# Design and Implementation of a Laboratory-scale Microgrid

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## Abstract

*This paper deals with the implementation of a single phase laboratory scale micro grid (MG) including a control system based on emulated energy resources and loads which permits the experimentation of various scenarios. The proposed MG is comprised of a wind turbine simulator, a solar photovoltaic (PV) and a battery bank which are connected to the MG via flexible Voltage Source Inverters respectively. Although a MG can operate either in grid connected mode or islanded mode, in our research we have mainly focused on islanded operation only. In that mode, bidirectional inverter performs a major role in maintaining the voltage and frequency at an acceptable level for safe collaborative operation. The results of these studies show the capability of developing a reliable control mechanism for islanding operation of micro grids based on the proposed concept.*


## 1. Introduction[1]

Legacy electrical infrastructure is failing to cater to the needs of modern energy intensive society due to the scarcity of conventional energy resources and negative environmental impact of non-renewable energy recourses. Thus there is a massive urgency to accelerate the utilization of Distributed Energy Resources (DERs). Of late DERs such as wind turbines, photovoltaic (PV), solar thermal and waste water from industries have been gaining wide interest due to the benefits such as high reliability, environmental concerns and energy cost reduction [1], [2]. However application of individual distributed generators in abundance can cause many problems such as uncertainty, randomness, intermittency and uncontrollability [3], [4].

A proper way to sort out these problems of distributed generation is to consider these DERs and associated loads as a subsystem or a "micro grid". When a fault occurs, these DERs and associated loads can be separated from the distribution system in order to isolate the micro grid's load from the main grid. This ability to island the DERs and associated loads together as a whole provides a higher local reliability in terms of power system stability.

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## 2. Methodology

*2.1 An Overview of a Microgrid*

A MG is a collective integral of DERs and a variety of loads which are located in close vicinity. A MG can operate either in grid-connected mode or islanded mode and hence increase the reliability of energy supplies by disconnecting from the utility grid once a network fault occurs. But our research MG only operates in islanded mode.

All the DERs namely Solar PV, Wind Simulator and the Battery Bank in this proposed architect are connected to the system via power electronic interfaces [5]. Since these DERs have no rotating masses, the inertia of the whole system is somewhat low compared to synchronous generators in the conventional power system. Further, this new system has a slow response to the dynamic transient situations which occur while in operation. Moreover, the conventional power systems have energy storage on rotating masses which provides energy balance in such situations. Hence MG requires some sort of energy storage like batteries or flywheels to face transients in islanded operation [6]. In our proposed architect we are using a battery bank for this purpose and it should be capable of absorbing or dispersing power during such transient conditions. In order to do that, the battery bank should have a higher capacity compared to solar PV and wind turbine simulator. The reason is that when there are no loads, the battery bank should be able to accept both the power coming from the wind turbine simulator and the solar PV.

There are many limitations and problems to be overcame in developing MG solutions. There is no accepted benchmark testing system for MGs. Hence it is rather difficult to validate the operation [7] of a MG unless a proper simulation is being done.

Further research in developing a hardware test bed to implement the control strategies and verify the economical operation of the MG is still necessary. This research is focused on design and development of a single-phase laboratory-scale MG system and coordination of individual components with a well-defined control system.

### *2.2 Laboratory Scale Micro Grid System*

I. System Description

The structure of the MG system is shown in Fig. 1. It is a single phase AC (Alternating current) system, with 230V, 50Hz; comprising solar PV, wind turbine simulator and battery storage. All the DERs are connected to the AC grid via flexible power electronic interface [8]. Also there is a Micro Grid Central Controller (MGCC) which is responsible for the optimization of the MG operation.

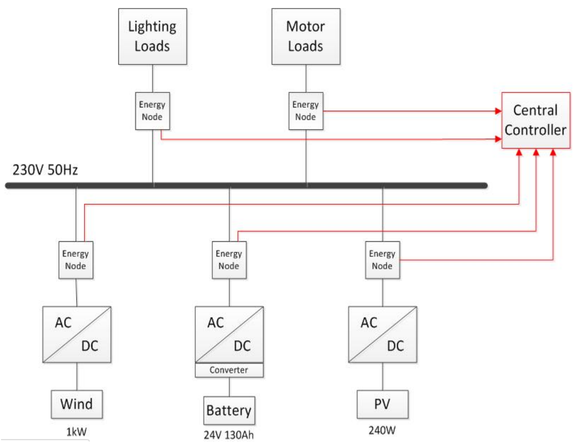


Figure 1- Schematic diagram of MG

II. Distributed Generator Simulators

1) Solar PV

The solar PV here is a 240W Direct Current (DC) voltage source, which is connected to the AC-grid by means of a DC-AC inverter. The topology for the PV inverter is a single-phase, self-commutated PV system as shown in Fig. 2.

