Comparison of electric motors used in electric vehicle propulsion system

Khalid S. Mohammad, Aqeel S. Jaber
Department of Electrical Power Techniques Engineering, Al-Ma'moon University College, Baghdad, Iraq

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ABSTRACT

Now days, it is vital to use electric vehicles (EVs) instead of traditional cars with internal combustion engines (ICEs) in order to reduce the high level of pollution in the environment, and many researchers are investigating the possible improvements on these vehicles. The main component of EVs is the electric motor and the selection of a motor with high efficiency, excellent dynamic response and high starting torque has a strong effect on the performance of EVs. In addition to that a reasonable price for the electric motor is required. This work focuses on the selection of the most suitable electric motor for EVs. Therefore, a detailed study to compare between the performance of the major types of electric motors that are used in EVs is addressed in this paper. The results of this comparative study is tabulated and by careful consideration for all these results, the appropriate electric motor for EVs has been chosen. From the other hand, the artificial intelligent (AI) techniques play a crucial role in the EVs technologies, and several kinds of AI techniques used in EVs applications are overviewed in this work.

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Corresponding Author:
Aqeel S. Jaber
Department of Electrical Power Techniques Engineering, Al-Ma'moon University College
Baghdad, Iraq
Email: aqe77el@ieee.com

1. INTRODUCTION

The majority of vehicles rely on natural resources; mainly fossil fuels, for their operation. Burning of these fossil fuels results in air pollution and global warming. Electric vehicles (Evs) have zero emissions because they do not use petrol or diesel fuel. Thus, the use of EVs can make the air cleaner and solve some of the environmental problems [1]. Furthermore, EVs are quite, and the cost of their maintenance is much less than with conventional vehicles. The Main drawback of EVs is the limitation of driving mileage. However, the batteries are recharged during regenerative braking and this will help to extend the driving range of EVs. Regenerative braking can extend an EV range by 30% on average [2].

An EV consists of three main parts; the power supply, the power converter with its controller and the electric motor. The specifications of the electric motors have a direct effect on the EVs performance, therefore a careful study for the characteristics and performance of the electric motors to be used in EVs applications is required. The major types of electric motors used in EVs applications are; DC motors, induction motors, permanent magnet brushless (PMBL) motors and switch reluctance (SR) motors. The main requirements for the electric motors in EVs applications are the high torque at low speed, high power at high speed and extended speed range ability. Moreover, the electric motors should have high efficiency over a wide range of speed and torque, smooth and quick acceleration, high power density and low cost. A lot of works have been done to improve the performance of electric motors, such as using a high energy permanent magnet materials and semiconductor switches to achieve electronic commutation. The performance of electric motors is determined by their torque-speed characteristics. The torque-speed characteristics of the electric motors in EVs applications should be very close to the ideal characteristics, which is presented in this study.

Although DC motors require easy speed control and provide high torque at low speed, but their use in EVs applications has decreased due to their low efficiency and require frequent maintenance. On the other hand the SR motors are still evolving for EVs applications. Induction motors and PMBL motors are the most widely used motors in EVs applications, and the researches on them are dominant. In spite of induction motors have high maturity, very reliable, low maintenance and low cost, the PMBL motors are more convenient to be used in EVs applications and offer the best performance in terms of high efficiency, high power density, very reliable, small size, high torque at low speed and high dynamic response due to the use of high energy permanent magnet materials such as samarium-cobalt. The reducing price of these permanent magnet materials and the developing of very fast semiconductor switches such as metal oxide semiconductor field effect transistors (MOSFETs) has made the PMBL motors more attractive for EVs applications [3], [4]. In this work, the performance and characteristics of the electric motors which are currently used in EVs applications have been compared and evaluated according to the requirements of an EV propulsion system. Also, conclusion has been made to identify the electric motor which offers the best performance for electric EVs.

Nowadays, it is becoming increasingly clear that intelligent control and optimization are entering the most exciting phase of their development and applications [5]–[10]. One of those applications is the use of artificial intelligence technologies in EVs, which has a high impact on the environment and economy, not only reduces the emissions of CO2 and other pollutants but also increases renewable energy resources [11]. Thus, electrical vehicles contribute to clean transportations and increase energy independence. The applications of AI techniques in EVs are classified into three types, intelligent control, battery optimization, and optimal charging. This paper also introduced an overview for the most intelligent applications that used in EVs.

