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Power Quality Analysis for Photovoltaic System Considering Unbalanced Voltage

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Abstract

Background/Objectives: Voltage unbalance is one of the most important power quality problems in distribution network. In this way, three phase Photo Voltaic (PV) system can increase voltage unbalance. **Methods/Statistical Analysis:** In this paper a three phase photovoltaic system with Maximum Power Point Tracking (MPPT) has been installed in an unbalance distribution network due to reduce Voltage Unbalance Factor (VUF). Also, a Dynamic Voltage Regulator (DVR) has been used to get better outcomes. **Results:** Results show that in the case in which load is balance and only network is unbalance, the system comprised of PV, MPPT and DVR can diminish VUF by 10%. Moreover, THD analysis is done and is obtained around 2.27%. This system is modeled in MATLAB/ SIMULINK. **Conclusion/Application:** Considering the benefits of using PV system for sustainable energy, utilizing MPPT and DVR can lessen voltage unbalance in distribution networks inclusive photovoltaic systems. First, output voltage waveform of three-phase photovoltaic system simulated in this paper with regard to existing controlling structure in PV system is balanced to radiation change (500 –1000W/m^2) in a good approximation and acts like a balanced three-phase source. Second, when this photovoltaic system approaches an unbalanced load which is located in an unbalanced network, the voltage imbalance decreases in that bus. Also when PV system gets further from the considered load, the impact of voltage imbalance reduction decreases in that load and also whatever the used photovoltaic system in the network is nearer to a special load, the imbalance compensating effect becomes more sensible. Also according to the performed simulations if there is a load which is sensible to the imposed voltage imbalance from network, PV-DVR system can be used for modify the observed voltage imbalance from network. It is worth noting that the PV-DVR system hasn't the ability to modify observed imbalance from network due to imbalance load. PV-DVR system in this paper has the ability to compensate voltage imbalance up to 10% and for more, the capabilities of both photovoltaic system and DVR must be added. In addition, or proposed network, FFT analysis is done. Therefore harmonic load flow illustrates the suggested photovoltaic system using PV-DVR is acceptable from harmonic distortion point of view. THD is obtained around 2.27% that is good value for PV-DVR system in comparison with 5% allowable standard value.

Keywords:

1. Introduction

Nowadays, fossil fuel resources have the largest contribution to generating electricity in the world. But problems such as the increasing price of these resources, the security issues of importing them from a small number of countries, environmental issues and climate changes due to the resulting pollution have challenged the essentiality of these resources for generating electrical power. Hence, the development of renewable energy sources and using new technologies of electricity generation are considered by governments.

Photovoltaic solar energy is a kind of renewable and clean energy which is highly reliable and sustainable. Solar energy through photovoltaic systems is directly converted into electric power and there is no need of using interface procedures. Photo cell and module production have had considerable proliferation in recent years, totally reaching to 2500 MW in the year peak. Also there are some problems in power distribution. The existing problems

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in distribution networks in power quality point of view could be discussed from two perspectives; network and consumer. In network view, the consumer is causing turbulence in the network and creates phenomena like flicker, imbalance load in which unbalanced current takes happen, and non-linear loads which receives harmonic currents from the network. These turbulences have adverse effects on consumers and network equipment. In the other hand, consumers believe the turbulence is imposed by the network and it creates other phenomena such as voltage imbalance, voltage harmonic turbulence, voltage sag, disruption, frequency deviation etc. Meanwhile, voltage and current imbalance are one of the most important issues of power quality in low voltage distribution networks[1].