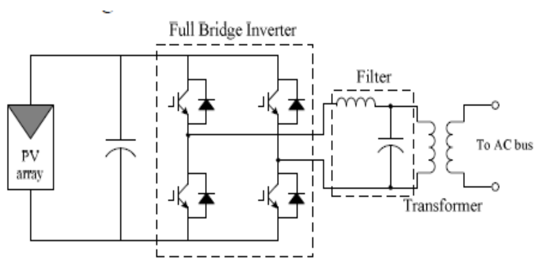


Figure 2 - Solar Inverter Circuit

The main circuit of the inverter includes a filter capacitor, a full-bridge converter and a LC filter which is limiting the high frequency harmonics injected into the AC system. The inverter is operating in the maximum power point tracking (MPPT) mode and a synthesized AC output voltage is produced by appropriately controlling the switches of the full-bridge converter.

2) Wind Simulator

A wind turbine simulator of 1kW has been already developed in order to duplicate the behavior of the wind turbine. It can operate at a point of wind characteristic curve by varying the applied voltage and the applied load.

As we know, the torque of wind turbine can be calculated by [9], [10]:

$$T_f = \frac{1}{2}\rho\pi C_T(\lambda)v^2R^3$$

Where ρ is the air density, ν is wind speed, R is the rotor radius of wind turbine, λ is the tip speed ratio and $C_T$ (λ) is the torque coefficient which can be calculated by:

$$C_T(\lambda) = a_0 + \sum_{i=1}^{6} a_i\lambda^i$$

Here a Direct current (DC) motor is driving a DC generator according to pre-fed wind data and it will be connected to the ac grid via a power electronic interface comprised of DC-DC Boost converter and DC-AC Voltage Source inverter with MPPT.

III. Energy Storage System

An important concept in battery selection is that the amp-hour rating of a battery is discharge-rate specific [11]. The greater the discharge rate, the lesser the energy; that can be withdrawn from a specific battery. In our research we have used 130Ah battery bank considering the maximum discharge rate of current and considering an allowable sustainable duration.

For the fluctuating energy generation by solar or wind energy and the fluctuating energy demand, a battery storage unit with a bi-directional inverter can be applied to ensure the power balance and stable operation of the MG system. The structure of the bi-directional inverter, which is the key component of the laboratory-scale MG, is shown in Fig.5. It is a two-stage topology consisting of a DC-AC voltage source pulse width modulation (PWM) inverter with a CUK DC-DC converter. The DC-AC full bridge inverter can operate in four-quadrant by means of pulse width modulation, while the CUK DC/DC converter, can provide the constant DC voltage to the DC/AC converter input. The high frequency (HF) transformer provides electrical isolation between the battery and the grid.

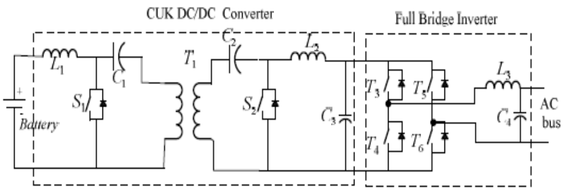


Figure 3 - Battery Inverter

IV. Loads

The system consists of two types of loads namely lighting loads and motor loads. Lighting loads comprise of four 60W bulbs and Motor Loads comprise of two 500W motors. Sometimes these loads are shed considering availability of sources and sustainability of loads through the MGCC.

*2.3 MGs Control Levels*

In this MG system, a hierarchical control architecture is proposed comprising two critical control levels. The different control levels are:

1. Local Micro generator Controllers (MC) and Load Controllers (LC)
2. Micro Grid System Central Controller (MGCC)

Figure 4 shows how the MG Controllers are placed. Here energy nodes serve the purpose of MC and LC whereas the Supervisory control and data acquisition (SCADA) system serves the purpose of MGCC.

