ELECTROHYDRAULIC CONTROL SYSTEMS FOR SKID-STEERING VEHICLES

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The paper presents an analysis of the performance of the modern tracked vehicles with electrohydraulic skid-type steering, and a realistic assessment of different similar types of driving system used for civil and military applications. The real performances of a classical electrohydraulic steering systems are considered as reference for the crawler steering systems ones. The authors designed and tested a classical tracked vehicle with multiple functions. A complete series of tests has shown that such a small power vehicle can be used for many functions, but covering short distance only. However, for civil engineering activities, the use of the hybrid electrohydraulic transmissions offers many combined functions, with a good efficiency, and remote control facilities too. A preliminary study of all these aspects is performed by numerical simulations, using realistic electric, hydraulic and mechanical data. Finally, the authors are discussing the problems raised by the design, full time operation and maintenance of the newest hybrid compact track vehicles.

Keywords: hybrid tracked vehicles, dynamic performances simulation and test, energy saving possibilities

1. Modern motion control systems for mobile equipment

The development of the modern mobile equipment with the local or remote digital control of all specific degrees of freedom increased the productivity and reduced the operator's effort. The main problem of this kind of equipment remains the motion control with skidding wheels or tracks. Other motions of different moving parts as arms for pushing or rising different type of loads etc. are also submitted to different type of options for electrohydraulic, electro mechanic or hybrid servomechanisms. The "green option" for any mobile equipment generated an entire family of electromechanical compact transmissions, replacing the

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electrohydraulic ones. The qualities of the industrial robots generated a remarkable progress in the field of the electric rod actuators. Step by step, the overall static and dynamic performances of these clean devices were improved both with the new ball-screws technology, and the new generation of compact power electronics, in close connection with the high-speed digital communication networks. In parallel, the new generation of digital industrial electrohydraulic servo valves extended on a wide scale the hydraulic actuators applications in all heavy industrial, agricultural, civil and military systems.

This paper offers a realistic analysis of the structure, performance and practical utility of the main types of skid steering vehicles. Preliminary numerical simulations of the steering dynamics are useful for understanding the limits of each type of control system.

2. Electrohydraulic general-purpose skid-steering mobile equipment

Many small mobile equipment driven by thermal engines are used all over the world both for civil and military purposes. The small fuel consumption and the simple local or remote control allow the use of these vehicles for different activities. A typical example, presented in figures 1…4, was designed by the Fluid Power Laboratory (FPL) of the University POLITEHNICA from Bucharest together with the Motion Control Laboratory (MCL) of the R&D Institute of Manufacturing Systems [1].

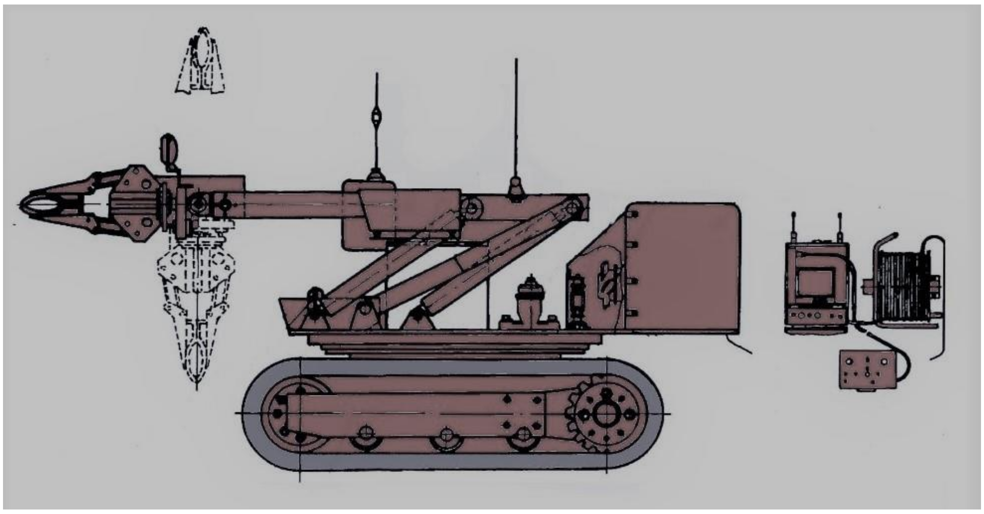

Fig. 1. Lateral view of the multifunctional electrohydraulic vehicle designed by FPL and MCL [1]

