Review of Power Quality Monitoring Systems

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***Abstract*— Power quality is gaining a lot of interest lately by researchers and engineers as electricity is a vital part of our daily life. The aim of this paper is to survey some of the recent existing systems, techniques and methods that are being used to monitor power quality. The survey focuses mainly on power quality monitoring systems which are composed of various tools, software, communication links etc. that work together as one coherent system. Another goal is to develop an understanding about the quality management in the area of power industry. Some of the methods and techniques that are presented discuss about power quality meter placement techniques. Finding the best locations to place the power quality monitors in the electrical grid is done by developing algorithms and approaches to find the appropriate number of monitors and the appropriate locations to place them in order to reduce the cost of the PQM system and increase its efficiency. Th**e paper discusses **the basic idea of each method or system in order to have an understanding about its importance and role. Then, a simple comparison is made between the techniques in terms of their advantages and disadvantages. After that, international industry practices and guidelines for power quality monitoring and management are discussed. Lastly, some examples for the efforts that are made in the area of power quality improvement are discussed.**

Keywords — PQM (Power Quality Monitoring)

I. INTRODUCTION

Monitoring power quality is important because of the increasing complexity and size of electrical networks. Regulating authorities and power suppliers around the world usually monitor the amount of power that is being delivered to the end users by placing meters at different points in the power grid. These meters measure different parameters such as voltage, current, frequency, etc. Analyzing power quality is very important for the economy as electronic equipment are somewhat sensitive to power supply events, therefore these parameters must be maintained at acceptable levels that will not cause any damages to the electronic devices at the user's side. Monitoring devices are being used for power monitoring and control. The monitoring devices enable the engineers and the network operators to analyze the network for certain quality attributes that can have major effects on the system. Some of these quality attributes are the frequency, supply voltage variation, Rapid voltage change (flicker), Supply voltage unbalance, harmonic and inter-harmonic voltage, main signaling voltage, voltage dips/ swells, interruptions on the supply voltage and transient over voltage. Voltage variation (flicker, dip/swell, etc.) and harmonics are considered to have greater effect on the quality of power. Harmonics occur due to the presence of non-linear loads. Those harmonics can affect the electrical devices by generating heat which might cause damage. There are many standards and classifications for the harmonics levels in distribution systems as specified by different standards such as IEC 1000-3-2, IEEE-519 and IEC 61000-4-30 Class A [23]. These standard values are referred to while analyzing and monitoring the network.

The monitoring systems help the engineers and operators to detected the previously mentioned power quality attributes and identify their causes. The monitoring process could be an online monitoring process whereby the system will be monitored continuously for any interference or failure that might occur. Then there could be an alarm indicator for the system operator to take the required action. It could also be a long-term monitoring process whereby the measurements of the various quality characteristics and attributes are being stored into databases for generating periodic reports that will help in improving the overall system, make future enhancements or take prevention actions.

Placing the monitors smartly in the network helps in reducing the cost of the power quality monitoring system. The figure below shows the overall electrical network with meters placed at various points in order to monitor the power [24].

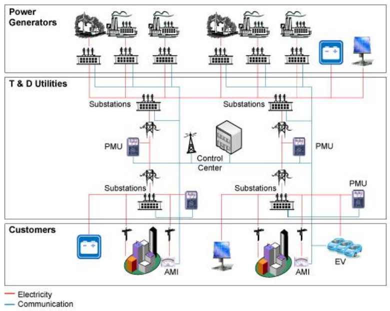

Fig. 1 PMU refers to the meters that are placed at various points in the network

One of the targets in quality is to achieve customer satisfaction. This is done by ensuring that the customer's needs and requirements are met. For that, it is important to understand about the type of end users (industrial, residential, etc.) in the network in order to supply power levels that match their needs. The interest in the area of power quality is driven mostly by the customers' complaints; therefore many efforts are being made to ensure that good power quality exists at all times. In the work presented by V. Becirovic et al. [20]. The main advantage of this classification was to make analysis on the overall system when two or more customers of the same group are having the same interference or problem. The proposed model is voltage dependent in such a way that the effect of voltage change is observed for every current waveform. The only drawback of the model proposed by Becirovic et al. is that it works only for the specified three groups of customers and any change in the classification requires re-identification [20].

