Improving energy performance of hydraulic torque converters

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Abstract. Torque converters are widely used in the transmissions of self-propelled vehicles for various purposes on wheeled and tracked chassis. A significant drawback of torque converters compared to mechanical transmissions is their relatively low efficiency. Therefore, the task of ensuring high efficiency values of torque converters in the entire range of gear ratios has been of importance since the invention of these hydraulic machines. Torque converters have the lowest efficiency values in the torque transformation mode among low and medium gear ratios from 0 to 0.7. In addition, the nature of the change in efficiency for an integrated torque converter in automatic transition to the fluid coupling mode also usually decreases sharply. This article discusses a number of motor and tractor torque converter designs aimed at obtaining high values of efficiency in the range of small or medium gear ratios. The considered technical solutions are associated with a reduction in energy losses when the working fluid enters the pump wheel of the torque converter.

1. Introduction

Hydromechanical transmissions (HMT) containing a torque converter are widely used in the transmissions of self-propelled vehicles for various purposes on wheeled and tracked chassis. Most often, relatively simple single-stage complex torque converters are used in the HMT, having one pump wheel (or pump) connected to the drive shaft, one turbine wheel (or turbine) connected to the driven shaft, and one or two reactor wheels connected to the HMT body through freewheel clutches [1, 2]. Transmissions with complex torque converters are characterized by a number of positive properties compared to mechanical transmissions:

– ability to transmit large energy flows (hundreds or thousands of kilowatts) with relatively small dimensions;
– automatic change in gear ratio depending on the load executed on the transmission with continuous transmission of engine torque;
– damping torsional vibrations and increasing durability of transmission elements;
– ability to work on fluid coupling with high values of efficiency;
– improving the controllability of the transmission and the machine as a whole, reducing driver fatigue.

The greatest effect from the use of torque converters is obtained by transport and technological machines operating under intense and alternating loads in poor road conditions and off-road [3]. Although multi-stage and multi-turbine torque converters demonstrate high converting properties compared to single-stage torque converters, they are not widely used in automobiles due to their more complex design [4]. In particular, multistage torque converters are currently used in HMT shunting diesel locomotives.
2. Theory
A significant drawback of torque converters is their relatively low efficiency compared to mechanical transmissions, due to the lack of a rigid connection between the master and slave units. Therefore, the task of ensuring high efficiency values of torque converters in the entire range of gear ratios has been of importance since the invention of these hydraulic machines by engineer H. Föttinger at the very beginning of the 20th century [5, 6].
Torque converters have the lowest efficiency values in the torque transformation mode in low and medium gear ratios (from 0 to 0.7), when the torque transformation coefficient has the highest values. In addition, the nature of the efficiency change for a complex torque converter in the area of automatic transition to the fluid coupling mode usually decreases steeply, forming a decrease (the so-called “failure”) in efficiency associated with an increase in the angle of attack at the inlet of the working fluid into the reactor [7]. Fig. 1 shows typical graphs of changes in efficiency and transformation ratio for a motor and tractor three-wheeled complex torque converter. Curve 1 shows the nature of change in efficiency, and curve 2 shows the nature of change in the transformation coefficient.

![Figure 1. Typical characteristics of an complex single-stage three-wheel torque converter](image)

Such a drop in efficiency observed in complex torque converters during the transition to the hydraulic clutch mode also significantly affects the efficiency of a self-propelled machine, since the transition area of the integrated torque converter to the hydraulic clutch mode belongs to the main operating modes of the HMT operation [8].

3. First target setting
It is also possible to reduce the indicated efficiency gap by reducing the attack angle in this mode and increasing the geometric angle of the working fluid inlet to the reactor, while reducing shock losses when the working fluid enters the pump wheel of the torque converter. Let us further consider methods for increasing the efficiency of motor and tractor torque converters.
The first technical solution to increase the efficiency of the torque converter is the invention of an integrated torque converter that can automatically switch to the fluid coupling mode in high gear ratios (over 0.8) by breaking the mechanical connection between the reactor and the vessel. Such a device was the Trilok torque converter in 1932 [9]. Integrated torque converters subsequently became the most popular elements of HMT self-propelled vehicles, almost completely displacing fluid couplings. In late 1940s, Chrysler and General Motors (GMC) began using integrated torque converters with a two-stage reactor in automobile HMTs [11, 12]. The reactor wheel in such torque converters consists of two parts, which made it possible to have two sections of joint operation in the torque converter with the engine and to reduce hydraulic losses when the working fluid enters the pump wheel. The
scheme of the four-wheel complex torque converter is shown in Fig. 2. The diagram shows body 1, input 2 and output 3 shafts, pump 4, turbine 5, wheels 6 and 7 of a two-stage reactor, connected to the body through freewheels 8 and 9, respectively.

