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Multi Units of Single Phase Distributed Generation Combined with Battery Energy Storage for Phase Power Balancing in Distribution Network

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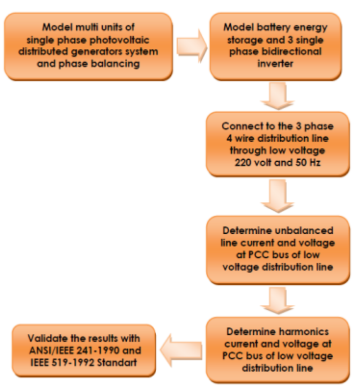
Graphical abstract



Abstract

Randomly installed distributed generators (DGs) in households may cause unbalanced line current in a distribution network. This research presents a battery energy system for balancing of line current in a distribution network involving multi units of single phase photovoltaic (PV) distributed generators (DGs). In this paper, the PV generators were simulated consisting of a buck-boost DC/DC converter and single phase DC/AC inverter. It was connected to the distribution line through the low voltage 220 volt 50 Hz. The proposed phase balancing system uses battery energy storage and three single phase bidirectional inverters. The inverter is capable of injecting current or absorbing power from the line to the battery. This inverter operation is arranged to balance each distribution line separately, as well as to improve other power quality parameters, such as voltage and current harmonics. Simulation results show that the system was capable of improving the unbalanced line current from 15.59 % to 11, 48 % and unbalanced line voltage from 1.76 % to 0.58 %. The system was able for increasing current harmonics from 0.98 % to 1.03% and voltage harmonics from 38.96% to 39.08%.

Keywords: Single Phase Photovoltaic, Battery Energy Storage, Phase Power Balancing, Power Quality

1.0 INTRODUCTION

Energy can be stored on a large scale e.g. using dams for water or reservoirs for oil/gas. Ideally, the electrical energy produced, should be distributed to customers. Unfortunately, photovoltaic (PV) energy has to be stored, because this energy is not capable of being produced at night or periods of cloudy days. Energy storage then becomes an important thing to ensure the power supply continues over time. The most widely used as a storage for PV systems is the battery bank, because it is inexpensive and simple to manufacture, reliable, and well understood technology, when used appropriately and correctly, is durable and provide dependable service. Battery energy storage is used to smooth the output fluctuations of the entire system of hybrid PV and battery. One of the most important factors for the studied PV based distributed generation (DG) is in terms of efficiency are: (i) it can directly convert PV power to the electricity system; (ii) it can extract stored energy from batteries if PV power is insufficient, and (iii) it can store energy into batteries, if the PV power is abundant [1]. There are two models of PV generator connected to the distribution network or grid, namely: (i) single phase PV generator is connected into the three phase four wire grid through a three phase DC/AC inverter and (ii) multi-unit of single phase PV generator is connected at random into the three phase four wire grid through a single phase DC/AC inverter. The existence of DG in the form of a single phase PV generator of households scale randomly inserted in a community can cause unbalance phase power in the distribution network.

Research on the modeling and improving the quality of grid connected PV generation/ battery system have been proposed. Researchers investigated PV array connected to the grid through a buck-boost DC/DC converter and optimized the output of PV using mppt and DC/AC inverter [2]. Other quality improvement methods such as the use of multilevel inverters are also proposed by researchers [3]. Method of phase power balancing for diesel generator hybrid has been proposed by researchers [4]. Unbalanced power in every phase is compensated by varying the power for charging batteries. Under power loaded is increased by higher power of battery charging. However, the system only discussed on power balancing and did not focus on the unbalanced voltage. Phase power method to balance the use of artificial intelligent in the hybrid system of diesel generator-battery has been done [5]. Unbalanced current and voltage is controlled by four arms inverter, which is supplied by batteries or renewable energy sources. Research on modeling and analysis of single-phase PV generator, connected to the three-phase four-wire grid, through three phase DC/AC inverter supplied battery energy storage has been done. However, in this study there was no detailed discussion on methods to balance the current and voltage phase between PV generator and grid [6]. Research on the battery energy storage to regulate the balance of power between PV generator and non-linear load connected grid considering power quality parameter at the point PCC bus has been carried out by [7]. The weakness of this study only considers the impact of integration system of PV/battery hybrid against current harmonics.

