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Research Article

Numerical Comparison of Different Electric Motors (IM and PM) effects on a Hybrid Electric Vehicle

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Abstract

The motor / generator instrument, which is the one of the key important components of hybrid electric vehicles, influence vehicle efficiency and emission scale with its types and features. For that reason, the electric motor (electric machine-EM) selection and identification are playing a crucial role. In this simulation study, effects of two different motors, Induction and Permanent Magnet (IM and PM) to emission and performance were compared for two driving cycles (FTP75 and NEDC) on a serial configuration hybrid electric vehicle which modeled with AVL Cruise. The general purpose of the work is, selecting electric motors that they have same output powers although the rotational speeds are different; and modeled for the same vehicle and identifing the effects of different driving cycles on the vehicles were compared. HEVs performance and emission results illustrated and electric machines performances and efficiency maps are graphically charted. Overall performance and emission outputs for two different driving cycles are discussed detailed. Also, a general concluded summary table that related the performance and emission outputs of different machines usage is presented. As a result, according to these modeling and test results, PM motor is more efficient than IM motor on overall simulation results, especially decreases the emission values at high speeds.

Key words: Hybrid electric vehicle, Permanent Magnet Motors, Induction Motors, Perfromance and emission.

Nomenclature

AC	Alternative Current
ACon	Adaptive Control
AVL	Anstalt für Verbrennungskraftmaschinen List
CO	Carbon monoxide
CO_2	Carbon dioxide
DC	Direct Current
EM	Electric Machine
EPA	Environmental Protection Agency
EV	Electric Vehicle
FC	Fuzzy Control
FOC	Field Oriented Control
FTP-75	Federal Test Procedure
HC	Hydrocarbon
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IM	Induction Machine
IPM	Interior PM Synchronous Machine
MR-PM	Magnetic-ring PM Machine
NC	Neural Control
NEDC	New European Driving Cycle
NO_x	Nitrogen Oxides
PID	Proportional–Integral–Derivative
NiMH	Nickel Metal Hydride
PM	Permanent Magnet Machine
PRM	Permanent-Magnet Assisted Reluctance Synchronous Machine

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RM	Variable Reluctance Machine
SFC	Specific Fuel Consumption
SOC	State of Charge
SPM	Surface PM Synchronous Machine
SRM	Switched Reluctance Machines
VVVF	Variable Voltage and Variable Frequency

1. Introductıon

The changing, renewing and tented to being more autonomous automotive sector has been improving over the past 30 years by developing its structure on hybrid and electric vehicles and its market products. These vehicles, which at the most basic purpose produce fewer exhaust gases and have lower fuel consumption, may begin to take over the place of conventional vehicles in the coming years. According to the 2017 automotive report [1], 72% of participants are still saying that they will choose internal combustion engines at the further in next term, but the country politics are increasingly reporting that they are going to seriously shrink fossil-fueled vehicles during 2030-2040.

Although they capable superior advantages like every new technology, HEV/EV faces disadvantages and limitations. In particular; battery technologies, range constraints, excessive mess of control systems, and technological high prices have shown that these technologies are still the way to built. Hybrid electric vehicles provide a perfect bridge between conventional vehicles and EVs as they provide both ICE and EM for propulsion.
In a simplest phrase, HEV is driven with both ICE and EM together. This assistant relationship between ICE and EM has come up with three merits within; fuel economy, higher efficiency and performance, and flexibility with smaller ICEs. HEVs specifications and classifications determined with the topologies and hybridization ratios. The configurations and architectures of HEVs are listed as; series, parallel and parallel-series (power split) hybrids. The ratio of electrical power to the full powertrain power is defined with hybridization ratio.

Multiple components usage in HEVs occur the whole system more complex. Indeed, researchers work by dividing into parts of the system in order to understand every aspect of this complicated structure. The one of the core elements of a HEV is electric machines and this study is related that topic too. Selection and determining the optimum electric machine for a HEV is very crucial phenomenon. There are several motor specifications and which one is used for which HEV item is very important. This papers references [2-27] are related this comparative selection and choosing procedure of HEV electric motors.

