A Survey on Traction Motor and Its Prototyping Method for Electric Vehicle Application

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***Abstract*—Electric vehicle (EVs) is the main solution to reduce air pollution from the transportation sector. The main component of an EV is the propulsion system, energy storage system, and auxiliary system. The propulsion system is consisting of a motor and its drives, while the energy storage system is a battery or other energy storage and its management system. Whereas the auxiliary is like a lamp and air conditioner. This research aims to review some electric motors and their prototyping method of an EV. There are several methods for programming electric motor drives in EVs. One of the fastest solutions in fast prototyping in the motor drive of an EV is using the Hardware in the Loop (HIL) method. These papers can be used as references to determine the type of traction motor used in EVs and the method for doing rapid prototyping of it.**

***Keywords*— survey, electric vehicle, traction motor, HIL**

I. INTRODUCTION

Electric Vehicles (EVs) are the most advanced technological developments compared to alternative vehicles with other technologies [1]. Currently, research and development of electric cars are continuing. At short distances, Internal Combustion Engine Vehicle (ICEV) will most likely remain the most cost-effective solution. In the medium range, a 15% probability for PHEV to be the most cost-effective solution in 2020 and a 44% probability in 2025[2]. In terms of TCO (Total Cost Ownership), EVs have relatively more efficient travel costs than conventional vehicles if used for a long period [1]. This suggests that EVs will be a more economical vehicle choice when compared to ICEVs only if the vehicles are driven longer than annual distances. Under special circumstances, the cost of ownership of an EV due to the payback period can be even shorter than that of other vehicles [3].

The development of EV technology needs supporting areas, such as batteries, charging, electric motors, charging infrastructure, etc. As the core of the propulsion system, electric motors are of concern to many researchers. There is various electric motor used in EVs. For example, the IM (Induction Motor) is used in Tesla Model S 2012 edition [4]. Vector control has been used to improve efficiency for IM. There are also PMSM (Permanent Magnet Synchronous Motor), especially the SM (Surface Mounted) types, to be found in many EV applications such as in Toyota Prius. It has high power density, high efficiency, and a simple structure [5]. Due to the advantages of high-power density and high efficiency, a permanent magnet-type motor is attractive for EV applications. While DC motor and Switched Reluctance Motor are also used in EVs which are Peugeot Berlingo and Holden Commodore, respectively.

Previous reviews regarding the electric motor have already been done by [6] and [7]. In [6] they focus on the motor's characteristics. Whereas in [7], they also discuss the control method used for electric motors in EVs. However, both are not discussing the prototyping methods. In this study, we compare some electric motors to verify which type of motor is most suitable for application in electric vehicles. As well as in controlling the electric motor, the focus is on using the HIL (Hardware in the Loop) method to overcome problems in terms of testing motor control on electric vehicles. HIL simulation uses two methods, namely the simulation method and the hardware method. This research is very important to do because the results of this research can be implemented as a foundation for further research regarding the components of the propulsion system in electric vehicles.

The rest of the paper is organized as follow: Section II review some electric motor commonly used in electric vehicle and compare their performance. In Section III, some method to do rapid prototyping with Hardware in the Loop (HIL) is presented. Finally, the conclusion is given in Section IV.

II. METHODS

This paper's primary objective is a review of the literature, which includes the analysis findings of several studies about traction motors. The use of keywords "electric motor" and "rapid prototyping" on the Google Scholar website are employed in the process of generating a quantifiable concept from the reviews that have been conducted. Further identifying the journal's widespread recognition and its assessed contribution in reference to the primary literature is made to supplement this technique. The same keywords were utilized to find connections to pertinent literature by looking for full-text publications that were available. In addition, the phrases "traction motor" and "hardware in the loop" were included in the search terms.

The next stage is to choose the literature review papers that will be used based on how well the abstract and introduction fit. If there are many articles in the exam, only one of them will be chosen. A sample of 23 papers was created from several procedures, and the analysis will contain the research questions at the conclusion of each of the 23 papers. The last action is a more thorough analysis of the 23 articles used as references to learn more about the information that can be found there and how it may be adjusted to the needs of this article's authoring.

