A Proposed IoT Architecture for Effective Energy Management in Smart Microgrids

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***Abstract*—The current electricity grid suffers from numerous challenges due to the lack of an effective energy management strategy that is able to match the generated power to the load demand. This problem becomes more pronounced with microgrids, where the variability of the load is obvious and the generation is mostly coming from renewables, as it depends on the usage of distributed energy sources. Building a smart microgrid would be much more economically feasible than converting the large electricity grid into a smart grid, as it would require huge investments in replacing legacy equipment with smart equipment. In this paper, application of Internet of Things (IoT) technology in different parts of the microgrid is carried out to achieve an effective IoT architecture in addition to proposing the Internet-of-Asset (IoA) concept that will be able to convert any legacy asset into a smart IoT-ready one. This will allow the effective connection of all assets to a cloud-based IoT. The role of which is to perform computations and big data analysis on the collected data from across the smart microgrid to send effective energy management and control commands to different controllers. Then the IoT cloud will send control actions to solve microgrid's technical issues such as solving energy mismatch problem by setting prediction models, increasing power quality by the effective commitment of DERs and eliminating load shedding by turning off only unnecessary loads so consumers won't suffer from power outages. The benefits of using IoT on various parts within the microgrid are also addressed.**

Keywords—Internet of things (IoT), microgrids, curtailment, active distribution network, smart grid 2.0.

I. Introduction

Electricity must be produced at the same second, it is being consumed. This statement sums up the biggest challenge for all electrical grid operators. The challenge of constantly matching generation with load demand, which can take two directions, the first is that the generation doesn't satisfy the load demand which would necessitate load shedding, or the grid operator might have to start up some additional power generation units, which will not be so efficient economic wise. The other direction this issue can take is that the generated power exceeds the load demand, in that case for the traditional thermal plants, the base-power plants which operate most efficiently at a certain power generation level will have to be reduced to a less efficient point as to match the low load demand. This reduction in efficiency means both an increase in the cost of generated power and more environmentally harmful emissions the effect of which is increasing and clearly shown in the climate change.

And because of the large increase in electricity demand in Egypt, which can be related to multiple reasons the main of which is the economic development and the addition of thousands of consumer appliances in homes into the load side of the grid, According to the 2018/2019 report from the Egyptian electricity holding company the residential sector makes up 39.6% of total energy sold in that fiscal year. Therefore a great share of the efforts toward renewable energy generation has been reported in Egypt since 2013 as a response to the peaking problems as for 2019 the installed capacity of renewable energy sources makes about 3.8% of the total installed capacity in Egypt and this percentage is expected to further increase in the upcoming years [1], These efforts started significantly since 2013 when the electricity consumption had expectations to nearly double by 2030 [2] while the global energy production is expected to increase 77% by the same year [3].

Although this approach of adding renewable energy resources (RES) somewhat resolves the environmental effect of increasing power demand as well as providing additional generated power during peak hours, but adding renewable energy sources doesn't ultimately resolve the challenge of matching generation against load demand, on the contrary adding renewable energy sources (RES) that bring with it a great deal of uncertainty about generated power at any time further increases the complexity of the problem. Moreover, any electrical grid has a limit called the hosting capacity (HC) at which any additional renewable generated power added to the grid will affect power quality and cause unacceptable performance [4].

Hence, the approach of using distributed energy resources (DERs) to match this rapidly increasing demand in different and remote parts of the world, without constructing long transmission lines that require additional generation for the central plants to supply the remote loads along with compensating for the transmission line losses. Using DER can solve the problem of low HC limit for some electrical grids. Henceforth the microgrid (MG) term was used to describe this remote electrical grid that uses distributed energy resources (DERs) as its main source of power, the MG can be connected to the main grid to be grid-connected MG that can rely on the grid during load peaks and supply the grid with any over-generation or to be isolated from the main grid in what's called islanded MGs. The concept of microgrids (MGs) has gained a lot of interest over recent years[5].