II. Discussion

A. POWER QUALITY MONITORING SYSTEMS & TECHNIQUES:

1. HIGH-RESOLUTION TECHNIQUE FOR FLICKER MEASUREMENT (HRT-FM)

One of the common interferences that occur in Electrical networks is Flicker. As described by Cheng et al. [2], flicker is defined as the fluctuation that might occur in the voltage coming from the power supply. The rapid change in the voltage level is unwanted as it might affect or damage the electrical equipment at the load side. A method that has high resolution is proposed by Cheng et al. in order to extract the flicker components form the signal. The purpose of extracting those frequency components from the signal is to be able to develop strategies that will help improve the power quality and system protection for any future failure. The system works based on the idea of analyzing the frequency spectrum of the signal in order to observe the flicker components. There are similar techniques to this approach, but this one is considered to be more accurate as it uses the Pony's method [2]. The advantages of this method are accuracy and robustness, while the disadvantage of it is the mathematical complexity.

2. S-TRANSFORM TECHNIQUES FOR POWER QUALITY SIGNALS DETECTION AND ANALYSIS (STPQSD)

A novel method for conducting power quality diagnosis is presented by M. Faisal et al. [9]. The method uses the S-Transform and rule based classification techniques. The functionality of the proposed method was tested by detecting some short term voltage disturbances and tracking their causes' weather if they are due to permanent or non-permanent faults. In order to identify the type of error or fault the frequency spectrum of the signal must be analyzed after finding the S-Transform.

To ensure the power quality, many electrical signal attributes must be taken into consideration such as the root mean squared voltage (V_{RMS}), total waveform distortion (TWD), the total harmonic distortion (THD), etc. N. H. T. Huda et al. [12] mention in their work that the S-Transform could be performed on the power quality signals in order to analyze the occurrences of phenomenon such as voltage sags, swells, harmonics, inter-harmonics, etc. The only drawback for this approach is also the mathematical complexity.

3. DATA-ACQUISITION SYSTEM FOR POWER QUALITY MONITORING (SEMCE DAC)

A data acquisition system called (SEMCE DAQ) was described by S. D. Grigorescu et al. [16]. The system was designed in order to measure the power quality parameters in a flexible way in smart grids. The system provides both real-time monitoring and long-term statistics for future improvements and considerations. The system enables the user to monitor the behavior of the electric parameters and the influence of power exchange over the network. The system measures different parameters such as the voltage, current, frequency, power (active or reactive), harmonics, etc. The accuracy and the informational performance of the system are considered to be very good. It is also suggested that this system could be implemented on current smart grids as it is special for its reduced cost and data transmission capabilities [16].

4. POWER QUALITY MONITORING SYSTEM OVER THE INTERNET (PQM-OI)

M. Zhang and Kaicheng Li, investigated the power quality monitoring system over the internet. The power quality monitoring system is defined as a collection of technologies including a web server, computers, communication networks and specialized PQM. The system transmits high-quality data over the communication line. The system uses technologies like GPS in order to synchronize the sampling data in the power quality meter along with .Net framework and ASP Net technologies. The monitoring system has a low cost and it could be implemented on the existing SCADA system (Supervisory Control and data acquisition) [5].

5. INTEGRATED POWER QUALITY MONITORING SYSTEM (I-PQM)

According to M. Music et al. [10], an integrated power quality monitoring system and the benefits of integrating smart meters is discussed, so instead of accumulating all the historical data, the integrated power quality monitoring system should collect only data from the measurement devices when there is problem or interference in order to identify the causes. The equipments that are used for power monitoring are all following the IEC610000-4-30 standard. A set of laboratory tests were conducted on a single smart meter and then a comparison was made between a power quality instrument and several smart meters. Overall, the IPQMS integrates data from all the available intelligent devices in the smart distribution grid The paper also suggests that the current communication infrastructure such as SCADA, EVMS, etc. should consider more data throughput for power quality monitoring [10].

6. POWER QUALITY MEASUREMENT SYSTEM USING FPGA(PQM-FPGA)

Due to the sensitivity of end users equipments, the power quality should be monitored continuously. The work by S. Folea et al. [19] presents a solution for monitoring the power quality at the customers' site. The developed network is composed of a printed circuit board with two special Hall sensors that are connected to a Spartan-3E Starter Kit which is used for data processing and display. Wifi module was used in order to connect the circuit that written in the FPGA with the personal computer. The FPGA board used in this system has two input analog channels for measuring both the voltage and the current for quality analysis and LCD for displaying the results. The power consumption of the system along with the storage capabilities needs to be improved [19].