2. ELECTRIC VEHICLES TYPES

The main components of any EV are the battery. The controller and the electric motor which converts electrical energy into mechanical energy. In general, there are two basic types of EVs.

2.1. Battery electric vehicles (BEV)

In this type of EVs, battery is the only source of energy. This energy is supplied to an electric motor which in turn runs the vehicle's wheels. The battery is recharged from the grid and during the regenerative braking. Figure 1 shows the main components of a BEV [3].

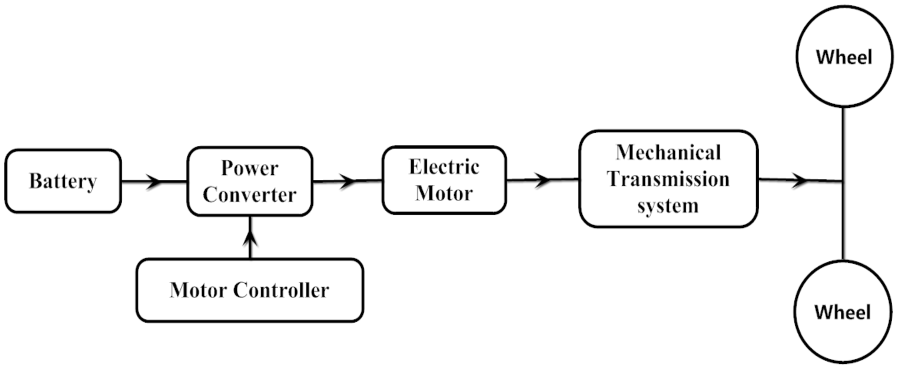

Figure 1. Basic propulsion system of a battery electric vehicle

2.2. Hybrid electric vehicles (HEV)

Although HEVs are high complex than similar conventional vehicles, a wide variety of HEV models are developed. In this type, both electric motors and internal combustion engine (ICE) are used to power HEV, consequently Batteries as well as fuel like petrol and diesel can be used as a sources of energy in this type of vehicles. Figure 2 shows the main components of HEV [4].

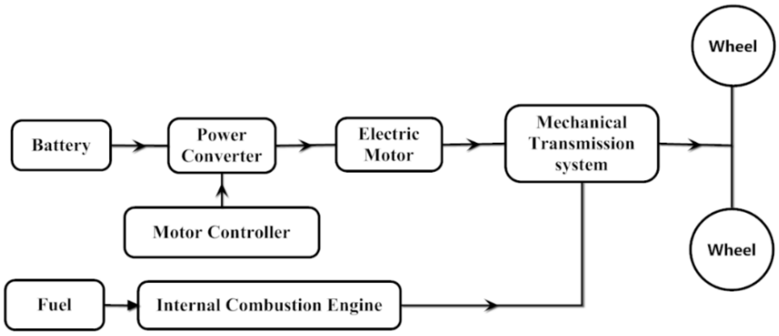

Figure 2. Basic propulsion system of a hybrid electric vehicle

3. IDEAL TORQUE-SPEED CHARACTERISTICS FOR ELECTRIC VEHCLES MOTOR DRIVES

Electric motor drive is the most important component in EV. In order to use an electric motor in EV, the motor should have the ideal torque-speed characteristics shown in Figure 3. These characteristics include two regions; constant-torque region and constant-power region. During starting, acceleration or hill climbing, peak torque is required and motor is operating in constant-torque region. In this region armature voltage is varied to control the speed while armature and field currents are kept constant so as to produce the required torque. For speed higher than the base speed, motor is operating at constant-power region. In this region the speed is controlled by varying the field current, while the armature voltage and current are kept constant at their rated values. As field current (flux) decreases, speed increases so that the motor back EMF remains almost constant and consequently the power remains substantially constant [12].

