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Integrating renewable energy in smart grid system: Architecture, virtualization and analysis

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A B S T R A C T

Renewable energy sources (RESs) and energy storage systems (ESSs) are the key technologies for smart grid applications and provide great opportunities to de-carbonize urban areas, regulate frequency, voltage deviations, and respond to severe time when the load exceeds the generation. Nevertheless, uncertainty and inherent intermittence of renewable power generation units impose severe stresses on power systems. Energy storage systems such as battery energy storage system enables the power grid to improve acceptability of intermittent renewable energy generation. To do so, a successful coordination between renewable power generation units, ESSs and the grid is required. Nonetheless, with the existing grid architecture, achieving the aforementioned targets is intangible. In this regard, coupling renewable energy systems with different generation characteristics and equipping the power systems with the battery storage systems require a smooth transition from the conventional power system to the smart grid. Indeed, this coordination requires not only robust but also innovative controls and models to promote the implementation of the next-generation grid architecture. In this context, the present research proposes a smart grid architecture depicting a smart grid consisting of the main grid and multiple embedded micro-grids. Moreover, a focus has been given to micro-grid systems by proposing a "Micro-grid Key Elements Model" (MKEM). The proposed model and architecture are tested and validated by virtualization. The implementation of the virtualized system integrates solar power generation units, battery energy storage systems with the proposed grid architecture. The virtualization of the proposed grid architecture addresses issues related to Photovoltaic (PV) penetration, back-feeding, and irregularity of supply. The simulation results show the effect of Renewable Energy (RE) integration into the grid and highlight the role of batteries that maintain the stability of the system.

1. Introduction

Notwithstanding the Paris Agreement, a technological transient from hydrocarbon-based power generating units to the post-petroleum-based sources, there is intangible projective evidence of such transition in the world [1]. For instance, recent studies into the projective period indicate that energy consumption will increase from 663 to 736 quadrillion Btu between 2015 and 2040 [2], with an expected increase in carbon dioxide annual emissions from 31.2 to 45.5 billion metric tons. Moreover, recent investigations demonstrate that the possibility of the energy paradigm shift to sustainable low carbon economy at European Union, although, has come into conflict between the Northern, Western Member states against Central and Eastern European, causing an obstruction of swiftly advancing de-carbonization [1]. To clarify the importance of integrated renewable energy sources, European Union set a goal of reaching 27% in gross final energy consumption from renewable energy sources by the end of 2030 [3]. Therefore, coupling of renewable energy sources (RESs) and electric grid has gained momentum and is being widely accepted as an alternative power supply. In Germany, expansion of renewable energies is a central pillar of the energy transition towards a non-nuclear renewable system [4]. In addition, the global installed capacity of solar photovoltaic (PV) has dramatically increased as part of a shift from fossil fuel-based power generations towards reliable, clean, efficient and sustainable fuels [5]. The

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Acronyms

RESs	Renewable energy sources
RE	Renewable energy
ESSs	Energy Storage Systems
MKEM	Micro-grid Key Elements Model
PV	Photovoltaic
RE	Renewable Energy
ICT	Information and Communication Technology
NIST	National Institute of Standards and Technology
SGCN	Smart Grid Communication Network
SGAM	Smart Grid Architecture Model
SGCG	Smart Grid Coordination Group
CSIRO	Commonwealth Scientific and Industrial Organization
DG	Distribution Generations
UCC	Universal Charge Controller
MAS	Multiagent System
EMS	Energy Management System
ESSs	Energy Storage Systems
SOS	System of Systems
MG	Micro-grid
LC	Local Controller
HAN	Home Area Network
BAN	Building Area Network
IAN	Industrial Area Network
SDs	Smart Devices
SP	Service Provider
HVAC	Heating Ventilating and Air Conditioning
PEVs	Plug in Electric Vehicles
SM	Smart Meter
TOU	Time of Use
RTP	Real Time Pricing
SSM	Supply Side Management
DC	Direct Current
AC	Alternating Current
IC	Incremental Conductance
SSM	Supply Side Management
SoC	State of Charge
BESS	Battery Energy Storage Systems
TMY	Typical Meteorological Year
SG	Smart Grid
GHG	Greenhouse gas

goal is to maintain grid stability with high penetration of RESs while satisfying consumer demand. In this regard, it is expected that this integration could reduce carbon dioxide emissions and other air pollutants. As mentioned before, by successful coordination between RESs and power systems, ESSs could improve the reliability, security, and resiliency of micro-grid applications by offering ancillary services such as peak shaving.

1.1. Literature review

The need for integration of RESs into the power system is to provide a wide variety of socioeconomic and environmental benefits, and to minimize the GHG emissions from conventional power plants [6]. Andújar et al. [7] explained two main reasons for justifying the transit towards coupling renewable energy sources with power plant-based fossil fuels. These reasons are [7]: environmental concerns, and power losses. However, the stochastic and the intermittent behavior of the PV power generations pose severe stresses to the grid lead to the instability in the electricity supply [8]. More precisely, the intermittent energy sources can fail to guarantee the continuity and reliability of the power supply [9]. Besides of the aforementioned challenges of PV integration, the back-feeding imposes tremendous operational challenges in power systems [10]. When the local PV generation exceeds the local load demand, reverse power flows occurs. The reverse power induces a voltage rise within distribution networks [10]. Along with that, Calpa et al. [11] analyzed the effects of high PV penetration as the main energy source for the Spanish electrical grid. The authors highlighted the effect of high PV penetration which can lead to a reduction on the local consumption or even negative consumption. The results showed that the electrical grid should be able to respond to this new shape by adapting the power generations, controlling consumption or using storage systems [11]. Similarly, Cohen et al. [12] simulated a use case of Sacramento feeders and showed negative values for load demand and a largest reverse power flow. It was shown that feeder location (i.e. climate) has a stronger impact than feeder type on the incidence of the reverse power flow and reductions in peak loading [12]. Moreover, Nguyen and Kleissl [13] highlighted the impact of PV power generation units, can be reverse power flow, high voltage level and increasing number of tap operations. To deal with the reverse power flow, decentralized PV power generation units have been proposed instead of the centralized generation units [13]. Besides that, integration of renewable power generation units as new distributed generations encompassing large scale at the transmission level, medium scale at the distribution level and small scale on commercial or residential building can present challenges for the dispatch ability and control ability of these resources and for operation of the electricity system [14].

In this context, the traditional grid must be improved to cope with the increased penetration of PV and its inherent intermittency. In this framework, energy storage systems can play a significant role in meeting or mitigating the mentioned challenges and dealing with the variations of PV. From technical expertise point of view, the energy storage technology is considered as a one of the disruptive technologies that could change the way the energy supply, for end-users [15]. For instance, by installing a storage battery as an energy buffer, system stability can be improved [15]. In this sense, the generated PV power can be stored, or fed into the micro-grid. Therefore, in order to accommodate uncertainty of future realizations of demand and generation, sizing energy storage systems plays a prominent role in the micro-grid [16]. This can mitigate the intermittent and fluctuations of PV power generation units. In addition, the integration of energy storage systems during peak load periods can be also useful to shift electrical demands from on-peak to off-peak [17,18]. In this regard, it is becoming critical to integrate analysis and design of power electronics and power systems in order to support this integration.