![Figure 2. Scheme of a four-wheel complex torque converter](image1)

This solution has for many years been popular with HMT designers and has been repeatedly considered in special and academic literature. In the USSR in the 1960s, the family of four-wheeled torque converters of the "LL" type with cast working wheels was developed under the leadership of S.M. Trusov [8]. Ford also designed a torque converter, in which the reactor consisted of four elements in series, but this original solution turned out to be functionally redundant [13].

Torque converters with a two-stage reactor were previously used in the HMT of city buses LAZ and LiAZ. Currently, four-wheel torque converters are used in the HMT of such heavy vehicles as MAZ, BelAZ, and MoAZ, wheel loaders AMKODOR and other self-propelled machines. Foreign transport engineering focuses on simpler classic three-wheeled complex torque converters with one reactor [14, 15].

In 1940-1950s, GMC manufactured HMT Dynaflow for passenger cars, which used a five-wheel complex torque converter [16]. The kinematic diagram of the Dynaflow torque converter is shown in Fig. 3.

![Figure 3. Scheme of the Dynaflow torque converter](image2)

Input shaft 1 of the Dynaflow torque converter is connected to the pump wheel, which consists of the main 2 and auxiliary 3 parts connected to each other through freewheel 4. Turbine 5 is connected to the output shaft 6. The torque converter contains two reactor wheels 7 and 8, which, using free-wheeling couplings 9 and 10 are connected to housing 11. The purpose of the auxiliary wheel of the pump installed at the outlet of the second reactor wheel is to reduce the loss of pressure on the working fluid when entering the pump at large angles of attack. Auxiliary pump 3, depending on the flow direction of the working fluid coming out of the second reactor wheel 8, either rotates freely, or with the help of a freewheel clutch wedges with the main pump and rotates with it as a whole [17, 18].
However, this technical solution, despite its structural simplicity, was ineffective due to the inability to control the movement of the auxiliary impeller of the torque converter. Therefore, in subsequent constructions of HMT, torque converters of the Dynaflow type were no longer used. In order to optimize the joint operation of the engine and the torque converter, torque converters with a mechanism for turning the pump wheel vanes were designed [19]. However, this method of regulating the transmission and increasing its efficiency is also not widespread due to a significant complication of the design of the torque converter.

Another and more practice-demanded way for increasing the energy efficiency of torque converters was to control them from the side of the reactor wheels. In this case, the rotation of the reactor blades could be carried out by the HMT control system in manual or automatic mode, depending on the movement conditions of the self-propelled machine. Reactor blades in automotive torque converters were proposed by GMC in 1950s. [20]. GMC equipped hydraulically driven rotary blades with multi-turbine torque converters in such HMT models as Super Turbine and Turboglide, etc. However, torque converter rotary blades of the reactor were not widely used either, due to the significant complexity of the design.

4. First experimental results
It is possible to overcome the problem associated with the complexity of the rotation mechanism of the rotor blades of a torque converter reactor by using a blade system of single-stage four-wheel torque converters with two reactors, if the reactors are independent of each other. In this case, such a torque converter acquires the ability to work in two different operating modes. The blades of one of the reactors are profiled with a small exit angle of the working fluid, and the blades of the other reactor with a large exit angle of the working fluid. The entry angles of the working fluid into the blades of both reactors can be the same or different.

Thus, depending on which of the two reactors is currently active, various properties of the torque converter and various ranges of its joint operation with the engine are provided. The design of such a torque converter and the HMT control system in each operating mode ensures the operation of only one of the two reactors: the active reactor is blocked with the HMT housing, while the inactive reactor rotates freely in the flow of the working fluid. As a result, in the presence of two reactors, the torque converter operates alternately with either one or the other reactor [21]. In this case, the efficiency of the torque converter can be optimized depending on the load on the transmission of the self-propelled machine by appropriate profiling of the reactor blades.

