OPERATION AND CONTROL STRATEGIES OF SOLAR PV BASED DC MICROGRID

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Abstract— Microgrid is a small-scale grid that is designed to provide power for local communities and is an aggregation of multiple distributed generators (DGs) such as renewable energy sources, conventional generators, in association with energy storage units which work together as a power supply network. Strategies for coordination among the sources, loads, and energy storages are developed based on dc voltage measurement. In grid connected mode RES (renewable energy storage) are expected to work in MPPT and deliver maximum available power to the grid. The utility grid is expected to support the balance of power and regulate the DC bus voltage. In autonomous mode of operation, the available power of RES units must meet the total load demand of microgrid, otherwise energy storage is required to supply the difference and in case of insufficient storage, system must undergo load shedding to match generation and load demand. This control enables the maximum renewable energy utilization during different operating modes of the microgrid. DC microgrid includes PV system, battery with bidirectional dc-dc converter and bidirectional inverter. To improve system reliability distributed control strategy known as DC bus signalling which is independent of central controller is introduced. Voltage level changes on the DC bus which occur as changes in the system load is used as the communication carrier for different modes of operation. Droop control method is a widely used technique for achieving load sharing in DC microgrid applications.

Index Terms— Solar PV system, bidirectional dc dc converter, battery charging-discharging, grid connected converter, DC bus signalling

I. INTRODUCTION

The environmental degradation across the globe is posing a major challenge and so movement towards the renewable energy field is necessary. By combining solar with other energy services, we can deliver an additional energy savings. The main or fundamental aim of microgrid is continuous supply of power. A microgrid consists of interconnected distributed continuous energy to meet significant portion of internal load demand. It possesses independent controls, and intentional islanding takes place with minimal service interruption [4]. A microgrid is an aggregation of multiple distributed generators (DGs) such as renewable energy sources, conventional generators, in association with energy storage units which work together as a power supply network. There are several factors for the selection of DC microgrid. Each power supply connected with the dc gird can be easily operated cooperatively because they control only the dc-grid voltage from the viewpoint of the system reliability, extendibility, and maintainability the followings are required for the power units connected with the dc grid:

The units can be connected to, or disconnected from the active dc gird, other units with different power ratings can be connected to the dc gird in the near future. At present, most of the microgrids adopt ac distribution, which have several disadvantages including synchronization requirements for multiple microsources, reactive power flow, and circulating currents due to differences in voltage magnitude, phase angle, or dc offset in a multi-inverter system [3]. Compared with ac microgrid, dc microgrid can enable easier interconnection of renewable energy sources. Because many of them, such as photovoltaic array (PVA), fuel cell (FC) and super-capacitor (SC) are natively dc sources. Adopting dc microgrid can reduce the number of conversion stages, thereby decreasing the system losses [5]. On the other hand, dc loads (eg. electric vehicle and electronic devices, etc.) can be directly supplied by low voltage dc power system.

Furthermore, power electronic interfaces for DGs have the ability to control the voltage and current disturbances. As a result, dc microgrids have now received a considerable attention from scholars and electric utility industry. The layout of the DC microgrid consists of solar PV system with MPPT, battery with bidirectional dc dc converter, grid side voltage source converter and DC loads. In order to supply an uninterrupted, highly efficient and high quality power to variable dc loads, power control and energy management strategies must be adopted, which must have the following functions: Maximum renewable energy utilisation during different operating modes, the upper/lower limits of state of charge (SoC) for battery must be considered and system can operate in either grid-connected or islanded mode. The main aim of DC microgrid is to maintain DC bus voltage as constant and for this a method called DC bus signalling is adopted here. In these methods DC bus voltage is maintained as constant [1].Control of different power electronic converters used in the microgrid is required for the stable operation either in grid connected or islanding mode. DC bus signalling is a decentralized control among which droop control method can be used for proper power sharing between power electronic converters. For the different modes of operation in DC microgrid there is maximum utilisation of renewable energy. In grid connected mode grid side voltage source converter balances the DC bus voltage by operating it as rectifier or inverter. In isolated mode battery is used to balance the power differences and maintain the DC bus voltage constant.