The main mechatronic features of the mobile equipment are: modular design; independent power supply; remote control (radio, wire); strong prehensile with three degrees of freedom; possibility of mounting any kind of disrupter; wide mobility; parallelogram type manipulator; cable vision system; spot light; specially developed accessories. Some suitable applications are: remote surveillance to evaluate the risk factor; manipulation and removal of suspicious objects outside of a dangerous area; annihilation of any suspicious object by destruction using a water disrupter or a strong laser beam. Typical areas of use are the parking lands, urban transport locations, passenger terminals, installations from open large halls. Basic configurations include: a manipulator, a prehensile, and color TV camera, remote control station mounted on a dolly with color TV monitor, a power switch box, and an electric battery.

Fig. 2. Back side of the vehicle with the engine

Fig. 3. The prehensile hydraulic actuator

Fig. 4. Electrohydraulic control block based on the Danfoss PVG 32 valves [2]

The main operation parameters of the vehicle are: extended length: 1880 mm; width: 880 mm; minimum height: 1120 mm; working boundaries: vertical

+2700 / 200 mm; horizontal reach: 1500 mm; wire control range: 100 m; radio control distance – 200 m; mass: 750 kg; maximum height of obstacles: 200 mm; maximum ascension slope: 30°; maximum mass of the load: 50 kg; speed control range: 0.04…4.0 km/h; temperature operating range: -10…50°C.

The control of all degrees of freedom is performed with high accuracy using linear and angular digital transducers using the controller developed by Danfoss Corporation for the family of PVG proportional servo valves [2]. All the operational regimes were tuned by numerical simulation with AMESIM software. The basic simulation network (Fig. 5) shows the control systems of all the motion degrees needed for accomplishing different operational missions.

