Selection of the capacity of the onboard energy storage device for a high-mobility wheeled vehicle wear-resistant brake system with an electric machine

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Abstract. With the growth of the average speed of wheeled vehicles, the wear-resistant brake system which would increase their mobility by improving their braking performance and lower the heat loads on the service brake system is gaining interest of the manufacturers. At the same time, a good option for increasing power efficiency of the high-mobility wheeled vehicles is to use an electric machine in the wear-resistant brake system. The electric machine can operate in the generator cycle and provide energy recuperation during braking. Recuperation at braking requires accumulation of high values of electric energy in a storage device (usually a molecular storage device), which brings to the forefront the problem of its efficient capacity selection. The article deals with the selection of the required capacity of an onboard energy storage device providing better power efficiency of the vehicle due to the use of an electric machine in the wear-resistant brake system. The method for the selection of the required capacity of the onboard energy storage device is based on the calculation of the energy spent by the vehicle for maintaining the given speed. The following strategy of the electric machine control was used in the research: the energy accumulated in the storage device after braking will be spent at the next acceleration. Therefore, the power efficiency can be increased only due to such compensation of the high frequency oscillations of the spent/accumulated electric energy in the potential storage device that would prevent reaching its maximum charge level in a typical driving cycle. Based on the results of the research the capacity of the storage device is assessed by the peak-to-peak amplitude of the time history of the accumulated/stored energy when driving along a given route. A method that allows formulation of the specifications for the onboard energy storage device used as an element of the wear-resistant brake system, the method uses statistical data on the road conditions of vehicles operation. The method provides selection of the optimal parameters (required capacity) of the electric energy storage device which would guarantee effective operation of high-mobility wheeled vehicles in typical driving cycles.

1. Introduction
A wear-resistant brake system of a high-mobility wheeled vehicle may have besides the exhaust brake installed inside the internal combustion engine and the transmission hydro- and electrodynamic brakes (retarder brakes) also an electric machine operating in the generator cycle [1, 2] with an onboard energy storage device. The main benefit of combining the electric machine with the energy storage device in
the brake system is the increased energy efficiency of the high-mobility vehicle due to the transformation of the vehicle kinetic energy into the electric energy (at recuperative braking) and accumulating it in the storage device for later use at acceleration [3, 4, 5, 6].

When the electric machine operates as an element of the wear-resistant brake system, a high-capacity electrical energy storage device (which can withstand high discharge/charge current) is needed. Storage devices which can operate at high values of electric power and at the same time have high capacity have a large mass and a high price.

In view of this, in order to decrease the required capacity of the storage device, the following strategy for the electric machine control is proposed: the energy accumulated in the storage device after braking will be spent at the next acceleration (deceleration by the electric machine with the use of the braking resistors is not addressed). It means that during the operation of the high-mobility wheeled vehicle the electric energy storage device does not discharge fully in a typical driving cycle. In this case, a molecular energy storage device (a super capacitor) can be utilized for energy recuperation at braking. Storage devices of this kind feature low volumetric efficiency but provide high discharge/charge power, which fact allows us to neglect the limitations on the input current at further analysis.

2. Selection of the capacity of the onboard energy storage device for a high-mobility wheeled vehicle wear-resistant brake system with an electric machine

For selection of the capacity of the onboard electric energy storage device the driving cycle of the vehicle close to the real-life operation cycle is used [7 – 14]. The proposed driving cycle was generated analytically by means of the quasi-stationary model of the high-mobility wheeled vehicle motion subject to the limitations on the longitudinal and lateral accelerations determined by the tractive characteristics of the tires, powerplant performance and physiological capability of the driver to withstand the accelerations (see figure 1) [15]. This driving cycle is also based on the assumption that the deceleration which would provide the reasonable average speed on the route is not higher than $a^* = 1 \text{ m/s}^2$ [16, 17].

Thus, we shall assume that at the acceleration/deceleration with the power less than $N_{ED}^{\max}$ ($N_{ED}^{\max}$ is the maximum power of the electric machine) the vehicle motion is provided only by the operation of the electric machine in the driving/generator mode, in other cases the extra braking power is provided by the internal combustion engine (ICE), the retarder or the service brake system (see figure 2) [18 – 20].
Figure 2. Dependence of the gearbox output shaft power required by the driving cycle of the high-mobility vehicle on the travelled distance.

\[
N_{\text{mech}}^{\text{req}_i} = \begin{cases} 
N_{\text{ED}}^{\text{max}}, & \text{if } N_{\text{req}_i} \geq N_{\text{ED}}^{\text{max}} \\
N_{\text{req}_i}, & \text{if } -N_{\text{ED}}^{\text{max}} < N_{\text{req}_i} < N_{\text{ED}}^{\text{max}} \\
-N_{\text{ED}}^{\text{max}}, & \text{if } N_{\text{req}_i} \leq -N_{\text{ED}}^{\text{max}}
\end{cases}
\]  

(1)

where \(N_{\text{mech}}^{\text{req}_i}\) is the power generated by the electric machine on the gearbox output shaft in the given driving cycle; \(N_{\text{req}_i}\) is the overall required power.