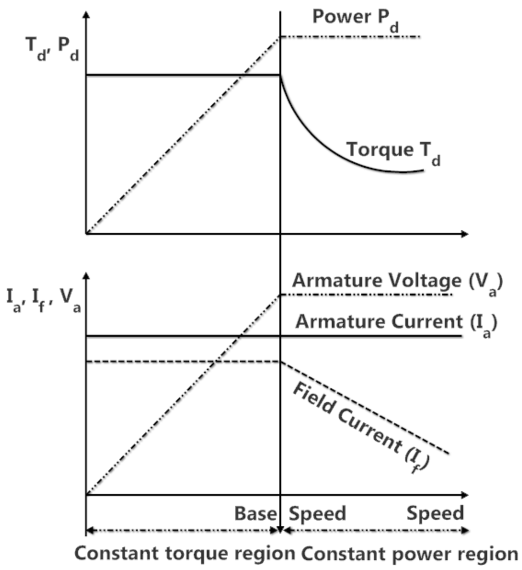

Figure 3. Required characteristics for electric vehicle motor drives

4. REQUIRED CHARACTERISTICS FOR ELECTRIC MOTORS USED IN EVs

In EVs, the required torque to turn the wheels is produced by an electric motor, therefore the performance of EVs mainly depends on their motors, which should have the following characteristics [13], [14]: i) high power density, ii) efficiency should be kept high over a wide range of speed and torque, iii) fast dynamic response, iv) high reliability under various operating conditions, v) both regions of operation, the constant-torque and constant-power should have a wide speed range, vi) high torque at low speeds, as well as high power at high speeds, and vii) reasonable cost. The advance in developing power converters at high power level, a sophisticated control techniques and permanent magnet materials of high energy level has improved the performance of the electric motors. Consequentially many types of these motors can be used in EVs, but the most widely motors are those described in the next subsection.

4.1. DC motors

The most important feature of DC motors is their ideal torque speed characteristics. They can produce high torque at low speed. Moreover, it is easy to control their speeds and torques. Due to these features DC motors have been used widely in EVs. There are five main kinds of DC motors: i) series DC motor, ii) shunt DC motor, iii) compound DC motor, iv) separately excited DC motor, and v) permanent magnet DC motor

The series DC motor is the most preferable one, since its torque at starting is high. Figure 4 shows the torque-speed characteristics of this type. It is clear that a high torque can be obtained at low speeds, while at high speeds the torque is low. In addition to that demagnetization of the motor magnetic field due to the armature reaction effect can be balanced by strengthening the field. However, the DC motors have some disadvantages, which are: i) High maintenance and limited maximum speed due to the friction between the commutator and the brushes. (ii) The stator and rotor windings have high copper loss, and this resulted in a low efficiency. Add to that, the mechanical commutation process has reduced the efficiency further. (iii) Large size and poor power density. Despite this, the DC motors are still used today on some EVs to keep the cost down [15], [16].

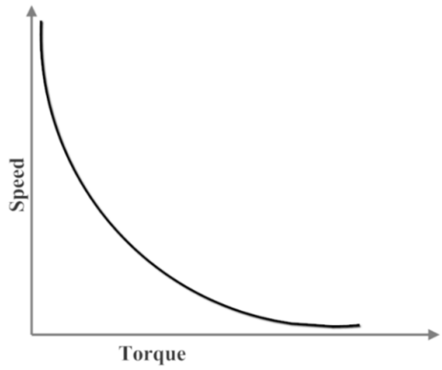

Figure 4: Torque-speed characteristics of a series DC motor

4.2. Induction motors

Induction motor consists of three-phase windings placed on the stator, and a rotor carries copper or aluminum bars which are short-circuited by end rings. When the stator windings are energized by a three phase AC currents a rotating magnetic field is produced. This magnetic field will cut the rotor circuit and according to the electromagnetic induction principle, currents flow through the rotor conductors. Consequently, a second magnetic field is established, and the interaction between the stator and rotor magnetic fields generates torque in the rotor. Due to this torque, the rotor will start to run in the direction of the stator field. Induction motors have excellent field-weakening performance and the field oriented control technique can be used to expand their speed rang up to five times the base speed. Also, external source to energize the rotor of an induction motor is not required and this makes both manufacturing and operation simpler. Due to these characteristics and to their ruggedness, reliability, good speed regulation and low maintenance, the induction motors are used in EVs industry. The disadvantage of induction motors is the low efficiency at high torque and low speed because of rotor loss. Using copper instead of aluminum to manufacture the rotor can improve the efficiency of induction motors. However, induction motors have higher efficiency than DC motors. Another disadvantage with IMs is the low starting torque. But, this torque can be increased by using voltage and frequency (VF) control technique. The other feature for induction motors which should be considered is that their speed control is not as easy as the speed control of dc motor and it requires complex control schemes [17], [18].

4.3. Permanent magnet brushless motors

Developing of a PMBL has been possible due to the advance in the power semiconductor switches technology and the availability of a strong permanent magnet materials such as samarium-cobalt. There are two types of PMBL motors [19].