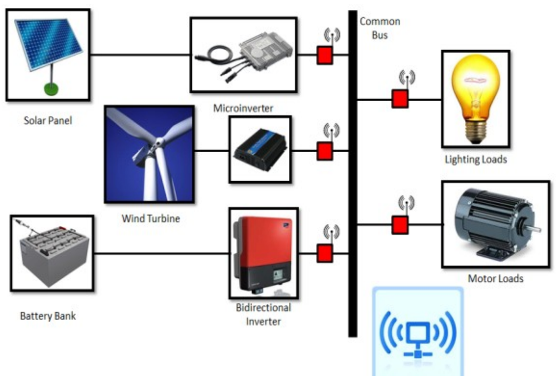


Figure 4 – Placement of MG controllers

MC uses information available at its terminals to control voltage and frequency of MG at transient conditions whereas LC provides load control capabilities. We are hoping to use wireless X-bee modules as energy nodes[12] at terminals which have the ability to calculate active and reactive power flow of each and every MS and load and that information will be communicated with MGCC.

The functions of MGCC range from monitoring the actual active and reactive power flow of DGs to optimizing the operation of micro grid by sending control signals to the relevant primary controllers via communication lines.

*2.4 DG interface inverter control*

I. PQ Control

The purpose of PQ control is to keep the active and reactive power flow of the DG according to the reference given. It does not control the frequency or voltage of the system and either the grid or some other DG with V/f control should maintain it. In our proposed architect all the DERs except battery bank run on PQ control mode.

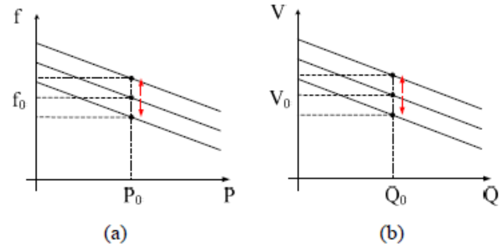


Figure 5 - PQ control

II. V/f Control

The purpose of V/f control is to maintain the frequency and voltage at a constant level regardless of their active or reactive power respectively. In our proposed architect battery bank runs on V/f control mode.

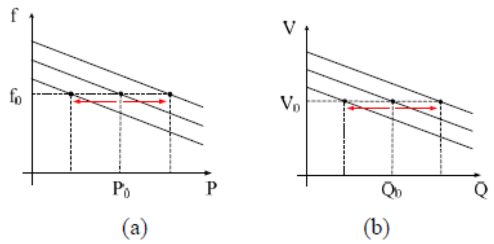


Figure 6 - V/f control

*2.5 Control system for the microgrid*

In islanded mode, this MG acts on the Master-Slave Strategy. According to this strategy slave controllers should obey the master controller through communication. MG needs no frequency regulation when connected to main grid system. However, when it is isolated from the main grid system, the master controller has the responsibility of maintaining the frequency and voltage at an acceptable level. As far as our system is concerned, this responsibility lies on the battery bank and it should operate in V/f control mode in a Master-Slave strategy in order to maintain frequency and voltage. But since all the microsources are connected via inverters to the MG, frequency is automatically regulated. So the master controller has to observe only the voltage in this case.

### *2.6 Control Algorithm of the MG*

As described earlier energy nodes send real time energy data to the SCADA system which is the central controller and when the data is received; it acts according to the following algorithm.

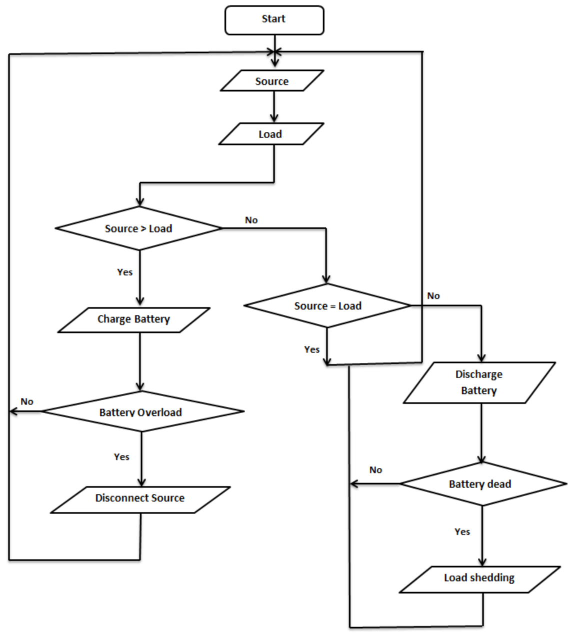


Figure 7 – Flow chart of the control algorithm

Control algorithm was then modeled using Matlab Simulink as follows.

