

Coordinated Control and Energy Management of Distributed Generation Inverters in a Microgrid

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Abstract—This paper presents a microgrid consisting of different distributed generation (DG) units that are connected to the distribution grid. An energy-management algorithm is implemented to coordinate the operations of the different DG units in the microgrid for grid-connected and islanded operations. The proposed microgrid consists of a photovoltaic (PV) array which functions as the primary generation unit of the microgrid and a proton-exchange membrane fuel cell to supplement the variability in the power generated by the PV array. A lithium-ion storage battery is incorporated into the microgrid to mitigate peak demands during grid-connected operation and to compensate for any shortage in the generated power during islanded operation. The control design for the DG inverters employs a new model predictive control algorithm which enables faster computational time for large power systems by optimizing the steady-state and the transient control problems separately. The design concept is verified through various test scenarios to demonstrate the operational capability of the proposed microgrid, and the obtained results are discussed.

Index Terms— Distributed generation (DG), energy management, microgrid, model predictive control (MPC).

I. INTRODUCTION

Over THE last decade, efficient and reliable communication and control technologies, coupled with an increase in smarter electrical facilities, such as electric vehicles and smart meters, have resulted in an increasing number of consumers participating in demand response management (DRM) [1]–[5]. The current research is also focused on achieving a smarter grid through demand-side management (DSM), increasing energy reserves and improving the power quality of the distribution system, such as harmonic compensation for nonlinear loads [5]–[8]. These new trends enable higher levels of penetration of renewable generation, such as wind and solar power into the grid. The integration of renewable sources can supplement the generation from the distribution grid. However, these renewable sources are intermittent in their generation and might compromise the reliability and stability of the distribution network. As a result, energy-storage devices, such as batteries and ultra-capacitors, are required to compensate for the variability in the renewable sources. The incorporation of energy-storage devices is also critical for managing peak demands and variations in the load demand. In this paper, a microgrid consisting of a photovoltaic (PV) array, a proton-exchange membrane fuel cell (PEMFC), and a lithium-ion storage battery (SB) is proposed. The PEMFC is used as a backup generator unit to compensate for the power generated by the intermittent nature of the PV array. The SB is implemented for peak shaving during grid-connected operation, and to supply power for any shortage in generated power during islanded operation and to maintain the stability of the distribution network. An energy-management algorithm is designed for the microgrid to coordinate the sharing of power among different DG units. The proposed controller for the inverters of DG units is based on a newly developed model predictive control (MPC) algorithm, which optimizes the steady-state and the transient control problems separately. In this way, the computation time is greatly reduced. In what follows, this paper provides a comprehensive solution for the operation of a microgrid which will simultaneously dispatch real and reactive power during both grid-connected and islanded operations, compensate for harmonics in the load currents, and perform peak shaving and load shedding under different operating conditions.

II. SYSTEM DESCRIPTION AND MODELING

A) *System Description* :Fig. 1 shows the configuration of the microgrid proposed in this paper that is designed to operate either in the grid-connected or islanded mode. The

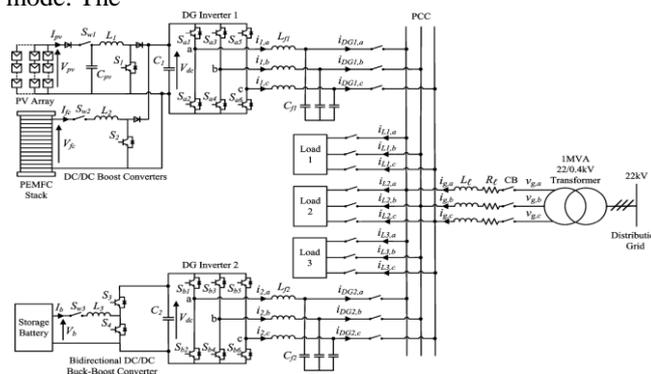


Fig. 1. Overall configuration of the proposed microgrid architecture.

