Microgrids are the part or whole of the distribution systems to allow safe interconnections and usage of microgrids [1]. Various innovative developments are undergoing world-wide low-cost technologies for installing and operating microgrids. First step includes the integration of required number and type of converters, which connects the common DC bus with distributed energy resources (DERs), utility grid and end user loads. Two types of DERs, such as solar energy storage and doubly fed induction generator (DFIG) based wind power generator, along side the utility grid are connected to the distribution bus. The simulation has been carried out for studying the stability of various system parameters with load variation at the consumer end. This study shows that the results from the simulation model widely correspond to the expected values. An experimental test bed is created to examine the validity of the dc microgrid system.

**Keywords—** Microgrid; Distributed Energy Resources; Power Electronics Converters.

I. INTRODUCTION

Several basic technologies are used for the operation and control of the microgrids. These include distributed generators (DGs), distributed energy storage (DES), interconnection switches and control systems. A few of the many challenges are the design, acceptance, and availability of low-cost technologies for installing and operating microgrids. Various innovative developments are undergoing world-wide to allow safe interconnections and usage of microgrids [1]. Microgrids are the part or whole of the distribution systems that has single or multiple distributed energy resources (DERs) and associated loads, which can seamlessly transfer between two states of the grid connected and isolated grid mode whenever required. In order to convert a passive distribution network into an active microgrid system, the implementation process should consider the modes of generation integration, nature of loads based on the power quality requirement, operating modes of distribution network and contingency management [2].

Based on the application, main drivers, benefits and operating modes, microgrids are broadly classified into three types, namely, utility microgrids, industrial/commercial microgrids and remote microgrids. Usually, utility microgrids are developed in urban or rural networks for outage management and integration of renewable energy sources. Industrial/commercial microgrids are developed in industrial parks, university campus, shopping centers, commercial or residential buildings to enhance the power quality, reliability and energy efficiency. Remote microgrids are designed to supply power to the consumers in remote communities and geographical islands [2]. Microgrids can be categorized into DC-based and AC-based microgrids based on the nature of electricity. The DC-based microgrids have some advantages and are given below.

- DC-based DGs such as photovoltaic cells and fuel cells can inject power directly to the DC microgrid.
- Asynchronous AC sources can be connected to the DC-grid by AC/DC converters without considering voltage phases.
- DC microgrid has the features of reducing the losses caused by the reactive power and overcoming the limitation of the power flow up to certain extent.
- The grid can supply power to the power electronics equipments directly. Hence, stand-by losses caused by the AC/DC conversion can be eliminated.

Recently many research works were carried out for the design of microgrid system. In [3], the conceptual design and the feasibility of DC-based microgrid system were discussed along with a proposition of voltage control method. Utilization of wind power and aero dynamical modeling were discussed in [4]-[6]. However, detailed description about individual converter control and their effect on DC-bus stability were not found in the available literature. The control of wind power generators varies depending on its type. In DFIG based system, the converter should be designed as an active and reactive power controller.

In this paper, different types of control have been implemented for stabilized operation of power electronics converter structures. These converters are used for the connection of three types of DERs, viz. fuel cell, battery bank and DFIG based wind power generators, with the DC-bus. Mainly, closed loop control theory has been used in the converters in order to stabilize the bus voltages. In Section II, the architecture of a DC-based microgrid is described with an elaboration on required converter structures. Simulation results and discussions on the stability analysis are presented in Section III. The concluding remarks of the proposed work are given in section IV.
II. DC-BASED MICROGRID ARCHITECTURE AND CONVERTER STRUCTURE

Depending on the geographical characteristics of a remote area and resource availability, diverse types of generation sources such as small-hydro, wind-turbine, solar PV, and fuel cell sources can be used to supply electricity. In remote microgrid design, the generation sources have to be sized to serve the entire load in the area along with an adequate level of reserve capacity for contingency management [7]-[8]. In addition, load dispersion and large differences between the minimum and maximum load of the microgrid make the technology selection, sizing, and sitting of distributed energy resources as a challenging task. A DC-based microgrid is one of the proposed architecture for the geographically remote users. The considered architecture can investigate the performance and feasibility of a DC-based microgrid for small domestic and industrial drive system as illustrated in Fig. 1. In this model, two types of sources, such as solar energy storage and DFIG based wind power generator, are connected to the DC distribution node. One isolated DC/DC boost converter has been used for connecting the solar energy storage and two PFC converters has been used for connecting the utility grid and DFIG based wind generator in order to deliver energy into DC distribution bus. The DC bus is connected to different types of loads, which may require power in the form of DC or AC and can be achieved by using DC/DC buck or DC/AC converters.

