Evaluation of Efficiency-Shifting Permanent Magnet Motor in Electric Vehicle

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***Abstract*—We have designed an efficiency-shifting radial-axial hybrid permanent magnet synchronous machine (ES-RA-HPMSM) for use in an electric vehicle (EV) and compared the maximum driving distance (d_{max}) and ratio of the d_{max} to the cost of the motor system with transmission (d_{max}/M_{cost}) of the conventional non-efficiency-shifting motor (ES-M) used in current EVs with either a single- or two-gear transmission (TR). An EV model, comprising a driver, motor and inverter, battery pack, TR, wheel, and chassis model, was constructed using MATLAB software. The proposed ES-RA-HPMSM with single-gear TR and four non-ES-M with either single- or two-gear TR were evaluated under typical city, highway, and city+highway drive cycles. The results show that the proposed ES-RA-HPMSM not only extends the d_{max} by 25.4 and 46.8 miles in the city, 30.4 and 44.9 miles in the highway, and 37.8 and 19.5 miles in city+highway drive cycles but also exhibits higher d_{max}/M_{cost} by 4 and 97 % in the city, 21 and 86 % in the highway, and 20 and 92 % in the city+highway drive cycles, compared to the conventional motor with single- or two-gear TR, respectively.**

Keywords—Electric vehicle, efficiency-shifting motor, motor with transmission, maximum driving range

I. Introduction

In 2015, Lim et al. reported that one of the key barriers to mass adoption of electric vehicles (EVs) is driving range anxiety; driving range may be insufficient to reach the driver's desired destination [1]. To mitigate this anxiety, high-efficiency EVs are in strong demand. One way to realize such a high-efficiency EV is operating an electric traction motor (ETM) in its highest efficiency region for various drive cycles, such as city, highway, and mountain road. However, due to inflexible high-efficiency operation region, as shown in Fig. 1, the ETM used in current EVs is not operating at peak efficiency for all driving conditions. Therefore, the maximum driving range decreases.

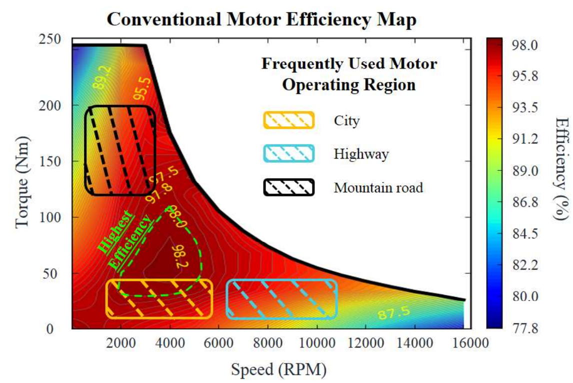

Fig. 1. Torque/speed characteristics and efficiency map of a conventional motor.

To increase the maximum driving range of EV, an EV with a two-gear transmission (TR) has been designed, and its driving efficiency performance was reported [2-4]. As a result, compared to the EV with single-gear TR, which is used in current EVs, the EV with two-gear TR not only improves the overall efficiency of the EV by 10-11 % but also increases the maximum torque at low speed and extends the maximum vehicle speed with respect to gear ratio [2-4]. However, an additional gear requires additional space and increases the total cost of the motor system.

Recently, we have designed a compact efficiency-shifting radial-axial hybrid permanent magnet synchronous motor (ES-RA-HPMSM) that improves the overall efficiency of an EV without sacrificing space by employing two stators with one shared rotor [5]. Fig. 2 shows the overall design and efficiency map of the designed ES-RA-HPMSM. The designed motor increases overall efficiency by shifting between two high-efficiency regions (> 92%) as similar to the two-gear TR with