The starting of the choosing most adaptable motor device is required some criteria's which related the HEVs architecture, performance, reliability and cost [10, 30]. As already known, in series HEV, ICE is responsible for acting the electric generator and generator drives the power flow the propulsion electric motor for motion the wheels. In other words, ICE does not give the power to wheels directly. Some companies that produce serial hybrid vehicles are Toyota, Honda, Ford and General Motors. [26], mentioned the advantages of serial HEV as; maximum efficiency region, reduction of emissions, needless multi gear, easiest control strategy [26].

Figure 1, illustrated the most common used electric motors in HEVs. In prevailing opinion, DC motors; IMs, also called Asynchronous motor/machine; PMs and SRMs are used mostly in HEV industry [4]. The major requirements of an electric machine can be summarized and listed as like; "high torque and high power density; wide speed range for climbing, starting and cruising; high efficiency over very wide speed range and regenerative braking; including constant-torque and constant-power regions; fast torque response; high reliability and robustness for various vehicle operating conditions; and acceptable cost" by [6, 8, 17 and 26].

For a reasonably clear comparison for this study, only IM and PM are compared and described deeply. IMs is the most widely used in the industry and is the most mature technology of AC machines and they have low capacity and cost scale especially in extreme conditions, reliable and more robust, also has low maintenance.

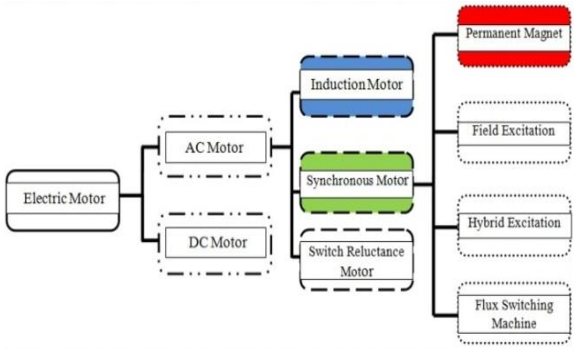


Figure 1. The most common used electric motors in HEVs

As already known, IM consists of a stator and a rotor which separated by air gap, like all rotating machines [4, 26].

The main reason for continuing the comparison between these two in academic community is; because of one could not outperform the other one. Most studies show that PM is more effective, while EVs, that are one step away from electrification, still choose IM (i. e. Tesla motors, and [7]'s approachment). In addition, [9], touched upon that, the PM is the appropriate solution for the HEV applications and offers significant merits in terms of performance and efficiency. [6] denote that; "Although IMs are cheaper and have better overload capability, they exhibit lower efficiency and power factor. Other electrical machines except PM, such as synchronous reluctance machines (*that they have significant problem of torque ripple, acoustics noise and vibration [6,8]*), wound field machines, as well as many other newly developed machines, are currently less attractive due to lower torque density and efficiency."

One of the most important technical differences that distinguish PM from other EMs is the excitation system. "PM machines use permanent magnets in the rotor as the field exciting circuit, which produces air-gap magnetic flux" [8]. Although abbreviations can vary by authors; PM rotor configurations give the names of these machines in the usage as; PRM, RM, SPM, IMP and MR-PM. [4].

PMs are very demanding traction machines which used for EVs and HEVs, because of their high efficiency and torque densities [15]. The merits and demerits of PM usage in EV/HEV traction is given in Table 1. Generally, [5, 6, 9-13, 15-19, 26 and 27] is mentioned that, PM is more preferable than IM.

Table 1. Merits and demerits of PMs in EV/HEVs [re-tabled from 6].

