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Učinkovitost energijskih pretvorb v hibridnih pogonskih sestavih

Study of the Energy-Conversion Efficiency of Hybrid Powertrains

Tomaž Katrašnik - Ferdinand Trenc - Samuel Rodman Oprešnik
(Fakulteta za strojništvo, Ljubljana)

V prispevku je predstavljena simulacijska in analitična analiza učinkovitosti energijskih pretvorb v vzporednih in zaporednih hibridnih pogonskih sestavih. Analitični postopek temelji na enačbah ohranitve energije, simulacijski postopek pa temelji na hitrem in natančnem simulacijskem programu za obravnavo vzporednih in zaporednih hibridnih pogonskih sestavov. Analiza energijske učinkovitosti različnih zasnov pogonskih sestavov, ki temelji na simulaciji termodinamičnih in energetskih procesov ter analitičnem izračunu, omogoča razumevanje postopkov v hibridnih pogonih in vnaprejšnjo določitev optimalne zasnove hibridnega pogonskega sestava glede na način uporabe. Iz prikazanih rezultatov je razvidno: 1) da vzporedno hibridno zasnovo odlikuje manjša poraba goriva kot zaporedno, za obe hibridni zasnovi pa je značilno največje povečanje učinkovitosti energijskih sprememb za testne cikle z nizko povprečno obremenitvijo in 2) izkoristek sprememb električne energije ima ključen vpliv na izboljšanje učinkovitosti energijskih pretvorb v hibridnih pogonskih sestavih.

(Ključne besede: hibridni pogonski sistemi, energijske pretvorbe, simuliranje, režimi delovanja)

This paper presents a simulation and analytical analysis of the energy-conversion efficiency in parallel and series hybrid powertrains. The analytical approach is based on energy-balance equations, whereas the simulation approach is based on an accurate and fast forward-facing simulation model for simulating parallel and series hybrid powertrains. This combined simulation and analytical analysis provides a deep insight into the energy-conversion phenomena in hybrid powertrains and reveals the advantages and disadvantages of both hybrid concepts running under different operating conditions. From the presented results we concluded that: 1) a parallel hybrid powertrain features better fuel economy than the series one for the applied test cycles, whereas both hybrid powertrain concepts have the best fuel economy during light-duty applications and 2) the electric conversion efficiency has a significant influence on the fuel-economy enhancement of hybrid powertrains.

(Keywords: hybrid powertrains, energy conversion, simulations, transient test cycle)

0 UVOD

Cestni promet se uvršča med največje onesnaževalnike v sodobni družbi, kar je privedlo do potrebe po razvoju bolj učinkovitih in okolju primernejših pogonskih sestavov. V skladu s to usmeritvijo se kot mogoče rešitve pojavljajo električna vozila (EV) , hibridna električna vozila (HEV) in vozila, ki jih poganjajo gorivne celice (VGC) [1]. Izmed možnih alternativnih pogonskih sestavov, se hibridnim pogonskim sestavom, sestavljenih iz motorja z notranjim zgorevanjem (MNZ) in elektromotorja (EM) (splošno priznana

0 INTRODUCTION

Road transport has become one of the largest sources of pollution in society; this makes it necessary to develop more energy-efficient and environmentally friendly propulsion technologies. New vehicle technologies in the form of electric vehicles (EVs), hybrid electric vehicles (HEVs) and fuel-cell vehicles (FCVs) have emerged as possible solutions [1]. Among the alternative powertrains being investigated, the hybrid electric vehicle (HEV) consisting of an internal combustion engine (ICE) and an electric motor (EM) (the generally definicija HEV po Chanu [2]) zaradi uporabe razmeroma majhnih naprav za shranjevanje električne energije in podobnosti z običajnimi vozili pripisuje največji potencial v kratkem in srednjeročnem obdobu ([1] in [3]).

V skladu s splošno priznanimi dejstvi hibridni pogonski sestavi omogočajo manjšo porabo goriva ([1] in [3] do [7]), ki ima za posledico manjšo emisijo škodljivih snovi v izpušnih plinih ([3] do [6]). Ta trditev pa ne velja brezpogojno, saj zasnova hibridnega pogonskega sestava, kot npr. vzporedni, zaporedni, vzporedno-zaporedni ali zapleteni HEV ([2] in [4]), izbira gradnikov hibridnega pogonskega sestava, njihovi sorazmerni deleži moči in izkoristki ter uporabljen vozni testni cikel znatno vplivajo na porabo goriva hibridnih pogonskih sestavov. Za razumevanje učinkovitosti energijskih pretvorb v hibridnih pogonskih sestavih je torej neobhodna analiza energijskih tokov in energijskih izgub v posameznih elementih hibridnih pogonskih sestavov. Poznavanje teh postopkov pa nato omogoča določitev optimalne sestave hibridnih pogonskih sestavov glede na način uporabe.

Tradicionalno se hibridni pogonski sestavi delijo na dve zasnovi, in sicer na vzporedne in zaporedne hibridne pogonske sestave (sl. 1). Za zaporedni hibridni pogonski sestav je značilno, da ves navor, ki je potreben za pogon vozila, razvije elektromotor, medtem ko vzporedni hibridni pogonski sestav pridobiva navor, ki je potreben za pogon vozila, iz MNZ in/ali EM. Lastnosti, prednosti in pomanjkljivosti obeh zasnov hibridnih pogonskih sestavov so podrobno predstavljeni v literaturi [4].

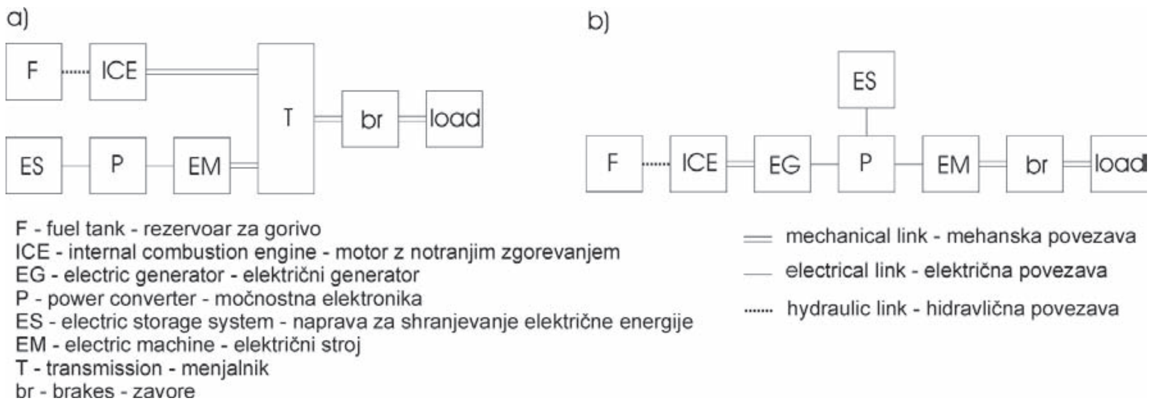
V tem prispevku je predstavljena temeljna analiza učinkovitosti energijskih pretvorb v vzporednih in zaporednih hibridnih pogonskih sestavih, ki tvori osnovo za izračun porabe goriva v različnih pogonskih sestavih. Analitično orodje, ki je izpeljano v nadaljevanju, omogoča določitev optimalne zasnove in izbiro optimalnih sestavnih delov za hibridne pogonske sestave. Analiza energijske učinkovitosti različnih zasnov pogonskih sestavov, ki temelji na simulacijski in analitični analizi, omogoča razumevanje procesov v hibridnih pogonih in nakaže pogoje in vplivne parametre, ki vodijo k zmanjšanju porabe goriva za posamezen hibridni pogonski sestav. V predstavljeni analizi je pozornost posvečana vplivu povprečne obremenitve testnega cikla in njegovemu zaviralnemu vzorcu, ter vplivu različnih vrst naprav za shranjevanje električne energije na učinkovitost energijskih pretvorb v hibridnih pogonskih sestavih.

accepted definition of a HEV according to Chan [2]) is considered to offer the most promise in the short to mid-term due to the use of a smaller battery pack and the similarity with conventional vehicles ([1] and [3]).

It is widely accepted that HEVs allow for improved fuel economy ([1] and [3] to [7]), which results in lower pollutant emissions ([3] to [6]). However, this statement is not unconditional, since the powertrain's configuration, i.e., parallel, series, series-parallel or complex HEV ([2] and [4]), its constituting components, and their relative power ratios and efficiencies as well as the applied driving-test cycle significantly affect the fuel economy of hybrid powertrains. For this reason it is necessary to analyze the energy flows and energy losses in the particular components of hybrid powertrains in order to obtain an insight into the energy-conversion phenomena and select the optimum hybrid configuration for the particular purpose.

Traditionally, there are two main configurations of HEV propulsive system, i.e., parallel and series hybrid powertrains, Fig. 1. In a series HEV configuration the entire torque required for the propulsion is provided by an electric motor, whereas in a parallel HEV configuration the propulsive power is obtained from an internal combustion engine and/or an electric motor. The features, advantages and disadvantages of both hybrid powertrain concepts have been widely analyzed by many authors, e.g., Chau et al. [4].

