Modelling of an Optimized Microgrid Model by Integrating DG Distributed Generation Sources to IEEE 13 Bus System

Bisma Imtiaz, Imran Zafar, and Cui Yuanhui

***Abstract* — Due to the rapid increase in energy demand with depleting conventional sources, the world's interest is moving towards renewable energy sources. Microgrid provides easy and reliable integration of distributed generation (DG) units based on renewable energy sources to the grid. The DG's are usually integrated to microgrid through inverters. For a reliable operation of microgrid, it must have to operate in grid connected as well as isolated mode. Due to sudden mode change, performance of the DG inverter system will be compromised. Design and simulation of an optimized microgrid model in MATLAB/Simulink is presented in this work. The goal of the designed model is to integrate the inverter-interfaced DG's to the microgrid in an efficient manner. The IEEE 13 bus test feeder has been converted to a microgrid by integration of DG's including diesel engine generator, photovoltaic (PV) block and battery. The main feature of the designed MG model is its optimization in both operated modes to ensure the high reliability. For reliable interconnection of designed MG model to the power grid, a control scheme for DG inverter system based on PI controllers and DQ-PLL (phase-locked loop) has been designed. This designed scheme provides constant voltage in isolated mode and constant currents in grid connected mode. For power quality improvement, the regulation of harmonic current insertion has been performed using LCL filter. The performance of the designed MG model has been evaluated from the simulation results in MATLAB/ Simulink.**

***Index Terms* — Distributed Generation (DG), microgrid, modelling of microgrid, IEEE 13 bus test feeder, inverter-interfaced DG, renewable energy sources.**

I. Introduction

With the increase in power demand, depletion of fossil fuels and necessity of clean energy, renewable energy sources have gained significant importance [1]. World has suffered major blackouts in recent years and the researchers have proposed distributed generation (DG) as the solution for these major problems [2]. Distributed generation, also known as centralized energy, proposes the idea of on-site generation [3]. The best way to integrate DG in power system without redesigning the whole distribution system and saving a lot of money, is introducing a microgrid [4]. According to the US department of energy, microgrid can be defined as: *"*group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode" [5].

The components of MG and their related issues can be classified and understood easily. But when all of these components are integrated to form a real time MG, the study as a whole system becomes quite difficult [6]. For the development of an adequate control and reliable system, modelling of MG is an important research topic these days. Modelling of the MG and its simulation is required for performing fault analysis, stability analysis, reliability operation, designing of protection and control scheme, application of optimization techniques, economic dispatch and unit commitment [7]–[14].

Different modelling schemes are adopted for designing and simulation of MG including mathematical modelling, real time-modelling and dynamic modelling as reviewed in literature[15]. Different software are available for designing and modelling of MG. [16]. Among them Simulink MATLAB, PSCAD, EMTDC, ATPDraw, ETAP µGrid, and RAPSim are commonly used. In this work, MATLAB/Simulink is used for its flexible nature and accurate results. It offers built-in modules and the users are allowed to create their own library as well [17]. Detailed explanation on MG structure based on different layers (component, communication, information, application, business) and classification of MG (MG for rural, urban or industrial use) is done in [18]. In order to ensure reliability, safety, and power quality of the system, proper handling in terms of control is required for installation of DG's into the power system [19]. In [20], the interconnection parameters for connecting DG's to the grid are explained.

When MG is in grid connected mode, all the control is provided by the main grid, but it still deals with some critical loads at Point of Common Coupling PCC. Therefore, it acts as PQ bus in grid connected mode. While in islanded mode, the main supply from the grid is cut-off. In this mode, the MG is responsible for maintaining constant frequency and voltage, thus MG acts as PV bus [21]. In grid-connected mode, MG has to maintain constant currents to follow the preset signals from the main grid and in isolated mode, it has to maintain constant voltages to supply load [22].