The dependence of the electric machine power \(N_{\text{ED}}^{\text{req}_i}\) required in the given driving cycle can be calculated from the following system of equations:

\[
N_{\text{ED}}^{\text{req}_i} = \begin{cases} 
N_{\text{mech}}^{\text{EDreq}_i}/\eta_{\text{ED}}, & \text{if } N_{\text{mech}}^{\text{EDreq}_i} \geq 0 \\
N_{\text{mech}}^{\text{EDreq}_i}/\eta_{\text{ED}}, & \text{if } N_{\text{mech}}^{\text{EDreq}_i} < 0
\end{cases}
\]  

(2)

where \(\eta_{\text{ED}}\) is the electric machine efficiency (for design calculations it is assumed to be constant \(\eta_{\text{ED}} = 0.9\)).

The electric energy \(E_{\text{ED}}\) spent at driving along the route as a function of time can be calculated as follows:

\[
E_{\text{ED}_{i+1}} = E_{\text{ED}_{i}} + N_{\text{ED}^{\text{req}_i}} \Delta t_{i} = E_{\text{ED}_{i}} + N_{\text{ED}^{\text{req}_i}} \frac{\Delta s_{i}}{v_{\text{mean}_i}}, \quad t_{i} = t_{i-1} + \frac{\Delta s_{i}}{v_{\text{mean}_i}}
\]  

(3)

where \(\Delta t_{i}\) is the time of travelling form route coordinate \(i-1\) to route coordinate \(i\); \(\Delta s_{i}\) is the distance increment after travelling form route coordinate \(i-1\) to route coordinate \(i\); \(t_{i}\) is the time of arriving to the \(i\)-th coordinate of the route.

The dependence of the spent electrical power \(E_{\text{ED}}\) on the time is shown in figure 3. The curve shows that the power balance is negative (the spent electric power is growing with time). It means that for the operating cycle of the electric machine shown in figure 2 an additional power source is needed.
The proposed approach to the electric machine use in the wear-resistant brake system does not require installation of such additional devices, therefore an increase in the vehicle power efficiency can be provided only by compensation of the oscillations of the spent/accumulated energy about the reference line (see figure 3). So, in order to estimate the required capacity of the onboard energy storage device during the calculation of the spent/accumulated energy (3) we must subtract from the value $N_{E_{\text{Dreq}}}$ such power that would provide a neutral power balance in the system (see figure 4):

$$E_{\text{cps}}^{\text{raw}}_{i+1} = E_{\text{cps}}^{\text{raw}}_i + \left(N_{E_{\text{Dreq}}}-E_{E_{\text{D}}} n_s/t_{n_s}\right) \frac{\Delta s_i}{v_{\text{mean}_i}},$$

(4)

where $E_{\text{cps}}^{\text{raw}}$ is the spent/accumulated electric energy of the onboard energy storage device; $n_s$ is the number of the segments of the route discretization.

The generated time history features definite low-frequency oscillations with large amplitude and therefore implies accumulation of much energy onboard. The proposed control strategy and use of the molecular energy storage device do not imply storing the electric energy for a long time in order to reduce the required capacity of the accumulator device (the charge of the storage device is supposed to be used soon after the recuperative braking). For the selection of the energy storage device capacity the low frequency oscillations of the generated curve must be filtered out. The research has shown that the best option for the cut-off frequency is 0.005 Hz (the oscillations with periods lower than 200 s will be
discarded). Filtration can be performed, for example, by the 1st order Butterworth filter. The time history of the spent/accumulated energy after filtration is shown in figure 5.

Then, according to the generated time history (see figure 5) the required capacity of the energy storage device can be estimated by the peak-to-peak amplitude:

\[ E_{\text{req}}^{\text{max}} = \max(E_{\text{req}}^f(t)) - \min(E_{\text{req}}^f(t)), \]

where \( E_{\text{req}}^{\text{max}} \) is the required capacity of the energy storage device; \( E_{\text{req}}^f(t) \) is the filtered time function of the spent/accumulated energy.

Thus, the method allows selecting the required capacity of the onboard energy storage device, which would provide operation of the electric machine according to the selected control strategy preventing the maximum charge in a typical driving cycle.