Merits of PMs in EV/HEVs	Demerits of PMs in EV/HEVs
1- High torque and power densities and hence light weight and smaller volume	1- Relatively high cost
2- High efficiency	2- Relatively difficult on flux weakening when the electric loading is limited
3- High power factor	3- Relatively lower efficiency at lower speed when compared IM
4- Good heat dissipation since the heat mainly arises in the stator	4- The risk of irreversible demagnetization of PM due to high temperature, high demagnetizing armature field or vibration.
5- Various configurations and adjustable performance	5- High back electromagnetic field at high speed under in case of fault.
6- Quick acceleration due to lower electromechanical time constant of the rotor.	

The main goal of this simulational study is determine and compare the PM and IM usage in modeled in a range extended serial configuration HEV with two different driving cycles for analyzed the effects of these machines to HEV performance and emissions. This study contents four section; 1st is introduction, elder studies and aim; 2nd is methodology in which divided on vehicle configuration, specifications of vehicle model and electric machines properties. 3rd one consist the results of HEV performance and emission analyses with different driving cycles. The 4th one is conclusion and future recommendations.

2. Metodology

2.1. Simulation Procedure, Model Vehicle and Electric Machines Specifications

Nowadays, simulations and modeling before prototyping and production have become almost a necessity in most engineering applications. Especially thanks to the evolving operating systems and the fast information processing, the identification and validation of the engineering properties are both profitable from time and costs. Simulation analyzes provide systematic and harmonized approaches to implementers in the development of environmentally and economically viable vehicles. Modeling and control strategies playing an important role for any simulations. Vehicle parameters, components basics, management systems and their communications, input/output variables and calculation strategies can be listed as the main topics of simulating an HEV.

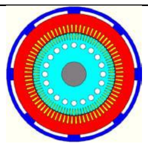
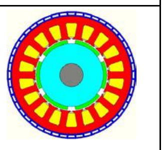
There are various simulation programs for HEVs and AVL interfaces are one of the pioneers of this industry. There are several studies which simulated the designs under AVL like [2]. He described maintains of powertrain differences effects on various EV and HEVs under NEDC cycle. In his study, he introduced the AVL cruise and its ability for determining and modeling procedure with this comparison. The ideal modeling of HEV vehicles should meet the maximum power with maximum efficiency. They have a complicated structure of design and control strategies. Especially in the electrical segment; electric machines, generators, consumers, batteries, regenerative breaking (if used) and brakes modeling and control calculations should be done very carefully and precisely.

In a HEV, PM and ICE connected each other between a transmission system which has series or parallel topology. This integration needs power electronics for connection and communications. [26] given a practical information's like; "power electronics are used several transistors (i.e. MOSFET or IGBT), and the command can be done with microprocessor, microcontroller or DSP using various techniques (*VVVF, FOC, ACon , NC, FC*)".

PID is used as the control algorithms in classical control; adaptive control, fuzzy control and neural network controls are also used. In this study PID control algorithm is controlled with C code programming which is related with operation controls of range extender, e-drive and brakes.

Operating modes for modeled HEV in this study is conducted for the simulated the effects of main importance of the selection of IM vs PM electric machines to performance and emission of the vehicle. The model vehicle and electric machines parameters are listed in Table 2.

Table 2. Model Vehicle and Electric motors Specifications

Specification	IM (4 poles) (Nominal Voltage =320 V)	PM (6 poles, Nominal Voltage =320 V)
Cross- Sections [23]		
Max. Speed/ Efficiency	10000 Rpm / 87%	8000 Rpm/ 94%
Generator	Nominal Voltage = 320 V, Max speed= 10000.	
Battery (40 cells- NiMH)	SOC (Min-Max) = 45-60%, Max. Charge= 5.0 Ah ,Nominal Voltage=7.2 V., Initial Charge / Resistant= 0,019 Ω,	
Transmission	Automatic Transmission, Single ratio, T_{ratio}=6.058, Efficiency= 0.96	
Vehicle and ICE	Frontal area = 1.97 m^2, 4 cylinder, 2 Lt, Max. P =103 kW	

2.2. Vehicle and Electric-Assistant with IM and PM

The vehicle operating conditions can be listed as; ICE operation, generator charging and mixing driving operation and only EM operation. In a regularly HEV the normal and other driving operations summarized by [9] like "In normal operating conditions engine power is divided by the power split device which turns the generator on to drive the motor and rest of the power drives the wheels directly. Extra power needed for additional acceleration is supplied from the battery, while the engine and high-output motor provide smooth response, for improved acceleration characteristics. The motor acts as a generator, driven by the vehicle's wheels in braking application in which system recovers kinetic energy as electrical energy further stored in the battery. The engine drives the generator to recharge the battery when necessary. Supervisory controller controls the power allocation to maximize efficiency."