DG's in microgrid are interfaced to the main grid through voltage source inverters. These inverters are responsible for supplying power from DG's in grid connected mode. But the

Submitted on March 02, 2021.
Published on March 24, 2021.
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inverters inject additional harmonic currents to the grid because of non-linear loads and voltage harmonics at PCC. It results in poor power quality and increases power losses too. While in islanded mode, harmonic current insertion becomes a major issue due to the droop control loops. The output impedance of inverter and line impedance are responsible for harmonic current sharing, which results in voltage distortions at PCC. Due to resonance in MG, these voltage distortions create stability issues [23], [24]. There is a certain limit to which harmonics can be injected to the grid. According to standard to IEEE Standard 1547, the THD Total Harmonic current Distortion should be less than 5% at the rated output power [25], [26]. In [27], a MG model is simulated in MATLAB for the comparison of harmonic insertion by DER's. Different techniques have been proposed by researchers for removing the harmonic contents. The common technique involves addition of series or shunt active and passive filters [28]–[30]. In literature [31], MG model using power converters based on PWM (Pulse Width Modulation) technique, is designed for supplying loads through DG's. In [32] a MG model based on PV(Photo Voltaic) and PEMFC (Proton Exchange Membrane Fuel Cell) along with power electronics interface, is modelled in MATLAB/Simulink. Modelling of MG model based on real time measurements, is done. The scheme for practical installation of MG in a power system is determined and the optimization approach operating Energy Storage devices is proposed [33]. But these methods are not cost effective and also they don't improve the voltage distortions in MG. The proposed method in this work, not only attenuates harmonics but also contributes in designing voltage control scheme for supplying constant voltages in isolated mode and constant current in grid-mode[34].

The designed Optimized MG model in this work is unique in following ways:

- Detailed modelling of each module in MATLAB/Simulink is explained separately.
- The performance is analyzed by integrating the DG's to IEEE 13-test feeder, which is a heavily loaded distribution feeder.
- Control Scheme for each block is designed for a reliable MG operation in both grid-connected as well as isolated mode.
- In PV array, the designed control scheme using Model Predictive Control MPC algorithm is following MPPT (Maximum Power Point Tracking) technique efficiently.
- A separate control scheme for inverter-based sources is designed for reliable integration of DG's to the main grid. The control scheme provides constant current in grid-connected mode and constant voltages in isolated mode.
- Further power quality is improved by mitigation of harmonics using LCL filter.

II. Modelling of Microgrid

In this work, an optimized microgrid model has been designed and simulated using MATLAB Simulink. In order to design the microgrid model, modification of IEEE test bus feeder is done by installing distributed generation sources. That includes diesel engine generator, PV module and battery module with a control scheme for optimizing MG reliability. The DG's are allocated in such a way that they support each other and ensure the smooth operation of microgrid. The control schemes within the modules are designed for each block to ensure the operation of microgrid in both grid connected and islanded mode. The detailed model of IEEE 13 bus test feeder is designed in MATLAB by ignoring voltage regulator. Separate models for load, line and other components are explained in detail. In diesel generator model, control scheme using diesel engine governor and hydraulic governor is explained in detail. In PV module, MPPT based model predictive algorithm is applied for tracking maximum output power. For the battery control, bidirectional voltage source converters are used to operate battery module for charging and discharging in grid connected and isolated mode. A separate voltage and current control schemes for inverter-based sources are designed to maintain constant voltages and constant currents in grid-connected and isolated mode respectively. LCL filters are used for improving harmonic current sharing. All of these blocks are designed in MATLAB (Simulink) and their detailed models with simulations are presented.

A. *Modelling of IEEE 13-bus Test Feeder System*

The grid is quite short (8200 ft), but heavily loaded regarding a voltage level of 4.16 kV. It consists of 13 buses that are interconnected by 10 overhead and underground lines, capacitor banks of 200 kVAr capacity, a voltage regulator that is capable to change secondary voltage in steps of 0.00625 pu, one 4.16 kV/480 V in-line transformer connected in Y-configuration, unbalanced spot, distributed loads and breaker.