The integration of new technologies into the conventional grid requires both innovative and robust modeling of various components to incentivize and implement Smart Grid architectures with RESs. In order to upgrade the current power grid, it is required to go through existing Smart Grid architectures. Indeed, an architecture that could support RESs integration and accommodate higher levels of variable ESSs. In this context, many researchers have proposed broad definitions of smart grid. A smart grid can be defined as an upgraded electrical network, relying on bi-directional communication infrastructure and power exchange between suppliers and consumers, due to the pervasive incorporation of intelligent communication monitoring and management systems [19]. It is the coexistence of power flow, Information and Communication Technology (ICT) and financial transactions. In this way, the ICT in the smart grid can make the existing infrastructure including generation, transmission, distribution, and consumers more efficient and yet can guarantee the successful coordination between local distributed renewable generation units and power system [20]. Thus, the smart grid is an evolution of the power grid, based on the integration of new technologies, smart devices, advanced communications and controls. In this regard, many researchers have proposed a design of Smart Grid architecture to support integration of RESs. In Ref. [21], a generic hierarchical architecture as a framework of various energy management systems has been proposed to deal with the challenges of the increase in penetration of the distributed renewable energy generation. Furthermore, the U.S. Energy Independence and Security Act directed the National Institute of Standards and Technology (NIST) to propose a NIST model defining the Smart Grid as a coexistence of seven domains in 2007 [18]. Whereas the NIST conceptual model provides a wide picture of how the fundamental components of the smart grid connect and communicate and seems to be a promising reference architecture for standardization of interfaces, it still presents some drawbacks related to the lack of definition of Micro-grid systems with owners of energy sources. Hence, the Smart Grid Coordination Group (SGCG), driven by the European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC) and European Telecommunications Standardization Institute (ETSI) designed the Smart Grid Architecture Model (SGAM) and thus by international experts [22]. The SGAM as a three-dimensional framework consisting of domains, zones, and layers, provides a structural approach for modeling smart grid use cases [23]. In this sense, the NIST model has been extended by the European Community which integrates a “Distributed Energy Resources” (DERs) domain. The updated model reflects the growing importance of DER, which includes non-traditional sources such as customer-owned solar and wind power systems. These DERs with advanced functionalities enable power system designers to incorporate “Micro-grids” into the existing grid architectures.

In this way, during the next decade, micro-grids will emerge as an alternative to the current centralized energy generation systems, because they can provide economic benefits through avoiding long distance transmission [24]. Also, they can enhance the integration of small and medium size of DER units into the electric grid [24]. Moreover, the micro-grids enable effectively the main grid to disconnect different part of that when power is disrupted. Hence the power system can be more adaptive and reliable against possible either fluctuation or fault. In this sense, a Micro-grid model is essential for after-the-fact event analysis. It can reduce system complexity and provide better insight into RESs integration studies. Furthermore, as one of the possible solution to the inherent intermittent renewable power generation units is coupled grid with ESSs, Wood et al. [25] has used the “UltraBattery” technology, an entire new class of advanced lead–acid batteries invented by the “Commonwealth Scientific and Industrial organization” (CSIRO), to manage variability and shift energy demand. This technology focused on Micro-grid systems to combine renewable energy sources with a storage system, thus providing multiple benefits, making renewable resources reliable and dispatchable [25]. Adonis et al. [26] presented an analysis of control strategies developed for a Micro-grid control structure, when it is integrated with renewable energy sources. The authors developed a control strategy for the load management and performed an analysis through MATLAB/Simulink simulation. The objective was to improve Micro-grid operation stability under irregularities of the input voltage. Similarly, in Ref. [27], distribution generations (DG) and renewables with seasonal variation at different locations have been modeled by employing PSCAD software. The goal was to maintain the power quality of the system when the load has fluctuation. The authors proposed a generalized approach to design, determine the capacity, required for the micro-grids with metrics to meet the power quality indexes [27].

1.2. Motivation, objectives, and innovative contribution

Generally, a micro-grid is composed of renewable energy generations, energy storage systems (ESSs), and loads, which can operate in grid-connected and stand-alone modes. The primary objective of the present article is to depict a smart grid architecture consisting of the main grid and multiple embedded micro-grids. In this article, “Micro-grid Key Element model” is employed to model the above architecture that would be double-beneficial: (1) predicting the effect of energy sources on power system such as solar energy (2) minimizing the cost and risk of the proposed architecture before implementation. Moreover, a virtualized power system would open new avenues for revenue generation as well as utilize computing and network resources more efficiently across the entire power grid. The virtualized grid system would provide increasing stability of the physical grid and isolate problems more quickly.

According to the literature, the proposed architecture in this article enjoys several advantages, compared to the recent studies [28–31]. For instance, Sermakani et al. [28] proposed a multiagent (mesh topology) system based on a decentralized micro-grid control. However, the maintenance of the proposed topology is very difficult along with its tough administration. Moreover, the cost of implementation of such architecture is higher than other network topologies, making it an expensive option. In addition, Wang et al. [29] proposed a three-layer architecture of a smart grid, highlighting the energy trading among MGs by employing Peer-to-Peer (P2P) networks. Nevertheless, the unstructured networks such as P2P lead to difficulties with communication resources, and limit the possibility for managing different plans [32]. To address the above drawbacks, the present article proposes a Smart Grid as a system of multiple embedded micro-grids, including a double-layer controller. The high-level of controller is the centralized controller at the main grid, and the low-level of controller, known as a local controller is associated with the micro-grid level. In addition, Ref. [30] proposed a transformative architecture for a normal operation and self-healing of networked micro-grids (MGs), composed of both cyber links for communication and a physical common bus for power exchange. However, the financial flow has not been considered within this architecture. Furthermore, Ghiani et al. [31] presented multidisciplinary key interactions in a Smart Distribution Network (SDN) to the strong connection between the design and operation of SDN. Therefore, the connections are established between three main fields: management and control system (MCS), monitoring system (MS), communication and processing system (CPS). Nevertheless, the market interaction and financial transactions have not been taken into consideration in terms of necessary multidisciplinary approach to the design of the smart grid architecture. In this regard, in addition to the above connections, the proposed smart grid architecture in the present article has a connection with the market interaction and financial transactions to address the above gaps.

The main contribution of the present article can be categorized as follows:

1. Presenting the Smart Grid as a System of multiple embedded micro-grids;

2. Introducing a micro-grid consisting of multiple nano-grids;
3. Coupling of the proposed grid structure with solar power generation units, and the effect of their penetration on power system is discussed;
4. The proposed MKEM is optimally designed and accurately modeled in the power-systems simulation tool GRIDLAB-D;
5. Integrating ESSs into the proposed grid structure to maintain system stability.

To sum up, in the following paragraphs, a smart grid architecture using embedded systems of micro-grids is presented and proposed through MKEM modeling. The main objective of introducing such architecture is to reduce system complexity and improve flexibility of the system. The introduced smart micro-grid is composed of renewable energy generations, energy storage systems (ESSs), and loads, which can operate in grid-connected and stand-alone modes. Then, the proposed micro-grid model is implemented to test integration and penetration of RESs.

In addition, the rest of the article is organized as follows: the proposed Smart Grid architecture is presented in Section 2. Section 3 depicts the elements of the proposed architecture by focusing on micro-grid and presenting a MKEM. Results and discussion are provided in Section 4. Finally, the outcome of the article is summarized and concluded in Section 5.

2. Proposed smart grid architecture

The backbone of a smart grid, known as a complex System of Systems (SOS) [33], highlights ESS technology to reach better asset utilization, while to maintain reliable system operation, demand response, and environmental protection through employing various generation types (e.g. solar and wind). In this regard, the main concept of the smart grid revolves around bi-directional communication and power flow according to the definition proposed by NIST Smart Grid Conceptual Reference Model, through seven domains which are: bulk generation, transmission, distribution, markets, operations, service provider, and customer.