Figure 4 shows the kinematic diagram of a single-stage complex torque converter with switchable reactors [22].

![Diagram of a torque converter with switchable reactors](image_url)

Figure 4. Scheme of a torque converter with switchable reactors

Pump 4 and turbine 5 are installed in torque converter 1 on driving shaft 2 and driven shaft 3, respectively. First reactor 6 and second reactor 7 are mounted on freewheel mechanisms 8 and 9, respectively, which ensures that the torque converter switches to the hydraulic clutch mode in each
range of the joint operation of the torque converter and the engine. Both free-wheeling mechanisms 8 and 9 can be mechanically coupled to the housing using controlled brakes 10 and 11. Fundamentally, such a torque converter works as a three-wheeled unit. The rotation of drive shaft 2 is transmitted to pump 4, and turbine 5 rotates driven shaft 3. The liquid exiting the turbine wheel then goes to the blades of reactors 6 and 7 and returns to pump 4. In the first mode of the torque converter, one of the brakes, for example brake 10, is turned off, and reactor 6 will freely rotate in the flow of the working fluid. The active brake 11 in this case turns on the reactor 7. In the second mode of operation, brake 10 is turned on, brake 11 is turned off. Reactor 6 will be turned on, and reactor 7 will freely rotate in the flow of the working fluid. The operation of the torque converter in the clutch mode is provided using the freewheel mechanisms 8 and 9. Manual or automatic on and off brakes 10 and 11 are provided using the HMT hydraulic system.

We also note that in the case of rotary blades of the reactor, when the blades rotate, both the entry angle and the exit angle of the working fluid change. In the proposed design of the torque converter there is no such a disadvantage, since the reactor blades are profiled independently of each other.

5. Second target settings

Another way to control the torque converter is to combine it with volumetric type converters. In one of the technical solutions of an adjustable single-stage torque converter containing two reactors, one of the reactors is kinematically connected to a volumetric machine, which in turn is connected to hydraulic units. The volumetric machine controls the direction and speed of rotation of the reactor coupled to it, which allows expanding the range of power control at high efficiency [23]. The HMT scheme with a torque converter adjustable by means of a volumetric hydraulic machine is shown in Fig. 5.

![Figure 5. Scheme of an adjustable torque converter [23]](image)

The diagram shows drive shaft 1 with a pump, a turbine 2, a first reactor 3, a second reactor 4 connected to a housing, a control hydraulic machine 5, hydraulic devices 6, a volume pump 7, driven by a drive shaft 1. The hydraulic machine 5 can operate in pump and motor modes with reverse fluid flow. With the help of hydraulic devices, an impact on the hydraulic machine 5 is carried out.

The regulation of this torque converter is carried out by changing the direction and speed of rotation of the reactor, installed in front of the pump wheel and connected to a volumetric hydraulic machine. The disadvantage of this device is the complexity of its design, due to the presence of an additional volumetric type hydraulic machine and a system of guides and control hydraulic units. The presence of an auxiliary hydraulic system for regulating the torque converter does not increase the efficiency of hydraulic transmission.

A further development of the considered method of combining a torque converter and a volumetric hydraulic machine is an adjustable complex torque converter, designed by engineers of the Minsk
Automobile Plant (MAZ). The scheme of the MAZ torque converter combined with an axial piston hydraulic machine is shown in Fig. 6 [24].

![Figure 6. Scheme of the MAZ adjustable complex torque converter [24]](image)

The torque converter contains a pump 1 and a turbine 2. Reactor 4 is mounted on shaft 3 with the possibility of free rotation, kinematically connected to the pump using a volumetric hydraulic machine, in the pressure hydraulic line 5 of which an adjustable throttle is installed 6. Moreover, the volumetric axial piston type hydraulic machine has a cylinder block 7 and an inclined disk 8, respectively connected with pump 1 and reactor 4, which is mounted on shaft 3 with the help of the overrunning clutch 9. Pistons (or plungers) are in contact with inclined disk 8.