1) *Load Model*

The IEEE test bus feeder is a heavily loaded system consisting of three phase and single phase loads with constant PQ, I or Z connected in delta or Y-configuration. The 3-phase balanced loads are modeled using three-phase dynamic load block in Simulink and the unbalanced loads are modeled by using single-phase dynamic load blocks. The real power P and reactive power Q for load are given by (1) and (2) [27]:

$$P = Po\left(\frac{U}{Uo}\right)^{np} \qquad (1)$$

$$Q = Qo\left(\frac{U}{Uo}\right)^{nq} \qquad (2)$$

where

P_o, Q_o and U_o are the initial values of active power, reactive power and voltages. The constant n_p and n_q are controlling the type of load as PQ, I or Z.

The details of the load models as specified by IEEE [35] are used in this model.

The total load at all of the three phases is unbalanced as shown in Table I:

TABLE I: TOTAL LOAD OF ALL THREE PHASES

Phases	Active Power P (MW)	Reactive Power Q (kVAR)
Phase A	1.175	416
Phase B	1.039	465
Phase C	1.625	878

2) Line Model

For modelling lines of distribution feeder, PI-line model as proposed in [27] is used as shown in Fig. 1. The line configuration data, the impedance and admittance data as specified by IEEE is available in [35]. The MATLAB script written to parameterize the load model is taken from [27].

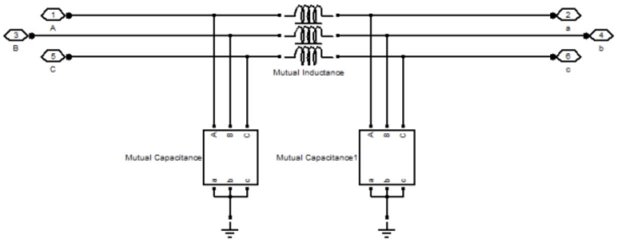


Fig. 1. 3-phase PI line model.

3) Transformer Model

3-phase transformer model block is used with the following parameters in Table II [35]:

TABLE II: TRANSFORMER BLOCK PARAMETERS

	kVA	kV-high	kV-low	R-%	X-%
Substation	5000	115-D	4.16-Gr.Y	1	8
XFM-1	500	4.16-Gr.W	0.48-Gr.W	1.1	2

4) Capacitor Model

The capacitor banks are modeled using series RLC branch and capacitor data is given in Table III [35]. 3-phase capacitor bank model is shown in Fig. 2.

TABLE III: CAPACITOR DATA

Node	Ph-A	Ph-B	Ph-C
	kVAr	kVAr	kVAr
675	200	200	200
611			100
Total	200	200	300

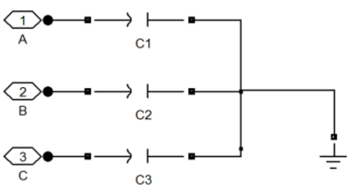


Fig. 2. 3-phase capacitor bank model.

5) Voltage Regulator

The goal of this research is to make a simpler model of micro gird using DG's without losing accuracy. To achieve this, IEEE-13 Bus system is modelled by excluding voltage regulator. As DG's may alters the voltage level in the grid [36].

6) Simulink Model of IEEE-13 Bus Test System

The model given in [37] is adjusted according to above parameters. The Simulink model of IEEE-13 bus test system is shown in Fig. 3.

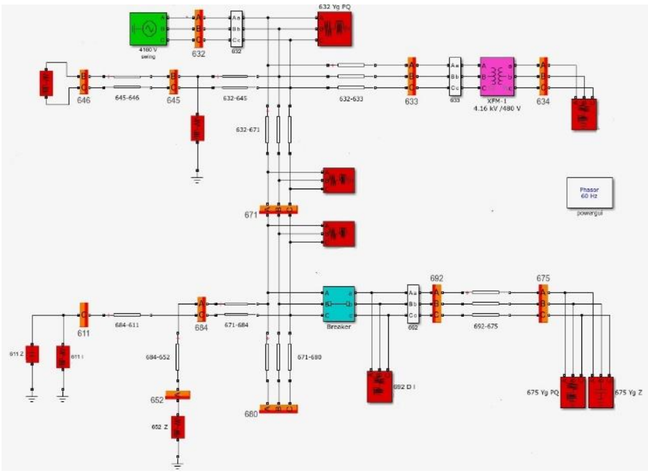


Fig. 3. Simulink model of IEEE 13-bus system.