2.2.1. Vehicle and ICE:

A front-wheel-driven, midsized passenger car is considered for this research. The longitudinal vehicle dynamics and the individual drive train components are modeled, following the quasi-static upstream modeling with the eq.1.

$$T_v = \left(f_R M_v g\, cos\, \emptyset + M_v g\, sin\, \emptyset + \frac{1}{2} C_D \rho A_v V_v^2\right) r_w \qquad (1)$$

where T_v is vehicle torque, V_v is the vehicle speed, M is vehicle mass, and A_v is vehicle frontal area, f_R is the friction coefficient, r_w is the radius of wheel, $\emptyset$ is the road grade, C_D and ρ are the drag coefficient and air density, and g is gravitational acceleration [29]. The total vehicle mass is the sum of the all components of the vehicle mass, ICE, EM and battery system, i.e.,

$$m_{HEV} = m_{Nhev} + m_{ice} + m_{btt} + m_{EM}. \qquad (2)$$

The internal combustion engine model's inputs delivered from the engines maps. Figure 2, illustrated the full characteristic load graphic which related to speed vs power. Fuel consumption map is given in Figure 3.

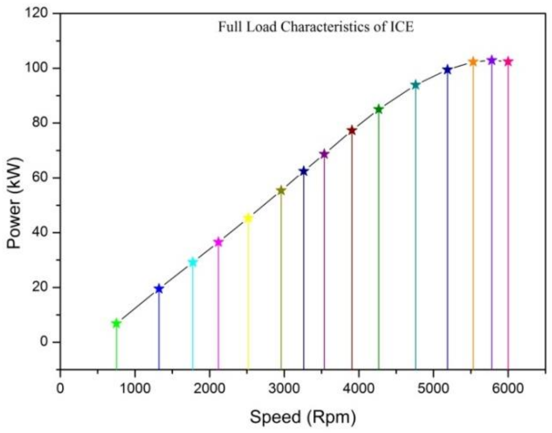


Figure 2. Full Load Characteristics of ICE

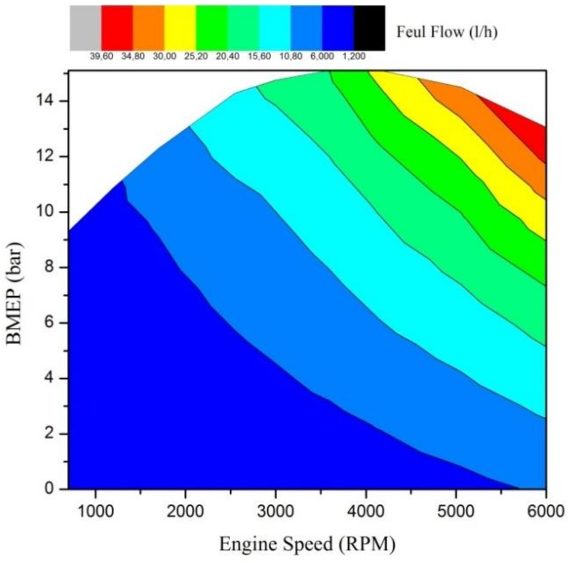


Figure 3. Fuel consumption map of engine

2.2.2. Battery:

The battery model is based on an AVL model of a 7.2 Ah NiMH battery with 40 cells. The battery is selected the same parametric for more valuable comparison for this study. The batteries operating temperature is set up in 25°. The SOC values were varying from 45-60%. The other properties of modeled battery are given in Table 2. In battery parameter general assumption of formulation is given in eq. 3 to 5.

