Enhancing the efficiency of electric vehicle’s motor using electro-mechanical continuously variable transmission

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Abstract. Over the last decades, significant progress has been made on the technologies of battery electric vehicle (BEV) powertrain system. As a result, the driving mileage of the latest EVs has been improved tremendously, making the ownership of BEV more viable now. Nevertheless, even with the latest progress, the driving mileage of a BEV is still generally lower as compared to the vehicle with an advanced internal combustion engine. Thus, this paper investigates the potential of increasing the mileage of a BEV further by using electro-mechanical continuously variable transmission (EMCVT) in its powertrain system. The purpose of the EMCVT is to allow the electric motor used in the BEV powertrain system to operate in its most efficient condition for a wide range of vehicle's speeds. This condition is defined using the efficiency mapping of a typical electric motor applied in the existing BEVs. Based on this mapping, the motor's efficiency when used with EMCVT is compared with the efficiency of the same motor when used with a single speed transmission for various vehicle speeds. In this investigation, the efficiency of the EM CVT is considered at 75% to 95%, and the BEV with EMCVT is considered to be 80 kg heavier than the BEV using a single speed transmission. The comparison between the BEV with and without EMCVT shows that the application of EMCVT allows the motor to operate in its most efficient condition for a wider range of the vehicle's velocity. However, the improved motor's efficiency is compromised by the losses in the EMCVT, making it challenging to achieve lower power consumption during driving. Therefore, to achieve meaningful improvement in terms of power consumption, the efficiency of the EMCVT has to be higher than 85%.

1. Introduction
Almost all of the battery electric vehicles (BEVs) in the market today use a single speed transmission to transmit the power from the electric motor to the vehicle’s wheels. The application of the single speed transmission is possible due to the characteristic of the electric motor that unlike an internal combustion engine (ICE), the electric motor can provide maximum torque at its low speed. In addition, the motor is also capable of operating at a very high speed, which means that the vehicle can also be driven at high speed without changing its transmission ratio. These characteristics eliminate the requirement of a variable transmission in a BEV which means its powertrain system is significantly less complex as compared to the conventional powertrain system with ICE.

However, similar to ICE, the efficiency of the electric motor is not constant throughout its speed range. As a result, the motor cannot operate at its most efficient condition if only a single speed transmission is used. Hofman and Janssen (2017) suggest that a continuously variable transmission
(CVT) that can be actuated independently without utilizing the power from ICE offers potentials to increase the efficiency of an electric motor used in a BEV. Next, Sluis et al. (2019) studied the potentials of using a continuously variable transmission (CVT) to improve the operating efficiency of the electric motor in a BEV. In the study, the proposed powertrain system consists of a downsized electric motor and a conventional hydraulically actuated CVT. The results showed that the proposed powertrain managed to reduce the power consumption by about 13% as compared to the typical BEV powertrain with a single speed transmission. Another work carried out in Ruan et al. (2018) involved the application of an electro-mechanical CVT (EMCVT) in the BEV powertrain system where the simulation works showed that the improvement in terms of power consumption can be gained by about 24% to 31%. Nevertheless, in the paper, the efficiency rate of the electric motor used was between 65% and 95%. As a comparison, the latest electric motors usually have the efficiency rate of at least 80%. Other works carried out to investigate the performance of an EV using variable transmission are described in Bottiglione et al. (2014), Zhu et al. (2015) and De Pinto et al. (2014). Therefore, in this paper, the role of EM CVT in enhancing the electric motor’s operating efficiency in a BEV is studied. The electric motor used in this paper has the efficiency rate between 80% and 98%.

2. Methodology

The main objective of this paper is to compare the efficiency of two different BEV powertrain systems when the BEV is travelling in a constant speed. Because of the constant vehicle speeds, this paper only considers aerodynamic drag, rolling drag and transmission drag. The two powertrain systems use the same electric motor with its efficiency mapping shown in Figure 1. The efficiency mapping is derived based on the performance of a permanent magnet synchronous motor typically used in a BEV. The motor has the maximum torque of up to 450 Nm and its maximum efficiency can be obtained if the motor operates at the torque of around 50 Nm with the speed of around 1500 RPM.