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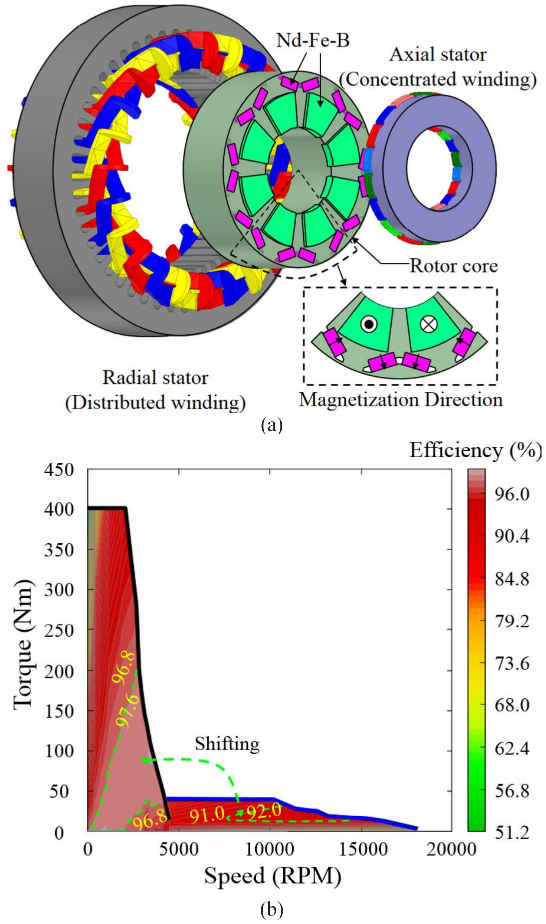

Fig. 2. (a) Design and (b) efficiency map of the proposed efficiency-shifting radial-axial hybrid permanent magnet synchronous motor [5].

high maximum torque (400 Nm) and maximum motor speed (18,000 revolutions-per-minute (rpm)). Detailed descriptions of the ES-RA-HPMSM are summarized in the following section. In [5], we have validated its efficiency-shifting functionality, but we have not yet investigated the maximum driving range of the ES-RA-HPMSM with a single-gear TR.

In this paper, we have estimated the maximum driving range (d_{max}) and cost (M_{cost}) of the ES-RA-HPMSM with a single-gear TR in EV using a full EV MATLAB simulation model under various drive cycles, and the estimated d_{max} and ratio of d_{max} to the M_{cost} (d_{max}/M_{cost}) were compared to those of four conventional motors with a single- or two-gear TR. Detailed descriptions of the constructed full EV model and motor performance are reported in the following sections.

II. Motor Structure and Operation Principle of Efficiency-Shifting Motor

Fig. 3 illustrates the detailed design of the aforementioned ES-RA-HPMSM, while Table I summarizes the specifications of the motor. The motor realizes two high-efficiency regions by employing a radial stator with 3-phase distributed winding, a axial stator with 3-phase concentrated winding, and one shared rotor comprising two rotor topologies, i.e. V-shaped interior-

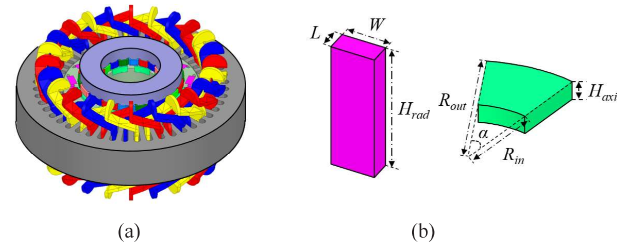

Fig. 3. Design of the efficiency-shifting radial-axial hybrid permanent magnet synchronous motor: (a) overall view and (b) cross-sectional view of permanent magnet.

TABLE I. Specification of Efficiency-Shifting Radial-Axial Hybrid Permanent Magnet Synchronous Motor

Parameter	Stator (Radial)	Stator (Axial)	Rotor
Outer/inner diameter [mm]	282.4/170	133.3/73.5	168.5/73.5
Stack length [mm]	100	30	100
Winding type	3Φ-distributed	3Φ-concentrated	-
# of slots or poles	48 slots	18 slots	8 poles
# of turns	11	30	-
Battery voltage [V]	500		-
Peak current [A_{rms}]	177	72	-
Core material	Non-oriented M19-29G		

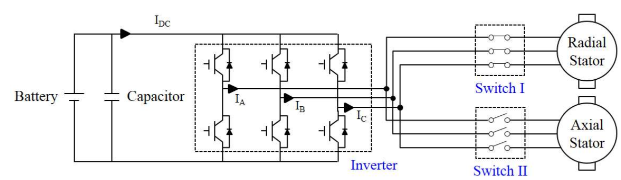

Fig. 4. A schematic circuit diagram of the ES-RA-HPMSM motor drive.