The volumetric hydraulic machine changes the gear ratio of the kinematic connection between the pump and the reactor, providing forced rotation of the reactor. The rotation speed of the reactor depends on the pressure in the hydraulic line 5, which is determined by the adjustment of throttle 6, overlapping hydraulic line 5.

Figure 7 shows graphs of changes in efficiency (η) and pump torque coefficient (λ) depending on changes in gear ratio ($i_T$) and reactor rotation speed [25]. The curves with index "a" correspond to the operation of the torque converter with a stationary reactor, and the curves "b" and "c" correspond to the operation of the torque converter with different speeds of the forced-rotation reactor.

![Figure 7. Graphs of changes in efficiency (η) and coefficient of pump torque (λ) for the controlled MAZ integrated torque converter [25]](image)

As a result, this torque converter provides an increase in efficiency in the area of transition to the fluid coupling mode by forcing the reactor wheel to rotate in the rotation direction of the pump wheel. Forced rotation of the reactor wheel, installed in front of the pump wheel, allows in one-reactor and two-reactor complex torque converters to stretch the point of a sharp transition to the fluid coupling mode over a fairly wide area. At the same time, the area of high efficiency of the torque converter significantly expands, its transparency increases, and the joint operation of the torque converter with an internal combustion engine improves.

However, this torque converter, despite its effectiveness, has a complex structure due to the presence of a special volumetric machine of axial-piston type.
As a prototype for the design of an energy-efficient torque converter with forced rotation of the reactor wheel, the HMT design by engineer B.V. Agaykin was chosen [26]. The kinematic diagram of the initial HMT is shown in Fig. 8.

![Figure 8. Scheme of the HMT design by B.V. Agaykin](image)

This HMT contains a housing 1, input 2 and output 3 shafts, a torque converter 4 and a planetary three-link mechanism 5. The torque converter contains a pump 6 and a turbine 7, as well as two dependent rotation reactors 8 and 10 installed on freewheels 9 and 11, respectively. The three-link planetary mechanism 5 comprises a carrier 14 with satellites 15, a ring gear 12 and a sun gear 13, the sun gear 13 being connected to the reactor 8 located on the pump side, and the reactor 10 located on the turbine side, connected to the ring gear 12. Planetary gear 5 has a fixed carrier 14 and works as an overdrive, i.e. until the torque converter switches to the fluid coupling mode, the angular velocity of the reactor 10 is higher than the angular velocity of the reactor 9. The presence of the impeller in front of the pump wheel and rotating in the same direction as the pump wheel allows increasing the efficiency of the torque converter due to the reduction of shock losses of the pressure of the working fluid at the inlet to pump wheel depending on the gear ratio of the torque converter.

The disadvantage of the considered HMT is that both reactor wheels do not have a stationary state during operation until the torque converter switches to the hydraulic clutch mode. For example, the torque converter in question switches to the fluid coupling mode with a gear ratio of 0.8. Then, at a zero gear ratio of the torque converter, the first reactor wheel located on the side of the turbine wheel has a maximum angular velocity, and the second reactor wheel located on the side of the pump wheel also rotates with a maximum angular speed; the rotation directions of the reactor wheels are opposite. As the gear ratio increases from 0 to 0.8, the angular velocity of both the first and second reactor wheels decreases to 0, which corresponds to the transition of the torque converter to the hydraulic clutch mode; however, both free-wheel clutches associated with the reactor wheels are jammed. When the torque converter switches to the hydraulic clutch mode, the overrunning clutches wedge and the reactor wheels begin to rotate freely in the flow of the working fluid, and the differential mechanism is not involved in the operation of the hydromechanical transmission. According to the authors, the lack of a stationary state of the reactor wheels until the transition to the fluid coupling mode does not provide for high converting properties of the prototype torque converter.

