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Izboljšanje dinamične karakteristike tlačno polnjenega motorja z uporabo električnih podpornih naprav

Improving the Transient Response of a Turbocharged Diesel Engine by using Electrical Assisting Systems

Tomaž Katrašnik - Ferdinand Trenc - Vladimir Medica - Samuel Rodman Oprešnik - Frančišek Bizjan

Za tlačno polnjene dizelske motorje je značilen daljši čas, potreben za odziv na nenadno povečanje obremenitve, v primerjavi s sesalnimi motorji, kar je posledica načina izmenjave energije med motorjem in turbopolnilnikom. Odzivnost tlačno polnjenega motorja je, z uporabo dodatnih električnih virov energije, mogoče izboljšati z neposrednim dovajanjem energije na ročično gred motorja z integriranim zaganjalnikom–generatorjem, ki je pritrjen na vztrajnik motorja in deluje kot dodatni elektromotor, ali s posrednim dovajanjem energije z uporabo elektromotorja, pritrjenega na gred turbopolnilnika. Za analizo vpliva obeh konceptov je bila uporabljena doslej večkrat preverjena brezrazsežna simulacijska metoda modeliranja pojavov v motorju, ki omogoča hitro in razmeroma natančno ovrednotenje dinamičnih karakteristik motorja. Eksperimentalno določene karakteristike elektromotorjev smo uporabili kot vhodne podatke simulacije, kar, povezano z natančnostjo simulacije, zagotavlja verodostojnost prikazanih rezultatov. V prispevku je analizirana interakcija motorja z električnimi podpornimi sistemi in nakazane so zahteve, ki jih morajo izpolnjevati električni motorji za učinkovito izboljšanje dinamične karakteristike motorja. Predstavljeni so rezultati simulacij različnih režimov vožnje vozila, ki nazorno prikazujejo značilnosti in razlike med obema zasnovama električne podpore.

(Ključne besede: motorji dizelski, polnjenje tlačno, simuliranje numerično, karakteristike dinamične)

It is a well-known fact that turbocharged Diesel engines suffer from inadequate response to sudden load increases, which is a consequence of the nature of the energy exchange between the engine and the turbocharger. The dynamic response of a turbocharged Diesel engine could be improved by the use of electrical assisting systems, either by direct energy supply with an integrated starter-generator mounted on the engine's flywheel or indirect energy supply with an electrically assisted turbocharger. A previously verified zero-dimensional computer-simulation method was used for the analysis of both concepts of electrical assistance. The reliability of the presented data is additionally ensured by the experimentally determined characteristics of the electric motors used as input parameters for the simulation. The paper offers an analysis of the interaction between the turbocharged Diesel engine and the electrical assisting systems as well as the requirements for electric motors that are suitable for the improvement of an engine's dynamic response in a vehicle. The presented results of vehicle dynamics indicate the features and differences of both concepts of electrical assistance.

(Keywords: Diesel engines, turbocharging, numerical simulations, dynamic response)

0 UVOD

Povečanje delovne sposobnosti sodobnih dizelskih motorjev je predvsem posledica tlačnega polnjenja in naknadnega hlajenja polnilnega zraka, saj se tako poveča masa svežega zraka v valju in s tem največja dovoljena količina vbrizganega goriva. Za takšne motorje je značilen slabši odziv na nenadno

0 INTRODUCTION

Turbocharging and subsequent charge cooling of the working medium causes an increase in the brake mean effective pressure (bmep) in a Diesel engine due to the increased in-cylinder mass of fresh air and, therefore, the maximum quantity of injected fuel. Poor performance during the engine load povečanje obremenitve kakor za sesalne motorje. Tlačno polnjeni motorji v fazi nenadnega povečanja obremenitve, zaradi prenizkega začetnega tlaka polnilnega zraka, z zakasnitvijo dosežejo največjo stacionarno vrednost srednjega efektivnega tlaka motorja. Doseganje največje stacionarne vrednosti srednjega efektivnega tlaka motorja je povezano z zagotovitvijo zadostne mase polnilnega zraka, ki omogoča popolno zgorevanje največje količine vbrizganega goriva. Masa svežega zraka v valju je neposredno povezana s tlakom v polnilnem zbiralniku. Na hitrost naraščanja tlaka v polnilnem zbiralniku imajo največji vpliv vztrajnostni moment rotorja turbopolnilnika ter karakteristike turbine in kompresorja. Večina sodobnih tlačno polnjenih dizelskih motorjev je opremljenih s sistemom za krmiljenje količine vbrizganega goriva v odvisnosti od tlaka polnilnega zraka – pnevmatski omejevalnik dobave goriva (PODG - LDA). Glavna naloga sistema je zagotavljanje popolnega zgorevanja v prehodnem režimu delovanja motorja ter posledično zmanjševanje emisije škodljivih snovi v izpušnih plinih, predvsem saj. PODG je nujen za doseganje strogih okoljevarstvenih norm. Emisija saj se bistveno poveča že pred nastopom nepopolnega zgorevanja, zato PODG običajno dopuščajo dobavo manjše količine goriva od količine, ki bi še lahko popolno zgorela. Zaradi omenjenega dejstva je odziv motorja, opremljenega s PODG , slabši od motorja brez PODG, saj je zaradi manjše količine vbrizganega goriva moč motorja manjša (neposredno zmanjšanje), hkrati pa je manjša tudi entalpija izpušnih plinov, kar vpliva na slabše pospeševanje turbopolnilnika ter posredno prek tlaka polnilnega zraka in PODG ponovno na zmanjšanje moči motorja v prehodnem režimu. Zahteve po izpolnjevanju strogih okoljevarstvenih norm, ki pa ne predstavljajo predmet raziskav tega prispevka, in izboljšanju dinamičnega odziva tlačno polnjenega motorja je mogoče izpolniti z uporabo električnih podpornih naprav. V nadaljevanju je predstavljen njihov vpliv na pospeševanje cestnega vozila in razložena interakcija z motorjem, ki poskuša osvetliti še neraziskano področje ter ponuditi temelj za nadaljnji razvoj električnih podpornih naprav.

1 SISTEM ZA DOBAVO GORIVA IN ELEKTRIČNE PODPORNE NAPRAVE

Motor MAN D826 LOH15, ki je predmet raziskav, je opremljen z vrstno visokotlačno tlačilko za gorivo ter PODG. Na sliki 1 je izrisana izmerjena karakteristika delovanja PODG pri različnih vrtljajih motorja v odvisnosti od nadtlaka v polnilnem zbiralniku (dp_2). Predstavljena karakteristika, ki je bila nespremenjena uporabljena v vseh prikazanih raziskanih primerih, določa najmanjši razmernik zraka, s katerim je, v istem motorju in ob podobnih delovnih pogojih, v prvem približku povezana emisija saj. S slike

increase, when compared with naturally aspired engines, is attributed to the nature of the energy exchange between the engine and the turbocharger. The maximum stationary bmep is reached with a delay, since it depends on there being a sufficient mass of fresh air in the cylinders to allow the complete combustion of a maximum amount of injected fuel. The mass of fresh air in the cylinder is directly proportional to the boost pressure, the increase rate of which is primarily influenced by the turbocharger's mass moment of inertia and the characteristics of the applied turbine and compressor. Advanced, turbocharged Diesel engines are usually equipped with a boost-pressure-controlled fuel-limiting system, called an LDA. The purpose of the LDA is to ensure complete combustion during engine-transient operating conditions, thereby reducing exhaust gas emissions, in particular, of black soot. Thus, the LDA is indispensable for meeting strict environmental regulations. Black-soot emission increases significantly before incomplete combustion occurs; the LDA therefore generally dictates the injection of a lower maximum fuel quantity than that which could have burned completely. The dynamic response of turbocharged Diesel engines equipped with an LDA is therefore slower than that of those without one. This phenomenon is firstly the consequence of direct engine-power reduction due to the lower quantity of fuel injected and secondly, the consequence of indirect engine-power reduction: the lower specific enthalpy of exhaust gases reduces turbocharger acceleration, resulting in a lower boost pressure and, via the LDA, in a reduced amount of fuel being injected. Meeting strict environmental regulations, on the one hand, which is not the subject of this paper, and improving the baseline engine dynamic response, on the other, is enabled by the application of electrical assistance systems. In this paper, the influence of electrical assisting systems on the dynamic-response improvent of a turbocharged Diesel engine propelling a truck is investigated. A variety of electrical assisting systems combined with the operation of the engine under various loading conditions should reveal an improvement in the dynamic response of a turbocharged Diesel engine equipped with electrical assisting systems, their interaction with the Diesel engine, as well as the demands placed on them.