main DG unit comprises a 40-kW PV array and a 15-kW PEMFC, which are connected in parallel to the dc side of the DG inverter 1 through dc/dc boost converters to regulate the dc-link voltage of the DG inverter at the desired level by delivering the necessary power. The PV array is implemented as the primary generation unit and the PEMFC is used to back up the intermittent generation of the PV array. When there is ample sunlight, the PV array operates in the MPPT mode to deliver maximum dc power P_{PV} , which is discussed in detail in [9] and [10], and the output voltage of the PV array is permitted to vary within an allowable range to ensure proper operation of the DG inverter. To maintain the level of the dc link voltage V_{dc} at the required level, the PEMFC supplements the generation of the PV array to deliver the necessary P_{fc} . When the output voltage of the PV array falls below a preset limit, the PV array is disconnected from the DG unit and the PEMFC functions as the main generation unit to deliver the required power. A 30-Ah lithium-ion SB is connected to the dc side of DG inverter 2 through a bidirectional dc/dc buck-boost converter to facilitate the charging and discharging operations. During islanded operation, the role of the SB is to maintain the power balance in the microgrid which is given by

$$P_{DG} + P_b = P_L \tag{1}$$

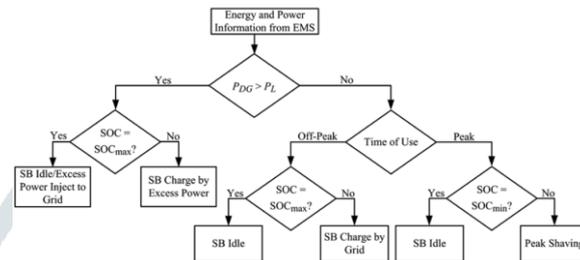


Fig. 2. Operation of the SB during grid-connected operation.

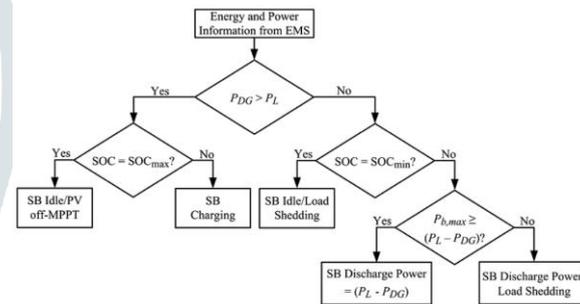


Fig. 3. Operation of the SB during islanded operation.

Where P_{DG} is the power delivered by the main DG unit, P_b is the SB power which is subjected to the charging and discharging constraints given by

$$P_b \leq P_{b, \max} \tag{2}$$

P_L is the real power delivered to the loads. The energy constraints of the SB are determined based on the state-of-charge (SOC) limits which are given as

$$SOC_{\min} \leq SOC \leq SOC_{\max} \tag{3}$$

Although the SOC of the battery cannot be measured directly, it can be determined through several estimation methods presented in [11] and [12]. When the microgrid operates islanded from the distribution grid, the SB can operate in the charging, discharging, or idle mode depending on its SOC and P_b . The flowcharts in Figs. 2 and 3 summarize the operation of the SB based on the output information provided by an energy-management system (EMS) during grid-connected and islanded operation, respectively. The EMS controls and monitors different aspects of power management, such as load forecasting, unit commitment, economic dispatch, and optimal power flow through a centralized server. Important information, such as field measurements from smart meters, transformer tap positions, and circuit-breaker (CB) status are all sent to the centralized server for processing through Ethernet. During grid-connected operation, the distribution grid is connected to the microgrid at the point of common coupling (PCC) through a circuit breaker (CB). The role of the main DG unit functions to provide local power and voltage support for the loads and, hence, reduces the burden of generation and delivery of power directly from the distribution grid. With the proliferation of power-electronics equipment being connected to the microgrid, the load currents could be distorted due to the presence of harmonic components. The DG units also function to compensate for any harmonics in the currents drawn by nonlinear loads in the microgrid, so that the harmonics will not propagate to other electrical networks connected to the PCC. Generally, there are variations in the power generated by the PV array and that demanded by the loads. If the power generated by the main DG unit is greater than the total load demand in the microgrid, the excess power can be used to charge the SB or injected into the distribution grid, depending on the SOC of the SB, as shown in Fig. 2. Conversely, when the total load demand is greater than the power generated by the main DG unit, the SB can be controlled to achieve different energy-management functions depending on its SOC and the time of use (TOU) of electricity. During off-peak periods as shown in Fig. 2, when the cost of

