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PhD Thesis

Experimental validation of optimal real-time energy management system for Microgrids

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To my wife, my father, mother, brothers and sister.

Abstract

Nowadays, power production, reliability, quality, efficiency and penetration of renewable energy sources are amongst the most important topics in the power systems analysis. The need to obtain optimal power management and economical dispatch are expressed at the same time. The interest in extracting an optimum performance minimizing market clearing price (MCP) for the consumers and provide better utilization of renewable energy sources has been increasing in recent years. Due to necessity of providing energy balance while having the fluctuations in the load demand and non-dispatchable nature of renewable sources, implementing an energy management system (EMS) is of great importance in Microgrids (MG). The appearance of new technologies such as energy storage (ES) has caused increase in the effort to present new and modified optimization methods for power management. Precise prediction of renewable energy sources power generation can only be provided with small anticipation. Hence, for increasing the efficiency of the presented optimization algorithm in large-dimension problems, new methods should be proposed, especially for short-term scheduling. Powerful optimization methods are needed to be applied in such a way to achieve maximum efficiency, enhance the economic dispatch as well as provide the best performance for these systems. Thus, real-time energy management within MG is an important factor for the operators to guarantee optimal and safe operation of the system. The proposed EMS should be able to schedule the MG generation with minimum information shares sent by generation units. To achieve this ability, the present thesis proposes an operational architecture for real time operation (RTO) of a MG operating in both islanding and grid-connected modes. The presented architecture is flexible and could be used for different configurations of MGs in different scenarios. A general formula is also presented to estimate optimum operation strategy, cost optimization plan and the reduction of the consumed electricity combined with applying demand response (DR). The proposed problem is formulated as an optimization problem with nonlinear constraints to minimize the cost related to generation sources and responsive load as well as reducing MCP. Several optimization methods including mixed linear programming, pivot source, imperialist competition, artificial bee colony, particle swarm, ant colony, and gravitational search algorithms are utilized to achieve the specified objectives. The main goal of the thesis is to validate experimentally the design of the real-time energy management system for MGs in both operating modes which is suitable for different size and types of generation resources and storage devices with plug-and-play structure. As a result, this system is capable of adapting itself to changes in the generation and storage assets in real-time, and delivering optimal operation commands to the assets quickly, using a local energy market (LEM) structure based on single side or double side auction. The study is aimed to figure the optimum operation of micro-sources out as well as to decrease the electricity production cost by hourly day-ahead and real time scheduling. Experimental results show the effectiveness of the proposed methods for optimal operation with minimum cost and plug-and-play capability in a MG. Moreover, these algorithms are feasible from computational viewpoints while having many advantages such as reducing the peak consumption, optimal operation and scheduling the generation unit as well as minimizing the electricity generation cost. Furthermore, capabilities such as the system development, reliability and flexibility are also considered in the proposed algorithms. The plug and play capability in real time applications is investigated by using different scenarios. As shown in this thesis, with decrease/increase of present microsources capacity or change of their specifications, it is not necessary to apply major changes for making the proposed algorithms compatible with new conditions. Also, this thesis aims to operate the MG in both operating modes, ensuring uninterruptable power supply services and reducing the global cost of generated power.

Resumen

Actualmente, producción, fiabilidad, calidad de la energía, eficiencia y penetración de las energías renovables son algunos de los temas más importantes en el análisis de sistemas eléctricos de potencia. Por eso, la gestión óptima de potencia y las políticas de despacho económicos son necesarias al mismo tiempo. En los últimos años ha aumentrado el interés por la obtención de un gran rendimiento minimizando el precio óptimo del mercado de compensación (MCP) para los consumidores, además de mejorar el uso de las fuentes renovables de energía. Debido a la necesidad del balance de potencias y a la variabilidad de la demanda y del carácter no gestionable de las fuentes renovables, se requiere implementar un sistema de gestin de energía (EMS) dentro de la Microred (MG). La aparición de nuevas tecnologías como el almacenamiento de energía (ES) ha provocado grandes modificaciones en la gestión del sistema eléctrico. Además, la predicción de la generación de las fuentes de energía renovables sólo puede realizarse con precisión a corto plazo. Por lo que, para aumentar la eficiencia del algoritmo de optimización, nuevos métodos deben ser propuestos. Se necesitan métodos de optimización capaces de lograr el máximo rendimiento, aumentar el despacho económico, así como la adquisición de las mejores prestaciones de estos sistemas. Además, la gestión de potencia en tiempo real dentro de MG es necesaria para garantizar un funcionamiento óptimo y seguro del sistema. El EMS debería ser capaz de programar la generación de la MG con la mínima información requerida. Con este fin, esta tesis presenta una arquitectura para operar la MG en tiempo real (RTO) la cual puede encontrarse trabajando tanto en modo isla o conectado a la red. La arquitectura presentada es