II. HISTORICAL BACKGROUND

A. AC and DC microgrid

In recent years, distributed generator (DG) technology has emerged as a solution to energy and environmental problems, such as global warming, depletion of fossil fuel resources, and growth of energy demand. Although DGs offer many advantages to a power system, they can cause problems such as voltage rise and protection issues as there is variation in DG penetration. The concept of a microgrid has been proposed to solve these problems. A microgrid is defined as an independent distribution network comprising various DGs, energy storage systems (ESSs), and controllable loads. There are two different microgrid concepts: the AC microgrid and the DC microgrid. Most systems adopt the AC microgrid concept, because it can utilize existing AC grid technologies, protection schemes, and standards. However, the DC microgrid concept has been introduced as the more suitable interconnection concept for DC loads and DC output DGs, such as photovoltaic systems, fuel cells, and batteries [3].

Our electric power system was designed to move central station alternating current (AC) power, via high voltage transmission lines and lower voltage distribution lines, to households and businesses that used the power in incandescent lights, AC motors, and other AC equipment. Today’s consumer equipment and tomorrows distributed renewable generation requires us to rethink this model. Electronic devices (such as computers, fluorescent lights, variable speed drives, and many other household and business appliances and equipment) need direct current (DC) input. However, all of these DC devices require conversion of the buildings AC power into DC for use, and that conversion typically uses inefficient rectifiers. Moreover, distributed renewable generation (such as rooftop solar) produces DC power but must be converted to AC to tie into the buildings electric system, only later to be reconverted to DC for many end uses. These AC-DC conversions (or DC-AC-DC in the case of rooftop solar) also result in substantial amount of energy losses. One possible solution is a DC micro-grid, which is a DC grid within a building (or serving several buildings) that minimizes or eliminates entirely these conversion losses. In the DC micro-grid system, AC power converts to DC when entering the DC grid using a highly efficiency rectifier, which then distributes the power directly to DC equipment served by the DC grid. On average, this system reduces AC to DC conversion losses from an average loss of about 32% down to 10% [6]. In addition, roof top photovoltaic (PV) and other distributed DC generation can be fed directly to DC equipment, via the DC micro-grid, without the double conversion loss (DC to AC to DC), which would be required if the DC generation output was fed into an AC system. The implementation cost and system size are reduced. Moreover, synchronization and reactive power problems, which are inherent drawbacks of an AC grid, do not occur in a DC microgrid. For protection, breaking of dc current is difficult as compared to that of ac current. This is due to the natural zero current condition (occurring twice in a power cycle frequency) in ac currents and there is no formation of problem like skin effect [6].

B. Stand-alone Systems and Grid-connected Systems

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. Photovoltaic systems can be designed to provide DC or AC power service, can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems. Thus photovoltaic systems can be classified as: Stand-alone systems, hybrid systems, grid-connected or utility interactive systems. Stand-alone PV systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC or AC electrical loads. These types of systems are powered by PV array. The simplest type of stand-alone PV system is a direct-coupled system, where the DC output of a PV module or array is directly connected to a DC load. Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours. However, the solar power outputs can fluctuate on an hourly or daily basis. The stand-alone system must, therefore, have some means of storing energy, which can be used later to supply the load during the periods of low or no power output. The hybrid system uses more than one power source which enhances the certainty of meeting load demands at all times. Photovoltaic systems can be made into hybrid systems by coupling them with various other sources (both conventional and non-conventional). Some of the non-conventional sources are: hybrid with Diesel Generator, hybrid with Fuel Cells, hybrid with biogas, hybrid with wind generated system [7]. Grid-connected PV systems are designed to operate in parallel with and interconnected with electric utility grid. The primary component in grid-connected PV systems is the inverter or power conditioning unit (PCU). The PCU converts the DC power produced by the PV array into AC power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energized. A bidirectional interface is made between the PV system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads or to back-feed the grid when the PV system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility. This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back into the utility grid when the grid is down for service or repair.