The research objectives and questions of this review are as follows:

1) What is the characteristic of electric motors mostly used as traction motors in electric vehicles?
2) How does the rapid prototyping method used in the application of electric motors in electric vehicles?

III. Results And Discussions

In this part, we will discuss the answer to the research objectives based on the literature review. There are two subs which are traction motors and rapid prototyping.

A. Traction Motors

1) *Induction Motor (IM)*

Induction motors can be made without any electrical connection to the rotor. The working principle of an induction motor is that due to electromagnetic induction, the stator winding generates a magnetic field and induced currents in the rotor which generate torque [8]. Induction motors are often applied to electric vehicles because of their simple structure, reliability, durability, low maintenance requirements, low cost, and ability to work in adverse environmental conditions [9]. Induction motors have a low power factor so the losses from induction motors are greater than permanent magnet motors, besides that induction motors have the highest copper losses [10]. The controller for an induction motor has a higher cost compared to a DC motor controller [6]. Induction motors have advantages when used under overload conditions compared to other types of motors [11]. Fig. 1 shows the structure of an IM.

2) *Permanent Magnet Synchronous Motor (PMSM)*

In the manufacture of permanent magnets, a material that has a high conductivity is used as the core of the permanent magnet synchronous motor (PMSM) rotor. PMSM motors are categorized into Interior-mounted PMSM (IPM) and Surface Mounted PMSM(SPM) [8]. Under the same conditions, IPM and SPM provide similar amounts of continuous power. However, IPM has the advantage of being able to work under overload conditions throughout its speed range, while the construction of SPM does not allow SPM to work with overload loads. The SPM suffers additional losses due to the excitation of the permanent magnet flux and permanent magnet losses at high speed. Conversely, at low speeds, IPM has greater losses [12] [13]. PMSM construction is depicted in Fig. 2.

3) *Switched Reluctance Motor (SRM)*

SRM is a type of stepper motor that runs on torque. In the mechanical design of the motor, no power is needed to move the parts, because the electrical design is very complicated, a switching system is needed to provide power. The main advantages of SRM for electric vehicles are simple controls, a wide constant power range at high speeds, fault tolerance, and robustness. SRM does not have a brush, collector, or magnet so the maintenance costs are low. When compared to induction motors and IPM, SRM has high iron losses but is the lightest type of motor and has a low initialization cost [10]. The main drawbacks of SRM motors are torque ripple and acoustic noise [6]. Fig. 3 shows the construction of an SRM.

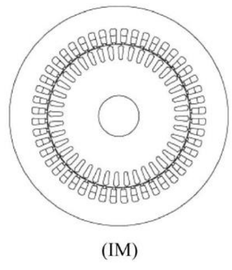

Fig. 1. Induction motor construction [11].

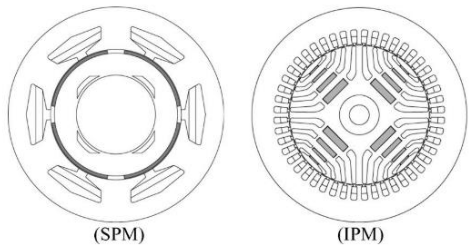

Fig. 2. PMSM construction [13].

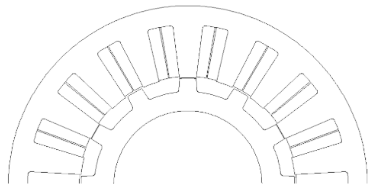

Fig. 3. SRM construction [10].

4) *Direct Current Motor (DC Motor)*

In general, DC motors can vary their speed by utilizing the voltage in the motor windings. DC motors can be applied in various fields, for applications in electric vehicles a DC motor that has a large size is needed. A commutator is connected to the end of the wire to energize the coils and brushes are used to connect the coils to an external power supply. DC motors are used in EVs because of their simple controls and durability. Brushed DC motors have high torque at low speeds, but have the disadvantages of large structures, low efficiency, low reliability, and high maintenance costs due to brush and collector structures [9]. There are two types of DC motors, namely series, and shunt. DC shunt motors have better control, while DC series motors have a high starting torque[6].

