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Fundamentals Of Energy Management System In Grid With Storage Using Converter Topology

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ABSTRACT:

The objective of this paper is to provide basic insights associated with optimal operation of an AC microgrid system against system uncertainties. In specific, the energy management methods addressed to solve the problem of system uncertainties/requirements is focused at fundamental level with the consideration of all the possible options. Therefore, in order to satisfy technological and financial restrictions while coordinating generation, storage, loads, and grid interaction, an Energy Management System (EMS) is needed. The principles of optimum energy management algorithms for AC microgrids are thoroughly examined in this work. The energy management problem's mathematical formulations, goal functions, operational limitations, forecasting needs, and key optimization techniques are all examined in this work. Metaheuristic algorithms, model predictive control, stochastic and robust optimization, multi-agent systems, and artificial intelligence-based methods are contrasted with traditional approaches like linear programming, nonlinear programming, mixed-integer linear programming, and mixed-integer nonlinear programming. Economic dispatch, battery scheduling, peak-load reduction, grid interaction, renewable energy use, and emission minimization are all given special consideration. In terms of computing complexity, uncertainty handling, scalability, and real-time implementation, the benefits and drawbacks of various algorithms are assessed. Lastly, new avenues for study are explored, including distributed EMS architectures, cybersecurity, data-driven forecasting, hybrid optimization, reinforcement learning, and real-world validation. The constraints pointing to system requirement along with operational objectives are discussed. Further, the methods pertaining to optimal system operation are categorized based on the outcome of employed optimization method. The overview of reported methods in the literature for each category is briefly discussed.

Keywords: AC microgrid, Distributed Generation (DG), Energy Management System (EMS) and optimal operation

INTRODUCTION

Now a days world is looking for the alternate technology to generate and utilize power energy, since depletion of fossil fuels takes place. Invention of microgrid technology from few decades is found to be the most promising option to community; which is mostly consisted of distributed renewable energy sources, energy storage devices, power electronic converters and communication elements. The ultimate purpose of micro-grid is to provide reliable, sustainable economic power to end consumer may be at remote area or grid connected or in isolated mode by maintaining green environment (reducing gas emission level) and technical limits of units. This paper focuses on study of one of the microgrid function i.e. optimal energy management system, to satisfy several objectives like maxi-mum supply from Renewable sources through optimal scheduling, maintain demand side load through energy storage device even in fault/valley time period, cost reduction in operation of units and many. Approach and methodology are also considered in this work. Renewable energy sources and storage de-vices are participating together in an organized manner to meet the increasing energy demand at distribution level leading to the formation of microgrid system. The microgrid system basically operates in grid-connected and stand-alone modes based on prevailing generation and system requirements.

The energy sources participating in the system can be unidirectional such as solar photo-voltaic, fuel cells, batteries etc. or alternating type such as wind energy systems. Hence, sources are inter-faced with the system through power electronic converters so as to yield DC or AC or hybrid AC-DC microgrid configurations. Usually, the power electronic converter employed is a Voltage Source Converter (VSC). The adoption of renewable energy technologies like photovoltaic (PV), wind energy, and small-scale distributed generation has increased due to the sharp rise in electricity demand and growing environmental concerns. Despite the fact that renewable resources

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offer substantial economic and environmental advantages, their unpredictable and changeable nature poses serious operational issues for power systems. Microgrids have become a significant way to combine regulated loads and dispersed energy resources inside a predetermined electrical border. During grid disruptions, a microgrid can often function either independently or in grid-connected mode. Coordinating these resources and ensuring dependable and cost-effective operation require an efficient energy management system. Economic dispatch, demand management, forecasting, unit commitment, and uncertainty management have all been identified as key elements of microgrid energy management in earlier studies. In general, high penetration of solar photo-voltaic will characterize the system to behave as a low-inertia system. Also, most of the microgrid systems are participating at distribution level where the network is resistive dominated.

These two distinct properties make the system operation different than the conventional power system. Figure.1 shows the general architecture of AC microgrid and figure.2 depicts the challenges associated with it that makes microgrid different than the conventional utility grid. An AC microgrid generally consists of renewable generation, conventional distributed generators, energy storage systems, AC loads, power electronic converters, and the utility grid. The increasing number of controllable components makes the management problem highly nonlinear and multi-objective. The fundamental objective of an optimal EMS is to determine the most appropriate operating schedule of the available resources while satisfying electrical and operational constraints. Depending on the application, the optimization objective may include:

Minimization of operating cost;

Minimization of emissions;

Maximization of renewable-energy utilization;

Minimization of battery degradation;

Reduction of peak demand;

Improvement of system reliability;

Minimization of power exchange with the utility;

Enhancement of energy efficiency; and

Improvement of resilience during grid disturbances.

Recent reviews show that mixed-integer optimization remains widely used because of its formulation flexibility, while metaheuristic techniques are particularly common for complex economic-dispatch problems. There are several operational and technical challenges associated with the smooth functioning of the microgrid system. The important among them are stated as follows:

Maintaining system stability

Fulfilling the criteria of energy balance

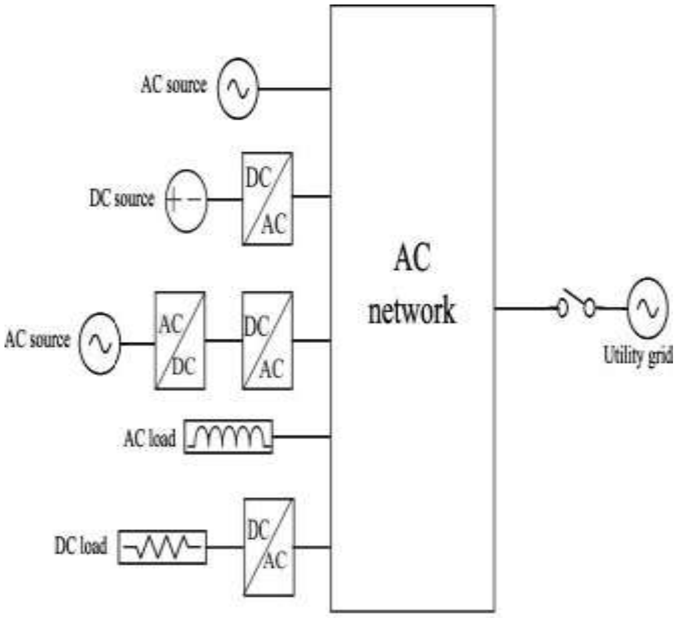
Energy management in the system

Achieving economic operation

Smooth transition from on-grid to off-grid and vice-versa

Protecting the system against faults and disturbances.