B. Photovoltaic (PV) Module

A PV Module of 0.5 MW capacity is modeled in MATLAB/SIMULINK. To extract highest power efficiency, the design of PV module is done using MPPT (Maximum Power Point Tracking) technique. To achieve the peak power voltage, MPPT compares the voltage produced by PV module with the battery voltage and then finds the best power to charge battery by providing maximum currents in battery [38]. There are lots of MPPT algorithms, among them (P&O) Perturb and Observe are widely used algorithms because of their 98% tracking efficiency. They are also easy to implement, as they do not need system parameters for their implementation. Their working principle is based on comparison of changing voltage and power levels to find maximum power point. In addition, these algorithms can calculate the desired parameters of voltage, current and duty cycle for the functioning of MPPT technique. Thus by controlling the voltage and current level, the operating point is shifted to achieve maximum power point requirements [39].

The PV module designed in this model is based on Model Predictive Control (MPC) algorithm. First the power converter stage is designed. Inverter control algorithm is combined with MPPT algorithm to control the active power and reactive power. The Park transform is used to get the currents in dq frame. The I_d gives the peak value of the current, to control I_d it is compared with I_{ref} (reference current). Then the error is applied to a PI controller. To control reactive power, I_q parameter is used. For generating reference signals, abc frame is used. MPPT algorithm is designed based on I_{ref} as shown in figure 6. The output of MPPT is connected to inverter control algorithm. The peak-power voltage is determined by MPPT and it generates (I_{ref}) reference current for inverters. The switching signals for operating 3-phase inverters are obtained by the MPC algorithm depending upon the reference current and then the power flow is determined [40]. PV array parameters are listed in Table IV. This PV model was connected to microgrid model using a step-up transformer of 1 MVA to step up the voltages to the grid voltage of 4.16 KV. The final Simulink model is shown in Fig. 4.

TABLE IV: PV ARRAY PARAMETERS

Module	SunPower SPR-230E-WHT-D
Parallel strings	11
Series connected modules per string	21
Max power	53kW at 1000 W/m^2
Tss	0.1us
Mpp voltage	850 V

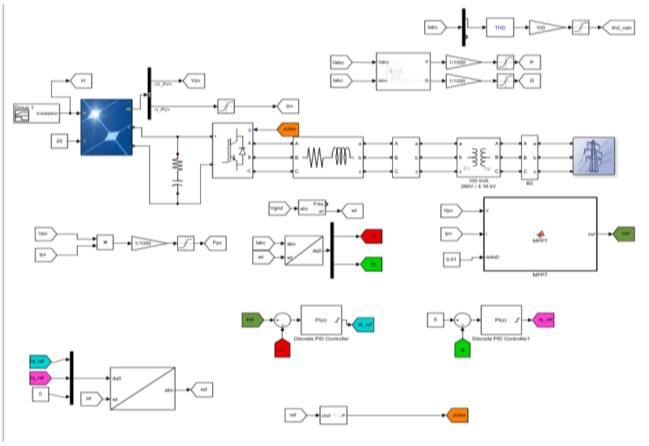


Fig. 4. Final Simulink model of PV Array.

C. Modelling of Diesel Generator

A diesel generator of 2.4 kV and 3.125 MVA capacity is connected to the IEEE 13 bus feeder using a step up transformer of capacity 5 MVA 2.4 kV/4.16 kV. The main purpose of installing diesel generator is to provide support to the grid. The output of the generator varies according to the load demand in order to satisfy the load curve.[41]

1) Diesel Engine Speed Regulator (Governor)

The governor is a mechanical or electromechanical device for controlling the speed of an engine automatically by adjusting the intake of the fuel [42]. In this microgrid model, Grid connected as well as the Islanding mode is implemented. In Grid connected mode, voltage and frequency references are maintained according to the grid. But in isolated mode, there is no signal from grid and the generator is providing the reference signal for maintaining frequency by using the diesel engine governor.