This paper provides fundamental knowledge about the energy-conversion phenomena in parallel and series hybrid powertrains and forms the basis for a fuel-economy evaluation of the different powertrains. The presented analytical framework makes possible a determination of the optimum powertrain configuration and the selection of the optimum constituting components of the HEVs. This combined simulation and analytical analysis provides a deep insight into the energy-conversion phenomena in hybrid powertrains and highlights the conditions and influences that lead to the improved fuel economy of a particular hybrid powertrain. In the presented analysis the emphasis is placed on the influence of the test cycle's average load and its deceleration pattern and on the influence of the electrical energy storage types on the energy-conversion efficiency of the analyzed powertrains.



Sl. 1. *Shema a) vzporednega in b) zaporednega hibridnega pogonskega sestava*
Fig. 1. *Scheme of a) parallel and b) series hybrid powertrain*

1 ANALIZA

Poraba goriva v vozilih se določi v skladu z izbranim testnim ciklom. Vse veličine, ki so uporabljene v nadaljevanju, so zato povprečne vrednosti, časovno povprečene čez določen testni cikel, razen v primerih, pri katerih je časovna odvisnost nakazana posebej. Enačbe ohranitve energije za vzporedni hibridni pogonski sestav so izčrpno izpeljane v [8], medtem ko so enačbe za zaporedni hibridni pogonski sestav predstavljene v [9]. Izpeljave teh enačb bodo zato v nadaljevanju zgolj povzete.

1.1 Pogonski sestav MNZ

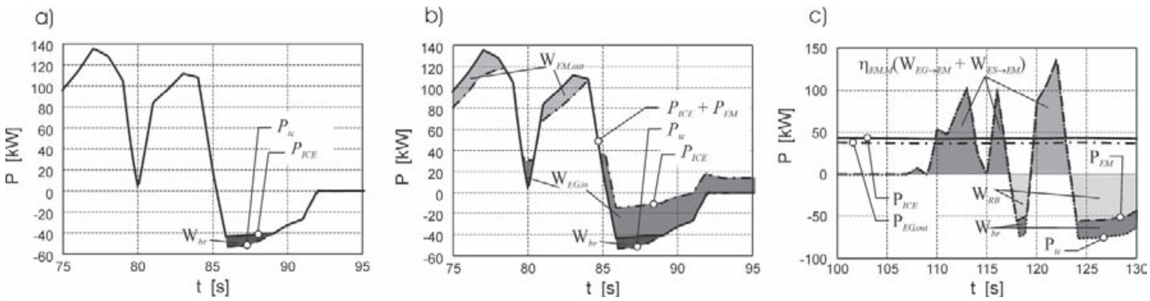
V običajnem pogonskem sestavu MNZ je energija, ki je potrebna za pogon vozila ali dinamometra, v skladu s testnim ciklom (W_{IC}) enaka energiji, ki jo odda MNZ (W_{ICE}) zmanjšani za energijo, ki jo med zaviranjem odvedemo z zavorami (W_{br}) (sl. 2 a)). Iz tega izhaja:

1 ANALYSIS

An analysis of the fuel consumption is generally performed for a specific test cycle. All the subsequently defined quantities are, therefore, averaged values over the applied test cycle, except in the case where the time dependency is explicitly indicated. The energy-balance equations of the parallel hybrid powertrain were derived in Ref. [8], whereas the analytical basis for analyzing the series hybrid powertrain was introduced in Ref. [9]. Therefore, these equations are only briefly summarized below.

1.1 ICE powertrain

Let us first consider the conventional, baseline ICE powertrain (consisting of an ICE only). The energy consumed to propel the vehicle or the dynamometer according to the test cycle (W_{IC}) is equal to the energy produced by the ICE (W_{ICE}) reduced by the energy consumed by the brakes (W_{br}); Fig. 2. a). Thus:



Sl. 2. *Točke testnega cikla in vhodne/izhodne moči a) običajnega pogonskega sestava MNZ, b) vzporednega in c) zaporednega hibridnega pogonskega sestava*
Fig. 2. *Test-cycle points and the power outputs/inputs of a) an ICE powertrain, b) a parallel and c) a series hybrid powertrain*

$$W_{tc} = \int_0^{t_{tc}} P_{tc} \mathrm{d}t = W_{ICE} - W_{br} = \int_0^{t_{tc}} P_{ICE} \mathrm{d}t - \int_0^{t_{tc}} P_{br} \mathrm{d}t \qquad P_{br}(t) = P_{ICE,\min}(t) - P_{tc}(t) \tag{1}$$

kjer so P_{tc} trenutna moč, ki jo vsiljuje testni cikel, P_{ICE} trenutna moč MNZ in P_{br} razlika med negativno močjo, potrebno za premagovanje lastne rabe – npr. trenja motorja pri določenih vrtilnih frekvencah ($P_{ICE,\min}$) in negativnim navorom, ki ga vsiljuje testni cikel.

where P_{tc} is the instant power imposed by the test cycle, P_{ICE} is the instant power of the ICE and P_{br} is the difference between the negative power required to drive the engine at a particular speed ($P_{ICE,\min}$) and the negative torque imposed by the test cycle.

1.2 Vzporedni hibridni pogonski sestav

Porabo goriva v hibridnih pogonskih sestavih je treba primerjati z uravnoteženim stanjem stopnje napolnjenosti (SOC) naprav za shranjevanje električne energije (ES), kar pomeni, da sta SOC na začetku in na koncu testnega cikla enaka. V nadaljevanju se indeks *h* uporablja za označevanje hibridnih pogonskih sestavov.

S slike 2 b) je razvidno, da vzporedni hibridni pogonski sestav (sl. 1a)) pridobiva energijo za pogon vozila ali dinamometra v skladu s testnim ciklom iz MNZ ($W_{ICE,h}$) in EM ($W_{EM,out}$), medtem ko se naprave za shranjevanje električne energije polnijo med regenerativnim zaviranjem in/ali med delovanjem MNZ pri večji obremenitvi. Električna energija se v hibridnih pogonskih sestavih nikoli ne proizvaja in porablja hkrati, saj vzporedni hibridni pogonski sestav sestavlja en električni stroj, ki deluje kot električni motor, ali pa kot električni generator. Enačbo ohranitve energije za vzporedni hibridni pogonski sestav zapišemo v obliki:

1.2 Parallel hybrid powertrain

It is obvious that it is necessary to analyze the fuel consumption of hybrid powertrains with a balanced state of charge (SOC) of the electric storage devices (ES), i.e., the SOC of all the electric storage devices at the beginning of the test cycle should be equal to the SOC at the end of the test cycle. Subsequently, index *h* indicates the hybrid powertrain.

Let us first consider the parallel hybrid powertrain (Fig. 1 a)). It is evident from Fig. 2 b) that the energy consumed to propel the vehicle or the dynamometer according to the test cycle is produced by the ICE ($W_{ICE,h}$) and the EM ($W_{EM,out}$), whereas the electric storage systems are charged by regenerative braking and/or by running the ICE at a higher torque output. In the parallel hybrid powertrain the electrical energy is never produced and consumed simultaneously, since they apply only one electric machine that operates either as the electric motor or as the electric generator. Thus, the energy balance of the parallel hybrid powertrain is equal to:

$$W_{tc} = W_{ICE,h} + W_{EM,out} - W_{EG,in} - W_{br,h} \qquad W_{EM,out} = \eta_{EL} W_{EG,in} \tag{2}$$

saj je SOC naprav za shranjevanje električne energije uravnotežen. $W_{EG,in}$ označuje delo, ki ga dovajamo električnemu generatorju (EG). Definirajmo izkoristek električnega generatorja $\eta_{EG} = \int_0^{t_{tc}} P_{EG,out} \mathrm{d}t \Big/ \int_0^{t_{tc}} P_{EG,in} \mathrm{d}t$, izkoristek električnega motorja $\eta_{EM} = \int_0^{t_{tc}} P_{EM,out} \mathrm{d}t \Big/ \int_0^{t_{tc}} P_{EM,in} \mathrm{d}t$, naprav za shranjevanje električne energije $\eta_{ES} = \eta_{ES,ch}\eta_{ES,disch}\eta_{eet}$, izkoristek pretvorb električne energije $\eta_{EL} = \eta_{EG}\eta_{EM}\eta_{ES}$. η_{ES} vsebuje izkoristke polnjenja - praznjenja naprav za shranjevanje električne energije ($\eta_{ES,ch}\eta_{ES,disch}$) in izkoristek prenosa električne energije (η_{eet}), ki vsebuje tudi izgube močnostne elektronike.

Dejanski izkoristek MNZ določimo kot razmerje dejanskega dela, ki ga razvije MNZ, in energije, ki mu je bila dovedena z gorivom ($m_{f,tc}Q_{LHV}$). Sledi:

since the SOC of all the electric storage systems is balanced. $W_{EG,in}$ identifies the input work of the electric generator (EG). Let us define the efficiency of the electric generator $\eta_{EG} = \int_0^{t_{tc}} P_{EG,out} \mathrm{d}t \Big/ \int_0^{t_{tc}} P_{EG,in} \mathrm{d}t$, the efficiencies of the electric motor $\eta_{EM} = \int_0^{t_{tc}} P_{EM,out} \mathrm{d}t \Big/ \int_0^{t_{tc}} P_{EM,in} \mathrm{d}t$, the electric storage devices $\eta_{ES} = \eta_{ES,ch}\eta_{ES,disch}\eta_{eet}$ and the electric conversion efficiency $\eta_{EL} = \eta_{EG}\eta_{EM}\eta_{ES}$. η_{ES} includes the charge-discharge efficiency of the electric storage systems ($\eta_{ES,ch}\eta_{ES,disch}$) and the efficiency of the electrical energy transfer (η_{eet}), which also considers the losses of the power converters.