$$P_{batt} = V_{oc} I_{batt} - I^2_{batt} R_{batt} \qquad (3)$$

$$Ibatt = \frac{Voc - \sqrt{Voc^2 - 4Rbatt * Pbatt}}{2Rbatt} \qquad (4)$$

$$SOC\ (k+1) = SOC\ (k) - [(I_{batt} * \Delta t)/Q_c] \qquad (5)$$

2.2.3. Electric Machines:

When it comes to generate a new HEV, the heart of EV/HEV is electric propulsion system. In this case, the core components of electric propulsion systems are electrical machines [6]. In this study, asynchronous motor (IM) is compared with permanent magnet synchronous machine (PM). The Clarke-transformation and the Park-transformation are used to transform the state variables from the three-phase system for using of PMs. Calculation formulas and fundamentally principles of IM and PM can be reachable in [26, 28].Although electric machines have high efficiencies (80-95%), they are exposed to certain losses due to conversion the mechanical power into electrical power. Three types of losess can be listed; 1. Copper losses (*Armature, Shunt field, Series field copper losses*), 2. Iron or core losses (*Hysteresis loss and eddy current loss*) and 3. Mechanical losses (*Friction and air flux gap*). All these losses increase the temperature of the machine that reduced the efficiency of the EMs. [20], mentioned and expressed the losses of PM and given detailed analyses with simulations. Also, related formulas could be attainable from there, too. As known, EM efficiency is a function of angular speed of motor/generator and torque. An efficiency map expresses the EM efficiency with basis of torque and speed variables with contour plots. Figure 4 and 5 is illustrated the efficiency maps of IM and PM, respectively.

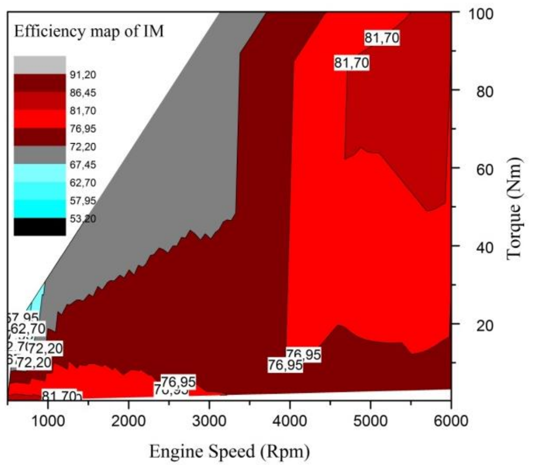


Figure 4. Induction Motor efficiency map

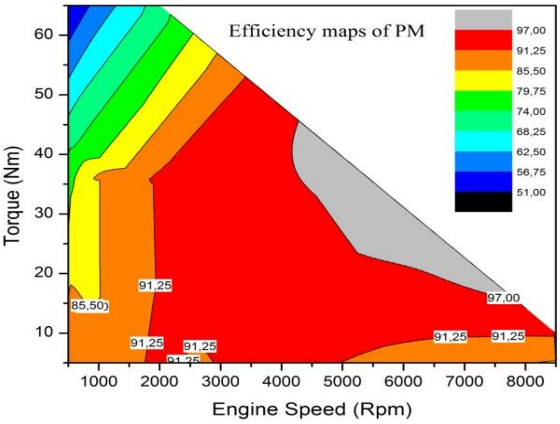


Figure 5. Permanent magnet synchronous Motor efficiency map

3. Results

The main goal of this section is announced the results of this studies top purpose that how influence the different electric machines (IM vs PM) of the model hybrid vehicle's performance, emissions and fuel consumptions. Thanks to driving cycles, these criteria can be measurable and evaluable. [15], summarized this approachment as; "the accepted means for evaluating vehicle energy efficiency is to examine its performance over standard driving cycles. A driving cycle is a representative vehicle velocity versus time profile."