The paper presents to balance of phase current and voltage due to the presence of multi-unit of single phase PV distributed generators (DGs) installed in large quantities at random in the three phases four wire distribution networks. The proposed system use the battery energy storage and three single phase bidirectional inverter for improving power quality issues. Power quality parameters studied are the voltage and current unbalanced, as well as harmonics.

2.0 METHODOLOGY

Figure 1 shows the proposed model of multi units of single phase PV distributed generators system and phase balancing with battery energy storage. It is connected to the three phase four wire distribution line through the low voltage 220 volt and 50 Hz. The circuit consists of multi circuit models numbering four single phase PV generators, a buck-boost DC/DC converter, and single phase DC/AC converter (Figure 1). The circuit is then combined with battery energy storage and subsequently entered into the distribution network through three single phase bidirectional inverter. A maximum power point tracking (MPPT) is attached in the PV generator to maximize the power, while the 3-phase bidirectional inverter regulates the battery energy storage for injecting or absorbing current from the network. Analysis of unbalance line current and unbalance line voltage carried on point of common coupling (PCC) bus refers to the ANSI/IEEE 241-1990 Standard.

This research also investigates impact of integration of four single phase PV distributed generators supplied battery energy storage to power quality (harmonics current and voltage) on the side of three phase four wire distribution network. Power quality analysis is performed by determining Total Harmonic Distortion (THD) of current and voltage on the PCC bus of distribution network. Harmonics values are compared against voltage and current THD is based on the IEEE Standard 519-1992 as the basis to determine level of power quality in the proposed model. Analysis of current unbalance, voltage unbalance, and power quality is performed before and after four single-phase PV generators combined with battery energy storage through three single phase bidirectional inverter. Circuit breakers (CBs) are added to realize the operation mode of this system.

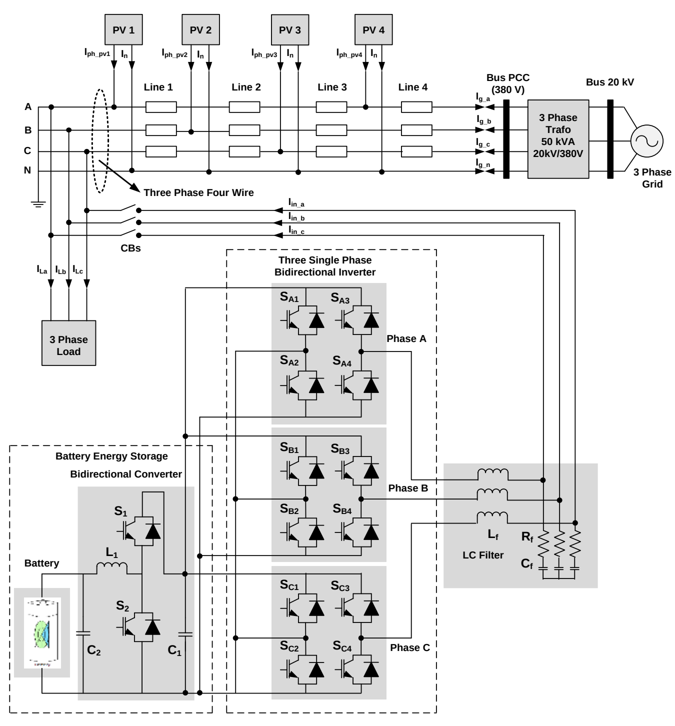


Figure 1 Proposed model of multi units of single phase PV distributed generators for phase power balancing with battery energy storage

2.1 Photovoltaic Array Model

Photovoltaic cells consist of a p-n junction made in a thin wafers or layers of semiconductors. There are a number of types of solar cells made of different materials. The material is usually monocrystalline or polycrystalline silicon. The ideal solar cell is the one which current source is connected in antiparallel with a diode as shown in Figure 1. When the cells exposed to sunlight, the direct current generated which value varies linearly with solar radiation. The model can be developed, including the effect of shunt resistance and series resistance. The equivalent circuit of the single diode model for PV cell is shown in Figure 2 [6].