For a further analysis let us define the effective efficiency of the ICE as the ratio of the energy delivered by the ICE to the energy supplied by the fuel ($m_{f,tc}Q_{LHV}$), thus:

$$\eta_{eff} = W_{ICE} \big/ m_{f,tc} Q_{LHV} = \int_0^{t_{tc}} P_{ICE} \mathrm{d}t \Big/ m_{f,tc} Q_{LHV} \tag{3}$$

Z združitvijo enačb (1) in (2), upoštevanjem en. (3) in poznejšem odštevanju 1 na obeh straneh enačbe dobimo[8]:

Combining Eqns. (2) with Eq. (1), inserting Eq. (3) and subtracting 1 from both sides of the equation gives, after rearrangement, [8]:

$$\Delta_{f,P} = \frac{m_{f,tc,h}}{m_{f,tc}} - 1 = \left[\frac{\eta_{eff}}{\eta_{eff,h}} - 1\right]_{1P} + \left[\frac{\eta_{eff}}{\eta_{eff,h}} \frac{(1-\eta_{EL})W_{EG,in}}{W_{ICE}}\right]_{2P} + \left[\frac{\eta_{eff}}{\eta_{eff,h}} \frac{W_{br,h} - W_{br}}{W_{ICE}}\right]_{3P} \quad (4).$$

V enačbi (4) tako členi, ki so večji od 0, nakazujejo povečanje porabe goriva in členi, ki so manjši od 0, nakazujejo zmanjšanje porabe goriva.

Leva stran en. (4) pomeni relativno spremembo porabe goriva vzporednega hibridnega pogonskega sestava glede na običajni pogonski sestav z MNZ. Prvi člen na desni strani en. (4) (rhs_{1P}) pomeni razmerje dejanskih izkoristkov osnovnega MNZ in MNZ vgrajenega v vzporedni hibridni pogonski sestav. Drugi člen na desni strani en. (4) (rhs_{2P}) popiše energijske izgube ob proizvodnji, shranjevanju in porabi električne energije ob upoštevanju razmerja dejanskih izkoristkov MNZ. Tretji člen na desni strani en. (4) (rhs_{3P}) upošteva razmerje razlike v energiji, ki je bila odvedena z zavorami, v posameznih opazovanih pogonskih sestavih in dejanskega dela osnovnega MNZ pomnoženo z razmerjem dejanskih izkoristkov MNZ.

Hence, the values of a particular term that are larger than 0 indicate an increase in the fuel consumption, and values lower than 0 indicate a reduction in the fuel consumption.

The left-hand side of Eq. (4) represents the relative change in the fuel consumption of the parallel hybrid powertrain compared to that of the baseline one. The first term on the right-hand side of Eq. (4) (rhs_{1P}) represents the ratio of the baseline ICE efficiency to the efficiency of the ICE of the hybrid powertrain. The second term on the right-hand side of Eq. (4) (rhs_{2P}) accounts for the energy losses due to electrical energy production, storage and consumption, multiplied by the efficiency ratio of the ICEs. The third term on the right-hand side of Eq. (4) (rhs_{3P}) considers the ratio of the difference between the energies consumed by the brakes in the relevant powertrains to the work produced by the baseline ICE and multiplied by the ratio of the ICE efficiencies.

1.3 Zaporedni hibridni pogonski sestav

V zaporednem hibridnem pogonskem sestavu (sl. 1 b) and 2 c)) se energija, ki jo razvije MNZ z uporabo električnega generatorja, pretvori v električno energijo, ki se nato porabi za pogon koles preko elektromotorja in/ali za polnjenje naprav za shranjevanje električne energije. Naprave za shranjevanje električne energije pa se lahko polnijo tudi med regenerativnim zaviranjem (W_{RB}) vozila, pri tem pa elektromotor deluje v generatorskem načinu delovanja. Iz opisanega je razvidno, da električni motor poganja vozilo ali dinamometer v skladu z izbranim testnim ciklom, medtem ko se energija, ki izhaja iz negativnih navorov testnega cikla, porablja za regenerativno zaviranje in po potrebi odvaja z zavorami. Sledi:

1.3 Series hybrid powertrain

When considering the series hybrid powertrain (Fig. 1 b) and 2 c)), it is evident that the energy supplied by the ICE is converted into electrical energy via an electric generator and is then used to propel the wheels via an electric motor and/or to charge the electric storage systems. Additionally, electric storage systems could also be charged by regenerative braking (W_{RB}), with the electric motor operating in generator mode. It is thus obvious that the electric motor is used to propel the vehicle or the dynamometer according to the test cycle, whereas the energy due to negative torque values is used for regenerative braking and, if needed, consumed by the brakes. Thus:

$$W_{tc} = W_{EM,out} - W_{RB} - W_{br,h} \quad (5).$$

Električno energijo, ki jo porablja elektromotor, dobavlja električni generator in/ali se dobi iz naprav za shranjevanje električne energije:

The electrical energy consumed by the electric motor is supplied by the electric generator and/or by the electric storage systems:

$$W_{EM,out} = \eta_{EM,M}\left(\eta_{eet,EG\rightarrow EM} W_{EG\rightarrow EM} + \eta_{eet,ES\rightarrow EM} W_{ES\rightarrow EM}\right) \quad (6).$$

Izkoristek prenosa električne energije (η_{eet}) je za zaporedne hibridne pogonske sestave definiran tako, da upošteva posamezne energijske tokove; dodatni indeks označuje energijsko pot. Izkoristek prenosa električne energije vsebuje tudi izgube močnostne krmilne elektronike.

Izkoristek električnega motorja, ki deluje v motorskem načinu delovanja ($\eta_{EM,M}$), je enak η_{EM} za vzporedni hibridni pogonski sestav, izkoristek električnega generatorja (η_{EG}) je enak izkoristku električnega generatorja za vzporedni hibridni pogonski sestav, medtem ko je izkoristek električnega motorja, ki deluje v generatorskem načinu delovanja določen z izrazom:

The electrical energy transfer efficiencies (η_{eet}) were redefined in order to account for the electrical energy losses of particular energy paths; an additional index indicates the energy path. The efficiencies of the electrical energy transfer also consider the losses of power converters.

The efficiency of the electric motor operating in the motor mode ($\eta_{EM,M}$) is equal to η_{EM} of the parallel hybrid powertrain and the efficiency of the electric generator (η_{EG}) is also equal to that of the parallel hybrid powertrain, whereas the efficiency of the electric motor operating in generator mode is defined by:

$$\eta_{EM,G} = \int_0^{t_{tc}} P_{EM \to ES} \mathrm{d}t \Big/ \int_0^{t_{tc}} P_{RB} \mathrm{d}t \qquad (7).$$

Energija, ki jo proizvede MNZ, se porablja za pogon električnega generatorja:

The energy produced by the ICE is used to propel the electric generator, thus:

$$W_{ICE,h} = W_{EG,in} = W_{EG,out} / \eta_{EG} \qquad (8),$$

medtem ko se električna energija, ki jo dobavlja električni generator, porablja za pogon elektromotorja in/ali za polnjenje naprav za shranjevanje električne energije:

whereas the electrical energy produced by the electric generator is consumed by the electric motor and/or used to charge the electric storage devices:

$$W_{EG,out} = W_{EG \to EM} + W_{EG \to ES} \qquad (9).$$

Električna energija, ki se proizvede pri regenerativnem zaviranju, se porablja za polnjenje naprav za shranjevanje električne energije, sledi:

The electrical energy recuperated by the regenerative braking is used to charge the electric storage systems, thus:

$$W_{EM \to ES} = \eta_{EM,G} W_{RB} \qquad (10).$$

Energijsko ravnovesje za naprave za shranjevanje električne energije zapišemo v naslednji obliki:

The energy-balance equation for the electric storage systems is:

$$W_{ES \to EM} = \eta_{ES} \left(\eta_{eet,EG \to ES} W_{EG \to ES} + \eta_{eet,EM \to ES} W_{EM \to ES} \right) \qquad (11),$$

kjer je SOC uravnotežen. V analizi zaporednega hibridnega pogonskega sestava je η_{ES} definiran kot $\eta_{ES} = \eta_{ES,ch} \eta_{ES,dch}$.

Z združitvijo enačb (5), (6) in (8) do (11) z en. (1) ter upoštevanjem en. (3) in dodatnim odštevanjem na obeh straneh enačbe dobimo [9]:

since the SOC of all the electric storage systems is balanced. η_{ES} is also redefined when considering the series hybrid powertrain, i.e., $\eta_{ES} = \eta_{ES,ch} \eta_{ES,dch}$.