In this study NEDC and FTP driving cycles selected for the simulation of modeled HEV. This section divided into three sub-sections for more stable and detailed comparisons. Related and most important outputs were given for each section with graphics. The first subsection is reserved for IM used HEVs performance and emissions. The second one is placed with PM used HEV performance and emissions and the last one is prepared for the driving cycles and comparison for IM and PM.

3.1. Performance and Emission Analyses of IM used HEV model

The major goal of usage HEV is reduce both of fuel consumption and harmful emission values. The performance and emission from simulated values can be listed as; (all related with ICE) ICE's speed, torque and SFC (Specific Fuel Consumption) and; emissions which are NOx, CO, CO_2 and HCs. Figure 6 and 7 is illustrated the performance and emissions of NEDC cycle variations for IM HEV. FTP-75 driving cycles performance and emissions are given in Figure 8 and 9 for HEV which has IM machine. When compared the whole scale of these figures, IM has given some electric assistant for ICE. It is clearly seen from Fig. 6 and 8, the time travel of driving cycles began with this electrical propulsion and when the engine speed started to decreased with braking mode, the IM is re torque by the helped of generator, that seen in figures with minus degrees of engine torque. When it comes to emission scale, upgraded engine speed produce more power that influence the increasing emission values except braking operations and e-derive sections. In Fig 7 and 9, the emission interaction with electrification operations have give the opportunity to decreased whole emission outputs.

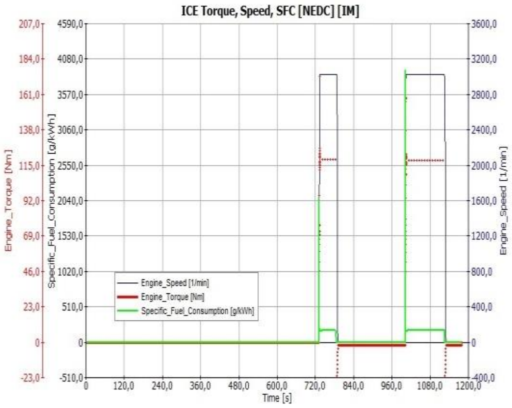


Figure 6. IM NEDC performance values (Torque, Speed, SFC)

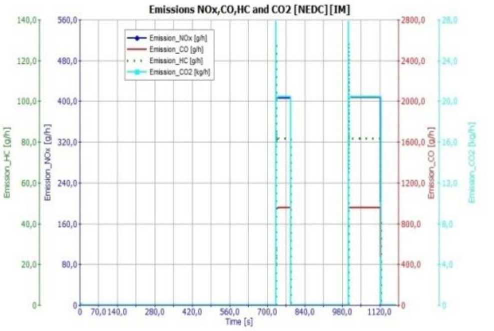


Figure 7. IM NEDC emission values (No_x, CO, HC, CO_2)

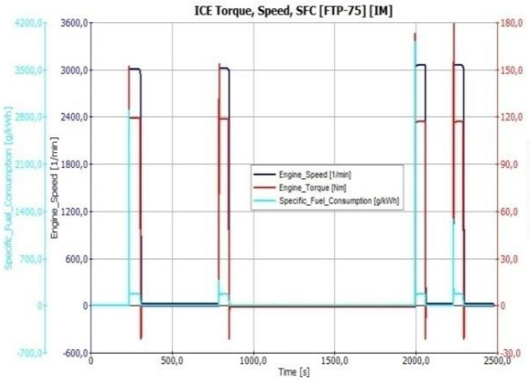


Figure 8. IM FTP75 performance values (ICE Torque, Speed, SFC)

