagram of a photovoltaic cell.

The parameters of the solar array that identify (1) relate to the solar panel parameters as follows:

$$I_{scpanel} = N_p I_{sc} \quad (2)$$

$$I_{0panel} = N_p I_0 \quad (3)$$

$$R_{S\ panel} = \frac{N_S}{N_P} R_S \quad (4)$$

$$R_{P\ panel} = \frac{N_S}{N_P} R_P \quad (5)$$

The photoelectric current (Iph) depends on irradiation and temperature:

$$I_{ph} = (I_{ph,n} + K_I.\Delta T).\frac{G}{G_n} \quad (6)$$

$$I_0 = \frac{I_{sc,n} + K_I.\Delta T}{\exp\left(\frac{V_{oc,n} + K_v.\Delta T}{A.V_{th}}\right) - 1} \quad (7)$$

$$\Delta T = T - T_n \quad (8)$$

where I_{scn} is the short-circuit current under nominal conditions (G_n=1000W/m^2, T_n =25°C). The cell's ambient and nominal temperatures are represented, respectively, by T and T_n, where the current and nominal irradiation are G and G_n, respectively. The short circuit current's temperature coefficient is K_I, while the open circuit voltage's is K_v. V_{th}, given in (1) is the thermal junction constant, equal to V_{th}=KT/q, where q is the electron charge.

V. DC/DC BUCK CONVERTER

A boost converter is the most widely used DC-DC converter since its input voltage is smaller than its output voltage. Filters composed of inductor and capacitor combinations are regularly used together to improve the performance of a converter [20]. Thus, in order to improve the solar panel's effectiveness, we use the MPPT technique. There are different techniques to follow the Maximum Power Point (MPP) [21-22]. In this paper, the Perturb and Observe (P&O) technique is used because it is straightforward and simple to use in real time. It is an algorithm based on perturbing and monitoring the solar panel's voltage until it reaches the optimal power level in the flowchart shown in Figure 4.

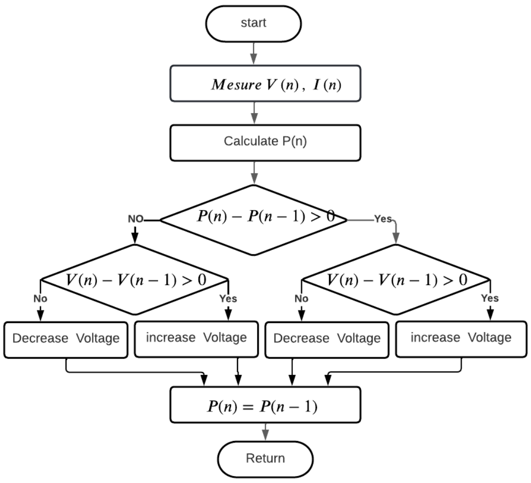

Fig. 4. Diagram of the P&O method.

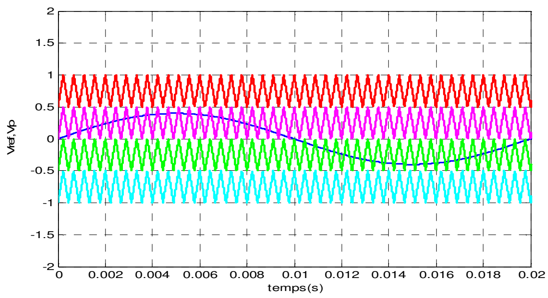

Fig. 5. Reference signal and four carrier waves.

VI. COMMANDS AND ALGORITHMS USED

A. Modulation

The proposed control utilizes a modulation technique that uses the sinusoidal PWM (SPWM) [19]. A 5-level voltage waveform requires 4 level-shifted carrier signals as shown in Figure 5. It is the sinusoidal modulation with multiple triangles which allows it. This technique requires (N-1) triangular signals with the same frequency f_p and the same amplitude A_p. These triangular signals are compared, for each phase, with a reference signal of amplitude A_{ref} and frequency f_{ref}. The expressions below provide the modulation rate m_a and the frequency ratio m_f:

