Real time Simulation of Grid-connected Photovoltaic Multilevel Inverter using Hybrid GA/PSO Optimization Algorithm

Hussein Zolfaghari¹, Dr. Hamidreza Momeni², Hossein Karimi³
Hussein.zolfaghari@modares.ac.ir¹, momeni_h@modares.ac.ir², Hossein.karimi@ucalgary.ca³

Abstract: This paper presents a new real-time intelligent optimization algorithm to minimize the voltage harmonics of a multilevel photovoltaic inverter. Hybrid Genetic algorithm/Particle swarm optimization algorithm is employed in a real-time simulation to identify the best fire angels of the multilevel inverter to eliminate any destructive effect, such as dc voltage variations and changes in line and dc-link resistors. The dual objective function of harmonic minimization and voltage regulation is considered in this real-time simulation. This approach can be applied to any multilevel inverter with various numbers of levels. The validity of the proposed algorithm is proven by real-time simulation of seven and an eleven-level inverter.

Key Words: Multilevel Inverter, Photovoltaic System, real time tuning, Hybrid GA/PSO

I. Introduction

Renewable energy has gained attention during the recent years due to their distinguishing features such as emission-free, low cost and high availability of resources. Due to the advancement of power electronic technique, Photovoltaic (PV) and wind turbine energy have become more popular among different kinds of renewable energy resources. Since photovoltaic systems commonly produce low voltage, they can constitute DC voltage of multilevel inverter. Also, multilevel inverter has gained attention due to their application in industry and different areas[¹]. Multilevel inverters enjoy high efficiency and their output voltage can be increased to very high voltage. Also, they can supply voltage with small step increase in voltage and its advantages are low harmonic distortion, lower stress on semiconductors devices, high quality of power, and lower switching loss.

There are commonly two general approach in switching method. High frequency Sinusoidal Pulse Weight Modulation (SPWM) or Space Vector Pulse Weight Modulation (SVPWM) technique make low THD, but cause a great deal of energy losses and also decrease switches efficient life [²-³]. The second method is a technique with low switching frequency which usually used in multilevel inverter.
This method usually needs solving transcendental equation. In [4] Selected Harmonic Elimination (SHE) approach has been used to remove low order harmonic. The equations are solved by Colonial Competitive algorithm. Genetic algorithm (GA) [5-6] is the most applicable heuristic algorithm which is used in this field to solve transcendental equation. In [7], GA has been utilized with Levenberg–Marquardt method. Particle Swarm Optimization (PSO) algorithm [8-9] is widely used to guess initial values in solving of Newton-Raphson equation solving method and also employed to solve transcendental equations numerically [10-11]. Ref [12-13] employed Artificial Neural Networks (ANN) to minimize harmonic distortion, but it just can be used in limited operating points. In [14], real time SHE is proposed. A nondeterministic method is used to solve the system and to obtain the data set for the training of ANN. The main drawback of this method is that only unequal DC voltage effect is considered for training of the ANN. In [15], GA has used to solve SHE equations offline for different DC voltage source and then data has been used to train ANN to work on real time corresponding to the new DC source values. Again, the main flaw of this method is that ANN can just work around the working points that provided by data for ANN training. Also, some conditions such as the effect of resistor of dc sources, switches and line are neglected. PSO[16], and other heuristic algorithm [17-18] are used in literature, which most of the solution were on solving SHE equation with varying DC source voltage without considering other effective factors. Using a Model predictive model research in paper [19] the researcher had implemented a new model for a bio-system that will use for a multilevel inverter. In this research the author implements a multiple model predictive controller for a biological system, and this model shows a successful control on this plant. In multilevel inverter this MMPC will improve the proficiency.

In [20] Model based predictive control has been represented. Using this technique, the researcher conquered the long-time delays using a MPC control. Furthermore, the researcher proposed a Robust Model Predictive Controllers (RMPCs) based on LMI and convex optimization to conquest the uncertainty in such complex systems.

In [21] the researchers proposed a reliable energy scheduling framework for distributed energy resources (DER) of a residential area to achieve an appropriate daily electricity consumption with the maximum affordable demand response. The efficiency has been improver using a mixed-integer-linear-programming (MILP) investigated using model-based predictive control (MPC). Considering Renewable energy resources, this paper practical constraints.
One of the disadvantages of SHE method is solving nonlinear transcendental equations and they are mostly used as an offline method to tune firing angles. Another important drawback of this method is that in a real system, DC voltage of each level may change and the firing angels must be adjusted again. Look up table or ANN training method can be used as a solution to change the fire angles if dc voltages get unequal. Similarly, the main disadvantages of this method is that for inverter with many levels, generating such a table (or ANN) is difficult and inaccurate. Also it is possible that inverter works in some conditions which has not been considered in look up table or ANN training. Online or real time for solving of SHE equations might be considered as a good solution, but this method does not work accurately when some effective factors such as resistor of DC voltage sources, switches, and lines exist.

