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EFFICIENCY TESTS OF THE CONTINUOUSLY VARIABLE CHAIN TRANSMISSION OF HYBRID DRIVING SYSTEM FOR A PASSENGER CAR

BADANIA SPRAWNOŚCI PROTOTYPOWEJ BEZSTOPNIOWEJ PRZEKŁADNI ŁAŃCUCHOWEJ HYBRYDOWEGO UKŁADU NAPĘDOWEGO SAMOCHODU OSOBOWEGO

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Summary

The article presents a research stand, a way of conducting and results of loss tests and prototype efficiency of a continuously variable chain transmission, which is to be used in a prototype hybrid drive system. This transmission is to serve as a continuous module connecting the secondary energy source - flywheel and combustion engine with vehicle wheels. In addition, the article presents the idea of a prototype drive system with an explanation of the operation.
In the proposed solution of the drive system, the efficiency of the continuously variable transmission

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is crucial both when transferring power to the drive wheels from the combustion engine and from the energy accumulator, as well as from the wheels to the energy accumulator.
The tests have shown that in the area of transmission of small loads, the efficiency of the transmission decreases, even though the losses increase with the increase of the transferred load. In addition, the tested transmission is characterized by greater efficiency when working in the reducer mode than the speed multiplier. The existence of the transmission's working area has been noticed and explained, where its mechanical losses are covered by the power supply from both directions.

Keywords: variable-speed transmission, CVT, losses, efficiency

Streszczenie

W artykule przedstawiono stanowisko badawcze, sposób prowadzenia oraz wyniki badań strat oraz sprawności prototypowej bezstopniowej przekładni łańcuchowej, która ma znaleźć zastosowanie w prototypowym hybrydowym układzie napędowym. Przekładnia ta ma służyć jako moduł bezstopniowy łączący wtórne źródło energii – koło zamachowe oraz silnik spalinowy z kołami pojazdu. Ponadto w artykule przedstawiono ideę prototypowego układu napędowego wraz z wyjaśnieniem działania.
W zaproponowanym rozwiązaniu układu napędowego kluczowa jest sprawność bezstopniowej przekładni zarówno podczas przenoszenia mocy do kół napędowych z silnika spalinowego i z akumulatora energii, jak i z kół do akumulatora energii.
Badania wykazały, że w obszarze przenoszenia małych obciążeń sprawność przekładni spada, mimo że ze wzrostem przenoszonego obciążenia straty rosną. Ponadto badana przekładnia charakteryzuje się większą sprawnością przy pracy w trybie reduktora niż multiplikatora prędkości obrotowej. Zauważono i wyjaśniono istnienie obszaru pracy przekładni, gdzie jej straty mechaniczne pokrywane są poprzez dopływ mocy z obu kierunków.

Słowa kluczowe: przekładnia bezstopniowa, CVT, straty, sprawność

1. Introduction

The introduction of the continuously variable transmission in the drive system of the car took place over a hundred years ago [3]. In 1958, thanks to DAF, this solution was used in the model 600 produced in series under the Variomatic name.

The rapid development of material engineering, electronics and automation has enabled the development of this type of transmission. As can be seen in Figure 1, the assumed number of automatic transmissions produced in 2017 in comparison to 2010 increased – including continuously variable transmissions.

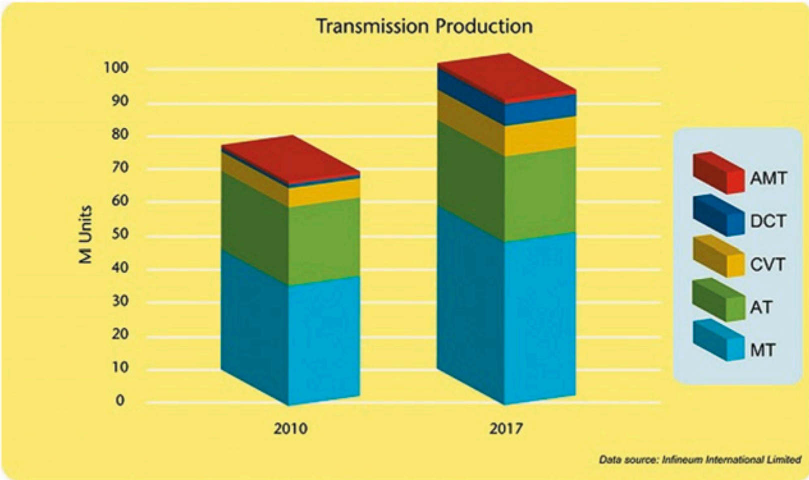

Fig. 1. A list of the share of particular types of transmissions in 2010 and 2017 [7]; AMT – automated manual transmissions; DCT – dual clutch transmissions; CVT – continuously variable transmissions; AT – classic automatic transmission; MT – manual transmission

The growing popularity of continuously variable transmissions in drive systems results from their advantages such as flexibility and the ability to implement various control strategies, for example the criterion of maximum torque, maximum power or the smallest unit fuel consumption.