1 FUEL-INJECTION EQUIPMENT AND ELECTRICAL ASSISTING SYSTEMS

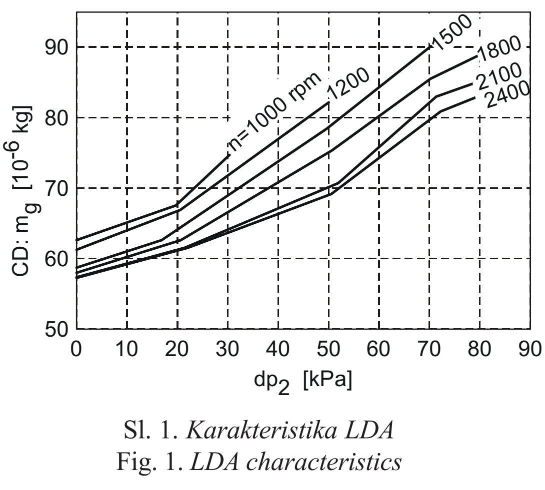
A simulated MAN engine (D0826 LOH 15) was equipped with a Bosch high-pressure fuel-injection pump linked with a pneumatically controlled LDA. Fig. 1 shows the influence of the gauge pressure (dp_2) on the cyclic fuel delivery (*CD*) for various engine speeds. The same LDA characteristics was used in all investigated cases, which results in nearly equal minimum air-fuel ratio that is, in the same engine and under similar operating conditions, in

1 je razvidno, da je karakteristika PODG za majhne nadtlake nekoliko položnejša, kar gre najverjetneje pripisati pnevmatskemu krmiljenju, nato pa narašča skoraj linearno. Z naraščajočimi vrtljaji se količina vbrizganega goriva pri nespremenljivem nadtlaku zmanjšuje, kar je, zaradi nespremenljivih krmilnih časov ventilov, posledica nižjega volumetričnega izkoristka motorja pri višjih vrtljajih, saj je tako zagotovljen približno enak najmanjši razmernik zraka pri različnih vrtljajih. Na sliki 2 je prikazana izmerjena največja ciklična dobava goriva (maks. m_g) ter ciklična dobava goriva pri okoliškem tlaku, pritisnjenem na PODG (m_g (dp_2=0)), v odvisnosti od vrtljajev. Zraven točk največje ciklične dobave goriva so vpisane vrednosti (v odstotkih) razmerja tlaka, pri katerem PODG dopušča dobavo največje količine goriva proti stacionarnem tlaku pri tej vbrizgani količini goriva. Iz prikazanega je razvidno, da pri 1000 in 1200 min^{-1} največje količine goriva ne omejuje karakteristika tlačilke za gorivo, ampak nastavitev PODG. Omenjeno dejstvo je predvsem posledica nelinearne naravne pretočne karakteristike turbine, ki v povezavi s kompresorjem pri nizkih vrtljajih motorja ne omogoča doseganja visokih polnilnih tlakov, kar, pri določeni najmanjši vrednosti razmernika zraka, rezultira v zmanjšano količino dobavljenega goriva. Od 1400 min^{-1} naprej PODG ne omejuje največje ciklične dobave goriva. Med 1400 min^{-1} in 2400 min^{-1} se največja ciklična dobava goriva zmanjšuje, s čimer je zagotovljen približno enak največji tlak v valjih in zmerne toplotne obremenitve motorja. Iz vrednosti razmerja tlakov je tudi razvidno, da je z večanjem vrtljajev motorja največja količina goriva dobavljena pri razmeroma nižjem tlaku. To razmerje se zmanjšuje hitreje od največje ciklične dobave goriva, kar je posledica prej omenjene nelinearne pretočne karakteristike turbopolnilnika.

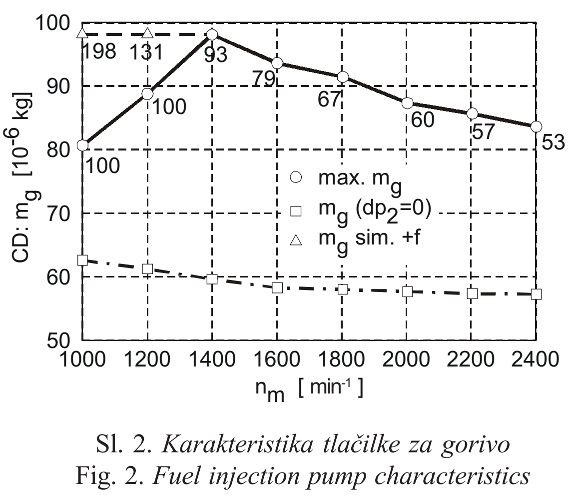
Zaradi opisane interakcije med tlačilko za gorivo in PODG pri 1000 in 1200 min^{-1} je bila v primeru posrednega dovajanja energije z elektromotorjem, pritrjenim na gred turbopolnilnika, ki omogoča doseganje polnilnih tlakov nad ustaljeno vrednostjo, največja količina dobavljenega goriva pri omenjenih

relatively strong relation to the emission of black soot. The quantity of injected fuel decreases with increasing engine speed at a constant boost pressure, thus enabling an almost constant in-cylinder air-fuel ratio due to a lower volumetric efficiency of the engine at higher engine speeds. Fig. 2 shows the maximum measured *CD* (max. m_g) and the *CD* for ambient pressure applied on the LDA (m_g (dp_2=0)) as functions of the engine speed. The ratia (in percentages) of the LDA full-fueling gauge pressure to stationary gauge pressure for the same quantity of injected fuel are plotted along the ‘max. m_g’ curve. It is obvious that at 1000 and 1200 rpm the *CD* is limited by the LDA setting rather than by the characteristics of the fuel-injection pump. This phenomenon is generally the consequence of the free-floating turbine flow characteristics, which in connection with the compressor produces a low boost pressure at low engine speeds, thus resulting in a low *CD* at the set minimum air-fuel ratio. Above 1400 rpm, the LDA no longer influences the stationary maximum *CD*. From 1400 to 2400 rpm the *CD* decreases, maintaining an almost constant maximum cylinder pressure and thermal loads of the engine. The relative pressure at which the LDA enables full fuel delivery decreases with increasing engine speed (Fig. 2); this ratio decreases faster than the maximum cyclic fuel delivery, due to the previously discussed turbocharger characteristics.

Because the maximum *CD* is limited by the operation of the LDA below 1400 rpm, the maximum *CD* will rise if the boost pressure is increased, as in the case when using an electrically assisted turbocharger. For the simulation of an engine with an electrically assisted turbocharger, a maximum *CD* below 1400 rpm was, in addition to the measured one, also set to a value equal to that at 1400 rpm. This is supposed to be an acceptable value when the peak cylinder pressure and the thermal loadings are



Sl. 1. *Karakteristika LDA*
Fig. 1. *LDA characteristics*



Sl. 2. *Karakteristika tlačilke za gorivo*
Fig. 2. *Fuel injection pump characteristics*

vrtljajih v simulaciji, poleg izmerjene, postavljena (izbrana) tudi na vrednost dovedenega goriva pri 1400 min^{-1} (slika 2: m_g sim. +f).

V simulaciji je kot neposredni dodatni vir energije uporabljen integriran in na vztrajnik motorja pritrjen zaganjalnik generator (ISG), izdelan v podjetju ISKRA Avtoelektrika. Uporabljena je karakteristika ISG s 36-voltnim napajanjem; največji navor 70 Nm ISG doseže pod 1200 min^{-1}, nato pa se navor zmanjša skoraj linearno do 10 Nm pri 2200 min^{-1}, ki predstavlja zgornjo mejo delovanja ISG. ISG naj bi delno kompenziral razliko med močjo v prehodnem režimu in največjo stacionarno močjo ter tako izboljšal odziv motorja.