But even in a microgrid system, the aforementioned challenges still remain, as it depends on renewable energy-based DERs which makes the energy management in these microgrids a real challenge as both the generation and load can vary unexpectedly causing different power quality and stability issues even malfunction of protection devices due to the uncertainty. Additionally, as a part of the efforts toward renewable energy sources, many grid end-users are now connecting their own small rooftop PV plants so now we have

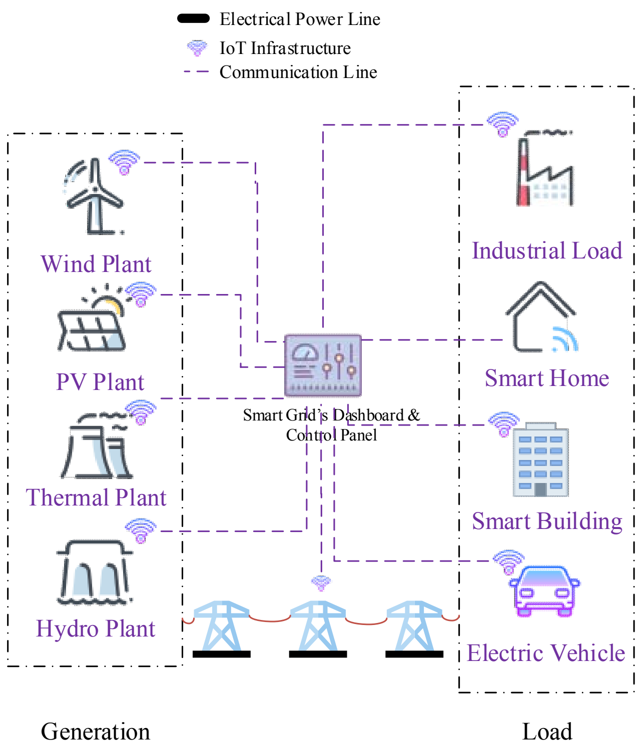

Fig. 1. A typical smart grid topology

two categories of end-users in the electrical grid consumers and those we are concerned with their loading behaviour and the prosumers who in addition to being consumers can now send to the grid electrical power generated at their PV systems, this type of generation isn't fully controlled by the grid operators which will be a concern when the number of prosumers connected to the grid increase, most of which are PV plants that would normally cause a peak of generation during noon.

Several attempts to mitigate these issues in microgrids were proposed in literature started from using a hierarchical droop-control inspired from ISA-95 standard other droop control methods were proposed like using an adaptive droop-control method as to balance SOC levels of different connected batteries subsequently keeping the bus voltage variation at its minimum levels [6]–[8] and in [9] the authors developed a smart power-voltage relays that are able to accurately determine fault type, regardless of the inherit microgrid's variations in power and voltage, but although this approach increases the reliability of the protection system is still not able to communicate the fault condition status, neither does it solve the initial problem of variations. The use of new ICT technologies to control power systems is now gaining more traction after achieving higher bandwidth and the increased reliability of the IT infrastructure.

Internet of Things (IoT) is a new disruptive technology that makes the best use of both embedded systems industry and the information and communication technology (ICT). Although multiple studies have been made in using the IoT technology in smart cities and smart grids [2]–[4]. However in this study the use of IoT technology into building smart microgrids is discussed, simply because it would be much more economically feasible to design and build new microgrids in the future as smart ones, than converting the old large electric grids into smart grids, which might require a budget at a 10-figure number [10].

This paper is the first paper of the ongoing study of using IoT technology to develop a smart microgrid that will benefit from both the advantages of microgrids and smart grids systems, to efficiently solve the energy management challenge while being economically sound for both building stage and operation. The paper at hand will discuss in detail the concept of smart grid 2.0 and the proposed IoT structure that will allow for effective observability and controllability of all system-connected assets. Afterwards, a discussion of possible implementations of IoT technology at different stages of the microgrid, to come up at the end with an IoT architecture for the energy management and control of a microgrid, then a discussion of how will this IoT architecture have the best potential to validate the first hypothesis of the study of solving the energy management problem while effectively controlling the microgrid in an economically sound way. Afterwards, in future work, further simulation and experimental validation of this architecture and the understudy hypothesis will be carried out.