In this paper, the authors proposed real time method by which a heuristic algorithm (here Hybrid GA/PSO) tunes fire angels to minimize THD. Not only this method is capable of considering unequal dc voltage, but also can handle unforeseen events such as one level failure. Heuristic algorithm such as PSO and GA can solve problems with multiple solutions and are not prone to be trapped in the local minima; additionally, they are applicable to multidimensional problems. So a real time heuristic algorithm can be used to directly control fire angels in order to find the best fire angel to minimize both THD and voltage RMS error. Heuristic algorithm can automatically consider all conditions by suggesting different solutions and evaluating them and has the ability to converge the solution in seconds.

The rest of paper are as follows: the section II gives a brief explanation on multilevel inverter. GA and PSO are given in section III. Section IV gives an elucidation on real time tuning and the proposed flowchart. Simulation results are presented in Section V and finally section VI concludes the paper.

II. Multilevel Inverter

There exist different structures for multilevel inverter, but here, cascade structure is used. H-bridge is the fundamental part of cascade multilevel inverter. Each H-bridge has two leg. Each leg has two switches with two freewheeling diodes as shown in fig 1. If H-bridges connected in series, multilevel inverter is conducted. m H-bridge connected in series can built an inverter with 2m+1 levels. Fig2 shows a multilevel H-bridge cascade inverter.
III. Combined GA-PSO

In this section, GA, PSO and, Hybrid GA/PSO are presented.

A. Genetic Algorithm

GA is an evolutionary algorithm inspired by natural selection [22]. The algorithm repeatedly modifies its population base on three main processes. The first process is
named selection, by which two parents are chosen to breed a new generation. This selection is upon a fitness-based process. In the second step, crossover is done to produce chromosome from one generation to the next. In the third part, mutation is done to keep genetic diversity [23]. More detail on GA can be found in literature [24].

B. Particle Swarm Optimization

PSO is an algorithm developed by Kennedy and Eberhart [25]. PSO operation is based on mimicking the behavior of birds or fishes in finding foods. Briefly, PSO has three movements which conduct its velocity. The first action of next movement of a particle is continuing its way in the same direction. The second movement is a move toward its best experience and final movement is random move in order to cover search space better. Velocity can be described as follows:

\[ v_{id}^{k+1} = w v_{id}^{k} + c_1 r_1 (p b_{id}^{k} - x_{id}^{k}) + c_2 r_2 (g b_{id}^{k} - x_{id}^{k}) \]  

(1)

Where \( i = 1, 2, ..., n \) and \( n \) is the size of population, \( w \) is the inertia weight, \( c_1 \) and \( c_2 \) are the acceleration constants, and \( r_1 \) and \( r_2 \) are two random values in range \([0,1]\).

The i-particle position is updated by

\[ x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \]  

(2)

More detail can be found in [26].

C. Combination of GA and PSO

The combination of GA and PSO is chosen since this algorithm will enjoy the merits of both optimization algorithms. Different literature has reported that Hybrid GA-PSO algorithm has significant privileges over other algorithm in both precision and rate of convergence [27-28]. Hybrid GA-PSO has six operators which enhance its performance by incorporating features from one paradigm into the other. In an iteration, PSO calls to mind the best solution between populations as “gbest” and the best position for each population as “pbest”. Maintaining gbest and pbest is very useful characteristics of PSO, which the GA lacks. Hence, the proposed hybrid algorithm has evolved a GA by trying to preserve pbest and gbest, and to utilize them in offspring procedures [29].

IV. The Proposed Strategy

This paper proposed a real time optimization method to achieve the best fire angle. Several online calculating methods are presented in literature. Most of them
calculated fire angles offline for different situations and applied them according to
the predicted events using a look up table. Some papers have employed artificial
intelligence instead of look up table, but actually this intelligent algorithm has been
trained based on a look up table. In the other word, they just substitute intelligent
algorithm instead of look up table, and if the look up table suffers from
comprehensive analysis, the intelligent algorithm suffers as well.