Combining Eqns. (5), (6) and (8) to (11) with Eq. (1), inserting Eq. (3) and subtracting 1 from both sides of the equation gives, after rearrangement, [9]:

$$\begin{aligned} \Delta_{f,S} = \frac{m_{f,tc,h}}{m_{f,tc}} - 1 = & \left[\frac{\eta_{eff}}{\eta_{EG} \eta_{eet,EG \to EM} \eta_{EM,M} \eta_{eff,h}} - 1 \right]_{1S} + \left[\frac{\eta_{eff}}{\eta_{EG} \eta_{eet,EG \to EM} \eta_{EM,M} \eta_{eff,h}} \times \right. \\ & \left. \frac{\eta_{EM,M} \left(\eta_{eet,EG \to EM} - \eta_{eet,EG \to ES} \eta_{ES} \eta_{eet,ES \to EM} \right) W_{EG \to ES}}{W_{ICE}} \right]_{2S} + \left[\frac{\eta_{eff}}{\eta_{EG} \eta_{eet,EG \to EM} \eta_{EM,M} \eta_{eff,h}} \times \right. \\ & \left. \frac{\left(1 - \eta_{EM,G} \eta_{eet,EM \to ES} \eta_{ES} \eta_{eet,ES \to EM} \eta_{EM,M} \right) W_{RB}}{W_{ICE}} \right]_{3S} + \left[\frac{\eta_{eff}}{\eta_{EG} \eta_{eet,EG \to EM} \eta_{EM,M} \eta_{eff,h}} \frac{W_{br,h} - W_{br}}{W_{ICE}} \right]_{4S} \end{aligned} \qquad (12).$$

V enačbi (12) členi, ki so večji od 0, ponovno nakazujejo povečanje porabe goriva in členi, ki so manjši od 0, nakazujejo zmanjšanje porabe goriva.

Leva stran en. (12) pomeni relativno spremembo porabe goriva zaporednega hibridnega pogonskega sestava glede na običajni pogonski sestav z MNZ. Prvi člen na desni strani en. (12) (rhs_{1S}) pomeni razmerje med energijsko učinkovitostjo običajnega pogonskega sestava (η_{eff}) in energijsko učinkovitostjo zaporednega hibridnega pogonskega sestava na energijski poti ICE→EG→EM ($\eta_{EG}\eta_{eet,EG\rightarrow EM}\eta_{EM,M}\eta_{eff,h}$); električna energija obide naprave za shranjevanje električne energije. Drugi člen na desni strani en. (12) (rhs_{2S}) popiše energijske izgube na poti ICE→EG→ES→EM (električna energija je najprej spravljena v ES in nato porabljena v EM), pomnožene z razmerjem izkoristkov pogonskih sestavov. Tretji člen na desni strani en. (12) (rhs_{3S}) popiše energijske izgube na poti RB→ES→EM (električna energija se proizvede z regenerativnim zaviranjem, spravljena v ES in nato porabljena v EM), pomnožene z razmerjem izkoristkov pogonskih sestavov. Četrti člen na desni strani en. (12) (rhs_{4S}) upošteva razmerje razlike v energiji, ki je bila odvedena z zavorami, v dotičnih pogonskih sestavih in dejanskega dela osnovnega MNZ pomnoženo z razmerjem dejanskih izkoristkov MNZ.

Again, the values of a particular term that are larger than 0 indicate an increase in the fuel consumption and values lower than 0 indicate a reduction in the fuel consumption.

The left-hand side of Eq. (12) represents the relative change in the fuel consumption of the series hybrid powertrain compared to that of the baseline one. The first term on the right-hand side of Eq. (12) (rhs_{1S}) represents the ratio of the energy-conversion efficiency of the conventional powertrain (η_{eff}) to the energy-conversion efficiency of the hybrid powertrain when the energy path ICE→EG→EM is considered ($\eta_{EG}\eta_{eet,EG\rightarrow EM}\eta_{EM,M}\eta_{eff,h}$), i.e., the electrical energy bypasses the electric storage systems. The second term on the right-hand side of Eq. (12) (rhs_{2S}) accounts for the energy losses due to the energy path ICE→EG→ES→EM, i.e., the electrical energy that is first stored in the ES and then consumed by the EM, multiplied by the ratio of the powertrain efficiencies. The third term on the right-hand side of Eq. (12) (rhs_{3S}) accounts for the energy losses due to the energy path RB→ES→EM, i.e., the electrical energy gained by the regenerative braking is stored in the ES and later consumed by the EM, multiplied by the ratio of the powertrain efficiencies. The fourth term on the right-hand side of Eq. (12) (rhs_{4S}) considers the ratio of the difference between the energies consumed by the brakes in the relevant powertrains to the work produced by the baseline ICE and multiplied by the ratio of the ICE efficiencies.

2 SIMULACIJSKI MODEL

Za simulacijo obeh hibridnih pogonskih zasnov je uporabljen simulacijski model, ki računa procese v gradnikih v smeri od virtualnega voznika proti porabniku, ki je v analiziranem primeru dinamometer. Simulacijski model je podrobno opisan v [8] in [9], v nadaljevanju so zato povzete le njegove bistvene značilnosti.

2 SIMULATION MODEL

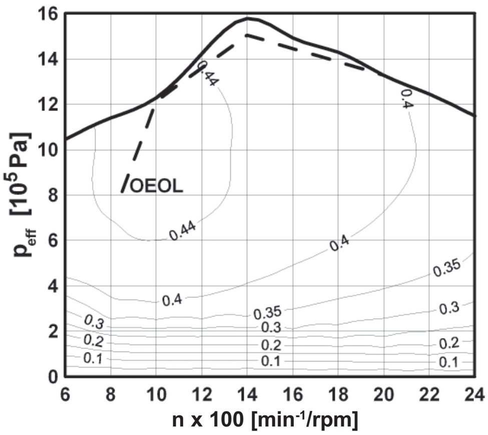
A forward-facing model was applied for the analysis of both hybrid powertrain configurations. The simulation model is described in detail in Ref. [8] and [9]; therefore, the main features of the model are only briefly summarized here.

2.1 Motor z notranjim zgorevanjem

Tlačno polnjeni dizelski motor MAN D0826 LOH 15 je uporabljen kot glavni pogonski motor z notranjim zgorevanjem. Slika 3 prikazuje potek največjega srednjega dejanskega tlaka v odvisnosti od vrtilne frekvence in polje dejanskega izkoristka za osnovni motor MAN; podrobnejši opis motorja lahko najdemo v [8], [10] do [12]. Simulacijski model za MNZ temelji na 0-D metodi polnjenja in

2.1 Internal combustion engine

A MAN D0826 LOH 15 turbocharged diesel engine was used as the baseline internal combustion engine. The maximum brake mean effective pressure vs. speed characteristics and the effective efficiency of the applied ICE are shown in Fig. 3; more details are presented in Refs. [8], [10] to [12]. The ICE simulation model is based on the 0-D filling and emptying method; the details and



Sl. 3. *Dejanski izkoristek osnovnega tlačno polnjenega motorja MAN z vrisano krivuljo OEOL krmilne strategije (poglavje 2.5)*

Fig. 3. *Effective efficiency of the MAN turbocharged diesel engine with the indicated OEOL control strategy (section 2.5)*

Preglednica 1. *Rezultati značilnosti običajnega pogonskega sestava z MNZ*

Table 1: *Results of the baseline powertrain*

TF	0,4	0,5	0,6	0,8	1
$m_{f,tc}$ [kg]	2,33	2,71	3,1	3,92	4,77
W_{ICE} [MJ]	26,8	35	43,2	59,6	75,8
η_{eff} [-]	0,269	0,303	0,326	0,356	0,373
$\langle p_{eff} \rangle$ [MPa]	0,174	0,227	0,28	0,387	0,493

praznjenja; podroben opis in vrednotenje metode najdemo v [8], [10] do [12]. V obeh alternativnih hibridnih pogonskih sestavih je vključen MNZ, ki ima delovno prostornino enako polovici delovne prostornine osnovnega motorja MAN.

2.2 Električni gradniki

Model za polnjenje in praznjenje akumulatorjev in določitev SOC je povzet po viru [13]. V predstavljeni raziskavi so bile uporabljene tri nadzorne strategije za določitev števila modulov akumulatorjev: 1) SOC posameznih enot električnih akumulatorjev mora biti večji od 0,4, 2) električni akumulatorji so izbrani tako, da ne omejujejo delovanja električnega motorja in 3) izkoristek polnjenja - praznjenja električnih akumulatorjev je približno 65%; podrobnejši opis je v [8]. Osnovna enota modula akumulatorjev je akumulator Genesis 12V, 28 Ah VRLA. Glavni modul električnih akumulatorjev je sestavljen iz 25 osnovnih enot, ki so povezane zaporedno, število akumulatorskih modulov pa je določeno v skladu s predhodnimi kriteriji.

verification of the model are presented in Refs. [8], [10] to [12]. Both hybrid powertrain configurations apply the ICE with a swept volume equal to 50% of the baseline engine's swept volume.