However, Smart Grids have to be analyzed from a SoS point of view to realize their full potential and optimize the whole system [33]. Arasteh et al. used the concept of SoS to model the expansion of DGs which may belong to the distribution companies or the private investors, considering the independent behavior of each system with respect to other entities [34]. As private investors and distribution companies are autonomous, heterogeneous and independently operable systems are connected to provide a common goal, their behavior could be analyzed from a SoS perspective to model their correlation. The SoS perspective aggregates different autonomous systems, interacting on various levels, which are characterized by operational and managerial independence [35]. A representative example of this perspective is the energy management sector in which the Smart Grid is known as a complex system composed of heterogeneous and independent sub-systems (e.g., consumers, producers, prosumers, storages, etc.) that interact to compete or cooperate [36]. Different strategies for coordinating constituent systems of a SoS exist such as centralized coordination, where a Central Controller (CC) coordinates constituent systems at the SoS level and all constituent systems have their own controllers for management and operations, known as Local Controllers (LC) [37]. A decentralized strategy for SoS can also be used, where neither a CC nor a pre-specified rule or agreement for constituent systems exists [37]. Another strategy for SoS is a coordinating strategy which is considered as a hybrid strategy that mixes both centralized and decentralized coordination.

In this regard, the Smart Grid should be considered as a complex system where the main grid contains multiple micro-grids. These micro-grids consist of several nano-grids known as small residential power systems with renewable sources, storage systems, and domestic loads. The nano-grids and micro-grids are the electric grids which correspond to the residential power systems and neighborhoods, respectively. They are also connected to the power distribution grid or to another micro-grid [31]. The micro-grid involves different technologies and contains loads, distributed generators (PV or wind turbines), Distributed Systems, Electric Vehicles (EVs), ESSs and power electronic systems [32,33]. In this regard, power electronic systems are required to enable the micro-grid to operate in grid-connected or island modes. Moreover, these systems are needed to connect DER to the nano-grids using inverters for PV or batteries to obtain the required frequency.

To deal effectively with the challenges of integrating RESs and nano/micro-grids with the electric grid, contemplating electric source intermittency and load inconsistency, this study proposes a smart grid architecture, depicted in Fig. 1. The proposed architecture consists of a double-layer controller, one of which is a centralized controller at the main grid level and the other one is a local controller (LC) that controls the micro-grid level. In centralized operation, each LC receives the set points of the corresponding Smart Grid (SG) Controller. However, this type of control has low reliability and redundancy [38]. In decentralized operation, each local controller decides locally [39]. In the present research, the proposed architecture uses a hybrid approach defining both the centralized and decentralized operations within the main grid. Moreover, three flows can be distinguished: the power flow which can be bidirectional in case of batteries or consumers with production capabilities, the information flow which consists of an ICT platform, and the financial flow related to the commercial transactions including pricing and wholesaling [18]. The proposed SoS architecture encompasses three levels which are: the macro-grid level referring to the main grid, the micro-grid level and the nano-grid level. The macro-grid level contains the transmission system with large scale generation systems, ESS to store different kind of electricity such as an electrochemical or mechanical energy system, and large industrial consumers. Moreover, a transmission system operator is used to transfer energy in different forms such as natural gas or the electrical power, and a service provider is used to interact with the operators and ensure proper functioning of the smart grid. At the micro-grid level, two objectives can be distinguished considering micro-grid operation modes. In grid-connected mode, financial transactions are made using interactions with the wholesale markets. However, in islanded mode, the energy and economic flows of the micro-grid are managed using a local market named retail market, and energy efficiency services are provided. In both modes, the micro-grid guarantees in real time the stability and the security of the network. At the nano-grid level, peak-shaving, load leveling, and load-shifting are performed to reduce energy losses and energy cost employing end user's preferences, price signals, management of local generation and local ESS. Moreover, the demand response can be achieved through dynamic pricing to reduce the gap between supply and generation. The smart meter is used for reading and transmitting measurements of the power consumption, generation, and voltage [40]. It also interacts with a two-way communication with retailers and controllers. Moreover, it handles various bill models such as Time of Use (TOU) or Real Time Pricing (RTP).

3. The proposed micro-grid model

The micro-grid is a distribution system with local DERs which is connected to the traditional centralized electrical grid but is able to operate autonomously [41]. A micro-grid could be a kind of smart grid equipped with advanced computer communication

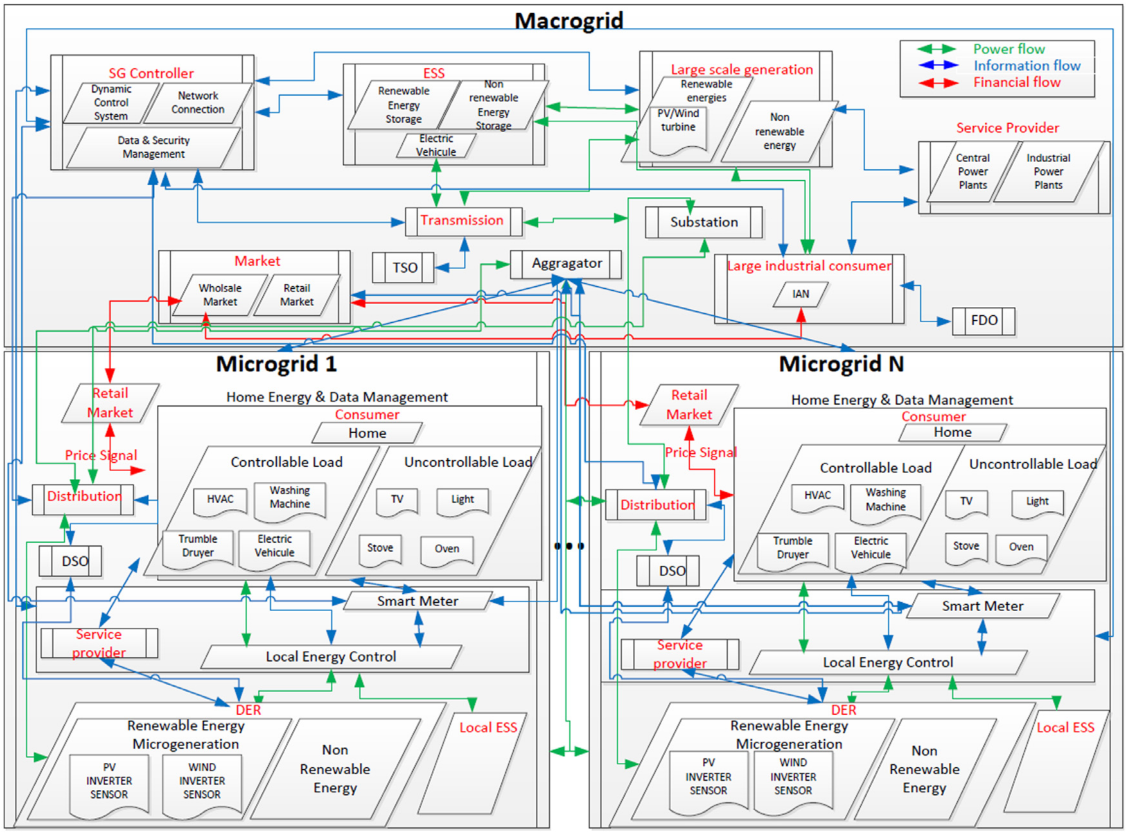

Fig. 1. The proposed smart grid architecture.

