Power Quality Analysis and Its Enhancement of Microgrid Integrated with Distributed Energy Resources

D Babu Rajendra Prasad *, A D Kulkarni**‡, T Ananthapadmanabha ***

* Electrical and Electronics Engineering, Vidyavardhaka College of Engineering, Karnataka, 570002, Mysore, India

** Electrical and Electronics Engineering, The National Institute of Engineering, Karnataka, 570008, Mysore, India

*** Electrical and Electronics Engineering, The National Institute of Engineering, Karnataka, 570008, Mysore, India

(brpvvce@gmail.com, adknie@gmail.com, drapn2015@gmail.com)

Abstract- In future power system, the penetration level of Renewable Energy Sources (RES) at distribution side will be at higher range because of its technical and environmental benefits. As these RES are intermittent in nature, integration cannot be done directly with the system means which needs indirect coupling through power converters. It is well known that Power converters placement at larger scale in distribution system leads to Power Quality (PQ) issues, hence in this paper Microgrid (MG) is created at distribution level with the penetration of RES and Total Harmonics Distortion of voltage and current generated are studied and mitigated when MG operating in both Grid connected & islanded mode. In this study standard IEEE12 bus test system and RES models (Photo Voltaic & wind-type1) are considered and analysis is carried out using MATLAB/SIMULINK software package.

Keywords- Power Quality, Microgrid, SIMULINK, Wind, Photo Voltaic (PV).

1. Introduction

Distributed Energy Resources (DERs) are significant in modern power system because of their advantages like transmission line loss reduction, Environmental and Economic Benefits. With the integration of various technology DERs i.e., PV, Wind, Micro-turbines and Fuel cells at distribution level it is possible to form MG as a combination of DERs, Controllers and loads. MG formation leads to reliable operation of system with the possibility of two modes of operation (Grid connected and Autonomous) and enables the continuous supply to the consumers [1,2]. One of the main challenges in implementation of MG is to maintain PQ because of Power electronic converters used in Controllers of DERs which creates PQ issues like Harmonics of voltage & current, Voltage sag, Voltage swell and Voltage unbalance. Hence PQ analysis of MG is of major interest to mitigate PQ issues and to construct MG simulation model with PQ improvement optimal control strategies. Many researchers are working on mitigation of PQ issues in MG power system at different conditions [3].

Presently lot of researchers are working on improvement of PQ in Electrical Power Distribution network operated with various loads and integrated with local generators [4]-[6]. The main reason for the low PQ is the integration of power electronic converters and non-linear in both industrial & commercial loads [7]. Ideally, Electrical power system is to have a balanced load, a pure sinusoidal phase power supply, a lot of the activity in a single, power factor and a zero distortion. However, in practice, it is impossible, because the system is composed of both linear and non-linear loads. Because it's a complicated process, and the changes in the parameters of the system i.e., Voltage, Current, and Frequency, will be collectively referred to as the "PQ problem"[8]. A substandard PQ is leading to the disruption of services and equipment, and thus, the voltage and current imbalances, creating less power factor and shortage of reactive power. Between these, harmonic is the most important indicator of a low PQ. Therefore, it is necessary to decrease the problem of PQ and to maintain Total Harmonic Distortion (THD) in percentage within certain limits, in accordance with the IEEE standard.

In the context of the developments in the domain of DERs technology, Chance of PQ issues will be more because of non-linearity in local Generators, Power controllers and loads. Hence in this work Analysis of PQ of MG integrated with DERs i.e. PV, Wind & Diesel is carried out under both Grid operated and islanded modes of operation. PQ analysis includes estimation of percentage voltage deviation at nodes and THD of Voltage & current created with the integration of DERs and its controllers.

This paper comprises of Five sections after introduction, where Section II explains about the modeling of DERs in MATLAB/SIMULINK software package, PQ indicators considered for the study is explained in section III, MG model considered in this work and its parameters are mentioned in section IV, Section V presents the results of PQ indicators under different cases and Section VI concludes the summary of the work carried out.