7. POWER QUALITY MONITORING USING OPNET (PQM-OPNET)

A research about power quality monitoring that uses OPNET was presented by Y. Bi et al. [22]. The research paper explores the methods of power quality monitoring and it reflects on the importance of on-line and real-time monitoring on the system management. Communication networks are needed for the online power quality monitoring, therefore different networks were studied in order to evaluate their performance and the OPNET simulator was used for the analysis. It was found that the 10M Ethernet was better for fulfilling the demand of the online monitoring system [22].

8. POWER QUALITY MONITORING SYSTEM USING SPECTRUM ANALYSIS(PQM_SA)

There are several ways to analyze the data obtained from the power quality monitors. Normally the collected data are in the time domain, so it could be easier for the analysis sometimes to convert to the frequency domain and analyze the frequency spectrum in order to extract desired features of any signal. A system for power quality monitoring that is based on spectrum analysis was developed by L. Penghui et al. [6]. The monitoring system uses LabVIEW for the analysis. The power quality index or characteristics that were considered in this system are the content of harmonic and the total harmonic distortion of the voltage and current wave in the electrical network. In order to analyze and test the proposed system, a transformer substation was considered. The system was tested and it was possible to find the content of harmonic and THD in the network along with the harmonic that is caused by the users [6].

9. POWER QUALITY MONITORING USING PSEUDOMEASURMENTS (PQM-P)

Pseudomeasurments were also used for power quality monitoring in distribution networks as described by S. R. K. Kanaesalingam et al. [17] whereby an intelligent application which is pseudo-measurement based was used in order to find the voltages and currents at various bus locations in the considered 33kV distribution network. This method could be used for analyzing large areas in order to identify the faults in the system, [17].

10. CO-OPERATIVE SENSOR NETWORK FOR POWER QUALITY MONITORING (PQM-CSN)

One of the most important quality characteristic of power is the voltage. Therefore, the voltage levels need to be monitored in order to make sure that it stays at stable levels. A cooperative sensor network for voltage quality monitoring was discussed by M. Bisceglie et al. [8]. The main features of this system are that it is scalable, self-organizing and distributed as it enables the system operator to access any node in the system or grid section in order to check the voltage quality without the need for the central fusion that acquire the processing of all the nodes acquisition [8].

N. Stanciu et al. [13], presented a case study where the voltage sag and the total harmonic distortion were studied as they constitute the main problems while monitoring the power quality of any electrical network. In the case study, two results were compared with each other. The first result came from an electricity meter with power quality capabilities while the second result came from a Class A Power quality monitoring equipment. This case study helps in developing a strategy for the choice and selection of the power quality measuring instruments depending on the user requirement. A simulation using Calmet C300, SN: CT/260/2011 was presented in the paper in order to prove the results and the claims that were made by the authors of the paper [13].

11. WEB-SERVICES FRAMEWORK FOR POWER QUALITY MONITORING (PQM-WSF)

According to F. Gomez et al. [3], a web services framework for power quality monitoring is established in order to process the power quality data that is collected by the smart meters in the network. The main purpose of the system is to implement signal processing algorithms in a distributed framework in order to characterize any disturbance like the voltage sag, generate some assessment and then determine the location of the fault in the system. The web-services presented are on-demand entities that can individually process information that is obtained from Power meters, SCADA or Databases. The results of the analysis could be used for improvement purposes along with the detection and diagnosis features. After simulating and testing the proposed system, it was found that the operation time was good, so the system could be implement in real environments for online power quality monitoring. Only some security issues were supposed to be taken into consideration in the design, but it was left for future work and development [3].

B. METER PLACEMENT METHODS FOR POWER QUALITY MONITORING:

1. OPTIMAL POWER QUALITY METER PLACEMENT (OPQMP)

Optimal Power Quality Monitor placement is another approach that was presented by A. Ibrahim et al. [1] which is a power quality assurance method that focuses on the placement of power quality monitors on the system. The presented method uses adaptive quantum-inspired binary gravitational search algorithm which is an algorithm that will help in selecting the best strategic locations for the PQMs in order to reduce the overall cost of the power quality monitoring system and reduce the redundancy of the data that is being measured by the monitors. In the paper, a comparison was made between the proposed algorithm and previously developed algorithms such as the conventional binary gravitational search algorithm, the binary particle swarm optimization, the quantum-inspired binary particle swarm optimization and generic algorithm. According to the analysis, the QBGSA proved to have optimal results in terms of speed and accuracy when compared to the other methods [1].