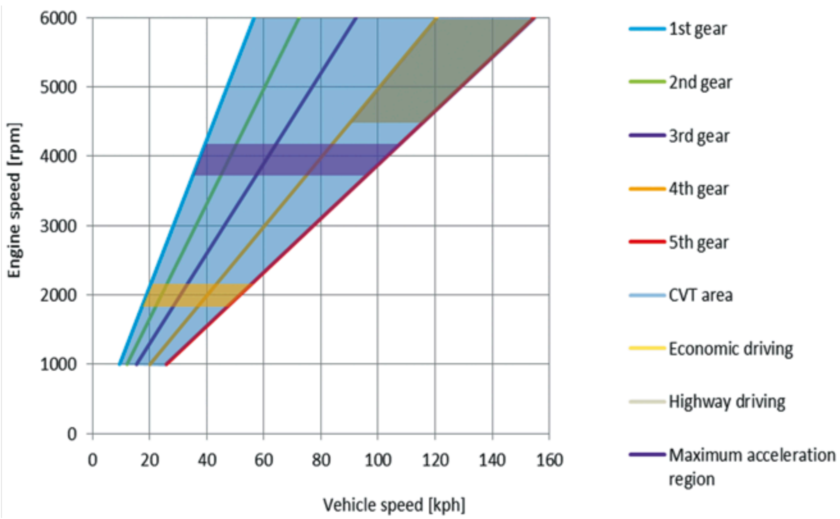

Fig. 2. The transmission range of the continuously variable transmission compared to a conventional five-speed transmission

Another advantage of using such a transmission is the continuity in transmitting the torque from the input element to the output one.

Therefore, the use of a transmission with infinitely variable transmission along with the correct control algorithm should move to:

- Lowering fuel consumption and reducing emissions of harmful substances in the exhaust.
- Improvement of dynamic properties of the vehicle.
- Increased driving comfort.
- The possibility of using less flexible, so cheaper engines.

2. A prototype hybrid drive system with a mechanical energy accumulator

In the proposed solution, a secondary energy source – a mechanical energy accumulator – has been added to the continuously variable drive system. In such system, when braking the vehicle its kinetic energy is converted into the kinetic energy of the flywheel and vice versa – when starting, the kinetic energy of the flywheel is converted into the kinetic energy of the car. In both cases, it is necessary to ensure angular acceleration or deceleration of the flywheel in order to create a braking torque or torque for the vehicle. In order to be able to transmit energy in this way, the ratio between the wheels of the car and the flywheel should change continuously. This is possible thanks to the continuously variable chain transmission - the same one that connects the primary energy source with the wheels.

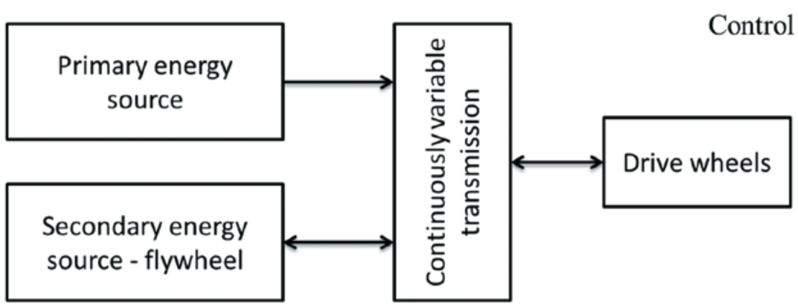

Fig. 3. The idea of a prototype hybrid drive system

The prototype system enables work in similar modes in which currently produced hybrid vehicles operate [4]:

- A mode using the primary energy source.
- A mode using a secondary energy source.

- A mode using two sources of energy.
- Braking with energy recovery.
- Mode of charging the energy accumulator with an internal combustion engine.