III. CONTROL AND OPERATIONAL METHODS OF DC MICROGRID

With the rapid increase in use of DC power generators and DC loads, the DC microgrid has been investigated for many years. Usually, DC microgrid should equip with energy storage components, otherwise, the variable DC sources would lead to unstable power supply. However, even equipped with energy storage, the DC sources still need to share their output power to stabilize the DC grid voltage. Power sharing control scheme for DC microgrid can be generally classified as active load sharing and droop control [4].

The active load-sharing techniques can be classified into three different types, i.e., centralized control, master slave and circular chain control. In centralized approach, it is necessary to measure the total load current, so it cannot be used in a large distributed system. In the master-slave control, the master module regulates output voltage [14]. the master acts as a voltage source converter, whereas the slave works as a current source converter. If the master unit fails, another module will take the role of master in order to avoid the overall failure of the system. There exist different variants of this control method, depending on the role of the master: (i) dedicated (ii) rotary, where the master is arbitrarily chosen, and (iii) high-crest current, where the module that brings the maximum current automatically becomes the master. The current limitation control is a variant of the circular chain control. In this case, the load voltage is controlled by the master module, whereas the slave modules are only for sharing the load current.

A. DC Bus Signalling

DBS is an extension of the concept of using charge/discharge thresholds to schedule individual sources in a distributed fashion [5]. Scheduling of the sources is achieved by making the operation of the source/storage interface converters dependent on the level of the dc bus in relation to their charge/discharge threshold; however, voltage droop is included to allow multiple converters to operate at each threshold. Voltage-level changes on the dc bus, which occur as changes in the system, force these converters to switch between voltage and constant power operation. These voltage-level changes on the dc bus are used by the source and storage interface converters to determine their mode of operation. DBS is a low-cost strategy that is implemented by setting the voltage threshold at which each source/storage interface converter becomes active. Control based on the voltage level can also be proposed to ensure high-priority loads in dc systems enjoy an uninterrupted supply of power under overload conditions. Prioritized load shedding is performed under overload conditions by controlling the loads to shut down at different voltage levels as the bus voltage collapses due to the overload. The main difference between the load shedding based on the voltage level of the dc bus and DBS is that DBS uses the dc-bus voltage for source scheduling, not load shedding. With DBS, the source and storage interface converters operate autonomously based on the voltage level of the dc bus. Each converter is assigned to a voltage threshold to trigger the point at which it begins discharging or charging.

The converters not only respond to the level of the dc bus, but they also change the level of the dc bus, automatically controlling other converters in the system. This autonomous operation is achieved by controlling the converters to exhibit three modes of operation: off, constant voltage, and constant power. Load changes and variations in generator output cause the interface converters to switch between constant voltage and constant power operation, changing the level of the dc bus. The utilization priority of each source is therefore dependent on the discharge/charge thresholds; hence, a control law is implemented by prioritizing these thresholds. The work presented here displays a DC microgrid composed of PV source connected through a DC/DC boost converter and a battery energy storage, which is connected through a bidirectional buck-boost DC/DC converter and grid side voltage source converter. Figure below shows the layout of DC microgrid

The main control objective for the individual devices can be summarized as follows.

1) Solar PV System: The primary source of power generation for the DC micro-grid is the PV system, which is controlled to operate a the maximum power point tracking (MPPT) mode to extract maximum power from the solar system. When the system load decreases and DC bus voltage decreases it operates in voltage control mode

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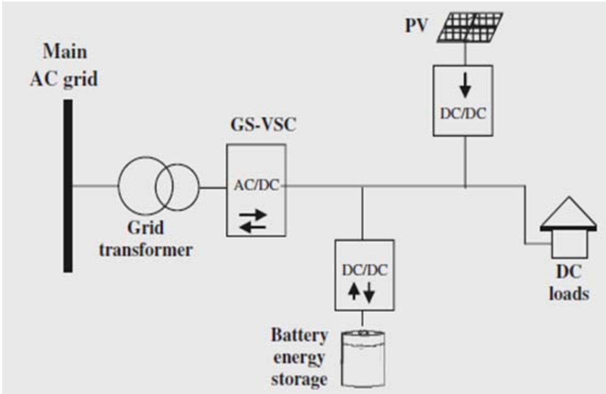

Fig.1 Layout of DC microgrid

2) Load: Under normal condition, the loads operate on their own merits. However, appropriate load management, which involves load shedding based on predefined load priority levels, may be necessary during abnormal or island conditions.