Kot posredni vir energije sta bila uporabljena dva elektromotorja z namenom, da čim hitreje zagotovita tlak v polnilnem zbiralniku, ki že omogoča vbrizgavanje največje količine goriva ter posledično doseganje največjega stacionarnega srednjega efektivnega tlaka motorja. Zgornja meja delovanja obeh elektromotorjev je 85000 min^{-1}, kar za simulirani motor predstavlja ekvivalent največjega polnilnega tlaka pri določenih vrtljajih motorja, pri katerih PODG še omejuje dobavo goriva [1]. Prvi elektromotor (EM2), ki je podrobno predstavljen v [1] do [3], razvije največji navor 0,2 Nm in ima masni vztrajnostni moment $6*10^{-5}$ kgm^2. Zaradi stvarnejše primerljivosti je v analizi uporabljen tudi elektromotor, izdelan v družbi za uporabno mestno okoljevarstvo (Gesellschaft für angewandte Stadtökologie - GfAS mbH), s karakteristikami, ki so predstavljene v [4]; največji navor znaša 0,57 Nm ob masnem vztrajnostnem momentu $2.87*10^{-5}$ kgm^2.

2 SIMULACIJSKI PROGRAM

Uporabljena je bila brezrazsežna simulacijska metoda, katere zasnova je predstavljena v [5], dopolnjena in razširjena trenutno uporabljena verzija pa v [1] do [3]. Za simulacijo, ki je uporabljena v tem prispevku je bil dodan podprogram za spreminjanje kota začetka vbrizgavanja goriva, ki omogoča doseganje natančnosti pod 4% med izmerjenimi in simuliranimi parametri po celotni zunanji karakteristiki motorja. Osnova simulacije cestne vožnje je bila povzeta po [6] ter razširjena za potrebe simulacije.

3 REZULTATI

V rezultatih so prikazana tri različna povečanja obremenitve motorja, vgrajenega v tovorno vozilo, ki simulirajo obnašanje vozila na cesti ter prikazujejo značilnosti in vpliv električnih podpornih naprav. Tovorno vozilo MAN 8.225 LC z največjo dovoljeno skupno maso 7490 kg je opremljeno s šeststopenjskim menjalnikom S6-850. Vanj je vgrajen 6-valjni tlačno polnjeni motor MAN 826D LOH15 s hladilnikom polnilnega zraka ter turbopolnilnikom HOLSET H1E-8264BF/H16WA8. Motor z delovno prostornino 6,87 dm^3, vrtino/gibom

concerned. This modified *CD* was labeled with 'm_g sim. +f' in Fig. 2 and denoted by the maximum added *CD*.

An integrated starter generator (ISG) produced and tested by ISKRA "Avtoelektrika" was used in the simulation as a direct energy-supply source. This ISG develops 70 Nm below 1200 rpm, decreasing almost linearly to 10 Nm at a maximum operating speed of 2200 rpm (at a voltage of 36 V). The ISG partially compensates the difference between the transient and stationary bmep, and therefore improves the dynamic behavior of the turbocharged engine.

Two electric motors mounted on the turbocharger shaft were used as an indirect energy supply, with the aim of ensuring faster boost pressure build-up to enable the simultaneous injection of a larger amount of fuel. Both electric motors operate up to a maximum of 85000 rpm, representing the equivalent to the maximum boost pressure still limiting full fuelling via an LDA [1]. A prototype asynchronous electric motor produced by ISKRA Avtoelektrika, labeled EM2, and presented in detail in [1] to [3], develops a maximum torque of 0.2 Nm and has a mass moment of inertia of $6*10^{-5}$ kgm^2. Another high-performance electric motor, denoted EMG, developing 0.57 Nm at 20000 rpm with $2.87*10^{-5}$ kgm^2 mass moment of inertia (produced by Gesellschaft für angewandte Stadtökologie - GfAS mbH [4]) was used in the simulations for better comparisons.

2 SIMULATION PROGRAM

The simulation program is based on the zero-dimensional filling and emptying method. The basis of the simulation method is presented in [5], whereas the extended code used here is described in detail in [1] to [3]. The recent version of the simulation program automatically adapts the start of fuel injection to the engine load and speed, enabling agreement between the experimental and simulated results of within 4% for the whole engine maximum-load characteristics. The vehicle dynamics simulation subroutine was developed according to [6].

3 RESULTS

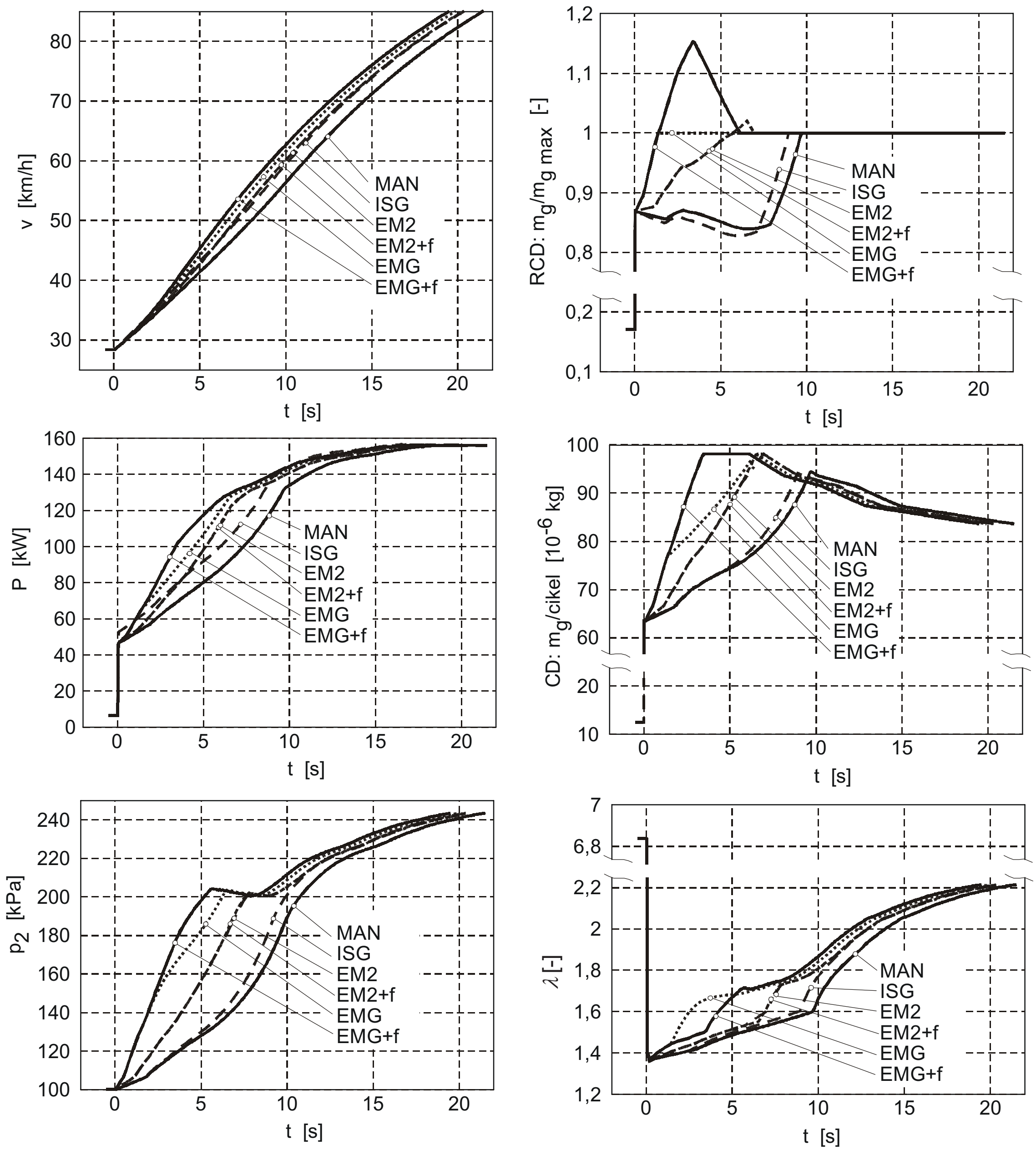
The results of three different loading cases of the engine powering a MAN 8.225 LC truck with a maximum gross weight of 7490 kg, equipped with an S6-850 gearbox, are presented. These results should reveal only improvement in the dynamic response of the turbocharged Diesel engine by electrical assisting systems and their characteristics. A 6.87 dm^3 six-cylinder MAN D0826 LOH 15 engine with a bore/stroke of 108/125 mm, a compression ratio of 18:1, which develops 162kW at 2400 rpm is equipped with a

108/125 mm ter kompresijskim razmerjem 18:1 razvije 162kW pri 2400 min^{-1}.