2 Modeling of Wind Turbine Generator (WTG)

In this work the PV, Diesel and Wind Turbine Generators are considered as DERs present in MG and Dynamic models of these DERs are considered for PQ analysis in Grid operated and Islanded modes of operation. Dynamic models of these DERs are explained as follows

2.1 Diesel Generator (DG)

A mathematical simulation model of diesel generator can be done by utilizing a conventional 6th order synchronous generator and the filed excitation system to regulate the terminal voltage of generator is modelled on the basis of Automatic voltage regulator-IEEE type AC1A excitation model [9] which is most suitable for large power system studies. The governor model used to control the frequency of electric power generated comprise of three major parts i.e. electrical controller, actuator and IC engine [10]. Figure.1 represents the mathematical model of diesel engine with controller and synchronous generator [10]. Time constants of controller box and actuators are from τ_{d1} to τ_{d6}, τ_{Dd} represents diesel engine's time constant, K_{ds} represents actuator gain, ω_e represents the rotor speed of generator and T_{min} & T_{max} represents lower and upper torque limit consequently.

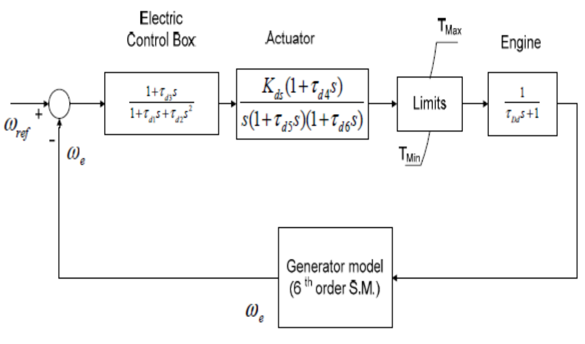

Figure.1. Model of Diesel Generator

2.2 Modeling of Wind Turbine Generator (WTG)

WTGs are classed into four types based on turbine speed, grid interfacing and type of generator coupled with the turbine as follows [11].

- **Type A:** Induction Generator(IG) coupled with constant speed wind turbine and which is directly interfaced with the grid.
- **Type B:** Variable rotor resistance IG coupled with Variable speed wind turbine and which can also be interfaced directly to the grid.
- **Type C:** IG with feedback generally called as doubly fed IG and DC-AC converter at rotor side coupled with variable speed wind turbine which can be connected directly with the grid.
- **Type D:** Synchronous machine coupled with variable speed wind turbine and power converter.

Research on RES integration in power system indicates that wind turbine generators of Type A, C and D dominates the electrical supply market of installed wind power generation [11]. Type A is commonly used in distribution systems as a Distributed generator as it is economical compare to other types. In [12], Suitable models are presented in order to analyse the dynamics of various types of wind turbines. Squirrel cage induction generator is one of the most customary constant speed wind turbines, which uses a Squirrel cage induction motor. This paradigm is accomplished and used in the present work. Fig.2 represents the schematic of the constant speed turbine coupled with IG Grid interfaced [13 &15]. where, I_r and I_m are direct & quadrature axes of stator currents respectively, ω_m is the angular speed of rotor, X_0, X', R_s and T'_0 are the parameters of IG.

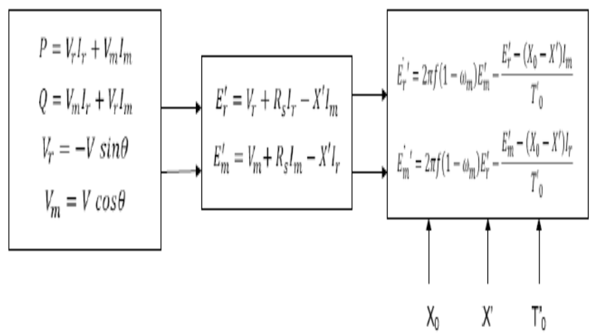

Figure.2. Schematic of constant speed turbine with IG

2.3 Modeling of PV Array

Fig.3 depicts the equivalent circuit of a PV cell. I_{ph} is the current source which represents the Photon current of cell. R_s and R_{sh} are the series & intrinsic shunt resistances of the cell respectively. Regularly R_{sh} value is high and that of Rs is low, in consequence both can be ignored in order to reduce the complexity of analysis. In practical, PV cells are clumped into substantial component to configure PV modules, which can be associated in combination of series and parallel to design PV arrays, later which is built as PV electrical source. Fig. 4 shows the PV array equivalent circuit. The V-I feature equation of a PV cell is delivered as module photocurrent I_{ph} as follows

$$I_{ph} = \frac{\left[\left(I_{sc} + K_i(T-298)\right) I_r\right]}{1000} \qquad 1$$

Where, I_{ph}-photocurrent (A); I_{sc}-short circuit current (A); K_i-short circuit current of cell at 25°C and 1000 W/m^2; T-operating temperature in kelvin; I_r-solar irradiation in W/m^2.