5) *Brushless DC Motor (BLDC)*

The BLDC electric motor is an electric motor that does not have a brush in its structure. The stator of a BLDC motor can be slotted or slotless. The slotless core has a lower inductance so it can run at very high speeds, and the cogging torque requirement of the slotless core BLDC decreases. The downside to slotless cores is the higher cost as they require more turns to compensate for the wider air gap. Permanent Magnet Synchronous Motors that have a trapezoidal waveform of Electromotive Force (EMF) are known as Permanent Magnet Brushless DC (PMBLDC) [14]. These motors are highly efficient at producing large amounts of torque over a very wide speed range. The power density and efficiency of electric motors are higher than other types of electric motors, this is because BLDC does not have rotor windings and losses from rotor copper [8]. Although BLDC motors require low maintenance costs, the initialization costs of BLDC motors are high [15]. The illustration of slotted and slotless BLDC is in Fig. 4.

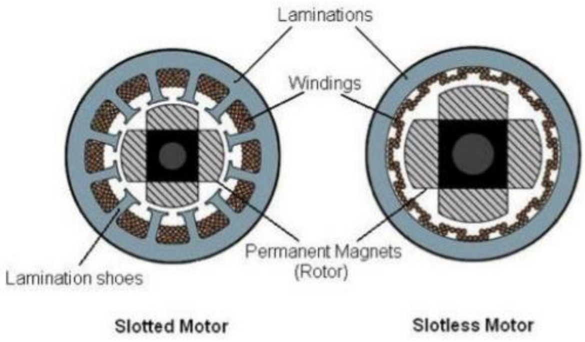

Fig. 4. BLDC construction [15].

6) *Motor Comparison*

Identifying the type of electric motor that is most suitable for use in electric vehicles is done by comparing the efficiency of the types of electric motors using secondary data obtained from published papers. Based on motor efficiency, BLDC, and PMSM have the highest efficiency among other types of motors, while DC motors are the motors that have the lowest performance. The efficiency of some electric motors is shown in Fig. 5 [8]. It can vary according to the application [16]. PMSM and BLDC have a similar construction but there are differences in the back EMF (Electromagnetic force), sinusoidal waves in PMSM, and trapezoidal in BLDC. PMSM has an advantage over BLDC in terms of power density and maximum speed. PMSM and BLDC are motors that are suitable for application in electric vehicles because they have high efficiency, reliability, and power density [14].

Zeraoulia et al. in [17] also compare the electric motor of a hybrid electric vehicle and resume the results as shown in Fig. 6. They give a score from 1 to 5 which a higher score means better. Using six criteria as power density, efficiency, controllability, reliability, technological maturity, and cost. In the first and second criteria, PMSM is superior with a score of 5 whereas DC motor is in the last position. PMSM use permanent magnet; therefore, its power density is good. In the controllability criteria, DC motor and IM win with the full score of 5. Next, for reliability, IM and SRM lead with the same score. In terms of technological maturity, DC motor, and IM has the full score. In the last criterion, which is cost, IM is the best with the lowest cost. In the total score of all criteria, they conclude that IM is the best. However, in some applications like electric vehicles, power density, and efficiency are important; therefore, a permanent magnet motor is chosen.

Fig. 5. Motor efficiency comparison based on [8].

B. *Rapid Prototyping*

Before implementing a motor control system in a validation vehicle, it must be carried out by simulating all systems to check the available torque over the entire operating range. There are four steps in the prototyping process to be ready for hardware products which are Model in the Loop (MIL), Software in the Loop (SIL), Processor in the Loop (PIL), and Hardware in the Loop (HIL). HIL simulation is mostly done for fast prototyping and usually for validating the specifications of a component. This method provides control system testing to prevent damage, and this has been done by many groups in the automotive industry. In the HIL step, there are various methods used in the design of electric vehicle prototypes, namely with a virtual platform and with an experimental platform. Virtual platforms, namely all EV models, architectures, and technologies to control components are simulated in software such as MATLAB/Simulink. Experimental platforms require hardware such as resources, and test benches to control devices that can be connected to software [18]. The comparison between the virtual and experimental platforms is illustrated in Fig. 7.