flexible y se podría utilizar para diferentes configuraciones de MG también en diferentes escenarios. Una fórmula general se presenta tambin para la estimación de la estrategia de funcionamiento óptimo, plan de optimización de costes y la reducción de la electricidad consumida combinado con respuesta de la demanda (DR). El problema propuesto se formula en combinación como un problema de optimización con restricciones no lineales para reducir al mínimo el coste relacionado con las fuentes de generación y la carga de respuesta. Se formula como un problema de optimización no lineal. Varios métodos de optimizacin como la programación lineal mixta, fuente de pivote, la competencia imperialista, colmena artificial, enjambre de partículas, colonia de hormigas, algoritmos de búsqueda gravitacionales son utilizados para lograr objetivos específicos. El objetivo principal de esta tesis es validar experimentalmente el diseño de un sistema de gestin de energía óptimo en tiempo real para los MGs en ambos modos de funcionamiento adecuado para diferentes tamaños y tipos de recursos de generación y dispositivos de almacenamiento con estructura de plug- and-play. Como resultado, este sistema es capaz de adaptarse a los cambios en la generación y activos de almacenamiento, en tiempo real, y la entrega de órdenes de operación óptimas para los activos de forma rápida, el uso de un mercado local de energía (LEM) estructura basada en una sola cara o de doble cara subasta. El estudio está dirigido a exponer la operación óptima de micro- fuentes a, así como para disminuir el costo de producción de electricidad por día y por hora en tiempo real por delante de programación. Los resultados experimentales muestran la eficacia de estos. Por otra parte, estos algoritmos son factibles desde puntos de vista computacionales. Por otra parte, también se consideran funciones como el desarrollo del sistema, la fiabilidad y la flexibilidad en los algoritmos propuestos. La capacidad de adaptación en aplicaciones de tiempo real se investiga mediante el uso de diferentes escenarios. Como se muestra en esta tesis, con la reducción/ aumento de la capacidad de las micro-fuentes presentados o el cambio de su especificación, los cambios importantes para la toma de los algoritmos propuestos compatibles con las nuevas condiciones no es necesario.

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Nomenclature

ABC	Artificial bee colony
BES	Battery Energy Storage
BIO	Biomass
CAE	Compressed Air Energy Storage
CCU	Central Controller Unit
CEMS	Centralized Energy Management System
COE	Cost of Energy
CTU	Combustion Turbines Unit
DAC	Data Acquisition
DAM	Day-Ahead Market
DER	Distributed Energy Resources
DGN	Diesel Generator
DSA	Double Side Auction
DSP	Digital Signal Processing
DR	Demand Response
ECS	Electrochemical System
EGP	Excess Generated Power
EMS	Energy Management Systems
ES	Energy Storage
ESc (ES+)	ES During Charging Mode
ESd (ES-)	ES During Discharging Mode
EWH	Electric Water Heater
EOS	Energy and Operation Schaduling
ESS	Energy Storage System

FCE	Fuel Cells
FLY	Flywheels
GAMS	General Algebraic Modeling Systems
GEO	Geothermal
GEN	Gas Engine
GTD	Gas Turbine devices
HDAS	Hourly Day Ahead Scheduling
IREC	Institut de Recerca en Energia de Catalunya
LEM	Local Energy Market
MABC	Multi-dimension Artificial Bee Colony
MACO	Multi-layer Ant Colony Optimization
MCEMS	Modified conventional EMS
MCF	Molten Carbonate Fuel cell
MCP	Market Clearing Price
MICA	Multi-dimension Imperialist Competition Algorithm
MINLP	Mixed Integer Non-linear Programming
MPSO	Multi-period Partial Swarm Optimization
MT	Microturbine
MTG	Microturbine Generator
MG	Microgrid
MGSA	Multi-dimension Gravitational Search Algorithm
NRL	Non-responsive Load
ODSM	Optimal Demand Side Management
OF	Objective Function
PSB	Pivot Source Based
PSS	Pumped Storage System
PAF	Phosphoric Acid Fuel cell
PEM	Proton Exchange Membrane
PV	Photovoltaic
REN	Reciprocating Engine
RES	Renewable Energy Sources
RLD	Responsive Load Demand
RTD	Real time dispatching
RTEMS	Real-Time Energy Management System
SG	SMART GRID
SHT	Small Hydro-Turbines
SME	Superconducting Magnetic Energy Storage
SOC	State-of-Charge
SOF	Solid Oxide Fuel Cell
SSA	Single Side Auction