Module reverse saturation current I_{rs} is given by

$$I_{rs} = \frac{I_{sc}}{\left[\exp\left(\frac{qV_0}{n_s k\, n\, T}\right) - 1\right]} \qquad 2$$

Where, q=electron charge = 1.6 × 10−19C; V_o=open circuit voltage in volts; n_s = number of cells connected in series; n= Ideality factor of the diode; k= Boltzmann's constant = 1.3805 × 10−23 J/K.

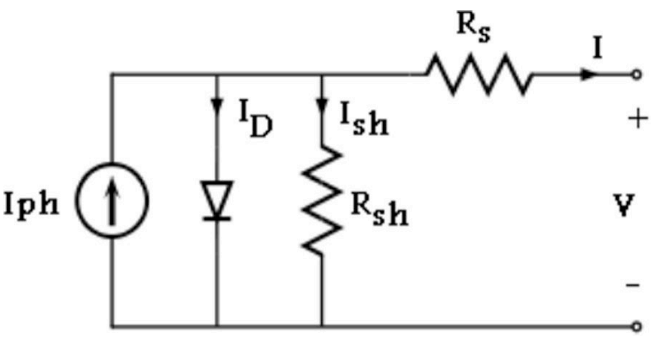

Figure.3. Equivalent circuit of PV cell

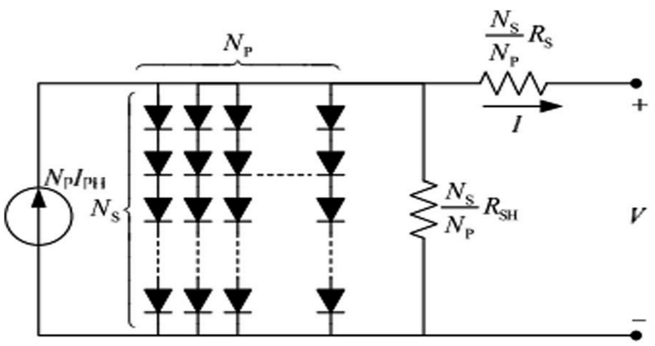

Figure.4. Solar array equivalent circuit

The saturation current of module I_0 varies with the operating temperature and Equation of I_0 is given by

$$I_0 = I_{rs}\left[\frac{T}{Tr}\right]^3 \exp\left[\frac{q \times E_{go}}{nk}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \qquad 3$$

Where, T_r=nominal temperature = 298.15 K; E_{g0}= band gap energy of the semiconductor = 1.1 eV;

PV module output current is given by

$$I = N_p \times \left(I_{ph} - N_p\right) \times I_0 \times \left[\exp\left(\frac{\left(\frac{V}{N_s}\right) + I \times \left(\frac{R_s}{N_p}\right)}{n \times Vt}\right) - 1\right] - I_{sh} \qquad 4$$

$$\& \qquad V_t = \frac{k \times T}{q} \qquad 5$$

$$\& \qquad I_{sh} = \frac{V \times \left(N_p/N_s\right) + I \times R_s}{R_{sh}} \qquad 6$$

Where: N_p= number of parallel PV modules; R_s=series resistance (Ω); R_{sh}=shunt resistance (Ω); V_t= Diode Thermal voltage (V).

3. Power Quality Analysis

Power Quality (PQ) is defined as the Quality of supply given to the consumers at desired voltage and frequency levels without any interruption. Components of PQ are as mentioned in fig.5. As we know that Distribution system is to be operated with pure sinusoidal voltage and current waveforms and the assessment of these signals are prime interest, because non sinusoidal signals damages the Electrical Equipment of the consumers and reduce the overall performance of Distribution system.

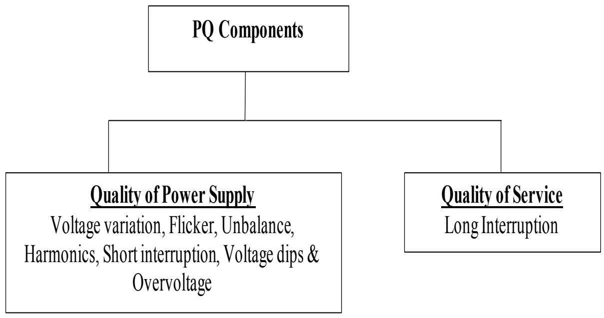

Figure.5: PQ Components

In this work majorly two indicators are considered for the PQ analysis which signifies the quality of voltage and quantity of harmonics in the distribution system.

