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Improving Power Quality of the Distribution Network by Connecting Photovoltaic Units in order to reduce the Harmonics using the Network Active Filter Resulting from the Nonlinear Load

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Abstract: *Aside from environmental concerns and the exhaustibility of fossil energy sources, becoming more economical and lowering the cost of installing solar systems is driving the development of photovoltaic systems for energy delivery in many nations across the world. The formation of harmonics in the network and the effect of PV units on it are examined in this article. In this context, an active filter in the PV unit is employed to eliminate network harmonics. According to the non-linear behavior of PV units, the electronic power converter is managed in this technique to limit network harmonics induced by the non-linear demand. The proposed technique runs on the enhanced IEEE 33-bus system. The simulation results confirm that using the strategy provided in this article improves the power quality of this system.*
***Keywords*:** *electricity distribution network, active filter, power quality, PV units, harmonic*

I.INTRODUCTION

Photovoltaic power generation technologies are advancing, and it is projected that in the near future, with the advancement and development of photovoltaic power generation, as well as price reductions, they will account for a major portion of the world's total power generation [1].

The growth of PV units at the distribution network level can be beneficial in enhancing or damaging power quality [2]. The performance of PV units utilizing power electronic converters influences power quality indicators, particularly harmonic distortion and current voltage and current characteristics [3] and [4].

In [5], the compensator in current control mode and the LCL output filter minimize the output harmonic current of a PV unit. In [6], a three-phase grid-independent photovoltaic system with a passive filter is created to improve the power quality of the residential grid. Harmonic injection by a solar unit linked to a single-phase network was examined and investigated in [7]. In addition, in [8], injected harmonics of PV units were solved using a multi-level inverter using the PSO algorithm. The research presented in reference [9] has been utilized in the micro grid by introducing the MFGTI algorithm to adjust for the power quality of the converters. One of the design's advantages is that it improves the performance of the converters' power quality. In [10], tests have been conducted to study the circulation current between two parallel inverters connected together in order to prove that the parallel connection of the inverters will reduce total harmonics.

On the other hand, with the rising number of sensitive customers, the demand for access to stable and standard quality electric power has increased significantly [11], and any interruption or shift outside the standard range in the quality of delivered power would result in economic loss [12]. According to these difficulties, using strategies that reduce network harmonics has a high value. Using an active filter to minimize harmonics in the power system enhances system power quality [12].

In this paper, active filter is used to improve harmonics of the power system and the PV system.

II.USING AND MODELING THE PV UNIT

A PV array is made up of photovoltaic panels connected in series and parallel [13]. The energy produced by photovoltaic arrays is affected by variables such as temperature and radiation.

2.1. Mathematical Equations of the PV array Model

Equivalent circuit of a PV cell is shown in Figure 1. This model is called the parallel resistance model of a PV cell, described using Eq. (1) [14], [15].

$$I = I_L - I_D - (\frac{V + IR_S}{R_P}) \quad (1)$$

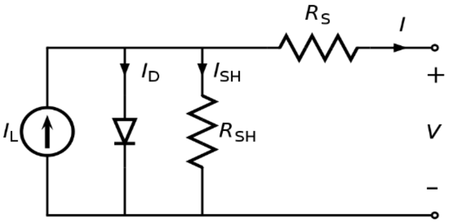

Figure 1. Equivalent circuit of a PV ell

Diode current (I_D) is described using Eq. (2).

$$I_D = I_0 \left(e^{\left(\frac{qV}{\alpha KT}\right)} - 1 \right) \quad (2)$$

Current resulting from irradiation is described using Eq. (4) [15].

$$I_L = \frac{G}{G_{ref}} \left(I_{L-ref} + \alpha_{Isc} \left(T_{cell-K} - T_{ref-K} \right) \right) \quad (3)$$

2.2. Maximum power tracking in PV array

Because the voltage-current characteristic of solar modules is affected by environmental factors such as temperature, the sun's radiation, and the load connected to it, by selecting the array's optimal working point, you can extract the maximum power. As a result, by employing maximum power point tracking techniques, the quantity of power received from the array can be kept at its maximum [16].