$$m_a = \frac{A_{ref}}{(N-1)A_p} \qquad (9)$$

$$m_f = \frac{f_p}{f_{ref}} \qquad (10)$$

VII. THE GENETIC ALGORITHM

Genetic Algorithms (GAs) are adaptive search algorithms built on the evolutionary principles of natural selection and genetics. The main goal of GAs is to mimic natural system processes that are necessary for evolution. They represent a clever use of a random search inside a defined search area. The core idea of GAs is to maintain a population of knowledge structures that evolve over time through a process of competition and controlled variation. Each population structure represents an answer to a particular problem and a corresponding fitness function, which is used to select which structures are used to generate new ones by genetic processes like mutation and crossover. In order to address concerns with search and optimization, GAs are quite prosperous. Their ability to leverage information about a search space that was previously unknown in order to influence subsequent searches towards beneficial subspaces may be credited with a substantial chunk of their effectiveness. A GA starts off with solutions produced by a population chosen at random. Advances made possible by chromosomes' employment of genetic operators, based on the principles of natural genetic processes. Within the population, evolution via natural selection takes place. In order to finally replace the vanishing relatively bad solutions, comparatively good solutions reproduce at every generation. The environment works as a function of evaluation or fitness to distinguish between good and bad solutions. When a GA is used, a generation is the period of time between the current and the subsequent population. Although the basic GA has a number of modifications, the fundamental mechanism consists of three parts:

- Assessment of each person's fitness.
- Creation of the gene pool.
- Mutation and recombination

TABLE II. THE STRUCTURE OF A SIMPLE GA [23]

1.	Initialization: A set of potential solutions (chromosomes or individuals) forming a population is initialized
2.	Evaluation: Each individual is then evaluated by calculating its quality (fitness value)
3.	Selection: Individuals with higher fitness value are selected for breeding
4.	Reproduction: During breeding, crossover and mutation operators are employed to selected individuals (parents) to produce new individuals (offspring)
5.	Termination: These steps continue over many generations or iterations until the predefined criteria are satisfied

VIII. OPTIMIZING THE PID REGULATOR WITH GENETIC ALGORITHM

The genetic encoding of the chromosome's PID regulator parameters defines the PID regulator parameters. There are two genes on the chromosome: K_i and K_p.

A. Generation of the Initial Population

The chromosomes in the initial population are produced by a stochastic generation. Each allele is defined in the subset:

$$S = [\min\ K_i\ \min K_p;\ \max K_i\ \max K_p] \tag{11}$$

Fig. 6. Chromosome representation.

B. Fitness Function

The PID regulator is trained with a given number of alleles and is then assessed using predetermined parameters to determine an individual's fitness. The Mean Square Error (MSE) at the conclusion of training characterizes best the quality of a PID regulator. It is the output of the PID regulator.

$$f(x) = \frac{\sum_{i=1}^{N} (Y_i - a_i)^2}{N} \tag{12}$$

IX. SIMULATION RESULTS

The main objectives when transferring the PV generated energy into the utility grid are:

- To track the PV's MPP.
- To obtain study voltage.

Control of the inverter output voltage requires a closed loop. The voltage V_a is measured and then compared to the reference voltage V_{ref}=311V which represents the maximum value of the simple network voltage. The counter error signal is injected at the PI controller with chosen parameters: K_p=0.1, K_i=0.01. GA is used to select the parameters of the PID regulator by minimizing the MSE. Table IV shows the GA parameters used to optimize the PID parameters and Table III gives the PID regulator values.

TABLE III. GA CONTROL PARAMETERS

No of generations	20
Population	70
Chromosome size	2
Crossover	1
Mutation probability	0.08

TABLE IV. GA PARAMETERS USED TO OPTIMIZE THE PID

PID parameter	**Value**
K_i	0.0011
K_p	0.0218

Figure 7 shows that for a step change in solar radiation (from 200 to 800W/m^2), the controller tracks instantaneously the MPP altering thus the DC bus voltage. From Figures 9-12 we can note that the conventional PI has bigger overshoot whereas the proposed PI-GA has better signal reduction of the reference signal for SPWM. Figures 9 and 10 show the 5-level output voltage of the inverter before the filter and after the LC low pass filter. Based on the harmonic analysis, TDH is less in the filtered output voltage of the 5-level inverter. From the FFT analysis shown in Figure 12, it is observed that the TDH is 0.30%. After comparing the results, we notice that when using the GA, the results were improved and the THD was reduced.

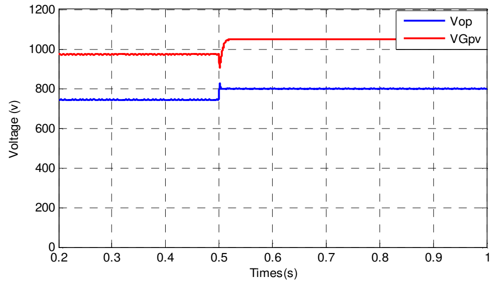

Fig. 7. PV generator output optimal voltage.