A. Voltage Deviation Index (VDI)

One of the parameters to measure Quality of supply is the magnitude of voltage available at the consumer end. Hence in this work Deviation of voltage with respect to reference is calculated at each bus using equation 7

$$\%V_D = \left[\frac{1 - V_b}{V_b}\right] \times 100 \qquad 7$$

To assess the Voltage quality of complete MG test system, Average Bus Voltage deviation index (ABVDI) is considered and defined as in equation 8

$$ABVDI = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{V_{ref} - V_{bi}}{V_{bi}} \times 100\right) \qquad 8$$

Where 1. V_b= Bus voltage in Per Unit (PU)
2. V_{ref}= Reference bus voltage in PU
3. n= Number of Buses in the test system

In this study V_{ref} is taken as 1 PU

B. Harmonic Distortions

Harmonics are the undesired frequency signals which are integer multiples of fundamental frequency. Major causes for Voltage and Current Harmonics are Power Electronic converters, Nonlinear loads and Nonlinear dynamics of the system. Since MG consists of DERs and Controllers, Harmonic analysis need to be done to enhance PQ of MG. In this study THD of voltage and current signals are calculated to assess the quantity of harmonics using FFT analyser and THD is obtained as the ratio of Root Mean Square (RMS) value of sum of all the distinct order harmonic components to the RMS value of fundamental component of signal. THD of current and voltage are calculated using following equations 9 and 10 respectively.

$$THD_I = \frac{\sqrt{I_{h_2}{}^2 + I_{h_3}{}^2 + I_{h_5}{}^2}}{I_{h_3}{}^2} \quad (9)$$

$$THD_V = \frac{\sqrt{U_{h_2}{}^2 + U_{h_3}{}^2 + U_{h_5}{}^2}}{U_{h_3}{}^2} \quad (10)$$

4. Microgrid Model

4.1 Modified IEEE Test system MG Model

In order to Develop MG model in this work IEEE 12 bus system is considered with base voltage of 11kV and PV array, Wind Turbine Generators and Diesel Generator are integrated to the system at weak voltage buses. Capacities of these Generators are selected such a way that integrated distribution system should be able to operate properly in autonomous model (i.e., Removal of Grid support). Table 1, 2 and 3 shows the details of line parameters, loads and DERs correspondingly. Single line diagram of MG model considered for this study is shown in Figure 6.

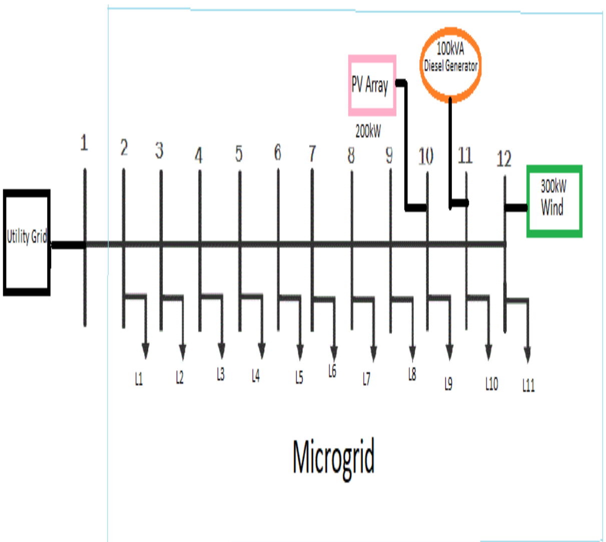

Figure 6: Typical Single line diagram of MG model

Table 1. Line data of standard 12 Bus RDS

Branch No.	From bus	To bus	R(Ω)	X(Ω)
1	1	2	1.093	0.455
2	2	3	1.184	0.494
3	3	4	2.095	0.873
4	4	5	3.1 88	1.329
5	5	6	1.093	0.455
6	6	7	1.002	0.41 7
7	7	8	4.403	1.21 5
8	8	9	5.642	1.597
9	9	10	2.89	0.81 8
10	10	11	1.514	0.428
11	11	12	1.238	0.351