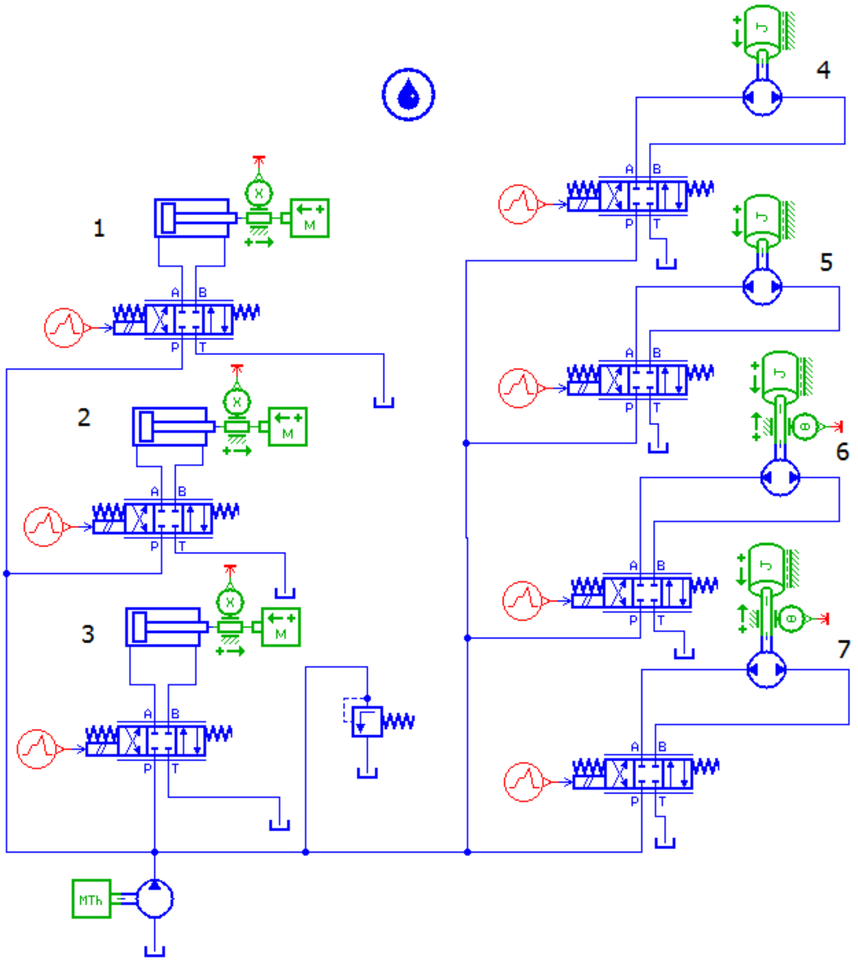

Fig. 5. AMESIM basic simulation network of the robot dynamics: 1-main arm; 2-secondary arm; 3-opening control of the prehensile; 4-angle position control of the prehensile; 5-right driving motor; 6-left driving motor; 7-turret driving control

The different optional functions were tested in various conditions, certifying the required performance. The most difficult test was the climbing of a normal stair inside an office building. The next step in the above research was the replacement of the thermal engine by an electric one supplied by a small lithium-ion battery of about 10 kWh, needed to drive the same gear pump during a typical daily activity.

Similar applications of the open loop electrohydraulic control systems are now developed by innovative companies for low and middle power mobile equipment with skid-steering type mobility. For example, CASE Construction Equipment Corporation [3] developed a new electric battery mini excavator (Fig. 6), while Doosan has developed two fully electric and hybrid small excavators powered by technology from Danfoss' Editron division [4-5].

Fig. 6. Electrohydraulic CASE CX15 EV mini excavator powdered by a 16 kW electric motor and 21.5 kWh lithium-ion battery [3]

3. Electrohydraulic skid-steering equipment with combustion engines

The high degree of versatility offered by the modern generation of front loaders driven by EURO 6 internal combustion engines keep them in the attention of all important manufacturers of construction equipment. The main way to save energy during harsh working conditions is to eliminate the direction control by high flow rate servo valves placed on the power hydraulic circuits. [6] The energy loses can be cut by 90% using proportional servo valves for controlling the displacements of two axial or radial pistons pumps which supply in closed loop two low speed hydraulic motors, without any planetary gears. A typical example of this energy saving system is promoted by POCLAIN CORPORATION (Fig. 7) and other manufacturers of low speed, high torque radial pistons hydraulic motors.

Fig. 7. Typical wheels and track skid type front loaders with combustion engine (POCLAIN)

For many reasons, two tandem axial pistons pumps are used (Fig. 8). A joystick with four quadrants is the only control tool of the loaders skid direction! The hydraulic scheme of the tandem servopumps (Fig. 9) reveals the use of a single auxiliary internal gear pump both for preventing the cavitation phenomena, and for supplying the two robust proportional servo valves with small nominal flows.

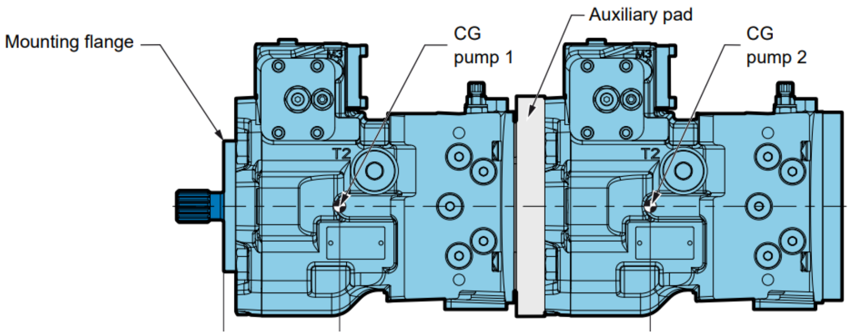

Fig. 8. Tandem pumps for skid steering vehicles (PM50-POCALAIN)