4.3.1. Permanent magnet brushless DC (PMBLDC) motor

PMBLDC motor has a permanent magnet rotor surrounded by a wound stator. The AC currents feeding into the stator winding are of rectangular form [20]–[23]. The winding in the stator gets commutated electronically, instead of with brushes and commutator. Figure 5 shows a three phase PMBLDC motor drive.

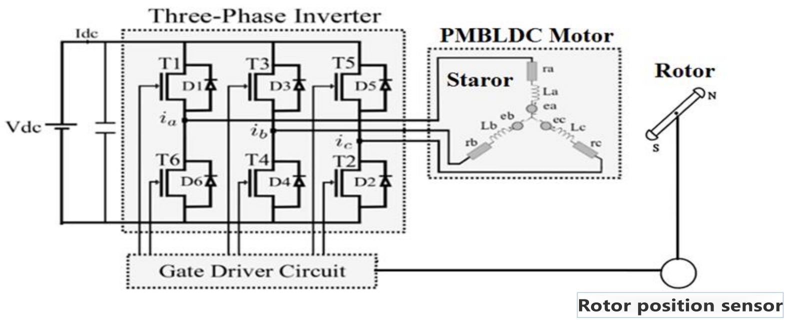

Figure 5. Three phase PMBLDC motor drive system

Electronic commutation is accomplished by the inverter, the gate drive circuit and the rotor position sensor. According to the signals of the rotor position sensor, the gate drive circuit turns on the switches of the inverter and consequently the current flows through the stator winding in a particular sequence as shown in Figure 6. Due to this sequence of energizing, the permanent magnet rotor is rotating continuously in the clockwise direction and maximum output torque is obtained.

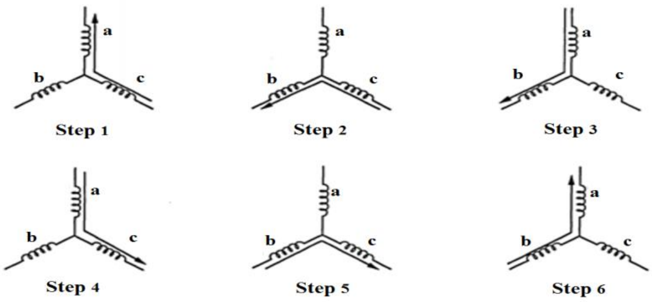

Figure 6. Energizing sequence of three phase PMBLDC motor

PMBLDC motor has many advantages because it does not have brushes and commutator, the rotor is made of a permanent magnet material and the windings are located on the stator. These advantages may be summarized as [24], [25]: i) reduced maintenance, low noise, no sparks, long life and the capability of operating at high speed due to the replacement of the brushes and commutator by the semiconductor switches, ii) high efficiency, due to electronic commutation, no rotor copper losses and the placement of armature windings on the stator, iii) the use of high energy permanent magnet, such as samarium-cobalt, has resulted in small diameter rotor and less inertia, allowing higher dynamic response and a reduction in rotational losses, iv) high torque at starting and at low speed, and v) reduced size and weight.

4.3.2. Permanent magnet brushless AC (PMBLAC) motor

This motor is also called a permanent magnet synchronous motor. It has a permanent magnet rotor and a three phase armature windings located on the stator as in PMBLDC motor. The difference is that in PMBLAC motor the currents, which flow through the armature windings have a sinusoidal waveform, while the PMBLDC motor has a rectangular current waveform. Also, the back EMF in PMBLAC motor has a sinusoidal shape, whereas the back EMF in PMBLDC motor has a trapezoidal shape. PMBLAC motor offers an array of advantages similar to that of PMBLDC motor, such as; high efficiency, high torque and power density, compact and low weight and high torque at low speed. However, PMBLDC motor has the ability to produce a larger torque than other motor at the same value of current and voltage.

The main drawback of the PMBL motors is that the permanent magnet materials are expensive. Also, the speed range in constant power region is short because the magnetic field produced by the permanent magnet rotor is fixed and cannot be adjusted. For EVs, it is very important to extend the constant power speed range and this can be achieved by controlling the conduction angle of the power converter [26]–[30].