2) Hydraulic Turbine Governor

When the microgrid is in grid-connected mode, the voltage and frequency control is done by the grid but there are still some critical loads at point of common coupling (PCC) that are handled by MG. The hydraulic turbine governor is responsible for maintaining frequency in microgrid during grid connected mode and it is taking reference signals from the grid. But in isolated mode, diesel engine governor is maintaining the frequency of microgrid by taking reference from generator and hydraulic turbine governor is maintaining frequency of grid by taking reference from the grid [43].The complete Simulink model of diesel generator is shown in Fig. 5.

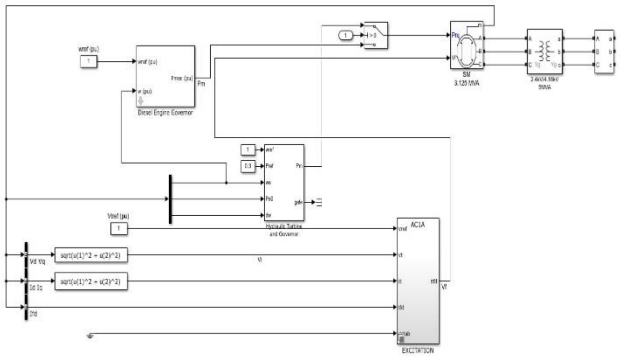


Fig. 5. Diesel engine model in Simulink.

D. Energy Storage Devices

To ensure the smooth operation in grid connected mode, lead acid battery is used in case of mismatch of voltage levels. In islanded mode, this battery is used to satisfy the load demand. By designing careful control scheme, the same storage device can be used in both grid connected and islanded mode of Microgrid.

1) Battery Model

The parameters for charge and discharge model of the battery are taken from [44] . Lead acid battery was used in this model and the model summary for Lead-Acid battery is given in (3) and (4) [44]:

$$\text{Discharge:} U_{batt} = E_o - R.i - K\frac{Q}{Q-it}.(it + i^*) + Exp(t) \quad (3)$$

$$\text{Charge}: U_{batt} = E_o - R.i - K\frac{Q}{it-0.1.Q}.i^* - K\frac{Q}{Q-it}.it + Exp(t) \quad (4)$$

where
Ubatt = battery voltage (V);
E0 = constant voltage of battery (V);
K = polarization constant (V/(Ah));
Q = capacity of battery (Ah);
it = idt = actual charge of battery c(Ah);
i = current of battery (A);
i∗ = filtered current (A);
Exp(t) = exponential zone voltage (U).

2) Battery Power Controllers

Bidirectional voltage source converter is used in this model that ensures the smooth operation of batteries by providing a uniform voltage supply and recharging the batteries at same events [45] [46]. For this purpose, bidirectional switches are connected with diodes that will allow bidirectional current flow. When battery is discharging, these converters act as buck converter by providing current to the main grid (i.e., current flow from battery to main grid). When battery is charging, it acts as a boost converter, while the current is flowing into the battery (i-e current flow from main grid to battery) [43].

3) Simulink Model of the Battery

This battery model is connected to the microgrid using a step-up transformer and is shown in Fig. 6.

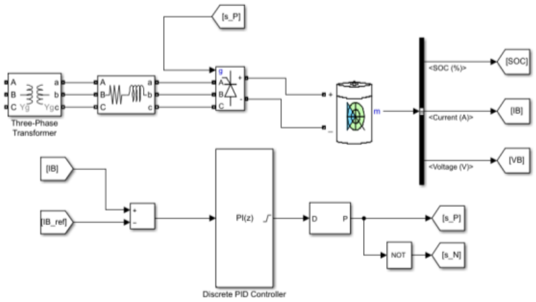


Fig. 6. Battery Model in simulink.

III. Control Scheme In Proposed Micorgrid Model

The proposed microgrid model is working in both isolated and grid connected mode. The converter controllers proposed in each distributed generation model are controlling the power flow in microgrid. In addition, LCL filter, current and voltage controllers are designed to supply reliable power quality in both modes.

A. LCL filter

To improve the harmonic current sharing, an LCL filter compensation is used on the grid side to filter the harmonics injected by the voltage source converters. The LCL filter is shown in Fig. 7.