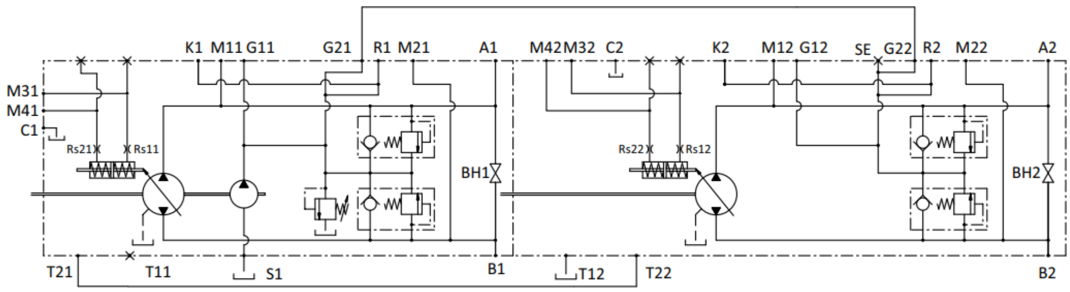

Fig. 9. Hydro mechanical scheme of the tandem servopumps (proportional servovalves not shown)

The best overall efficiency of the split hydrostatic transmissions is obtained using radial pistons hydraulic motors with disk brakes, directly driving the tracks (Figs. 10 and 11).

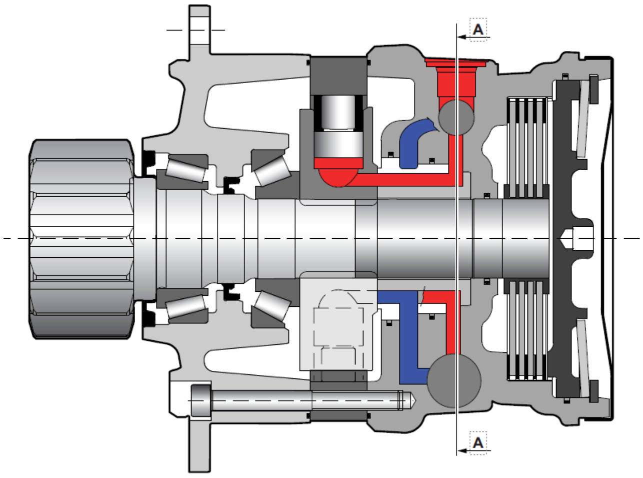

Fig. 10. Heavy duty radial pistons hydraulic motors with disk brake for swing drive

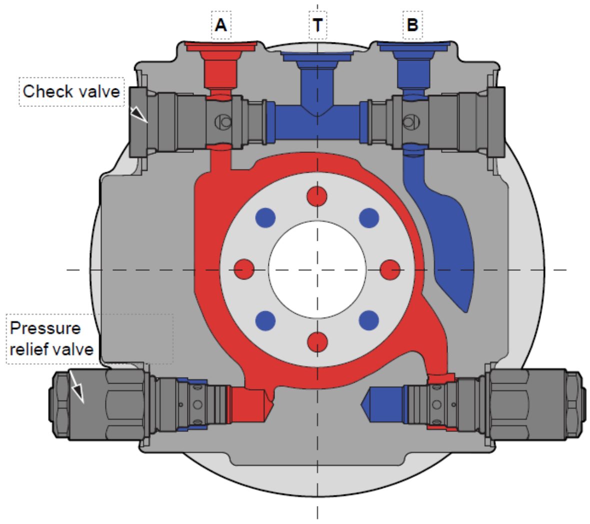

Fig. 11. Pressure relief valves and anti-cavitation check valves of the hydraulic motor

A preliminary study of the steering system dynamics can be performed by AMESIM software, taking into account the main power components only. The deep understanding of all the steering process details can be obtained by the aid of a complete model including the vehicle dynamics [7]. The modern studies on the skid-steering vehicles [8-15] point out the big number of physical parameters of the steering process, starting with the soil properties. The simplest simulation network of the studied transmission is presented in the next two figures (12 and 13). The relevant parameters variations are presented in figures 14…23.