![Efficiency mapping of the permanent magnet synchronous motor used in this study](image)

In terms of the transmission, the first powertrain system only uses a single speed transmission with the overall ratio of 9.73 while the second system uses an EMCVT developed by the researchers in Universiti Teknologi Malaysia (Mazali et al., 2017). Unlike a conventional CVT currently used in the market, the EMCVT uses power screw mechanism instead of a hydraulic system for varying its ratio and also for maintaining the belt’s clamping force. The application of power screw mechanism helps in reducing the loss caused by the hydraulic system. Besides, the EMCVT also features a clamping force adjustment mechanism and with this mechanism, the clamping force applied on the CVT belt
can be optimized. Latest study by Liu et al. (2020) highlights that the optimization of the belt’s clamping force can increase the transmission efficiency by up to 9%. In terms of the ratio range, the EMCVT is capable of varying the ratio from 0.60 to 2.60 and it uses a differential with the ratio of 4.10. Therefore, the overall ratio of the CVT ranges from 2.46 to 10.66.

With the inclusion of the EMCVT, the second powertrain system is considered to be 80 kg heavier than the first powertrain system. The weight of the EV without EMCVT here is assumed at 1600 kg, hence, the total weight of the vehicle with EMCVT is 1680 kg. The other vehicle parameters like tire size and type (radial ply tire with \(d_{\text{tyre}}\) of 0.67 mm), aerodynamic drag coefficient \((c_D)\) of 0.35, rolling resistance coefficient \((f_k)\) of 0.01, frontal area \((A_{\text{front}})\) of 2.35 m\(^2\) and air density \((\rho_{\text{air}})\) of 1.25 kg/m\(^3\) are considered to be identical for the two systems. In terms of the transmission efficiency, the single speed transmission is considered to be 97% while the EMCVT is assumed to have the efficiency from 75% to 95%. The efficiency of 75% represents the EMCVT with no optimizing on its belt’s clamping force, while the efficiency of 95% represents the EMCVT with the optimized belt’s clamping force. Comparison between the parameters of the BEV with and without EMCVT is depicted in Table 1.

| Vehicle Parameters         | BEV without EMCVT | BEV with EMCVT |
|----------------------------|-------------------|----------------|
| Total Mass, \(m_{\text{car}}\) (kg) | 1600              | 1680           |
| Overall transmission ratio, \(R\) (-) | 9.73              | 2.46 to 10.66  |
| Transmission efficiency, \(\eta_T\) (%) | 97                | 75 to 95       |
| Tyre diameter, \(r_{\text{tyre}}\) (m) | 0.67              |                |
| Aero drag coeff., \(c_D\) (-) | 0.35              |                |
| Rolling resistance coeff., \(f_k\) (-) | 0.01              |                |
| Frontal area, \(A_{\text{front}}\) (m\(^2\)) | 2.35              |                |
| Air density, \(\rho_{\text{air}}\) (kg/m\(^3\)) | 1.25              |                |

To compare the efficiency of both types of the powertrain system, the required power \((P_{\text{req}})\) based on the amount of the total drags is calculated using Equation 1 for the vehicle speed \((v_{\text{car}})\) ranging from 0 m/s to 33.36 m/s (120 km/h). From the data of \(P_{\text{req}}\), the required torque \((T_{\text{req}})\) is determined with reference to the motor speed \((n_{\text{motor}})\) and the transmission ratio \((R)\) via Equation 2. The data of required torque and motor speed is then plotted in the motor’s efficiency mapping (Figure 1) so that its efficiency rate at a specific vehicle speed can be obtained. With the efficiency rate, the power consumption of the vehicle in terms of kWh/100km can be estimated using Equation 3. In this equation, \(v_{\text{car}}\) is in km/h and \(P_{\text{req}}\) is in kW.

\[
P_{\text{req}} = \left(\frac{m_{\text{car}} g f_k + \frac{1}{2} c_D \rho_{\text{air}} A_{\text{front}} v_{\text{car}}^2}{\eta_T}\right) v_{\text{car}}
\]

\[
T_{\text{req}} = \frac{9.5488 P_{\text{req}}}{n_{\text{motor}}}
\]

\[
P_{\text{cons}} = \frac{100 P_{\text{req}}}{v_{\text{car}} \eta_{\text{motor}}}
\]
3. Results and Discussions

The efficiency of the motor when it is coupled to a single speed transmission and the EMCVT (with 85% transmission’s efficiency) is depicted in Figures 2 and 3, respectively. In general, the application of EMCVT widens the motor’s operating range, thus allowing it to operate in its high efficient range for a broad range of the vehicle’s speed. For example, without EMCVT, the motor’s efficiency stands at less than 90% when the vehicle is travelling at 40 km/h. As the speed increases, the efficiency decreases until it falls at about 80% when the speed is 80 km/h. For a comparison, the EMCVT allows the motor to operate at about 96% to 97% efficiency when the vehicle is travelling at 40 km/h due to its minimum overall ratio of 2.46. Also with the same ratio, the motor’s efficiency can be kept at least 96% for the speed range from 10 km/h to 100 km/h.