STS	Solar Thermal System
TCP	Total Consumed Power
TPP	Total Produced Power
TGP	Total generation power
TRP	Total Required Power
UP	Undelivered Power
WT	Wind Turbine
Variables	
π^A	The supply bids by A (€/kWh) A $\in \{WT, PV, MT, ESd, ESc, UP, DR \; \& \; EWH\}$
λ_t^{MCP}, $\lambda_t'^{MCP}$, $\lambda_t''^{MCP}$	MCP at each time t in $MCEMS$, $EMS-MINLP$ and $EMS-MACO_{-LEM}$, respectively (€/kWh)
P_t^B, $P_t'^B$, $P_t''^B$	Available power of B in $MCEMS$, $EMS-MINLP$ and $EMS-MACO_{-LEM}$, respectively (kW)
$\tilde{P}_t^B$, $\tilde{P}_t'^B$, $\tilde{P}_t''^B$	Real power set-points of B in $MCEMS$, $EMS-MINLP$ and $EMS-MACO_{-LEM}$, respectively (kW) B $\in \{A, TCP, TPP \& EGP\}$
$P_{i,t}^B$	Available power of B in i^{th} scenario (kW)
$P_{i,t}^n$	Uncontrollable load demand at each time step in i^{th} scenario (kW) i $\in \{1,2,3,4\}$, $i=1$: Normal Operation, $i=2$: Scenario 1, $i=3$: Scenario 2, $i=4$: Scenario 3
SOC_t, SOC_t', SOC_t''	Battery SOC in $MCEMS$, $EMS-MINLP$, $EMS-MACO_{-LEM}$, respectively (%)
$\overline{P}$, $\underline{P}$	Limit of power (kW)
$\overline{E}$, $\underline{E}$	Limit of energy (kWh)
$\overline{SOC}$	Maximum State-of-Charge (SOC) (%)
$\underline{SOC}$	Minimum SOC (%)
$Q_t^{j,b}$	The quantity produced by generation unit j in step b at time t, in (kWh)
Q_t^{TRE}	The total required energy by costumers (kWh)
Q_t^{TGE}	The total generated energy by micro-sources (kWh)
$P_t^{g,i}$	Active power generated by source i at time t (kW)
$P_t^{c,j}$	Active power consumed by Responsible Load Demand (RLD) j (kW)
$\overline{T}^i$, $\underline{T}^i$	Minimum up/down time of unit i, respectively (min)
$\overline{R}^i$, $\underline{R}^i$	Ramp up/down rate of unit i, respectively (kW/min)
t	Time interval
d	Duration of a time interval

n	Total number of sources
m	Total number of consumers
α, β	Coefficients with number values
c_1, c_2	Self-learning coefficients
I	Number of recursions
$\overline{I}$	Maximum recursions
$X_{t,j}^{b}$	The best position of the j the particle at instant t
$X_{t,j}^{i}$	The present position of the j^{th} particle at instant t and the i^{th} recursion
$X_{t,Tot}^{b}$	The best position that all the particles have obtained in the search space
$V_{t,j}^{i}$	Status the velocity vector of the j^{th} particle at the i^{th} recursion and at instant t
$V_{t,j}^{b}$	The velocity of the j^{th} particle in the direction of the least optimum point found by each individual particle up to this instant
$V_{t,Tot}^{b}$	The velocity of the particle in the direction of the least optimum point found by all of the particles up to this instant
r_1, r_2	Random number between 0 and 1
Δt	Energy management time step

1 Introduction

1.1 Microgrid concept

While smart grid is known as power system for future, smart microgrids (briefly called microgrid) are considered as the driving technology to achieve smart grids′ goals [2,3]. Although the idea of MGs seems to be similar to the various areas of operation in the traditional power system, they are different in which they have to be fully capable of autonomous operation in islanded mode. In addition, MGs could be formed in a small-scale as a commercial building to as large as power system of a town. A typical configuration of a MG is shown in Figure 1.1. Its consists of a group of radial feeders, a point of common coupling, responsive and non-responsive loads and micro-sources [4]