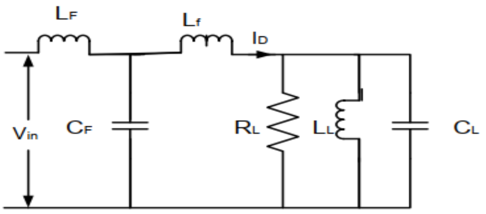


Fig. 7. LCL filter and parallel RLC load circuit.

B. Islanded Mode

When the MG is isolated from the main grid, the main supply is cut off. In isolated mode, grid isn't providing any reference signal to MG for maintaining voltage and frequency. In this case, MG has to follow a new reference in order to supply reliable power quality. This new reference is generated using droop control, phase locked loop DQ-PLL and PI controller [47], [48]. The battery and PV module in both modes (grid connected and isolated modes) are operated in PQ (active power-reactive power). The control scheme based on dq reference as proposed in [49] is used for designing control strategy as shown in Fig. 8. The proposed controller is composed of power control and current control loop. The power control loop is responsible for providing set-points for current. This can be achieved by aligning d-axis according to grid voltage. The dq reference is rotated at fundamental frequency in order to achieve control strategy. PLL block is responsible for calculating fundamental frequency. The PLL blocks use park's transformation to get the voltage and current output of the converter. By using dq reference, the sinusoidal command is converted to DC command and PI compensators can be integrated in control design blocks [49].

1) Voltage Controller

During islanded mode, voltage controller is designed to supply constant voltage to the load through inverters. Current compensation is utilized to achieve voltage regulation[50] . The designed control scheme is composed of two loops 1.inner current loop 2.outer current loop. The block diagram including LCL filter, RCL filter and PI controllers is shown in Fig. 9. Transfer function for PI controllers is given in (5) [22].

$$C(S) = K_p + \frac{K_1}{S} \qquad (5)$$

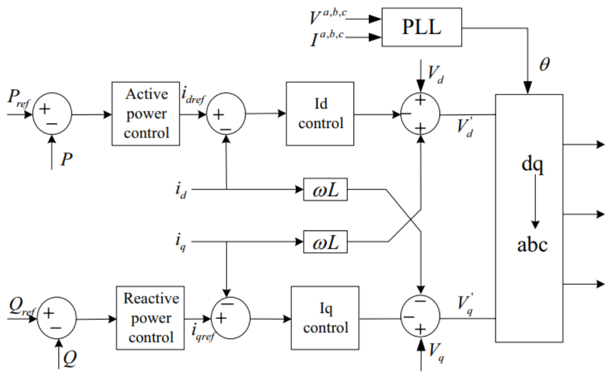


Fig. 8. PQ (active power-reactive power) control strategy.

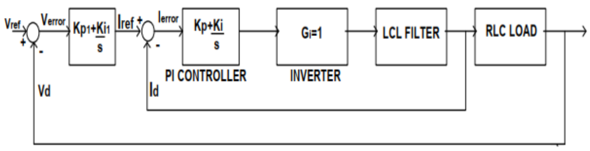


Fig. 9. Block diagram of voltage control inverter.

C. Grid Connected Mode

In Grid connected mode voltage and frequency references are maintained according to the grid. In this mode, the grid is responsible to satisfy load demand but there are still some critical loads at point of common coupling (PCC) that are handled by MG. The hydraulic turbine governor is following grid's frequency and voltage to generate reference signals for MG. All the distributed generations are following this reference signal generated by hydraulic turbine governor.

1) Current Controller

In grid connected mode, the MG has to strictly follow the preset power and acts in constant current mode. The purpose of current controller is to maintain constant current output [51]. To calculate the transfer function for current controller, LCL filter and RLC load circuit blocks are utilized. The gain is ideally taken to be 1. The block diagram is shown in Fig. 10. The transfer function for PI controller block is given in (5) [22].

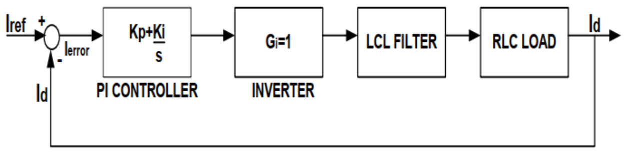


Fig. 10. Block diagram of current control inverter.

