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Robust Parallel Operated Inverters in Microgrid with SRF(Synchronous Reference Frame) – PLL(Phase Locked Loop) and SRF - Virtual Impedance Compensation Loop for Proportional Load Sharing

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Abstract: Power flow control is most important in inverter interfaced Microgrids with highly penetrated DERs in islanded mode for their functionality to feed the connected loads. The different types of interfacing inverters connected to DERs, have been discussed for their principle of operation. The conventional inverters with droop control method of, P-f, Q-v alone failed to control with unequal line impedances. New inverters with SRF-virtual impedance compensation and SRF-phase locked loop along with droop charactestics have been implemented for defined functionalities in this paper. The design guidelines have been provided and the results are evaluated in Matlab/ Simulink platform to prove the effectiveness of the methodology.

Keywords: DOE-Dept. Of Energy, US-United States, GHG-Green House Gas, DERs-Distributed Energy Resources , MPPT-Maximum Power Point Tracking, DG-Distributed Generators , P-Active power, Q-Reactive power, ESD-Energy Storage Device, SOC- State Of Charge,. CCM-Current Control Mode, VCM-Voltage Control Mode, DG- Distributed Generators, WT-Wind Turbine

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I. INTRODUCTION

The conventional energy resources like coal, gas, nuclear fuels are exhausting in the nature as they are being explored and hence the renewable energy sources are becoming popular through Microgrids. The whole world is exploring for renewable energy sources like, solar, wind, hydro, tidal, fuel gases, biomasses etc. All the nations are establishing research centers for commercial implementation of the available renewable resources. In this process Microgrids emerged for a possible solution to reduce the GHGemission to reduce burden on generation, transmission and distribution.

In this paper it is established how an interfacing, parallel operated inverters can contribute to the stable, reliable,resilient Microgrid by controlling voltage, frequency, active and reactive power flows[5]. Especially in islanded mode stability of Microgrid is to be taken care for power sharing, [11] [22] by specially designed inverters, which will take into account virtual impedances along with droop characterstics. Theseinvertersaretested in Matlab/Simulink platform for the effectiveness and the results are discussed for the targeted goals.

Distributed Generation is fast developing so that the remote areas and the congested town areas are getting the maximum benefit by the usage of renewable resources like solar, wind, battery energy systems etc[9]. These are not only helping the statuatary agencies but also contributing to the ecological balance . By continuous researches in the microgrid controls, the challenges ofmaking DERs dispatchable, are possible now. [1]

The microgrid has three modes of operation, viz., grid mode, islanded mode and re-synchronization or black start mode. In all these modes, the interfacing inverters are needed to integrate the DERs (dispatchable, non-dispatchable resources, battery storage systems) into Microgrid, so that the loads are fed with power without interruption. In this paper different types of parallel interfaced inverters are discussed so that all DERs will share the power proportionally, along with voltage and frequency control.

These inverters compensate for the virtual impedance for active and reactive power flow and utilizes also droop/reverse droop characterstics, for regulating voltage and frequency. This is applicable in bothgrid mode and islanded mode of the microgrid [4][12].

II. MICROGRID ARCHITECTURE

A Microgrid is an integration platform consisting of DERs (DGs and storage devices) with flexible loads, connected to a low voltage distribution network. Different control agents are required to make DERs supply power to loads in grid and islandedmode, so that the Microgrid is stable, reliable and economical.

2.1. Main elements of Microgrid

The very structure of Microgrid is a cluster of renewables (non-dispatchable, like PV, wind etc.,), non-renewables (dispatchable like diesel, fuel cells etc.) and flexible loads, integrated in Microgrid and connected to utility grid via static transfer switch with an overall energy management system (EMS)/ Central Controller, to have hierarchical power flow control in primary, secondary and tertiary levels for the effectiveperformance of the Microgrid. All the DERs are connected to the AC bus through two sets of power converters. The first converter is connected DER through DC/DC or AC/DC to optimize the operating point of DER.

The second converter is an inverter which is used to regulate the active and reactive power flows at the point of common coupling (PCC) and regulate voltage and frequency in the Microgrid. The Microgrid has two operating modes, grid connected mode and islanded mode. In grid mode the fault currents level is high as the inertia of synchronous machines is high. But in islanded mode the fault current level is low because of power electronics presence. Also the current is bi-directional in grid mode as the Solar/ WT may generate more power based on solar radiation/wind velocity *and that time, the.*

2.2 Microgrid Control Theory

The hierarchical AC Microgrid control is in four levels. Level 0 and 1 are within inverter level. Level 2 and 3 are in Microgrid level [10].

