Reactive Power Control with an Energy Management System in Single Phase AC Microgrids

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Abstract—This paper presents a novel control strategy to achieve unity power factor with an energy management system (EMS) in an AC microgrid. The digitally controlled, power electronics based EMS controls the microgrid in both grid-connected and islanding mode by making sure that energy is harvested from distributed resources, stored in batteries, and available at all times for critical loads. In this paper a new EMS prototype is presented which offers reactive power compensation as an auxiliary service. Modeling and simulations are presented and verified experimentally on a laboratory prototype.

Keywords—energy management system; reactive power control; microgrids; power converters.

I. INTRODUCTION

The proliferation of distributed energy resources (DERs), including distributed generation (DG) and distributed storage (DS), has led to the development of power converter topologies and control methods to interface DERs to existing power systems. Power electronics is one of the enabling technologies in the development of microgrids, small scale electrical grids where DERs are located closer to the user than traditional power plants [1]. Microgrids have the ability to improve the power system reliability by operating in islanding mode when the main grid is off. Islanding mode implies disconnecting the local power system from the main grid and servicing it with the power available from the DERs within the microgrid.

An energy management system (EMS) is a power electronics system that can be used to control a small number of DERs in a microgrid and manage the loads in both grid-connected and islanding modes of operation. This concept can be found in [2] through [7] where an EMS has control of loads, DS and, in some cases, DG sources such photovoltaic (PV) arrays, wind turbines, microturbines, diesel generators, etc. The EMS detects grid failure and maneuvers the local power system into islanding mode if necessary. In addition the EMS can provide ancillary services [9] such as peak shaving [4], load scheduling [6], power quality control [10] and reactive power compensation. The latter is the main focus of this paper.

This paper demonstrates the use of an EMS as a current source to achieve unity power factor at the grid when the system is operating in grid connected mode. The power factor angle is determined using a zero-crossing detection algorithm. The appropriate amount of compensating reactive current is then injected into the system at the point of common coupling (PCC) and controlled using closed-loop current control. No synchronous frame control system needs to be implemented in order to achieve real and reactive power flow control, therefore making the proposed control system simple to implement, yet very effective. This novel control method is simulated and then validated in the laboratory on a new EMS prototype.

II. EMS DESCRIPTION AND FUNCTIONALITY

A digitally controlled, power electronics based EMS has been developed at the Naval Postgraduate School (NPS) over the past three years to help the US Department of Defense (DoD) achieve its goals of energy efficiency. An EMS manages a group of DERs so that a microgrid can be created with respect to the main AC power grid. An EMS can also be used in independent microgrids, such as remote military installations [6]. The block diagram in Figure 1 illustrates the EMS set up to form a microgrid. The EMS manages the DERs and loads to ensure that critical loads are powered at all times, even when the AC grid is unavailable. Critical loads are those loads that are essential to the operation of the installation where the microgrid operates. All other loads can be shed if the grid power is unavailable and the available DERs cannot sustain all loads [4]. The EMS provides power to critical loads through the main AC grid, if available, or through DERs such as PV panels and batteries.

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Figure 1. An EMS connected to the main grid and microgrid.

The EMS monitors the power quality of the main AC grid and decides whether the microgrid operates in grid-connected or islanding mode. The user can program the EMS or manually
interact with the EMS to support such decisions. When operating in grid-connected mode the EMS can provide additional power to the load from energy storage to reduce fuel consumption [6] or achieve peak power shaving to reduce the cost of electricity [7]. In grid connected mode the EMS provides ancillary services [9] such as unity power factor as demonstrated in this paper.

The EMS functionality includes:

- Energy storage with a battery including a battery management system
- Peak power shaving
- Islanding to achieve improved reliability and energy security through redundancy especially for critical loads
- Load shedding control to manage peak power
- Harvesting renewable energy. For example storing solar energy when it is generated but not consumed immediately

Some of these capabilities have been demonstrated on low power EMS prototypes and reported in [4][6][7][8]. This paper presents a new EMS prototype designed and built in the NPS laboratory which features increased power rating and the ability to control the load and source currents thus achieving power factor correction in addition to the functionality listed above.

A schematic of the EMS’ architecture is provided in Figure 2 where the load and grid connections are also shown. Loads are distinguished in critical and non-critical, with the non-critical load bus controlled by the EMS in case load shedding is necessary. Note the thyristor connected to the non-critical load and the one in series with the AC grid: the EMS can open those switches if the user or the higher level controller requires it. As a result the EMS can shed non-critical loads and/or switch from grid-connected to islanding mode. The higher level controller is indicated as “secondary controller” in Figure 2. This controller makes decisions such as when to go into islanding mode or return to grid connected mode, when to implement peak shaving or load shedding, when to charge the batteries or to supplement the load with battery power. All these decisions are made by the secondary controller based on input from the user or algorithms that include cost of electricity, battery state of charge and lifetime, time of day, etc. The control systems which send the gate drive signals to the power converters are part of the primary control system. Both primary and secondary controllers are embedded into one field programmable gate array (FPGA), which is part of the EMS presented in this paper. In Figure 2 the primary controller is included inside a green box which interacts with the EMS logic block where the secondary controller’s algorithms are.