generation from the grid is low and if the SB's SOC is below the maximum SOC limit SOC_{max} , the SB can be charged by the grid and the loads will be supplied by the main DG unit and the grid. During peak periods, when the cost of generation from the grid is high and if the SB's SOC is above the minimum SOC limit SOC_{min} , the SB can deliver power to the grid to achieve peak shaving.

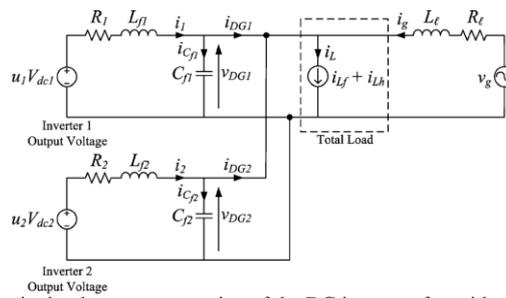


Fig. 4. Equivalent single-phase representation of the DG inverters for grid connected operation.

When a fault occurs on the upstream network of the distribution grid, the CB operates to disconnect the microgrid from the distribution grid. The main DG unit and the SB are the sole power sources left to regulate the loads. In the case when the generation capacity of the main DG unit is unable to meet the total load demand, the SB is required to provide for the shortage in real and reactive power to maintain the power balance and stability of the microgrid as shown in Fig. 3. When the total load demand exceeds the generation capacity of the main DG unit and the SB, the EMS detects a drop in the system frequency and load shedding for noncritical loads is required to restore the system frequency and maintain the stability of the microgrid.

B) DG Inverter Modeling

Figs. 4 and 5 show the equivalent single-phase representation of the DG inverters for grid-connected and islanded operation, respectively [13]–[15].

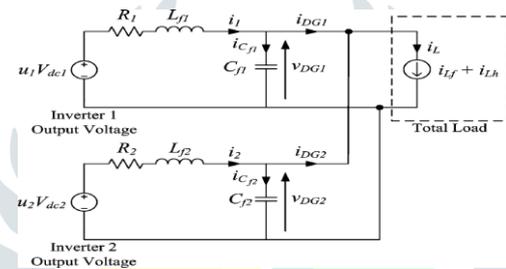


Fig. 5. Equivalent single-phase representation of the DG inverters for islanded operation.

In the grid-connected mode, the grid voltage is known and the microgrid shares the load demand with the grid. Hence, to control the power delivered to the loads, the output current of the DG inverter is controlled using the current control mode (CCM). During islanded operation, the microgrid will supply the overall load demand as shown in Fig. 5, and it is required that the output voltage be regulated to a pure sine wave with a fixed magnitude. This can be achieved through the voltage-control mode (VCM).

III. CONTROL DESIGN

With the mathematical model presented in Section II-B, this paper proposes a novel MPC algorithm for the control of the DG inverters of the microgrid. The proposed algorithm is a newly developed MPC algorithm specifically designed for fast-sampling systems, to track periodic signals so as to deal with the dual-mode operation of the microgrid. The algorithm decomposes the MPC optimization into a steady-state sub-problem and a transient sub-problem, which can be solved in parallel in a receding horizon fashion. Furthermore, the steady-state sub problem adopts a dynamic policy approach in which the computational complexity is adjustable. The decomposition also allows the steady-state sub-problem to be solved at a lower rate than the transient sub-problem if necessary. These features help to achieve a lower computational complexity and make it suitable for implementation in a fast-sampling system like our microgrid applications. In the simulation studies in this paper, the sampling interval is chosen as 0.2ms, which is considered pretty small in conventional MPC applications, but necessary for the high order of harmonics being tackled for our problem. According to [16], sampling in the range of tens of kHz is possible with state-of-the-art code generation techniques.