Voltage imbalance can have adverse consequences on electrical equipment and power systems. In case of voltage imbalance, the power network sustains more losses and also less stability[2,3]. Given that in reality, the utilization of distribution network results in voltage imbalance, IEC the standard, 2% voltage imbalance has been proposed for electrical systems[4]. In study [5], some methods include positive/negative phase shift sequences, voltage drop curves, distance effect, unbalanced voltage drop sensitivity and combinations of different line configurations supported by these methods of analysis, general guidelines and recommendations for phase load arrangement are found to reduce voltage imbalance and excessive voltage drop for a certain phase. This provides a direction for network adjustment rather than guessing the way of modification by checking numerous load flow results. In Some studies new algorithms for maximum power point tracking has been presented. In study [6], two large Photo Voltaic (PV) systems has been use to demonstrate effectiveness of Load Power Controller (LPC) for the enhancement of loading balance in a Taipower distribution system. Results show that the loading balance of distribution systems with intermittent PV power generation can be obtained effectively by the implementation of LPC to achieve adaptive control of load transfer between distribution feeders. The power loss reduction of test feeders after loading balance by LPC has also been derived in this paper.

In study [7] different high frequency switching methods for multilevel inverters which has been proposed for PV applications is analyzed; furthermore, the output harmonics content of Phase Shifted PWM (PSPWM) and In Phase Disposition PWM (IPDPWM) switching methods are comprised. Study [8] presents a new approach of the Design and simulation of a photovoltaic cell using decrement resistance algorithm for Maximum Power Point Tracking (MPPT). The algorithm detects the maximum power point of the PV cell. It includes module BP SX 150S for a solar photovoltaic. This paper claims that the proposed algorithm is better than IncCond algorithm due to easy determination and implementation. According to presented descriptions, this paper tries to benefit from the combination of three-phase photovoltaic systems with MPPT and DVR (Dynamic Voltage Restorer) converter to modify voltage imbalance in a typical distribution network. For this purpose, at first a rather general model is used for three-phase photovoltaic system with maximum power point tracking, in which some environmental indicators such as instant power received from the sun and environmental temperature are involved. Then the effect of photovoltaic system on voltage imbalance compensating is investigated on a typical distribution network. In the next step, a combination of photovoltaic system and DVR converter is applied to an unbalanced distribution network. It can be seen that voltage imbalance in a considered network is modified and degrades to the standard defined level. All simulations are performed in the MATLAB/SIMIULINK.

2. Photovoltaic Systems and Voltage Imbalance

In this section, mathematical relations, structure of three phase photovoltaic systems with MPPT, control system and voltage imbalance is discussed.

2.1 Photovoltaic System with MPPT

The word "photovoltaic" is comprised of two words "photo" meaning light and "voltaic" meaning electricity generation. The solar energy moves free electrons in atoms of semiconductor material applied in solar cells, and the current of electron movements through the matter generates electricity. This direct procedure of converting light to electricity is called photovoltaic[9]. Photovoltaic cell is described by Equation 1 neglecting the shunt resister.

$$I=I_{ph}-I_0\,(exp(q(V+IR_s)/KTm-1) \tag{1}$$

where k, m, T and q represent Boltzmann's constant, the ideality factor of the diode, absolute temperature of the cell and electron charge, respectively. The darkness saturation current of the cell is also represented by I_0, I_{ph} and R_s represents cell photocurrent and internal resistance of the cell respectively[7]. Using MPPT the maximum of possible electric power is extracted from the photovoltaic array, a task which is performed by displacement of electrical work of PV array by a DC-DC converter. This converter changes the level of the working voltage to reach the maximum power. Two common methods have been used which aim for maximum power in photovoltaic systems: the Perturb and Observe (P&O) method and the Incremental Conductance (INC-COND) method[10]. Because of simple operation and higher running speed, the P&O method, is used in this paper. In Figure 1 the architectural model of a Boost converter is presented. Given that the change of Duty cycle (D) is used to control output power, the controlling operation contains a Boost converter[11]. Figure 2 shows method operation flowchart. The output power of PV is measured and if less than instant power, D will be decreased, otherwise the amount of D would be increased. In the following flowchart Duty$^+$ means increasing in amount of D and Duty$^-$ means decrease of it.

In relation 2, V_{in} and V_{out} are input and output voltages of converter D respectively in switching time of S; it is assumed that converter is ideal, so relation 3 is obtained.