The development of artificial intelligence and data-driven techniques has further expanded the possibilities for real-time microgrid energy management. Recent research increasingly considers machine learning, reinforcement learning, data-driven MPC, evolutionary algorithms, and distributed intelligence for handling uncertainty and dynamic operating conditions



. **Figure 1: General architecture of an AC microgrid**

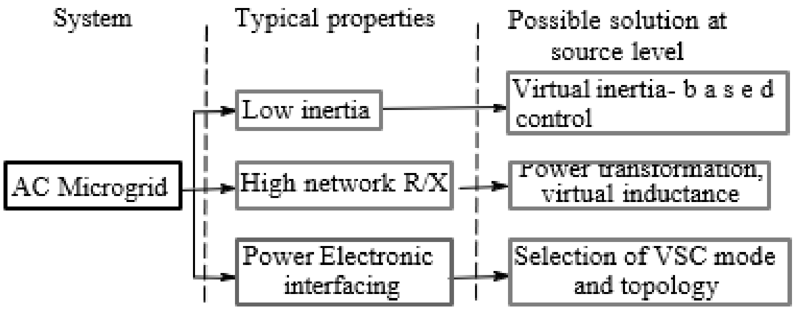


Figure 2: Typical properties of AC microgrid and its solutions

Being a low-inertia system, stable operation of microgrid is an important operational challenge. However, virtual inertia- b a s e d control/regulation of sources is an appropriate option to mitigate the problem of low system inertia. One of the familiar features of the microgrid system is uncertainty in power generation and power consumption. Hence, maintaining energy balance thereby attaining system stability is indeed an important concern to deal with. The followed measures to alleviate the problem of power balancing in stand-alone operation are; (a) adjustment of deficit/surplus power through storage devices/back-up option, and (b) load curtailment to manage the deficit power. The deficit/surplus power can be managed from utility grid in utility interactive operation. This particular activity of energy exchange to handle system uncertainties is referred as Energy management. The algorithms developed to fulfill the criteria of energy management criteria are referred as energy management algorithms. It can also be carried out in a cost-effective manner so as to achieve economic as well as stable operation. In general, energy management algorithms are executed in a centralized architecture manner which requires a reliable communication network. However, in few applications it can also be implemented in a decentralized manner from source terminal measurements only.

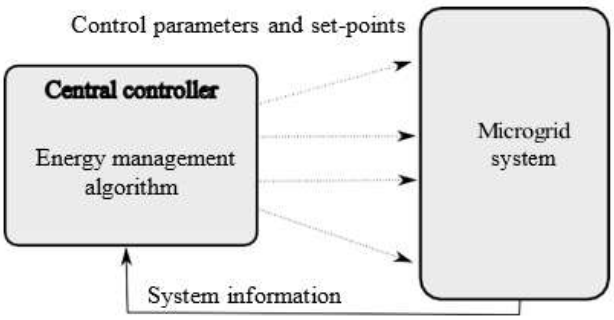


Figure 3: Centralized control architecture of AC microgrid

The contribution of this work is to provide sufficient insights with regard to reported energy management techniques and the details associated with optimal operation of AC micro-grid. The information collected from various literature is briefly discussed to benefit the beginners interested to work on energy management algorithms. An AC microgrid is a localized power system consisting of multiple distributed energy resources and loads connected to an AC distribution network.

1. A typical AC microgrid contains:

Renewable energy sources

Solar PV

Wind turbines

Small hydro systems

Conventional distributed generators

Diesel generators

Gas generators

Combined heat and power units

Energy storage

Lithium-ion batteries

Lead-acid batteries

Flow batteries

Other electrochemical storage technologies

Loads

Residential loads

Commercial loads

Industrial loads

Flexible and interruptible loads

Power electronic interfaces

Grid-connected inverters

DC/AC converters

Bidirectional battery converters

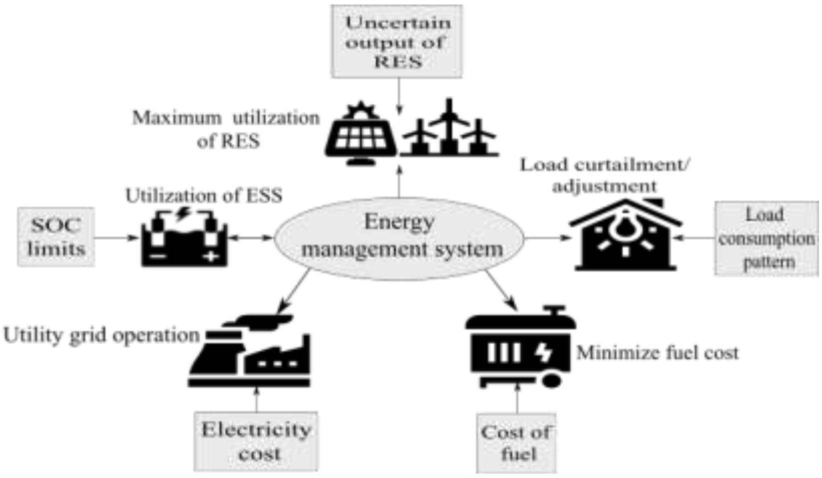
Utility grid

Energy Management System

The EMS operates at a supervisory level and determines how energy should be generated, stored, consumed, or exchanged with the utility.

Broad view of energy management options

A general understanding of role of energy management system in microgrid can be interpreted as shown in figure.4. The EMS acts as the decision-making layer of the microgrid. It receives information from generation units, energy-storage systems, loads, electricity markets, and weather/forecasting systems



The system uncertainties can be handled through possible options such as;

Regulation of source output powers: The sources participating in the system are controlled to deliver required amount of power as per system demand. The sources are provided with reference commands/set-points as dictated by the energy management algorithms. The power outputs of sources are regulated with in their respective capacities. The operational limits on source power ratings are given as follows:

$P_{min} \leq P \leq P_{max}$ (1)

$Q_{min} \leq Q \leq Q_{max}$ (2)

Regulation of source power inputs is in turn linked with maintaining source terminal voltage and achieving power balance criteria.