In this solution, a high speed and precision of the transmission ratio of the continuously variable transmission is required in its entire range.

Hydraulic actuators are responsible for changing the ratio and tension of the chain.

The thrust forces in the cone transmissions are generated by the pressure (P1 and P2, respectively) on the pressure surfaces - these surfaces are equal. In this arrangement, the primary pulley is responsible for determining the ratio, and the secondary pulley is responsible for tightening the belt so that it is able to move the torque without slip. This division results from the fact of placing the stops of the axial displacement of the movable cone wheel on the input pulley. A more comprehensive description of the power supply system for the continuously variable transmission can be found in [5] and [6].

3. Test bench

Figure 4 shows the diagram of the station located at the Department of Vehicles and Machine Building Basics of the Lodz University of Technology, where research was carried out.

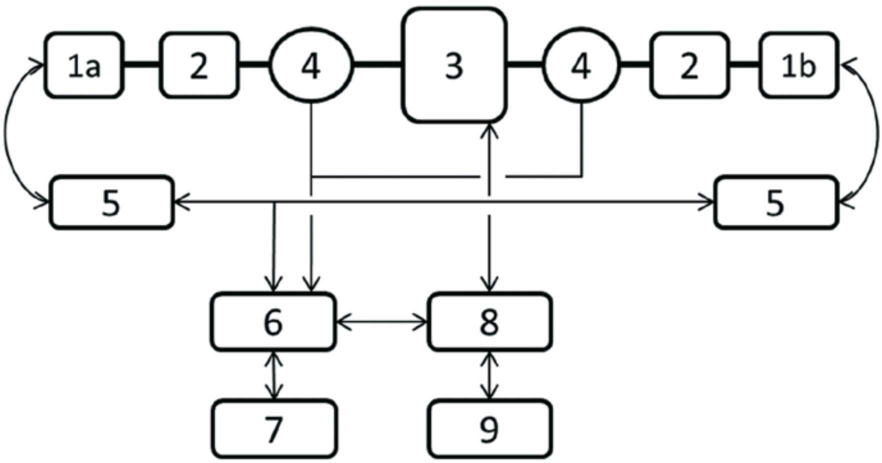

Fig. 4. Scheme of the test station; 1 – Electric machines; 2 – Mechanical transmissions; 3 – Tested continuously variable transmission; 4 – Torque metres; 5 – Inverters; 6 – Controller with an extensive input/output system; 7 – User interface; 8 – Hydraulic blocks (hydraulic distributors); 9 – Hydraulic group

The electric machines (1) were used for driving and braking the tested continuously variable transmission (3). Thanks to the inverters (5), it was possible to smoothly control these machines in the torque ranges of ± 500Nm or the speed of ± 3000 rpm. In order to match the maximum possible rotational speeds, mechanical transmissions used as reducer and multiplier (2) were used for the tested object. Two torque gauges (4) were used to measure the torque at the input and output of the tested transmission. More information about the drive unit of the station, in which to reduce the power consumption, the phenomenon of circulating power is found in [1].

The construction of the prototype continuously variable transmission assumes its control with the use of an electro-hydraulic system. The external hydraulic group (9) was used to supply the hydraulic blocks (8) enabling a smooth change of pressure (and thus the change of the transmission ratio and the chain tensioning force).

Through the user interface (7), the operator interacts with the controller (6). Thanks to this, it is possible to set and read data related to the work of the station and the object under test.

4. Carried out research

In the presented results, torque from the side of the combustion engine or flywheel acting on the primary pulley was named the moment "from the propulsion source". The sign of this moment is positive when the energy flow is from the engine (flywheel) to the wheels of the vehicle. It is negative when the energy flow is in the opposite direction.

At the station, the equivalent of energy sources is machine 1a, and the equivalent of vehicle wheels – machine 1b.

In the conducted research, the velocity ratio of the continuously variable transmission was defined as:

$$Icvt = \frac{\omega 2}{\omega 1} \tag{1}$$

Where:

ω_2 – rotational speed of the output element (rpm),

ω_1 – rotational speed of the input element (rpm).

4.1. The influence of wading resistance on losses

During the research, insufficient oil drainage from the body of the tested transmission was noticed. The creation of overpressure (hereinafter referred to as P) by supplying air to the inside of the body by increasing the speed of oil outflow reduced its level. It has contributed to the reduction of losses resulting from wading resistance. The graph in Figure 5 shows this phenomenon during the test performed under the following conditions:

- Oil temperature: 80 °C.
- Input speed: 2000 rpm.