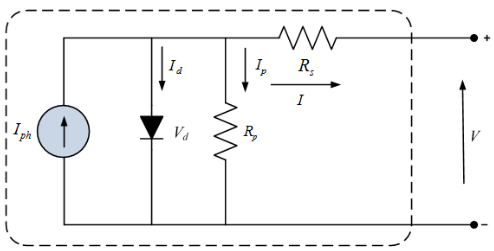


Figure 2 Equivalent circuit of photovoltaic cell based on single diode model

The output current of PV panel can be derived from Kirchhoff's laws, as expressed in the equation $I_{PV} = I_{ph} - I_d - I_p$ where I_{PV} is the cell current, I_{ph} is the photocurrent, I_d is internal diode current, and I_p is the shunt current passes through the p-n junction. PV module consists of several PV cells connected in parallel or series depending on power of PV modules. The power of a PV module is limited to a few hundred watts. When higher power is required, the PV modules connected in series and parallel to obtain the PV array. The theoretical model of PV array developed from single PV cell. The general equation of current and voltage of the solar cell is given as follows:

$$I_{PV} = I_{ph} - I_d - I_p = I_{ph} - I_o\left[e^{\left(\frac{qV_d}{KFT}\right)^{-1}} - 1\right] - \frac{V_d}{R_p} \quad (1)$$

Where, I_o is saturation current, V_d is diode voltage is expressed in volts, K is Boltzmann constant, F is PV cell ideally constant, q is number of electrons, T_{PV} is temperature of the cell, R_s is series resistance, R_p is parallel resistance. The equivalent circuit of PV cells arranged in parallel N_P and N_S series is shown in Figure 3 [6], the current and voltage PV array becomes:

$$I_{PV} = N_p I_{ph} - I_o\left[e^{\left(\frac{q\left(\frac{V_d}{R_s} + \frac{IR_s}{R_p}\right)}{N_s KFT_{PV}}\right)^{-1}} - 1\right] - \frac{N_p V_d / N_s}{R_p} \quad (2)$$

Where N_p shows the number of modules in parallel. Notes that each module consist of N_s cells connected in series. N_s, I_{ph} related to short circuit current of PV array

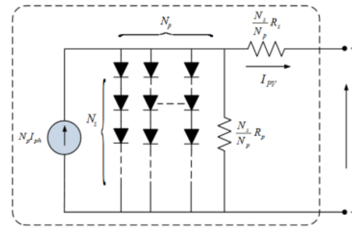


Figure 3 Electrical equivalent of solar array circuit

2.2 Battery Model

Battery is the main storage technology used in PV systems. Various types of battery models have been developed for different application fields. For example, the electrochemical models are used in the design of batteries. The models describe the battery in its very detail using a set of six coupled differential equations. Another example is the electrical circuit's models in electrical engineering, which focus on the electrical properties of the batteries. Although these models describe the battery accurately. A simple equivalent battery is shown in Figure 4 [6]. A various models show predicts battery behavior to varying degrees of accuracy. The circuit models of the internal resistance and transient behavior of the battery using the series and two branches of RC circuit.