$V_{min} \leq V \leq V_{max}$ (3)

A simplified energy balance can be expressed as

PPV(t)+PWT(t)+PDG(t)+Pgrid(t)+Pdis(t)=PL(t)+Pch(t) (4)

where:

P_{PV}= photovoltaic generation;

P_{WT}= wind generation;

P_{DG}= conventional generator output;

P_{grid}= power exchanged with the utility;

P_{dis}= battery discharge power;

P_{L}= load demand;

P_{ch}= battery charging power.

This power-balance equation forms one of the fundamental constraints of an EMS optimization problem.

Scheduled tapping of energy from utility system: The deficit and surplus energy in the system is managed through energy exchange with the utility grid. However, there may be restriction on energy tapped from the grid based on the terms and conditions with the utility grid and more importantly prevailing energy price of the grid will be the deciding factor for energy exchange. At times, the energy from utility grid may not be received due to grid faults or loss of mains

Adjustment/curtailment of loads: At times, the energy balance in the system is maintained through load adjustment/curtailment in the case of limited power from the source. It is also to be noted that end-user is participating in generation in the form of roof-top solar system and they are modifying the power consumption pattern as per the prevailing tariff. The information from day-ahead scheduling or real-time power consumption data is usually considered in the energy management algorithm.

Extent of support from battery energy storage systems: Battery energy storage systems play a crucial role to handle the uncertainty in power generation. The aspects of number of life cycles and State of Charge (SoC) are considered for deciding the extent of energy to be injected from the battery energy storage systems. The operational limit on SoC of the back-up source:

$$SoC_{min} \leq SoC \leq SoC_{max} \quad (5)$$

Other options: Diesel generator is an additional option to handle the deficit energy. Minimizing system loss is also an option to maintain power balance in the system. Network loss is the major loss component in the system, which in turn, depends on topology of the network. Hence network reconfiguration methods are suggested to minimize network loss. The aforementioned options are applied in a coordinated and organized manner with due consideration of all the system conditions and requirements. The technique/algorithm employed to achieve specific system or operational objective by making use of these options is referred as energy management algorithm.

2. Energy Management System (EMS)

Today's world has become a complete energy dependent world in which electricity is of prime importance. Electricity has made life very easy and thus its consumption is increasing day-by-day. In order to generate this electrical energy in its original form, a lot of natural resources are being used. Traditionally electricity was generated only from non-renewable energy resources but now renewables have come into picture. Although renewables are used for generation of electricity, the system and equipment needed to produce electricity from them are costly and thus can't be afforded by every common man. Hence this has led to the depletion of the natural resources. Therefore it is essential to switch to new and better options like smart grid, smart metering, and zero energy buildings that will help to reduce dependency on these reserves by reducing energy consumption and improving use of renewable energies. And in order to increase the efficiency of our power system Energy Management Systems (EMS) are essential. It is a comprehensive offering that combines energy and process optimization and, where appropriate, incorporates the solution into online advanced control and optimization strategies. This paper focuses mainly on the present scenario of energy usage systems in India and suggests some methods and techniques adopted, that will lead to the improvement of energy usage and efficiency. The advantages of EMS along with the barriers faced and the solutions to deal with these barriers so that EMS can be brought into operation in the existing industries as well as residential and commercial organizations are also discussed

What is an Energy Management System?

An Energy Management System is a series of policies, processes and procedures to manage operational energy use. Energy, in the context of organizational use, can be defined as the direct consumption of fuel (Gas, Oil, etc.) and indirect consumption of fuel (Electricity) required to perform the organizational functions. It is a strategy of adjusting and optimizing energy, using systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing the total costs of producing the output from these systems. Thus EMS leads to the judicious and effective use of energy in order to maximize the profits by reducing the operational costs and hence enhance the competitive positions. Energy management systems are used by power system operators to monitor power grid operating conditions and control grids in a reliable, secure, and economical fashion. An energy management system interfaces with the grid through a supervisory control and data acquisition (SCADA) system. The SCADA system transmits thousands of measurements at critical points of a power system in real time to the energy management system and command signals from the energy management system to field devices to take control actions. An energy management system integrates application software such as state estimation, contingency analysis, automatic generation control, and economic dispatch. These applications typically operate the grid in a reactive (e.g., load following) or preventive (e.g., security constrained dispatch) fashion.

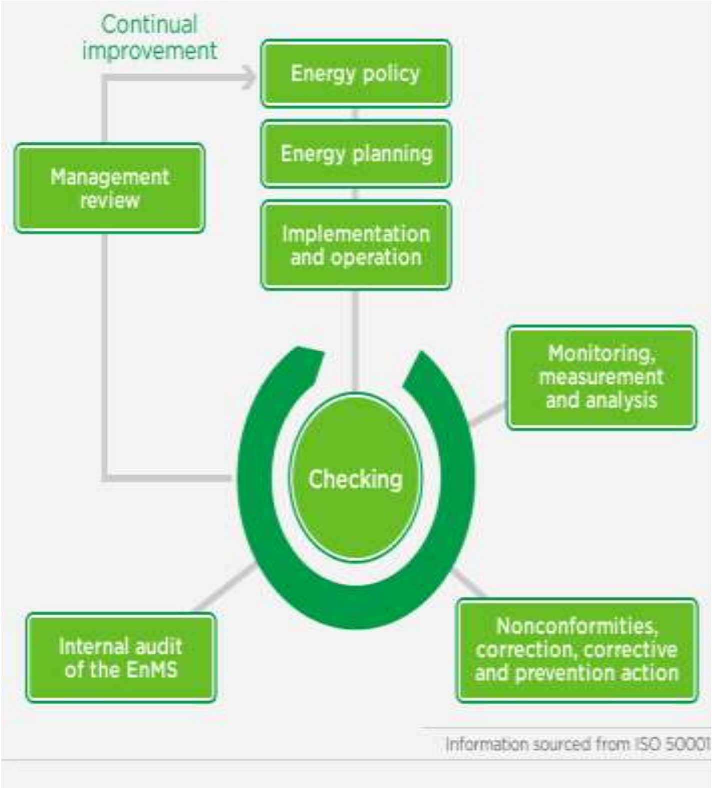


Figure.5: Basic Block Diagram of an EMS

The increased penetration of renewable generation on the power grid imposes great challenges to the current energy management system scheme as renewable resources largely differ from conventional generation because of their uncertainty and variability

To thrive in this situation, energy management system technologies need to evolve into a proactive, look-ahead paradigm. Advanced energy management system technology is also sorely needed at the distribution system level. The traditional distribution energy management system is much less integrated than the transmission energy management system. Operational challenges arise from the significantly increased complexity of modern distribution systems, especially from distributed renewable resources, electric vehicles, and demand-side management. A fully integrated and intelligent distributed energy management system is a key to meet these challenges. This is based on an international standard for Energy Management. The ISO 50001 Energy Management Systems Standard was released in August 2011. This International Standard establishes a framework for industrial plants; commercial; institutional and government facilities and entire organizations to manage their energy. The Standard is based on the classic business planning cycle "Plan-Do-Check-Act" and provides guidance for organizations in establishing energy policies, programs and action plans to improve their energy use.