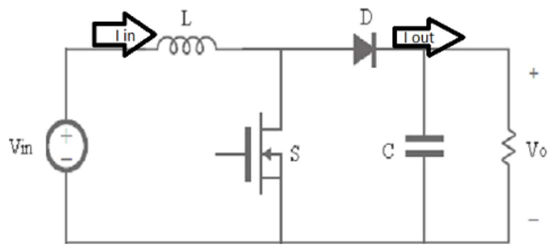

Figure 1. Circuit model of a Boost converter.

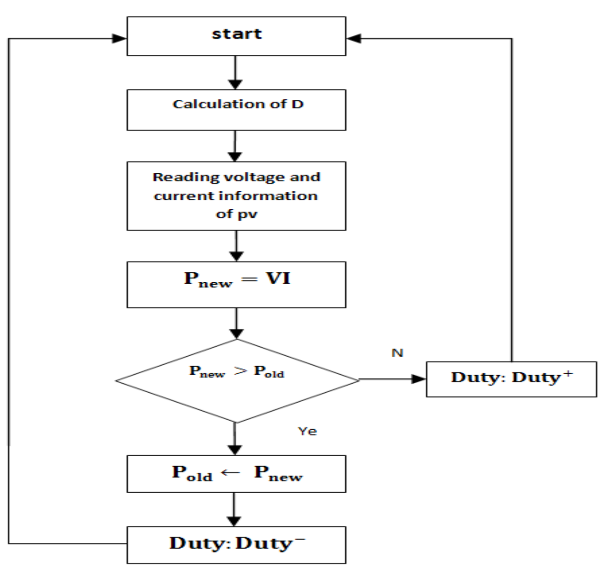

Figure 2. The output power calculation flowchart of PV.

Where D is duty cycle and defined as percentage of one period in which a signal is active.

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \tag{2}$$

$$I_{out} = I_{in}\left(1-D\right) \tag{3}$$

Relation 4 states, if load (R_{out}) was constant; it is possible to set the amount of E in a way that load achieve the maximum power.

$$\mathrm{R_{in}} = \frac{\mathrm{V_{in}}}{\mathrm{I_{in}}} = \frac{\mathrm{V_{out}}}{\mathrm{I_{out}}}\left(1-\mathrm{D}\right)^2 = \mathrm{R_{out\left(1-D^2\right)}} \tag{4}$$

2.2 Voltage Imbalance

Electrical energy losses due to remarkable damages which it imposes to power industry are considered by power industry experts and its harmful effect in network requires to be analyzed to determine the practical procedures of its reduction. One factor of energy loss which occurs usually in network distribution is voltage imbalance which it is possible to take positive steps of losses reduction with adjusting it[1]. Electrical power losses appear from load imbalance in distribution networks. These networks have various loads; industrial, domestic, commercial and the biggest portion of them one-phase loads[12]. Increasing in loss, energizing of neutral point of network, warming electrical motors and transformers and saturation of magnetic cores are some examples of load imbalance adverse results[13]. European standards, define the voltage unbalanced factor Voltage Unbalance Factor (VUF) as the ratio of negative voltage sequence (V^-) to positive voltage sequence (V^+) as shown in relation 5. Positive, zero and negative sequence of voltage are convertaed to V_a, V_b and V_c which are three-phase line voltages as shown in relation 6 and V^+, V^0 and V^- are the voltage elements of positive, zero and negative sequences.

$$VUF\left(\%\right) = \frac{V^-}{V^+} \tag{5}$$

$$\begin{bmatrix} \mathrm{V_a} \\ \mathrm{V_b} \\ \mathrm{V_c} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \mathrm{a} & \mathrm{a}^2 \\ 1 & \mathrm{a}^2 & \mathrm{a} \end{bmatrix}\begin{bmatrix} V^0 \\ V^+ \\ V^- \end{bmatrix} \tag{6}$$