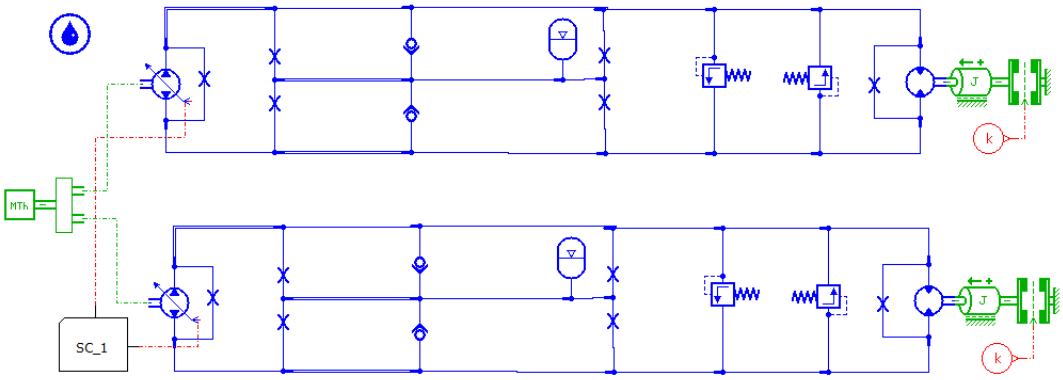

Fig. 12. Basic simulation network for the electrohydraulic split power transmission