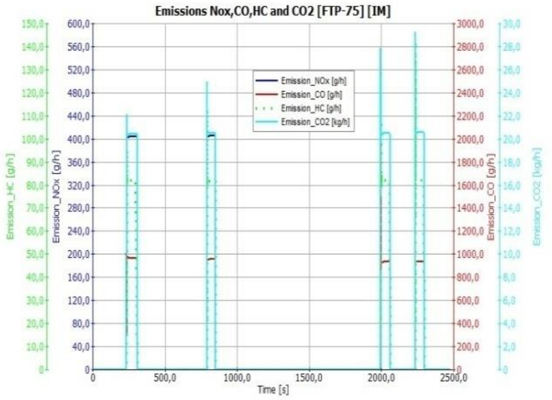


Figure 9. IM FTP75 emission values (No$_x$, CO, HC, CO$_2$)

3.2. Performance and Emission Analyses of PM used HEV model

Permanent magnet synchronous machine usage effects on HEV’s performance and emissions are given with related studies in references part. PMs are widely used machine types in this scale as we mentioned previously. For this studies inputs and variables; the effects of PM on HEVs performance and emissions are given in Figure 10-13. Figure 10 and 12 is expressed the performance analyses of PM for NEDC and FTP-75 driving cycles, respectively. And also, Figure 11 and 13 have shown the result of emissions of PM HEV for these driving cycles. As seen from figures, PM, which has more efficient from IM, gives more satisfactory results when compared IM. Especially, emission results of both NEDC and FTP-75 driving cycles is less than IM configuration HEV. These findings are shown similarity with the previous studies, too. Detailed comparison is given in the next sub-heading for making a more quantitative comparison.

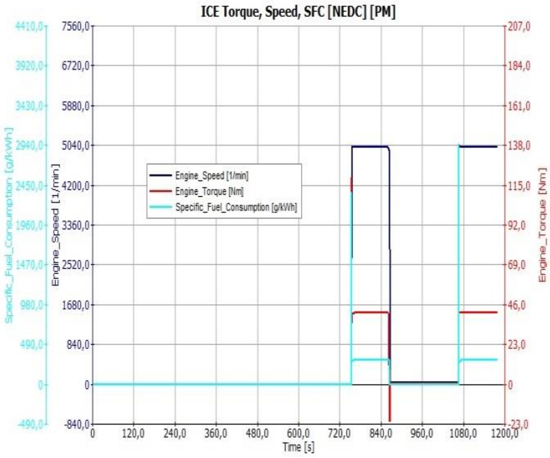


Figure 10. PM NEDC performance values (Torque, Speed, SFC)

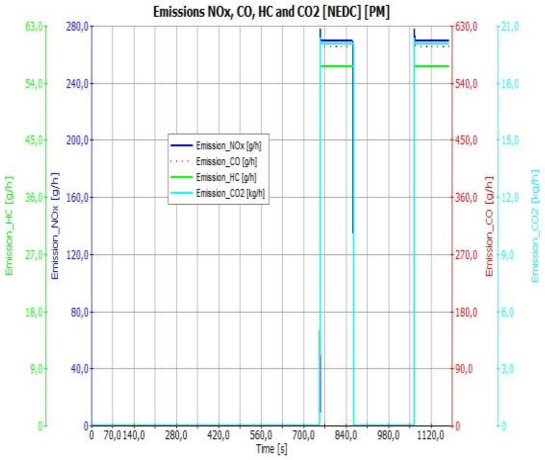


Figure 11. PM NEDC emission values (No$_x$, CO, HC, CO$_2$)

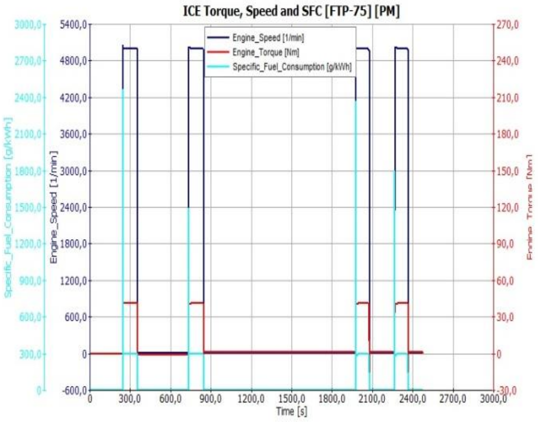


Figure 12. PM FTP75 performance values (ICE Torque, Speed, SFC)