2.3 The Usual Methods of Modifying Voltage Imbalance in Distribution Systems Containing a Photovoltaic System

Problems casing voltage imbalance are divided in two categories; structural and operational factors. Three methods will be discussed in this section to improve current. The first of all is increasing of feeder cross section. This leads voltage sag reduction in feeder, so causes a low difference in three-phase voltage amplitude at the end of a feeder. Results of statistical studies are shown in Figure 3 for two different cross sections, 70 and 95 mm. As can be seen, Voltage Unbalance (VU) is decreased from 1.84 to 1.56% in the feeder terminal[14]. The second effective method is to install switched capacitors in low pressure feeders. Based on IEEE guideline for using parallel power capacitors, in distributed uniform loads, the capacitor must be installed at 2/3rd distance to the distribution transformer. It is essential to note that if a three-phase capacitor is installed on a low pressure feeder, voltage imbalance will remain the same. But if three one-phase switching capacitors are used while only an one-phase capacitor is connected to the phase in which voltage amplitude is lower than 0.95 pu, if correct instruction is used to adjust the capacitor, voltage profile on that phase can be reduced and reached to an amplitude near to voltage amplitude of other phases. In this case, the voltage imbalance can be improved as well. Monte Carlo results for these materials are shown in Figure 3 in part b and it shows while a capacitor 15 KVAR with the described features is installed at 2/3 of feeder length from its beginning, VU decreases from 0.36% to 0.28% in the beginning of the line and from 1.84% to 1.41% in the end of the line. The same methods could be used to find the best place for capacitor installation. The last method to improve current is a combination of the two previous ways, the capacitor installation and the increase of feeder cross-section. VU improvement in this method has remarkable results compared to using these methods separately. In the examined case, VU has been decreased from 1.84% to 1.18% at the end of the feeder which is shown in Figure 3 in part c.

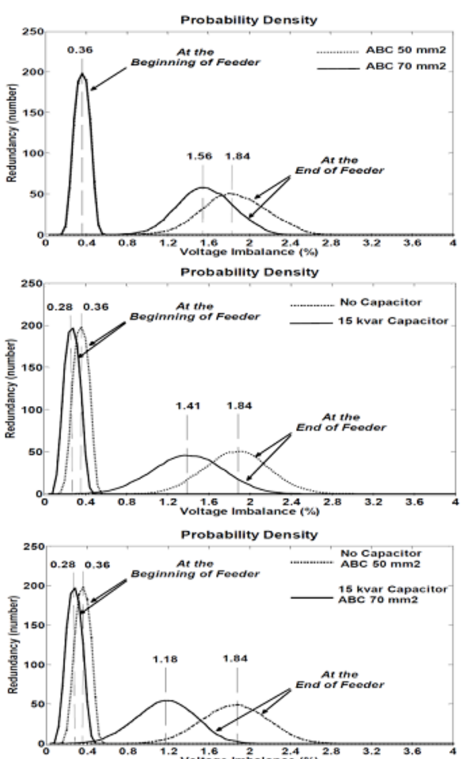

Figure 3. Probability density function of the feeder end a) the increase of cross-section, b) capacitor installation, c) the both combination a&b.

3. Modeling

In this section, simulation block of three-phase photovoltaic system with MPPT block is addressed. In Figure 4, the system outline is given and Figure 5 shows

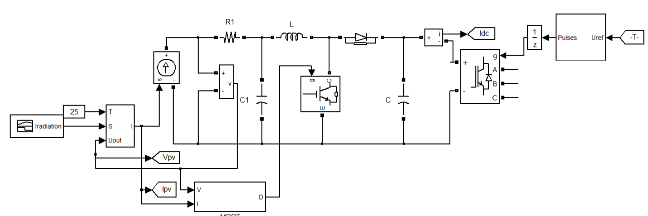

Figure 4. The general simulation block of photovoltaic system along with the maximum power point tracking system.

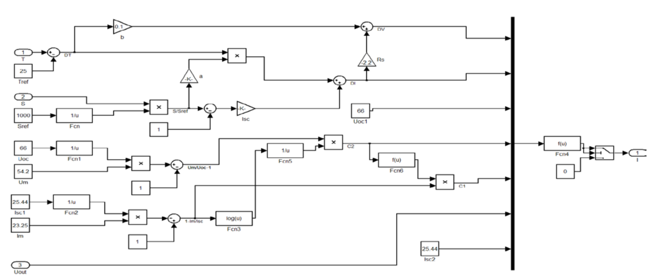

Figure 5. The block related to the entrance of photovoltaic system.

the contents of photovoltaic system block based on the general relation governing the system. It is noteworthy that temperature and the amount of radiation are assumed to be at 25°C and 1000 W/m^2 respectively.