2.2 Electrical components

The battery charging, discharging and the determination of the SOC were performed in accordance with the model proposed by Kutluay et al. [13]. Three control strategies were applied to the number of battery modules in this study, i.e., 1.) the SOC of the battery units must be greater than 0.4, 2.) the batteries are of such a size that they do not limit the performance of the electric motor and 3.) the charge-discharge efficiency of the batteries is approximately 65%; the details are presented in Ref. [8]. The Genesis 12V, 28 Ah VRLA battery was considered as the module of the storage system. The basic storage module used in the simulation consists of 25 batteries connected in series, whereas the number of modules is selected on the basis of previous criteria.

Za ultrakondenzatorje (UC) je značilna zelo velika gostota razpoložljive moči, ki je bistevno večja kakor pri električnih akumulatorjih, za katere so značilne velike notranje izgube v primeru hitrega praznjenja. Ultrakondenzatorji so zato potencialno zelo primerni za uporabo v HEV, saj je poleg bistveno večje gostote moči zanje značilen tudi večji izkoristek polnjenja - praznjenja in daljša doba trajanja v primerjavi z običajnimi električnimi akumulatorji. Ultrakondenzatorji imajo navadno manjšo gostoto energije kakor električni akumulatorji, vendar pa je za najsodobnejše UC že značilna primerljiva gostota energije. V analizi hibridnih pogonskih sestavov je bil uporabljen NESSCAP EMHSP-0051 C0-340R0 ultrakondenzator z imensko kapaciteto 51 F in imensko napetostjo 340 V. Model UC je povzet po [14].

Modeli električnih strojev računajo izhodni/vhodni navor, porabo/proizvodnjo električne energije in izkoristek na podlagi izmerjenih podatkov električnih strojev in vhodnih signalov drugih podmodelov v simulacijskem modelu. Največji navor električnih strojev je bil prilagojen zahtevam posameznih zasnov hibridnih pogonskih sestavov v skladu z omejitvami, ki so podane v naslednjem poglavju, pri tem so bili ustrezno prilagojeni tudi izkoristki. Značilnosti električnih strojev so predstavljene v [8] in [9].

2.3 Zasnove hibridnih pogonskih sestavov

Gradniki obeh hibridnih pogonskih sestavov so izbrani v skladu z naslednjima omejitvama: $\left(M_{ICE,h}+M_{EM}\right)\big|_{n(M_{ICE,b,\max})}=M_{ICE,b}\big|_{n(M_{ICE,b,\max})}$ za vzporedni hibridni pogonski sestav in $M_{EM}\big|_{n(M_{ICE,b,\max})}=M_{ICE,b}\big|_{n(M_{ICE,b,\max})}$ za zaporedni hibridni pogonski sestav, kjer je $n(M_{ICE,b,\max})$ vrtilna frekvenca motorja, ki ustreza največjemu navoru osnovnega motorja MAN. V skladu s podanimi omejitvami imajo običajni pogonski sestav z MNZ in oba hibridna pogonska sestava enak največji navor pri $n(M_{ICE,b,\max})$. Hibridizacijsko razmerje vzporednega hibridnega pogonskega sestava je tako v skladu z definicijo podano v [8] $\mathrm{HF'}=\left(M_{EM}/\left(M_{EM}+M_{ICE,h}=konst.\right)\right)\Big|_{n(M_{ICE,b,\max})}=0,53$ in v skladu z definicijo, podano v [1] $\mathrm{HF}=\left(P_{EM}/\left(P_{EM}+P_{ICE,h}\right)\right)\Big|_{n(P_{ICE,b,\max})}=0,46$, kjer je $n\left(P_{ICE,b,\max}\right)$ vrtilna frekvenca motorja, ki ustreza največji moči glavnega motorja MAN.

It well known that ultra-capacitors (UCs) have the advantage of near-instantaneous energy delivery, in contrast to batteries, which experience high internal losses if they are discharged too quickly. Thus, UCs are of considerable interest for HEV applications, due to their higher power density, higher charge-discharge efficiency and extended life cycle compared to batteries. The energy density of UCs is typically lower than that of the batteries; however, UC models with a high energy density have been produced recently. The NESSCAP EMHSP-0051 C0-340R0 UC with a nominal capacitance of 51 F and a rated voltage of 340 V was used when analyzing the hybrid powertrain parameters. The model of the UC consists of the capacitance and an equivalent series resistance, as proposed by Amrhein and Krein [14].

The model of the electric machine evaluates the torque output/input, the electrical energy consumption/production and an efficiency estimation based on the measured input data of the electric machine and the input signals from other sub-models of the simulation model. The electric machine was scaled according to the constraints given in the next section in order to ensure the required torque output of the powertrain's components, while its efficiency characteristics were also modified simultaneously. The characteristics of the electric machines are presented in Refs. [8] and [9].

2.3 Powertrain configurations

The components of both hybrid powertrains were sized according to the following constraint $\left(M_{ICE,h}+M_{EM}\right)\big|_{n(M_{ICE,b,\max})}=M_{ICE,b}\big|_{n(M_{ICE,b,\max})}$ for the parallel hybrid powertrain, and $M_{EM}\big|_{n(M_{ICE,b,\max})}=M_{ICE,b}\big|_{n(M_{ICE,b,\max})}$ for the series one, where $n(M_{ICE,b,\max})$ represents the engine speed that corresponds to the maximum torque of the baseline engine. The baseline powertrain and both hybrid powertrains thus feature the same maximum torque at $n(M_{ICE,b,\max})$. The hybridization factor of the parallel hybrid powertrain according to Ref. [8] amounts to $\mathrm{HF'}=\left(M_{EM}/\left(M_{EM}+M_{ICE,h}=konst.\right)\right)\Big|_{n(M_{ICE,b,\max})}=0.53$ and the hybridization factor according to Ref. [1] amounts to $\mathrm{HF}=\left(P_{EM}/\left(P_{EM}+P_{ICE,h}\right)\right)\Big|_{n(P_{ICE,b,\max})}=0.46$, where $n\left(P_{ICE,b,\max}\right)$ represents the engine speed that corresponds to the maximum power output of the baseline MAN engine.

2.4 Testni cikel

Parametri pogonskih sestavov so ovrednoteni v skladu z dinamometrsko različico cikla ETC [15]. Dinamometerska različica testnega cikla je bila izbrana, ker, v nasprotju z vozilsko različico cikla, omogoča ustrezno ovrednotenje sprememb v hibridnih pogonskih sestavih, brez vplivov strategije menjavanja prestav, parametrov vozila in krmilnih strategij med postanki vozila. V skladu z definicijo, podano v [15], je negativni navor testnega cikla pri določeni vrtilni frekvenci enak 40% največjega pozitivnega navora pri tej vrtilni frekvenci.

V [16] je bilo pokazano, da je povprečni navor ETC sorazmerno velik. V predstavljeni analizi smo se zato odločili sistematično raziskati vpliv različnih povprečnih obremenitev testnega cikla ob enaki sledi vrtilnih frekvenc na parametre pogonskih sestavov. V prvi fazi smo tako pomnožili točke pozitivnih navorov testnega cikla z navornimi pomnožitvenimi faktorji (TF) 0,4; 0,5; 0.6 in 0,8 in tako dobili testne cikle z manjšim povprečnim navorom. Ta sprememba povprečnega navora testnega cikla bi v resničnih delovnih razmerah ustrezala pogonu vozil, ki prevažajo različna bremena. V drugi fazi analize smo točke negativnih navorov testnega cikla pomnožili z negativnimi navornimi pomnožitvenimi faktorji (TF_{neg}) 1,5 in 2 ob nespremenjenih vrednostih točk pozitivnih navorov, kar bi v resničnih delovnih razmerah ustrezalo različnim vzorcem zaviranja.

2.5 Krmilne strategije

Krmilne strategije delovanja elementov vzporednega hibridnega pogonskega sestava so podrobno opisane v [8] in omogočajo: 1) hkratno delovanje EM in MNZ, da bi zagotovili zadosten navor pogonskega sestava, 2) polnjenje naprav za shranjevanje električne energije zaradi delovanja MNZ pri večji obremenitvi, 3) regenerativno zaviranje, 4) hkratno delovanje EM in MNZ, da bi preprečili polnjenje naprav za shranjevanje električne energije prek določene meje in 5) običajni pogon z MNZ.

MNZ v zaporednem hibridnem pogonskem sestavu deluje v skladu z OEOL krmilno strategijo ([2] in [4]), ki je prikazana na sliki 3 - OEOL. V prikazani raziskavi OEOL krmilno strategijo upravljamo na podlagi SOC, in sicer lega letve za dodajanje goriva (*FR*) je sorazmerna s SOC in

2.4 Driving test cycle

The powertrain parameters were evaluated according to the ETC (European Transient Cycle) engine dynamometer transient cycle [15]. An engine dynamometer version of the ETC was chosen rather than a vehicle one, since it enables an appropriate evaluation of the changes in the powertrain configuration solely, excluding the influences of the gearshift strategy, the vehicle parameters, and the control strategies during the vehicle stops. In accordance with Ref. [15] the negative torque values equal to –40 % of the positive torque available at the associated speed point were selected.