The P&O technique is utilized in this article to track the maximum operating point [17]. This algorithm's adjustments are done in such a way that if the output power increases after a slight variation in the operating point, the next changes should be made in the same direction.

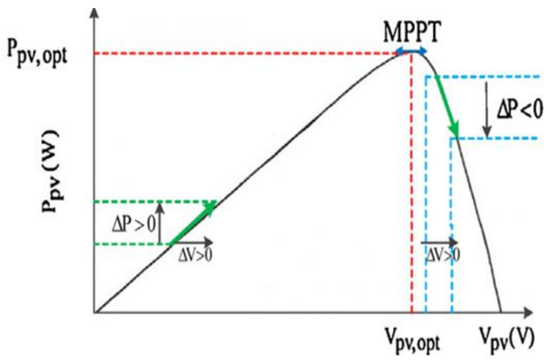

Figure 2. General rule of MPP tracking

According to Figure 2., the P&O method is modeled by the following terms.

If $\frac{dP}{dV} \approx 0$, then the operating point is on MPP.

If $\frac{dP}{dV} \succ 0$, then the operating point is on the left side of MPP.

If $\frac{dP}{dV} \prec 0$, then the operating point is on the right side of MPP.

Flowchart of the P&O method is shown in Figure 3.

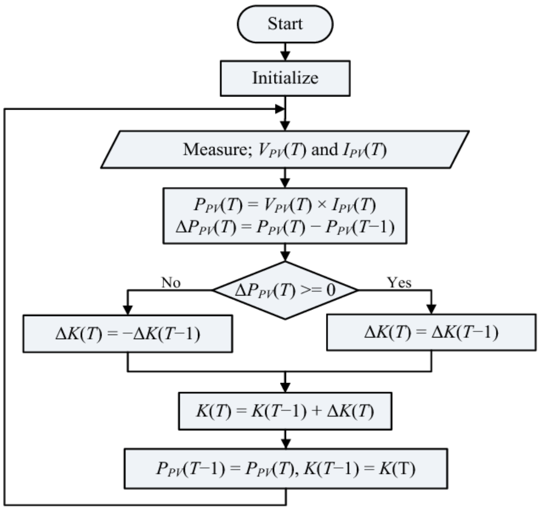

Figure 3. Flowchart of maximum power absorption in solar array based on P&O method

2.3. Modeling the Inverter of the PV unit

This article's electrical power converter is modeled using a three-lelvel IGBT bridge, and bandwidth modulation control. Figure 4. shows the control block diagram and how to link to the power electronic converter network. The inverter control system in this model consists of the five systems listed below:

2.3.1. The (P&O) approach is used to control the maximum power point tracking[17].
2.3.2. DC voltage regulator: current regulation and current extraction in static reference I_d and I_q [18].
2.3.3. Current regulator: a regulator of the inverter's reference voltage based on the static reference currents Id and Iq [19].
2.3.4. Phase lock lopp: used to synchronize the voltage and measure the network's current and phase [20].
2.3.5. Bandwidth modulation control: The fire angle of the IGBTs is determined by the required reference voltage. The carrier frequency in this case is set at 1980 Hz (60 x 33) [20].