3.1 Block Structure and MPPT Block

In this section, the block related to maximum power point tracking system is simulated identically based on the P&O technique. To explain further, the possible maximum electric power from photovoltaic array is obtained using MPPT, and this task is performed by electrical work point displacement of PV array by Boost converter. In Figure 6, the system's internal schema is given according to the mentioned algorithm. The output of photovoltaic system block consists of an inverter that converts output DC voltage from Boost converter to AC voltage. To calculate voltage imbalance, the quantitative factor of voltage imbalance (VUF %) is used which is equal to the ratio of voltage negative sequence to voltage positive sequence. According to Figure 7 at first the considered bus three-phase voltage sampling is performed. Also as it is shown in Figure 9, first three phases A, B, C is converted to positive,

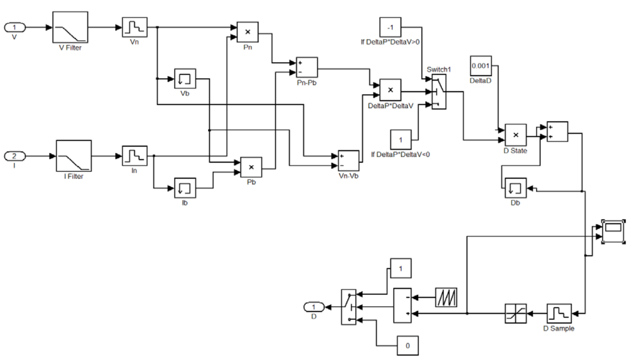

Figure 6. The block related to MPPT system.

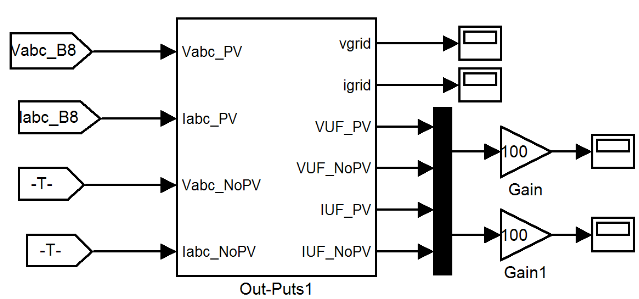

Figure 7. Outline of the calculation block of voltage imbalance factor.

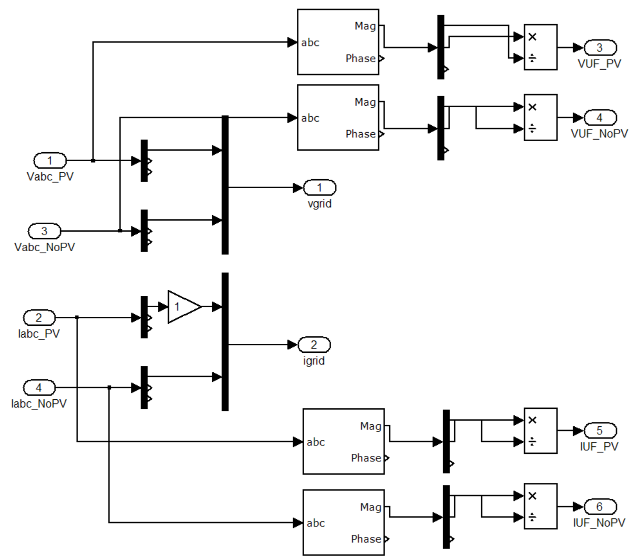

Figure 8. Internal scheme for the calculation block of voltage imbalance factor.