IV. Microgrid Model And Simulations

Bus 650 is considered as point of common coupling PCC. Bidirectional power flow can occur at this point. Swing generator is connected at PCC in order to model the main grid (set to 4.16 kV) and it will adapt to system configurations accordingly. Therefore, there will be no need to perform load flow according to generator settings again [36]. Integration of DG helps in reducing power losses, but it comes on the expense of worse voltage profile. In order to improve voltage profile, allocation of DG units must be done in a very efficient manner to achieve the optimized performance. DG allocation is treated as a constrained non-linear optimization problem that is solved by iterative methods or complex heuristic techniques [52], [53]. For solving optimization problem, power quality and economics benefits are treated as constraints. The DG optimal allocation points are chosen to be bus 675 for integrating diesel generator, bus 632 for integrating battery and bus 671 for integrating PV array as shown in Fig. 11. The complete model of Microgrid in Simulink after integrating 3 DG's is shown in Fig. 12.

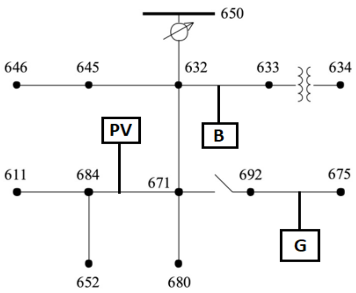


Fig. 11. Modified IEEE 13-Bus feeder.

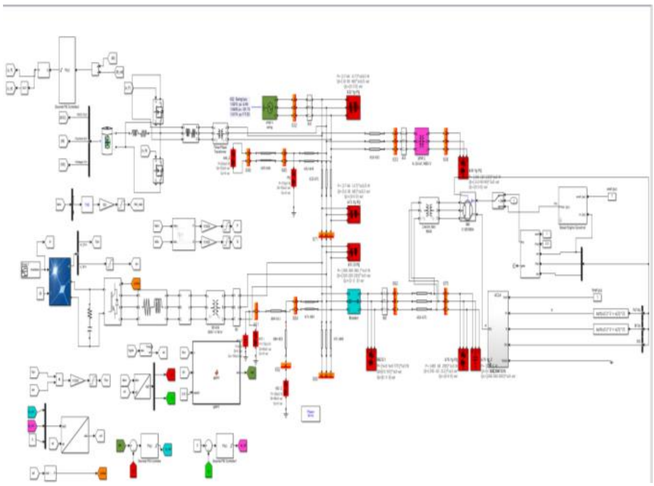


Fig. 12. Microgrid Model in Simulink.

A. Simulations

The PV module is simulated separately, to evaluate the performance of MPPT algorithm. The designed algorithm is working efficiently as shown in MPPT curve and $P_{\_pv}$ as shown in Fig. 13.

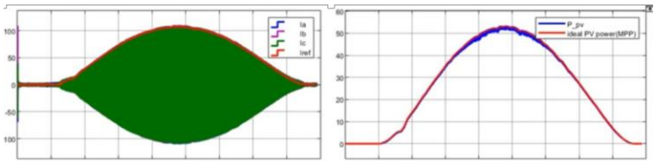
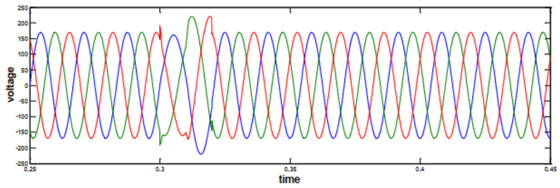
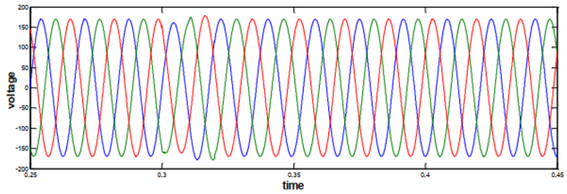


Fig. 13. Simulations of PV array module (I_{ref} curve, MPPT and PV Power curve).

The designed Microgrid model is isolated from the grid, by disconnecting it from the main supply. At first the performance is analyzed without integrating voltage controller. In this scenario the voltage profile show fluctuations as shown in Fig. 14 (a). To improve the voltage profile, voltage controller is integrated. The designed controller scheme for voltage control works efficiently as shown in Fig. 14 (b).