mounted and surface inset-mounted rotor topologies, to efficiently exploit the radial and axial winding, respectively. Nd-Fe-B permanent magnets (PMs) having remanent flux density of 1.23 T and coercivity of 890 kA/m were used for both rotor topologies [6]. The PM employed in the V-shaped interior-mounted rotor topology has a width (W) of 17.8 mm, length (L) of 8.4 mm, and height (H_{rad}) of 100 mm, while the PM used in the surface-mounted topology has an outer radius (R_{out}) of 133.3 mm, inner radius (R_{in}) of 73.5 mm, height (H_{axi}) of 20 mm, and arc angle (α) of 31.5 °. The motor performance was evaluated using ANSYS Maxwell v. 18.1 with 3D-finite element analysis.

In the proposed motor, there are two modes to rotate the rotor of the proposed motor: a radial (R-mode) and an axial mode (A-mode). In the R-mode, the interaction between flux produced from the PM of the V-shaped interior topology and current flown through the radial winding rotates the rotor, while in the A-mode, the interaction between flux produced from the PM of the surface inset-mounted topology and the current flown through the axial winding rotates the motor. These modes are realized by controlling two three-phase switches as shown in Fig. 4. The R-mode activates when the motor speed is below 4,250 revolutions-per-minute (rpm) by switching on Switch I and off

TABLE II. PERFORMANCE COMPARISON BETWEEN FREEDOMCAR 2020 AND EFFICIENCY-SHIFTING MOTOR

Parameter	FreedomCAR 2020	ES-RA-HPMSM (UA)
Peak Power [kW]	55	94
Peak Torque [Nm]	200	400
Maximum Speed [rpm]	14000	18000
Max. Back-EMF [V_{peak}]	600	600
Max. Current [A_{rms}]	400	177
Peak Power Density [kW/L]	5.7	5.6
Peak Specific Power [kW/kg]	1.6	1.4
Peak Torque Density [Nm/L]	20.6	23.7
Peak Specific Torque [Nm/kg]	5.7	5.8
Peak Efficiency (10-100% of Max. Speed) [%]	> 95	> 91

Switch II, while the A-mode activates when the motor speed exceeds 4,250 rpm by switching off Switch I and on Switch II.

The motor performance of the ES-RA-HPMSM with cooling case was compared with the motor performance that was set by U.S. Department of Energy (DOE) funded FreedomCAR 2020 program [7] and are summarized in Table II. The dimensions of the cooling case was approximated with respect to the case used by Toyota Prius 2010 [8]. As a result, the ES-RA-HPMSM performs near to the FreedomCAR 2020 required motor specification with 14.9 % and 2.1 % better peak torque density and specific torque, respectively, except for 4 % lower peak efficiency and 25 % higher torque ripple, which will be improved in future work.

Fig. 5 shows the waveform of the back electromotive force (back-EMF) at the maximum speed of each mode. It was observed that the maximum back-EMF at the maximum speed of the R- and A-mode were measured as 523 V and 600 V, respectively, which are under required maximum back-EMF of 600 V.

Fig. 6 shows the waveform of the torque at the corner speed of each mode. The maximum torque at the corner speed of the R- (2000 rpm) and A-mode (10,000 rpm) were 400 and 40 Nm with the torque ripple of 30 and 13 %, respectively. High torque of 400 Nm meets the requirement of FreedomCar 2020 target, but not for torque ripple. This high torque ripple will be mitigated by skewing, teeth notching, and non-uniform airgap [9, 10].