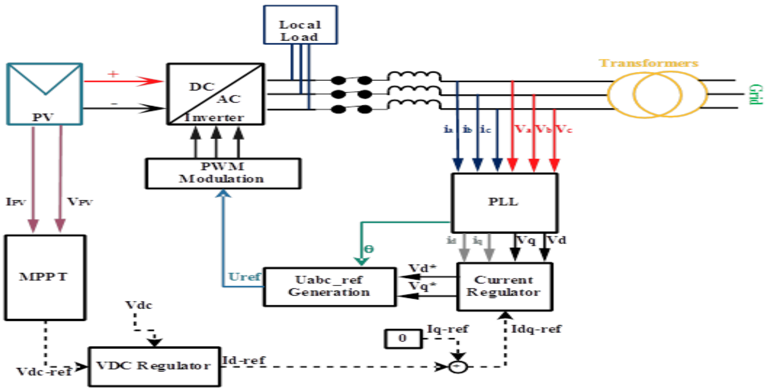

Figure 4. Block diagram of the inverter control system

III.THE METHOD PROPOSED TO IMPROVE POWER QUALITY OF THE HARMONICS RESULTING FROM NONLINEAR LOADS

One of the photovoltaic unit's characteristics is that its electronic power converter can be managed in such a way that the harmonic induced in the network by the non-linear demand is reduced. The harmonic of the entire network is also lowered using this strategy. In this article, an active filter is employed to decrease harmonics [21].

The non-linear load current should be measured in this regard, and the major component of its harmonics should be isolated. The nonlinear load current is initially transferred from the triple reference (abc) to the stationary frame (α-β). The nonlinear load current is calculated as the sum of the main frequency current and harmonics.

$$i_{L\alpha}=i_{L\alpha f}+i_{L\alpha h} \quad (4)$$

$$i_{L\beta}=i_{L\beta f}+i_{L\beta h} \quad (5)$$

($i_{L\alpha h}$ and $i_{L\beta h}$) and ($i_{L\alpha f}$ and $i_{L\beta f}$) are the harmonic and primary components of the nonlinear load current in these relationships. The harmonic components of the load current are determined by subtracting the value of the primary component of the nonlinear load current from the load current, according to Eq. (4) and Eq. (5). This method's block diagram is depicted in Figure 5.

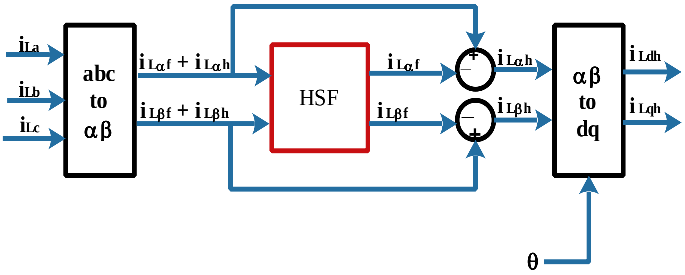

Figure 5. The active filter structure used to isolate the harmonic components

A high-pass filter (HSF) is used to separate the primary current component from the (α-β) components. The HSF transformation function is as follows [22].

$$\hat{H}(S) = \frac{\hat{i}_{\alpha\beta}}{i_{\alpha\beta}} = k\frac{(s+k)+j\omega}{(s+k)^2+j\omega^2} \quad (6)$$

In this equation, $i_{\alpha\beta}$ and $i_{\alpha\beta}$ are the filter's inputs and out pus, which are obtained as follows:

$$i_{\alpha\beta}(s) = i_{\alpha}(s) + ji_{\beta}(s) \quad (7)$$

$$\hat{i}_{\alpha\beta}(s) = \hat{i}_{\alpha}(s) + j\hat{i}_{\beta}(s) \quad (8)$$

According to Eq. (6), Eq. (7), and Eq. (8), the primary current component of the HSF outputs are obtained as follows:

$$\hat{i}_{\alpha}(s) = \frac{K}{S}\left[i_{\alpha}(s) - \hat{i}_{\alpha}(s)\right] - \frac{\omega}{S}\hat{i}_{\beta}(s) \quad (9)$$

$$\hat{\boldsymbol{i}}_{\boldsymbol{\beta}}(\boldsymbol{s}) = \frac{\boldsymbol{K}}{\boldsymbol{S}}\left[\boldsymbol{i}_{\boldsymbol{\beta}}(\boldsymbol{s}) - \hat{\boldsymbol{i}}_{\boldsymbol{\beta}}(\boldsymbol{s})\right] - \frac{\boldsymbol{\omega}}{\boldsymbol{S}}\hat{\boldsymbol{i}}_{\boldsymbol{\alpha}}(\boldsymbol{s}) \quad (10)$$

Where i_{α} and i_{β} are the primary current components, ω is the rated frequency, and K is a constant equal to 80 [23].