technologies and smart meters providing more flexibility and reliability for control and protection of the system [41]. Today, the micro-grids include different types of renewable sources to achieve environmental and economic benefits [42]. In this sense, the micro-grid has emerged as a flexible architecture for deploying distributed energy resources (DERs) that can meet wide-range of needs for different communities [43]. Especially, PV system is one of the most effective DERs in micro-grids [41]. Moreover, the micro-grids enhance market operations and consumer participation [44]. In this regard, the micro-grid energy markets allow small-scale participants such as consumers to actively trade energy within their community in real time [44]. Therefore, they facilitate a sustainable, reliable, and local balance of generation and consumption [44]. In this context, Eq. (1) identifies the relationship between the generated power and the load power within a micro-grid at each time interval:

$$\sum P_{loads} = P_{pv} + P_{ESS} + P_{market} \tag{1}$$

where P_{loads}, P_{pv}, P_{ESS}, and P_{market} are the load, the power generated by the PV systems, the power provided by ESS, and the purchased and sold power from/to Micro-grid, respectively. To gather the requirements of a system including internal and external influences and highlight the role of RESs and ESSs, use cases and standards are considered as an efficient method to determine requirements and to address interoperability issues. In this regard, Unified Modeling Language (UML) is recommended to allow the use within further model-based development efforts and to ease the customization by implementers in their own tool chain [23]. For instance, Eger et al. identified essential use-cases of a microgrid scenario by employing UML diagrams [45]. Further, the actors involved in the use-cases were divided into "people & organization" such as prosumer, service provider, consumer, retailer, and "systems & devices". Similarly, Gopalakrishnan et al. analyzed micro-grid operational scenarios using UML and defined business use-cases, and technical use-cases referring to control and management use-cases [46]. Business use-cases involve selling and buying energy to/from external markets, selling balancing and ancillary services, providing islanding mode, and offering communication platform for energy trading. However, the technical and management use cases include balancing supply and demand on the varied time scales, auto configuration, monitoring and state analyses, forecasting generation and consumption, and optimizing power flow to reduce losses. Furthermore, Sultan et al. focused on two components of smart power system that are transformers and smart meters and presented system requirements through UML use-case diagrams that are used to describe actions and functionalities of the system [47]. Moreover, in Ref. [48], the authors focused on modeling smart grid functional requirements using use-case descriptors and UML class diagrams to easily track disturbances and outage events that can happen in the electric grid environment. In this regard, the main purpose of using model driven methodology and high level or summary use-case diagrams is to clearly describe the functional requirement of a system, help manage complexity and pave a way for building smart grid applications [49,50]. In this context, a "Micro-grid Key Elements Model" (MKEM) as high-level use-case diagram combining business and control and management aspects is proposed.

The Fig. 2 shows the interactions of actors, the functionalities captured and the relationships among actors within business, control and management levels. The proposed MKEM consists of eight actors which are defined as follows:

3.1. Consumer

End-user or consumer can be classified into three groups: a residential customer, a commercial customer, and an industrial

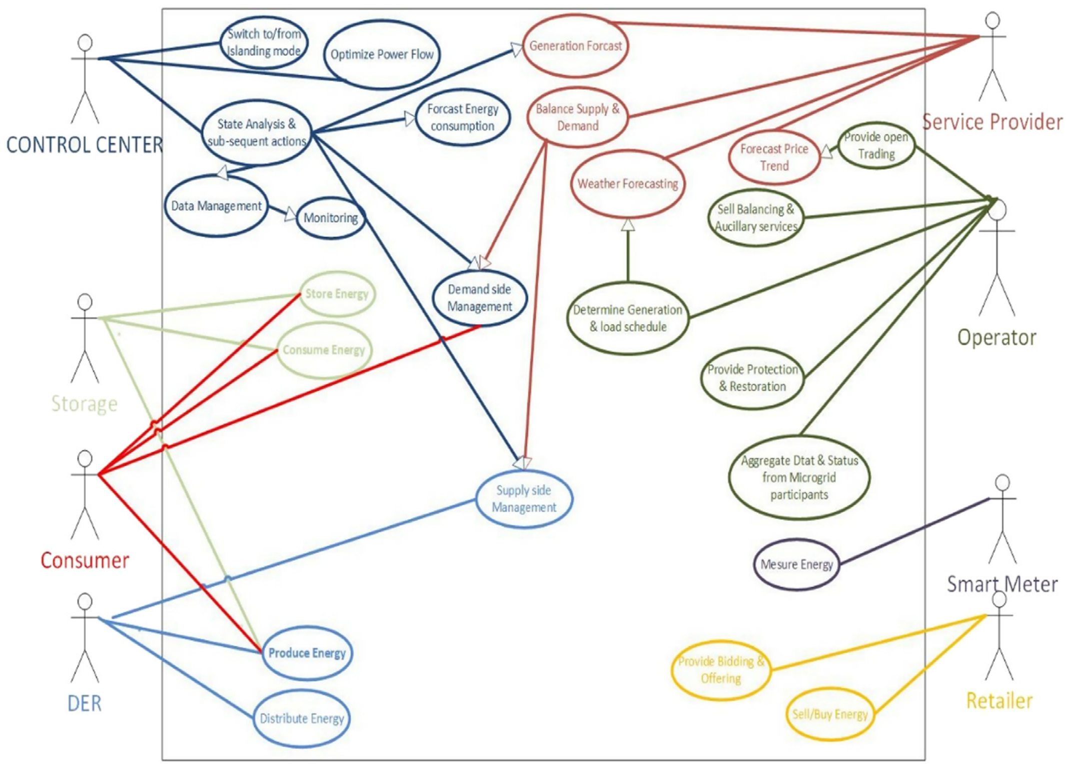

Fig. 2. Proposed MKEM model.

customer. Therefore, three networks can be defined as follows: Home Area Network (HAN), Building Area Network (BAN) and Industrial Area Network (IAN). The HAN consists of the following entities: smart devices (SDs), a home gateway (HG) and a service provider (SP) [51]. It is a network connecting devices able to send and receive signals from other devices and applications. The HAN is thus an enabling factor for the evolution of the smart home and other applications, such as home energy management (HEM) systems [52]. In addition, BAN and IAN are used for commercial and industrial customers with focus on building automation, heating ventilating and air conditioning (HVAC) and other industrial energy management applications [53]. In this regard, the consumer within a micro-grid can have a controllable load such as HVAC, washing machine, water heater, electric vehicle, and an uncontrollable load such as TV, lights, stove, and oven. These smart appliances provide the consumers with information on incentives and disincentives, offering choices and motivations, to change their consumption profiles. The objective is to help balancing supply and demand and to ensure reliability for dynamic pricing and demand response services considering consumer preferences. This can be achieved by employing billing, bidirectional flows of energy, information and financial transactions.

In this regard, the consumer can perform the following functionalities:

- Use electricity, generate electricity, store electricity;
- Engage in DSM to consume less energy during high-consumption hours (peak hours) or shift its consumption (to off-peak periods).

3.2. Smart meter

A smart meter is an electronic device that measures energy consumption and exchanges the information with the electricity supplier for monitoring and billing. This component can provide the required measurements for various control strategies [18]. By such devices, consumers can communicate with power generation units and pave a way for controlling the load.

The Smart Meter can perform the following functionalities:

- Measure energy flow;
- Exchange information with the electricity supplier.

3.3. DER

DER generally include the distributed generation, and storage systems. These components can provide benefits such as reducing power losses in transmission system, maintaining grid stability, and improving resiliency. DERs are essential components for the micro-grid whose role is to integrate RESs into the power system and to keep the balance between energy demand and supply. Moreover, DERs can improve grid reliability, to better manage energy consumption and to achieve energy efficiency guidelines. However, the main disadvantage of using DERs is their intermittent nature. Therefore, modern electric grids have to support the integration of the conventional generation technologies, renewable energy resources, energy storage devices and dynamic loads [54]. This interconnection highlights the concept of micro-grid and mitigates the issues related to the intermittency behavior of RESs. To enhance the independency aspect, ESSs are disconnected from DER and presented as independent components in the proposed model.

DER can perform the following functionalities:

- Distribute and produce energy;
- Perform Supply Side Management (SSM) with ESSs.