Since high penetration of renewable energy and storage devices are expected to be employed in the MGs, their stable operation through frequency and voltage control (traditionally known as ancillary services in the power system) is an important issue for the future power system. This goal can be obtained by balancing the generation and load demand in real time. For an islanded MG, traditional ancillary services (i.e., spinning and non-spinning reserve) are not available while more variation in generation would exist because of uncertain nature of renewable energy systems (e.g., wind and solar systems). The uncertainly of the operation increases with any failure of the generation systems and unpredictable load variations. Storage devices (such as batteries) are usually available to match generation and load demand instantly, but their capacity is limited because of their costs. In addition, demand response (DR) might be available for balancing service.

MG can significantly improve the efficiency of energy production to main-

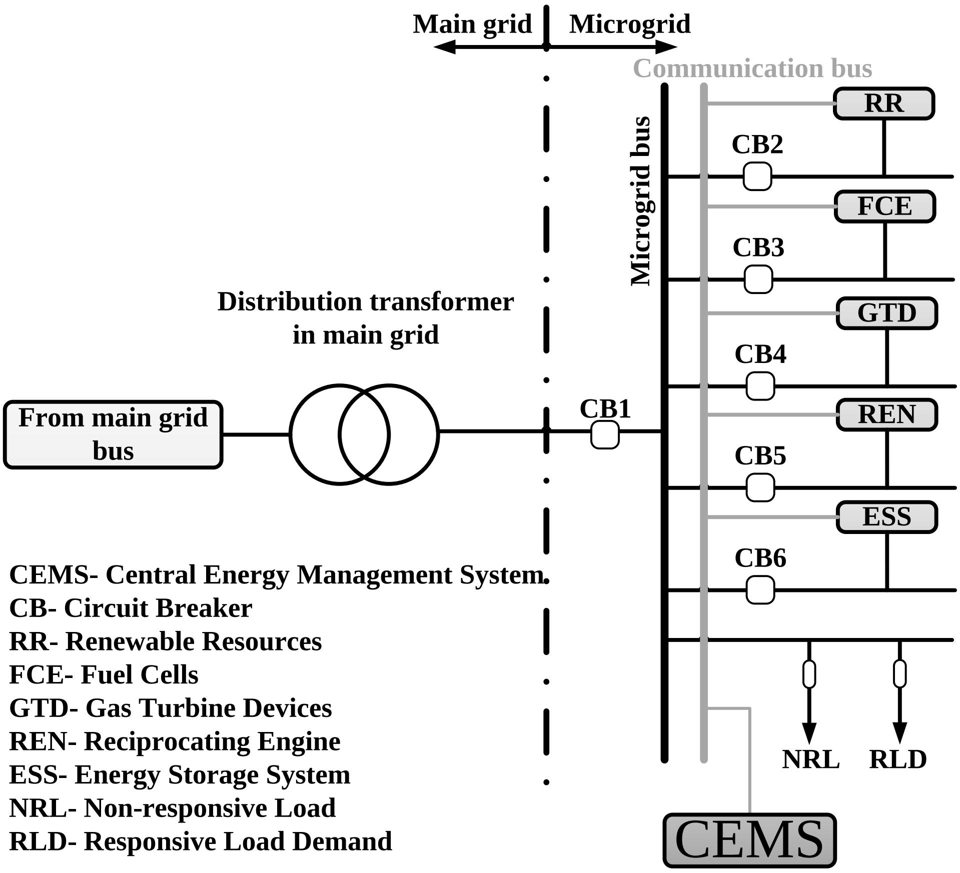

Figure 1.1: A basic MG architecture

tain the balance between power generation and load demand mostly at the distribution level. It is also desired to obtain measurable reduction in environmental emissions and increased power quality through MGs.

If a MG system wants to ensure the feeding of its consumers in line with the increase of reliability, stability of power supply and proper cost and price, presenting new initiatives for the optimization of the performance of these systems and also the exact programming of the microsources should be considered as a critical fact. In concentrated and grid connected MG, the fluctuations of load demand results in frequency problems and reactive power fluctuations, but the feeding of electricity can decrease or increase in accordance with the demand. That is because, these systems obtain part of their energy from technologies that are controllable and dispatchable. However, isolated MG system often use renewable energy technologies that are considered non-dispatchable and may vary depending on the climatic conditions. So, variations in feeding and conformity of electricity production and its consumption by the customers are considered as a challenging problem in the systems based on DGs [5–11]. An isolated MG, with no choice has much more limitations than a MG connected to a Macrogrid [12, 13].