Level 0 is the control of inverter output voltage and current loops at higher speed through switches. These inverters follow sinusoidal voltages and currents.

Level 1 control regulates power flow into AC Microgrid from DERs. For dispatchable DERs the P and Q are defined on type selected like droop characterstic but for non-dispatchable DERs. P and Q depends on MPPT, which has current limitation. ESD inverteralso follows the droop characterstics to control P and Q [7].

Level 2 has two objectives, to regulate frequency and voltage of the Microgrid by adjusting power flows fixed by level 1,and to synchronize Microgrid to main grid from islanded to grid connected mode .

Level 3 takes care of optimization of power flows which are minimization ofmain grid cost and maximization of Microgrid by reducing running costs, electricity markets survey, weather forecast for renewables etc [15].

2.3. Types of inverters in AC Microgrid

There are three types of inverters function wise in AC Microgrids. They are grid following or grid feeding, grid forming and grid supporting [3] .

2.3.1Grid following or grid feeding Inverters :

These inverters inject sinusoidal currents in phase with the referenced voltage from AC bus to follow the grid in current control mode (CCM) either in grid mode or islanded mode. The input to this inverter is DC/DC converter which does the operation of MPPT. These are interfaced with PV, WT etc. represented by high impedance in parallel with inverter.

2.3.2 Grid forming Inverters :

These inverters have two controls, one in grid mode, to regulate active and reactive power and maintain SOC of ESD(battery, super capacitor etc), other to inject sinusoidal voltages into grid in voltage control mode (VCM). This is represented with a low impedance in series with the inverter [9][13].

2.3.3 Grid supporting Inverters :

These are to support Microgrid during islanding to maintain voltage, frequency, active, reactive powers with droop control to maintain power quality and voltage.

2.4.Inverter Control Theory :

Irrespective of the type of the inverter, any inverter converts into the Synchronous Reference Frame (SRF)-

PLL(Phase Locked Loop)[16] and SRF-Virtual Impedance loop [8], for transforming from abc to dq0 (rotating orthogonal vectors in direct axis and quadrature axis) /αβ to simplify control. To suppress phase voltage harmonics, a low pass LCL filteris used. This reduces the harmonics in the output current[20].

2.5.Microgrid single line diagram :

The DERs selected in this microgrid are a PV source and parallel battery source[13] , interfaced by converters, inverters, connected to PCC throughbreakers, for, protection to isolate with the Utility grid.

Single line diagram of Microgrid

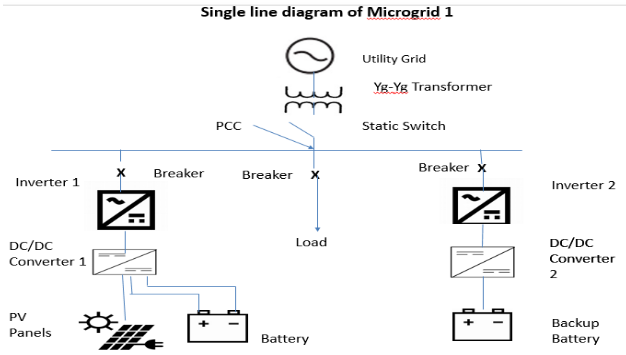

Fig : Single line diagram of Microgrid

2.6. Microgrid Components :

2.6.1.AC Microgrid :

A 400V AC, 3 Phase, 4 wire, 50 Hz , 25 Amps, fault level, 20 MVA.

2.6.2.PV Source :

A 2 KW Solar PV Panels used to control P,Q in CCM mode during grid mode and islanded mode .

2.6.3.DC/DC Boost Converter:

A 3 KW DC/DC, Converter is used in voltage controlled mode to control voltage and frequency in both grid mode and islanded mode.

2.6.4. DC/AC inverter :

A 3 KW DC/AC, Inverter is used in voltage controlled mode to control voltage and frequency in both grid mode and islanded mode.

2.6.5. Battery Source :

A 100Ah, 12 VDCbattery source is used.

2.6.6. Backup Battery Source :

A100Ah, 12VDC source is used for reliability.

2.6.7. A3 Phase Load :

A 3 phase balanced load of 2 kw is used.