The proposed strategy in this paper is a real time computing based on the hybrid GA-
PSO algorithm. This method enjoys six different operators which do the real time
computing better in both accuracy and speed. Real time computing can be activated
by two ways.

Hybrid GA-PSO involves both operators of GA and PSO simultaneously. GA
operators are selection, crossover and mutation which are combined by position and
velocity update of PSO. The main merit of this approach is evaluating and assessing
the system in real time. This method can remove any defect which might not be
considered in those method which works offline or those approaches which are real
time or online but their bases are mainly offline. Ref [2] to [7] are offline tuning
method which are prone to error in situations such as DC source and line resistor
variations and sudden voltage of one level. Some of online/real time approaches
[14], [17], and [30] exist which seems to be online/real time, but actually they are
not real time. Ref [14] is a real time approach which works based on ANN. The ANN
are trained by data provided by a look up table. The look up table are built offline,
and just for a few situations of varying dc link voltage are considered. This look up
table might be prone to error when the system runs into a new condition. So the
trained ANN is also prone to error.

This paper tries to solve the abovementioned problems by a real time approach. The
main drawback of abovementioned studies is restricting the problem from different
aspects, therefore some unforeseen situations might be ignored unintentionally. This
paper does not restrict the problem and any situation in which the system can run
into can be considered since there is no offline tuning, predetermined situations for
some inequality in dc link voltage; therefore, all possible situations which can occur
are considered.

The proposed real time flowchart is presented in Fig3.
Fig 3. Flowchart of The Proposed Algorithm

The flowchart works as follows:
1. There exist two criteria to activate the process. If any changes in DC voltage or circuit is detected the flowchart is started to adapt fire angles to the new situation. Also, some changes might not be detected. So a time interval should be defined to evaluate the situation. Moreover, the process can be started by a human order.

2. If any activation criteria is satisfied the flowchart start to work

3. Hybrid process can be done in parallel or series. So if the hybrid process is series, generating of one population suffice that process to be started. This population is used both by PSO and GA. If the process is parallel, two populations namely, particles and chromosomes are needed. Since this paper uses series process, generating one population is enough.

4. PSO updates the velocity and position of the population based on the pbest and gbest.

5. updated positions are evaluated.

6. Based on the new population, which has remembered their pbest and gbest, selection is done. The main merit of this process is that each particle/chromosome preserved its best experience and population also maintains its global experience. This trick will remove the main drawback of GA in preserving its best experiences. Then, crossover and mutation are done.

7. Algorithm evaluate new population and sort them according to their fitness value and delete the extra population.

8. if any of stop criteria is not met, go to step 3.

9. print the result and give the best fire angles to the inverter
V. Numerical Study and Results

To evaluate the proposed method, two multilevel inverters with 7 and 11 levels are simulated in Matlab/Simulink. Inverter nominal power is considered 10 kW. The hybrid GA/PSO algorithm is used to tune fire angels of inverter in real time. For comparison purpose, the ANN method used in [14] is simulated in matlab/Simulink as well. For a 50Hz voltage, in each 0.02 second, algorithm produces a set of fire angles to build a voltage and evaluate it. In this study, based on trial and error experiment, optimization time is selected 10 second which evaluate voltages 500 (10*50) times with different fire angels. As, there is no restriction on the proposed GA/PSO algorithm, it is expected that the proposed method generally handles any situation since heuristic algorithms solution does not depend on the kind of problem, and just need objective function information to search the problem space. Also, it can reach to the best answer with any initial value. Therefore, the algorithm gives the best possible answer in any situations.

At first step, to evaluate the proposed method, seven level and eleven level inverter are simulated. The population of the algorithm is chosen 20. The dc voltage for each level of seven level inverter is 100 V and 60V for eleven level. The objective of the problem is producing a 220 V rms voltage with minimum harmonic and is as follows:

\[ OF = THD(\%) + K_v |220 - V_{rms}| \]  (2)

Which \( OF \) stands for Objective Function and \( K_v \) is weight vector. Time Simulation is 30 seconds. In first 10 second, the real time GA/PSA hybrid algorithm tries to cover all search space to find the best fire angle. Fig4 shows real time objective function value which is variable in first 10 second, since in every single period, algorithm gives a new fire angle and reads the voltage values during the period to calculates THD and Voltage RMS. This calculation is done up to 10 second. 10 second is chosen since it is enough for the algorithm to find the optimal fire angles. Also, Fig 5 shows two terms of objective function i.e. THD and RMS Voltage. Fig 6 shows fire angles (in degree) during real time simulation. As can be seen, fire angles can increase up to 90 degrees. Fig 6 also shows that algorithm searches the whole space to find the best answer. Fig 7 shows, optimized output voltage of inverter which its THD is 15.36%.
Fig 4. Real Time Objective Function Value