Description of Proposed system

The EMS presented in this paper includes batteries and a three-leg power module controlled by a field programmable gate array (FPGA).

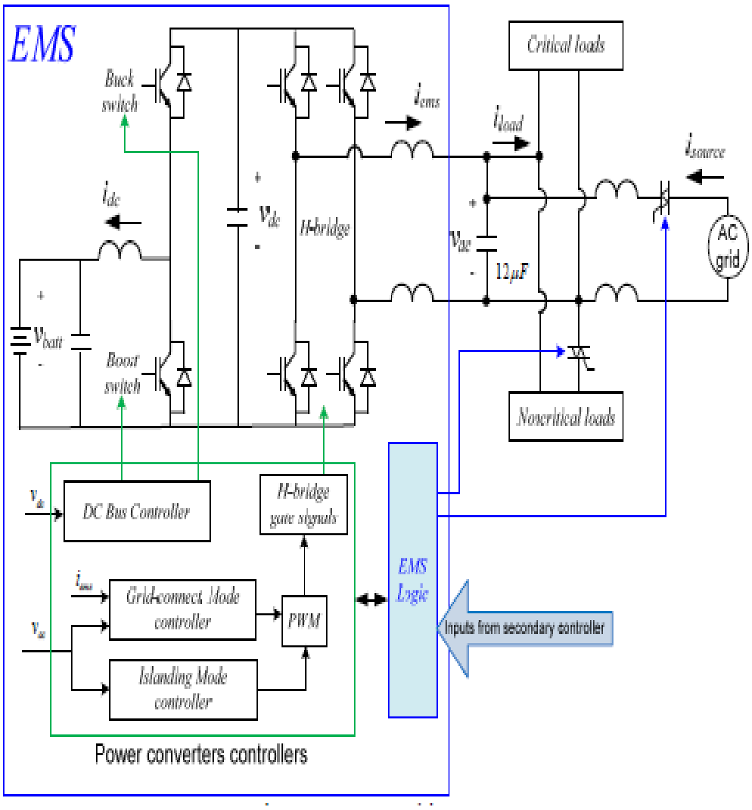


Figure.6: EMS architecture'

The schematic in Figure-2 depicts the EMS architecture. A three phase IGBT power module is controlled to achieve buck and boost power flow from one leg of the module and single-phase voltage source operation (H-bridge inverter) from the other two legs of the module. The H-bridge inverter thus formed is connected to an output LC filter to produce the sinusoidal voltage for the AC loads. There are two voltage sensors to monitor the voltages *vdc* and *vac*. There are two current sensors to monitor *iems* and *iload*. A battery pack is connected to the buck-boost leg to accomplish bidirectional power flow to/from the battery. The battery consists of six, 12V battery cells in series, forming a 72V battery pack. Note that a 300V battery pack would eliminate the need for the buck/boost stage of the EMS, thus forming the DC bus for the H-bridge inverter. Critical loads are connected directly to the AC voltage created by the EMS which is labeled *Vac* in Figure.6.

Critical loads are those loads that must be powered at all times because they are critical to the mission. Noncritical loads are connected in parallel to *Vac* however they can be shed when necessary, using a thyristor switch. This increases the control of the power that can be directed to the critical loads when necessary. The AC grid can also be disconnected from *Vac* if needed to island the operation of the EMS. Typically, islanding mode occurs when the AC grid fails. In this mode of operation power to critical loads is guaranteed by drawing energy from the battery pack. The EMS functionality is demonstrated in this paper are: -

Peak shaving by tapping the energy storage system during high power demand.

Islanding or standalone mode of operation when the main AC grid is no longer available.

Battery charging mode.

By accomplishing these goals, the EMS can be very useful in grid connected systems where there is a limit on the user's power consumption. This limit maybe enforced by circuit breakers controlled by a power meter. If the EMS keeps the source current below a set threshold at all times by load management and shedding, then the user can operate loads beyond the steady state power limits of the AC grid for short times without worrying about the circuit breaker interrupting service.

EMS Control System

It is important to distinguish the different levels of control for the EMS. The primary control system includes the power converter module controllers which generate the gate drive signals given reference voltages and currents. The secondary control system is a higher level controller which can include the user input and makes decisions based on factors such as battery state of charge and lifetime, cost of electricity, time of day, load priority, etc. The basic functions of the primary controller are included in Figure -6 and will be examined in details in this section

Figure-7 shows the EMS primary controller logic flowchart, which is a detailed visualization of the "EMS Logic" block in Figure-6. The operator or the secondary controller inputs four distinct logical commands; Run, Charge, Source Connect (SC) and Current Threshold (CT). CT is the load current level when the EMS will begin peak shaving. If Run is low then the EMS does nothing. When Run is high the EMS will operate in islanding mode. If SC is also high then the EMS will connect *vac* to the AC source if the AC source RMS voltage is above 100 Vrms (VRMS OK is high). If the load current exceeds the peak shaving limit (CT) then the EMS will continue to inject current otherwise the EMS will turn off after connecting to the AC source. If Charge is set high then the EMS will charge the batteries when the AC source is present and peak shaving is not demanded.