2. BINARY FIREFLY ALGORITHM FOR POWER QUALITY METER PLACEMENT (BFA)

There have been many studies about the optimal power quality monitor placement as it is a crucial aspect that influences the performance of the power quality monitoring system. One of these studies or approaches is the application of Binary Firefly Algorithm which was presented by W. Ling et al. [21]. The firefly algorithm as the name implies is an algorithm created based on the fireflies behavior. It is simply built around three rules. First, all the fireflies have the same sex, so they will be attracted to each other regardless of the sex. Second, the fireflies will be attracted to each other based on the brightness of each one, so the brighter the firefly, the more others it will attract. Third, the brightness level of each firefly is decided from the objective function. In this system that uses the firefly algorithm, a multi-objective function is used for the optimal position selection process. This function is made up of three main parts which are the number of monitors needed, monitor coverage index and sag propagation index. The method was tested on IEEE 118 bus system and it was found that the algorithm could be used in order to find the optimal PQM location in the system [21].

3. INTELLIGENT METER PLACEMENT METHOD (IMP)

As part of the efforts to optimize the meter placement in power grids, S. Ali et al. [18] have presented an intelligent meter placement method for power quality estimation in smart grid. The main purpose was to reduce the uncertainty of the power quality values on the power links that are not monitored. This was achieved by modeling the network as a data-driven network. Then the entropy based measurements and Bayesian network models were used to develop an algorithm that will help in finding the best power links for meter placement. The results show that the algorithm that was developed using the prediction error has achieved better results. There is still further work on this method in order to increase the scalability of the approaches. The running time of the algorithm needs to be improved and larger networks must be considered for the model to be more efficient. Also, there should be an evaluation method to find the best number of meters that need to be placed in the system for optima power quality monitor [18].

C. COMPARISON BETWEEN MONITORING SYSTEMS & TEQNIQUES:

As described previously, the power quality monitoring systems and techniques vary in terms of their goals and contribution to the power quality improvement field. After going through the various methods and techniques, it was possible to develop some understanding about the basic operation of the system or technique. It was also possible to see from the research papers some graphs, signal waveforms, tables, etc. that display the results of the simulation that was conducted by researchers in labs using software or operators who tested their systems on existing electrical grids. The table below displays all the methods that were summarized in this paper and that are classified into two main categories which are PQM systems and PQ meter placement. The table below shows the advantages and disadvantages of each one of the surveyed methods:

TABLE 1: COMPARISON BETWEEN PQM SYSTEMS

#	Type	PQM Method	Name	Advantages	Disadvantages	Monitoring scheme	Monitored PQ Attributes
1	PQM System or Technique	*HRT-FM*	*High-resolution technique for flicker measurement*	Accuracy Robustness	Mathematical Complexity	Long-term	Flicker
2	PQM System or Technique	*STPQSD*	*S-transform techniques for power quality signals detection and analysis*	Accuracy	Mathematical Complexity	Long-term	Voltage sag, swell& interruption THD
3	PQM System or Technique	*SEMCE DAC*	*Ata-acquisition system for power quality monitoring (SEMCE DAC)*	Reduced Cost Data Transmission Capabilities System flexibility	Data Transmission	Real-time &Long-term	Voltage, current, frequency. & harmonics, THD
4	PQM System or Technique	*PQM-OI*	Power quality monitoring system over the internet	Low cost Could be implemented over SCADA	Security	Real-time	Current voltage
5	PQM System or Technique	*I-PQM*	*Integrated power quality monitoring system*	Efficiency	Cost of smart meters	Real-time	Voltage harmonics
6	PQM System or Technique	*PQM-FPGA*	*Power quality measurement system using FPGA*	Easy to implement Cheap	Difficult system to handle (power consumption & Storage issues)	Real-time	Voltage Current
7	PQM System or Technique	*PQM-OPNET*	*Power quality monitoring using OPNET*	Online Monitoring	Absence of long-term monitoring	Real-time	Transmission time of some PQ attributes was measured
8	PQM System or Technique	*PQM_SA*	*Power quality monitoring system using spectrum analysis*	Efficiency	Mathematical Complexity	Long-term	Harmonics THD
9	PQM System or Technique	*PQM-P*	*Power quality monitoring using pseudomeasurments*	Ability to analyze large areas	Mathematical Complexity	Real-time	Voltage current
10	PQM System or Technique	*PQM-CSN*	*Co-operative sensor network for power quality monitoring*	Scalable and Self organizing method	Expensive tools	Real-time & Long-term	Voltage
11	PQM System or Technique	*PQM-WSF*	*Web-services framework for power quality monitoring*	Good Operation time	Complexity	Real-time & Long-term	Voltage sag
12	Meter Placement method for PQM	OPQMP	*Optimal power quality meter placement*	Speed Accuracy	Mathematical complexity	-	-
13	Meter Placement method for PQM	BFA	*Binary firefly algorithm for power quality meter placement*	Solving the multi objective optimization problem for OPQM	Mathematical complexity	-	-
14	Meter Placement method for PQM	IMP	*Intelligent meter placement method*	Reduce uncertainty over non-monitored links	Running time not very good	-	-