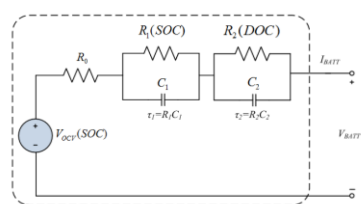


Figure 4 Equivalent circuit of 2nd order Randle model

Figure 4 [6] shows a second order Randle model circuit where R_o is the internal resistance of the battery's terminal and inter-cell connections. The other resistances and capacitors are used to model the cell dynamics. The battery model takes into account of the battery state of charge *(SOC)* and the deep of charge *(DOC)*. Where, the first branch R_1 and C_1 is associated with the battery's *SOC*, the second branch R_2 and C_2 is associated with the battery's *DOC*. Furthermore, the second order Randle models voltage generator *(V_{OCV})* models the open circuit voltage (which is a voltage of the cell when it is rested) as a function of *SOC*. It depends on the *SOC*, temperature, and also the design of devices. The battery voltage is expressed as follows;

$$V_{BATT} = V_{OCV}(SOC) - I_{BATT}\left(R_0 + \frac{R_1}{1+sR_1C_1} + \frac{R_2}{1+sR_2C_2}\right) \quad (3)$$

$$V_{BATT} = V_{OCV}(SOC) - I_{BATT}R_0 - I_{BATT}\left(\frac{K(1+sK_1)}{(1+sK_2)(1+sK_3)}\right) \quad (4)$$

$$R_1 = R_{10}e(-K_1(1-SOC)) \quad (5)$$

$$R_2 = \frac{R_{20}}{DOC} \quad (6)$$

$$SOC = 1 - \frac{1}{C_n}\int I_{BATT}\,d\tau \quad (7)$$

$$DOC = 1 - \frac{1}{C(i_{avg})}\int I_{BATT}\,d\tau \quad (8)$$

Where V_{BAT} is battery voltage V, V_{OCV} is battery voltage generator V, I_{BAT} is battery current A, SOC is the state of the charge of the battery, DOC is the deep of the charge of battery, C_n is the battery capacity, $C\ (i_{avg})$ is the current dependent battery capacity, E_0 is the open circuit voltage when the battery is fully charge, R_{10} is the first RC branch constant in Ω, $\tau 1$ is the first RC branch time constant in sec, $K1$ is a constant, R_{20} is the second RC branch constant in Ω, $\tau 2$ is the second RC branch time constant in Ω.

2.3 Battery Energy Storage

Battery energy storage consists of two parts, a battery and a bidirectional converter circuit. Bidirectional converter is a converter that is capable of raising and lowering the voltage in both directions. When bidirectional converter uses to charge the battery energy storage, bidirectional converters is operating on buck mode or lowers the voltage. When bidirectional converter uses to discharge the battery energy storage, bidirectional converters is operating as boost mode or raises the voltage. Bidirectional converter has two switches which are used to turn buck or boost mode and change the direction of current flow charging and discharging the battery energy storage. Battery energy storage circuit is shown in Figure 5. Equation 9 and 10 are used to model bidirectional converter in continuous Conduction Mode [8, 9].

$$L = \frac{V_o(V_{DC} - V_o)}{\Delta I_L F_s V_{DC}} \quad (9)$$

$$C_{2(\min)} = \frac{\Delta I_L}{8F_s\Delta V_o} \quad (10)$$

In this paper, the battery energy storage functions to balance line current and voltage in three phase four wire low voltage 220 volt 50 hz distribution network by compensating the unbalance current of each phase. The operation of battery energy storage is regulated according to energy management system before and after connected to three phase four wire low voltage distribution network. The PCC voltage distribution network is fixed by utility grid. The battery energy storage functions to balance the power of each phase so that the grid still supplies the balance power to three phase four wire low voltage distribution network [9].