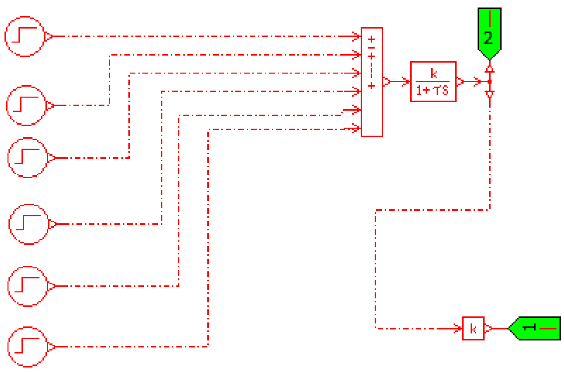

Fig. 13. The input signal applied to the servopumps

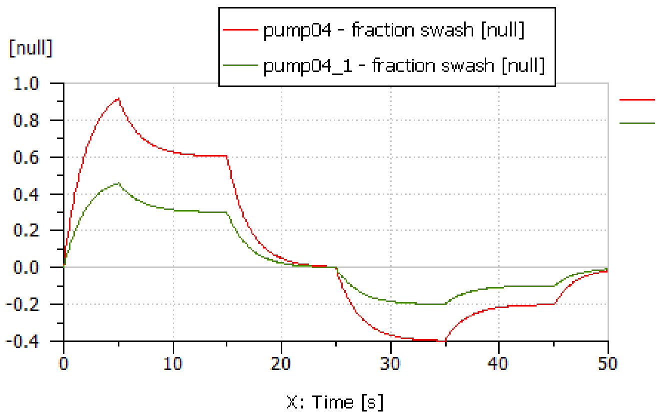

Fig. 14. Pumps swash fractions variation during a turn to left

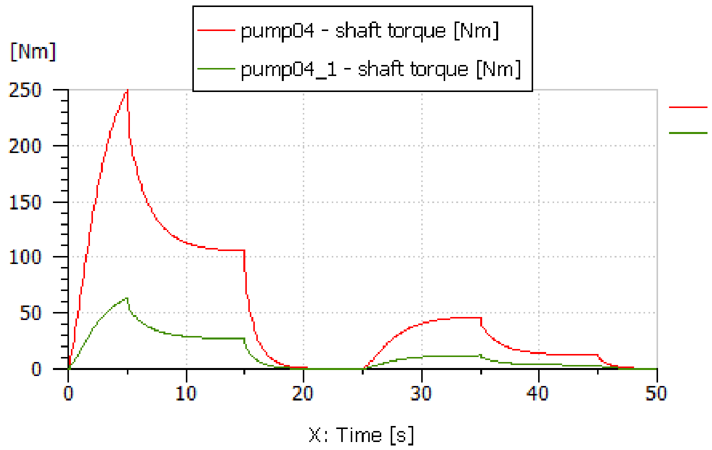

Fig. 15. The pumps shaft torques variations

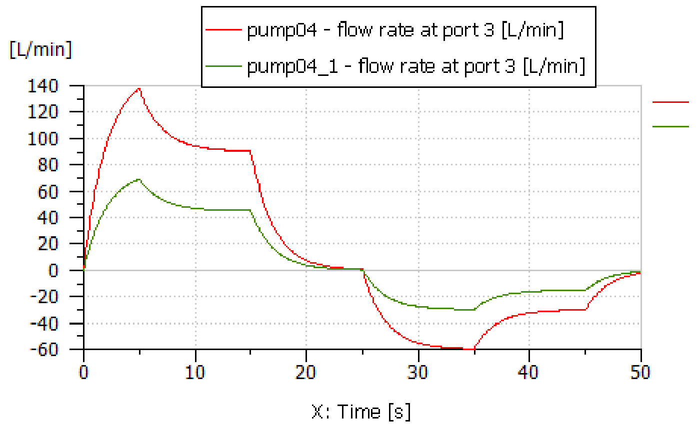

Fig. 16. Pumps flow rates

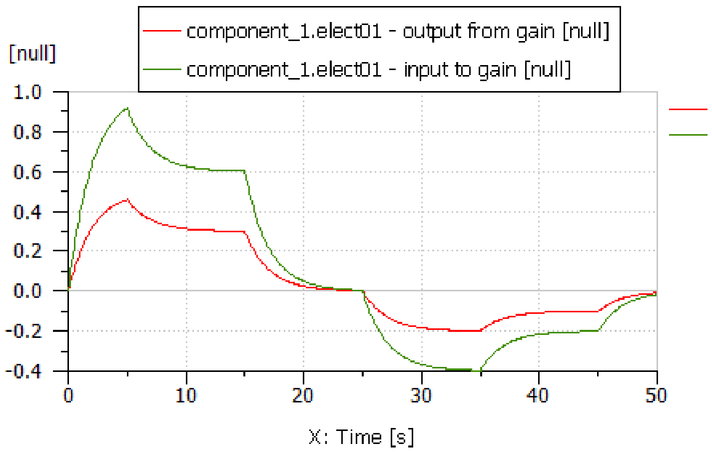

Fig. 17. Input and output from the controller block