The isolated MG based on renewable sources has limited amount of energy in access. Moreover, in such systems, there exists fluctuation in most of time intervals which depend on climatic conditions [12]. Hence, intelligent systems shall be developed for feeding the energy needed by the consumers by using non-dispatchable DG units [7, 12]. In the present power systems, the adequate feeding of the demand side sources have significant importance because of the limitations of using renewable sources. In this route, different methods for balancing energy in the MGs has been presented in the literature [7]. Reference [14] suggested to eliminate the problems regarding to energy storage technologies. Surplus electrical power generated by energy distributed sources which is more than the local loads demand can used to help to other sources that are not able to supply the power needed by their local loads. At present, energy storage can be implemented only in small scale and in a short time interval, although, technologies such as lead-acid have had significant growth in the current years [2, 3].

Moreover, demand response mechanism can cause reduction of the fluctuations resulting from random and unwanted requests [15–19].

In recent years, application of substitute energy sources such as wind, biomass, solar, hydro and etc has become more common as the result of continuous increase of the need for more reliability, better power quality, higher flexibility, lower electricity price and less environmental effects. In other words, in recent years, distributed generation sources such as PV, microturbines, fuel cells and energy storing sources have significant role in generating electricity more economically and with lower carbon emission [2, 3, 5, 9, 20]. Meanwhile, the high penetration of DGs in the grid have created new challenges about safe and effective use of these systems in power grids. The challenges can be removed to some extent by applying MGs that are defined as a set of DGs, electrical loads and generation sources connected to each other [12, 21–23]. In this regards, methodologies that are continuously improving are implemented for the management and control of MGs performance to make these grids more optimized and effective. In the other hand, severe need is felt for presenting algorithms for implementing more precise scheduling of energy sources in the MGs by including different objectives such as reducing production cost, increasing the profit of the generators, reducing environmental pollutions and etc. [24–26]. So far many research works on MG system performance scheduling under various loading conditions by considering different objectives have been developed [8,27–30].

Using DERs and competitive markets that have been created during the recent years have revealed the need for specific technical conditions considering the characteristics of smart grid [2, 3, 31]. Furthermore, recently, generation of electricity from WT and PV systems plays an important role in designing smart grid systems especially in isolated operating mode. But, the main problems encountered with RES are the problems related to continuity and unpredictability of these sources. The output of some of these sources are affected by climatic conditions. In order to solve this problem, energy storage (ES) systems can be used to support these sources. Although, there is no limitation in the select the type and choosing of the capacity of ES systems, the main problem of these systems is high initial capital investment. Moreover, DR shall also be considered as a very suitable energy source in connection with other energy resources for optimizing production cost [32]. In addition, application these sources in smart grids necessitates the present on of new control methodologies which improve the performance. Thus, an EMS whose function is to continually monitor the energy consumption, improve the utilisation of the system as well as to increase the reliability of the system could be used to optimize the operation.

Application of DER have also increased the number of variables that must be considered in the problems related to economic dispatch. With a very large number of variables it is necessary to find proper tools for solving these complex problems. So, new approaches should be developed in order to improve the efficiency of economic dispatch methods. Using deterministic optimization techniques for solving DER scheduling problems needs very fast computing devices with enough memory.

Artificial intelligence techniques such as heuristic methods inspired by biological process can have competitive advantages compared to common optimization techniques. The problems of applying common deterministic methods for scheduling DER in a realistic environment has motivated using these methods.

Electricity generation by using DG is an adequate paradigm of providing a reliable electricity source. DG can become integrated through controllable platform called MG inside distributed systems [2, 3]. In the MGs, if energy generation sources cannot provide sufficient power for feeding the requested load, the system will encounter supply demand mismatch.