2.6.8. Static Transfer Switch :

The static transfer switch is a semiconductor switch which is used for smooth transferring from utility grid mode to islanding and resynchronizing back to utility grid mode from islanding mode. This switch during grid modeallows to export to utility when PV power is greater than load and when PV power is less than load, it imports power from grid. During islanding mode, PV excesspower is used to charge battery to SOC level, while supplying to load

2.6.9. Utility Transformer :

The utility transformer is a 100 KVA transformer with 11KV/415V, 3 phase, 50Hz, oil immersed transformer star/star, neutral solidly grounded.

III. NETWORK IN MATLAB / SIMULINK

Matlab /Simulink model is given below for both grid mode and islanding mode

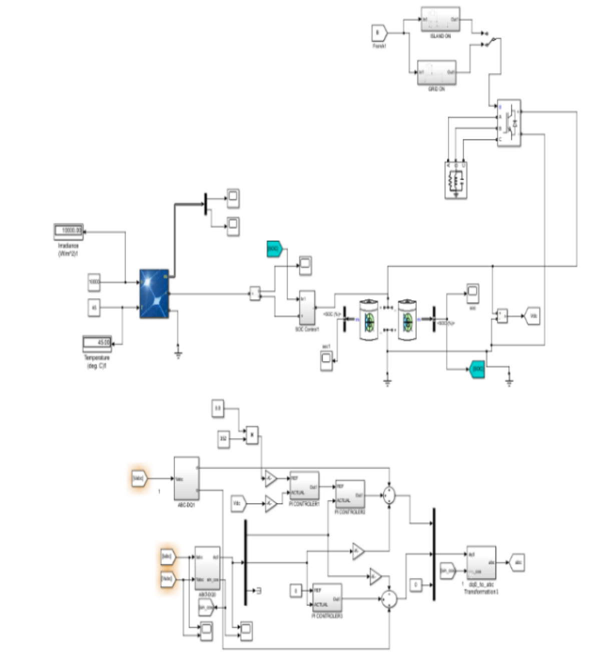

Fig 2 : Proposed Microgrid system in islanding mode

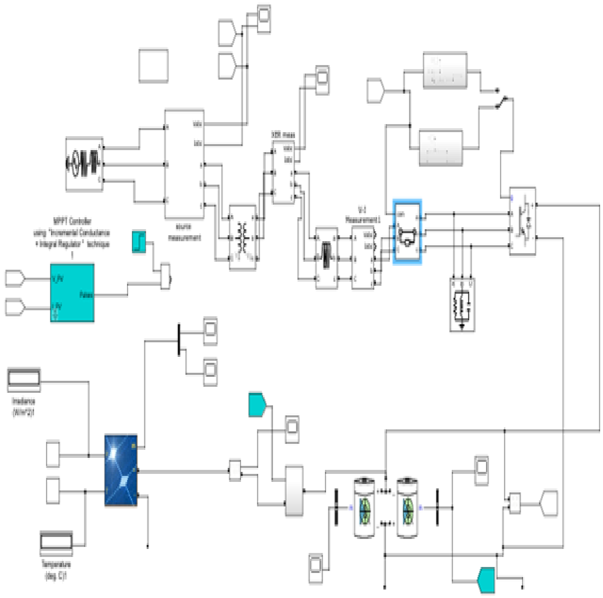

Fig 3 : Proposed Microgrid system in grid mode

IV. CONTROL METHODOLOGY

The type of P, Q, V, F controls change depending on Microgrid mode. DGs bidirectional power flow, follows droop control either in grid mode at PCC, for P, Q between grid and utility grid. This is determined by frequency and voltage droop [14] .

4.1 Grid connected Mode :

In grid connected mode, DGs generate active and reactive power at PCC as per the reference, by taking into consideration MPPT, in CCM. For better control of V,f and for decoupling of P and Q, is achieved by transforming abcvectorquanties to dq, synchronous reference frame(orthogonal rotating fame). [2]