Fig 5. THD and RMS Voltage Value in real time
Moreover, for the eleven level inverter, five fire angles should be tuned. So the search space is a little bigger; therefore, optimization time is chosen 15 second. Real time objective function value and THD and RMS value of voltage are shown in Fig 8 and Fig 9, respectively. Five fire angles are shown in Fig 10. As can be seen, when
simulation time approaches to 15 S, convergence gets better. Moreover, optimized voltage is shown in Fig 11 which the THD values is 7.47%.

**Fig 8. Real Time Objective Function Value**

**Fig 9. THD and RMS Voltage Value in real time**
To evaluate the proposed method to handle the effect of DC link voltage variations, line resistor, and sudden change of DC voltage, two scenarios for seven and eleven level inverter are considered.

A. Seven Level Inverter
In this scenario, DC link voltages for seven level inverter are changed according to the table 1. Non-equal DC link voltage changes both THD and RMS value of voltage. In [14], a look up table is designed to tune the fire angles according to the changes of DC voltages. The changes are considered up to ±50%. Then, ANN is trained to work instead of look up table. In look up table approach, when DC voltage variations are between two values, i.e. \( V1 \) to \( V2 \), fire angles change discontinuously i.e. from \( \theta 1 \) to \( \theta 2 \). However, the trained ANN can provide the inverter with a continuous changes of fire angles fits with DC voltage variation. So, in this case, ANN does a better job in comparison to the look up table. But ANN cannot work beyond the range in which it has been trained. In other word, its performance gets worse as far as input values goes beyond the range. So the first restriction of this method is limit on voltage range that some voltages might have not been considered for ANN training. The second weakness of the proposed ANN is that if there is a noticeable distance between inverter and network, the resistor plays an important role in Voltage RMS. Also, DC voltage might be provided by far apart photovoltaic cells and there might exist a resistor between them which affect both RMS and THD of voltage. So, a resistor of 0.1 ohm is considered between level 1 and 2 and another 0.15-ohm resistor is considered between inverter and network.

| Item                      | Change (%) |
|---------------------------|------------|
| DC Source of level 1      | +10        |
| DC Source of level 2      | +50        |
| DC Source of level 3      | -60        |

Table 1: DC link voltage variation

Objective function value during 50 seconds simulation is depicted in Fig 12. At the second of 5s, DC voltages are changed according to the table 1. ANN detect the changes and provide the inverter with new Fire Angles (FA) immediately. Since ANN has been trained before, it generates new FA so fast. However, the proposed real time optimization method needs a few seconds to find the best FAs. According to the hybrid GA/PSO algorithm, it initially suggests some random FAs and evaluate them and as time goes forward find the best FA. Although, ANN method gives the fitted FAs instantly, it might not be the best FAs, and some new effective factors might be ignored in finding the best FAs. In Contrast, the proposed method provides the FAs after a while by inherently evaluating different factors. As Fig 12 shows, the proposed method try evaluating different FAs and finding the best FAs between the time of 5s and 15s. The objective function of both methods are the same. After the
time of 15s, the proposed method finds a better answer in comparison to the non-real time ANN.

The first and second term of objective function i.e. THD and Voltage RMS error are shown in Fig 13. It shows, both THD and voltage RMS error converge to a better solution in the proposed real time method. Objective function value of these two method besides of each terms are given in Table 2. Here, for a better optimization $K_v$ is set to 0.5.

|                | THD    | RMS Voltage Error | Objective Function |
|----------------|--------|-------------------|--------------------|
| Proposed method| 14.68% | 1.46 V            | 17.41              |
| ANN            | 16 %   | 7 V               | 19.5               |

Table 2. Objective function values

Fig12: objective Function value of seven level inverter
Fig 12: THD and Voltage RMS error of real time proposed method and ANN.

The Fire Angles (FA) variation during the simulation are shown in Fig 13. The final FAs of the both methods are given in Table 3.