1.2 Energy management system

According to the above explanations, a supervisory control and top-level management system is a necessary part of MGs to operate the system with minimum cost within safe margins. Modern energy management and control systems could help to reduce the cost of energy. However, they are applied either in a complex manner or a too simple way to achieve the desired goal. To maximize energy savings, minimize related costs and obtain a fast payback in MG systems, it is vital and most desirable to optimally operate an aggregated number of micro-sources to achieve the lowest possible production cost. In a MG, this can be achieved by applying optimization methods and adjusting the generators output to minimize the production costs. The optimization procedure may interact with public network information. For example, energy for storage devices can be bought when prices are low, and sold when required. It is also desired for the EMS to adapt itself in real-time to any changes in the types and capacity of the generation and storage assets without any manual modification in the EMS. Other objectives of the EMSs are maximizing the benefit of MG operation (equivalently minimizing the cost of operation) [21, 23, 27, 33, 34], minimizing the emission [35], maximizing the lifetime of assets [35], increasing the reliability of the MG [10, 36–53] or a combination of multiple objectives as a multi-objective EMS [21]. The EMSs fall in two different categories: central energy management system (CEMS) and distributed energy management system (DEMS). There are certain advantages and drawbacks for each one as reviewed in [54]. Various configurations for EMS with different algorithms and different MG structures have been presented in the literature [2, 55–73].

Some references have developed optimization methods for EMSs aiming to obtain scheduling operations and optimal operating strategy [2, 57–66]. The objective function (OF) in these references allows autonomous or grid-connected decision-making to determine the hourly optimal dispatch of generators depending on system constraints and market parameters. The economic concepts of EMSs in the MG market and the development of strategies to achieve such benefits are reported in [67–73].

Effective energy management can provide the necessary optimal and sustainable energy supply with maximum ability. Furthermore, given the intermittent nature of renewable energy resources, EMS should be able to find the best solution to supply consumers quickly and continuously, i.e., every minute or few minutes. In general, gradient-based optimal EMSs are too slow to be used for real-time energy management problems. As a result, recent research in this area has been focused on the off-line application of intelligent methods for energy utilization in the hybrid energy systems, e.g. [74, 75]. Only few other studies have been reported with limited simulation evaluations for real-time management in specific applications [33, 76]. This thesis has focused on real-time implementation of EMS with additional constraints for battery operation and its life time extension. Real time operation have been investigated in the literature [33,77,78] but these algorithms have never been tested in experimental MGs.

The increase of distributed generation (DG) penetration into power systems and the introduction of private market in recent years have caused numerous challenges in the design and planning [2, 3, 70–73]. In the future, the consumers can have an isolated MG that includes micro generation systems and their consumption management can be done by EMS according to real time electricity cost.

Among the main constraints related to renewable energy sources are problems related to reliability and dispatchability associated with their performance [79] because the output power of renewable sources changes with weather conditions. As a result, power balance between producers and consumers considering reserve sources for supplying shortage of system power is considered as a key problems in EMS design. Complex constraints and the impossibility of complete accordance of all DG generation sources with the paradigms of power system, has led to the presentation of smart grid concept. The main specifications of a smart grid are as follows:

1. Capability of executing programs such as demand response management for controlling the shiftable loads (shift to times with lower cost and less electricity consumption);

2. Error tolerance, this tolerance must also be considered for confronting the transient errors;

3. Load curtailment ability when the MG cannot feed its load completely or when the electricity prices are high [79];

4. High reliability, power quality, security and system efficiency;

5. Self revival which means that the system can revive itself after the occurrence of error in it;

6. Plug and play capability of all the devices that are added to the system as microsources with any capacity or are put out of the system is provided automatically by EMS.

For obtaining the characteristics mentioned for SGs, it is necessary to consider short-term scheduling (STS) and very short-term scheduling (VSTS). STS can fulfill the characteristics (1-3) mentioned above.

Short term economic dispatch [79–89] is a very important choice in the modern energy management systems and by using it, the system performance cost can be reduced. It is demonstrated that demand response as a very important energy source which it must be paid attention to such as generating sources and ES sources to optimize the system performance. Distributed energy resources (DER)s significantly increase the number of variables that must enter the economic dispatch problem. So, it is necessary to present new methodologies for improving the efficiency of these methods.

For presenting these methodologies, very fast and adequate response must be considered for the optimization problems with a lot of variables [79, 90]. Deterministic optimization techniques need significant calculations and also the execution time of these methods is not compatible with short-term scheduling.

So, it is necessary to use alternative methodologies which have the fast response for multi-variable optimization problems. Intelligent competitive techniques called methaheuristic methods inspired from biological process can provide this desired characteristic.