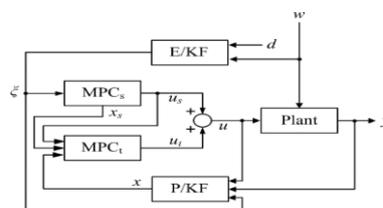


Fig. 7 Overall MPC controller for the DG inverter with E/KF denoting the exogenous Kalman filter and P/KF denoting the plant Kalman filter.

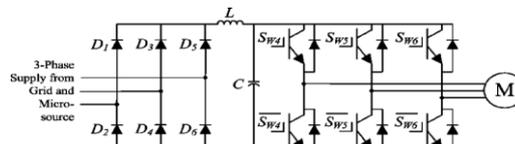


Fig. 8. Configuration of a 15-kVA three-phase ASD.

IV. SIMULATION STUDIES

The simulation model of the microgrid shown in Fig. 1 is realized in Matlab/Simulink. The microgrid is tested under various conditions to evaluate its capabilities when operating connected and islated from the distribution grid.

Three different load types consisting of linear and nonlinear loads are considered in the studies. For load 1, a 15-kVA three-phase PWM adjustable speed drive (ASD) with its configuration as shown in Fig. 8 is used and load 2 is made up of a three-phase RL load rated at $P_{L2}=28KW$ and $Q_{L2}=18.5KVar$. Load 3 is a noncritical three-phase dimmer load rated at $P_{L3}= 18KW$ and $Q_{L3}= 12.3 KVar$. Which is nonlinear in nature and will be shed under emergency conditions when the generation of the microgrid is unable to meet the load demand. The per-phase currents i_{L1} , i_{L2} , i_{L3} and drawn by loads 1, 2, and 3 for $0 \leq t \leq 0.2$ s are shown in Fig. 9.