Prvi primer obremenitve ustreza preizkusu prožnosti motorja; pri vrtilni frekvenci motorja 800 min^{-1} v peti prestavi pri polno obteženem vozilu v času nič na ravni cesti dodamo polni plin. Z izboljšanjem dinamičnega odziva motorja se zmanjša potreba po pretikanju, posledica pa je boljše pospeševanje vozila ali možno podaljšanje prestavnih razmerij ob enaki odzivnosti vozila. Na sliki 3 so predstavljeni hitrost vozila (v), moč motorja (P), polnilni tlak (p_2), ciklična dobava goriva (CD), razmernik zraka (λ) in relativna ciklična dobava goriva (RCD) za opisano obremenitev. RCD predstavlja razmerje med trenutno dobavljeno maso goriva in

charge air cooler and a HOLSET H1E-8264BF/H16WA8 turbocharger.

First, the fully loaded vehicle was running at a constant speed of 30 km/h (800 rpm) in fifth gear on a flat road. At time t=0 the fuel rack was pushed to its maximum. The use of electrical assisting systems enables better vehicle dynamics, or allows the introduction of gearboxes with fewer gears. Fig. 3 shows the vehicle speed (v), the engine power (P), the boost pressure (p_2), the cyclic fuel delivery (CD), the air-fuel ratio (λ) and the relative cyclic fuel delivery (RCD) for the described acceleration. The RCD represents the ratio of instant injected-fuel quantity to the maximum cyclic fuel delivery (Fig. 2 max. m_g), and thus the ratio of the instant to the maximum



Sl. 3. *Pospeševanje od 800 do 2400 min^{-1} v peti prestavi*
Fig. 3. *Vehicle acceleration from 800 to 2400 min^{-1} in fifth gear*

največjo ciklično dobavo goriva (sl. 2: maks. m_g) ter neposredno razmerje med trenutnim in največjim stacionarnim srednjim efektivnim tlakom motorja pri določenih vrtljajih (zanemarjene razlike zaradi dela izmenjave delovnega medija). V primeru uporabe elektromotorja, pritrjenega na gred turbopolnilnika, je za vrtljaje motorja, manjše od 1400 min^{-1} in dodatno količino vbrizganega goriva (sl. 2: m_g sim. +f), to razmerje lahko tudi večje od 1.

S slike 3 je nazorno razvidno obnašanje tlačno polnjenega motorja, opremljenega s PODG v prehodnem režimu delovanja. Motor MAN (osnovna inačica motorja) v začetku dobavi 87% največje količine goriva. Zaradi povečane entalpije izpušnih plinov začne naraščati tlak v polnilnem zbiralniku, kar posledično, prek PODG, vpliva na povečanje *CD*. Kljub povečanju *CD* pa se *RCD* zmanjšuje, saj v tem času vozilo pospešuje (zvečanje vrtljajev motorja), največja ciklična dobava goriva pa se proti 1400 min^{-1} zvečuje. Za motor MAN se začne *RCD* zvečevati po 7,9s, ko motor doseže 1400 min^{-1} (ekstrem *CD*; sl.2), saj se tlak p_2 še zvišuje, največja ciklična dobava goriva pa se začne zmanjševati. Največjo ciklično dobavo goriva (*RCD*=1) motor MAN doseže po 9,8 s, kar je povezano s prenehanjem omejevanja dobave goriva s PODG. Tlak p_2 se je zvišal nad vrednost, pri kateri, pri 1570 min^{-1}, PODG še omejuje gorivo. Opisani pojav je lepo viden tudi kot vrh na sliki 3-*CD*, kot sprememba strmine krivulje moči (sl. 3-*P*) in razmernika zraka (sl.3-λ).

Motor, opremljen z ISG, ki se vklopi v trenutku dodajanja pedala za plin, brez zakasnitve poveča moč motorja, kar je razvidno iz poteka moči motorja (sl.3-*P*). Ker ISG dodaja moč neposredno na gred motorja, s tem ne povečuje polnilnega tlaka. Polnilni tlak se zvišuje le nekoliko hitreje kakor pri motorju MAN, kar je posledica večjega masnega toka skozi motor, povezanega z višjo vrtilno frekvenco motorja, saj motor z ISG pospešuje hitreje. Manjša vrednost *RCD* kakor pri motorju MAN do 7s je posledica še večjega zaostajanja polnilnega tlaka za vrtljaji motorja, saj ISG dovaja moč na gred motorja in ne turbopolnilniku. Po 7s motor z ISG doseže 1400 min^{-1} in *RCD* se začne zviševati zaradi že opisanega dejstva.

S slike 3: *p2*, *CD* in *RCD* je razvidno, da zaradi višjega polnilnega tlaka motor z EM2, zaradi karakteristike PODG, dobiva več goriva, kar vpliva na večjo *CD*, *RCD* in moč motorja. Na hitrost zviševanja tlaka motorja z EM2 poleg navora elektromotorja (EM) vpliva tudi večji navor turbine, ki je posledica večje *CD*. Opisana pojava sta aditivna, kar pomeni, da se razlika v p_2 med motorjem z EM2 in motorjem MAN povečuje premosorazmerno s časom do časa največje ciklične dobave goriva motorja z EM2, ki znaša 5,9 s, kar je bistveno manj kakor v obeh prejšnjih primerih. Moč motorja z ISG

stationary bmep, ignoring the influence of the medium exchange bmep. The maximum cyclic fuel delivery of the baseline engine was used as a reference value to form a realistic base for evaluating the improvements. The use of an electrically assisted turbocharger and the injection of an added fuel quantitiy (Fig. 2: m_g sim. +f) could raise the *RCD* above 1 below 1400 rpm due to the facts previously discussed.

The acceleration of the baseline MAN engine represents typical behavior of turbocharged engine operating under transient conditions (Fig. 3). Only 87% of the maximum *CD* is injected immediately as a consequence of the LDA operation. p_2 increases due to the larger enthalpy of the exhaust gasses, enabling greater *CD* via the LDA. The *RCD* decreases, despite the increasing *CD,* because at the same time the vehicle and, therefore the engine, is accelerating; 'max. m_g' increases up to 1400 rpm. After 7.9 seconds the engine reaches 1400 rpm and the RCD starts to rise due to decreasing 'max. m_g' and the growing boost pressure. The maximum cyclic fuel delivery (*RCD*=1) is reached after 9.8 seconds. At this point the engine is running at 1570 rpm and the boost pressure has just reached the value at which the LDA allows full fueling at this speed. The phenomenon is clearly seen as a peak of the *CD* in Fig. 3-*CD*, as well as the curve slope change in the engine power (Fig. 3-*P*) and the air-fuel ratio (Fig. 3-λ).

Turning on the ISG at the time of fuel rack change (increase) increases the engine power with no delay (Fig. 3-*P*). The ISG adds power directly to the crankshaft and therefore does not directly affect the boost pressure. The boost pressure of the engine with the ISG rises only slightly faster than that of the MAN engine, due to a greater mass flow through the engine, as a consequence of higher vehicle speed, and therefore higher engine speed. The lower value of the *RCD* compared to that of the MAN up to 7 seconds is the consequence of a still greater boost-pressure delay vs. engine speed, resulting from the energy addition to the crankshaft and not to the turbocharger. After 7 seconds the engine equipped with the ISG reaches 1400 rpm, and the *RCD* increases for the reasons already mentioned.