Propulsion Systems / Characteristics	DC	IM	PM	SRM
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	4	3
Reliability	3	5	4	5
Technological maturity	5	5	4	4
Cost	4	5	3	4
Σ Total	**22**	**27**	**25**	**23**

Fig. 6. Comparison of some electric motors used in HEV based on [17].

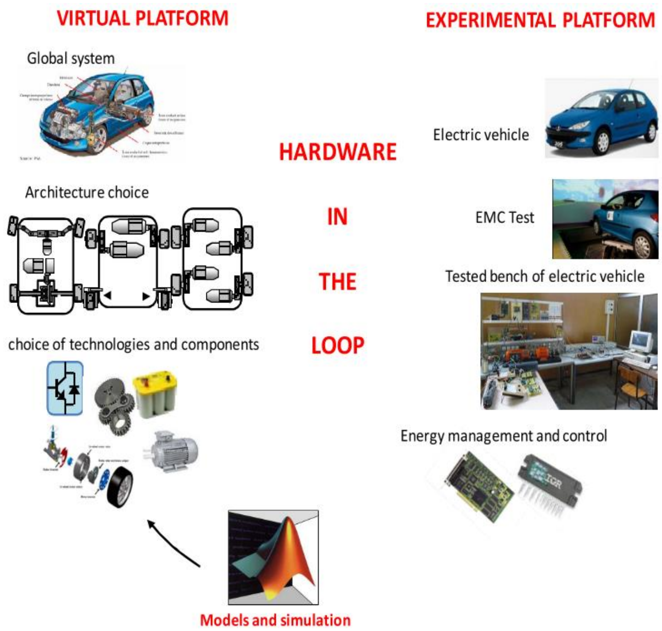

Fig. 7. Step by-step of HIL with different platforms [18].

1) *HIL using HIL Device*

The easy way to do rapid prototyping with HIL is by using HIL devices such as MicroAutoBox and Typhoon. Using the HIL device, the hardware can be imitated in the form of programming. However, this device is costly. The HIL method with dSpace MicroAutoBox II hardware is used for rapid prototyping and validating the electric motor propulsion system to be used in electric vehicles [19]. The HIL simulation method allows the development of the HEV (Hybrid Electric Vehicle) architecture to be accelerated without waiting for prototyping auxiliary devices such as batteries and other electric propulsion devices. Using the DSpace ControlDesk monitoring software can be used to obtain data, observe and change variables so that real-time interface development can be achieved. This dSpace can be linked to MATLAB / Simulink to record simulation results and for further analysis purposes. The setup is shown in Fig. 8.

The Typhoon HIL device is used by Dang et al. [20]. They demonstrate HIL simulation for an electric vehicle including PMSM in the propulsion system and with multi-energy storage which is battery and super-capacitor. Using this device, they can get the measurement graph both in the PC as the control center and in the oscilloscope.

2) *HIL using FPGA (Field Programmable Gate Array)*

FPGAs are used for high-speed parallel operation, processing of simple logic operations, and for high-speed sampling. Reference [21] integrates the FPGA and DSP to make a HIL system as shown in Fig. 9. The DSP itself obtains the phase voltage data and then calculates the state of the motor such as phase current. Meanwhile, FPGA is responsible for data processing logic including interaction data with DSP, ADC (Analog-to-Digital Converter), and DAC (Digital-to-Analog Converter). The simulation is used to test the interpolation method used to improve accuracy by changing the motor state according to the phase voltage signal in real time. The results obtained using this HIL simulation are testing the interpolation approach method to increase accuracy so that the efficiency of the BLDC motor can increase.

Fig. 8. HIL setup using dSpace [19].

