Reverse rotation stator of torque converter in automotive powertrain system

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Abstract. Global economy demonstrates a steady elevated demand for heavy mobile equipment for construction and mining enterprises. At the same time wheel loaders, the total annual world output of which is about 160-170 thousand units are in high demand. Many wheel buckets and forklifts are equipped with hydro-mechanical transmissions containing a torque converter and a manual gearbox with hydraulic control. The positive properties of self-regulating torque converters are particularly favorable for equipment operating under stress. The transmission is equipped with a gear due to insufficient transforming properties of the torque converter. In order to improve the dynamic properties of self-propelled machines, designers increase the number of stages in gearboxes. However, multi-stage boxes complicate the hydro-mechanical transmission and its control system. One of the ways to improve the hydro-mechanical gears of mobile machines is to fully utilize the motor and tractor torque converters by using the opposite rotation of the torque converter reactor in the forward and reverse modes of the transmission. The article discusses circuit solutions for a hydro-mechanical transmission with a single-stage torque converter without a multi-stage gearbox, intended for use in transmissions of wheeled transport and loading and other self-propelled machines.

1. Introduction
Global economy demonstrates an increased demand for heavy mobile equipment. In the past 10 years the global heavy mobile equipment industry has enjoyed an annual growth rate of around 6%. Experts predict that in 2015-2020 the production of hoisting, road building and earthmoving machinery will grow by about 8-9% per year. The sales of equipment for the mining industry, and loading and unloading operations are expected to be even higher. By 2020, the growth in production of bucket front loaders, widely used in the mining industry, will be more than 44% [1]. A report by The Global Wheeled Loader Industry, prepared in 2018 by the British Off-Highway Research, states that the demand for loaders in 2017 was 163,139 units, which is 33% more than in 2016. Global sales of wheel loaders in 2018 are expected to reach more than 170,000 pieces. According to Off-Highway Research, the number of wheel loaders in the world has grown by about 75% over the past decade: from 1.3 million vehicles in 2008 to 2.23 million in 2018. Construction and mining companies are the biggest buyers of wheel loaders. Other significant groups of buyers are agricultural and forestry enterprises [2].

Currently, transmissions of many self-propelled wheeled and tracked vehicles are equipped with hydro-mechanical transmissions (HMT), which contain a series-connected hydrodynamic torque transformer and a manual hydraulically controlled gearbox. The positive properties of torque converters are most fully manifested in transport and technological machines operating with variable
loads in adverse road conditions and off-road. Such machines are, for example, mining dump trucks, front bucket and forklift trucks, earth-moving equipment, etc. The HMT provides for the transmission of large energy flows, high machine productivity, easy and convenient transmission control for the operator. In connection with the increase in the output of cargo-transport and road-building machines, the production of torque converters and HMT for this type of equipment also increases, respectively [3].

2. Target setting
A common disadvantage of automotive HMT is the relatively small range of stepless engine torque control due to the limited transforming properties of single-stage torque converters with three or four impellers. The transformation ratio of such torque converters is in the range of 2-4. Classic three-wheel torque converters of the complex type are characterized by simplicity of design and low cost, so they are very widely used, despite their shortcomings. To compensate for the lack of transforming properties of single-stage torque converters when designing transmissions for the HMT, they increase the number of mechanical stages [4]. An analysis of the transmission designs for commercial vehicles presented at the Moscow international specialized exhibitions Bauma CTT RUSSIA, COMTRANS-2017, BUSWORLD-2018 shows that the number of mechanical gears in the HMT of heavy trucks and tractors reaches 12-16. For some models of buses equipped with a HMT, the number of stages in gearboxes reaches 12. The same tendency is observed for cars HMT: gearboxes with 8-9 stages are increasingly used, although they usually operate in much more favorable conditions than commercial vehicles [5].

However, the increase in the number of stages in HMT gearboxes has its reasonable limits. In addition to the complexity of the mechanical part of the gearbox, the complexity of the hydraulic transmission control system also increases proportionally. In particular, the supply of working fluid to the numerous friction clutches and brakes in planetary and non-planetary gearboxes becomes more complicated. At the same time, the efficiency factor of the transmission is also deteriorating due to an increase in engine power take-off to perform control functions [6].