II. Smart Grids 2.0 and Smart Microgrids

Internet of Energy (IoE) is the representation of using IoT in controlling energy in any system, and when it's an electrical grid the term smart grid is used to denote the use of ICT technologies in electric grids to perform a different function from monitoring, detection and taking corrective actions all autonomously [3]. The Egyptian electricity holding company has shown large steps toward the smart grid approach, mainly by releasing a number of smart meters as a first step toward the smart grid [11]. The motivation for using IoT technology is that to achieve the required level of controllability with the large and diverse number of grid assets that differ in nature and can output large amounts of data with different communication protocols it's required to have that central IoT network that will use lateral sensing and signal conversion devices to read all the data from these different equipment paired with different information of the actual equipment. This will give the cloud-based controller system the ability to oversee the condition of each element of the grid in real-time and make the right decision instantly.

The aforementioned concept is called the second generation of smart grids which means the utilization of existing smart metering devices and that each piece of equipment is already compatible with the smart grid [3]. Even for some small loads or generation resources such as Vehicle to Grid connections (V2Gs) or the increasing number of prosumers whose contribution to the grid needs to be measured and accounted for. Thus, the typical smart grid system would look like what's shown in Fig. 1.

Thus, this paper focusses on applying IoT technology into making a smart microgrid. As it's more feasible to build a smart microgrid from the ground up than going for an already existing electric grid and replace each piece of the thousands of pieces of legacy equipment into smart-grid-compatible equipment.

III. Proposed IoT Architecture

After a thorough investigation of the required functionality and flexibility needed to design an effective yet economic smart microgrid, The IoT architecture shown in Fig. 2 represents the proposed IoT architecture for energy management and control of microgrids, as it shows the major component of any microgrid such as generation represented in

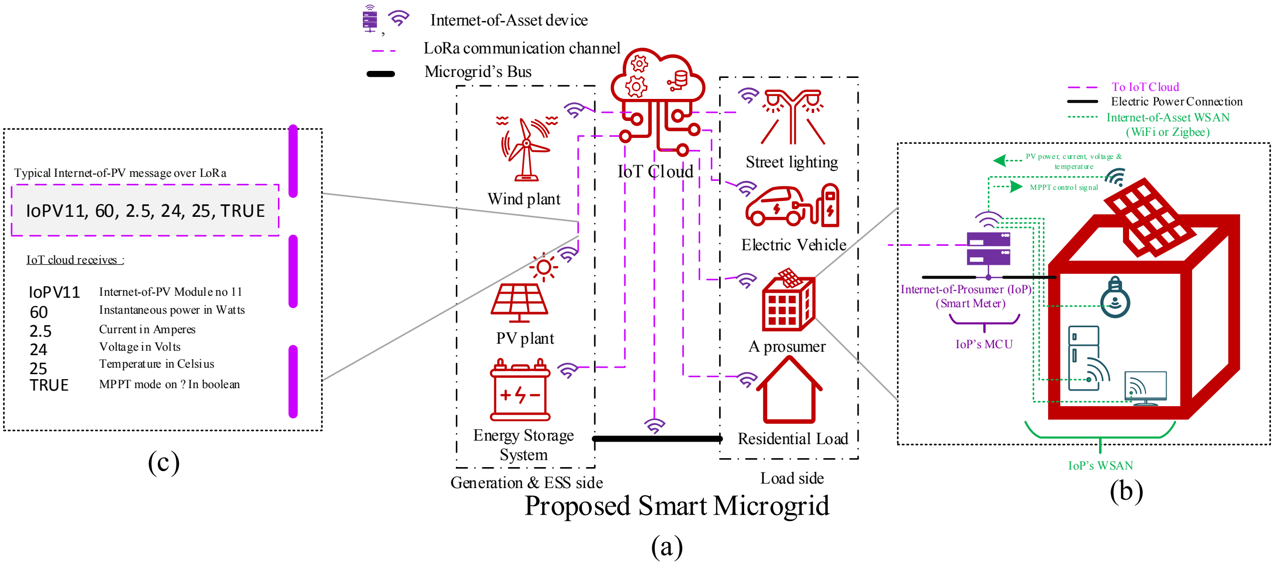

Fig. 2. (a) The proposed smart microgrid architecture.
(b) The proposed Internet-of-Asset architecture.
(c) A typical communication message carries informative message requiring only a small bandwidth.