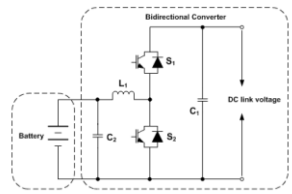


Figure 5 Model of battery energy storage

2.4 Single Phase PV Generator Model

Figure 6 shows the model of single phase PV generator [10]. The circuit consists of PV array, boost-buck converter circuit, and single phase DC/AC full bridge inverter. A boost-buck type DC/DC converter is proposed as the first stage with regulated output current inductor and full bridge circuit with the line frequency of 50 or 60 Hz is applied on DC-AC stage, which generated a pure sinusoidal current. The circuit operates either in boost and buck mode. Since only the boost DC/DC converter operates with high switching frequency all the time in proposed system, the efficiency is improved [11]. And because of that equipment is only one high frequency power processing stage in personal computer (PC), the reability can be greatly increase [12].

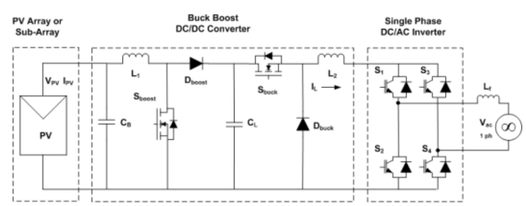


Figure 6 Single Phase PV Generator Model

2.3 Voltage and Current Unbalance

There are several standards that can be used to determine the level of voltage unbalance in three-phase systems, e.g. IEC, NEMA, and IEEE. In this study, the value of unbalance voltage use Equation 11 is based ANSI / IEEE 241-1990 standard [14] as follows:

$$V(\%) = \frac{\left|V_{a\,varage} - V_{a,b,c\,minor\,max}\right|}{V_{a\,varage}} \times 100\% \quad (11)$$

By using Equation 11, value of unbalance voltage expressed in percent (%) and is defined as follows; $V_{avarage}$ is the average value of maximum voltage on phase a, b, c, (volt), $V_{a,b,c\ min}$ is minimum voltage on phase a, b, c, (volt), $V_{a,b,c\ max}$ is maximum voltage on phase a, b, c (volt). By using the same equation, then the percentage of unbalance current can be calculated by replacing the voltage magnitude into the current magnitude.

3.0 RESULTS AND DISCUSSION

Table 1 shows devices, parameters, and design values of simulation data multi units of single phase PV with battery energy storage.

Table 1 Simulation Data

Devices	Parameters	Design Value
Each single phase PV generator	Active Power	0.6 kW
	Temperature	25^0 C
	Irradiance	1000 W/m^2
Three phase grid	MVA_{SC}	100 MVA
	Voltage (L-L)	380 volt
	Frequency	50 Hz
Transformer	Power	50 kVA
	Voltage	20/380 kV
	Frequency	50 Hz
Three phase load	Active Power	1 kW
	Voltage	380 Volt
	Frequency	50 Hz
Low voltage distributed line 3 phase 4 wire	Resistance	R = 0,1273 Ohm
	Inductance	L = 93,37 mH
	Capasitance	C = 0,1274 µF
LC filter	Resistance	R = 2 Ohm
	Inductance	L = 10 mH
	Capacitance	C = 10 µF
Battery	Type	Nickel Metal Hibrid
	DC Voltage	400 V
	Rated Cap.	100 Ah
	Initial SOC	100%
Bidirectional Converter	Inductance	6 mH
	Capacitance 1	200 µF
	Capacitance 2	200 µF
	Switching Freq.	4 kHz
	Mod. Index	0.8
	Frequency	50 Hz
Three single phase Bidirectional inverter	Switching Freq.	4 kHz
	Mod. Index	0.8
	Frequency	50 Hz

Figure 7 and 8 show a phase current of three-phase four-wire grid on the bus point of PCC bus, before and after multi units of single phase PV distribution generators (DGs) combined with battery energy storage (BES) and three single phase bidirectional inverter. Figure 9 presents inverter current.