It was shown in Ref. [16] that the average torque of the ETC is relatively high. The original ETC was, therefore, scaled to obtain test cycles with a lower average torque in order to enable a systematic comparison and analysis of the powertrain parameters when operating according to test cycles with different average loads and the same engine speed trace. Firstly, the positive torque values of the ETC were multiplied by the torque factors (TF) 0.4, 0.5, 0.6 and 0.8 in order to determine the new test cycles. This scaling might be considered as an operation of the vehicles carrying different loads when real driving conditions are concerned. Secondly, the negative torque values of the original ETC were multiplied by the factors (TF_{neg}) 1.5 and 2 and the positive torque values were unaltered. This scaling should mimic more progressive deceleration patterns.

2.5 Control strategy

The control strategy of the parallel hybrid powertrain is exhaustively described in Ref. [8] and allows for: 1) electric assistance of the ICE, 2.) replenishing the electric storage devices by operating the ICE at a higher torque output, 3) regenerative braking, 4) simultaneous operation of the ICE and the EM in order to prevent charging of the electric storage devices above the specified limit and 5) normal operation of the ICE.

The optimum engine-operation line (Fig. 3-OEOL) ([2] and [4]) control strategy was applied when analyzing the series hybrid powertrain. In the presented analysis the OEOL control strategy was based on the battery's SOC, i.e., the fuel rack position (*FR*) is proportional to the SOC and the vrtilna frekvenca MNZ (n) je sorazmerna z lego letve za dodajanje goriva: $FR \propto$ SOC in $n \propto FR$.

3 REZULTATI

V nadaljevanju so predstavljeni rezultati analize delovanja vzporednega in zaporednega hibridnega pogonskega sestava. V preglednici 1 so zbrani rezultati delovanja običajnega pogonskega sestava z MNZ v skladu z ETC in njegovimi izpeljankami (poglavje 2.4). Za takšen pogonski sestav je značilno, da so parametri pogonskega sestava za testne cikle z TF_{neg} = 1,5 in 2 enaki parametrom osnovnega cikla (TF=1).

Rezultati analiz obeh pogonskih sestavov za različne TF (točke pozitivnih navorov ETC so pomnožene z navornimi pomnožitvenimi faktorji TF) so predstavljeni in analizirani v poglavjih 3.1 in 3.2, medtem ko so rezultati analiz za različne vrednosti TF_{neg} in različne vrste naprav za shranjevanje električne energije predstavljeni in analizirani v poglavju 3.3.

V nadaljevanju se indeks P nanaša na vzporedni hibridni pogonski sestav in indeks S na zaporedni hibridni pogonski sestav.

3.1 Vzporedni hibridni pogonski sestav

Slika 4 a) prikazuje $\Delta_{f,P}$, rhs_{1P}, rhs_{2P} in rhs_{3P}; en. (4). Iz poteka krivulje $\Delta_{f,P}$, ki pada z manjšajočim se TF, je razvidno, da je z vzporednimi hibridnimi pogonskimi sestavi mogoče doseči znatno zmanjšanje porabe goriva za testne cikle z majhno povprečno obremenitvijo. Iz poteka krivulje pa je prav tako razvidno, da analizirani vzporedni hibridni pogonski sestav za testne cikle z veliko povprečno obremenitvijo porabi več goriva kakor običajni pogonski sestav z MNZ. Opisane pojave je mogoče razložiti z analizo posameznih členov v enačbi (4).

Iz krivulj na sliki 4 a) razberemo, da je majhna poraba goriva za testne cikle z majhno povprečno obremenitvijo posledica večjega izkoristka MNZ v vzporednem hibridnem pogonskem sestavu (sl. 4 a) - rhs_{1P}) in regenerativnega zaviranja (sl. 4 a) – rhs_{3P}), medtem ko krivulja rhs_{2P} na sliki 4 a) nakazuje pomembnost upoštevanja izgub ob pretvorbah električne energije, ki lahko znatno prispevajo k zmanjšanju učinkovitosti energijskih pretvorb v vzporednih hibridnih pogonskih sestavih. Povečanje porabe goriva vzporednega hibridnega pogonskega sestava v primerjavi z običajnim pogonskim sestavom z MNZ za testne cikle z veliko povprečno

ICE speed (n) is proportional to the fuel rack position: $FR \propto$ SOC and $n \propto FR$.

3 RESULTS

The results of the parallel and the series hybrid powertrains are presented in this section. Table 1 shows the results of the baseline powertrain when running according to the ETC and its variations (section 2.4). It should be noted that the test cycles with TF_{neg} = 1.5 and 2 feature the same parameters as the original test cycle (TF=1) for the baseline (ICE) powertrain.

The results of both hybrid powertrains for different TFs, i.e., positive torque values of the ETC were multiplied by the torque factors (TFs), are presented and analyzed in Sections 3.1 and 3.2, whereas the analysis of the results for different negative torque factors (TF_{neg}) and different types of electrical-energy storage devices are presented and analyzed in Section 3.3.

Subsequently, index P denotes the parallel hybrid powertrain and index S denotes series one.

3.1 Parallel hybrid powertrain

Fig. 4 a) presents $\Delta_{f,P}$, rhs_{1P}, rhs_{2P} and rhs_{3P}; Eq. (4). It is clear from Fig. 4 a) that $\Delta_{f,P}$ decreases with decreasing TF, indicating that a substantial reduction in the fuel consumption can be achieved for drive cycles with a low average load, whereas for the test cycles with a high average load the fuel consumption of the parallel hybrid powertrain can exceed that of the baseline one. It is necessary to analyze the individual terms of Eq. (4) in order to adequately interpret this phenomenon.

The good fuel economy for the test cycles with a low average load is due to an increase in the effective efficiency of the ICE in the parallel hybrid powertrain (Fig. 4 a) - rhs_{1P}) and due to the regenerative braking (Fig. 4 a) - rhs_{3P}), whereas it is discernable that the electrical losses (Fig. 4 a) - rhs_{2P}) should not be neglected, since they significantly reduce the fuel economy of the hybrid powertrain. On the other hand, it is clear that the fuel consumption of the parallel hybrid powertrain can exceed that of the baseline one for the test cycles with a high average load due to smaller improvements in the obremenitvijo pa je predvsem posledica manjšega deleža izboljšanja dejanskega izkoristka MNZ (sl. 4 a) - rhs_{1P}) in zaradi regenerativnega zaviranja (sl. 4 a) – rhs_{3P}), ter velikih izgub ob pretvorbah električne energije (sl. 4 a) – rhs_{2P})

3.2 Zaporedni hibridni pogonski sestav

Na sliki 4 b) so predstavljene krivulje $\Delta_{f,S}$, rhs_{1S}, rhs_{2S} in rhs_{3S}; en. (12) in $\Delta_{\eta_{eff},S} = \eta_{eff} / \eta_{eff,h} - 1$. S slike 4 b) je razvidno, da je poraba goriva zaporednega hibridnega pogonskega sestava ($\Delta_{f,S}$) večja od porabe goriva običajnega pogonskega sestava z MNZ za celoten razpon analiziranih TF, kljub bistvenemu izboljšanju dejanskega izkoristka MNZ v zaporednem hibridnem pogonskem sestavu ($\Delta_{\eta_{eff},S}$), ki deluje v optimalnem delovnem polju. Iz opisanih dejstev in slike 4 b) lahko povzamemo, da je manjša učinkovitost energijskih pretvorb v zaporednem hibridnem pogonskem sestavu posledica daljše verige energijskih pretvorb, v katero so neobhodno vključeni EM, EG in močnostna elektronika, ter izgub pri shranjevanju električne energije.

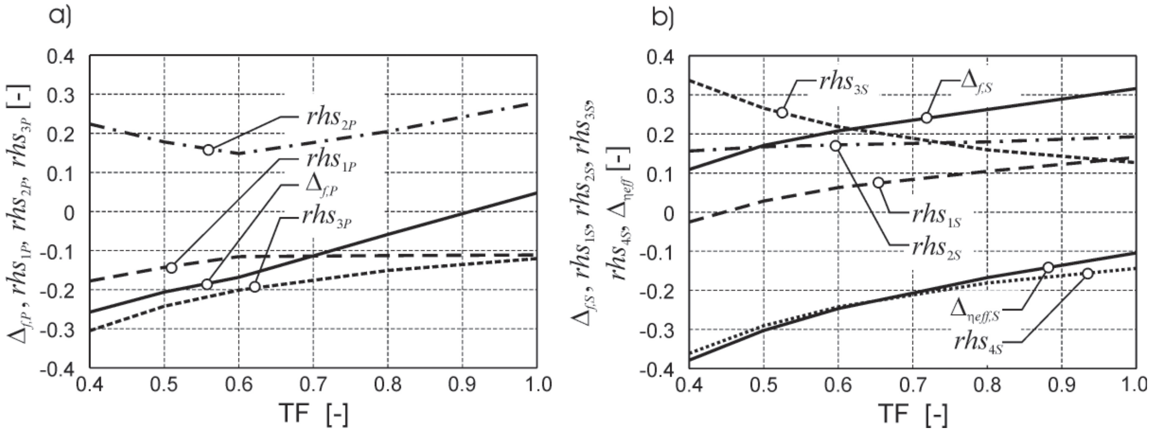
Ustrezni parameter za popis razmerja izkoristkov pogonskih sestavov je tako rhs_{1S}, ki upošteva izkoristke električnih komponent, ki so vključene v verigo energijskih pretvorb. Iz slike 4 b) je razvidno, da imata krivulji $\Delta_{f,S}$ in rhs_{1S} podoben potek kakor krivulja $\Delta_{\eta_{eff},S}$, saj je vsota členov rhs_{2S}, rhs_{3S} in rhs_{4S} približno stalna, izkoristki EG, EM in močnostne elektronike pa se tudi bistveno ne spreminjajo v opazovanem območju TF. Relativna količina električne energije, ki jo proizvede EG in se shrani v ES ter jo kasneje porabi EM, je skoraj neodvisna od TF, kar pojasni potek krivulje rhs_{2S}. Slednji pojav je mogoče pojasniti tudi z dejstvom, da MNZ deluje v določenem optimalnem polju in ne sledi nenadnim spremembam obremenitev v testnem ciklu. Vsota rhs_{3S} in rhs_{4S} je približno stalna, saj oba člena popisujeta procese, ki nastanejo zaradi regenerativnega zaviranja. rhs_{4S} je sorazmeren z $W_{br,h} < W_{br}$ in tako popisuje pozitivne vplive regenerativnega zaviranja, medtem ko rhs_{3S} upošteva izgube zaradi proizvodnje, shranjevanja in porabe električne energije, pridobljene z regenerativnim zaviranjem; za idealizirani primer brez električnih izgub sledi $\eta_{EM,G}\eta_{eet,EM\to ES}\eta_{ES}\eta_{eet,ES\to EM}\eta_{EM,M}$ in $rhs_{3S} \to 0$.