![Figure 2. EMS architecture with only one buck/boost and battery pack shown.](image-url)
The EMS architecture also includes a three leg power module, two single leg modules and a battery pack. The two single leg power modules are employed as a single-phase bidirectional H-bridge converter which can be controlled as a current source to inject power from the battery pack to the microgrid or as a voltage source when the microgrid is disconnected from the main grid. The latter mode of operation is known as islanding mode. When the converter operates in grid connected mode it controls the real and reactive power using feedback provided by a sensor positioned at the load. A low-pass filter at the output of the inverter includes an inductor which is split in two in order to balance the circuit. The three legs of the power module are operated as bidirectional buck/boost converters to either charge the battery bank or draw energy from it to support critical loads. Only one of the 3 buck/boost converters is shown in Figure 2. The buck and boost converters also regulate the DC bus to about 200V. This voltage, indicated as $v_{dc}$ in Figure 2, is monitored through a voltage sensor and is regulated by two different proportional integral (PI) controllers for the two cases: battery charging and current injection. In the former case the top switch is controlled (buck converter mode) in the latter case the bottom switch is controlled (boost converter mode).

When the H-bridge inverter operates in grid connected mode it has three possible modes of operation: 1) the converter is off, 2) the converter charges the battery pack drawing power from the main grid, 3) the converter supplies real and/or reactive power from the battery pack to the loads. The latter mode of operation is addressed in this paper. This mode of operation can occur for many different reasons, one of which can be peak shaving which consists of reducing the power drawn from the AC grid during peak hours of operation by supplementing the load power with DER power [4]. If the PV panels produce power, that power can be used, otherwise battery power is used to reduce the peak power drawn from the AC grid when the cost of electricity is highest [7]. The PV panel’s interface, which connects to the DC bus, is not shown in Figure 2 because its operation is beyond the scope of this paper.

### III. Reactive Power Control

While the EMS is supplying additional power to the loads its output current $i_{ems}$ is controlled by current control algorithm that regulates the amount of real and reactive current injected into the system. This current control system is depicted in Figure 3. A zero-crossing detection algorithm determines the power factor angle $\phi_i$ at the grid, which is the difference between the voltage phase angle and the current phase angle ($\theta_v - \theta_i$ in Figure 3). A power factor angle error correction algorithm (PEC in Figure 3) eliminates any numerical error in the $\phi_i$ calculation that may result from transients in the source current $i_s$. The current $i_{ems}$ is generated by the EMS and controlled using a PI controller that adjusts the amplitude of $i_{ems}$ to drive $\phi_i$ to zero. This eliminates the reactive power demand on the grid by achieving unity power factor.

![Figure 3. Block diagram of the reactive power compensation control system. PEC = phase error corrector.](image)

The phase error cannot be sent to the PI controller as it is, but needs to be corrected due to the rollover of the digital counters as shown in Figure 4. At the beginning of each period the phase error has a discontinuity due to the reset of the digital counters as shown in the middle plot of Figure 4. This discontinuity must be corrected before the phase error can be processed by the PI controller.

The schematic in Figure 5 shows the phase error correction algorithm implemented in Simulink with Xilinx blocks. The FPGA which controls the EMS is programmed using Systems Generator, a Xilinx software package that works in Simulink and allows the programmer to generate VHDL code from Simulink. When the phase error is greater than $\pi$, or less than $-\pi$, the quantity $2\pi$ is subtracted from the angle or added to the angle respectively. The result is the compensated error shown in the bottom plot of Figure 4. The compensated error is filtered before being sent to the PI controller. The filtered compensated error is also shown in the bottom plot of Figure 4.

![Figure 4. V-I phase angle correction waveforms.](image)
A physics based model of the simplified system, as shown in Figure 6, was developed and implemented in Simulink. The model disregards the EMS’ power electronics by modeling the EMS as a current source. Modeling the EMS in this fashion assumes a clean sinusoidal current $i_{ems}$ signal from the H-bridge inverter without considering the PWM switching signals used to generate the current $i_{ems}$. The goal of the model is to assist in the design of the current control system shown in Figure 3 which is included in the Simulink model. The PI gains are tuned based on time domain simulations run with this model.

A simulation was performed with the inductive load shown in Figure 6. The EMS compensates for the reactive power demanded by the load by acting as a capacitive load in delivering magnetizing VARs to the system. The EMS injects a capacitive $i_{ems}$ into the system which brings the source current $i_s$ in phase with the grid voltage $v_s$. This system response is demonstrated in Figure 7. Initially the power factor is lagging and the EMS is off. At 0.3 seconds the EMS is turned on and it starts injecting a current $i_{ems}$ whose amplitude increases until it reaches steady-state operation with unity power factor. Note that the source current amplitude (top of Figure 7) decreases as a consequence of having its reactive component reduced to zero.

The change in current amplitude described above is illustrated in the phasor diagram of Figure 9 where the steady state currents are represented by phasors.