PV and wind power plants, in addition to Energy Storage System (ESS) and the load side contains residential loads other common loads and EVs.

In the proposed architecture a separate device that operates as a communication interface is added to the traditional equipment along with some wireless sensors and actuators network (WSAN) to convert the legacy asset into a smart asset, this device will be called after the asset as follows "internet-of-asset" (IoA) so for example, for a battery it will have an internet-of-battery device that will contain a WSAN that has current measuring and voltage measuring sensors at the terminals of the battery, these sensors communicate using a quick wireless network such as Wi-Fi or ZigBee to the internet-of-battery's Microcontroller Unit (MCU) that can be anything from a simple ESP8266 NodeMCU to a Raspberry Pi 4 or higher according to the complexity of the equipment, this MCU will have two tasks, the first to perform local calculations needed for the BMS, the second is to send all its raw data in addition to the calculation data to the IoT cloud by working as a gateway to transfer the Wi-Fi or ZigBee protocol to another wide area protocol such as LoRa, Sigfox, cellular or using the world wide web. This method will allow for the internet-of-asset (IoA) device to be able to perform quick control actions locally and send the data to the IoT cloud to store the data, analyze it and send grid-wide energy management and control commands.

Another advantage of this architecture is that this separate internet-of-asset (IoA) device will allow the economic and easy conversion of legacy equipment to be smart, this will save much more money compared to buying all new smart, or IoT-ready equipment from certain manufacturers at a prime price. This is done by providing an MCU unit that is compatible with different types of wirelessly connected sensors, then dispersing the sensors across the asset's terminals and points of interest as to collect data and send it to the MCU as shown in Fig. 2(b), this allows for high modularity of the internet-of-asset (IoA) device to suit any type of asset and the ability to add more sensors in the future if required, the exploitation of the WSAN will encourage the use of more sensors to get more accurate data about any process inside the asset.

Then for each internet-of-asset (IoA), it gets a specific MQTT address, IP address or URL, according to the used protocol, this address should be unique and descriptive, as it should indicate the geolocation of the asset, the type of the asset and its functional group. So that for the IoT-cloud it can be able to have a system to address any internet-of-asset (IoA) device in the microgrid, afterwards the IoT-cloud according to the address of each asset will be able to determine the number, size and frequency of messages it should expect from each internet-of-asset (IoA) and create a digital twin in the IoT cloud for each asset in the field. Using this addressing and predefinition architecture will require low bandwidth low-cost communication channel because the IoA will have to only send a simple message through the carrier network containing only its address followed by the values of the predefined variables of that IoA as shown in Fig. 2(c).

For the future work on this study, the proposed IoT architecture will be implemented. A variation of MCUs will be used such as NodeMCU, Raspberry Pi, XBee and LoRa Modules. The ThingSpeak will be the used Application Enablement Platform (AEP) because of its compatibility with MATLAB code which will allow for testing of different energy management and control algorithms both proposed and from the literature. This AEP also provides an elastic data storage to store historic data of weather, loading and other conditions of the microgrid to be analyzed for future predictions. The MQTT protocol will be used for being a lightweight and quick communication protocol, and communication latency will be minimized when a LoRa network used as well. In this architecture the communication latency issue will be approached using 3 methods:

1. Using a lightweight protocol i.e. MQTT with a quick network 5G or LoRa.

2. The Internet-of-Asset device MCU has the ability to perform some calculations and execute local control loops, for example in case of a fault detection or network cut off, so that the asset's local control actions won't be affected.

3. An Artificial Intelligence (AI) Model is to be implemented to analyze the big data collected from different IoAs across the microgrid and this AI model is then used to bridge the gaps created due to communication latency or loss.