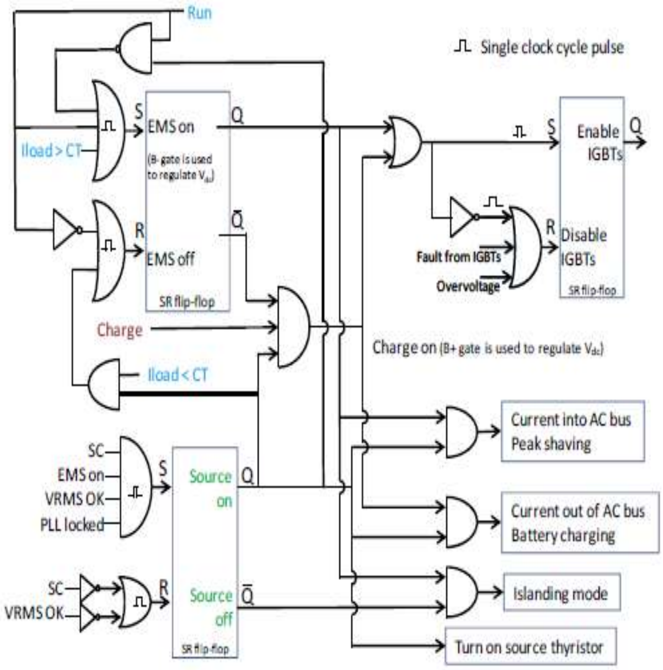


Figure-7. EMS logic flowchart. Run, Charge, SC and CT are inputs from the operator or secondary controller

There are two other internal variables: phase locked loop (PLL) locked and voltage root mean square (VRMS) OK. When the signal VRMS OK is high, the AC grid RMS voltage is above a set threshold. When this signal is low, the EMS switches from grid connect to islanding mode of operation. These four commands coming from the secondary controller can be set based on several factors. The secondary control system will set the charging command and the peak shaving thresholds in order to achieve the best performance. The information that will be used by the higher-level controller will include state-of-charge, time of day, cost of electricity and other factors. The different components of the EMS primary control system for the different modes of operation are presented in the following subsections

SIMULATION AND RESULT DISCUSSION

Peak shaving is a known technique used to achieve this objective by use of stored energy. Electrical energy is stored during the times when electricity cost is lowest (typically at night) and used during the times when electricity cost is highest, in order to reduce the overall electricity charges. While it may not be cost effective to acquire a battery pack with the sole purpose of peak shaving, if storage is part of an existing EMS installed to improve the reliability of the local power system, then using it to accomplish peak shaving is very cost effective.

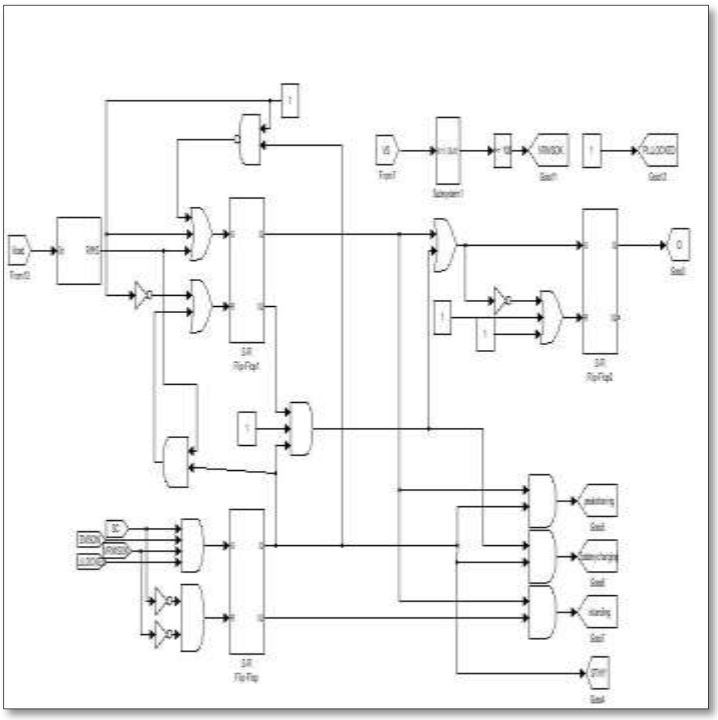


Figure-8: EMS Controlling subsystem

Peak shaving is achieved by controlling the RMS current in the load, which is related to the source current. A threshold is set for the load current such that when the load RMS current exceeds this threshold the EMS supplies some of the load current. This keeps the peak current drawn from the AC grid below a set limit. In the simulation results here, the threshold for the load current is such that the peak shaving feature turns on when the load current is greater than 2.2 Arms and turns off when the load current is below 2.1 Arms. When peak shaving turns on the EMS behaves as a current source supplying to the load a sinusoidal current with unity power factor. The threshold value can be changed by modifying the EMS reference current by the secondary controller. The EMS can be programmed to provide reactive power as well as current harmonics as needed by the user or the secondary controller.

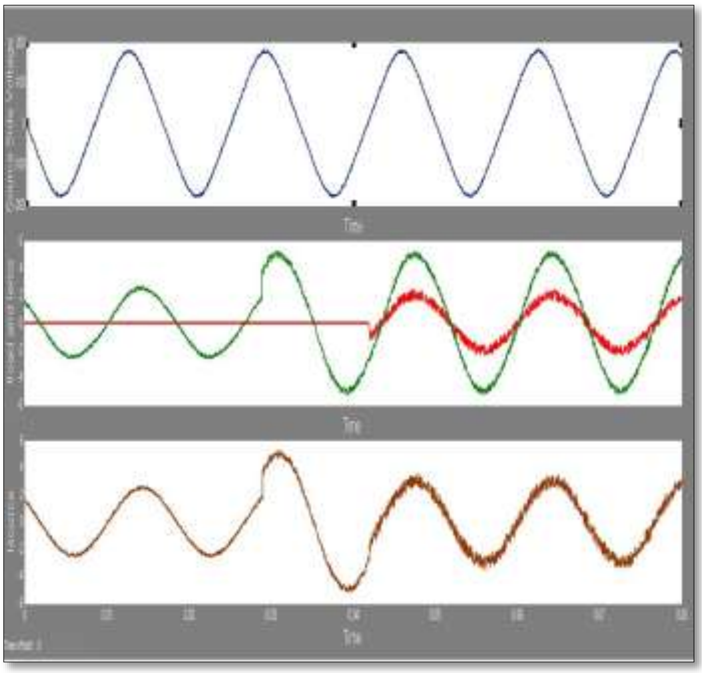


Figure.9- Peak shaving with the EMS providing some of the load current from the battery pack when the load increases. Load 2 steps from 600Ω to 80 Ω and then the EMS turns on (B). All the loads are linear.