Applying proper EMS is also crucial in order not to encounter this problem. An EMS makes the optimum use of distributed energy sources possible alongside assurance of their quality and reliability. Although, it is possible that these systems fail in load feeding if the total demand is more than the maximum accessible capacity of the generation sources. Under such a scenario, applying supporting systems such as diesel generators, distributed storages or implementing demand side management (DSM) options can be useful to reduce the supply-demand mismatch [5, 9, 26, 91]. In recent years, the operation and maintenance costs and the levels of emission of pollutants in the generators based on fossil fuel has been increasing significantly. As a result, special attention is considered in using such support systems in addition to DSM and storage systems. The main objectives of DSM program is minimizing mismatch between fed power and load during consumption peak by changing the system load curve. The variation of system load curve can be done through both the distribution system facilities and end-use customers [92–94].

1.3 Research motivations and objectives

In this thesis, a general CEMS framework with plug-and-play structure will be proposed to minimize the operation cost of the MG. The plug-and-play capability of the proposed CEMS facilitates automatic modification of the management problem since any change in the generation and storage resources is dealt with in real-time to achieve optimal operation of the MGs. It is also assumed that each generation and storage device sends a signal to the CEMS to establish itself in the management system at the time of attaching to the MG. As a result, the proposed CEMS can be developed as an autopilot product, capable of adapting itself to any MGs.
As mentioned earlier, the objective of the proposed CEMS is to optimally operate any MG with any size and types of generation and storage devices by minimizing the cost of operation. To achieve this goal so in real-time, a comprehensive database of available generation and storage technologies for MG operation (called technology database in this thesis) is considered with appropriate mathematical cost function and operational constraints. Assuming a two-way communication between each asset in the MG and CEMS (which is an inherent feature of smart MG), each device at the beginning of connection and after each change will inform the CEMS about its type and capacity. The proposed CEMS framework also includes optimization unit, LEM unit and real time dispatching, which are explained in Chapters 2 and 3. The LEM is based on SSA and DSA to calculate the price of energy in real-time for the consumers.

In this thesis, by using the profile of non-dispatchable sources and non-responsive loads, the optimum power setpoints for the spinning reserve sources, energy storage and also demand response are sent to them by using the proposed algorithm by the central controller unit (CCU). Moreover, the concept of virtual generation sources has been introduced and are extracted according to the information of load demand and the total power generated in each time interval. Some DR constraints are manipulated and stated by using the modeled information with the situation flags. Optimum scheduling in a combinatorial topology of production sources and DR by minimizing the total system performance cost and the reducing MCP in each time interval using several proposed optimization algorithms are considered as one of the main innovations of this thesis. The cost function presented includes the cost of all generation and storage assets considering the DR cost with respect to the constraints considered for each one of them.

1.4 Thesis contributions

The contributions of this thesis can be briefly clarified as follows:

1. Proposal of a CEMS which is flexible to adapt itself to any type of MG [J7];
2. Develop of a plug-and-play operation of the generation and storage assets in real-time with comprehensive technology database of generation and storage devices, NRL and Responsive Loads (RL) [J1, J7];
3. Applying a real-time optimization for the future generation forecast [J9];
4. Proposal of a fast, flexible and extendable RTO architecture to coordinate DAS and RTS and improve of ES operation considering two extra operation modes for the ES including Over Charging Protection Mode and Over Discharging Protection Mode [J1];
5. Presentation of some novel optimal EMSs in a day-ahead market to minimize the total cost of operation in both islanded and grid connected MG [J2-J10];
6. Experimental implementation of the proposed optimization algorithms over on a real MG Testbed [J1-J10].

1.5 Thesis outline

The organization of this thesis falls into seven chapters:

1. **Chapter 2** defines the generalized formulas and the proposed structure including the optimization and local energy market units that will be used intensively in the rest of the thesis [J5].
2. **Chapter 3** studies several local energy market structures to obtain unit commitment based on cost considering the production cost minimization. The results presented in this chapter have also appeared in [2, 3].
3. **Chapter B** provides a review of heuristic algorithms tends to make an assessment of their advantages and drawbacks relative to others regarding the real time operation support [J6-J10].

4. **Chapter 4** allows us to address the mathematical subtleties of the optimization algorithms while being able to satisfy all constrains. Results of this chapter have also contained in [J2-J10].

5. **Chapter 5** presents the simulation and experimental approaches and the results and discussion for MG in both isolated and grid-connected operation mode [J2-J10].

6. **Chapter 6.1** summarizes the previous chapters, draws the achieved conclusion about this research and gives some suggestions for future improvements and work.