The electrically assisted turbocharger enables (via the LDA), due to the higher boost pressure, the injection of a larger quantity of fuel in comparison to the baseline engine, resulting in a higher *RCD* and a higher engine power. The faster boost-pressure build-up of the engine with the electrically assisted turbocharger is the consequence of additional electric-motor (EM) torque and a higher turbine torque due to the higher *CD* and therefore a higher enthalpy of exhaust gasses. Both phenomena are additive, resulting in a time-proportional increase of the boost-pressure difference between the MAN and the EM engines until the full fueling is reached (Fig. 3-p_2 and *CD*). The engine with the EM2 reaches *RCD*=1 at 1270 rpm after 5.9 seconds, being a je do 3,9 s večja od moči motorja z EM2, saj je v primeru motorja z EM2 potreben določen čas, da EM zagotovi zadosten polnilni tlak, ki omogoča vbrizganje dodatne količine goriva, ki je ustrezna moči ISG. V območju 3,9 do 8,9 s je motor z EM2 močnejši od motorja z ISG, saj je razlika v moči zaradi večje *CD* večja od moči ISG. Od 8,9 s je ponovno močnejši motor z ISG, saj se ta čas za motor z ISG ujema z *RCD*=1, kar pomeni, da se v oba motorja vbrizga največja količina goriva; v primeru motorja z ISG pa je na voljo še dodatni navor ISG. Moči motorjev z ISG in EM2 je smiselno primerjati, ker je zaradi skoraj enake hitrosti vozila primerljiva tudi vrtilna frekvenca motorja. Iz primera motorja z EM2+f, pri katerem je pod 1400 min^{-1} dovoljena dodatna *CD* (sl. 2: m_g sim. +f), je razvidno, da je največja ciklična dobava goriva, enako kakor pri motorju z EM2, dosežena po 5,9 s, v tem času se motor vrti s frekvenco 1300 min^{-1}. Dodatna količina goriva se tako vbrizgava le v času od 5,9 do 7 s, ko motor doseže 1400 min^{-1}. Pojav je viden kot vrh (vrednosti nad 1) na sliki 3-*RCD* ter kot razlika med masama goriva (sl.3-*CD*) in razmernikoma zraka (sl. 3-λ) za motorja z EM2+f in EM2. Razlika v moči motorja pa je zaradi majhne razlike v *CD* majhna, prav tako pa je majhna razlika v hitrosti vozila in p_2. S slike 3-*CD* je razvidno, da se največja dodatna količina goriva (m_g sim. +f) vbrizgava le od 6,6 do 7 s. Iz opisanega izhaja, da je EM2 prešibek, da bi v teh delovnih razmerah omogočil vbrizgavanje znatne količine dodatnega goriva.

Motor z EMG že po 1,35 s in pri 900 min^{-1} doseže največjo ciklično dobavo goriva ter v primeru EMG+f do 6,2 s (ustreza 1400 min^{-1}) omogoča dobavo dodatne količine goriva. Zaradi velikega navora EM oba motorja z EMG in EMG+f dosežeta moč motorja z ISG že po 0,9s. V primeru uporabe EMG je dovod dodatne količine goriva smiseln, saj motorju z EMG sistem LDA omejuje količino dobavljenega goriva le 1,35 s, v nadaljevanju pa, zaradi omejene največje količne goriva, ostaja vpliv višjega polnilnega tlaka neizkoriščen. Zaradi dodatne količine goriva, ki se vbrizga od 1,35 do 6,2 s, je moč motorja z EMG+f znatno večja od moči motorja z EMG, posledica tega je občutna razlika pri hitrosti vozila ter tudi višji tlak p_2. Največja dodatna količina goriva se v primeru uporabe motorja z EMG+f vbrizga od 3,5 do 6,2 s, kar nakazuje, da bi močnejši EM še dodatno izboljšal pospeševanje vozila v teh delovnih razmerah. Od 4,1 do 5,7 s EM deluje z vmesnim izklapljanjem ter zagotavlja vrtilno frekvenco 85000 min^{-1}. Po 5,7 s se EM popolnoma izklopi, saj motor pospeši turbopolnilnik nad 85000 1/min. Opisan pojav je viden kot pojemanje polnilnega tlaka na sliki 3-p_2, kar je posledica počasnega pospeševanja turbopolnilnika ter karakteristike kompresorja pri nespremenljivih vrtljajih ob povečanju masnega toka.

substantially shorter time than that required by both previous versions. The power of the engine with the ISG is greater than that of the engine with the EM2 up to 3.9 seconds, because of the time required for the boost pressure to reach a value enabling the injection of an additional fuel quantity, equivalent to the power of the ISG. The power of the engine with the EM2 is then greater from 3.9 to 8.9 seconds, as the power gain due to a larger *CD* is higher than the power of the ISG. After 8.9 seconds the power of the engine with the ISG is higher again, since at that time the engine with the ISG reaches *RCD*=1, indicating that both engines are supplied with 'max. m_g', while the engine with the ISG still has the ISG power benefit. A comparison of the instant power of the engines with the ISG and the EM2 is justified by an almost equal vehicle speed and, therefore, a similar engine speed. Both the engine with the EM2 and the engine EM2+f reach maximum *CD* after 5.9 seconds, when the engine is running at 1300 rpm. From Fig. 3-*RCD* it is clear that the use of the EM2+f enables the injection of an added fuel quantity (RCD>1) only between 5.9 and 7 seconds, corresponding to engine speeds of 1300 to 1400 rpm. The difference in the engine power and, therefore, in the vehicle speed is low, due to the small difference in *CD*. From Fig. 3-CD it is clear that the maximum added fuel quantity is injected only between 6.6 and 7 seconds. It is obvious that the EM2 is not powerful enough to make possible the injection of a significant amount of added fuel under these operating conditions.

An engine equipped with the EMG reaches *RCD*=1 after only 1.35 seconds at 900 rpm, and enables the injection of added fuel up to 6.2 seconds with the EMG+f, reaching 1400 rpm (Fig. 3-*RCD*). The power of the engine with the ISG is reached after only 0.9 seconds. The injection of an added fuel quantity is reasonable when using the EMG, since the LDA restricts the injected quantity of fuel only for first 1.35 seconds; the potential of a higher boost pressure remain unused thereafter. An added fuel quantity injected from 1.35 to 6.2 seconds results in a larger engine-power output and, therefore, higher vehicle speeds and p_2 when comparing engines with EMG+f and EMG. The maximum added *CD* is injected from 3.5 to 6.2 seconds (Fig. 3-*CD*) for the engine with EMG+f, indicating that an even more powerful electric motor would still have the potential to improve the acceleration of the vehicle under these loading conditions. The EMG operates with intermediate switching off between 4.1 and 5.7 seconds, maintaining a constant turbocharger speed of 85000 rpm; the slope of the boost-pressure curve changes at 4.1 seconds (Fig. 3-p_2). After 5.7 seconds the EMG switches off completely, while the engine speeds up the turbocharger beyond 85000 rpm. This phenomenon can be clearly seen as the boost pressure decreases (Fig. 3-p_2) due to the slow turbocharger acceleration and the compressor characteristics at constant turbocharger speed, while increasing the mass flow by engine acceleration.