![Fig. 1. DC-based microgrid architecture](image1)

![Fig. 2. Isolated full bridge DC/DC converter](image2)

The structure of isolated DC/DC full bridge converter used for connecting the solar energy storage to the dc bus is shown in Fig. 2. It consists of four switches and a transformer to achieve the desired output voltage level. Furthermore, there is isolation between input and output. The closed loop control block diagram is given in Fig. 3. This will ensure dc bus voltage constant and stabilize the dc bus during disturbances. The current supplied by this isolated dc/dc full bridge converter is $I_1$. The schematic of the power factor correction (PFC) control block diagram is shown in Fig. 4. A synchronous link inductor between utility and front end converter is incorporated to control the input current to be sinusoidal at unity power factor during its operation. Inductance on each phase serves as short time energy storage device in order to achieve DC-side voltage control and AC-side current control. The current supplied by this PFC converter is $I_2$.

![Fig. 3. Control block diagram of a full bridge DC/DC converter](image3)

![Fig. 4. PFC converter-control block diagram](image4)

The $V/f$ control structure of IG is shown in Fig. 5. A voltage controller is designed to control the slip speed ($\omega_{sl}$). Voltage controller produces negative slip speed, which is added with the measured rotor speed ($\omega_r$) to generate the frequency of excitation. A look up table is used to calculate the voltage command to the inverter for constant flux control. The control implementation is exercised in arbitrary rotating reference frame ($\omega_f$) [9]. The d-axis voltage is set to zero and the q-axis voltage is set to the peak phase voltage (in equivalent star-connection) of the machine, which is calculated from look-up table. The current supplied by this IG is $I_3$. 

![Fig. 5. V/f control structure of IG](image5)
After DC bus voltage stabilization, the loads are connected to the dc-bus. There are mixed types (AC and DC) of loads. DC loads are supplied by a DC/DC buck converter. The structure of DC/DC buck converter is shown in Fig. 6. It delivers pulses of current to the output by being in one of the two switch-states, on or off. During the on-state the diode becomes reverse biased and the input provides energy to the load and to the inductor L. During the off-state, the inductor will discharge its stored energy to the load. The capacitor C provides a stable voltage across the output load. The current supplied to the load is $I_4$.

Fig. 5. Control scheme for induction generator

Fig. 6. DC/DC buck converter

Fig. 7. Typical industrial drive system

One type of the load that requires DC power supply is connected through a DC/DC buck converter and the other type of load that requires AC power supply for industrial drives are connected through an inverter (DC/AC converter) as shown in Fig. 7. The current drawn from the dc bus is $I_5$. The power electronics interface, also, consists of protective devices for both the power electronics equipments and the local electric power systems that allow paralleling and disconnection from the system. These power electronic interfaces provide a unique capability to the energy source units and can enhance the operational reliability of a dc microgrid.

III. SIMULATION AND EXPERIMENTAL RESULTS

To validate the proposed dc microgrid architecture, extensive computer simulations have been carried out using Matlab/Simulink version 7.8. Initially, all the power electronics converters operated in open loop system, without any closed loop control. It is seen that the closed loop system operates as per specification of the reference value. Whereas the open loop system operates in unstable mode. However, if there is any mismatch in power demand or sudden change in load, the open loop system shares maximum part of the load current. This leads to unstable dc bus voltage (rise high or low). So closed loop control is provided to all the power electronics converters. All the converters are modeled and closed loop controllers are designed for each converter [...]. There are three sections, section-A deals with sudden dc-load change, section-B deals with step change in industrial loads and section-C discusses disconnection of heavy industrial load. The simulation results are shown below. The initial dc bus reference voltage is set to be rated value of 600 V. The value of the capacitor is optimized taking care of ripple and current harmonics. The true response of the current loops can, therefore, be determined. Subsequently, dc bus voltage control loop is added to verify the dynamic response of the current and voltage control loop simultaneously of the IG and PFC converter.