In this paper, the generated power P_{pv} by PV component can be calculated via using solar irradiance and PV temperature as showed in Eq. (2):

$$P_{pv} = P_n \times (R \div R_{ref}) \times [1 + K_t \times (T_c - T_{ref})] \qquad (2)$$

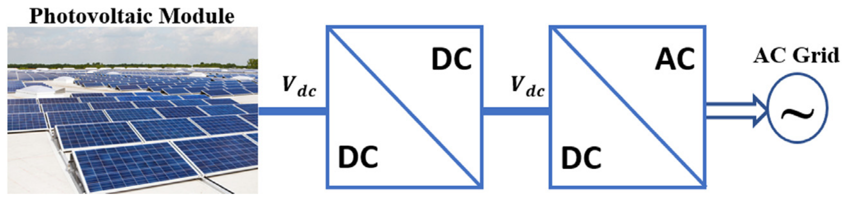

Fig. 3. PV system topology.

where P_n is nominal power of PV system at reference conditions, R is solar irradiance, R_{ref} is solar irradiance at reference conditions, K_t is temperature coefficient of PV systems, T_c is temperature of PV system °C, T_{ref} is temperature of PV system at reference conditions, R_{ref} is set to 2 MW/ft^2, $T_{ref} = 25$ °C.

$T_c = T_{amb} + (0.0256 \times R)$ and T_{amb} is the ambient temperature.

To maintain the stability of the system, the power output of PV system must follow some regulations to be within appropriate limits as indicated in Eq. (3):

$$P_{pv}\ min\,(t) \leq P_{pv}\,(t) \leq P_{pv}\ max\,(t) \tag{3}$$

Moreover, the PV system is connected to the grid via an inverter employed to convert Direct Current (DC) to Alternating Current (AC). The topology used in this article is depicted in Fig. 3:

3.4. Retailer

The Retailer is used to sell energy to small lots. Indeed, energy can be bought at the Wholesale Market and sold to consumers at the Retail Market using bi-directional transactions. The retail market provides various services to consumers such as creating a small market for trading energy using bidding and auction for energy sale. Therefore, electricity consumers can easily switch between different retail electricity providers. This encourages consumers to provide load reductions using convenient prices.

The retailer can perform the following functionalities:

- Sell and buy energy;
- Provide bidding and offering.

3.5. Local controller

The LC interacts with SG Controller when the micro-grid is connected to the main grid. Moreover, DER, storage, and controllable loads have a LC, and a two-way communication is established with the SG Controller. Especially, at the consumer premises, the LC has bidirectional communications with the Smart Meter (SM) [40]. The controller is connected to the smart meters installed in a home and connected to home appliances in order to reduce energy use and aggregate loads via the AMI networks [53]. In this regard, the SM acting as a gateway is able to aggregate information related to power consumption and generation [40]. Therefore, the LC can also gather this information and then send it to the SG Controller. In addition, the LC is responsible for managing the decision of energy consumption based on local information and the operator prospects.

One of the main advantages of employing LC is to provide flexibility with the main grid in terms of successful interconnection between RESs and the power system. Moreover, when an outage occurs, the micro-grid should disconnect from the main utility and maintain the normal operating condition. In this sense, the Local Controller can perform the following functionalities:

- Switch to/from islanding mode;
- Optimize power flow through implementation of optimization algorithms, and optimize Battery to Grid (B2G) and Grid to Battery (G2B) operations;
- State analysis and subsequent actions such as: DSM and Supply Side Management (SSM) to balance supply and demand, forecast both energy generation, and consumption, and Data management to perform monitoring.

3.6. Operator

The main strategic goal of operators is to achieve operational excellence by reducing costs involving operation, maintenance and planning of the electric power transmission and distribution networks [55]. Moreover, the operators are able to be operated effectively when both consumers and generation units interact with each other.

The operators can perform the following functionalities:

- Sell balancing and auxiliary services;
- Provide open trading through the forecasted price by the service provider and bidding offered by Retailers;
- Determine generation and load schedule through data collected by smart meters and forecast of weather and generation performed by the micro-grid service provider;
- Aggregate data and status from micro-grid participants;
- Provide protection and restoration.

These functionalities are performed by means of smart meters which collect the required data such as the output of generation, the load behavior, the weather condition, the voltage data and the market prices. Moreover, demand response informs the consumer about its energy usage, allows financial transaction between the consumer and the retailer and provides information about the prices (low or high) which could be useful to determine the behavior of the battery, whether to charge or discharge.

3.7. Service provider

The Service Provider affords different kinds of services to the operators to support them in the operation of the main grid. In this regard, the Service Provider executes services to customers and utilities. The operators need to interact with various service suppliers for ensuring proper functionality of the smart grid. In this context, the service supplier is a key player in the power market in the framework of smart grids. Moreover, it takes part in the energy market analysis and coordinates with the consumer. The service provider can charge customers with time-varying prices such as TOU and RTP. Furthermore, it contributes to other services such as weather forecasts.

The Service Provider can perform the following functionalities:

- Forecast Generation and weather;
- Forecast Price trend;
- Balance Supply and Demand;

3.8. Local ESS

Local ESS is a local provider of storage capacity for storing and delivering energy. It is needed to cover periods of time when the sun is down, and the wind is not blowing [56]. Local Storage units

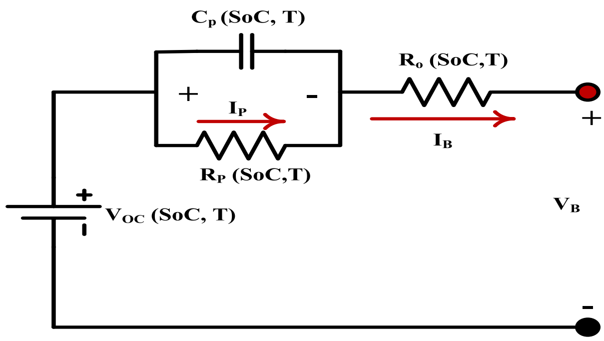

Fig. 4. Battery model.

ensure the balancing of volatile supply and demand. Pumped Hydro Storage, Compressed Air Energy Storage, Batteries, Supercapacitors and Electric Vehicles can be classified under ESS. In this regard, Local ESS and energy management units are important to avoid wasting the harvested RESs and to enhance its utilization.

The Local Storage can perform the following functionalities:

- Store Energy;
- Produce and consume energy;
- Manage Energy to balance supply and demand;

In fact, the ESS can provide power until it reaches a low state of charge (SoC) then the main energy source turns on to charge the ESS [57]. The means of storing that will be used in this work is Battery Energy Storage Systems (BESS).

Fig. 4 shows the battery model. All elements in this model depend on the battery state of charge (SoC) and the temperature (T). The battery system contains a package with N_{Bs} cells that are connected in series and N_{BP} that are connected in parallel.

The parameters of the Li-ion battery are defined via look-up tables based on experimental data. The terminal voltage of the battery pack V_B can be calculated as follows [58]:

$$V_B = N_{Bs}(V_{OC} - R_o I_B - R_P I_P) \tag{4}$$

$$SoC_B = SoC_B\,(0) + \frac{1}{3600}\int \frac{I_B}{C_B}dt \tag{5}$$

where:

$$\frac{dI_P}{dt} = \frac{(I_L - I_P)}{R_P {*} C_P} = \frac{(I_L - I_P)}{\tau_P} \tag{6}$$

R_o is internal resistance, C_p *is* polarization capacitance, R_p is polarization resistance, V_{OC} is open circuit voltage, and SoC is battery state of charge.

In this context, an inverter is used to convert DC from batteries to AC. The input variables of the inverter is the substation voltage V_{SUB}, the substation current I_{SUB}, and the transformer Root Mean Square (RMS) line to line voltage V_{LL} [59]. In addition, the inverter current will be a reference current set by the power flow controller depending on the substation voltage. The inverter model is shown in Fig. 5:

Furthermore, BESS are connected to the network through a power converter, to receive the energy of the system. Then this energy will be stored in the battery. In this case, the batteries are not recharged externally. The subsystem is shown in Fig. 6 [60]. The outputs of the block are the battery voltage and, the state of charge.