Hydrostatic transmissions (HST) with infinitely variable control have such positive properties as the transmission of a continuous power flow and a smooth change in torque. However, compared to mechanical transmissions, hydrostatic transmissions have large overall dimensions and weight, lower efficiency (75-80%) and higher cost due to the high complexity of hydraulic units [7]. Therefore, hydrostatic transmissions cannot yet completely replace the HMT with torque converters in transmissions of self-propelled machines.

There are samples of multistage and multiturbine torque converters, which, compared with single-stage counterparts, have higher torque transformation ratios. The transformation ratio in multistage and multi-turbine torque converters reaches 4.5-6, which allows reducing the number of stages in the manual transmission and thereby somewhat simplify the transmission control system. Multistage and multiturbine torque converters, once popular in automotive and tractor transmissions, are not used in transmissions of modern self-propelled machines [8].

Based on the prevailing circumstances, improving the HMT design for mobile transport loading machines remains an urgent scientific and technical challenge.

3. Theory
One of the directions in designing HMT for self-propelled special-purpose machines operating in adverse road conditions and off-road is the more complete use of the classic single-stage torque converters. One of the ways to increase efficiency is to use the reverse mode (relative to the rotation direction of the pump and turbine wheels) of the torque converter reactor rotation. Let us remember that in the torque transformation mode the torque converter reactor must be stationary.

The first technical solution for the practical use for reverse rotation of a torque converter reactor was the invention of Karl Gustav Ahlen, an engineer from the Swedish Svenska Rotor Maskiner AB (SRM), which was later renamed in S.R.M. Hydromekanik AB. The first inventions of SRM in this field were made in the late 1940s. In 1950-1960s SRM transmissions were further developed. Various
designs of torque converters and control devices were implemented in the SRM transmissions, aiming at achieving high performance properties of self-propelled machines [9].

SRM HMT was designed for heavy trucks and tractors. In the SRM HMT the torque converter reactor is connected to the output shaft of the HMT via a planetary transmission and at low angular speeds, the turbine wheel rotates in the direction opposite to the rotation of the impeller. This operation mode of the torque converter allows getting a large torque on the turbine wheel in the area of small ratios of the torque converter (from 0 to 0.4). Reverse-rotating reactor of the SRM HMT torque converter is similar to another turbine wheel of the torque converter, the torque from which is added to the torque of the main turbine wheel using a planetary mechanism on the driven shaft. As a result, in the range of small transmission ratios of the torque converter, an increase in engine torque increases sharply to high values [10].

Fig. 1 shows the basic kinematic scheme of an SRM transmission with a S and DS type torque converter using the reverse rotation mode of the torque converter reactor. The SRM transmission torque converter consists of a pump wheel 1, a two-stage turbine wheel 2 and a reactor wheel 3. The arrows indicate the direction of movement of the working fluid in the circulation of the torque converter. The pump wheel is connected to the drive shaft 4. The turbine wheel is connected to the driven shaft 5, as well as to the epicyclic (crown) gear 6 of the planetary mechanism. The shaft on which the reactor wheel is mounted is connected to the sun gear 10 and the drum of the friction brake 12. The brake drum is also connected to the pinion frame 7, on which the satellites 9 are placed. The driver can be stopped with the help of the friction brake 8.

![Figure 1. Principal kinematic scheme for SRM DS HMT.](image)

The work of the SRM HMT is as follows. At the initial moment of the converter operation, the reactor brake is released, and the planetary carrier brake is tightened, the planetary carrier is stationary. When filling the torque converter with working fluid and rotating the pump and turbine wheels, the crown gear 6, connected to the driven shaft through the satellites 9 and the sun gear 10 begins to rotate the reactor wheel 3 in the direction opposite to the rotation of the impeller. At the same time, with the zero torque ratio of the torque converter, the torque on the turbine wheel increases as compared with the torque on the pump wheel by 8-10 times. When the torque converter reaches a gear ratio of 0.35, brake 8 is released and brake 12 is clamped, stopping the reactor wheel. The transmission works as with the usual torque converter. Thus, in one torque converter there are two modes, as when working on two separate torque converters. The torque converter can be equipped with locking clutch 13, which, with
a gear ratio of 0.7, connects the pump and turbine wheels to the driven shaft of the transmission; brakes 8 and 12 are released.