IV. IoT in the Generation Stage

Generation units in microgrids have some differences than its counterparts in a traditional grid, the first prevalent is that since the idea of microgrids was motivated by renewable energy sources, most of the generation is based on renewables commonly PV and wind generation. The other difference that microgrids depend heavily on DERs, as in traditional electricity grids the grid operator had only to control a few large generation units, in microgrids the grid operator have to manage the generated power out of many small generation units, even those prosumers with rooftop PV systems are considered as part of the generation in the microgrid. Add this to the first different that these DERs are mostly renewable energy sources the generation of which follow the stochastic nature of the weather condition, so it's fair to say that generation dispatch and control in microgrids are much more complex than in traditional electricity grids. So, the traditional way of committing generation units through decisions made by operators in the Regional Control Centers will not be viable in the case of a microgrid with this many DERs, so a more intelligent Machine to Machine (M2M) control strategy should be taken, and considering the area if the microgrid a technology as the IoT is needed to be implemented as to perform supervision, data acquisition, analysis in the cloud and control actions are sent to commit different generation units, as per proposed architecture.

A. IoT-ready PV power plant

For instance, the IoT-ready PV system should have an Internet-of-PV that provides the sensors set that can sense radiation, temperature and PV units currents and voltages, these sensors should be connected in a WSAN and send its data in real-time to the Internet-of-PV's MCU for local processing of MPPT and management of the solar charger with batteries if exist, then all sensor data and computed data are sent over the internet, 5G or LoRa networks to the IoT cloud, for data analyses, storage and for energy management and commitment. So, the IoT cloud will be able to control the Internet-of-PV and in turn control the PV's output to the microgrid.

B. IoT-ready wind power plant

Another example for an IoT-ready wind power system the Internet-of-Wind's required sensors are more than those needed for the PV system, so we can group them into five operational groups the first being the environmental measuring sensors such as wind speed sensors, humidity sensors and temperature sensors. The second group is the mechanical sensors which has sensors to measure the speed of the turbine blades, position and direction, angles, stresses and strain, bearings temperature and fluids pressure, level and flow sensors. The last group of sensors are the electrical sensors that should take readings of voltages, current, power factors and frequencies. Also, for each wind turbine, it's necessary to be able to receive commands from the remote IoT cloud, to send appropriate control actions for each wind turbine to set its speed and power output as needed. The Internet-of-wind should also incorporate internal algorithms in its local MCU that can take critical corrective actions as fault ride-through using nearby assets like energy storage and supercapacitors [12, 13] independently from the IoT cloud, then it can report to the IoT cloud, and the IoT cloud manages minimizing the fault consequences.

C. Other types of DERs

From the previous two examples, you can get the idea that for any other types of DERs e.g. microturbine, diesel generators or gas turbines, to be IoT-ready it requires some set of sensors that can be connected to the network (as inputs to the IoT cloud), and for the power interface to be controllable by the IoT cloud after the analysis is made on the sensed data and in regard of the MGs whole condition a control action is sent to be performed by the DER and to determine its required power contribution.

V. IoT in Energy Storage

Energy storage plays a very important part in the microgrid, for sometimes it can be the only available source of power for the loads, its voltage level mostly determines the microgrid's bus voltage and it is one of the most costly and critical parts of the microgrid.

For this significance for energy storage the Internet-of-Battery requires continuous and real-time monitoring of the batteries state of charge (SoC), health and condition should be made by the IoT cloud that should take current and voltage measurements for each battery unit for the Battery Management System, in addition to environmental data such as ambient temperature and humidity this with the historic charging and discharging data to be able to accurately determine the health of each battery unit, this, in turn, will be taken into consideration when committing batteries for different loading conditions and implement advanced techniques as in [14] as to maximize the lifetime for the batteries and minimize the cost of energy storage by using. Also, in relatively large microgrids the geolocation of each Energy Storage System (ESS) can be taken into consideration when committing it to supply nearby loads as to minimize power losses.