Besides that, BESS are characterized by a capacity C, and the state of charge (SoC) of BESS is defined using Eq. (5). Moreover, the charging or discharging power of BESS and the amount of stored energy must follow limitations to avoid any damage and

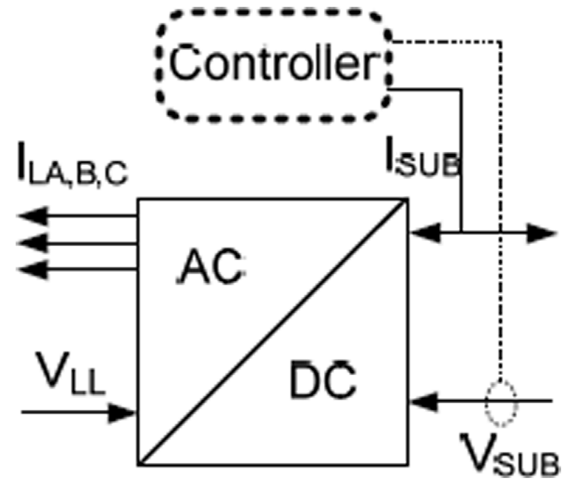

Fig. 5. Block diagram of inverter model.

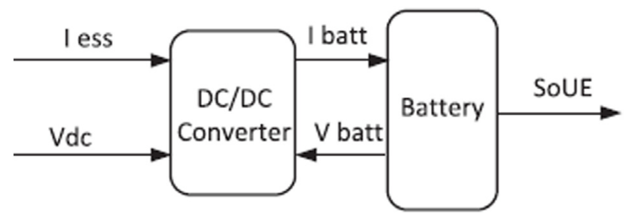

Fig. 6. Battery based ESS model [60].

to maximize the lifetime of BESS. Eqs. (7) and (8) illustrate these limits:

$$P_{ESS}\ min\,(t) \leq P_{ESS}\,(t) \leq P_{ESS}\ max\,(t) \tag{7}$$

$$SOC_{min} \leq SOC \leq SOC_{max} \tag{8}$$

4. Simulation and performance evaluation

To evaluate the implementation of the proposed model and the MKEM, a residential distribution grid has been modeled using power system modeling tools: MATLAB, and GRIDLAB-D. GRIDLAB-D is a widely used open-source power-systems simulation tool. It was developed and maintained by the Pacific Northwest National Laboratory (PNNL) in the U.S [61,62]. It has various objects and modules to analyze the electric power flow, residential load and energy management. Furthermore, it can simulate both single-phase and three-phase balanced and unbalanced systems, with distributed customers [62]. GRIDLAB-D includes models of various distribution system components and can also be combined with other simulation tools such as: MATLAB or NS3 [63], [64].

To demonstrate the effectiveness of the proposed model and enhance the roles played by actors within a micro-grid, the effect of RESs' penetration has been analyzed. In that regard, the modified version of the IEEE 13 Node Test System has been used to show the effect of integration of PV systems into the grid. IEEE 13 Node Test System has been modified to integrate lights, power loads and ZIP load models. Moreover, smart appliances such as multi-state physical load models of the HVAC and water heaters have been used. Furthermore, the Typical Meteorological Year data (TMY2) of WA-Seattle has been used for weather data [65]. Overall, the size of both renewable energy sources and energy storage systems depends on the location and the weather used in the simulation. Subsequently, the outcome of the simulation setting provided a 13-node test system with total of 1247 single-family residences. Each residence has been equipped with a water heater, a HVAC, ZIP models of different appliances and triplex meters to measure the required data. Furthermore, for each residential home, a controller has been used to control the smart appliances such as the water heater and HVAC. These controllers are known as transactive controllers and can interact with the market using price information [66]. In this context, a local double-auction market has been used. In a double-auction market, bidding is done from both the market players i.e. customer and provider. Hence, a double-auction market uses a two-way communication strategy where both buyers and sellers have an opportunity to reach a transaction. In this regard, the market operator collects, buys and sells bids to clear a double auction, then finds a common cleared market price and quantity and broadcasts this information back to the participants. As a result, the existence of a double-auction market enhances the involvement of buyers and sellers in defining the suitable price and quantity of electricity.

In addition, given the proposed model, electric loads connected at each node and voltage at the substation, a power flow calculation has been performed to determine the steady state node voltages and line currents at each point of the system. In this article, Newton–Raphson has been used. Among the various numerical methods used for solving the power flow problem, Newton–Raphson iterative method is the most widely used, since it is more reliable, and the number of iterations required for convergence is independent of the power system size [67,68].

Moreover, in the proposed model, one node is designed as a swing or slack bus. This node represents an infinite bus and provides the fixed voltage reference for the solver iterations. Furthermore, the scenario that used for the simulation is the integration of power generation units consisting of solar into the grid using a virtualization of the proposed micro-grid model. Energy demand and cost have been evaluated under different PV penetrations. Moreover, analysis have been made to show the impact of RESs on energy cost, energy losses and energy demand. The power factor control of the converter was enabled to operate at a constant power factor. In addition, the inverter efficiency was defined as 94% and the rated power for a one inverter was defined as 25 kVA. Moreover, the inverter is assumed to provide ideal maximum power-point tracking, capable of converting the maximum power from the solar installation. When the inverter is controlled to produce less than this power, it is assumed the PV system is loaded to supply this power and the possible power output of the panel is not fully reached. In this regard, the inverter controls the power flow from the PV and the selected control mode 'CONSTANT_PF' defaults to only generating real power, transiting all the available energy produced by the solar PV installation onto the grid. In this simulation, the PV penetration in the virtualized micro-grid has been measured by summing the power rating of all PV systems used in the residential power system. Indeed, the surface area of the PV system was defined as 5382 ft^2 and the daily insolation level that the cell was rated for was defined as 4 kWh/m^2.

This article has focused on introducing BESS to improve the key issues of several problems that have been introduced after RESs integration into the grid and perform peak-shaving. Using GRIDLAB-D to simulate a summer residential load profile, combination of BESS and PV has been analyzed to provide the most effective mitigation of restricting issues under high PV penetration. Therefore, to enhance their role in energy management; batteries have been used with inverters. Each inverter was linked to a triplex meter. Moreover, a double-auction retail market has been implemented and augmented with a Real-Time Price (RTP) for bill mode to enhance demand response and customer participation in energy management. In this sense, the market can accept demand, supply bids and clear on five-minute intervals. In addition, it can also be designed to manage capacity constraints at substations.

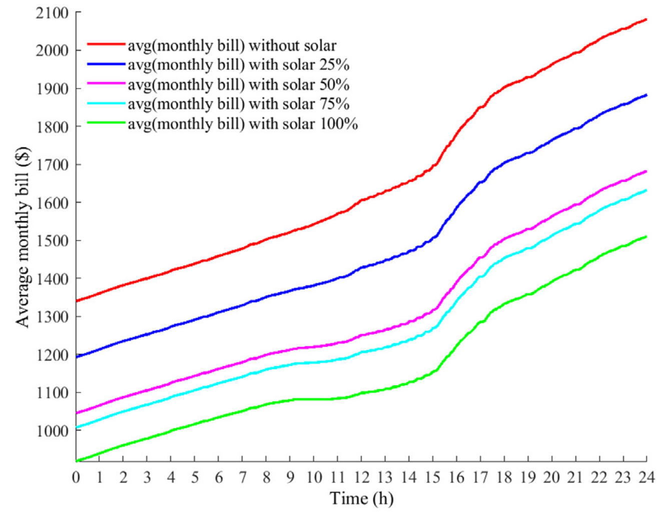

Fig. 7. Monthly bill with varying PV penetrations, on a sunny day.