Table 2. Load data of standard 12 Bus RDS

Type of DER	Specification	Interface
PV array	11kV,200kW	DC/AC Power Converter
Wind	11kV,250kW	Induction Generator-Sq. cage
Diesel	11kV,100kVA	Synchronous Generator

Table 3. Details of DERs

Bus No.	Real power load in kW	Reactive power load in kVAR
1	0	0
2	60	60
3	40	30
4	55	55
5	30	30
6	20	15
7	55	55
8	45	45
9	40	40
10	35	30
11	40	30
12	15	15

4.2 Power Flow Analysis

Considered test system and Dynamic model of PV, Wind turbine Generator & Diesel Generator is simulated in MATLAB/SIMULINK software package. Newton Raphson technique for Power flow analysis is used to obtain Harmonics of voltage and current, Voltage profile and Power flows. Power flow study is carried out in two operational modes i.e., Grid operated and Autonomous.

5. Results and Discussion

Considered MG test system is modelled in MATLAB/SIMULINK software package and Load flow simulation is carried out for four different cases i.e. case 1: Both Utility Grid and DERs are operating which is called as Grid connected mode, case 2: Only DERs are operating by isolating utility grid which is called as Islanded mode where 500kVAR Star type capacitor interfaced at Point of Common Coupling(PCC) to provide required Reactive support, case 3: Islanded mode operation with Delta type 500kVAR capacitor & case 4: Islanded mode operation with Three phase Harmonic filter. In each case VDI at all buses and THD of Bus voltage and current are obtained using load flow solution and explained as follows

Case 1: Grid Connected

Both Utility and DERs are made operating to supply the Loads in this case. Power simulation of considered MG is carried out and using flow results obtained VDI is calculated at all the buses. THD value of Bus voltage and current signals are obtained using FFT analyser and obtained results are tabulated in Table.4

Table 4. Values of VDI and THD- Case 1

Bus No.	VDI	THD_V	THD_I
1	0	0	8.74
2	0.23089	0.05	8.74
3	0.39543	0.1	9.65
4	0.58703	0.19	10.08
5	0.65337	0.33	10.86
6	0.63211	0.38	11.24
7	0.58460	0.42	11.34
8	-0.10564	0.6	11.73
9	-1.26527	0.83	11.79
10	-1.98248	0.95	11.65
11	-2.19372	1	15.33
12	-2.35624	1.02	11.22

From these Results it is inferred that with the Grid Support voltage deviation at all the buses are minimum which indicates that steady state voltage stability margin is better and Harmonic distortions of Voltage at all buses are within 5% as per IEEE 519-1992 for 11kV system and Current Harmonic distortions are more than 10% at most buses which needs to be considered while designing compensators. Since Balanced three phase loads are considered in this work current harmonics are not much of interest.

Case 2 & 3: Islanded Mode with Capacitor bank

In this case, Utility grid is isolated using three phase breaker and DERs alone need to supply the existing loads. To provide desired Reactive power support in islanded condition, Initially Star type 500kVA capacitor is interfaced at PCC and simulation is carried out. Simulation is repeated for Delta type capacitor bank and results obtained in both configurations of Capacitor banks are tabulated in Table.5

Table 5. Values of VDI and THD- Case 2 & 3

Bus No.	VDI	THD_V	THD_I
2	3.31905	21.84	22.07
3	3.44152	21.84	22.1
4	3.55898	21.83	22.1
5	3.51401	21.82	22.1
6	3.45577	21.81	22.08
7	3.37500	21.81	22.05
8	2.60631	21.8	21.98
9	1.35746	21.79	21.9
10	0.60039	21.78	21.82
11	0.38682	21.77	22.04
12	0.20946	21.77	22.05

From these Results it can be observed that without Grid Support also voltage deviation at all the buses are within 5% with the desired reactive support provided by capacitor bank connected at PCC. But Harmonic distortions of Voltage and current exceeds acceptable level which indicates the significance of support Grid. Hence use of capacitor bank will provide better voltage profile but fails to mitigate harmonic distortions in the absence of Grid support.