3) Grid side VSC (GS-VSC): A bi-directional DC/AC converter called GS-VSC is also used to connect the DC bus and AC main grid, which enables bi-directional power flow. When the dc microgrid is grid connected, the aim of the GS-VSC is to maintain a constant dc voltage by controlling its power exchange between the ac and dc systems to ensure active power is balanced within the dc microgrid.

4) BESS (Battery energy storage system): The BESS is utilized to balance the power difference between the PV power supply and load demand in islanding mode. Under normal conditions, the battery ES system simply operates at standby or charge/discharge mode, where a charge or discharge current order can be given by the system operator or the battery-management system based on the condition of the battery/system to ensure optimal performance. However, during abnormal conditions (e.g., ac grid fault or islanding), the ability of the GS-VSC for dc voltage control is likely to be severely affected or completely lost. Consequently, the BESS system is required to provide necessary dc voltage regulation under these conditions. The battery meets the sensitive load demand to maintain a continuous supply of power in case of fluctuations in the main grid or during islanding operation. PV and BESS are at different location in the system therefore a decentralized control strategy based on DBS is considered for the coordination of PV and BESS in the system.ie, three types of power electronic interfaces are used in this system, namely boost converter, bidirectional dc/dc converter and voltage source converter.

B. System Operating Mode and its Control

A distributed power management strategy using DBS method is used here to maintain the power balance and stable operation of DC micro-grid under any generation or load conditions. Each power electronic converter includes current and voltage controllers by suitably adjusting the reference values of current and voltage by the power management controller, each PECs can be operated in con-
stant current, constant voltage, constant power or maximum power point tracking mode. Using droop based methods has the advantage that it allows for the dc bus voltage amplitude to be used as an instantaneous global decision parameter for locally computing control actions in order to maintain the system operational and stable without making use of external communication channels. In voltage or current control mode, output voltage or current of the power electronic converter is maintained at its reference value. In case of constant power mode, output current is adjusted such that output power is equal to its reference value. For maximum power point tracking, feedback of solar PV current and voltage is used to set the
duty cycle of power electronic converter. To achieve the control objectives mentioned power management control should determine one of the following mode: maximum power point tracking (MPPT), constant current, constant voltage or constant power. DC system voltage is used as a means of communication between power electronic converters. System voltage is allowed to vary within a specified band. This allowed band is divided among various zones. Number of zones depends on the number and types of sources and storage elements used. For the dc system allowed voltage band is divided among 6 zones given below. In each zone at least one source is operating in voltage control mode and regulates the system voltage. Other sources behave as constant power sources. Zones are named based on the source operating in voltage control mode. In this approach DC bus voltage level change is utilized to communicate between sources and storages and to recognize different operating modes according to the voltage levels

defined. Voltage threshold values at which different converters become active are: (i) grid feeding controlled (ii) no charging or discharge of battery (iii) battery in discharging mode (iv) battery in charging mode (v) PV in voltage control mode (vi)Load shedding mode.

For a dc microgrid, the common dc voltage must be well maintained with a limited variation band. An abnormal dc-link voltage can disrupt normal operation or even cause the whole system to collapse. Furthermore, a constant dc voltage indicates balanced active power flow among the multi- sources and consumers (loads). Thus, the active power flow within the dc grid must be balanced under any condition. For the satisfactory operation of the dc microgrid during the variations of PV generation, load, and grid connection conditions, there are a number of different operation modes that need to be considered in order to ensure a secure and reliable power supply .The operation of the system is categorized into five modes: Mode 1(Grid connected mode with inversion), Mode 2(Grid connected mode with rectification), Mode 3(Isolated mode with battery charging),Mode 4(Isolated mode with battery discharging), Mode5(Isolated mode with load shedding)