The simulation was run for one month, and weather condition of August from TMY data regarding WA-Seattle has been used [65]. In addition, the preheating mode for HVAC was eliminated.

Fig. 7 shows the impact of PV on energy cost. It compares the system with and without solar power generation units on a sunny day and shows the effect of introducing different capacities of PV systems (25%, 50%, 75% and 100%) on the monthly bill consisting of the purchased energy price per month. As can be seen in Fig. 7, the accumulative monthly bill, collected by triplex meter (and meters) is reduced when a high PV penetration is integrated. It provides end-users with the financial incentives to increase PV penetration, leading to a considerable reduction in monthly bill as shown in Fig. 7.

Moreover, the integration of RESs reduces transmission losses. RESs have the capacity to retain the energy loss at a minimum level. The Fig. 8 shows power losses through the transformer under different PV penetrations. Significant energy loss reduction can be achieved for this scenario with high PV penetrations. Note that the fluctuation in the power losses is associated with the agent-based simulation, the agents such as consumers, producers, or grid operators, which are the decision-making entities and the main interconnections between the different flow networks, try to reduce power losses and interact with the environment that evolves over the time [69]. Therefore, the environment is affected by the agents, leading to a small fluctuation [70]. Indeed, the demand response strategy used by end-use customers modifies the normal consumption patterns in response to incentives from grid operators along with the fluctuations of high penetration of PV systems [71].

However, the integration of high PV penetrations into the system induces some disturbances and issues on the distribution level. In the following, issues related to PV integration into the micro-grid are discussed based on the use cases presented in Table 1.

4.1. Back-feeding

Rapid introduction of solar panels impacts the energy demand curve. This impact is most obvious during the middle of the

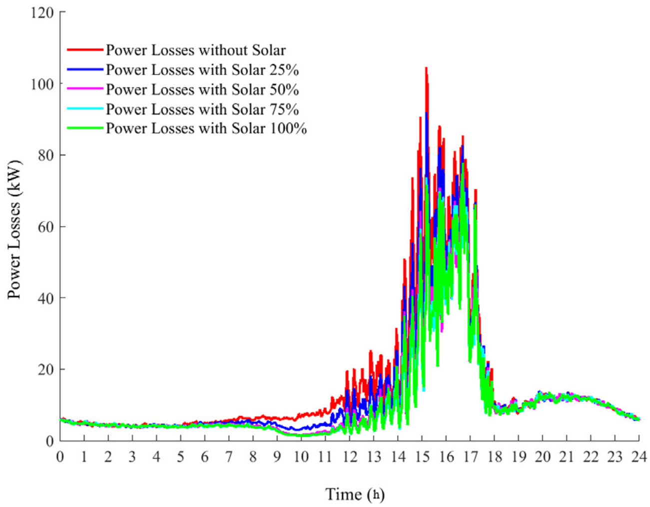

Fig. 8. Transformer power losses with varying PV penetrations, on a sunny day.

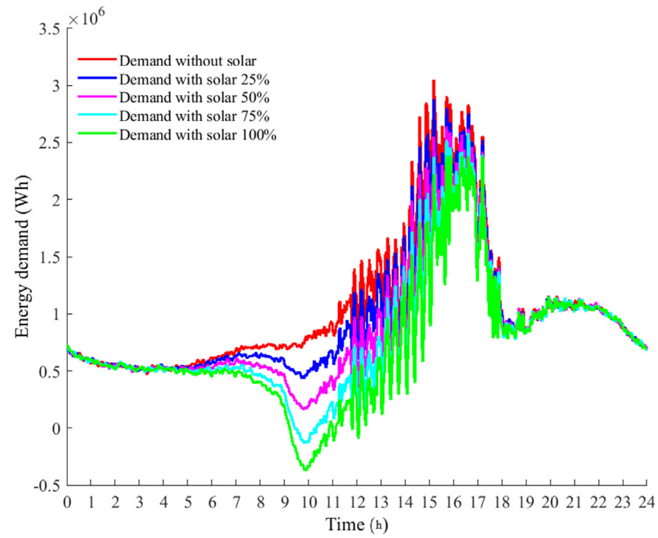

Fig. 9. Energy demand of the micro-grid in different PV Penetration scenarios, on a sunny day.

Table 1
Studied use cases.

Use cases
Integrating different PV penetrations
Integrating 75% PV penetration and ESS
Integrating 50% PV penetration and ESS
Integrating PV with different PV efficiencies
Integrating PV with 0.15 PV efficiency and ESS

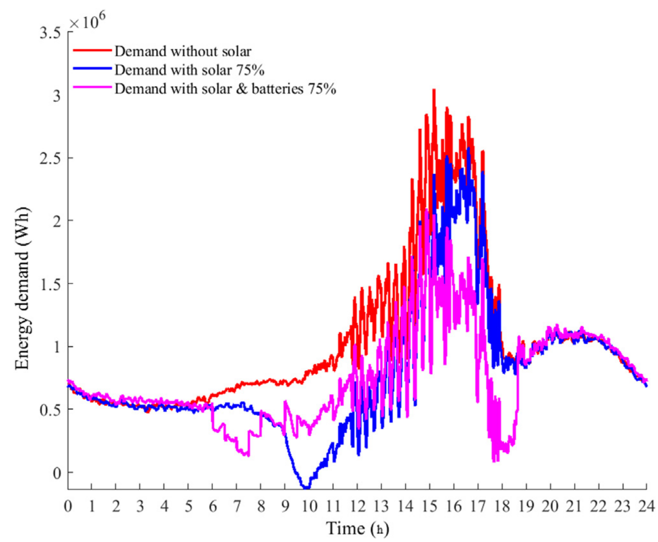

Fig. 10. Energy demand of the micro-grid with, and without 75% PV penetration and BESS on a sunny day.

day when the irradiation is at its highest and leads to a substantial demand reduction as shown in Fig. 9. Capacities at 75% PV penetration and greater than 75% PV penetration resulted in PV back-feeding to the main grid during peak radiation times. However, the night peak load remains unchanged even with high PV penetration due to lack of irradiation. The Back-feeding occurs when PV generation exceeds demand and losses on a feeder. In this regard, integration of Renewable Energy (RE) systems causes reverse power flows, i.e., feeding back into the grid as they are generally connected near the load center. However, under high penetration of distributed generation, this issue may cause local overvoltage in the distribution grid [72]. Besides that, Fig. 9 shows fluctuation in the energy demand, derived from using a double-auction market with demand response strategy, the RTP billing mode where prices are varied every 5 min and demand pattern. The variation in the electricity price leads to the sustained undamped fluctuation in the system [73]. Indeed, the demand response strategy could lead to such fluctuation as explained in [74,75]. Moreover, the output power fluctuation of RESs due to the dependency of these sources on weather conditions could cause such oscillation in the energy flow [76]. In this regard, the fluctuation of electricity prices due to the RTP billing mode along with the consumption's dependency on the electricity price and RESs output power lead to the fluctuation in the energy demand. In the following, effective management of PV integration to mitigate this issues and tackle Back-feeding problem has been pointed out.

In that regard, the increasing penetration of solar generation imposes challenges on the existing distribution infrastructure inducing shifts in peak demand. As the percentage share of generated PV energy is increasing in the total energy basket, it is necessary to integrate energy storage with PV. Combining solar PV with energy storage can provide an effective solution for regulating the load. This combination will have a positive impact on consumers, utilities and communities by means of effective cost, improved reliability and power quality. Furthermore, integrating PV with storage systems provides potential benefits to the grid, such as peak shaving, load shifting, load leveling, voltage and frequency regulation, outage protection, and other ancillary services. In this regard, to achieve the above benefits, the existence of energy storage in the presented scenario is mandatory to allow storing solar energy, mitigating back-feeding and using the stored energy at high energy prices.