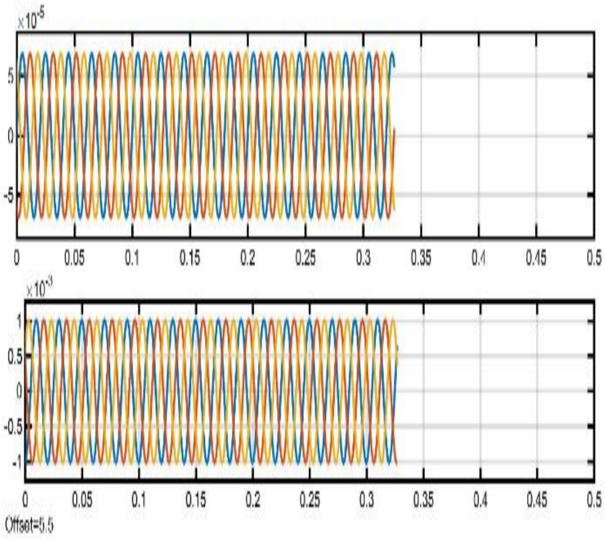

Fig 4 : Utility voltages and currents

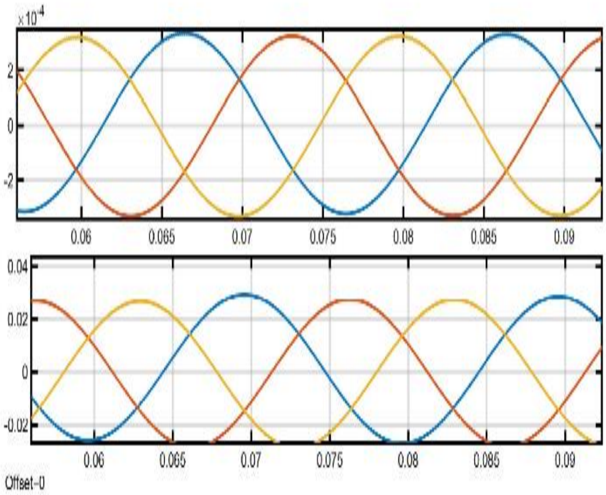

Fig 5: Transformer Secondary voltages & currents.

4.2 Islanded Mode :

In islanded mode, DGs share active and reactive power depending on load, Pm and Qm. During islanding, the inverters follow reverse droop control for maintaining Voltage and frequency [1][17].

V. POWER FLOW EQUATIONS

The power flow equations for grid connected mode and islanded more are given separately [24].

5.1.Grid connected mode :

The DGs operate in CCM control and supply P and Q to PCC as per reference with MPPT. The difference of real time and ratings of frequency and voltage are given by [20] ,

$$\omega_{MG} = \omega_G^* - \left(k_\omega + \frac{k_i\omega}{s}\right)(P_G - P_G^*), \quad \text{---(1)}$$

$$E_{MG} = E_G^* - \left(k_p + \frac{k_i E}{s}\right)(Q_G - Q_G^*). \quad \text{----(2)}$$

where ω_G^* and E_G^* are the frequency and amplitude voltage references provided by a PLL monitoring the PCC voltage P_G^*, Q_G^*, $k_i\omega$ and k_iE are the active and reactive power reference, the integral frequency and voltage drooping coefficients, respectively.

5.2.Islanded mode :

In islanding mode DGs share the load proportionally. The active and reactive powers shared are given by [18],

VI. SIMULATION MODEL

In either grid connected mode or islanded mode the microgrid must be stable maintaining voltage, frequency droops, virtual impedance compensation [5] [16] [24]and sharing active and reactive powers proportionally keeping minimum phase angle droop [19][23].

6.1.Grid connected mode simulation:

In grid the DG inverters operate in droop control modePQ, charging the batteries to the SOC level. The main voltage and frequency is maintained by the main grid [19][6].

6.2. Islanded mode simulation :

In islanding mode, interfacing inverters operate in reverse droop control mode for maintenance of V, F, and sharing active and reactive powers proportionally [18][21].

VII. MATLAB / SIMULINK MODEL

7.1. Parameters table

SL NO	PARAMETER	SYMBOL	VALUE	UNIT
1	Nominal bus voltage	V	380	Vm
2	Nominal bus frequency	f	50	Hz
3	Filter inductor of DG	Lf	2	mH
4	Filter capacitor	Cf	5	µF
5	Battery	Battery	400,60	V, Ah
6	Max active power	Pmax	3	KW
7	Max reactive power	Qmax	2	KVAr