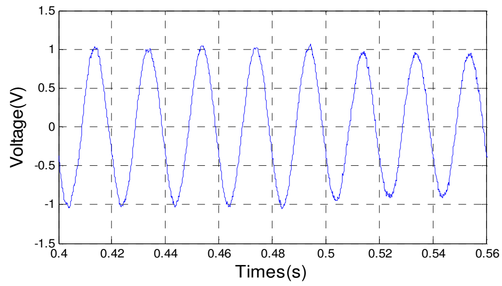

Fig. 8. Reference voltage with GA for SPWM.

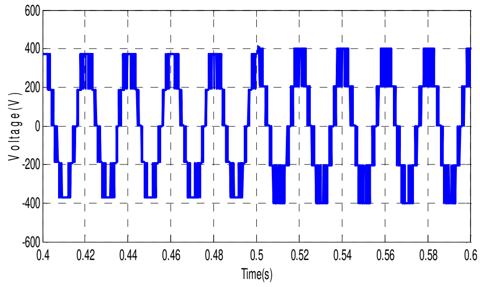

Fig. 9. Output voltage for a step change in solar insolation.

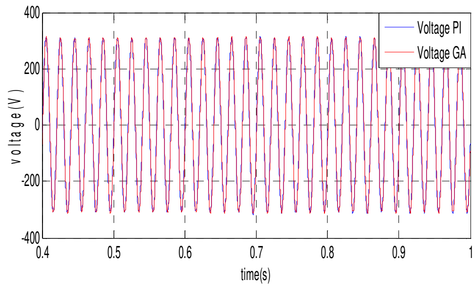

Fig. 10. Output voltage after filtering.

X. CONCLUSION

In order to secure the dc-ac conversion stage, the current research developed a 3-phase 5-level NPC multilevel grid-connected photovoltaic system. Such a topology is primarily employed to meet the needs of connecting and transmitting high power between the PV system power source and the main grid. When compared to the traditional inverter topologies utilized in such applications, this topology has impressively demonstrated its efficacy and adaptability and offers various advantages, including a reduction in output voltage harmonics.

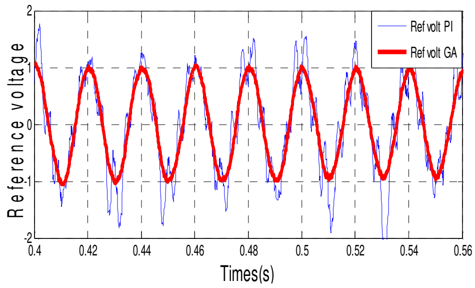

Fig. 11. Reference voltage.

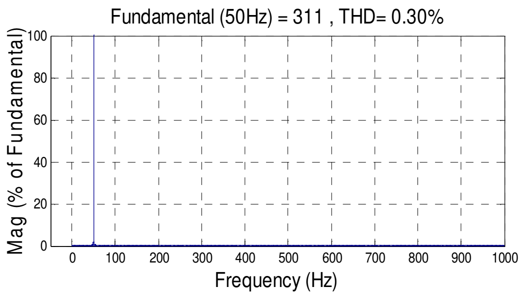

Fig. 12. FFT analysis for the 5-evel inverter.

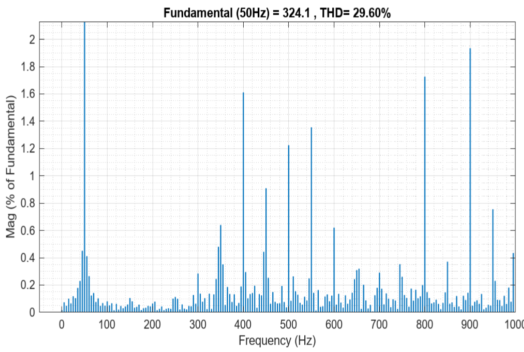

Fig. 13. Voltage FFT analysis before filtering.

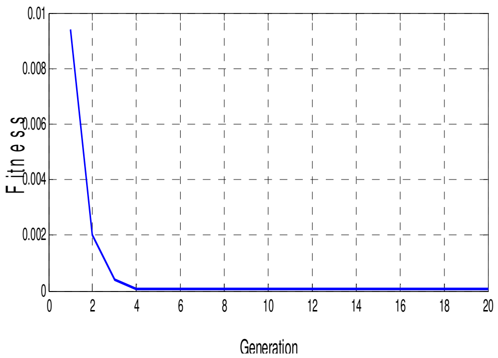

Fig. 14. Evolution of GA.

Regarding future work, the behavior of various blocks can be further improved, i.e. regarding the dc/dc converter, the possibility of using a buck/boost converter can be examined and regarding the dc/ac converter new topologies can be inspected. The possibility of practical implementation using the D Space card is also considered.

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