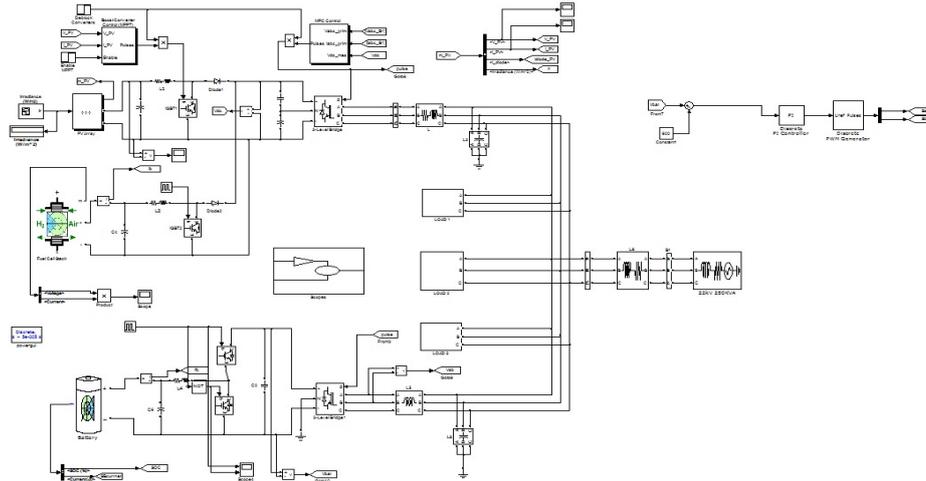


Fig9 : Grid Connected Operation

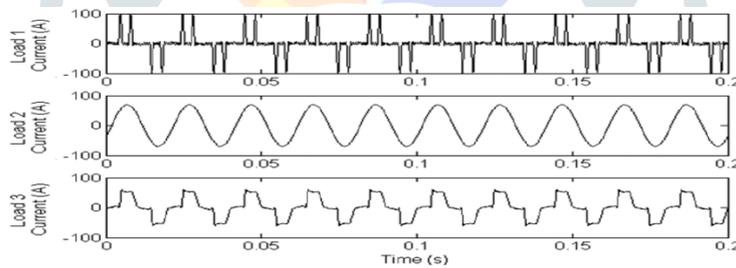


Fig10 : Per phase currents drawn by loads 1,2 and 3

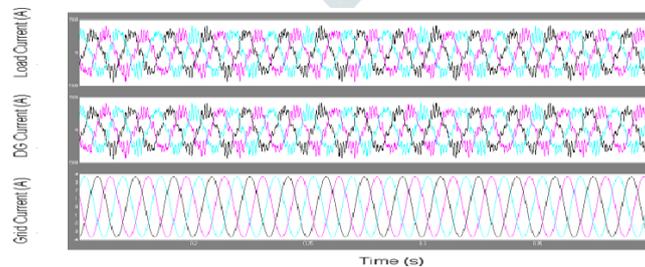


Fig :11 Three phase load current, three phase DG current, and three phase grid current