No one can argue that electric vehicles (EVs) have secured their place in the future. Hence, a wise design for the IoT architecture of microgrids of the future should involve EVs in it. As for the most part, a lot of studies has been made in (V2G) for smart grids of the future[15]. In microgrids, this V2G concept takes an additional level because EVs are not just considered as batteries that need to be charged at off-peak times, but for a small microgrid when the energy storage capabilities cannot instantaneously meet the load demand, the IoT cloud can dispatch some of the EVs stored energy during these load peaks, this energy transaction from and to EVs should be managed through the internet-of-EV that's implemented in the parking lot's charging station, to be able to connect to all parked EVs its assumed that a wireless charging system is implemented in the parking lot so that all parked EVs are connected to the smart microgrid and seen as a parallel battery pack.

VI. IoT in the Distribution side

Microgrids suffer from issues like poor power quality, repeated load shedding and PV generation curtailment. All of which are related to poor energy management inside the microgrid. The utilization of an IoT infrastructure that is able to monitor the condition of all load units in real-time that will provide the critical parameters required for fine-tuning of the control system. For example, This is done simply by the connected smart meters at residential loads that will give the exact value of the required power, this, in turn, will be analyzed in the cloud to give control action to the DERs and ESS to provide the exact amount of required energy and using artificial intelligence techniques the IoT cloud can predict and perform day-ahead scheduling [16]. A new idea that has been proposed is to enrol in some sort of a bonus program that will give the smart microgrid's IoT cloud access to lower your consumption by letting it automatically turn off some appliances or light bulbs that you've previously marked as unnecessary. This program will turn off these unnecessary loads during peak loading hours, to release the stress off the grid in exchange of some sort of bonus or reward program [17], the idea here is that if the IoT cloud manages by this autonomous method to mitigate load peaking it will prevent a lot of the load shedding that was possible to happen. The same idea can even be applied in the future for EVs that are parked on wireless-charging parking lots, so that the microgrid's IoT cloud will be able to use its stored power during peak loading to assess the ESS, the idea here is also for the smart IoT cloud to be able to commit a little percentage say only 1% of each EV's battery so as not to drain the battery for the EV's owner, but this 1% from each EV multiplied by the number of EVs connected to the microgrid will provide a considerable amount of backup energy storage for the microgrid to use when necessary. For this EV utilization scenario and for prosumers who have rooftop PV systems, a smart bidirectional metering will be needed inside the IoA of Internet-of-prosumer and Internet-of-EV as to encourage prosumers to produce, and the IoT cloud controls and commits the power produced by each of the prosumers through sending control signals to the internet-of-prosumer devices.

VII. Microgrid's IoT Transports, Protocols and AEPs

IoT is defined as being the interrelation between sensors, actuators and computing device through the internet, which is not necessarily the world wide web, as it can be a local server-based network or a peer-to-peer network. The main difference between various IoT networks in different applications are the transports, the communication protocols and Application Enablement Platforms (AEPs), at the following subsection we will define and discuss them in more detail.

A. IoT Transports

The transports here are as the name indicates the method that data are transported from your device i.e. sensors to the internet. Ethernet is the most common, worldwide used, open and free standard transport that can be used anywhere and can maintain high speeds up to 1 GB/s. After which is the WiFi which inherits all the advantages of Ethernet connectivity and adds to it being wireless, requires authentication and has a fairly good range. There are also a variety of WiFi chipsets that are popular like the most common IEEE 802.11 standards family that operates at 2.4 GHz. Another common wireless transport is the ZigBee specification which is based on the IEEE 802.15.4 standard. The last common transport is the cellular network which excels in being a worldwide grid, provides direct internet connectivity and SMS/voice connectivity, but in exchange of being expensive and dependent on large and power-hungry modules, but the new LTE and 5G are promising as they have been built with the IoT applications in mind. Other not very common in IoT applications is Bluetooth which requires an additional gateway to be connected to the internet, there is also the new Bluetooth low energy (BLE) the most consumes less energy and is good for short hops up top 20 meters. In this sense also low-power wide-area network standards (LPWAN) were developed such as LoRa which stands for Long Range which was developed by Semtech and allegedly can cover a physical range of 10km [18]. Sigfox is also another known name in the LPWAN family which is run by a global operator of the same name as a paid service.