![Figure 2](image1.png)

**Figure 2.** Operating range of the motor when used with a single speed transmission

![Figure 3](image2.png)

**Figure 3.** Operating range of the motor when used with the EMCVT (85% efficiency)

Besides, the EMCVT also allows the vehicle to be driven at the maximum speed of 120 km/h. Such speed is achieved at the motor speed of around 2400 RPM with the overall EMCVT ratio of 2.46. As a
comparison, the maximum speed that the vehicle can reach is only 80km/h if a single speed transmission is used. To go beyond 80km/h with a single speed transmission, the motor needs to increase its speed past 6000 RPM.

Even though the application of the EMCVT has the benefit in allowing the motor to operate at its most efficient range, such benefit is negated by the losses in the CVT. For instance, as shown in Figure 4, if the efficiency of the CVT is considered to be 75% (losses of 25%), the power consumption is rated at 16.01 kWh/100km when the vehicle is travelling at 80 km/h with the ratio of 2.46. This is higher than 14.73 kWh/100km obtained when it is travelling at the same speed with the single speed transmission (ratio 9.73). This proves that allowing the motor to operate more efficiently alone (97% efficiency in the EMCVT as opposed to 80% efficiency in the single speed transmission when the vehicle speed is 80 km/h) is not enough to improve the power consumption of the BEV. The same trend can also be observed for the vehicle speed of 10 km/h to 70 km/h, where the power consumption is higher in the BEV with EMCVT that in the EV with the single speed transmission.

![Figure 4. Power consumption for the EV with EMCVT against single speed transmission](image)

The results depicted in Figure 4 also indicate that the improvement in the power consumption can only be meaningfully achieved if the efficiency of the EMCVT is 95%. For example, at the speed of 80 km/h, the power consumption of the EV with the EMCVT is 12.64 kWh/100km which is about 14.2% lower than the EV with the single speed transmission at 14.73 kWh/100km. Apart from the speed of 10 km/h to 20 km/h, the application of EMCVT with 95% efficiency yields better power consumption as compared to the application of the single speed transmission. Thus, to improve the driving mileage of an EV using EMCVT, the efficiency of the EMCVT has to be at least 95%. To ensure such efficiency is achieved, an effective belt’s clamping force control must be implemented in the EMCVT. Other area that can be focused on is the downsizing of the electric motor since the excessively high motor torque (up to 450 Nm) is not necessary if the motor is coupled to the EMCVT.

4. Conclusions
The results in this paper highlight that the application of EMCVT in a BEV helps in improving the operating efficiency of the electric motor. The EMCVT used in this paper can vary its ratio from 10.66 to 2.46 and because of that, the motor’s efficiency can be improved for most of the driving speeds ranging from 10 km/h to 80 km/h as compared to the application of a single speed transmission. The biggest improvement can be gained at the speeds of 60 km/h to 80 km/h, where the motor’s efficiency is increased to 97% with the EMCVT as opposed to 80% when the single speed transmission is used. Besides, the EMCVT also allows the BEV to travel up to 120 km/h without exceeding the motor speed of 6000 RPM. As a comparison, the maximum speed that the BEV with single speed transmission can travel with the same motor speed range is only 80 km/h.

Nevertheless, the improvement gained in terms of the motor’s efficiency is compromised because of the losses in the EMCVT and the extra weight due to the application of the EMCVT. As such, when
the EMCVT’s efficiency is estimated at 75% (losses by 25%), the power consumption of the BEV with EMCVT is still higher than the BEV with single speed transmission. The results also indicate that the power consumption can only be improved convincingly if the amount of losses in the EMCVT is reduced to only 5%. Therefore, the future works in this area should focus on improving the efficiency of the EMCVT which can be achieved by optimising the belt’s clamping force, lubrication and ratio coverage. Other area that can also be studied is the downsizing of the electric motor in terms of its weight and torque capability to suit the application in typical passenger cars.

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