6. Second experimental results

In order to overcome the aforementioned disadvantage of the HMT torque converter by engineer B.V. Agaykin, the authors proposed a modified design of a torque converter with a stationary reactor. Figure 9 shows the kinematic diagram of a HMT with an improved torque converter with three reactor wheels [27].
The considerable HMT comprises a housing 1, a leading 2 and driven shafts 3, a torque converter 4 and a three-link differential mechanism 5. Torque converter 4 comprises a pump 6 connected to drive shaft 2, turbine 7 connected to driven shaft 3, first reactor 8 mounted on the side of turbine 7 and installed on freewheel 9, the second reactor 10 installed on the pump side 6 and installed on the freewheel 11. Differential mechanism 5 includes a ring gear 12, a sun gear 13, a carrier 14 with satellites 15. The freewheel 9 is connected to the ring gear 12 of the differential mechanism 5, the freewheel 11 is connected to the sun gear 13 of the differential mechanism 5. Carrier 14 of the differential mechanism 5 is connected to housing 1.

![Figure 9. Scheme of the torque converter according to RU2695477 patent](image)

In order to improve the transforming properties of the initial torque converter between the first 8 and the second 10 reactors, there is a third (middle) reactor 16, also mounted on a freewheel 17 connected to the carrier 14 of the differential mechanism 5 and, accordingly, to the housing 1.

HMT works with this torque converter as follows. Drive shaft 3 drives pump 6 which creates the flow and pressure of the working fluid. The working fluid flows further into the turbine 7, which rotates output shaft 3. The working fluid, leaving turbine 7, creates a negative torque on the first reactor 8, which is transmitted through the jammed freewheel 9 to the ring gear 12. Reactor 8 rotates to the side, opposite the rotation direction of the pump 6, and by means of an accelerating differential mechanism 5 rotates the reactor 10 in the direction of rotation of the pump 6. The rotation of the reactor 10 helps to reduce the energy intensity of the pump wheel by reducing shock sweat pressure of the working fluid at the inlet to pump 6, which leads to an increase in the efficiency of the torque converter and the HMT as a whole.

In the process of accelerating the self-propelled machine and increasing the gear ratio of the torque converter, the third reactor 16 is stationary, since the freewheel 17 connected to the stationary carrier 14, is jammed. Thus, the torque converter in question works as a regular single-stage three-wheel complex torque converter.

With the acceleration of the self-propelled machine and the increase in the gear ratio of the torque converter, the rotation speed of reactors 8 and 10 is self-regulated in the direction of their decrease, in the future their shutdown. When the torque converter switches to the fluid coupling mode, all reactors 8, 10 and 16 rotate in the rotation direction of pump 6 and turbine 7 wheels due to wedging of the freewheels 9, 11 and 17. In the fluid coupling mode, the pump and the turbine wheels can be blocked in order to ensure maximum transmission efficiency at steady motion of a self-propelled vehicle.

The optimal rotation mode of reactor wheel 10 is determined by selecting the appropriate gear ratio of the differential mechanism 5.

The designed torque converter, in comparison with the prototype torque converter, has higher converting properties due to the additional reactor wheel. Using the proposed hydromechanical
transmission can improve the dynamic properties of a self-propelled machine by increasing the maximum value of the transformation coefficient of the hydromechanical transmission. When implementing this hydromechanical transmission, a blade system can be borrowed from a unified three-wheel motor and tractor torque converter for the manufacture of pump and turbine wheels, as well as the third (middle) reactor wheel of the torque converter.

7. Discussion of results
Patent search and retrospective analysis of well-known and little-known designs of domestic and foreign torque converters and HMTs based on them allowed the authors to theoretically substantiate and design modified torque converters aimed at achieving effective operation with the drive engine of a self-propelled machine. The technical solutions developed by the authors are primarily aimed at increasing the efficiency of torque converters in small and medium gear ratios. Designed torque converters are characterized by various levels of structural and technological complexity. Therefore, the practical implementation of the designed torque converters involves, for the purpose of unification, the widespread use of structural elements and blade systems of mass-produced motor and tractor torque converters. As a result, the proposed designs allow us to expand the operational capabilities of self-propelled machines by improving the adaptability of its transmission to changing external loads.

8. Summary and conclusions
The considered designs of torque converters are intended for use mainly in transmissions of self-propelled transport-loading, transport-technological and traction machines. Such torque converters can be in demand in HMTs of self-propelled vehicles operating under varying loads, which include city buses, bucket and fork loaders, road construction vehicles, dump trucks, tractors, railway locomotives, and special-purpose vehicles. In addition to self-propelled machines, designed torque converters can be in demand for transmissions of stationary technological machines.

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