effective efficiency of the ICE (Fig. 4 a) - rhs_{1P}) and in the regenerative braking (Fig. 4 a) - rhs_{3P}) and due to high electrical losses (Fig. 4 a) - rhs_{2P}).

3.2 Series hybrid powertrain

Fig. 4 b) presents $\Delta_{f,S}$, rhs_{1S}, rhs_{2S} and rhs_{3S}; Eq. (12), and $\Delta_{\eta_{eff},S} = \eta_{eff} / \eta_{eff,h} - 1$. From analyzing Fig. 4 b) it can be concluded that the fuel consumption of the series hybrid powertrain ($\Delta_{f,S}$) exceeds that of the baseline one for the whole range of the TF, despite a much higher effective efficiency of the ICE ($\Delta_{\eta_{eff},S}$), which can be operated in a selected optimum regime. Thus, the lower energy-conversion efficiency of the series hybrid powertrain is a consequence of a longer energy-conversion chain, i.e., EG, EM and the power converter are unavoidably included in the energy transfer, and due to the losses accompanying the storage of the electrical energy.

The relevant parameter representing the ratio of the powertrain efficiencies is therefore rhs_{1S}, which includes the efficiencies of the electric devices incorporated in the energy-conversion chain. The curves of $\Delta_{f,S}$ and rhs_{1S} have a similar trend to the $\Delta_{\eta_{eff},S}$ one, since the sum of rhs_{2S}, rhs_{3S} and rhs_{4S} is nearly constant and the efficiencies of the EG, the EM and the power converter also do not change significantly for the analyzed range of TFs. rhs_{2S} is nearly constant, since the relative amount of electrical energy that is produced by the EG, stored in the ES and later consumed by the EM remains nearly constant, regardless of the TF. This is somehow intuitive, since the ICE of the series hybrid powertrain operates in a selected optimal field or line and does not follow the instant changes of speed and load. The sum of rhs_{3S} and rhs_{4S} is also nearly constant, since they both address energy flows related to the regenerative braking. rhs_{4S} accounts for the positive effect due to regenerative braking ($W_{br,h} < W_{br}$), whereas rhs_{3S} accounts only for the electrical losses due to production, storage and the consumption of the electrical energy gained by the regenerative braking, i.e., if $\eta_{EM,G}\eta_{eet,EM\to ES}\eta_{ES}\eta_{eet,ES\to EM}\eta_{EM,M}$ then $rhs_{3S} \to 0$.



Sl. 4. *Parametri a) vzporednega hibridnega pogonskega sestava in b) zaporednega hibridnega pogonskega sestava*

Fig. 4. *Parameters of a) parallel hybrid powertrain and b) series hybrid powertrain*

3.3 Analiza in povzetek

Na podlagi rezultatov analize lahko povzamemo, da se $\Delta_{f,S}$ in $\Delta_{f,P}$, ki sta izračunana neposredno iz rezultatov simulacij, popolnoma ujemata s $\Delta_{f,S}$ in $\Delta_{f,P}$, ki sta izračunana z enačbama (4) in (12). Ta ugotovitev potrjuje pravilnost in splošno uporabnost enačb (4) in (12) za analizo učinkovitosti energijskih pretvorb poljubnih vzporednih in zaporednih hibridnih pogonskih zasnov.

S slike 4 je razvidno, da je $\Delta_{f,P}$ mnogo manjši od $\Delta_{f,S}$ v vseh analiziranih delovnih režimih. Vzporedni hibridni pogonski sestav porabi v analiziranih primerih manj goriva kakor zaporedni hibridni pogonski sestav zaradi krajše verige energijskih sprememb. V zaporednem hibridnem pogonskem sestavu so v verigo energijskih sprememb neobhodno vključeni EM, EG in močnostna elektronika, kar ima za posledico $rhs_{1P} < rhs_{1S}$. Za vzporedni hibridni pogonski sestav je značilno, da se količina energije, ki jo porablja elektromotor, zmajšuje z zmanjšanjem TF in da se ES polnijo izključno z regenerativnim zaviranjem za TF≤0,6. Nasprotno pa je za zaporedni hibridni pogonski sestav značilno, da je relativna količina energije, ki jo proizvede MNZ in se shranjuje v ES (rhs_{2S}), približno stalna. Izgube, ki izvirajo iz proizvodnje električne energije z delovanjem MNZ pri večji obremenitvi, so za TF<1 tako manjše za vzporedni hibridni pogonski sestav.

Negativni navori, ki jih predpisuje testni protokol za dinamometrsko različico ETC so sorazmerno majhni. Ob nenadnih zaviranjih vozil

3.3 Analysis and summary

It should be noted that both $\Delta_{f,S}$ and $\Delta_{f,P}$ calculated directly from the simulation results and $\Delta_{f,S}$ and $\Delta_{f,P}$ calculated by Eqns. (4) and (12) coincide perfectly for all the analyzed cases. Thus, Eqns. (4) and (12) are generally valid and could be applied for the calculation of any parallel and series hybrid powertrain configuration.

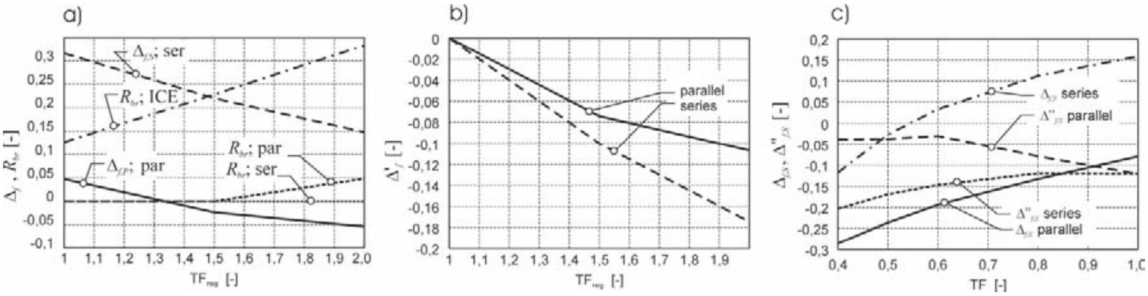
It is obvious from Fig. 4 that $\Delta_{f,P}$ is much smaller than $\Delta_{f,S}$ for all the operating regimes. From the presented results it can thus be concluded that for the analyzed cases the parallel hybrid powertrain possesses a greater potential for fuel-economy enhancement due to the shorter energy-conversion chain, since the series hybrid powertrain is forced to incorporate the electric generator, the electric motor and the power converter resulting in $rhs_{1P} < rhs_{1S}$. It can additionally be concluded that in a parallel hybrid powertrain the need for the EM assistance diminishes with decreasing TF, and ES are charged solely by the regenerative braking for TF≤0.6. In contrast, in the series hybrid powertrain the relative amount of energy produced by the ICE and stored in the ES (rhs_{2S}) is nearly constant, as discussed in the previous section. Thus, the negative impact of the losses due to the electrical energy production by the ICE on Δ_f is smaller for a parallel hybrid powertrain than for the series hybrid powertrain for TF<1.