Also, it is necessary to mention the line start permanent magnet synchronous motor (LSPMSM), which is a combination of an induction motor and permanent magnet synchronous motor. The rotor of LSPMSM consists of squirrel cage and permanent magnets. Due to this structure, the LSPMSM produces asynchronous torque during the transient period, while at steady state, a synchronous torque is generated by the permanent magnets. The rotor losses are eliminated at steady state because there are no induced current in the rotor cage. Therefore, LSPMSM has higher efficiency than that of an induction motor. Moreover, it has high power density and high power factor [31]. LSPMSM has a good performance in applications where constant speed is required [32]. However, the behavior of the LSPMSM during the transient starting and synchronization requires more improvements. Therefore, the use of such motor in EVs needs further researches.

4.4. Switch reluctance (SR) motors

The SR motors have a doubly salient construction. The stator has a salient poles with concentrated windings wound around them and the diametrically opposite windings are connected to form a stator phase. The rotor also has a salient poles, but without windings or permanent magnets. In SR motors, the stator phase currents are switched on and off in synchronism with rotor position to ensure continuous operation as in PMBLDC motor. Excitation of a stator phase causes the most adjacent pair of rotor poles to be attracted into alignment with the magnetized stator poles. Machine torque is produced by reluctance variation; thus, rotor moves to the position where the reluctance of the energized stator winding is minimum. The SR motors are not expensive because of their simple construction. Moreover, they have a very high starting torque and a wide speed range, which can be extended up to six times the base speed. The main drawback of SR motors is the high torque ripple which contributes to high level of noise and vibration. Furthermore, they also requires complex and costly converters and controllers [33], [34].

5. COMPARISON OF MAJOR ELECTRICAL MOTORS USED IN EVS

A performance comparison of major electrical motors used in EVs is summarized in Table 1. The comparison is based on many factors such as; efficiency, speed range, power density, maximums torque, reliability, cost and the maturity of the technology. Also, five types of motors that are widely applied in EVs are selected for the comparison.

Table 1. Performance comparison of major electrical motors used in electric vehicle applications

Performance	DC motors	Induction motors	PMBL DC motors	PMBL AC Motors	SR Motors
Power density	L	M	H	H	M
Reliability	M	V.H	H	H	V.H
Efficiency	L	M	H	H	M
Cost	M	L	H	H	M
Size	M	M	S	S	La
Controllability	V.H	V.H	H	H	M
Speed range	M	M	L	L	H
Maximum torque	M	M	H	H	H
Torque ripple	L	L	M	L	H
Acoustic noise	M	L	L	L	H
Technology maturity	V.H	V.H	H	H	H

Where: L = Low, M= Medium, H = High, V.H = Very high, S = Small, and La = Large

Comparing on the basis of power density, PMBL motors have the highest power density, while DC motors have the lowest. In terms of reliability, induction motors and SR motors are the most reliable and the least reliability are the DC motors. The most efficient motors are the PMBL motors and, once again, DC motors have the lowest efficiency. In terms of cost, induction motors have the lowest price, while PMBL motors are the most expensive. Considering the size of the motors, PMBL motors have the smallest size, while the SR motors have the largest. Now comparing on the basis of the maturity of the technology for being used in EVs, DC motors and induction motors are the highest as a large number of researches and development were done on them over the past.

6. ARTIFICAL INTELLIGANT TECHQNIQUES IN EVS

Since the artificial intelligent applications started to have a real application, the intelligent control and optimization strategies are getting very fast development and modifications to be applied for all engineering, medicine, and economic challenges [35]–[40]. The intelligent systems improve the EVs operation and efficiency by several strategies, such as control the driver, optimizing the batteries, and develop a smart power system. For example, a developing for the tunable control structure have been done for determining the torque split between the internal combustion (IC) engine and the electric motor based on efficiency and emissions by using the global positioning system (GPS) for adapting a fuzzy logic controller [41]. Wei Li, *et al*. [42] proposed a design for the battery pack by optimal combination, materials selection for battery electrodes, and state of health (SOH). The configurations of the cells, thermal design, case of the battery, and recycling aspects of the battery were the main goal of theirs work. Optimal intelligent energy-management strategies were proposed for plug-in hybrid electric vehicles (PHEVs). Two strategies were done for two levels, first level, strategy depended on vehicle location, rode characteristics, and real-time of the trip from intelligent transportation system technologies in generating a synthesized velocity trajectory. The second strategy used the benefit of the first steps to charge the battery to minimize the total fuel consumption [43].