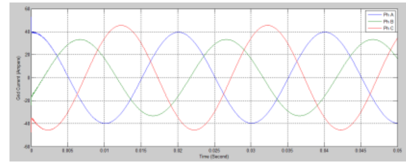


Figure 7 Phase current of three phase four-wire distribution network on PCC bus before multi units of single phase PV DGs combined with BES

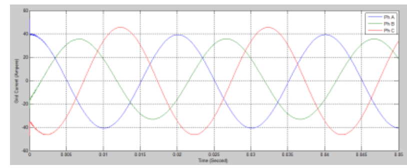


Figure 8 Phase current of three phase four-wire distribution network on PCC bus after multi units of single phase PV DGs combined with BES

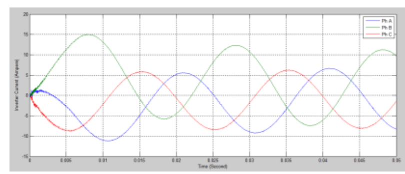


Figure 9 Inverter current after multi units of single phase PV DGs combined with BES

Figure 10 and 11 show a phase voltage of three-phase four-wire distribution nework on the PCC bus, before and after multi units of single phase PV DGs combined with battery energy storage and three single phase bidirectional inverter. Figure 12 presents inverter voltage after multi units of single phase PV DGs combined with BES.

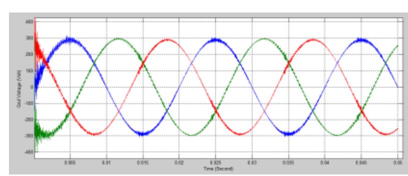


Figure 10 Phase voltage of three phase four wire distribution network on PCC bus before multi units of single phase PV DGs combined with BES

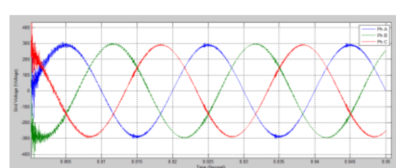


Figure 11 Phase voltage of three phase four wire distribution network on PCC bus after multi units of single phase PV DGs combined with BES

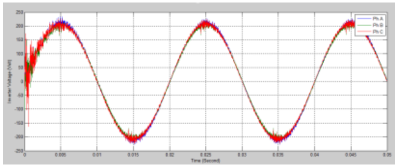


Figure 12 Inverter voltages after multi units of single phase PV DGs combined with BES

From Figure 7, 8, 10, and 11, we get phase current and voltage of three-phase four-wire grid on PCC bus before and after multi units of single phase PV DGs combined with battery energy storage and three phase bidirectional inverter. The value of maximum phase current and phase voltage on each phase (phase A, B, and C) is inserted into Equation 11 to obtain the value of current and voltage unbalance based ANSI/IEEE 241-1990 Standard [14].

Based on the maximum current and voltage on phase A, B, and C, we get the value of current and voltage unbalance of three-phase four-wire grid on PCC bus before and after multi units of single phase PV generator combined with battery energy storage and three single phase bidirectional inverter, which the results are shown in Table 2.

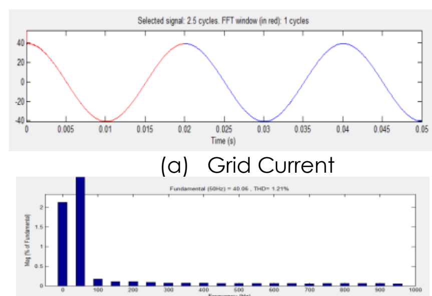
Table 2 shows that, before multi units of single PV DGs combined with battery energy storage and three single phase bidirectional inverter, the peak currents in phase A, B, and C are 39, 33 and 45 ampere respectively which generates an unbalanced line current of 15.39 %. On the condition after multi units of single PV DGs combined with battery energy storage and three single phase bidirectional inverter, the peak current in phase A, B, and C are 40, 36, and 46 amperes respectively, thus causing the unbalance line current reduces to 11.48 %.