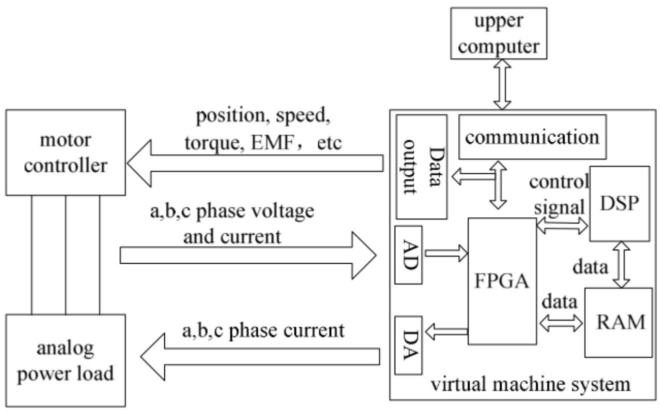

Fig. 9. HIL setup using a combination of FPGA and DSP [21].

3) *HIL using DSP (Digital Signal Processor)*

Making motor control prototypes on electric vehicles takes a lot of time such as using bench tests, preparing for mechanical tests, and others. In this case, the HIL method can be utilized by replacing real BLDC motors with simulated hardware as done by [22]. The device used is a special microcontroller for motor control, namely the

C2000, to enter the mathematical model of the motor into a program. Then a Power Stage circuit provides phase current output and an AFE (Analog Front-end) circuit to measure the voltage value. The result achieved with this method is that the motor can be modeled using a DSP with the addition of a bilinear transformation model and an inverse Z transformation. The simulation tools used to model the motor achieves high accuracy with low computational costs.

4) *HIL using Microcontroller*

The HIL method using a microcontroller can be used with MATLAB/Simulink software to simulate both components, controllers, and motors. This method can be used to handle programming and testing BLDC motors as done by [23] as shown in Fig. 11. Furthermore, after the suitable motor controller prototype model, the results are compared by connecting the model on Simulink with the Arduino microcontroller device. The results obtained from this method are the overall model simulation results which are not much different from the Arduino. This proves that the use of the control system with the HIL method can handle the testing of motor devices with the BLDC type.

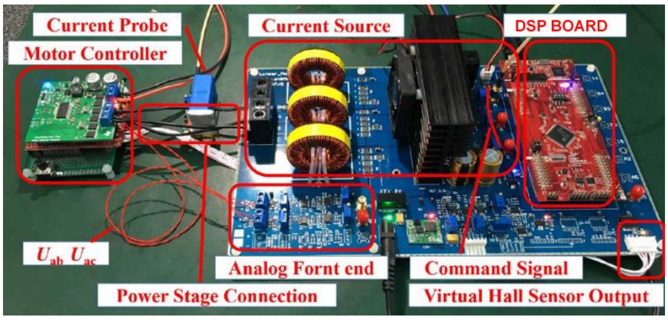

Fig. 10. Virtual motor inside a DSP [22].

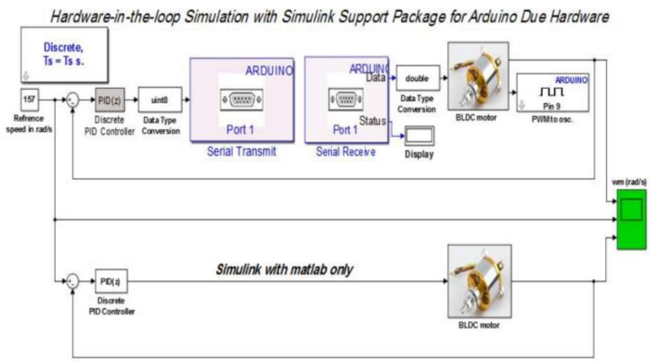

Fig. 11. Implementasi Metode HIL terhubung Arduino DUE [23].

IV. Conclusion

Currently, research and development of electric cars are continuing. The development of EV technology needs supporting areas, such as batteries, charging, electronic motors, charging infrastructure, etc. As the core of the propulsion system, electric motors are of concern to many researchers. The traction motor mostly used in EV applications are induction motors, permanent magnet synchronous motors, switched reluctance motors, DC motors, and brushless DC motors. Even, though an induction motor is superior in terms of controllability, reliability, maturity, and cost, a permanent magnet-type motor is preferred in the EV application due to its better power density and efficiency. Regarding the rapid prototyping of motor drives, HIL simulation is one used by a lot of researchers. This method has a minimum risk to the motor tested and saves the cost. Some of the HIL platforms are HIL devices, FPGA, DSP, and microcontrollers.

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