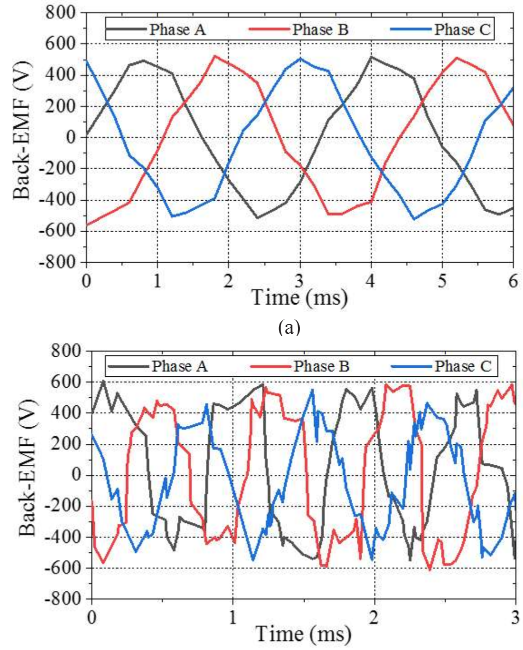

Fig. 5. Three-phase back-EMF at the maximum speed of (a) 4,500 rpm for radial-mode and (b) 18,000 rpm for axial-mode.

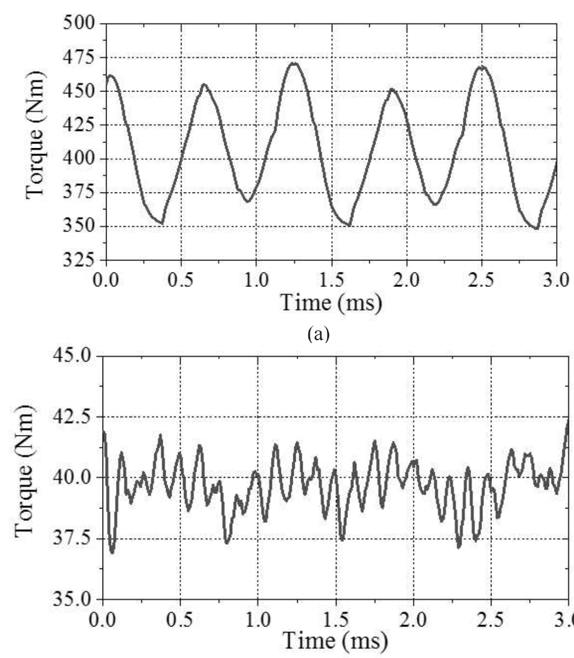

Fig. 6. Torque at the corner speed of (a) 2,000 rpm for radial-mode and (b) 10,000 rpm for axial-mode.

III. STRUCTURE AND SPECIFICATIONS OF ELECTRIC VEHICLE MODEL

Fig. 7 shows the overall powertrain configuration schematic and block diagram of the EV model used in the performance simulation. Table III summarizes overall vehicle specifications used in the simulation. For chassis and battery specifications, Tesla Model S 75D AWD was used [9, 10]. A detailed description of each block is presented below for motor performance simulation.

A. Driver

The primary goal of the driver block is to determine required torque (T_{req}) to track the reference drive cycle, where the references drive cycle is an Urban Dynamometer Driving Schedule (UDDS) for the city, Highway Fuel Economy Test (HWFET) for highway, and US06 for the city + highway drive

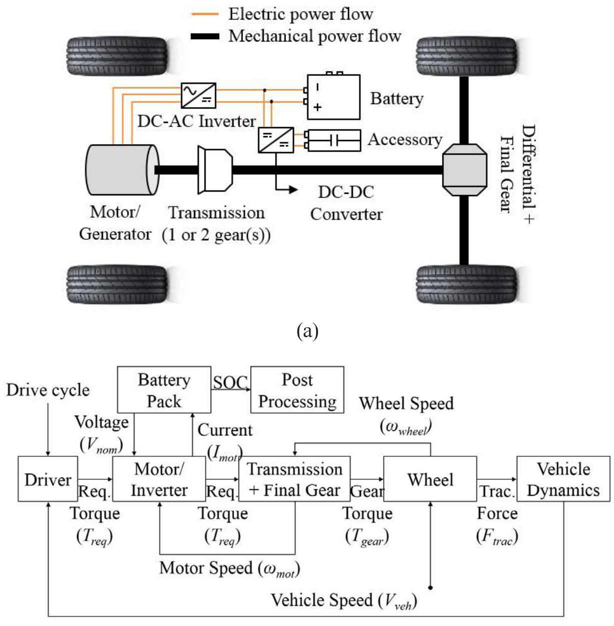

Fig. 7. Overall (a) powertrain configuration schematic and (b) block diagram of electric vehicle model.