6.2. Matlab / Simulink control Methodology

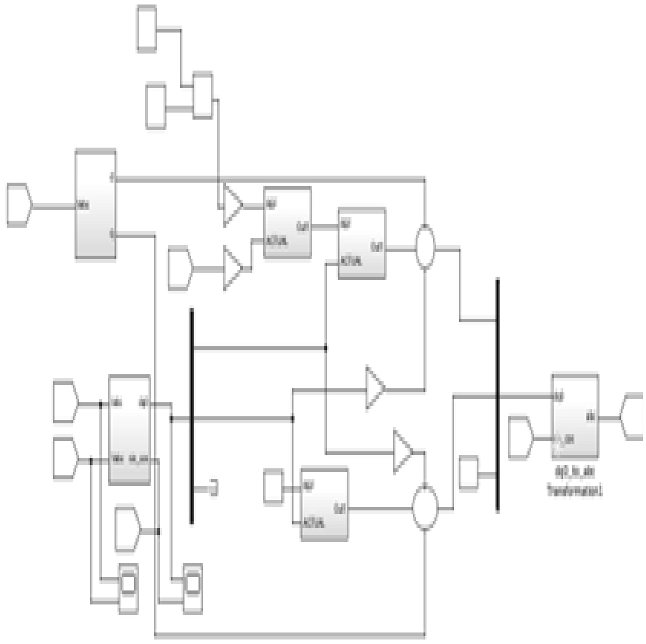

Fig 4 : Control methodology of Matlab/Simulink

VIII. RESULTS DISCUSSION

In this paper, grid connected mode, the load is supplied by utility grid. The utility supply charges the backup battery and PV charges its battery upto SOC. In islanded mode both PV battery and backup battery, share the load proportionally [6]. The below Matlab results show the effectiveness of the scheme

8.1.Results(wave forms) Grid mode:

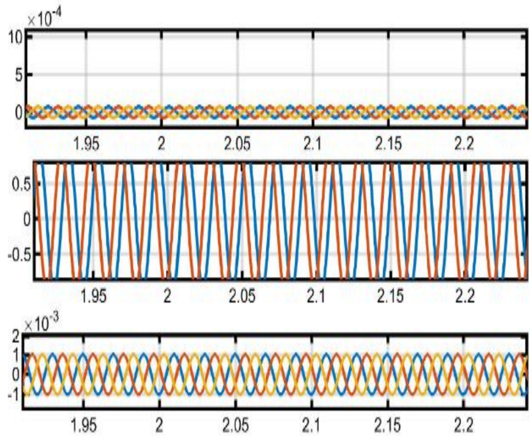

Fig 7 : grid mode wave form of dq1

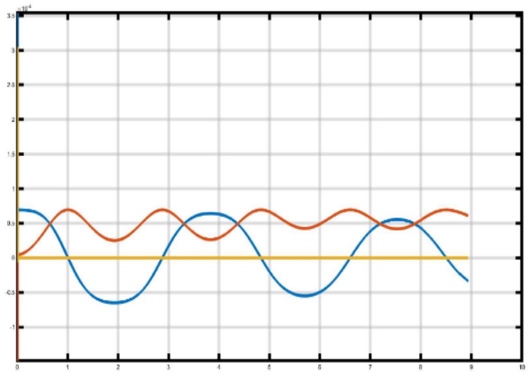

Fig 8 : grid mode wave form of dq

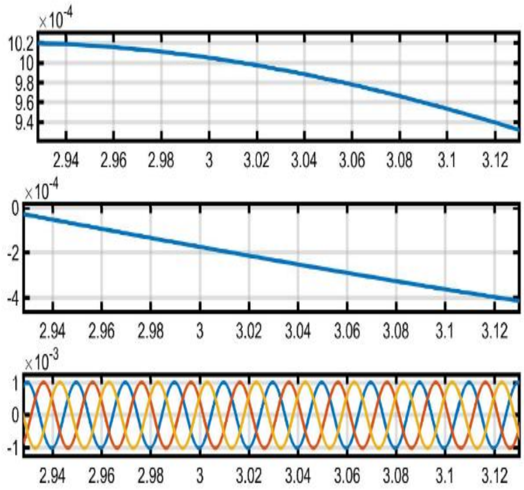

Fig 9: abc to dq in grid mode.

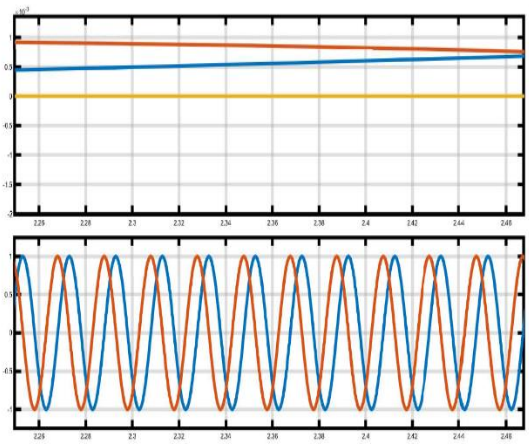

Fig 10 :Dq to abc in grid mode

8.2.Results(wave forms) Islanded mode:

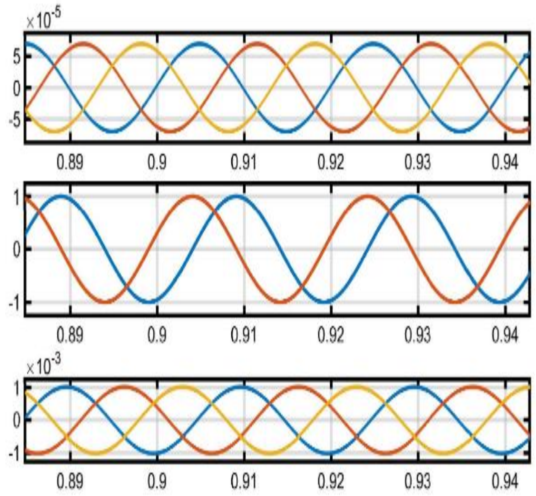

Fig 11 : dq1 wave form in islanded mode

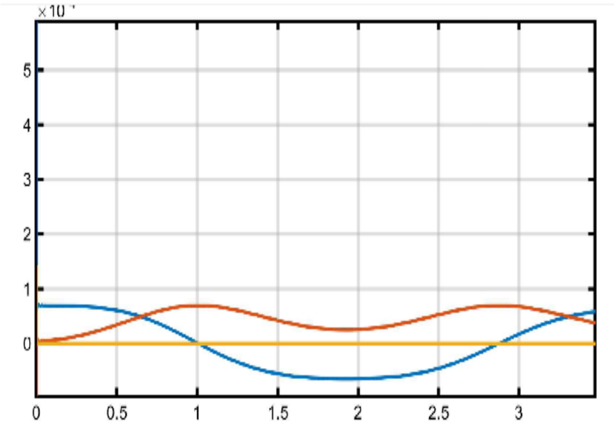

Fig 12: dq wave form in islanded mode

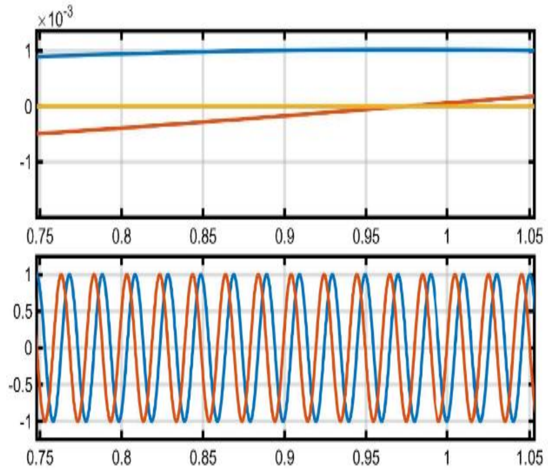

Fig 13 : sin cos dq in islanded mode

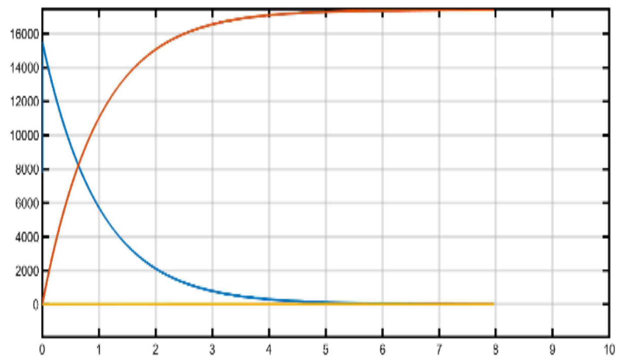

Fig 14 : solar pv array output

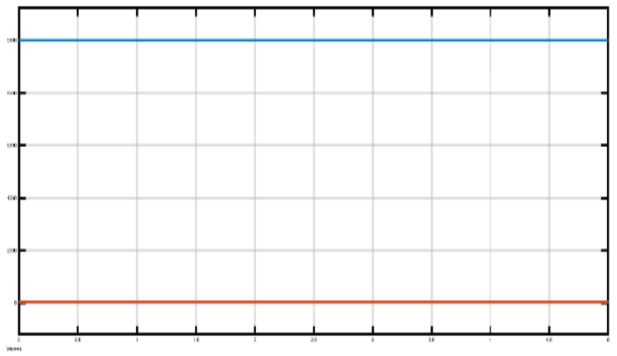

Fig15 :pv array output

IX. CONCLUSION AND FUTURE WORK

Microgrid with WT inverter and diesel generator inverter supplying power to load in islanding mode, connected to this Microgrid will be studied for " Interconneced Microgrids Reliable Power Supply".

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