Stvarno oceno podpornih sistemov kaže potek hitrosti vozila. Do 1,9 s je največja hitrost vozila, opremljenega z ISG, kar je posledica njegovega takojšnjega odziva. Pri 6,2 s motor z EM2 preseže hitrost motorja z ISG, kar je posledica večje moči od 3,9 s naprej, saj hitrost približno predstavlja integral moči motorja. Razlika v hitrosti vozil z motorjema z EM2 in EM2+f je zanemarljiva zaradi majhne dodatne količine dobavljenega goriva. Le-ta pa ima velik vpliv pri uporabi EMG, ki omogoča vbrizgavanje znatne količine dodatnega goriva, kar je tudi razvidno iz hitrosti vozila (sl.3-*v*). Največje vrtljaje (2400 min^{-1}) oz. hitrost vozila 85 km/h dosežejo motorji z ISG, EM2 in EM2+f 5,4%, EMG 7,5% ter EMG+f 9,3% hitreje kakor osnovna različica MAN. Za pospeševanje vozila do hitrosti 56 km/h (1600 min^{-1}) pa potrebujejo motor z ISG 8,8%, EM2 in EM2+f 11,3%, EMG 16% ter EMG+f 20,8% manj časa kakor osnovni motor MAN. Za opisano pospeševanje so električne podporne naprave potrebovale: ISG 106,4 kJ (0,7 Ah), EM2 in EM2+f 13,3 kJ (0,09 Ah), EMG 17,8 kJ (0,12 Ah) ter EMG+f 16,5 kJ (0,11 Ah) električne energije oziroma naboja pri 42 V.

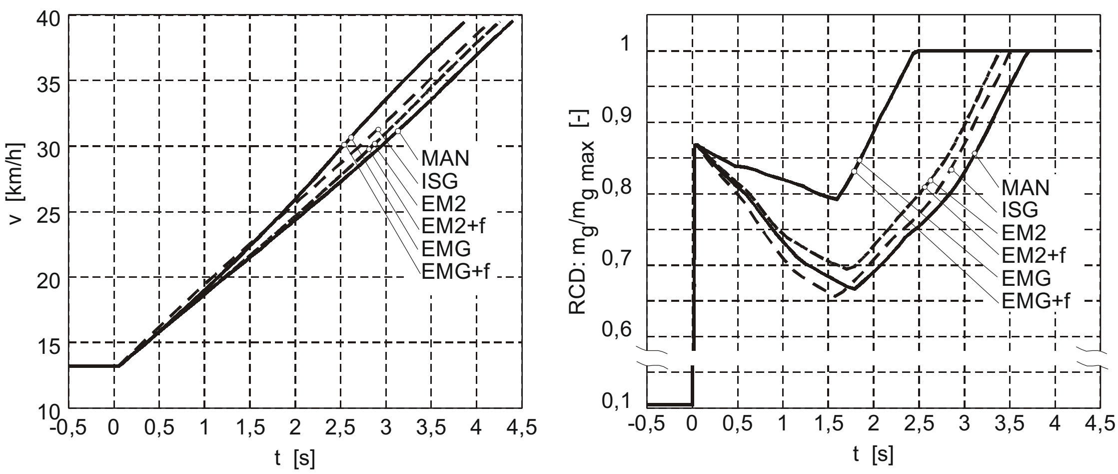
Na sliki 4 in 5 sta predstavljena pospeševanje v tretji prestavi in pospeševanje v šesti prestavi v klanec s strmino 1°, vsi drugi pogoji pa so enaki kot pri pospeševanju v peti prestavi. Ta dva primera sta bila izbrana, ker skupaj s sliko 3 podajata celostno razumevanje delovanja električnih podpornih naprav.

Na sliki 4 je predstavljeno pospeševanje od 800 do 2400 min^{-1} v tretji prestavi, ki traja bistveno krajši čas kakor enako pospeševanje v peti prestavi. Pri motorju MAN *RCD* ponovno skoči na 87%, vendar nato bolj strmo pada do 1,8 s (1400 min^{-1}), saj je na voljo manj časa za povišanje tlaka p_2, kar, zaradi PODG, rezultira v nižjo *CD*. Največjo ciklično dobavo goriva motor doseže po 3,7 s pri 2100 min^{-1},

The realistic judgment of electrical assisting systems is reflected in the variation of vehicle velocity, as it is the only parameter perceptible to the driver. The velocity of a vehicle equipped with the ISG is higher than that of an engine with the EMG up to 1.9 seconds, and up to 6.2 seconds considering the engine with EM2: this being the consequence of the ISG's immediate power addition. The above-mentioned times are greater than those for engines with an EM, reaching the power output of the engine with the ISG, since the velocity can be seen as a kind of integral of the power output. The difference in vehicle speed for engines with EM2 and EM2+f is very small due to the minimum difference in *CD*. On the other hand, the EMG ensures faster acceleration due to the injection of a significant amount of added fuel quantity. A maximum engine speed of 2400 rpm, corresponding to 85km/h, is reached faster for the engine with the ISG, EM2 and EM2+f by 5.4%, EMG by 7.5% and EMG+f by 9.3% than with the MAN engine, whereas 1600 rpm is correspondingly reached faster by 8.8% for the engine with ISG, 11.3% with EM2 and EM2+f, 16% with EMG and 20.8% for the engine with the EMG+f than with the MAN engine. The electrical assisting systems consumed: ISG 106.4 kJ (0.7 Ah), EM2 in EM2+f 13.3 kJ (0.09 Ah), EMG 17.8 kJ (0.12 Ah) and EMG+f 16.5 kJ (0.11 Ah) of electrical energy or electric charge at 42 V respectively.

Fig. 4 and 5 show the vehicle acceleration in third gear and in sixth gear on a road inclined at 1°, with all other conditions identical to the case explained in Fig. 3. These two loading cases were chosen since they allow a deeper insight into the interaction between the electrical assisting systems and the TC Diesel engine.

The acceleration in third gear (Fig. 4) is the representative case of fast engine acceleration. The *RCD* of the MAN engine again rises up to 87%, but then decreases faster until 1.8 seconds (1400 rpm), due to a still larger boost-pressure lag behind the engine speed compared to acceleration in fifth gear, resulting in a lower *CD*. The maximum *CD* (*RCD*=1) is



Sl. 4. *Pospeševanje od 800 do 2400 min^{-1} v tretji prestavi*
Fig. 4. *Vehicle acceleration from 800 to 2400 rpm in third gear*

kar je bistveno več od 1570 min^{-1} pri pospeševanju v peti prestavi. Omenjeno dejstvo je posledica zelo kratkega časa, potrebnega za pospeševanje motorja, le-ta pa, zaradi vztrajnostnega momenta turbopolnilnika in končne prostornine polnilnega in izpušnega zbiralnika, povzroča še večje zaostajanje polnilnega tlaka za vrtljaji motorja. Vpliv ISG je v tem režimu pospeševanja večji, saj je razmerje moči ISG proti moči motorja, zaradi manjše *CD*, večje. Iz enakega poteka krivulj motorjev z EM2 in EM2+f je razvidno, da EM2 ni zmožen zagotoviti polnilnega tlaka, potrebnega za dobavo dodatne količine goriva. S slike 4-*RCD* je razvidno, da je *CD* motorja z EM2 le nekoliko večja od motorja MAN, saj doseže največjo ciklično dobavo šele po 3,4 s (pri 2050 min^{-1}). Omenjeno dejstvo je posledica dinamike turbopolnilnika. EM poleg dodatnega navora prispeva tudi k povečanju masnega vztrajnostnega momenta rotorja turbopolnilnika in izboljša pospeševanje le v primeru, ko je razmerje vsote navorov turbine kompresorja in EM proti skupnemu vztrajnostnemu momentu večje od razmerja vsote navorov turbine in kompresorja proti vztrajnostnemu momentu osnovnega turbopolnilnika ([1] do [3]). V analiziranem primeru se zaradi hitrega povečanja vrtljajev motorja hitro zveča tudi masni tok skozi motor, posledica česar je hiter odziv turbopolnilnika. Dinamika turbopolnilnika, opremljenega z EM2, je v tem primeru le nekoliko boljša od dinamike osnovnega turbopolnilnika. Pri enakem pospeševanju v drugi prestavi, ki traja še krajši čas, je dinamika obeh turbopolnilnikov enaka, v primeru pospeševanja v prvi prestavi, ki je še krajše, pa EM2 povzroča slabšo dinamiko turbopolnilnika. Tako kakor EM2 tudi uporaba EMG ne omogoča dobave dodatne količine goriva (sl.4-*RCD*), vendar pa zaradi boljše dinamike turbopolnilnika (zaradi boljših karakteristik EMG v primerjavi z EM2) omogoča večjo *CD*, kar je lepo razvidno s slike 4-*RCD* ter posledično tudi iz hitrosti vozila (sl. 4-*v*). Za izboljšanje dinamične karakteristike motorja pri hitrem pospeševanju (v nizkih prestavah) so primerni EM z velikim navorom na enoto vztrajnostnega momenta, ki pa hkrati razvijajo razmeroma velik navor.