Case 4: Islanded Mode with Harmonic filter

In this case, Utility grid is isolated using three phase breaker and DERs alone need to supply the existing loads. Since Capacitor banks failed to mitigate the harmonics, 500kVA three phase harmonic filter which is combination of single- tuned filter and Double- tuned filter is connected at PCC and simulation is carried out. obtained results are tabulated in Table.6

From these Results it can be observed that without Grid Support also voltage deviation at all the buses are within 5% with the desired reactive support provided by Three phase harmonic filter connected at PCC. Compared to case 2 & 3, with the use of Harmonic filter instead of capacitor bank Harmonic distortions of voltage and current can be reduced considerably.

Table 6. Values of VDI and THD- Case 4

BUS	VDI	THDV	THDI
2	3.90816	13.08	13.46
3	4.00359	13.08	13.52
4	4.07233	13.07	13.53
5	3.95176	13.07	13.56
6	3.86741	13.07	13.57
7	3.76219	13.07	13.56
8	2.89059	13.07	13.53
9	1.51406	13.07	13.49
10	0.69396	13.07	13.44
11	0.44849	13.07	14.46
12	0.27089	13.07	13.18

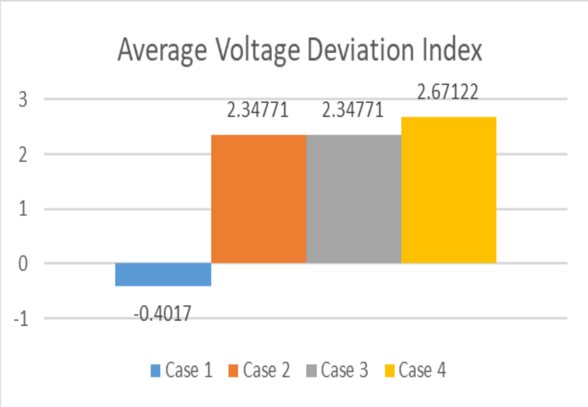

Figure 7. Values of Average Voltage Deviation Index

From figure.7 it is inferred that values of Average bus voltage deviation index of MG is within acceptable level under both Grid operated and Islanded modes of operation. In Grid connected mode with the integration of DERs, Voltage Quality of system can be enhanced compared to conventional system (i.e. without DERs) and in Islanded modes of operation, Capacitor banks will provide sufficient reactive power support to the MG which regulates the voltage within acceptable limits. Replacement of capacitor bank with Three Phase Harmonic filter also maintains voltage Quality of the system.

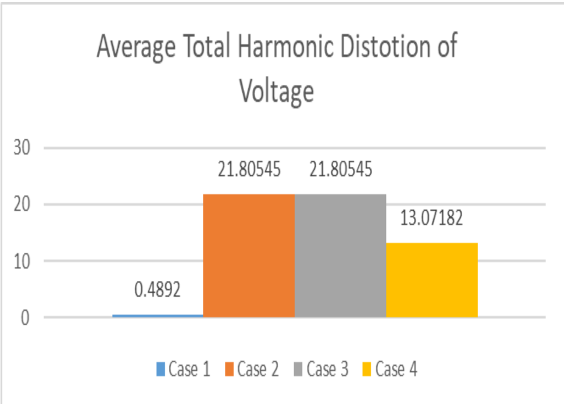

Figure 8. Values of Average THD_V

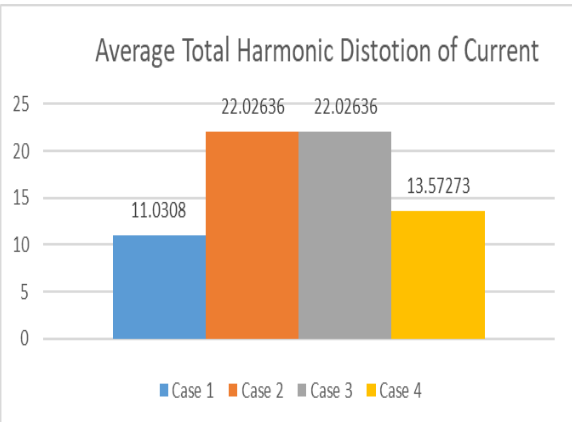

Figure 9. Values of Average THD_V

Figure 8 & 9 depicts the Values of Average THD_V and THD_I at all considered cases. It can be observed that in Grid connected mode operation of MG average THD_V is well within 5% and in islanded operation of MG, average THD_V increases which depends on type of reactive power compensator used. When Star and Delta type Capacitor banks used as Reactive power compensators average THD_V is 21.8% which will affect the Electrical equipment of MG badly and this can be brought to 13.07% by replacing Capacitor bank with three phase harmonic filter. Similarly, Average THD_I is significantly reduced when MG integrated with three phase harmonic filter.