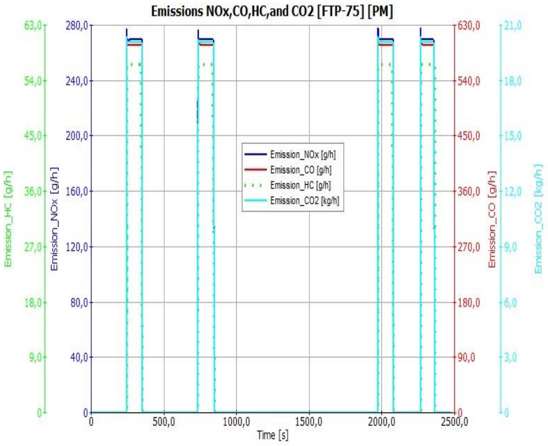


Figure 13. PM FTP75 emission values (No$_x$, CO, HC, CO$_2$)

3.3. Driving Cycles results in comparison of IM and PM influence to performance and emission of HEV

Particularly, determining the full (all vehicle) energy consumptions and losses, driving cycles playing an indispensable role in HEV. The NEDC is used as reference cycle for collaborating vehicles in Europe. The FTP cycle has been performed by US EPA to achieve an inter-changing cycle that parts of urban driving containing frequent stops and a part of highway driving.

Table 3 is prepared for these two driving cycles comparison for IM vs. PM. An overall road of driving cycles gives the difference between IM and PM usage HEVs performance and emissions. Durations, basement characteristic of driving cycles, overall consumptions, emissions and fuel consumptions calculated comparisons are given detailed with average data in Table 3. It is clearly seen from the simulation results, PM is more preferable in terms of performance and emission situation when compared with IM on the basis of using in HEV.

4- Conclusion

Reduction of both fuel consumption and undesirable emissions is one of the key features expected from a hybrid electric vehicle.

Table 3. PM vs IM usage on HEV's simulation results on basis of comparison under NEDC and FTP-75.

PARAMETER	NEDC		FTP-75	
	PM	***IM***	***PM***	***IM***
Distance	10897	16937	10926	17783
ICE SFC (l/100km)	3. 97	3.88	3.51	3.69
E- Motor Consump. (kW/100 km)	0.9	-2.02	0.43	-1.3
NO_x (g)	16.7	20.1	26.5	29
CO (g)	37.2	47	60.8	69
HC (g)	3.53	4.07	5.67	5.9
CO_2 (g/km)	92.7	92.9	83.3	84.2

The correct designation of electrical machines to be used in HEV vehicles for making this improvement and reducing negativities is among the subjects that are being studied by researchers. In this simulation study, the series configuration HEV is modeled with AVL Cruise for determining the difference effects of using electric motors/machines with the helped of various driving cycles.

The electric machines are selected as IM and PM for comparison. The main purpose of this selection is determine how effects these machines to HEV's performance and emissions. Modeling, efficiency maps and simulating principles were expressed briefly and results given with graphs and figures.

In concluded, the major findings can be listed as;

1. For this studies variables; the PM is slightly better behaviors than IM both fuel consumption (3-6%) and emission reducing (12-21% for various emissions).

2. Both IM and PM is assisted the ICE for reducing the fuel consumption and emissions.

3. As a performance approach, like similarity with literature, PM is more preferable than IM in modeled HEV.

4. In cumulative SFC, model PM-HEV is prefable for FTP-75 driving cycle with 3.51.

5. The most attractive greener emission is presented in NEDC with PM-HEV.

For future recommendation can be added with; newly future works could be focus on minimizing the thermal, electrical and mechanical losses of PMs that influence the efficiency of electric machines hardly and these losses affected negatively to HEV performances.

Acknowledgments

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