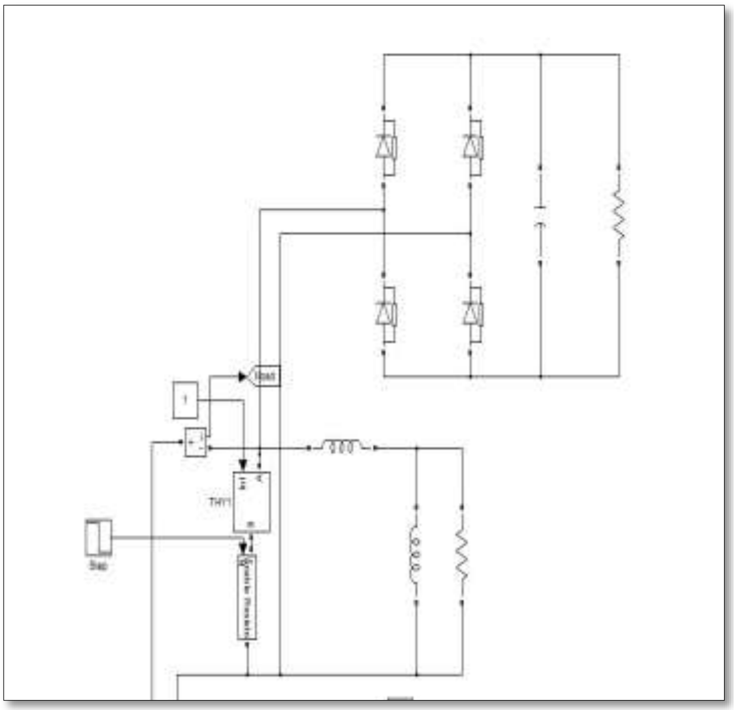


Figure.10- Variable load condition

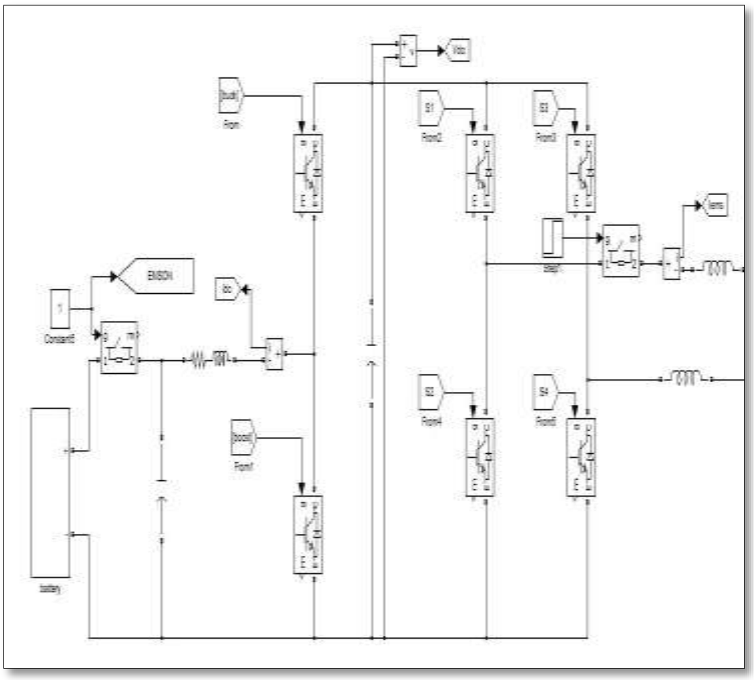


Figure.11- EMS controlling system

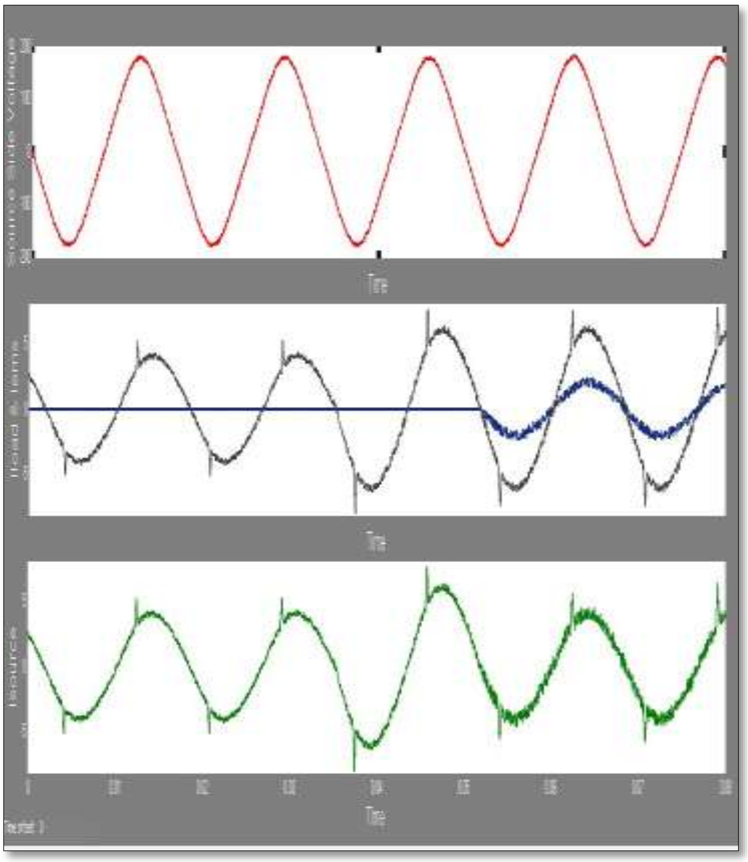


Figure.12- Peak shaving with the EMS providing some of the load current from the battery pack when the load increases. Load 2 steps from 1200 Ω to 85.7 Ω and then the EMS turns on (B). The load includes a diode rectifier