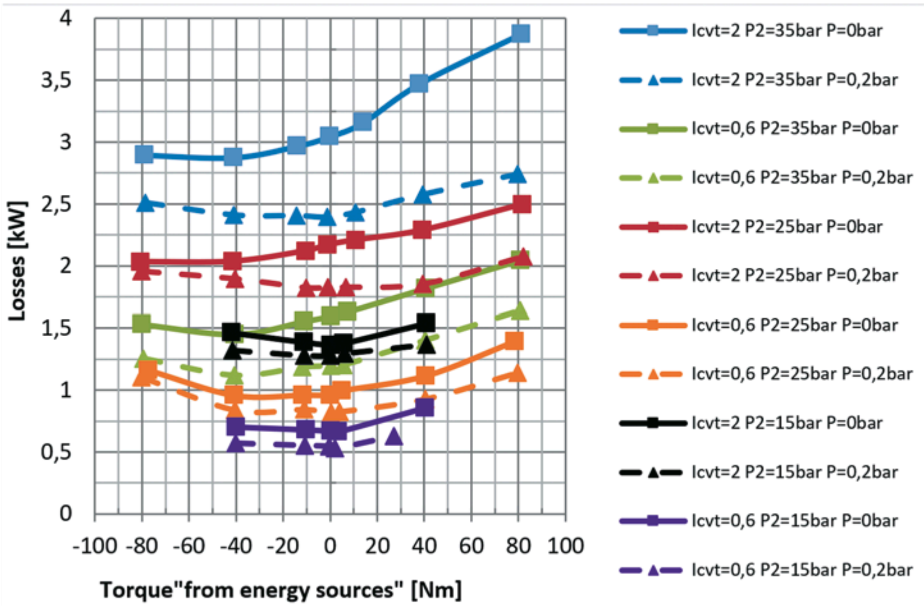

Fig. 5. The effect of lowering the oil level on losses

The relatively high value of the impact of wading losses indicates the need to look for structural solutions that allow to reduce these losses. In order to reduce these losses during the research, only cases with hypertension P = 0.2 bar will be presented in the further part of the article.

4.2. Losses generated by the transmission

In the process of energy transfer, a very important factor conditioning the selection of an energy converter is the level of losses generated by it. Figure 6 presents the results of tests to determine them made under the following conditions:

- Oil temperature: 80 °C.
- Secondary pulley cylinder pressure (P2): 35 bar (minimum risk of chain slipping).
- Input speed: 2000 rpm.

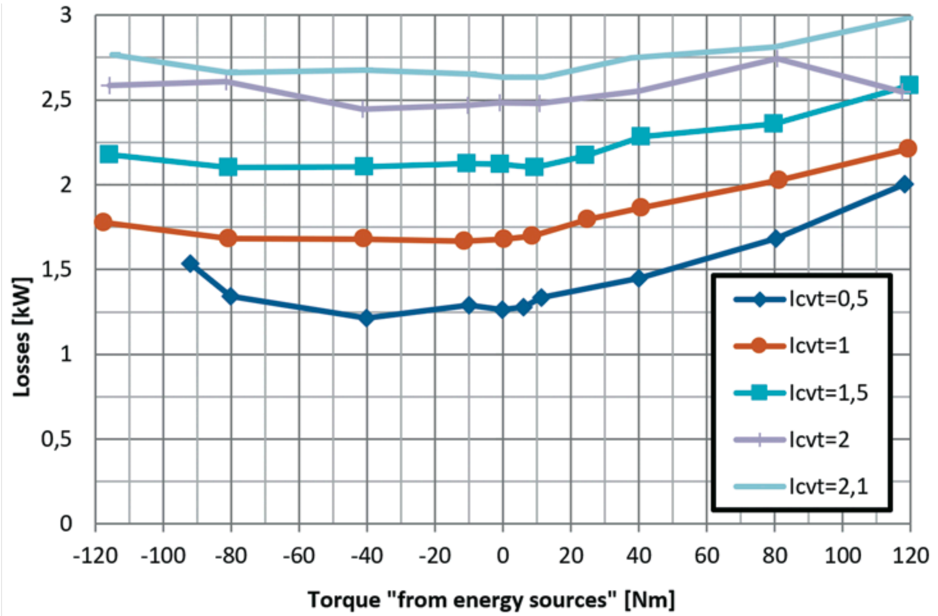

Fig. 6. Losses generated by a continuously variable transmission

The losses generated are all the greater, the greater the transmission ratio and the larger the transmission (torque, both negative and positive). The decisive part of the losses is the part independent of the transmitted torque.