TABLE III. ELECTRIC VEHICLE SPECIFICATION

Parameter	Description	Value
M_{veh}	Curb weight of vehicle [11]	2107.8 kg
C_{rr}	Rolling coefficient [12]	0.013
C_{drag}	Aero drag coefficient [12]	0.23
A_v	Frontal area of vehicle [11]	2.574 m^2
R_{wheel}	Wheel radius [11]	0.352 m
G_1 and G_2	Transmission gear ratio	1 and 1.82
FDR	Final drive ratio [12]	9.34
V_{nom}	Nominal battery pack voltage [11]	350 V
E_{cap}	Nominal battery pack capacity [11]	242 Ah

cycle. The output T_{req} is calculated by 1) determining the error between reference drive cycle and actual vehicle speed (V_{veh}), produced from the vehicle dynamics block, 2) applying the calculated error to proportional-integral (PI) controller to determine an applied pedal position (APP), and 3) multiplying the APP by the maximum allowable torque at a given motor speed to calculate the T_{req}.

B. Motor/Inverters

The primary goal of the motor/inverter block is to calculate the current required by the motor (I_{mot}) to produce the T_{req} from the driver block. The inputs for this block are T_{req} and V_{nom} from the battery block. The output I_{mot} is calculated by

$$I_{mot} = T_{req}\omega_{mot} / \left(V_{nom}\eta_{mot}\right), \qquad (1)$$

where ω_{mot} is the motor speed in rad/s, and η_{mot} is the efficiency of each motor, listed in Table IV, from the corresponding

TABLE IV. MOTOR PERFORMANCE SPECIFICATIONS

Motor	Max Torque [Nm]	Max. Power [kW]	Max Speed [rpm]
2017 Ford Focus EV [13]	253	107	10,000
2012 Nissan Leaf [14]	280	80	10,000
2017 Toyota Camry [13]	270	105	14,500
UQM 45/125 [13, 15]	300	125	8,150
ES-RA-HPMSM (this work)	400	94	18,000

efficiency map. A constant value of 350 V was used for V_{nom} in the simulation.

C. Battery Pack

The battery pack block is used to calculate the term SOC_{final_single}, which is state-of-charge (SOC) that is remained in the battery after a single drive cycle is driven. The SOC_{final_single} is determined by

$$SOC_{final\_single} = SOC_{init} - 100 \cdot \int \left(\left(I_{mot}\right) / 3600\right) / E_{cap} dt \qquad (2)$$

in which SOC_{init} is the initial SOC of the battery pack and E_{cap} is listed in Table III. A SOC_{init} of 90 % was used for this simulation.

D. Transmission+Final Gear

The transmission+final gear block is to convert the T_{req} and wheel speed (ω_{wheel}) from the wheel block to gear torque (T_{gear}) and ω_{mot}. The T_{gear} and ω_{mot} are determined by

$$T_{gear} = T_{req} \cdot FDR \cdot G_{1,2} \qquad (3)$$

$$\omega_{mot} = \omega_{wheel} \cdot FDR \cdot G_{1,2}, \qquad (4)$$

where *FDR* is final drive ratio, listed in Table III. For the single-gear TR, both G_1 and G_2 are 1, while for the two-gear TR, G_1 and G_2 are 1.82 and 1, respectively. The transmission controller that is used in [13] is adopted to change the gear ratios in two-gear TR.

E. Wheel

The wheel block is to convert the T_{gear} from the transmission+final gear block to traction force (F_{trac}) and the V_{veh} from the vehicle dynamic block to the ω_{wheel}. The F_{trac} and ω_{wheel} are calculated by

$$F_{trac} = T_{wheel} / R_{wheel} \qquad (5)$$

$$\omega_{wheel} = V_{veh} / R_{wheel}, \qquad (6)$$

where R_{wheel} is the wheel radius, listed in Table III.

F. Vehicle Dynamics

This subsystem converts the F_{trac} from the wheel block to the actual vehicle speed (V_{veh}). The V_{veh} is calculated by

$$V_{veh} = \frac{1}{M_i} \int \left(F_{trac} - F_{loss}\right) dt \qquad (7)$$

TABLE V. MOTOR MATERIAL COSTS

Material	Cost ($)
Copper	7.1
Laminated Core	2.1
Permanent Magnet	82.3

$$F_{loss} = \frac{1}{2}\rho A_v C_d \left(V_{veh}\right)^2 + m_{veh} g \cdot C_{rr}\,, \tag{8}$$

where g is gravity (9.8 m/s^2) and ρ is air density (1.204 kg/m^3). Additional parameters are listed in Table III.