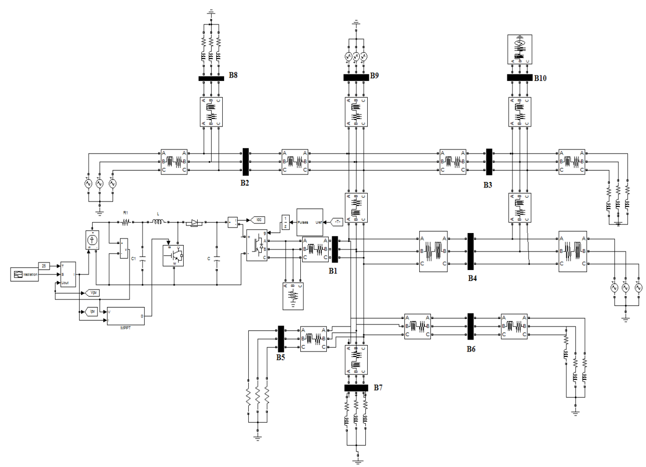

Figure 9. The connection of photovoltaic system to the bus number 1.

negative and zero sequences and then voltage imbalance factor is obtained from the division of negative sequence value to positive sequence value of three phase voltage.

4. Analysis and Simulation of Voltage Imbalance Factor for the Proposed Network

Photovoltaic system is connected to the network in Figure 9, the connection of photovoltaic system to the bus number 1 is shown and so photovoltaic system is connected to buses, number 2 and number 8 respectively.

Figures 10, 11 and 12 show the amount of voltage imbalance in the bus number 8 after the connection of photovoltaic system to buses number 1, 2 and 8 respectively. As it is clear from the simulation results, the voltage imbalance factor in the bus 8 is decreased by connecting photovoltaic system. Moreover, sensible reduction is observable when this system is connected to the same bus which VU is measured on it. Also, according to the obtained results it is observable that with increasing in distance of photovoltaic system from the considered bus which is been observing for more than the bus 1, this system has no remarkable change in voltage imbalance with respect to the bus 1. Hence the calculation of voltage imbalance has been neglected for other phases. As it is shown in Figures 10, 11 and 12, the voltage imbalance factor in the bus number 8 in a stable state is equal to 2.54%, 2.48% and 1.98% respectively.

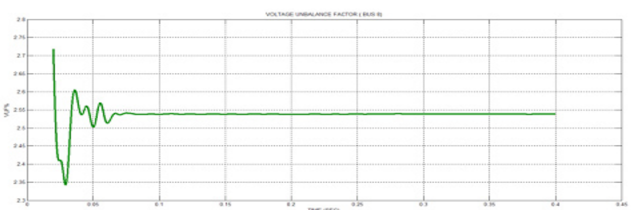

Figure 10. The amount of voltage imbalance in the bus number 8 after connecting of photovoltaic system to the bus 1.

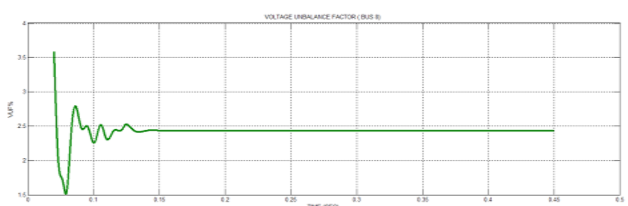

Figure 11. The amount of voltage imbalance of the bus number 8 after the connection of photovoltaic system to the bus number 2.

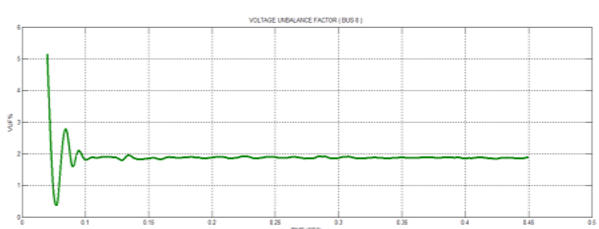

Figure 12. The amount of voltage imbalance in the bus number 8 after the connection of the photovoltaic system to the bus number 8.

5. Presenting PV-DVR Structure to Decrease Voltage Imbalance Factor

This section tries to simulate and investigate a more efficient structure for compensating voltage imbalance.