A fuzzy logic controller has been introduced to study the relationship between the three elements of driving patterns. Moreover, a model of load profile modeling framework (LPMF) for PHEVs was selected to synthesize both the characteristics of driving patterns and vehicle parameters into a load profile prediction system. PHEV of two-layer evolution strategy particle swarm optimization (ESPSO) algorithm was tested to integrate PHEVs into a residential distribution grid [44]. Two objectives along a rod in China, Chengdu which are, the location of the charging stations and the emission of CO2 have been minimized by using particle swarm optimization PSO [45]. The barking of EVs was also toke a researchers efforts using AI, a smart management and scheduling model were tested for a huge number of EVs. The consideration of the practical constraints such as charging price, battery capacity, charging time, and age of the battery were the base of model design [46]. An auto-scheduling design for an intelligent car park with a photovoltaic system and DGs was introduced where the practical constraints, solar radiation uncertainty, spinning reserve requirements, and electric vehicles owner satisfaction are considered [47]. Online intelligent demand coordination for (PEVs) was tested in a distribution system. The model was based on the assignment of scores for PEVs using fuzzy logic. Maximizing the owners' satisfaction, without changing grid operational constraints was done by optimal charging of EVs [48]. AI dual-loop motor controller to predict energy management of PHEVs was introduced [49]. Inspired by fuzzy granulation technology, a deep fuzzy predictor is created to achieve driver-oriented velocity prediction, and a finite-state Markov chain is exploited to learn transition probabilities between vehicle speed and acceleration [49]. An algorithm has developed to determine the shortest distance to charge the EVs using GPS based on efficient estimation of state of the charge at the destination [50].

7. CONCLUSION

In this paper, the major electric motors used in EVs have been reviewed and compared on the basis of the EV propulsion system requirements. Advantages and disadvantages of these motors (DC motors, Induction motors, SR motors and PMBL motors) are analyzed and evaluated. The main conclusions drawn from this comparative evaluation are: i) PMBL motors are the most energy efficient and they have the highest power density, moreover they have the ability to produce larger torque than other motors at the same values of currents and voltages. However, the use of permanent magnet increases the cost, ii) Induction motors have very high reliability and the most cost effective motors, iii) DC motors are easy to control, but have high maintenance and low efficiency, iv) SR motors can offer long constant power range and high reliability. However, it produces high torque ripple and acoustic noise, v) PMBL motors and induction motor are the most appropriate electric motors for EVs applications and widely found in the EVs market, while DC motors have limited use now days in EVs applications. SR motor is gaining much interest by EVs manufacturers, but still need more researches to improve its characteristics, vi) In this paper many studies and researches about different AI techniques which are used to improve the performance of EVs were presented and it was shown that the intelligent systems are suitable to control and optimize the EVs challenges.

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BIOGRAPHIES OF AUTHORS

Kahid S. Mohammad was born in Haditha, Iraq, in 1956. He receive the B.Sc. degrees in Electrical Engineering from the University of Technology, Baghdad, Iraq, in 1979 and the Ph.D. degree from Loughborough University of Technology, UK., in 1993.Between 1993 and 1999 He was with GEC ALSTHOM Ltd. and POWERNETICS Ltd., U.K., as an Engineer, system analysis. He became a lecturer at Electrical Engineering from the University of Technology, Baghdad, Iraq. Until 2004, and then He join the University of Anber, Ramadi Iraq. As a head of Electrical Engineering Department. In 2012 he became the head of the Computer Science Department in Al-Maarif University College, Ramadi, Iraq. He has been with the Department of Electrical Power Engineering Techniques, Al-Ma'moon University College, Baghdad, Iraq as a lecturer since 2017. In 2021 he became the head of the Department of Electrical Power Engineering Techniques, Al-Ma'moon University College. He can be contacted at email: khalid.s.al-hadithi@almamonuc.edu.iq.

Aqeel S. Jaber was born in Iraq in 1977. He received the B.E., M.E., degrees from University of Technology, Bagdad, Iraq, in 2001, 2007 respectively, and Ph.D. degree from University Malaysia Pahang, Pahang, Malaysia, in 2015. He has held lecturing positions at the department of Electrical Power Engineering Techniques, Al-Mamon University collage, Baghdad, Iraq since 2009. Until Oct, 2021 he was an Associate professor at the Al-Mamon University collage. He can be contacted at email: aqe77el@ieee.com.