Za opisan primer obremenitve je značilno, da elektromotorja, pritrjena na gred turbopolnilnika, izboljšata dinamiko motorja predsem pri višjih vrtljajih motorja, kar je dokaj neobičajno. Omenjen pojav je posledica zelo hitrega odziva motorja in turbopolnilnika. Največja razlika v *RCD*, *CD* in moči motorja ter posledično v pospešku vozila med motorjem z EMG in drugimi različicami se pojavi šele pri 2,5s, ko se motor že vrti s 1800 min^{-1}. Zato, v primerjavi s pospeševanjem v peti prestavi, motor z ISG razvija večjo hitrost od motorja z EMG razmeroma daljši čas, v primerjavi z motorjem z EM2 pa v celotni fazi pospeševanja. Največje vrtljaje ter hitrost 39,5

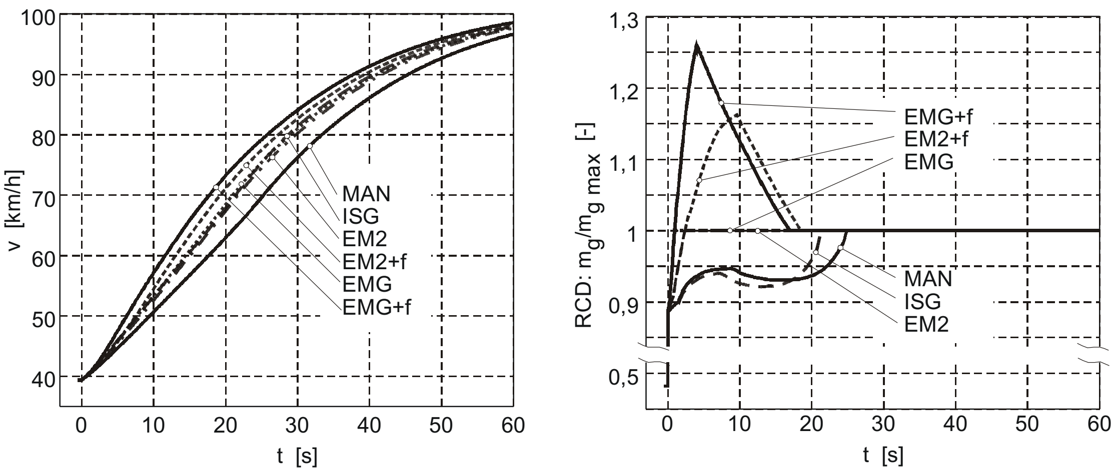
achieved after 3.7 s at 2100 rpm, giving a much higher value than 1570 rpm when accelerating in fifth gear. This is a consequence of the very short time required for engine acceleration, which results in a large turbocharger lag due to the inertia of the turbocharger and the finite capacity of the inlet and exhaust manifolds. The influence of the ISG is larger during fast accelerations of the engine, since the ratio of ISG power to engine power is higher due to the lower *CD*. From the *RCD* curve for the engines with the EM2 and EM2+f (Fig 4-*RCD*) it is obvious that the EM2 is unable to raise the boost pressure above a value allowing the injection of an added fuel quantity, even more, the *CD* and also the *RCD* of the engines with the EM2 is only slightly higher than that of the baseline MAN engine. The engine with the EM2 reaches *RCD*=1 as late as 3.4 seconds at 2050 rpm. This is the consequence of turbocharger dynamics. The EM improves the turbocharger dynamics only if the ratio of the sum of the turbine, the EM, and compressor torque to the common mass moment of inertia is larger than the ratio of the sum of the turbine and the compressor torque to the mass moment of inertia of the baseline turbocharger ([1] to [3]). Mass flow through the engine increases rapidly, due to the high engine acceleration, resulting in fast turbocharger acceleration. The dynamics of the turbocharger with the EM2 is therefore only slightly better than that of the baseline one, when accelerating in third gear. When performing the same acceleration in second gear, the duration of which is shorter, the dynamics of the turbocharger with the EM2 and the baseline one are the same, while at still faster acceleration in first gear the dynamics of the baseline turbocharger is better. Neither the EM2 nor the EMG enables the injection of an added fuel quantity (Fig.4-*RCD*). Better EMG characteristics result in better turbocharger dynamics; consequently, more fuel can be injected (Fig.4-*RCD*) and faster vehicle acceleration is achieved (Fig.4-*v*) in comparison with the engine to the EM2. The example described reveals the need for an EM with a very high torque to mass moment of inertia ratio at a relatively high torque output when assisting turbochargers during fast engine acceleration.

It is characteristic of the case presented that an electrically assisted turbocharger improves engine dynamics, especially at high engine speed, which is rather unusual. This phenomenon is evident from Fig. 4-*RCD*, since the largest difference in the *RCD* and therefore in the *CD,* the engine power and the vehicle acceleration between both engines with the EMG and other engines is observed at approximately 2.5 seconds, when the engine is running at 1800 rpm. The speed of the vehicle equipped with the engine with the ISG is therefore higher than that of the engine with the EMG for a relatively longer time compared with the acceleration in the fifth gear, and throughout km/h (sl. 4-v) doseže motor z ISG 6,4%, EM2 3,3% ter EMG 12% hitreje kakor osnovni motor MAN. Za polovico razlike v hitrosti (26 km/h) pa potrebujejo v enakem vrstnem redu 9,4%, 3% ter 12% manj časa. Poraba električne energije je v enakem vrstnem redu znašala 24,1 kJ (0,16 Ah), 4,7 kJ (0,031 Ah) ter 5,55 kJ (0,037 Ah).

Na sliki 5 je prikazano pospeševanje vozila (motorja od 800 min^{-1}) v 6. prestavi v klanec s strmino 1°, ki predstavlja primer izrazito počasnega pospeševanja. Zaradi omejene kapacitete akumulatorjev je bil čas vklopa električnih podpornih naprav navzgor omejen s 30s, kar velja za ISG, saj so se EM, pritrjeni na gred turbopolnilnika, ki delujejo do 85000 min^{-1}, izklopili že prej. Krivulja *RCD* (sl. 5) za motor MAN ne pade pod začetno vrednost 89%, kar je posledica počasnega večanja vrtljajev motorja, največjo ciklično dobavo goriva pa doseže že pri 1420 min^{-1}. Zaradi vožnje v klanec je moč, ki je potrebna za premikanje vozila, večja, kar pomeni, da je razlika v moči motorja in moči bremena, ki je ustrezna pospešku, manjša, posledica česar je večja razlika v hitrosti motorja MAN in preostalih različic na polovici razlike v hitrosti. Zaradi počasnega pospeševanja je pospeševanje različice motorjev z EM2 in EMG skoraj enako, kar izhaja iz majhne razlike v *CD* in *RCD*. Motor z ISG razvije po 21s (*RCD*=1) večjo moč od motorjev z EM2 in EMG, kar je razvidno iz pospeška. Zaradi počasnega pospeševanja je v tem primeru vpliv dodatne količine goriva opazen tudi v primeru EM2+f, saj omogoča vbrizgavanje znatne dodatne količine goriva, vendar pa je ta v primeru EMG, zaradi večjega navora EMG in posledično višjega polnilnega tlaka, večja, kar se izraža na krivulji hitrosti. V primeru počasnega pospeševanja je za učinkovito izboljšanje dinamične karakteristike motorja pomembnejši velik navor EM, pritrjenega na gred turbopolnilnika, kakor velik navor na enoto vztrajnostnega momenta, saj se počasno pospeševanje v limiti približa stacionarnemu delovanju.

whole acceleration when compared to the engines with EM2. The maximum engine speed 39.5 km/h (Fig. 4-*v*) is reached with the engine with the ISG 6.4%, the EM2 3.3%, and the EMG 12%, faster than with the MAN engine, whereas 1600 rpm (26km/h) is reached 9.4%, 3% and 12% faster than with the MAN engine. The electric energy consumption was 24.1 kJ (0.16 Ah), 4.7 kJ (0.031 Ah) and 5.55 kJ (0.037 Ah) of electric energy or electric charge at 42 V, respectively.