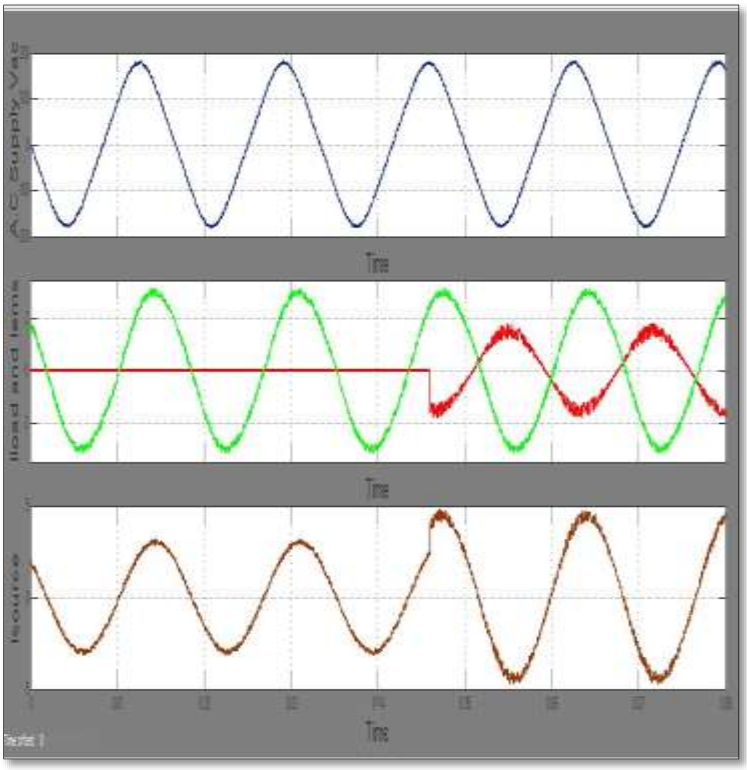


Figure.13- EMS turning on at *t=0* to charge the battery pack

There is a delay between the load increase and the EMS turning on due to the RMS current computation algorithm, which is described in the next section.

EMS Powering Critical Loads when the AC Grid Fails – Islanding Mode of Operation

In order to provide power to critical loads when the AC grid fails, the EMS detects grid failure and acts as a voltage source for the critical loads. In this mode of operation non critical loads can be shed depending on the state of charge of the batteries and other factors determined by the user or by the secondary control system. Non critical load shedding is easily accomplished by the EMS by opening the thyristor switch connected to the non-critical loads (shown in Figure 10). When the AC grid is available again, then the EMS restores the loads to the AC grid, therefore terminating the islanding mode of operation. At this point, if non critical loads had been previously disconnected, they can be restored as determined by the secondary control system. The secondary control system determines if the EMS should try to reconnect to the AC grid or not.

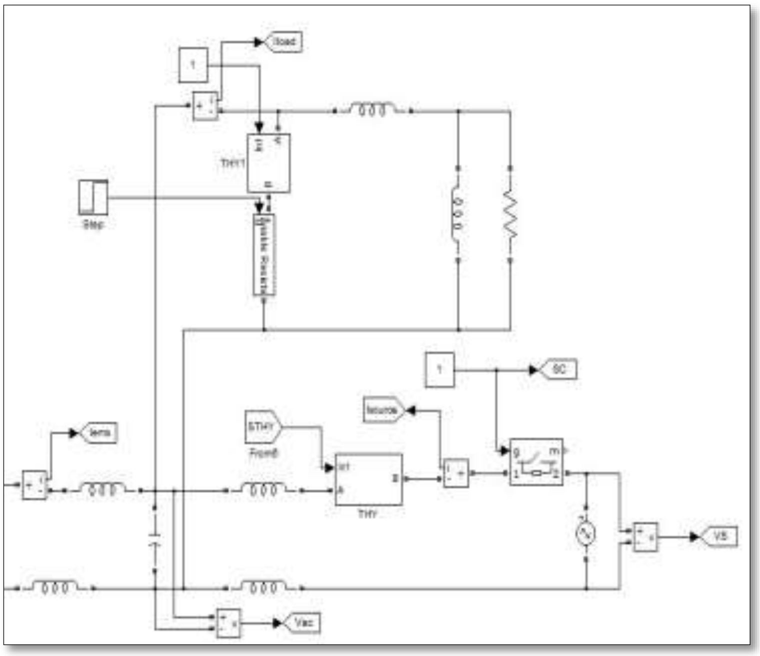


Figure.14- EMS Powering Critical Loads when the AC Grid Fails – Islanding Mode of Operation