B. IoT Communicaiton Protocols

If transports are the medium that messages travel on, then protocols are the language that messages are written in. The most famous protocol being the HTTP protocol which stands for Hyper Text Transfer Protocol, which is familiar being used globally in the world wide web, it's most important features for our discussion being a synchronous protocol and pulls only, this simply means for the client to pull data from the server both the client and the server are required to be online at the same time and client must wait for the server to send data. That's why the most common protocol with web services is the REST protocol which stands for Representational State Transfer which uses GET, PUT, POST and DELETE requests to manipulate data, this makes the REST protocol the easiest to interface with already existing web APIs. The most common protocol with IoT application is the MQTT which stands for Message Queue Telemetry Transport, it's an open, royalty-free, oasis open standard. Uses PUBLISH/SUBSCRIBE requests as to manipulate data, its advantage and what makes it heavily used for IoT application is that it's extremely simple and lightweight and it can stay connected all the time. The Constrained Application Protocol (CoAP) which was designed for resource-constrained nodes, to take the benefits of the REST protocol of easily transferring data between web applications and the benefit of MQTT protocol of being able to become an 'observer' and get asynchronous updates to a topic. Another common communication protocol used with SCADA systems in the power systems and industrial control systems is the Modbus, it's common to be used to connect the SCADA system with Remote Terminal Units (RTUs) and Programmable Logic Controllers (PLCs) using Modbus, but isn't be used in application further than that due to its limitations, so it's important further in the experimental validation of this study to find a suitable way to gateway the Modbus protocol to any other IoT-friendly protocol.

C. Application Enablement Platforms

Due to the complexity of setting up an IoT system that is able to deal with hundreds of different types of sensors and collect data from different application areas with different protocols, and all of this collected data that's always increasing needs a suitable elastic data storage solution to be stored, and most importantly the ability to perform analytical and computational tasks on the collected data, and being able to visualize it all in real-time, and for the end-user to have a user-friendly GUI that can be used on different screen sizes and can control the process through the internet from virtually any place in the world. It's infeasible to develop all of these solutions individually for each IoT system, that's why it's common to use an already made Application Enablement Platform (AEP) that provides a solution to all aforementioned issues and provides an easy development interface for programmers and a user-friendly interface for the end-user that is web-based so that it can be run from any device connected to the internet. Most common AEPs are

ThingsSpeak, FIWARE, Siemens Mindsphere, Schneider electric Wonderware, Master of Things and a lot of other AEPs that vary in features, targeted application, pricing and subscription bundles.

VIII. CONCLUSIONS

In this paper, the problem of energy mismatch was discussed. An IoT-based smart microgrid architecture was proposed. Then, a discussion of the role of IoT in different parts of the smart microgrid. Afterwards, an overview of the IoT technology's values chain of different carriers, protocols and AEPs were briefly reviewed.

The proposed architecture was based on the concept of Internet-of-Asset (IoA), which is a separate device for each asset that manages the different sensors and actuators inside the WSAN of the asset. And has many benefits as follows:

1- IoA ease the conversion of some legacy equipment into smart assets, by using the required set of sensors and actuators.

2- The proposed architecture depends on the WSAN inside the asset that will allow for the use of sensors without worrying about wiring issues, and will allow for a large degree of modularity to add more sensors to the same IoA when required, and simply configure the IoA's MCU with the added sensor.

3- The IoA on consumer side would be the next generation smart meters, that will allow for continuous real-time supervision on the consumer's pattern of consumption.

4- Then the data collected from different parts of the microgrid are processed and analyzed inside the IoT Cloud which will allow for intelligent energy management and control of generation/consumption of energy as to minimize the mismatch and improve power quality.

5- The ability to implement a power-loss or emergency loading management strategies such as using additional energy stored in EVs batteries, or take out only the already marked unnecessary loads, instead of load shedding whole parts of the microgrid.

6- Initiates local control loops that are essential during critical incidents, such as a fault. This local control can operate as well when the connection to the IoT cloud is lost to maintain high reliability.

7- The IoT network will be based upon quick communication protocol such as MQTT and uses a reliable high bandwidth carrier such as 5G or LoRa, while the IoA network will be composed of a WSAN that used WiFi, Zigbee or BLE.

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