Mode 1: DC microgrid connected to an external AC microgrid through grid side voltage source converter. At first portion of the demanded load is supplied by PV and insufficient power and the battery charging power is provided by GS-VSC by means of rectifying AC power. GS-VSC is regulating the DC voltage and PV is working in MPPT mode-Power feeding into the grid P_G,

$$P_G=P_L+P_B-P_{PV} \quad (1)$$

Mode 2: A large portion of DC load switches off and PV power generation is more than the load and battery charging power demand. The GS-VSC moves to inverting mode. Power consumption from the grid, P_G

$$P_G=P_{pv}-P_L-P_B \quad (2)$$

Mode 3: DC microgrid moves to islanding mode. PV power generation is less than the demanded load and the insufficient power is supplied by BESS, by discharging the battery energy and controls the DC voltage.

$$P_L=P_{pv}+P_B \quad (3)$$

Mode 4: PV power is larger than demanded load and battery is not fully charged. In this case battery is partially charged in constant voltage mode and BESS controls the DC voltage. PV tracks MPPT during this time.

$$P_{pv}=P_L+P_B \quad (4)$$

Mode 5: Battery fully charged and maximum generated power of PV is greater than demanded load. PV enters into voltage control mode to regulate DC voltage by controlling output power. PV works in off MPPT.

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C. Operating Strategy

The operating strategy is designed to satisfy load demand under different operating conditions. . Since DC bus signalling method is used to operate the different modes of operation, the necessary measurements are performed based on the voltage thresholds at which each converter is operating. In this section DP represents demanded power and PV represents photovoltaic power.

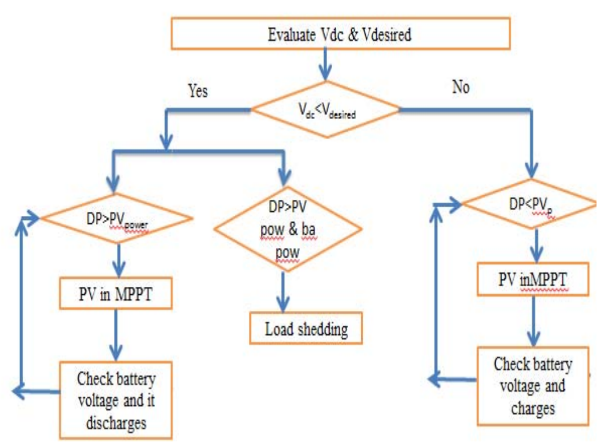

Fig.2 DC bus voltage control in isolated mode

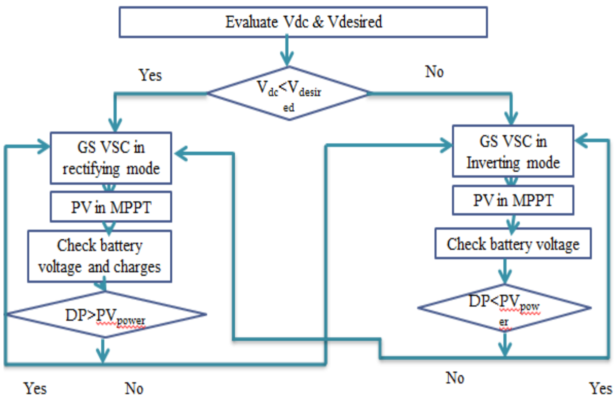

Fig.3 DC bus voltage control in grid connected mode

In order to maintain the DC bus voltage constant (our desired voltage), always check the demanded power and PV power. PV can be operated either in voltage control mode or MPPT in order to meet our requirements. In grid connected mode we are checking these powers to know whether the GS-VSC is operating as rectifier or inverter.

IV. CONCLUSION

DC micro-grids can create power systems that are more efficient and more compatible with the fastest growing segment of the load today. Here proposed a control strategy for distributed integration of PV and energy storage systems in a DC micro-grid including variable loads and solar radiation. The aim of maintaining constant DC bus voltage using DC bus signalling will be realized, considering different operating modes in grid connected and islanding states. The proposed control enables the maximum utilization of PV power during different operating conditions of the micro-grid. DC bus voltage levels are used as a communication link in order to coordinate the sources and storages in the system and acts as a control input for the operating mode switching during different operation conditions. By using decentralized control method the system turns into more flexible and expandable and can integrate more microgrids without changing the control method. System simulations will be carried out in order to validate the proposed control methods for the distributed integration of PV and energy storage in a DC microgrid.

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