IV.SIMULATION AND RESULTS

4.1. Studied System

Figure 6. depicts the analyzed system's single-line diagram. This system consists of three distribution feeders, each of which is linked to a 13.8 kV bus (PCC). A 69/13.8 15MvA transformer connects the PCC to the main grid. The main network has a 69-kV voltage source with an X/R ratio of 22.2, and a rated power of 1000 MvA. The network is also powered by a 15MW capacitor bank. L1 to L5 are local linear loads.

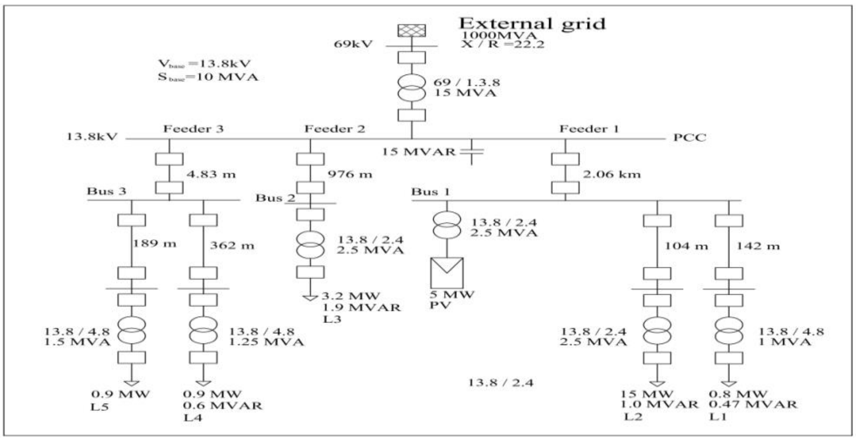

Figure 6. Single-line diagram of the studied system

The PV units with rated power of 5MvA is connected to PCC1 through a 13.8/0.575 transformer [24]. The PV panel modeled in this paper is a Y250C Yengli PV panel [25].

4.2. Simulation Results

In order to show the effect of the method used to reduce the harmonics of the electricity distribution network, two approaches 4.2.1 and 4.2.2 have been included in the simulation.

4.2.1. First approach, weather changes

In this paper, as can be seen in Figure 7, the daily solar radiation curve in the presence of passing clouds corresponds to the day of June 13, 2016 and the latitude of Esfahan province ("27.46'38°32 N). Also Figure 8 shows the average daily temperature modeled using satellite data [26] and [27] as the input data of the photovoltaic unit.