Table 2 Unbalance line current and voltage

No.	Parameter	Phase	Max	Unbalance (%)
	Before 1ϕ PV DGs combined with BES			
1	Current (A)	A	39	15.39
		B	33	
		C	35	
	Voltage (V)	A	280	1.76
		B	290	
		C	285	
	After 1ϕ PV DGs combined with BES			
2	Current (A)	A	1.21	11.48
		B	0.87	
		C	1.02	
	Voltage (V)	A	290	0.58
		B	295	
		C	290	

Table 2 also shows that, before multi unit of single phase PV DGs combined with battery energy storage and three single phase bidirectional inverter, the peak voltage in phase A, B, and C are 280, 290 and 285 volts respectively, which produces the value of unbalance line voltage of 1.76 %. On the condition after multi unit of single phase PV distributed generators combined with battery energy storage and three single phase bidirectional inverter, it is obtained the peak voltage on the phase A, B, and C are 290, 295, and 290 volts respectively, as well as results decline of the unbalance line voltage of 0.58%.

The research also investigates the impact of the combination multi units of single phase PV DGs with battery energy storage to power quality on three phase four wire low voltage of distribution line 220 volt and 50 Hz. Power quality analysis is done by determining the value of current (THD_I) and voltage harmonic (THD_V) on the bus PCC of distribution network. Figure 13 shows the harmonics spectrum of current (phase A) in three phase four wire on the bus PCC of distribution network after multi unit of single phase PV DGs combined with BES and three single phase bidirectional inverter. By the same prosedure the value of current (THD_I) and voltage harmonic (THD_V) in phase B and C can be determined, to obtain the average THD of current and voltage, which the results are shown in Table 3.



(a) Grid Current

(b) Harmonic spectrum of current (phase A)

Figure 13 Harmonic spectrum of current (phase A) in three phase four wire grid on the PCC bus after multi units of single phase PV DGs combined with BES

Table 3 Current and voltage harmonics

No.	Parameter	Phase	THD	Av-THD (%)
	Before 1ϕ PV DGs combined with BES			
1	Current (A)	A	1.16	0.98
		B	0.83	
		C	0.96	
	Voltage (V)	A	29.77	38.96
		B	35.72	
		C	51.39	
	After 1ϕ PV DGs combined with BES			
2	Current (A)	A	1.21	1.03
		B	0.87	
		C	1.02	
	Voltage (V)	A	29.97	39.08
		B	35.77	
		C	51.50	

Table 3 shows the average value of current harmonic (THD_I) of three-phase four-wire distribution network on the PCC bus, before and after multi units of single phase PV DGs combined with battery energy storage and three phase bidirectional inverter, increase from is 0.98 % to 1.03%. Both the average THD values of current is still below the 5% limit of harmonic currents based on IEEE Standard 519-1992 [15]. Table 3 also shows the average value of voltage harmonic (THD_V) of three phase four wire distribution network on PCC bus, before and after multi units of single phase PV DGs combined with battery energy storage and three single phase bidirectional inverter rises started from 38.96% to 39.08%. Both the average value of voltage harmonic (THD_V) has exceeded the 5% limits harmonic voltage based on IEEE Standard 519-1992.

4.0 CONCLUSION

A method for balancing line current and line voltage as a result of a multi unit of single phase PV DGs in household installed at random in the three phase four wire low voltage distribution line 220 V and 50 Hz using battery energy storage and three single phase bidirectional inverter has been presented in this paper. In this paper also has been presented the impact of combination multi units of single phase PV distributed generators with battery energy storage to power quality on three phase four wire distribution network. From the analysis, combination of multi units of single phase PV DGs with battery energy storage and three single phase bidirectional inverter to three phase four wire distribution network able to reduce unbalanced line current from 15.39% to 11.48% and unbalance line voltage of 1.76% to 0.58%. Reviewed from the power quality parameters, the combination of a multi-unit of single PV DGs with battery energy storage and three single phase bidirectional inverter to three single phase four wire distribution network able to increase average harmonic of current from 0.98% to 1.03% and average harmonic of voltage from 38.96% and 39.08%.

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