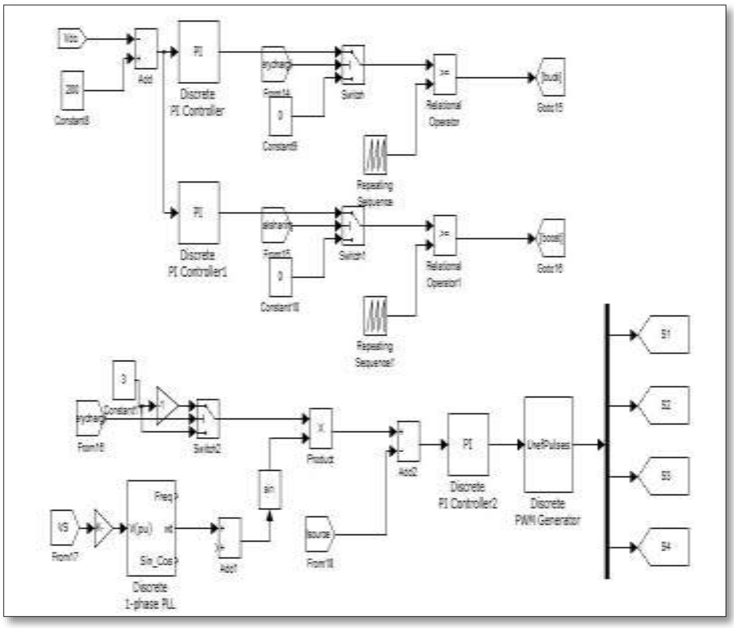


Figure.15- Controlling subsystem for EMS switching control

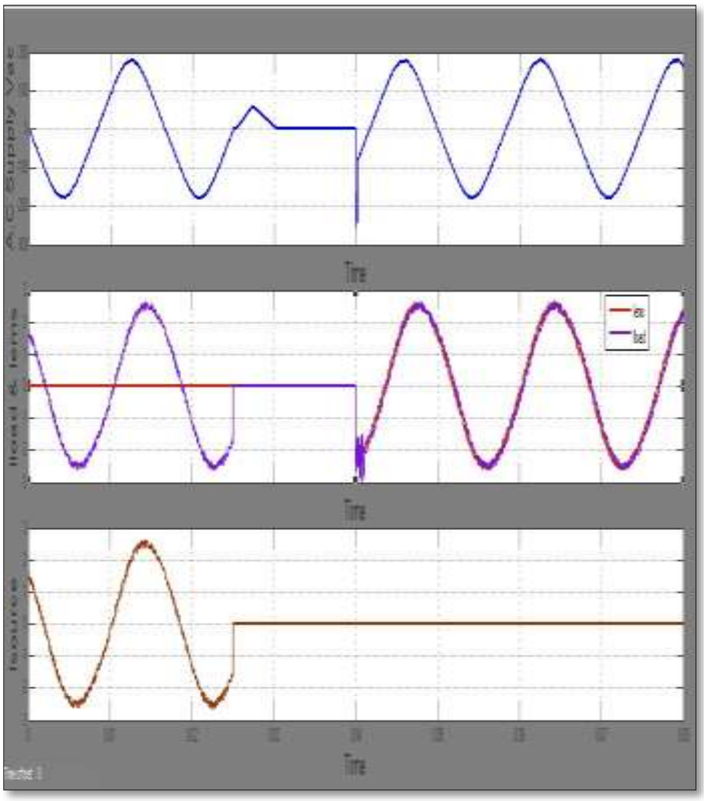


Figure-16: Simulation waveforms showing AC grid failure and the EMS taking the loads into islanding mode

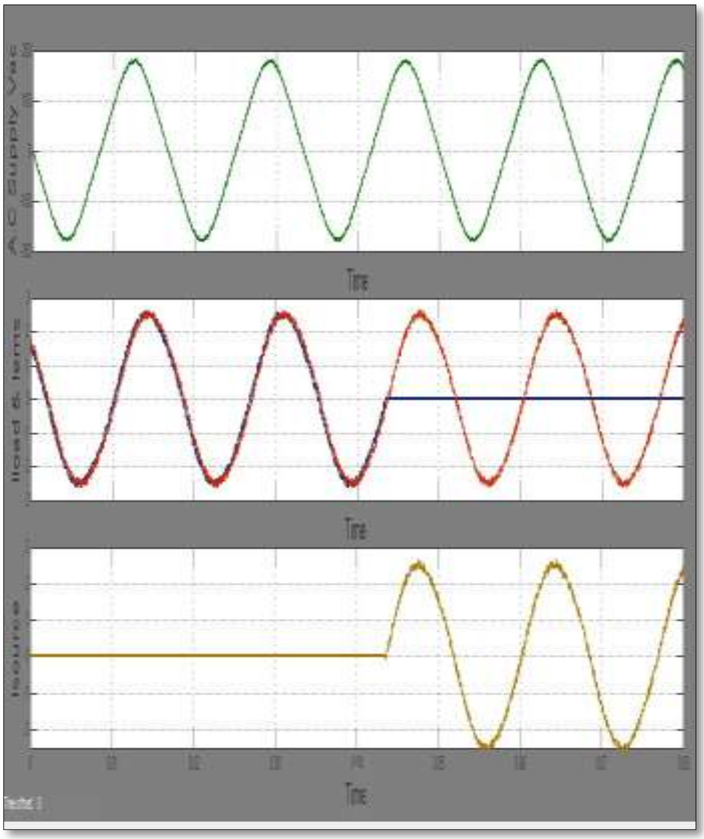


Figure.17: Simulation waveforms showing the AC grid being restored at *t=0*.

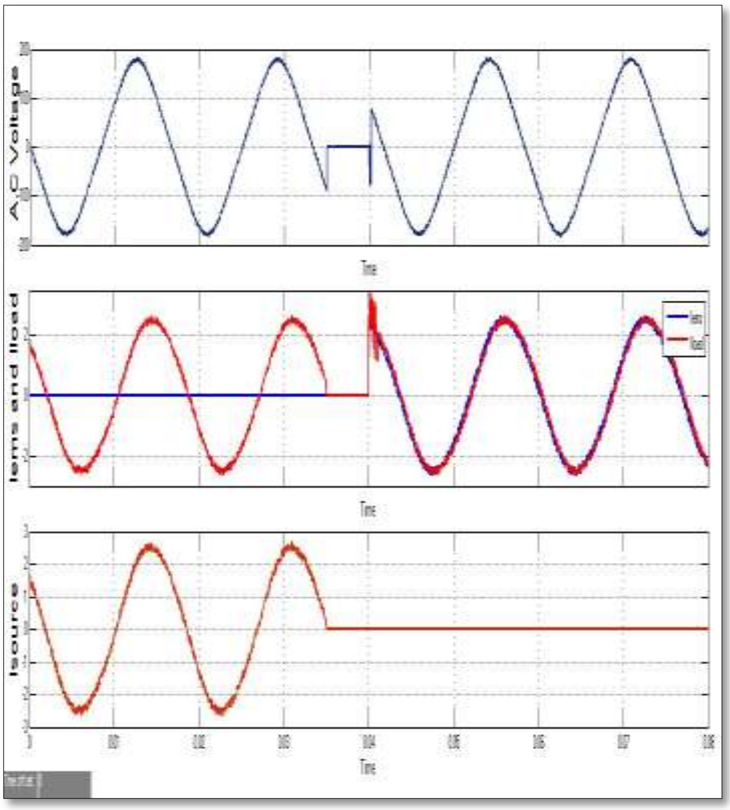


Figure.18: Simulation waveforms showing AC grid failure (A) and the EMS taking the loads into islanding mode (B). α= 60 Л.

CONCLUSION

In this work, the referred literature on fundamental aspects of optimal energy management in an AC microgrid is segregated into four categories, i.e., algorithms based on economic optimization, control optimization, performance optimization and multi-objective optimization. The brief information pertaining to each work is tabulated for providing preliminary insights into the performed work. In this paper the functionality of a power electronics-based EMS is demonstrated with a Simulink model. The control system designed to perform the experimental implementation of typical scenarios is presented in detail. Simulation data is shown to demonstrate how the EMS supports critical loads when the AC grid becomes unavailable and how the connection to the AC grid is restored by the EMS when the AC grid becomes available again. Additionally, the EMS can accomplish other advantageous tasks such as peak shaving. Experimental measurements with linear and non-linear loads demonstrate how the EMS, controlled in current mode, provides some of the power to the loads to accomplish peak shaving, thus reducing the cost of electricity. The Matlab simulation is successfully done for different case analysis as shown in the simulation results for Energy Management System in Matlab-Simulink

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