IV. Results and Discussion

To compare the performance of the ES-RA-HPMSM to four conventional motors, the d_{max} was calculated using the following equation

$$d_{max} = d_{cycle\_tot} \cdot SOC_{tot} \,/\, \left(SOC_{init} - SOC_{final\_single}\right), \tag{9}$$

where d_{cycle_tot} is the total distance for each drive cycle in miles and SOC_{tot} is the total usable SOC with full charge in %. For SOC_{tot}, 80 % is used. The d_{max} was calculated by the (9) for two different cases: one for one-gear TR and the other for two-gear TR. The results are summarized in Table VII and IX, respectively.

Further, a cost analysis was conducted by comparing d_{max}/M_{cost}, which is the ratio of the calculated d_{max} to the estimated price of the motor with either single- or two-gear TR, namely M_{cost}. The price of the ES-RA-HPMSM was calculated by multiplying the weight of copper winding, laminated core, and PM used in the motor with the reported material cost, summarized in Table V [16]. The price of the conventional motors were approximated by calculating the price per peak power ($/kW) of the Toyota Prius 2010 based on the reported motor specification [10] and material cost, and then multiplying with the listed peak power in Table IV. The total costs for each motor system were determined by adding the cost of the motor and the single- ($900) and two-gear TR ($2,000) [17] and are summarized in Table VI. The resultant d_{max}/M_{cost} with the single- and two-gear TR are determined and summarized in Table VIII and X, respectively.

A. With Single-gear Transmission

Table VII summarizes the d_{max} per 80 % SOC with a single-gear TR. The proposed ES-RA-HPMSM extends the d_{max} by 25.4, 56, and 37.8 miles compared to the motor used in the 2017 Ford Focus EV and 39.3, 30.4, and 17.5 miles than the motor used in the 2012 Nissan Leaf in the city, the highway, and the city+highway drive cycle, respectively. Furthermore, the proposed ES-RA-HPMSM provides 30.2 and 6.4 miles more in d_{max} for the city and highway drive cycle, respectively, than the motor used in the 2017 Toyota Camry. However, it is noted that the motor used in the 2017 Toyota Camry allowed 20.3 miles more d_{max} for the city+highway drive cycle than the proposed motor. This is mainly attributed to lower maximum speed (Max Spd) of the motor used in the 2017 Toyota Camry than the proposed ES-RA-HPMSM, demanding less current. The Max Spd of the motor used in the 2017 Toyota Camry is 64 miles per hour (mph), whereas the Max Spd of the proposed ES-RA-HPMSM is more than 80 mph. A similar trend was observed for the UQM 45/125 motor. Compared to the UQM 45/125, the proposed motor allows 4.4 miles more d_{max} in city drive cycle, but 144.6 and 243.5 miles less in highway and US06 drive cycle, respectively. High d_{max} for highway and US06 drive cycle is attributed to limited Max Spd of the UQM 45/125 motor, which is only 36 mph.

TABLE VI. TOTAL MOTOR WITH TRANSMISSION COST

Motor	Motor Cost ($)	With Single-gear Transmission ($)	With Two-gear Transmission ($)
2017 Ford Focus EV	238.6	1138.6	2238.6
2012 Nissan Leaf	178.4	1078.4	2178.4
2017 Toyota Camry	234.2	1134.2	2234.2
UQM 45/125	278.8	1178.8	2278.8
ES-RA-HPMSM	301.7	1201.7	

TABLE VII. MAXIMUM DRIVING RANGE (MILES) PER 80 % SOC – WITH SINGLE-GEAR TRANSMISSION

Motor	City (UDDS)	Highway (HWFET)	City+Highway (US06)
2017 Ford Focus EV	269.7	203.7	142.5 (Max Spd > 80 mph)
2012 Nissan Leaf	255.8	229.3	162.8 (Max Spd > 80 mph)
2017 Toyota Camry	264.9	253.3	200.6 (Max Spd 64 mph)
UQM 45/125	290.7	404.3	423.8 (Max Spd 36 mph)
ES-RA-HPMSM	295.1	259.7	180.3 (Max Spd > 80 mph)