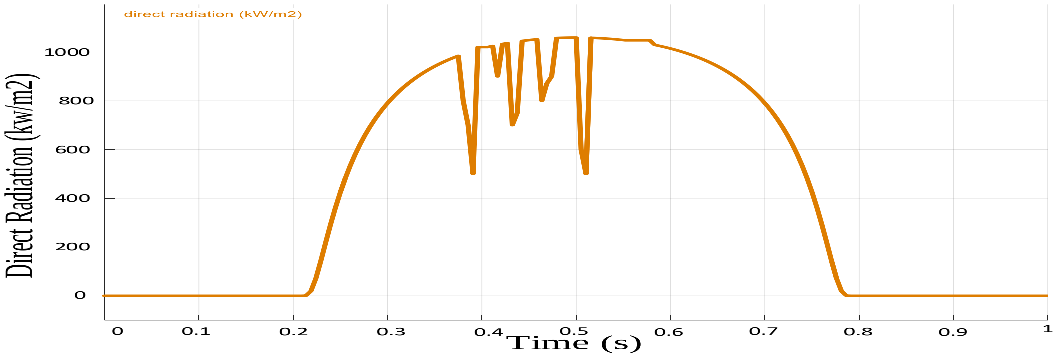

Figure 7. Daily solar radiation in the presence of passing clouds

Corresponding to June 13, 2016 and Esfahan province latitude

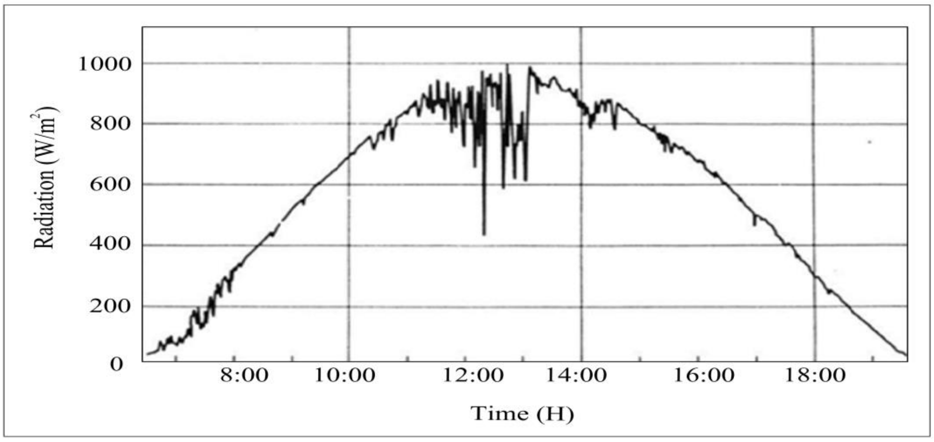

Figure 8. Daily temperature Corresponding to June 13, 2016 and Esfahan province latitude

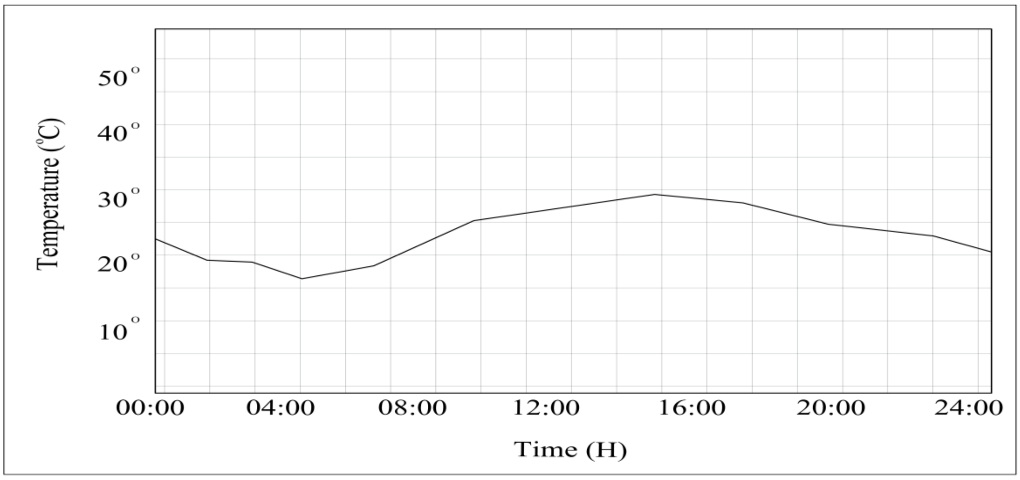

Figure 9. daily solar radiation in the presence of passing clouds in Simuling/Matlab (PV input)