A. Step change in dc-load

Proposed dc microgrid structure is tested for all the adverse condition for the stability of dc bus. Initially the dc-bus is charged and all the sources and loads are connected.

Fig. 8. Steady state currents of dc-microgrid architecture, (a) $I_1$, (b) $I_2$, (c) $I_3$

Fig. 8 shows the steady state current drawn by the dc-bus to supply the load. The capacitor across the dc bus filters high frequency variations under normal operating conditions, while the output current may change according to the input energy from a solar, utility grid or wind turbine. The developed closed loop controller also guarantees the dynamic performance of the dc link voltage, and prevents excessive overshoot and oscillation under sudden changes in the output current. One
important function of the developed closed loop controller is to offer protection: if the overshoot in dc link voltage is too high, the system will enter the protection mode and then shut down the operation. Fig. 9 shows the steady state response after the dc-link voltage has settled. The reference capacitor voltage in the present case is taken as 600 V.

A sudden dc-load (I_4) is applied at t = 0.5 s and sudden change in industrial load (torque) at t = 1 s, the current responses are shown in Fig. 13. It is clearly visible the current rise and the dc bus voltage shown in Figs. 10 and 11. It is observed that there is a drop in the dc bus voltage but the dc bus stabilizes with in small period of time. Fig. 12 shows the dc bus voltage when a heavy industrial load is switched off. There is a sudden rise in dc bus voltage but developed closed loop controller prevents excessive overshoot and oscillation under sudden changes in the output current. Fig. 14 shows the current drawn by three phase load. At t = 1 s, a step load torque is applied and at t = 2 s the load is switched off. It is observed that there is no jerk in industrial drives as shown in Fig. 15. It is observed that there is no over shoot in the current.

The experimental setup is developed in this section to verify the ac-dc conversion and stabilization of the DC microgrid control. A LabVIEW based digital processor that runs on National Instruments (NI) data acquisition system (PCI-MIO16-E-4), is employed for the control of dc-microgrid. The analog input sensor signals are sampled at the rate of 20 kHz/channel. A proportional plus integral controller is implemented using NI LabVIEW Real Time (RT) programming that carries out floating point operations required for the controller implementation. The three-phase converter
bridge comprises three dual IGBT modules (SKM75GB128DN; 1200 V and 100 A). The output capacitor bank (Hitachi make, HCG F6A) has a rating of 3300 μF, 500 V dc. The power circuit is energized by increasing voltage through an autotransformer. The switching signals for IGBT's are then applied that results in usual operation of the GSC. Two current sensors (LA-55P) and a voltage sensor (LV-25P) are used and the signals are fed to A/D converter of the data acquisition card for control purpose.

Selected experimental results for ac-dc converters and load performance of dc-microgrid as shown in Fig. 1 are given in Figs. 16 -18. Fig. 16 shows the steady state result of phase voltage and current for unity power factor operation of PFC. When the dc-load is changed from 1 KW to 6 KW, the dc bus voltage remains constant and it is stable as shown in Figs. 17.

![Fig. 15. Industrial load torque and speed](image1)

![Fig. 16. Phase voltage and current with unity power factor. (Experimental)](image2)

![Fig. 17. DC-link voltage and step change in dc-load (Experimental)](image3)

![Fig. 18. Response of dc-link voltage and motor speed under reverse motoring to forward motoring (Experimental)](image4)

![Fig. 19. Phase current harmonic](image5)

### IV. CONCLUSION

The proposed dc-microgrid concepts and control, a laboratory set-up has been designed. By defining multilevel control objectives for the system module, it has been shown that the proposed system can stable during load change, maintain good-quality voltage and achieve flexible power control.

### REFERENCES