TABLE VIII. MAXIMUM DRIVING RANGE (MILES) PER COST ($)– WITH SINGLE-GEAR TRANSMISSION

Motor	City (UDDS)	Highway (HWFET)	City+Highway (US06)
2017 Ford Focus EV	0.237	0.179	0.125 (Max Spd > 80 mph)
2012 Nissan Leaf	0.237	0.213	0.151 (Max Spd > 80 mph)
2017 Toyota Camry	0.234	0.223	0.177 (Max Spd 64 mph)
UQM 45/125	0.247	0.343	0.360 (Max Spd 36 mph)
ES-RA-HPMSM	0.246	0.216	0.150 (Max Spd > 80 mph)

Table VIII summarizes the ratio of the calculated d_{max} to the cost of the motor with the single-gear TR. The proposed ES-RA-HPMSM shows either equivalent or 4, 21, and 20 % higher ratio than the conventional motors with the single-gear TR in the city, highway, and city+highway drive cycles, respectively.

TABLE IX. MAXIMUM DRIVING RANGE (MILES) PER 80 % SOC – WITH TWO-GEAR TRANSMISSION

Motor	City (UDDS)	Highway (HWFET)	City+Highway (US06)
2017 Ford Focus EV	269.7	233.8	160.8 (Max Spd > 80 mph)
2012 Nissan Leaf	269.7	238.6	170.2 (Max Spd > 80 mph)
2017 Toyota Camry	289.3	258.1	173.4 (Max Spd > 80 mph)
UQM 45/125	248.3	214.8	188.8 (Max Spd 60 mph)
ES-RA-HPMSM (With single-gear TR)	295.1	259.7	180.3 (Max Spd > 80 mph)

TABLE X. MAXIMUM DRIVING RANGE (MILES) PER COST ($)– WITH TWO-GEAR TRANSMISSION

Motor	City (UDDS)	Highway (HWFET)	City+Highway (US06)
2017 Ford Focus EV	0.120	0.104	0.072 (Max Spd > 80 mph)
2012 Nissan Leaf	0.124	0.129	0.078 (Max Spd > 80 mph)
2017 Toyota Camry	0.129	0.116	0.078 (Max Spd > 80 mph)
UQM 45/125	0.109	0.094	0.083 (Max Spd 60 mph)
ES-RA-HPMSM (With single-gear TR)	0.246	0.216	0.150 (Max Spd > 80 mph)

B. *With Two-gear Transmission*

Table IX summarizes the d_{max} per 80 % SOC with the two-gear TR. Compared to the motor used in the 2017 Ford Focus EV, 2012 Nissan Leaf, and 2017 Toyota Camry and UQM 45/125, the proposed motor with the single-gear TR extends the d_{max} by 25.4, 25.4, 5.8, and 46.8 miles more in the city, respectively, 25.9, 21.1, 1.6, and 44.9 miles more in the highway, respectively, and 19.5, 10.1, 6.9, and -8.5 miles more in the city+highway drive cycle, respectively. The main reason for less d_{max} of the proposed motor than the UQM 45/125 in the city+highway drive cycle is due to limited Max Spd of the UQM 45/125, which is only 60 mph.

Table X summarizes the ratio of the calculated d_{max} to the cost of the motor with the two-gear TR. The proposed ES-RA-HPMSM shows 97, 86, and 92 % higher ratio than the conventional motors with the two-gear TR in the city, highway, and city+ highway drive cycle, respectively.