Therefore, using a virtual system of the proposed micro-grid, batteries have been implemented on each transformer triplex meter. In addition, residential houses obtain the power from three sources; the power grid, the rooftop solar panel and the battery which is charged from solar power generation units in the middle of the day, when the sun is at its peak. The battery can also be charged from the power grid during off-peak hours. Fig. 10 shows the effect of integrating battery systems into the grid. The PV back-feeding has been removed by the introduction of BESS for 75% of PV penetration. Moreover, in Fig. 11, these systems regulate the demand of energy and contribute to load

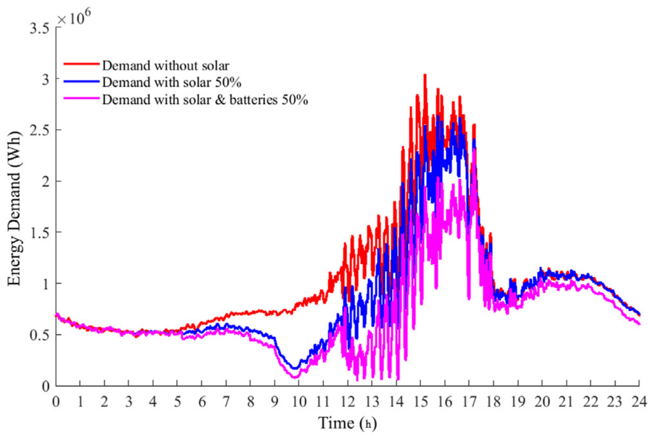

Fig. 11. Energy demand of the micro-grid with 50% PV and BESS on a sunny day.

shifting and peak shaving for 50% of PV penetration. Hence, when using batteries, the demand of energy shifts into a more suitable operating region.

4.2. Intermittent power due to the components' efficiency

Non-renewable sources are known as reliable and controllable sources, generating a known amount of energy. However, RESs do not generate a stable energy quantity and are influenced by various parameters. For instance, the performance of solar panels depends on the quantity of sunlight, efficiency, air density, temperature and other factors. Moreover, PV parameters are derived from a physics-level perspective. The area, efficiency, panel type and orientation, power production models, all these parameters are used to determine how this installation can generate energy as the solar conditions change throughout the day due to the weather conditions. Subsequently, the main challenge in using RESs is their intermittency and stochastic behavior [77].

Besides that, solar panels need to absorb sun rays to generate electricity. Thus, the panels should have the best efficiency and face for the best direction to maximize generation of energy. Therefore, it is essential to determine the correct size of the PV to satisfy the energy demand. This can be performed by considering the efficiency of power conversion from the solar insolation to DC power and the maximum power output of solar. In addition to the previous requirements, supporting devices such as inverters with effective controls are needed to allow better management of the produced energy. In this paper, the proposed model has been implemented using 100% PV penetration and different values of solar efficiency. As shown in Fig. 12, high efficiencies have an apparent negative effect on the entire grid.

Moreover, the efficiency at "0.15" and greater than "0.15" induce significant demand reduction during peak hours. In Fig. 13, the intermittent power issue has been removed by integrating the optimal size of BESS under an efficiency of "0.15".

As a result, the virtual system of the proposed micro-grid model provided a normal behavior once power generation units consisting of solar energy, integrated into the grid. The local ESS modeled in the proposed architecture, designed in the proposed MKEM and implemented in the virtual system performed its role. Consequently, the integration of RES and BESS in power systems has beneficial effect; this integration not only contribute to the reinforcement of the distribution networks and reduce power losses, but also perform peak shaving, load shifting, and reduce energy cost.

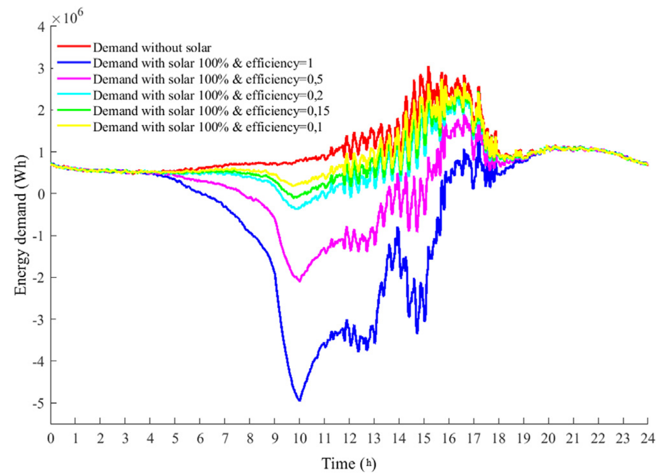

Fig. 12. Energy demand of the micro-grid varying PV efficiency, on a sunny day.

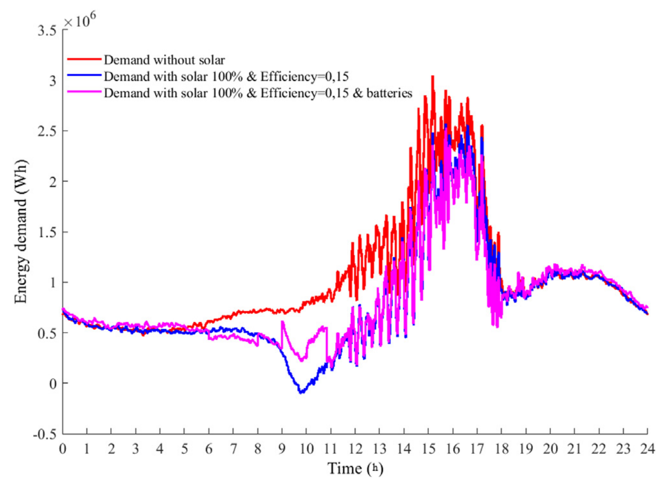

Fig. 13. Energy demand of the micro-grid with 0.15 solar efficiency and BESS on a sunny.

5. Conclusion

In this article, a smart gird architecture was presented by means of System of Systems (SOS) technique. The proposed architecture integrated several micro-grids and nano-grids, known as small residential power systems with renewable sources, battery storage, and domestic load. Such integration can increase the complexity of system modeling. By employing a micro-gird key element approach, this article tried to address the system complexity. Moreover, the integration of renewable power generation units was analyzed and investigated by virtualization of the introduced architecture through MKEM approach to test system stability. The system was analyzed under various PV penetrations with different PV efficiency to demonstrate the effectiveness and performance of the proposed framework, as well as the employed approach. The result showed that the proposed model could reduce energy cost and power losses. Moreover, the proposed framework addressed the dependency of renewable power generation units on weather condition by utilizing energy storage systems to reduce and control the fluctuation of such distributed generations. Indeed, ESSs acted as not only load but also as generation to shift and bring down the power flow. Furthermore, in this article, it was demonstrated that the MKEM can effectively be utilized as a robust approach for reliability study, outage detection, advanced control, demand response, advanced metering infrastructure and storage management.

Hence the present article proposed a smart grid architecture to provide beneficial opportunities for grid-friendly deployment of ESSs in smart grid systems. Nevertheless, the following limitations need to be addressed in future studies:

- Since battery energy storage systems have a significant impact on the total operation cost and the life-time of the battery reduces during charging and discharging cycles, the degradation cost of battery should be considered as a target in cost-effectiveness analysis.
- Vehicle electrification has recently drawn considerable attention which raises concern about bi-directional power flow besides vehicle-to-grid and grid-to-vehicle functionalities that need to be assessed.
- As recent studies focus on technical and economic aspects of PV-battery systems, further investigations are merited in terms of voltage deviation and total cost of investment in such technologies by studying weighted multi-objective functions.

Declaration of competing interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work.

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