4.3. The effect of pressure in the secondary pulley cylinder on losses

It is known that the losses increase as the belt tension increases, which is obtained by increasing the pressure in the secondary pulley cylinder. It is important to assess this impact. The results are given in the chart in Figure 7.

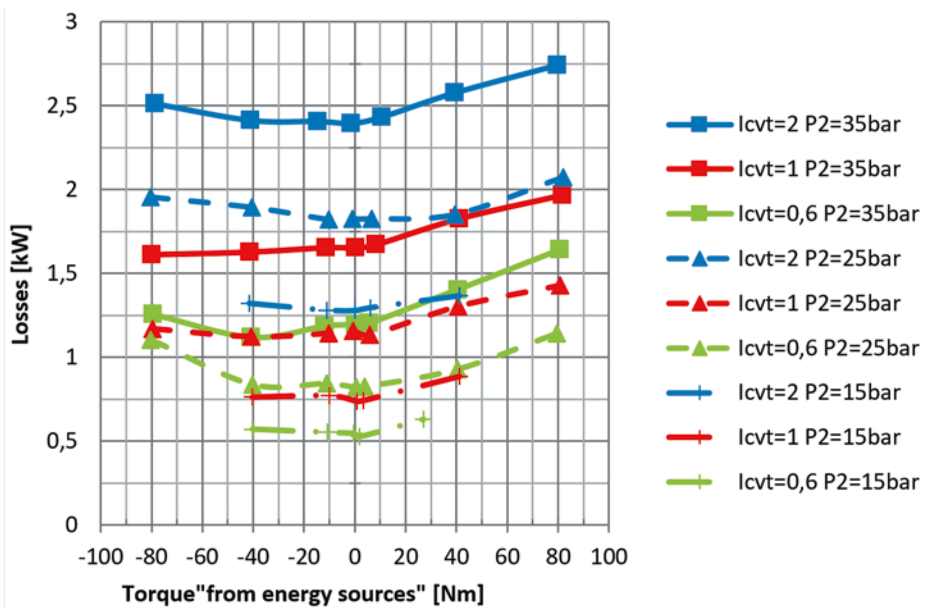

Fig. 7. The effect of P2 pressure reduction on losses

The obtained results clearly indicate that the smaller the P2 is, the smaller the losses are. However, this pressure cannot be reduced below the limit of permanent slip. For this reason, it is understandable to control the transmission in the area of micro-slip, which is described in more detail in [2].

4.4. The area of inability to determine efficiency

Figure 8 compares the reduced (taking into account the ratio) moment "from wheels" and the moment "from energy sources". If there were no transmission losses, both straight lines would overlap. Positive torque from the sources means that the transmission receives power from this side. Similarly, a negative moment from the wheels means obtaining power from the wheel side. An interesting area shaded in the drawing is noticed, where transmission losses are covered by power supplies from both sides. The power supplied from the sources is not enough to overcome losses and these must be partly covered by the drive on the wheel side.

By definition, transmission efficiency is the ratio of outgoing power to power in the process of power transmission. If you want to apply this definition to the area, it is difficult to determine what is actually the entrance and what is the output, and in both cases the value of efficiency would be negative. Therefore, it is proposed that it should not be calculated in this area.

- Transmission ratio: 1.
- Oil temperature: 60 °C.
- Secondary pulley cylinder pressure (P2): 35 bar (minimum risk of chain slipping).
- Input speed: 2000 rpm.