It is expected that in unbalanced network, consumers would not suffer by using this structure. According to the above explanation, the bus bar number 8 in Figure 13 is considered as the feeding location of PV-DVR system. Now for comparison, at first an infinite bus bar that has a voltage imbalance and is representative of an unbalanced distribution network is connected to a set of photovoltaic system and DVR. It appears that the balanced load which is located after this structure doesn't recognize the source to have any imbalance. However, two phases of three phase source three phases have about 10% voltage imbalance. As it could be seen in Figures 14 and 15, voltage wave form in bus number 13 has the voltage imbalance of 8% and after using the PV-DVR system, the voltage imbalance level decreases to zero. It is noteworthy that the above system has an ability to modify voltage imbalance up to 10%.

For proposed network, Fast Fourier Transform (FFT) analysis is done. Therefore harmonic load flow illustrates

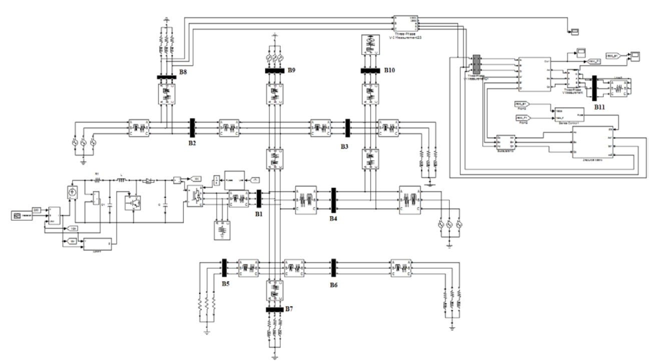

Figure 13. The connection of PV-DVR system to a typical distribution network.

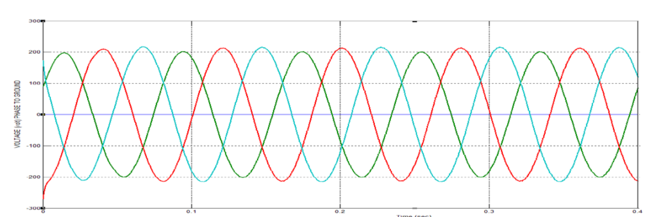

Figure 14. Unbalanced supply voltage waveform before the connection of PV-DVR system to the typical distribution network.

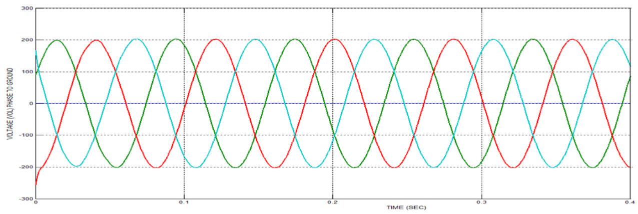

Figure 15. Balanced load voltage waveform after the connection of PV-DVR system to the typical distribution network.

the suggested photovoltaic system using PV-DVR is acceptable from harmonic distortion point of view. For this aim, Total Harmonic Distortion (THD) formula is used according to relation (6):

$$THD_F = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1} \tag{6}$$

In relation (6), V_n, $n = 1,2,3,\ldots$ is the RMS voltage of n^{th} harmonic and $n = 1$ is fundamental frequency[15].

THD is obtained around 2.27% that is good value for PV-DVR system in comparison with 5% allowable standard value.

6. Conclusion

First, output voltage waveform of three-phase photovoltaic system simulated in this paper with regard to existing controlling structure in PV system is balanced to radiation change (500-1000 W/m^2) in a good approximation and acts like a balanced three-phase source. Second, when this photovoltaic system approaches an unbalanced load which is located in an unbalanced network, the voltage imbalance decreases in that bus. Also when PV system gets further from the considered load, the impact of voltage imbalance reduction also decreases in that load and also whatever the used photovoltaic system in the network is nearer to a special load, the imbalance compensating effect becomes more sensible. Also according to the performed simulations if there is a load which is sensible to the imposed voltage imbalance from network, PV-DVR system can be used for modify the observed voltage imbalance from network. It is worth noting that the PV-DVR system hasn't the ability to modify observed imbalance from network due to imbalance load. PV-DVR system in this paper has the ability to compensate voltage imbalance up to 10% and for more, the capabilities of both photovoltaic system and DVR must be added.

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