Fig. 2 shows the characteristics of the SRM HMT, where $i$ is the gear ratio, $K$ is the torque transformation ratio, $\eta$ is the transmission efficiency [10]. The graphs indicate the high performance properties of the HMT.

![Figure 2. Principal features of SRM DS HMT.](image)

The second way to use the reverse rotation of the reactor in the motor and tractor torque converter is the implementation of the reverse mode in the transmission of a self-propelled machine. If in a hydrodynamic torque converter the turbine wheel is stopped and the reactor is at the same time free, the reactor will rotate in the direction opposite to the rotation direction of the impeller. In this case, the fixed turbine wheel plays the role of the reactor, and the rotating reactor that of the turbine wheel. However, the transformation ratio of the torque is reduced by one [13]. In particular, this effect was practically used in the HMT of the Buick Special passenger car [14]. A similar solution was implemented in the Mack HMT for city buses [15]. Since the reversing mode for most self-propelled machines is short-lived, a short-term inversion in the functions of the turbine wheel and the reactor in the torque converter can also have a positive effect for the HMT wheel loader.

4. Experimental results

Fig. 3 shows the first basic kinematic diagram of the HMT for a self-propelled machine, in which the reverse rotation of the torque converter reactor is used in both forward and reverse modes [16]. In the proposed HMT it is possible to use standardized three-wheel and four-wheel single-stage complex torque converters with cast impellers, e.g. Russian ГТ-543 (GT-543) torque converters and similar ones. These complex torque converters have a centrifugal pumping wheel and a centripetal turbine wheel, which ensure efficient operation in the hydraulic coupling mode. Four-wheel torque converters (with two reactors) such as "ЛГ" (LG) and "ГТ" (GT) are used in HMT of city buses, mining trucks, wheel bucket and forklift trucks, motor graders, tractors and bulldozers, self-propelled scrapers, shunting locomotives and other special-purpose machines [17]. The principal operational possibility of such torque converters in the counter-rotation mode of the reactor was considered in [18].
The first version of the kinematic scheme provides for the non-axial connection of the engine and the HMT. The coupling of the HMT with the subsequent transmission units is coaxial. Fig. 4 shows an alternative principal kinematic scheme of the HMT, which differs in the method of connecting a self-propelled machine to the engine and subsequent transmission units. In the second case, the conjugation of the engine and the HMT is coaxial, and the output of the HMT is non-axial. The output shaft of the HMT in the transmission of an all-wheel drive wheeled vehicle is, as a rule, connected to the torque divider.

Regardless of the version of the kinematic scheme, each considered HMT contains a single-stage torque converter 1 with a dependent rotation reactor 2, pumping and turbine wheels 3 and 4 connected to the input and output shafts 5 and 6 respectively of the transmission, the three-link planetary mechanism 7 consisting of drove 8 with satellites 9, sun and crown gears 10. Reactor 2 is connected by a hollow shaft 12 to the sun gear 10. The HMT also includes controllable clutches mounted on output shaft 6 13, 14, 15. Clutch 13 is connected to turbine wheel 3, clutch 14 is connected with carrier
8, coupling 15 are connected with crown gear 10. Four brakes are also used to control the HMT: brake 16 is for stopping shaft 12, brake 17 is for stopping drove 8, brake 18 is to stop the turbine wheel 2, brake 19 is to stop the crown gear 10. Reactor 2 of the torque converter 1 is installed on shaft 12 by means of the free-wheeling mechanism 20. When using a three-wheel torque converter, reactor 21 and the corresponding free-wheeling mechanism 22 are missing.

In the initial state of the HMT, all brakes are off and the clutches are open. In the first forward drive mode, brake 17 is engaged and carrier 8 is stopped. Turbine wheel 4, through the included clutch 13, rotates the output shaft 6. The output shaft 6 in turn, through included clutch 15, rotates crown gear 11 of planetary gear 7, which works as a reverse gear with a fixed carrier. Sun gear 10 through shaft 12 rotates while the reactor 2 in the direction, the reverse side of the rotation of the pump and turbine wheels 3 and 4. Clutch 14 is turned off. This mode of movement of the self-propelled machine, or the mode of pulling away, takes place in the range of transmission ratios of the torque converter from 0 to 0.4. It can be compared with the inclusion of a downshift in a manual transmission.