6. Conclusion

Major advantage of MG is ability to operate in islanded mode to ensure continuous supply to consumer. This study gives clear picture PQ issues of MG in terms of Voltage magnitude and Harmonics comes into existence when Grid support removed. In Islanded mode operation of MG, PQ issues mitigators should be used and this study suggests that use of Three phase harmonic filter (combination of single-tuned and double- tuned filter) is better compared to capacitor banks because of better reduction of voltage & current Harmonics. But Three phase harmonic filter is not best to reduce harmonics to the desired level during fault conditions, Hence Custom power devices like D-Statcom, DVR and UPQC can be used in Islanded mode operation of MG to improve PQ during dynamic state of system.

References

[1] N. Hatziargyriou, *Microgrids : Architectures and Control*: Jhon Wiley & Sons, 2013.

[2] S. Chowdhury, S. Chowdhury, and P. Crossley, *Microgrids and active distribution networks*: Institution of Engineering and Technology, 2009.

[3] M. Farhoodnea, A. Mohamed, H. Shareef, and H. Zayandehroodi, "PQ impact of renewable energy based generators and electric vehicles on distribution systems," *Procedia Technology,* vol. 11, pp. 11- 17, 2013.

[4] Khadkikar V. Enhancing electrical PQ using UPQC: A comprehensive overview. IEEE Transaction on Power Electronics. 2012; 27(2): p. 2284–2297.

[5] Chaoui A, Gaubert JP, Krim F, Champenois G. PI Controlled Three-phase Shunt Active Power Filter for PQ Improvement. Electric power components and systems. 2007; 35(1): p. 1331–1344.

[6] Grady WM, Samotyj MJ, Noyola AH. Survey of active power line conditioning methodologies. IEEE Transaction on Power Delivery. 1990; 5(3): p. 1536-1542.

[7] Mikkili S, Panda AK. Performance analysis and real-time implementation of shunt active filter current control strategy with type-1 and type-2 FLC triangular M.F. International Transactions on Electrical Energy Systems. John Wiley. 2014; 24(3): p. 347–362.

[8] Farhoodnea, M. et.al: PQ analysis of gird connected photovoltaic systems in distribution networks," Przeglad Elektrotechniczny, 2013, Vol. 89 (2A), pp. 208-213.

[9] "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies." IEEE Standard, Vol. 421, No. 5, 2005 (Revision of IEEE 521.5-1992).

[10] Y. Zhu and K. Tomsovic, "Development of models for analyzing the load-following performance of microturbines and fuel cells," Electric Power Systems Research, vol. 62, no. 1, pp. 1-11, 2002.

[11] Ehsan Nasr Azadani, Student Member, Claudio Canizares, Fellow, IEEE, Kankar Bhattacharya, Senior Member, IEEE "Modeling and Stability Analysis of Distributed Generation" 978-1-4673-2729-9/12/$31.00 ©2012IEEE.

[12] V. Akhmatov, "Analysis of dynamic behavior of electric power systems with large amount of wind power," Ph.D. dissertation, Technical university of Denmark, Denmark, 2003.

[13] Ehsan Nasr Azadani, Claudio Canizares, Kankar and Bhattacharya, "Modeling and Stability Analysis of Distributed Generation" Published in: 2012 IEEE Power and Energy Society General Meeting.

[14] M Lokesh, A.D. Kulkarni, T. Ananthapadmanabha, Nagaling Gurav, K J Sandeep Kumar, "Enhancement of Transient Stability and Voltage Quality of MG with Multiple DERs", 2021 5th International Conference on Intelligent Computing and Control Systems (ICICCS), 2021.

[15] K J Sandeep Kumar, A.D. Kulkarni, ""Determination of Minimum Reactive Power Compensation for the stable operation of Type-I WTG in Grid connected mode", IJRTE ,ISSN: 2277-3878, Vol. 8 Issue 5, January 2020.

[16] Yousfi Abdelkader, Tayeb Allaoui and Chaker Abdelkader. "Power Quality Improvement Based on Five-Level Shunt APF Using Sliding Mode Control Scheme Connected to a Photovoltaic". International Journal Of Smart Grid, Vol. 1, No. 1, 2017.