It could be observed from the table above that the first eleven methods were compared in terms of their, advantages, disadvantages, monitoring schemes and the quality attributes that are being monitored. Some of the systems provide real-time or long-term monitoring for power quality attributes only, but others provide both which is considered much better. In addition it was noticed that some of the systems were designed to monitor a single or couple PQ attributes whereas there could be more attributes to consider in the system to become optimal. Some methods and approaches include very detailed and complicated algorithms which could be considered as a draw back since the mathematical complexity could decrease the processing time of data. Form the surveyed methods it was found that the (SEMCE DAC) which was presented by S. D. Grigorescu et al. [16] is the best one comparing to the others as it provides both real-time and long-term monitoring of different power quality attributes. It also has many advantages such as the reduced cost and the system flexibility.

D. INTERNATIONAL INDUSTRY PRACTICE & GUIDELINES FOR POWER QUALITY MONITORING:

It is important to develop some knowledge and gather information about the worldwide efforts that are taking place in order to insure the delivery of good quality power service from the supplier to the end users. A survey was conducted by J. V. Milanovic et al. [4] in 43 countries across the world regarding the industry practice on Power-Quality Monitoring. The survey summarizes the key findings of 114 responses to a questionnaire that was given to the power companies and the different power suppliers around the world. Most of the electrical networks have power quality monitors installed and control centers dedicated for the continuous system monitoring in order to handle any fault or interference in the network. The results of the survey showed that the practice is largely uniform around the world with only few differences in some cases. Some of the findings of the survey could be listed below:

- 82% of system operators carry out continuous power quality monitoring using fixed monitors.
- Customers complaints was the primary reason for power quality monitoring
- The selection of the installation location of the permanent monitor depends on the need to see the characteristics at the customer's site
- The monitors are selected based on the performance rather than standards
- Each individual utility uses only few different models of PQ monitors
- In more than 90% of the cases, all the three phases are monitored and system current is more common than just specific customer current
- The results of data processing are used for internal or external reporting on specific events
- Two thirds of voltage measurements are line-to-natural voltages rather than line to line voltages.

There are certain common guidelines that need to be followed while monitoring the voltage quality of the electrical grids. Some of these guidelines were highlighted by M. Bollen [11]. The guidelines are generally published by CEER and ECRB and they contain some general recommendation about the number and placement of power quality monitors.

E. EXAMPLES OF POWER QUALITY IMPROVEMENT EFFORTS AROUND THE WORLD:

Efforts are being made and initiatives are taking place in order to improve and enhance the power quality. There are many examples around the world of countries that implemented the new technologies in power quality monitoring area such as using smart meters and having dedicated networks for the continuous online power quality monitoring. One example for the long term power quality monitoring is the illustrated by P. Santarious et al. [14]. Certain power quality attributes were selected and monitored over selected periods of time (between 1997 and 2005). These attributes were harmonics, unbalance and flicker. It was noticed after conducting the research that the biggest change in the system or the main cause of disturbances was because of flicker parameters. In another research that was conducted by L. Campus et al. [7], the power quality of supply was characterized in the Portuguese electricity and transmission grid. As part of the efforts to monitor the power quality, the voltage is measured continuously monitored at the delivery points. The study presents the results of implementing a methodology for selecting the buses and bars on the system were the monitors should be placed in order to monitor the voltage. This methodology is explained in the paper as well as the results that were found between 2010 and 2011. It was found that flicker occurred many times in the system due to some steelwork that was taking place in some construction and industrial locations. Also, it was noticed that some voltage dips have occurred due to some natural phenomenon like lightening.