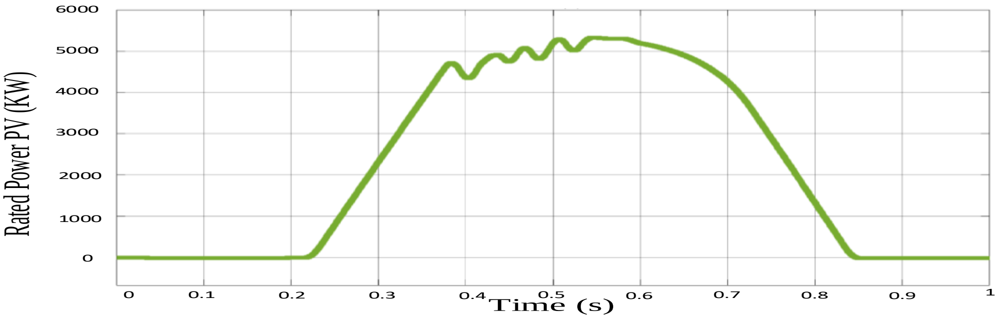

Figure 10. DC electric power of the PV unit

Figure 9. shows the solar radiation curves used as PV input. Also, the DC power of the PV units considering the variable inputs of temperature and solar radiation are given in Figure 10.

4.2.2. Second Approach, Reducing Network Harmonics

A nonlinear load is connected to the PV bus in the distribution system. The nonlinear load current is injected into the grid with a total harmonic distortion equal to 26.21%. Table 1. shows the harmonic characteristics of the nonlinear load.

Table 1. Harmonic characteristics of the nonlinear load

Harmonic order	Fundamental harmonic (60)	Fifth harmonic	Seventh harmonic	Eleventh harmonic	THD
Amplitude (%)	100	20	14.29	9.09	26.21

The harmonic characteristics of PCC and PV bus voltages before and after the proposed active filter are summarized in Table 2.

Table 2. Harmonic characteristics of the voltage waveforms with and without the proposed active filter

	Voltage of PV (%)		Voltage of PCC (%)	
Harmonic order	filter	WO filter	Filter	WO filter
Fundamental (60)	100	100	100	100
fifth	4.15	4.88	2.27	2.89
seventh	3.89	5.29	2.65	3.66
eleventh	0.15	0.19	1.52	1.9
THD (%)	6.79	8.04	3.82	5.05

According to Table 2, the fifth harmonics in the PCC and PV buses have been reduced by 1.2 and 1.1%, respectively, in the presence of the filter. Also, the 7th and 11th harmonics in PCC and PV buses have been reduced by 1.3, 1.3, 1.2 and 1.2%, respectively. The harmonic distortion coefficient (THD), the voltage of PCC and PV buses have also been reduced to 1.3% and 1.1%, respectively. Also, the harmonic characteristics of the current of PCC and PV buses before and after the proposed active filter are summarized in Table 3.

Table 4. Harmonic characteristics of the current waveforms with and without the proposed active filter

	Current of PV (%)		Current of PCC (%)	
Harmonic order	filter	WO filter	Filter	WO filter
Fundamental (60)	100	100	100	100
fifth	5.8	9.74	5.53	14.26
seventh	2.16	4.82	4.62	12.88
eleventh	1.96	3.79	1.65	4.25
THD (%)	6.50	12.12	7.59	19.89

In Table 3., the fifth harmonics of the current of the PCC and PV buses are shown, which are reduced by 2.5 and 1.6%, respectively, in the presence of the filter. Also, the 7th and 11th harmonics in PCC and PV buses have been reduced by 2.7, 2.2, 2.6 and 1.9%, respectively. The harmonic distortion coefficient (THD) of the voltage of the PCC and PV buses has also decreased to 2.4% and 1.8%, respectively.

V.CONCLUSION

In this article, the effect of using an active filter to reduce harmonics caused by photovoltaic sources and nonlinear loads has been evaluated. The proposed method, with its special control approach, has the necessary efficiency and accuracy to reduce grid harmonics despite the nonlinear load and nonlinear temperature and radiation curve of photovoltaic units. The simulation results show that using the proposed method reduces harmonics in two situations of nonlinear load or changes in weather conditions.

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