The phase angle of the source current with respect to the grid voltage is corrected from about 1 radian to almost 0 radians in ½ second. The simulation also shows how the EMS current amplitude increases over that period of time. Note that the EMS current amplitude (top of Figure 7) decreases as a consequence of having its reactive component reduced to zero.

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Where $I$ is the amplitude of the sinusoidal current and the current’s phasor is indicated by bold letters. The phasor transform in (1) transfers the sinusoidal current from the time domain into the frequency domain. In rectangular form (1) becomes:

$$I = I \cos \theta + jI \sin \theta = I_{Re} + jI_{Im}$$

(2)

Where the real and imaginary part of the current are indicated by the subscripts “Re” and “Im” respectively. Note that (2) is obtained using Euler’s identity:

$$e^{j\theta} = \cos \theta \pm j \sin \theta$$

(3)

The steady state represented in Figure 9 is when unity power factor is achieved and the source current $i_s$ is in phase with the AC grid voltage $v_s$. The phasors in Figure 9 demonstrate how the EMS creates a positive current on the imaginary axis that is equal in amplitude to the reactive component of the load current $I_{load,Im}$ thus cancelling it from the source current $I_s$. As a consequence the source current $I_s$ becomes equal to the real component of the load current, $I_{load,Re}$ which is smaller than the load current $I_{load}$. In Figure 9 the rms values of the currents are used for the phasor’s amplitudes and they match the time domain simulation shown in Figure 7. The rms value of the source current drops from 3.64A (amplitude of the load current) to 2.4A after the reactive power is compensated for by the EMS.

![Figure 9. Phasor diagram for the currents with the reactive power correction.](image)

V. EXPERIMENTAL VALIDATION

In this section the EMS prototype is presented and experimental measurements are reported to validate the model and simulations of the previous section.

A. Hardware Implementation

The EMS laboratory prototype is shown in Figure 2, however the load used in this paper’s experiments is the one shown in Figure 6 with resistors and inductors to match the simulations shown in the previous section. The DC bus voltage is regulated at 193V and no thyristors are used to connect to the AC grid or the load, since the goal of this paper is to demonstrate reactive power control during grid-connected mode. A photograph of the EMS laboratory prototype is shown in Figure 10 where 3 printed circuit boards (PCB) can be observed. The bottom PCB includes the power modules, a DC power supply, current and voltage sensors. Note the cooling fans mounted on top of the three Insulated Gate Bipolar Transistors (IGBT) integrated power modules (IPMs). Two single leg IPMs are used to form the H-bridge inverter and the other, a three leg IPM, is used for the three buck/boost converters designed to interface to battery packs or PV arrays. In this paper only one buck/boost is used for the experiments and it is connected to a DC power supply. The PCB in the middle is a Xilinx development board with an embedded Virtex 4 FPGA which can be programmed through a Joint Test Action Group (JTAG) cable. The top PCB includes A/D converters and several other connections to interface with the other two boards. A block diagram of the hardware implementation of the EMS control system is shown in Figure 11 highlighting the main components embedded in each PCB and their interconnections.

![Figure 10. Photograph of the laboratory prototype.](image)

![Figure 11. Block diagram of the EMS control hardware.](image)
B. Experimental Measurements

The experimental measurements from the laboratory prototype are shown in Figure 12 and Figure 13 when the EMS is off and on respectively. When the EMS is not turned on, its current $i_{ems}$ is zero and the effects of the inductive power demand on the grid can be observed. Note in Figure 12 that the ohmic-inductive load creates a lagging power factor at the grid and $i$ lags $v$ by approximately $30^\circ$. This matches the simulation results shown in the first 100ms of the plots in Figure 7. Once the EMS is turned on, capacitive power is delivered to the system via a leading $i_{ems}$ causing the phase angle of $i$ to match that of $v$ as shown in Figure 13.

Observe in Figure 12 and Figure 13 the obvious presence of harmonics in the currents due to the PWM switching. They are not evident in the simulation results since the circuit modeled in Simulink disregards the PWM associated with the EMS’ power electronics.

The plots in Figure 14 and Figure 15 show how the FPGA embedded controller operates. These plots are integrated logic analyzer recordings of the signals inside the FPGA. The phase angle between source voltage and current is measured using the waveforms in Figure 14 and, once the EMS is turned on, the phase angle is reduced to zero by the controller as shown in Figure 15.

VI. CONCLUSIONS

This paper presents an EMS designed to provide reactive power compensation at the PCC with the AC grid. This feature is used when the EMS keeps the microgrid connected to the AC grid and operates as a current source. In this mode of operation the EMS can supplement the AC grid’s power with additional power from the DERs. In this paper the ability of an EMS to operate as a current source compensating the reactive power demand on the grid is successfully demonstrated. A novel zero-crossing detection algorithm tracks the power factor.
angle between the source voltage and current so that an appropriate amount of reactive current can be injected into the system at the PCC in order to achieve unity power factor at the grid. The process was simulated to predict the system’s response to reactive power demands on the grid. A laboratory experiment was then conducted with a new EMS prototype to validate the VARs compensation method.

REFERENCES