In the second mode of the forward stroke, brake 17 is turned off, and brake 16 is activated, stopping shaft 12. The turbine wheel 3, through the included clutch 13, still rotates the output shaft 6. In this mode, the planetary mechanism 7 does not participate in the operation of the HMT, but the transmission of the whole torque is carried out only through torque converter 1, which now works as a complex due to the connection of reactor 2 with free mechanism 20. Clutches 14 and 15 are turned off. In the reverse mode, brakes 18 and 19 are engaged, stopping the turbine wheel 4 and the ring gear 11, respectively. Brakes 16 and 17 are off. Reactor 2 at the same time rotates in the direction opposite to the side of rotation of impeller 3, and through shaft 12 rotates sun gear 10. Planetary mechanism 7 in this mode works as a downward gear transmission, compensating for the reduction in the transformation ratio of the torque converter during 1. Carrier 8 transfers the reverse rotation from sun gear 10 to output shaft 6 through engaged coupling 14. Stationary turbine wheel 4 and the stationary ring gear 10 are disconnected from the output shaft 6 by means of disconnected clutches 13 and 15 respectively.

The dynamic brake mode is carried out when screw clutches 13 and 14 are on, while screw clutch 15 is switched off. Brake 19 is on, and brakes 16, 17, and 18 are off. In this case, planetary mechanism 7 works as a stepping reducer, the driving link of which is carrier 8, the driven link is sun gear 10, and the fixed link is ring gear 11. Sun gear 10 through shaft 12 and the stuck free-running clutch 20 causes reactor 2 to rotate. Working fluid flow coming out of the turbine wheel 4 and reactor 2 have opposite directions of movement, which creates a braking torque on output shaft 6.

When simultaneously coupling screw clutches 13, 14, 15 and their respective brakes 18, 16, 17 (or all of these screw clutches and brakes simultaneously), output shaft 6 is braked and, accordingly, the self-propelled machine.

A hydraulic system is used to activate the forward and reverse modes of the HMT, as well as the automatic switching of the brakes and screw clutches during the movement of the machine. The forced downshift mode can be automated depending on the amount of torque that occurs in the stationary reactor 22. The original torque converter can be equipped with a lock-up clutch connecting the pump and turbine wheels to improve the efficiency of the transmission when the self-propelled car moves in good driving conditions.

5. Discussion of results

From the point of view of combining various operating modes of self-propelled machines' transmissions, the circuitry of the considered HMT simultaneously combines the properties of single-flow and double-flow HMTs [19]. The double-flow mode appears when the reactor is rotating backward due to the separation of the power flow inside the torque converter. However, there are increased values of the transformation ratio and transmission efficiency in the range of small gear ratios, when the transmission of the self-propelled machine is under high loads (e.g., when the loader bucket collects soil). Single-flow operation of the HMT occurs under conditions of relatively low loads on the transmission of a self-propelled machine, when the torque converter reactor is stationary, and also in reverse mode. With single-flow operation of the HMT in the forward drive mode, increased efficiency values are achieved in the range of large gear ratios. As a result, the combination
of the HMT operating modes contributes to an increase in the average efficiency of the transmission of a self-propelled machine compared to a transmission equipped with a traditional HMT with a single-stage torque converter, while providing high transforming properties in the zone of small gear ratios.

6. Summary and conclusions
Compared with the basic HMT, equipped with single-stage torque converters of the same size, this transmission has a more compact design. The maximum value of the transformation ratio of the engine torque at zero gear ratio is greater than the maximum transformation ratio of the original four-wheel torque converter. The practical implementation of the proposed project allows expanding the operational capabilities of a self-propelled machine, as well as to simplify its transmission as a whole due to the fuller use of the torque converter and the planetary mechanism in all operation modes of the HMT. The considered technical solutions can give a positive effect in transmissions of wheel bucket and fork loaders.

7. References
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