The dynamometer version of the ETC features relatively low negative torque values and thus much higher negative torques can occur during se lahko pojavijo mnogo večji negativni navori, kar smo v analizi upoštevali z vpeljavo pomnožitvenega faktorja (TF_{neg}) za točke negativnih navorov testnega cikla. S slike 5 a) je razvidno, da je povečanje absolutnih vrednosti negativnega navora bolj vplivalo na izboljšanje Δ_f zaporednega hibridnega pogonskega sestava kakor na izboljšanje Δ_f vzporednega hibridnega pogonskega sestava, kar je posledica manšje imenske moči električnega stroja, ki je vgrajen v vzporedni hibridni pogonski sestav. Ta ugotovitev se kaže tudi na krivuljah relativnega dela, ki ga odvedemo z zavorami, (sl. 5 a) - R_{br}); $R_{br} = W_{br}/W_{ICE}$, kjer W_{br} predstavlja delo zaviranja pri običajnem pogonu z MNZ in obeh hibridnih pogonskih sestavov. R_{br} za vzporedni hibridni pogonski sestav je večji je od R_{br} za zaporedni hibridni pogonski sestav, po pričakovanju pa je največji R_{br} za običajni pogon z MNZ. Navedene ugotovitve bolj nazorno prikažemo s potekom krivulje $\Delta'_f = m_{f,tc,h,TF_{neg}>1} / m_{f,tc,h,TF_{neg}=1} - 1$, ki nakaže večje izboljšanje Δ'_f za zaporedni hibridni pogonski sestav. Prikazani rezultati nakazujejo, da bi zaporedni hibridni pogonski sestavi lahko bili primerni za uporabo pri mestni vožnji, pri kateri prihaja do pogostih naglih zaviranj.

Slika 4 in enačbi (4) in (12) nakazujejo velik vpliv izkoristka polnjenja - praznjenja naprav za shranjevanje električne energije na porabo goriva v hibridnih pogonskih sestavih. Ultrakondenzatorji z izkoristkom polnjenja-praznjenja, ki v analiziranih primerih znaša 87 do 94% (za 36 do 46% izboljšanje v primerjavi z električnimi akumulatorji) zato bistveno zmanjšajo porabo goriva obeh hibridnih zasnov (sl. 5 c)), kar je očitno iz primerjave rezultatov Δ_f na slikah 4 in 5 c). Zmanjšanje porabe goriva v primerjavi s hibridnimi pogonskimi sestavi, ki uporabljajo električne akumulatorje, nazorno prika□e

the vehicle driving cycles, i.e., rapid deceleration. Therefore, an additional analysis where the negative torque values were multiplied by a factor (TFneg) of 1.5 and 2 was performed in order to analyze the influences of the negative torque magnitudes, i.e., the deceleration pattern, on the Δ_f. Fig. 5 a) shows that an improvement in Δ_f of a series hybrid powertrain due to increasing absolute values of the negative torque is more significant than an improvement in Δ_f of the parallel powertrain, since the electric machine of the parallel hybrid powertrain is not powerful enough to recuperate all the available energy by regenerative braking. This conclusion is clear from Fig. 5 a) - R_{br} indicating the larger braking work of the parallel hybrid powertrain in comparison to that of the series hybrid powertrain; it is obvious that R_{br} of the baseline powertrain is the largest. $R_{br} = W_{br}/W_{ICE}$, where W_{br} represents the braking work of the baseline and hybrid powertrains. It can, therefore, be concluded that $\Delta'_f = m_{f,tc,h,TF_{neg}>1} / m_{f,tc,h,TF_{neg}=1} - 1$ of the series hybrid powertrain decreases more progressively with increasing TFneg than R_{br} of the parallel hybrid powertrain; Fig. 5 b). These results indicate that series hybrid powertrains might be a suitable choice when drive cycles with frequent rapid decelerations, i.e., urban driving, are concerned.

Figure 4 and Eqns. (4) and (12) suggest that the charge-discharge efficiency of the electrical-energy storage devices significantly influences the fuel economy of the hybrid powertrains. It is therefore logical that ultra-capacitors featuring a charge-discharge efficiency in the range of 87-94% for the analyzed cases (a 36-46% improvement over the batteries), possess significant potential to improve the fuel economy of the hybrid powertrains (Fig. 5 c)). Considering Δ_f in Figs. 4 and 5 c) it can be concluded that the application of ultra-capacitors significantly



Sl. 5. *Vpliv TF_{neg} na a) Δ_f in R_{br} ter b) Δ'_f in c) parametri obeh hibridnih zasnov v primeru uporabe ultrakondenzatorjev*

Fig. 5. *Influence of TFneg on a) Δ_f and R_{br} and b) Δ'_f, and c) powertrain parameters of both hybrid powertrains applying ultra-capacitors*

potek krivulje $\Delta"_f = m_{f,tc,h,UC} / m_{f,tc,h,bat} - 1$. Iz tega poteka krivulj $\Delta"_f$ je razvidno, da, razen za TF=1, uporaba ultrakondenzatorjev znatneje izboljša gospodarnost zaporednih hibridnih pogonskih sestavov. Ta ugotovitev izhaja iz predhodne analize, saj je relativna količina energije, ki jo razvije MNZ in se shranjuje v ES (rhs_{2S}), približno stalna za zaporedni hibridni pogonski sestav, medtem ko se ES pri vzporednem hibridnem pogonskem sestavu polnijo izključno z regenerativnim zaviranjem za TF≤0,6, kar vpliva na manjši $\Delta"_f$. $\Delta"_f$ v zaporednem hibridnem pogonskem sestavu se zmerno zmanjšuje z zmanjšanjem TF, saj se izboljšanje v η_{ES} zaradi uporabe ultrakondenzatorjev zmerno povečuje z manjšanjem TF

4 SKLEP

Učinkovitost energijskih sprememb v vzporednih in zaporednih hibridnih pogonskih sestavih je bila analizirana z analitično in simulacijsko metodo. Izkoristek vzporednega hibridnega pogonskega sestava je za analizirane testne cikle višji od izkoristka zaporednega hibridnega pogonskega sestava zaradi krajše verige energijskih pretvorb. Za obe hibridni različici je sorazmerno povečanje učinkovitosti energijskih pretvorb znatnejše za testne cikle z majhno povprečno obremenitvijo. Iz prikazanih rezultatov lahko sklepamo, da je analizirani vzporedni hibridni pogonski sestav energijsko učinkovit za testne cikle z majhno povprečno obremenitvijo, medtem ko so za testne cikle z večjo povprečno obremenitvijo primerni vzporedni hibridni pogonski sestavi z nizkim hibridizacijskim razmerjem, vendar je za slednje značilen nižji potencial možnosti zmanjšanja porabe goriva. Rezultati kažejo, da je za zaporedni hibridni pogonski sestav značilna manjša učinkovitost energijskih pretvorb, vendar pa je bilo v analizi nakazano, da bi zaporedni hibridni pogonski sestavi lahko bili primerni za uporabo v mestni vožnji, kjer smo priča pogostih naglih zaviranj. Rezultati analize uporabe ultrakondenzatorjev so pokazali, da so ultrakondenzatorji potencialno primerna rešitev za nadaljnjo izboljšanje učinkovitosti energijskih pretvorb v hibridnih pogonskih sestavi in njihov prodor na trgu.

improves the fuel economy of both hybrid powertrains. However, except for TF=1, the fuel-economy enhancement over the battery hybrid powertrain, i.e., $\Delta"_f = m_{f,tc,h,UC} / m_{f,tc,h,bat} - 1$, is more pronounced for the series hybrid powertrain than for the parallel hybrid powertrain. These conclusions follow from the above analysis, since in a series hybrid powertrain the relative amount of energy produced by the ICE and stored in the ES is nearly constant, whereas in the parallel hybrid powertrain the ES are charged solely by regenerative braking for TF≤0.6, thus resulting in a smaller $\Delta"_f$. $\Delta"_f$ of the series hybrid powertrain decreases slightly with decreasing TF, since the improvement in η_{ES} due to the application of ultra-capacitors increases with a decreasing TF.

4 CONCLUSION

The energy-conversion efficiency of the parallel and series hybrid powertrains was analyzed by means of a simulation and analytical approach. It was shown that for the analyzed test cycles the parallel hybrid powertrain features a better fuel economy than the series one due to a shorter energy-conversion chain. From the presented results it is clear that the improvement in the fuel economy of both hybrid powertrains increases with decreasing the test cycle average load. It can, therefore, be concluded that the analyzed parallel hybrid powertrain performs best for the test cycles with a lower average load, i.e., light-duty applications, whereas heavy-duty applications require powertrains with a low hybridization factor, resulting in smaller benefits in the fuel consumption. On the other hand, the series hybrid powertrain features a lower fuel-conversion efficiency, although it might be applicable for drive cycles featuring frequent rapid decelerations, which enable the recuperation of a large amount of the energy by regenerative braking. It was also highlighted in the paper that ultra-capacitors with sufficient storage capacity represent a promising solution for a further reduction in the fuel consumption of hybrid powertrains and their increased penetration of the market.

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Naslov avtorjev: doc. dr. Tomaž Katrašnik
prof. dr. Ferdinand Trenc
dr. Samuel Rodman Oprešnik
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
tomaz.katrasnik@fs.uni-lj.si

Authors' Address: Doc. Dr. Tomaž Katrašnik
Prof. Dr. Ferdinand Trenc
Dr. Samuel Rodman Oprešnik
University of Ljubljana
Faculty of Mechanical Eng.
Aškerčeva 6
1000 Ljubljana, Slovenia
tomaz.katrasnik@fs.uni-lj.si

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