V. CONCLUSION

We compared the maximum driving range of the proposed efficiency-shifting motor with that of the conventional non-efficiency-shifting motor integrated with either a single- or two-gear transmission (TR). In addition, the ratios of the maximum driving range to the cost of the motor with either single- or two-gear TR were determined and compared. Compared to the conventional motors with single-gear TR, the proposed efficiency-shifting motor with a single-gear TR provided not only the maximum driving range in range of 4.4 – 25.4 miles, 6.4 – 30.4 miles, and 10.1 – 37.8 miles more but also 4, 21, and 20 % higher distance to cost ratio in the city, highway, and city+highway drive cycles, respectively, with 16 – 44 miles per hour (mph) higher maximum speed. Furthermore, compared to the conventional motors with the two-gear TR, the proposed efficiency-shifting motor with single-gear TR performed 5.8 – 46.8 miles, 1.6 – 44.9 miles, and 6.9 – 19.5 miles more in the maximum driving range and 97, 86, and 92 % higher ratio in the city, highway, and city+highway drive cycles, respectively, with 20 mph higher maximum speed

REFERENCES

[1] M. K. Lim, H. Mak, and Y. Rong, "Toward Mass Adoption of Electric Vehicles: Impact of the Range and Resale Anxieties", *Manufacturing & Service Operations Management*, vol. 17, iss. 1, pp. 1-134, 2015

[2] B. Gao, Q. Liang, Y. Xiang, L. Guo, and H. Chen, "Gear ratio optimization and shift control of 2-speed I-AMT in electric vehicle," *Mech Syst Signal PR*, vol. 50-51, pp. 615, Jun. 2014.

[3] A. Sorniotti, T. Holdstock, and G. Loro Pilone, "Analysis and Simulation of the Gearshift Methodology for a Novel Two-speed Transmission System for Electric Powertrains with Central Motor," *Proc. Inst. Mech. Eng. D: J. Automob. Eng.*, vol. 226, pp. 915-929.

[4] X. Zhou, P. Walker, N. Zhang, and B. Zhu, "Performance Improvement of a Two Speed EV through Combined Gear Ratio and Shift Schedule Optimization," *SAE 2013 World Congress & Exhibition,* Apr. 2013.

[5] Y. Hong, H. Won, and W. Lee, "Energy Efficient Permanent Magnet Synchronous Motor," U. S. Application No. 62/735,541, filed on Sept. 24, 2018.

[6] Hitachi metals LTD, "Radial Anisotropic Ring Magnets," NEOMAX datasheet, 2014.

[7] U. S. Department of Energy, "FY 2011 Vehicle Technologies Program Wide Funding Opportunity Announcement Funding Opportunity Number: DE-FOA-0000239," pp. 17-18, 2011.

[8] M. Olszewski, "Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System," *FY2011 Oak Ridge National Laboratory Report*, Mar. 2011.

[9] W. Ren, Q. Xu, Q. Li, and L. Chen, "Reducing Cogging Torque and Suppressing Torque Ripple in PMASynRM for EV/HEV Applications," *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific*, Nov. 2014.

[10] E. Carraro and N. Bianchi, "Design and Comparison of Interior Permanent Magnet Synchronous Motors with Non-uniform Airgap and Conventional Rotor for Electric Vehicle Applications," *IET Elec. Power Appl.,* vol. 8, pp. 240-249, Jul. 2014.

[11] Tesla, *Model S Owner's Manual*, Tesla, Inc., Aug. 2018. [URL: https://www.tesla.com/sites/default/files/model_s_owners_manual_north_america_en_us.pdf].

[12] D. Sherman, "Drag Queens, Five Slippery Cars Enter a Wind Tunnel; One Slinks Out A Winner," *Caranddriver.com*, Jun. 2016. [Online]. Available: https://www.caranddriver.com/features/drag-queens-aerodynamics-compared-comparison-test. [Accessed Nov. 22, 2018].

[13] Autonomie, "Autonomie," http://www.autonomie.net/. [Accessed: Aug. 10, 2018].

[14] T. Burress, "Benchmarking State-of-the-Art Technologies," *2013 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting*, May 2013. [Online]. Available: https://www.energy.gov/sites/prod/files/2014/03/f13/ape006_burress_2013_o.pdf. [Accessed Nov. 22. 2018].

[15] UQM, "Powerphase 125 for electric, hybird electric, and fuel cell powered vehicles," Powerphase 125 datasheet, Aug. 2017.

[16] C. Du-bar, "Design of a Fault-tolerant Fractional Slot PMSM for a Vehicle Application," *Thesis*, Chalmers University of Technology, Sweden, 2015.

[17] [Online]. Available: https://www.evwest.com/catalog/index.php?cPath=4.