Fig. 5 shows the vehicle acceleration in sixth gear on a road inclined at 1°, with all other conditions identical to those explained in Fig. 3. It is an example of slow engine acceleration. The operating time of the electrical assisting systems was limited to 30 seconds, due to limited accumulator capacity and cooling ability (regarding only the ISG in the particular case, since the EM attached to the turbocharger shaft operating up to 85000 rpm, switched off earlier). The MAN *RCD* curve (Fig. 5-*RCD*) does not fall below its initial value of 89% due to slow engine acceleration, resulting in a smaller boost-pressure lag behind the engine speed. Full fueling of the MAN engine is therefore reached at 1420 rpm. The difference between the engine power and the load power is smaller when driving uphill, resulting in slower vehicle acceleration and therefore larger velocity differences between the MAN engine and other engines during the first phase of acceleration. The velocity difference for the vehicles equipped with engines with the EM2 and EMG is smaller than that presented in former cases because the slower engine acceleration enables the injection of a significant added fuel quantity, even with the use of the EM2+f (Fig. 5-*v* and *RCD*). Slow engine acceleration places higher demands on EM torque output than on high torque to mass moment of the inertia ratio, since in the limiting case it approaches stationary-state operation.



Sl. 5. *Pospeševanje od 800 min^{-1} v šesti prestavi na klancu s strmino 1°*
Fig. 5. *Vehicle acceleration from 800 rpm in sixth gear on a road inclined at 1°*

V tem primeru obremenitve motor ne dosеže 2400 min^{-1}, zato je primerjava narejena pri hitrosti 79 km/h, kar ustreza 1600 min^{-1}. Motor z ISG potrebuje 14%, EM2 11%, EM2+f 18,5%, EMG 13,3% ter EMG+f 23,5% manj časa za dosego 79 km/h kot osnovna različica MAN. Poraba električne energije je v enakem vrstnem redu znašala 252 kJ (1,67 Ah), 45,4 kJ (0,3 Ah), 41,8 kJ (0,28 Ah), 58,6 kJ (0,39 Ah) ter 50 kJ (0,33 Ah).

4 SKLEP

Iz prikazanih rezultatov je razvidno, da je že z dosedanjimi električnimi podpornimi napravami mogoče izboljšati odzivnost motorja na ravni cesti za 20%, kar pa, kakor je nakazano, še ni zgornja meja. Pri vožnji v klanec je izboljšanje odzivnosti lahko bistveno večje od te vrednosti. Prikazani primeri nakazujejo, da uporaba električnih podpornih naprav omogoča izboljšanje dinamične karakteristike motorja, ali pa, pri enakih zahtevah po dinamiki motorja, uporabo menjalnikov z manj prestavami ali uporabo motorjev z manjšo delovno prostornino. Slednja primera lahko zmajšata proizvodne stroške, zadnji pa tudi porabo goriva.

ISG je uspešen predvsem v začetni fazi pospeševanja, saj je njegov dodatni navor na voljo brez zakasnitve ter v področju največje ciklične dobave goriva, kjer je moč motorja mogoče povečati le še z neposrednim dovajanjem energije na gred motorja. Za izboljšanje dinamične karakteristike motorja je primeren ISG, ki razvija čim večji navor v širokem delovnem področju, vendar je treba najti primerni kompromis med močjo in porabo električne energije. ISG je najprimernejša električna podporna naprava v primeru nenadnega povečanje moči bremena, vendar je v podrejenem položaju proti elektromotorju, pritrjenemu na gred turbopolnilnika, glede razmerja porabljene električne energije za enako izboljšanje dinamične karakteristike motorja pri daljšem delovanju.

Elektromotor, pritrjen na gred turbopolnilnika je primernejši od ISG za uporabo v vozilih, saj so tipični časi delovanja električnih podpornih naprav daljši od nekaj sekund. EM, pritrjen na gred turbopolnilnika, ponuja boljše razmerje med izbojšanjem dinamične karakteristike motorja in porabo električne energije kakor tudi večji potencial za izboljšanje dinamične karakteristike, saj je dodatna moč ISG običajno manjša od povečanja moči motorja zaradi dodatnega vbrizganega goriva. Z večanjem specifične moči motorja se veča izboljšanje dinamične karakteristike motorja zaradi uporabe EM, pritrjenega na gred turbopolnilnika, v primerjavi z uporabo ISG. Za dvig stacionarnega srednjega efektivnega tlaka je primeren elektromotor, ki razvija velik navor. Za izboljšanje dinamične karakteristike motorjev, namenjenih za hitro pospeševanje, pa so primerni EM z velikim navorom na enoto vztrajnostnega momenta, ki pa hkrati razvijajo razmeroma velik navor, ki omogoča hiter dvig tlaka in s tem dobavo znatne količine dodatnega goriva.

All engines do not reach 2400 rpm under these operating conditions, so a comparison was made only at 1600 rpm, corresponding to 79 km/h. The engine with the ISG requires 14%, the EM2 11%, the EM2+f 18.5%, the EMG 13.3% and the EMG+f 23.5% less time than the MAN engine to achieve 1600 rpm. The electrical assisting system's energy consumption was 252 kJ (1.67 Ah), 45.4 kJ (0.3 Ah), 41.8 kJ (0.28 Ah), 58.6 kJ (0.39 Ah) and 50 kJ (0.33 Ah) of electrical energy or electric charge at 42 V, respectively.

4 CONCLUSION

It is evident from the results that present electrically assisted systems improve the turbocharged engine dynamics by up to 20% when driving on a flat road, and even more when driving uphill. All the cases presented indicate that the use of electrically assisted systems enable better vehicle dynamics, on the one hand, or allow the introduction of gearboxes with fewer gears, or the use of smaller displacement engines for the same engine dynamics, on the other. Both of the latter cases reduce production costs, while the last case could lead to a reduction in fuel consumption.

The ISG is effective, especially in the first phase of load increase, since it increases engine power without any delay, and after reaching full fueling, since thereafter engine power could only be increased with a direct power supply. A compromise considering engine applications should be made between the ISG power output, the operational time, and the electrical energy consumption. The ISG is the best electrically assisted solution in cases of a large, instant engine load increase, whereas it does not outperform electrically assisted turbochargers in terms of electrical energy consumption with the same engine dynamics improvement when operating for longer periods.

For vehicle applications, an electrically assisted turbocharger is superior to an ISG, since the typical operational times of electrical assisting systems are longer than a few seconds, thus offering a better ratio of engine dynamics improvement to electrical energy consumption, as well as a greater potential for engine dynamics improvement, since the ISG power potential hardly competes with that of additional fueling. The higher the rating of the turbocharged engine the greater is the benefit of an electrically assisted turbocharger in comparison to the ISG. For a stationary bmep rise, an EM with a high torque output is demanded, whereas to improve the dynamics of rapidly accelerating engines an EM with a high torque to mass moment of inertia ratio is required, thus also developing relatively high torque output to substantially increase boost pressure, enabling additional fueling.

5 OZNAČBE
5 SYMBOLS

ciklična dobava goriva	CD	kg/cikel	cyclic fuel delivery
nadtlak v polnilnem zbiralniku	dp_2	kPa	gauge pressure
razmernik zraka	λ	-	air-fuel ratio
moč	P	kW	power
relativna ciklična dobava goriva	RCD	-	relative cyclic fuel delivery
tlak v polnilnem zbiralniku	p_2	kPa	boost pressure
čas	t	s	time
hitrost vozila	v	km/h	vehicle velocity

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6 REFERENCES

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