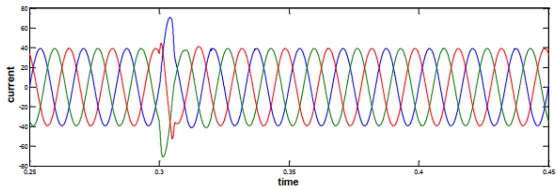
(a)



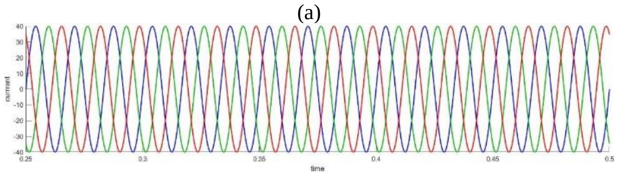
(b)

Fig. 14. Line voltage without voltage controller (a) and with voltage controller (b).

Once the isolated mode is implemented, grid connected mode is analyzed. The current profile without and with integrating current controller is compared in Fig. 15 (a) and Fig. 15 (b).



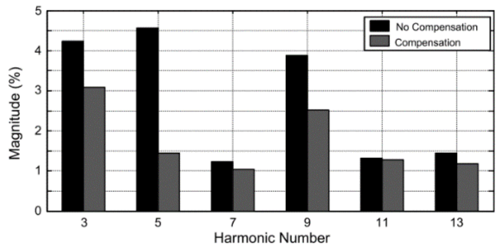
(a)



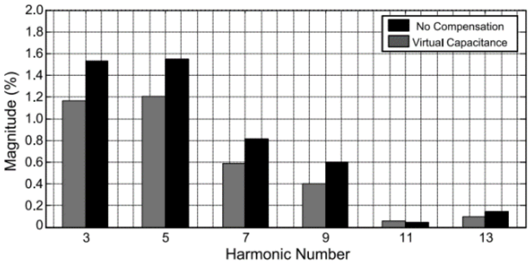
(b)

Fig. 15. Line current without current regulator (a) and with current regulator (b).

During grid connected mode, the currents at point of common coupling PCC (bus 650) are measured without and with integrating LCL filter compensation. The comparison is plotted as shown in Fig. 16 (a). It is evident that, LCL filter compensation reduces the harmonic current sharing at PCC. In isolated mode, the voltage harmonics V_{THD} are compared at PCC. When the compensation is introduced, the V_{THD} was reduced. The comparison is shown in Fig. 16 (b).



(a)



(b)

Fig. 16. Current harmonics (a) and voltage harmonics (b) at PCC.

B. Results

An optimized micro grid model is designed by integrating distributed generation sources in IEEE test bus feeder. The control schemes are designed, to operate the microgrid model for both isolated as well as grid connected mode. In grid connected mode, the DG's are following the reference signal based on main grid's voltage, whereas in isolated mode a new reference for voltage is generated based on droop control loop. The line voltages are successfully improved in isolated mode with voltage converter as shown in Fig. 14 (a) and Fig. 14 (b). In grid connected mode, the designed current controller is keeping the current constant as shown in Fig. 15 (a) and Fig. 15 (b). The designed control in PV module based on MPPT technique is tracking maximum output as shown in Fig. 13. The harmonic current sharing is improved and voltage harmonics V_{THD} are reduced as shown in Fig. 16 (a) and Fig. 16 (b). The presented model can be used as a base work for performing different analysis on microgrid and for creating more complex microgrid designs. As a future work, wind turbine module can also be integrated in the system to analyze the effects of integrating wind power in power system.

V. CONCLUSION

In this work, detailed modelling of microgrid, its components and design of control schemes for integration of DG's to IEEE 13 bus distribution network has been done successfully. The designed microgrid model is working efficiently in both grid-connected and isolated-mode. The work has been accomplished after substantial research. Control schemes for each module is chosen to achieve optimized results and their performance have been evaluated by performing simulations in MATLAB. The aim of this work, an optimized MG model design with improved power quality has been achieved.

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