**Figure 5.** Time history of the spent energy of the storage device.

3. Analysis of the efficiency of the electric machine as an element of a wear-resistant brake system of a high-mobility wheeled vehicle

The most important problem during analysis of the performance of the vehicles equipped with an electric machine as an element of the wear-resistant brake system is the estimation of their efficiency improvement. This estimation can be performed by comparison of the mechanical energy used by the internal combustion engine for keeping the vehicle speed in two cases: with an electric machine and without an electric machine in the brake system.

Braking by the ICE, service brake system, and retarder does not provide energy recuperation. Therefore, when there is no electric machine in the brake system, the mechanical energy of the engine is considered to be spent in all cases when the power required for driving \( P_{\text{req}} \) is more than 0 (the vehicle operates in the driving mode).

\[ E_{\text{ICE}}^{\text{req}} = E_{\text{ICE}} + \max(N_{\text{req}}, 0) \cdot \Delta s_i/\nu_{\text{mean}_i}, \]

where \( E_{\text{ICE}} \) is the mechanical energy spent by the engine without an electric machine.

When there is an electric machine in the wear-resistant brake system, the mechanical energy of the engine is considered to be spent when the molecular energy storage device becomes discharged or when there is not enough tractive power for keeping the vehicle speed (when there is not enough power of the electric machine at braking, the mechanical energy of the engine is not spent).
where $E_{cps}$ is the effective charge of the energy storage device; $E_{ICE}^{ED}$ is the mechanical energy spent by the engine with the electric machine.

Results of the numerical experiment performed with regard of the described behavior of the system at zero initial charge of the energy storage device are shown in figure 6. By way of example, a high-mobility wheeled vehicle with the following parameters is used: gross weight 34 t, ICE power-to-weight ratio 15 kW/t in driving mode, ICE power-to-weight ratio 6 kW/t in braking mode, electric machine power 100 kW (power-to-weight ratio 3 kW/t), capacity of the onboard energy storage device 0.45.

Estimate of the reduction of the energy spent by the ICE in the case of the electric machine installation can be done by the following equation (see figure 7):

$$E_{cps_{i+1}} = \begin{cases} E_{cps_{i}} - \min \left( N_{req_{i}} N_{max_{ED}} \right) \cdot \Delta s_{i} / \left( v_{mean_{i}} \cdot \eta_{ED} \right), & \text{if } N_{req_{i}} \geq 0 \\ E_{cps_{i}} - \max \left( N_{req_{i}} - N_{max_{ED}} \right) \cdot \Delta s_{i} \eta_{ED} / v_{mean_{i}}, & \text{if } N_{req_{i}} < 0, \quad 0, & \text{if } E_{cps_{i+1}} < 0 \\ E_{max_{cps}}, & \text{if } E_{cps_{i+1}} > E_{max_{cps}} \end{cases}$$

$$E_{ICE_{i+1}}^{ED} = \begin{cases} E_{ICE_{i}}^{ED} + \max \left( N_{req_{i}}, 0 \right) \cdot \Delta s_{i} / \nu_{cp}, & \text{if } E_{kon_{i}} = 0 \\ E_{ICE_{i}}^{ED} + \max \left( N_{req_{i}} - N_{max_{ED}}, 0 \right) \cdot \Delta s_{i} / \nu_{mean_{i}}, & \text{if } E_{kon_{i}} \neq 0 \end{cases}$$

Figure 6. a) mechanical energy of the engine with and without the electric machine; b) energy variation in the energy storage device.
\[ \eta_{eff} = 100\% \cdot \left( \frac{E_{ICE} - E^{ED}_{ICE}}{E_{ICE}} \right) \] (8)

Figure 7. Reduction of the energy spent by the ICE in the case of the electric machine installation.

From the analysis results we can conclude that installation of the electric machine in the wear-resistant brake system for the analyzed driving cycle (see figure 1, the case when the lateral acceleration is limited \( a_y = 0.1g \) and deceleration \( a^* = 1 \text{ m/s}^2 \)) provides reduction of the mechanical energy spent by the ICE by 30.8%.

In order to estimate the effect of the driving cycle intensity (effect of the lateral and longitudinal acceleration limitation) on the reduction of the ICE energy consumption due to the installation of the electric machine in the brake system, the selection of the onboard energy storage device and assessment of the electric machine efficiency in different driving cycles according to the proposed method must be performed under the following conditions:

- without limitation of the lateral acceleration and with limited deceleration – reduction in the energy consumption 15%;
- with limited lateral acceleration, but without limitation on the deceleration – reduction in the energy consumption 13.5%;
- without limitation on the lateral acceleration and with limited deceleration – reduction in the energy consumption 4.3%.