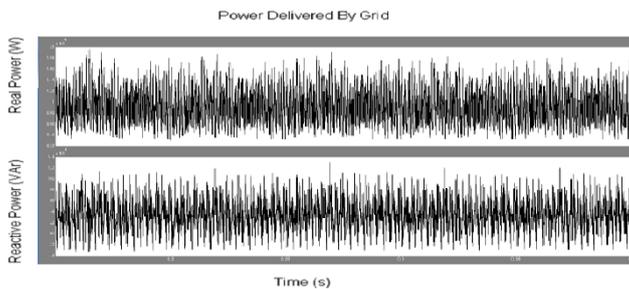


Fig :12 Real and reactive power delivered by the main DG unit

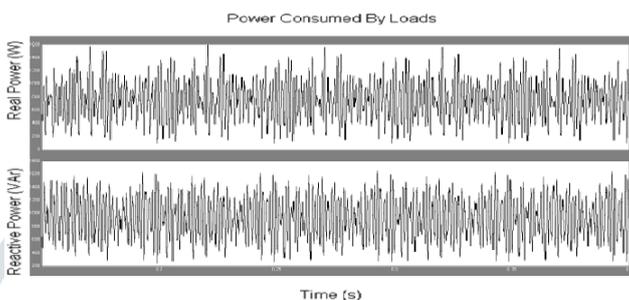


Fig:13 Real and reactive power consumed by loads

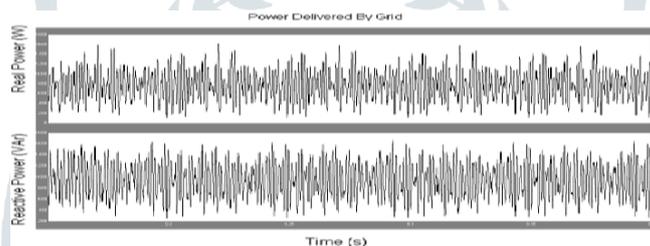


Fig:14 Real and reactive power delivered by the grid

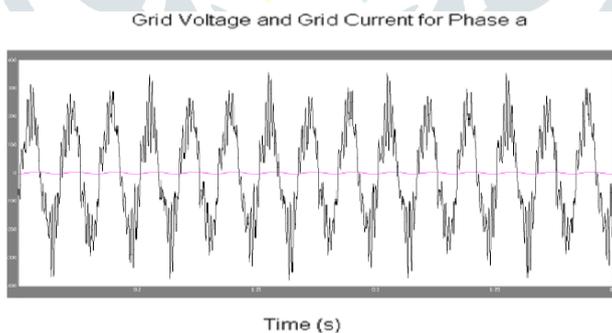


Fig:15 Grid voltage and grid current for phase a

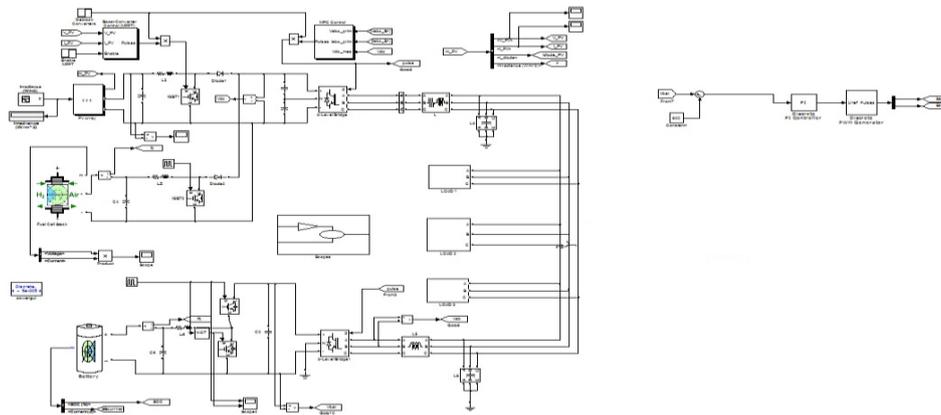


Fig:16 islanded operation

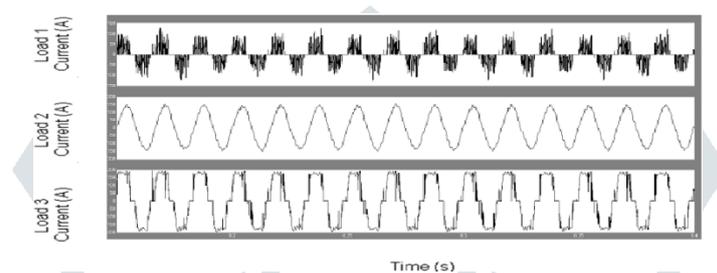


Fig:17 Per phase currents drawn by loads 1, 2 and 3

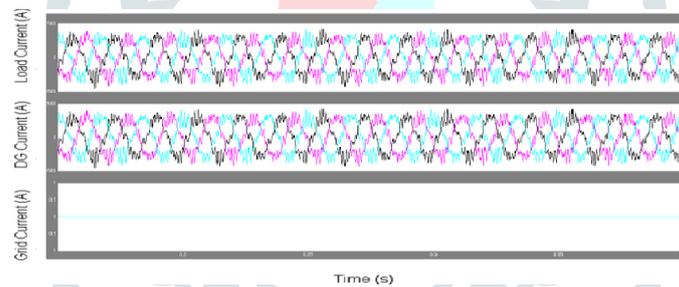


Fig: 18 Three phase load current, three phase DG current, and three phase grid curren

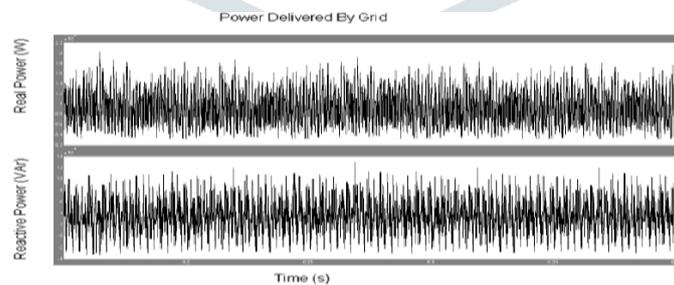


Fig: 19 Real and reactive power delivered by the main DG unit

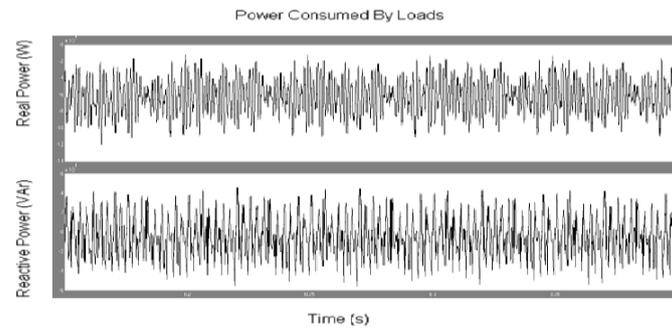


Fig: 20 Real and reactive power consumed by loads



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