The electrical distribution networks were also evaluated in terms of power quality as illustrated by S. Sultan et al. [15]. Some of the results that were shown are the sources of PQ disturbances, the solution equipment's along with their percentages of contribution and lastly, the PQ causes of disturbances. It was found also in the research that some of the power quality issues came from the lack of awareness in some less developed areas in Libya

III. CONCLUSION

Overall, this paper presents a survey over some of the existing modern power quality monitoring systems and techniques that were developed over the past years. It was noticed that some of the research was done to develop efficient quality monitoring systems and other to find the best location for meters in the electrical grid which will help to improve the PQM system. The surveyed power quality monitoring systems were explained along with the various quality attributes that they capture such as flickers, voltage sags, etc. The monitoring systems could be designed for real-time monitoring, long-term monitoring or both. It was noticed that some systems were designed for both which is considered as an advantage. An evaluation of the power quality monitoring systems was presented in form of comparison between the methods in terms of their advantages and disadvantages. The methods were varying between simple and complex or cheap and expensive. Some of the systems had tools and software that could be very expensive and hard to implement which was considered as drawback in the comparison. After comparing the methods and systems, it was found that the (SEMCE DAC) was the best example for PQM system as it has many advantages such as reduced cost and flexibility.

New renewable energy systems add new challenges to power quality. The inertia of renewable energy systems is way less than that of the grid. Hence, fault signatures are not the same. The revolution in the communication industry is a challenge and an opportunity. New wireless communication capabilities make it easier and less expensive to monitor more signals at lower costs, hence improve the power quality of the system. On the other hand, signal interference in the low power communication lines due to the high power lines is a challenge.

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BIOGRAPHY

Dr. Basel Alsayyed is an assistant professor at the department of mechanical engineering in the United Arab Emirates University. With over 16 years of experience in academia in many colleges and universities, and over 12 years of industrial experience, most of which are in the American automotive industry, Dr. Alsayyed has a passion for education in general and teaching in particular. Teaching is an art, a trust, a valuable transformation of students using certain methods and tools, and it is holy, are all part of his belief. He practices it in all aspects of his life, and to Dr. Alsayyed, students are the most valuable element in the education process; their needs have to be addressed in any continuous improvement discussion of the education process. Integration of academia and industry goals and activities are paramount. Sensing the industry needs and prepare future engineers to meet the challenges is an important dimension of Dr. Alsayyed's activities. Dr. Alsayyed research interests are in the areas of advanced manufacturing, quality & reliability, renewable energy, engineering education and knowledge management.

Abbas Fardoun (SM 2005, M'90) was born in Lebanon. He received his BS degree from the University of Houston, in 1988, & MS and Ph.D. from the University of Colorado, Boulder in 1990 and 1994, respectively. He was with Advanced Energy Inc. from 1994-1996 where he was involved with high frequency power supply design. From 1996 until 1998, he was with Delphi where he worked on Electrical Power Steering. From 1998 until 2006, Dr. Fardoun has been with TRW Automotive working on electrical power steering development . Since 2006, Dr. Fardoun has been with the Department of Electrical Engineering at the United Arab Emirates University (UAEU) where he is an associate professor and director of the renewable energy laboratory. Dr. Fardoun received the Hariri Foundation distinguished graduate award in 1994. He holds seven awarded patents related to ac drives & automotive applications. His main interests are AC-DC and DC-DC power supplies for renewable energy applications.

Hoda H. ElSheikh is a master student at the United Arab Emirates University, Al Ain. She received her B.Sc from American University in Dubai before joining the United Arab Emirates University and becoming a teaching assistant. Before coming to UAEU, Hoda worked in different part-time jobs such as working as a Library Assistant for two years at AUD and then as an administrator for six months at Emirates Aluminum. Hoda is a student member in IEEE and she was an active member in the IEEE student club branch at AUD whereby she helped in organizing events such as seminars, workshops, field trips, etc. She has also been part of many club organizations, charity events while studying at AUD.