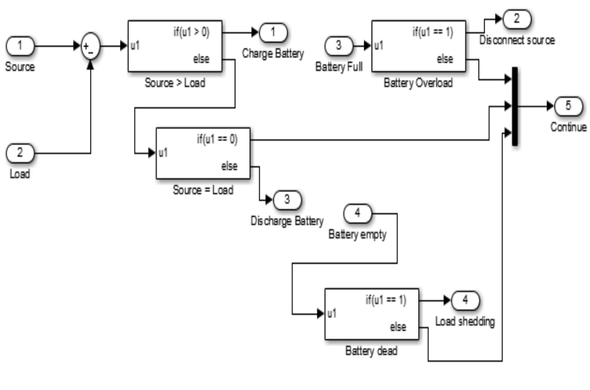


Figure 8- Matlab Simulink model of control algorithm

Here, once when the data is received it compares generation data with load data.

If source power is higher than the load required it will charge the battery. This happens until the source power gets equal to zero or until the battery get overcharged. Once when the battery gets overloaded, the SCADA system should send a control signal to disconnect one of the sources as required.

If the source power is equal to the load, there is no requirement for any change. But if the source power is less than the load, then the battery storage needs to be discharged until the source power becomes equal to zero or until the battery becomes dead. Once when the battery becomes dead, the SCADA system should send a control signal to disconnect one of the sources as required.

## 3 Results and Discussion

### *3.1 Simulation*

Our proposed system was modeled using Mat lab Simulink and following were some of the simulation results obtained.

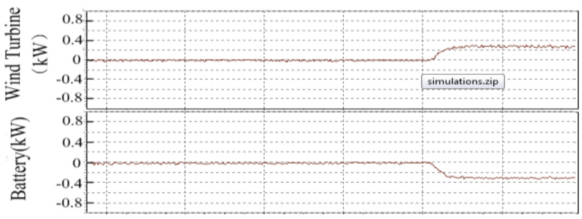


Figure 9 - Active power operation (a)

Initially, the Solar PV and the battery storage are parallel in operation, feeding a local load. But in the above case power is not drawn from the battery although it is connected. In this phase, the solar PV has a constant power output, and the battery inverter, which is working in constant V/f control, is setting the voltage and frequency of the MG. The voltage and frequency of the MG is 230V, 50Hz.

At some point, the wind turbine simulator is connecting to the MG. With the wind simulator power output gradually increasing, there is no change in solar PV power output. However the battery will decrease its output for the balance of the power.

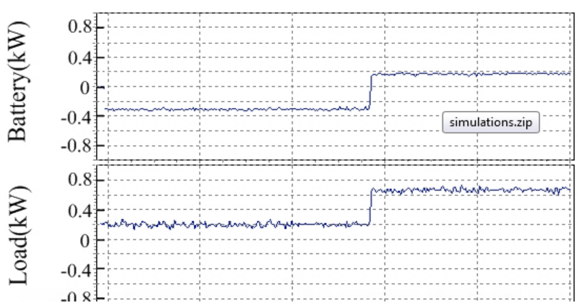


Figure 10 - Active Power Operation (b)

According to the above case, there is a sudden increase of the local load. Because of the constant output of the solar PV and wind simulator, the battery power output has to be increased correspondingly. This means that the battery inverter will change its operation mode from charging to discharging. In this islanded mode, a sudden change in the power output of solar PV and wind simulator or in the local load, the power requirement has to be supplied immediately by the battery storage and the constant voltage and frequency will be maintained.

### *3.2 Conclusion*

In this paper, various scenarios which are encountered when designing and implementing a laboratory-scale MG are discussed. This proposed MG comprised of two generators, a solar PV, a wind generator and also a battery storage which is responsible for maintaining the voltage of the system. Actually this battery bank should have the necessary capacity to absorb or disperse power in transient conditions. As far as the control system is concerned, the energy data which is acquired via energy nodes is communicated with the MGCC for the sake of the optimization of the operation of the MG. Furthermore, the control system algorithm of the MG is also discussed using a flow chart. The simulation results show that the laboratory-scale MG system can operate in the islanded mode hence increasing the reliability of energy supplies. Implementation and experimentation with the micro grid under investigation will improve future research on micro grid and smart grid projects.

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