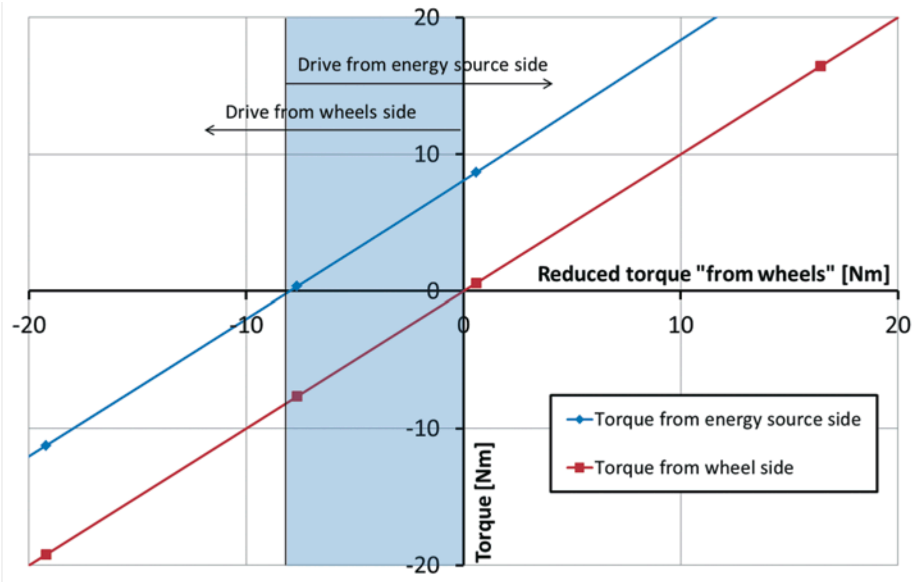

Fig. 8. Comparison of moments on both sides of the transmission

4.5. The efficiency of power transmission of the tested variable transmission

Figure 9 shows the charts of the efficiency of the transmission in the function of the transmitted torque. As could be expected from the course of losses, the efficiency increases with the increase of the absolute moment value. For the area of very small loads, according to the analysis given in point 4.4, efficiency was not calculated. The efficiency characteristics were determined under the following conditions:

- Oil temperature: 80 °C.
- Pressure in the secondary pulley cylinder (P2): 35 bar.
- Input speed: 2000 rpm.

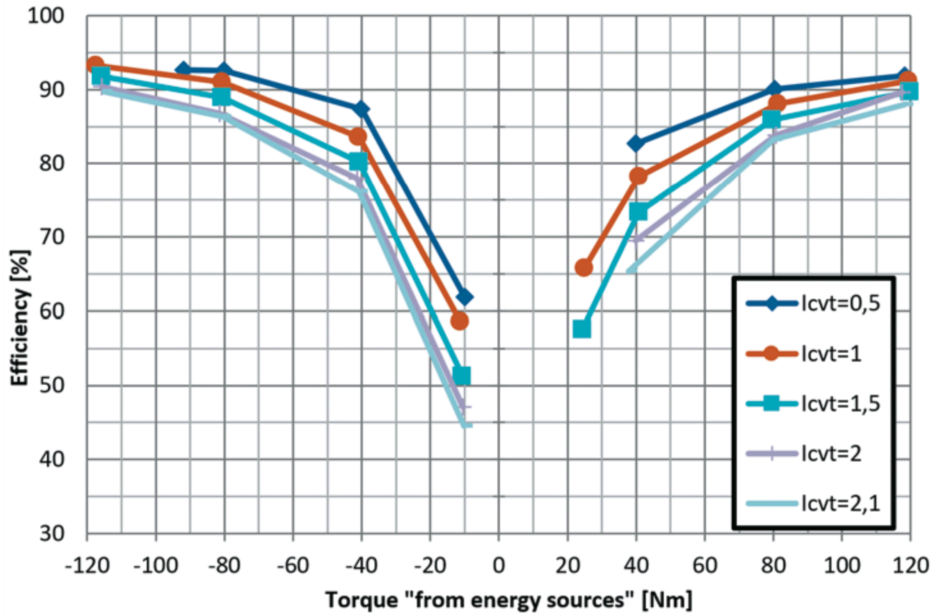

Fig. 9. Efficiency of the tested continuously variable transmission

5. Conclusions

1. It is worth looking for structural solutions that reduce the impact of wading losses due to their large share in total losses.
2. The lower the pressure causing the chain tension is, the lower the losses are. Nevertheless, too low a pressure, i.e. a chain tensioning force, poses a greater risk of skidding. It is therefore worth looking for solutions in control systems that will enable work just above the safe margin to prevent damage to the transmission.
3. The losses and efficiency of the transmissions obtained during the tests do not exclude it as a continuous hybrid module of the drive system. Nevertheless, it is worth looking for solutions that reduce losses.

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The full text of the article is available in Polish online on the website http://archiwummotoryzacji.pl.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie http://archiwummotoryzacji.pl.

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