Table 3. Final Fire Angle for the seven-level inverter

|                      | FA1 (Degree) | FA2 (D) | FA3 (D) |
|----------------------|--------------|---------|---------|
| Proposed Real Time   | 10.87        | 37.17   | 66.66   |
| ANN trained by look up table | 11.24  | 36.27   | 54.99   |
Fig 13. Fire angle variation during 50 second

Voltage produced by ANN and the proposed method is shown in Fig 14.

Fig 14. The produced voltage of two methods

Moreover, current injected to the grid are shown in Fig 15 and Fig 16. Current THD of the proposed method is 4.96%, while ANN current THD is 5.13. Also, current
injected to the grid by the ANN is less than the proposed method, since there is a voltage drop in ANN method.

**Fig 15. Current of the proposed method injected to the grid**

**Fig 16. Current of the ANN method injected to the grid**

**B. Eleven Level Inverter**

In this section, the proposed method is employed on an inverter with 11 levels. The DC voltages are changed according to the table 4. In this scenario, since there are 5 FAs, simulation time for optimization of the proposed method is considered 15s. The
objective function value of both methods are shown in Fig 17. THD and voltage RMS Error are shown in Fig 18. As can be seen, the proposed real time optimization method gives a better response in comparison to the non-real time method. Also, optimized FAs and final voltage of eleven level inverter are shown in Fig 19 and Fig 20, respectively. THD and RMS voltage Error for this scenario are given in Table 5. Moreover, optimized FAs are given in Table 6.

Table 4. DC voltage Variations

| Item                | Change (%) |
|---------------------|------------|
| DC Source of level 1| +15        |
| DC Source of level 2| +25        |
| DC Source of level 3| -20        |
| DC Source of level 4| +35        |
| DC Source of level 5| -60        |

Fig 17. Objective function value of the system in the proposed method and ANN method
Fig 18. THD and RMS voltage Error of eleven level inverter.

Fig 19. Optimized fire angles for 11 level inverter.
Fig 20. Output Voltage of 11 level inverter.

Table 5. Objective function values for the 11-level inverter

|                | THD   | RMS Voltage Error | Objective Function |
|----------------|-------|-------------------|--------------------|
| Proposed method| 9.56% | 0.4 V             | 9.76               |
| ANN            | 10.3% | 11.8 V            | 16.2               |

Table 6. Final Fire Angle for the 11-level inverter

|               | FA1 (Degree) | FA2 (D) | FA3 (D) | FA4 (D) | FA5 (D) |
|---------------|--------------|---------|---------|---------|---------|
| Proposed Real Time | 5.28         | 17.4    | 34.73   | 50.7    | 53.8    |
| Non real Time ANN   | 13.6         | 19.9    | 28.8    | 52.29   | 68.88   |

Injected current of the proposed method and ANN method to the grid are shown in Fig 21 and Fig 22, respectively. THD of current in the proposed method is 2.65 while by ANN method is 3.19.
C. Discussion

Different factors take part in voltage quality. Voltage produced by multilevel inverter is prone to DC voltage variations. Also, the DC voltage source might not be so close to each other and a small value of resistor by a big current could easily cause a big change both in RMS value and THD. This paper proposed a real time approach
to find the best FAs. This method takes advantages of both merits of PSO and GA algorithm in finding the best solution. Since there is no restriction for finding the best answer, any effective factor, beyond on whatever is considered in this paper, in THD and RMS voltage is considered by this algorithm naturally. However, there is an issue when the multilevel inverter is being connected to the grid and the real time method is going to be done. As seen in simulation, during optimization process, when algorithm suggests different FAs, the output voltage RMS might be increased/decreased significantly, which may damage the grid or load. In this case, when a change is detected by the algorithm, at first the system can be disconnected from grid until algorithm reach to the convergence. Since the convergence speed is very high, it takes only 10 to 20s to find the best FAs in any circumstance. Furthermore, the proposed method can be activated by three methods. The first one is when a change is detected, which is very common. The second way is determining a specific time interval, such as every two hours, to activate the process. The final way is activating the process by hand. All these three ways can work together in parallel, but the first way seems to be more common.

VI. Conclusion

This paper proposed a real time process for maximizing the power quality of a multilevel inverter connected to the grid. The algorithm includes almost any factor by which the quality of power might be changed. This process enjoys advantages of both GA and PSO, simultaneously, which empower the method in both accuracy and speed. The proposed method has been employed for a seven and an eleven level inverter. The proposed method is compared with an ANN, and the results show a significant improvement THD and Voltage RMS of the inverter in steady state. This approach can be implemented for any inverter with any levels.
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