Thus, installation of the electric machine with an onboard energy storage device in the wear-resistant brake system of the high-mobility wheeled vehicle in question (the gross weight 34 t) theoretically provides up to 30% reduction of the mechanical energy consumption.

4. Conclusion

Installation of the electric machine in the wear-resistant brake system provides up to 30% reduction of the mechanical energy spent by the ICE of a high-mobility wheeled vehicle. Reduction in the energy consumption depends on the driving cycle: the more intensive the driving cycle is, the lower the effect of the electric machine installation is. This feature can be explained by the fact that at the intensive deceleration of the high-mobility wheeled vehicle the most part of the energy is not accumulated in the storage device but is dissipated by means of the brake system.

References

[1] Heinz Heisler Advanced Vehicle Technology London: Butterworth-Heinemann 2002 p 656 doi: 10.1016/B978-0-7506-5131-8.X5000-3
[2] Krasovsky A, Gorbunova E, Bychkov M and Fedorenko A 2018 Torque Control of Switched Reluctance Drive in Generating Mode 25th International Workshop on Electric Drives: Optimization in Control of Electric Drives (IWED) Moscow Russia

[3] Kharitonov S A [et al.] 2010 Analiz i proektirovanie gibridnykh transmissiy transportnykh sredstv na osnove planetarnykh mekanizmov M.: MGTU im. N.E. Bauman p 92

[4] Kositsyn B B 2017 Metod opredeleniya energoeffektivnogo zakona dvizheniya elektrobusa po gorodskomu marshrutu: diss. …kand. tekhn. nauk: 05.05.03. M.: MGTU im. N.E. Bauman p 165

[5] Electric Drive Study: Technical report (final): U.S. Army Tank-Automotive Command Research Development & Engineering Center; General Dynamics Land Systems Division – Warren Michigan 1987 – p 396

[6] Barlow T J [et al.] 2009 A reference book of driving cycles for use in the measurement of road vehicle emissions TRL limited p 276

[7] Keller A and Aliukov S 2015 Analysis of possible ways of power distribution in an all-wheel drive vehicle Lecture Notes in Engineering and Computer Science 2218 pp 1154-1158.

[8] Keller A, Aliukov S, Anchukov V and Ushnurcev S 2016 Investigations of Power Distribution in Transmissions of Heavy Trucks SAE Technical Paper 2016-01-1100

[9] Keller A and Aliukov S 2016 Efficient Power Distribution in an All-Wheel Ground Vehicles SAE Technical Paper 2016-01-1105

[10] Aliukov S, Keller A, and Alyukov A 2015 On the Question of Mathematical Model of an Overrunning Clutch Lecture Notes in Engineering and Computer Science: Proceedings of The World Congress on Engineering pp1319-1324.

[11] Shtang A A and Yaroslavtsev M V 2016 Opredelenie osnovnykh kharakteristik kombinirovannoy energeticheskov ustanovki dlya gorodskogo bezrel'sovogo transporta Doklady Akademii Nauk Vysshey Shkoly Rossiyyskoy Federatsii 4 doi: 10.172121727-2769-2016-4-111-120

[12] Yaroslavtsev M V 2014 Opredelenie parametrov energoustanovki gibridnogo avtomobilya modelirovaniem protsessa potrebleniya energii Elektrotekhnika 12 pp 17-21

[13] Sarach E, Kotiev G and Beketov S 2018 Methods for road microprofile statistical data transformation MATEC Web of Conferences 224 article 04009

[14] Kotiev G O, Miroshnichenko A V, Stadukhin A A and Kositsyn B B 2019 Estimating operation modes for the individual wheel electric drive of the all-wheel drive vehicle with the use of the driving simulator IOP Conf. Series: Materials Science and Engineering 534 012004

[15] Rotenberg R V 1972 Podveska avtomobiliya lzd 3-e pererabot. i dop. M.: Mashinostroenie p 392

[16] Tarasik V P 2006 Teoriya dvizheniya avtomobiliya Spb BVKh-Peterburg p 478

[17] Kravets V N 2014 Teoriya dvizheniya avtomobiliya Nizhniy Novgorod: Nizhniy Novgorod p 696

[18] Nosko A L, Safronov E V, Soloviev V A 2018 Study of Friction and Wear Characteristics of the Friction Pair of Centrifugal Brake Rollers Journal of Friction and Wear 39 No 2 pp 145–151

[19] Gekker F R 1998 Generalized dynamic model of 'dry' friction units Trenie i Iznos 19 Issue 2 pp 165-70

[20] Yudin E G Vartanyan V A and Vasilieva E I 1998 Improvement of quality and tribological performance of transmission parts by electrochemical polishing Journal of Friction and Wear Vol 19 Issue 2 pp 81-6