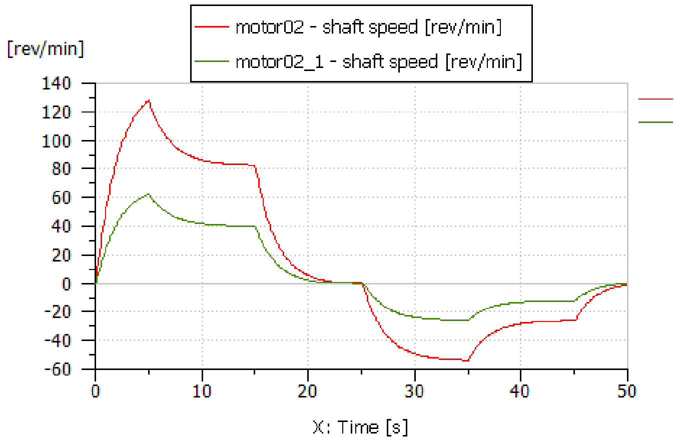

Fig. 18. Speed of the hydraulic motor

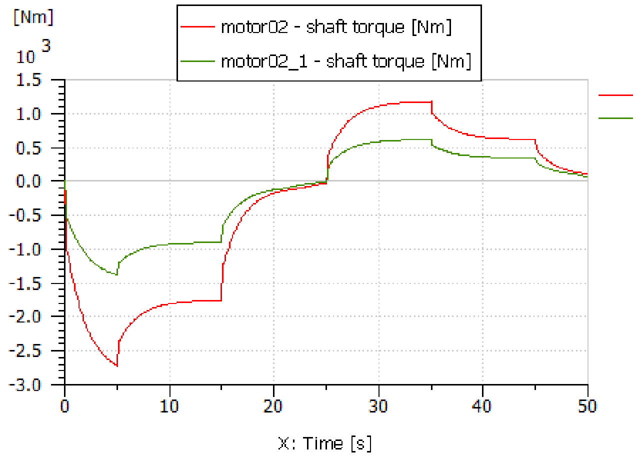

Fig. 19. Torque developed by the hydraulic motors

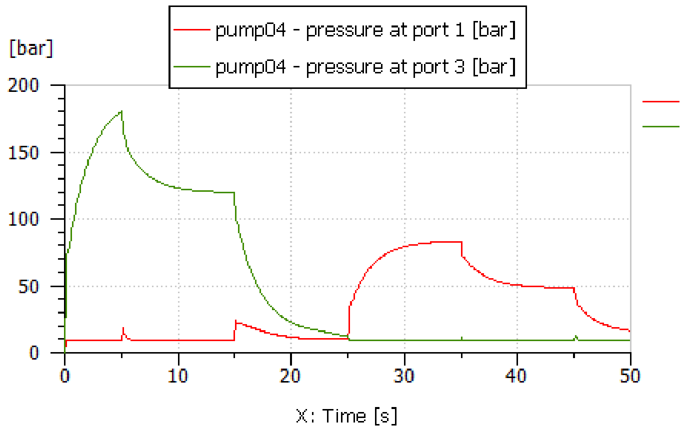

Fig. 20. Pressure variations at the first pump ports

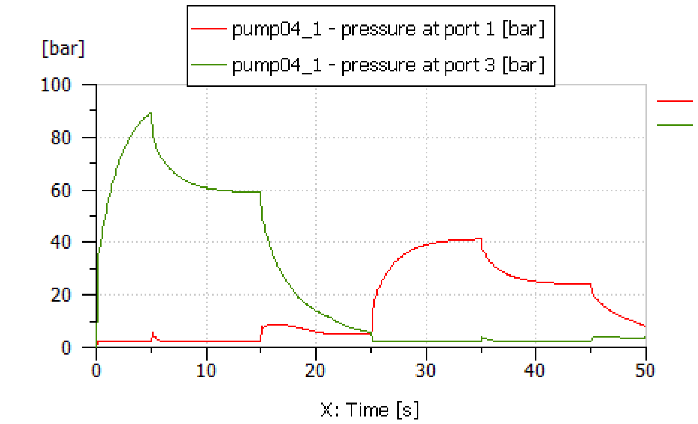

Fig. 21. Pressure variations at the ports of the second pump

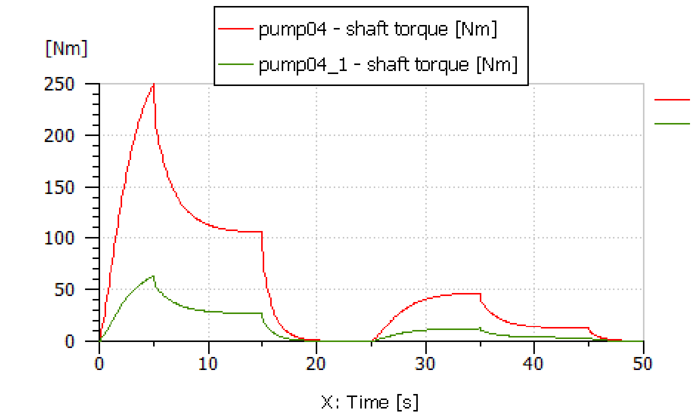

Fig. 22. Torque applied to the shafts of pumps

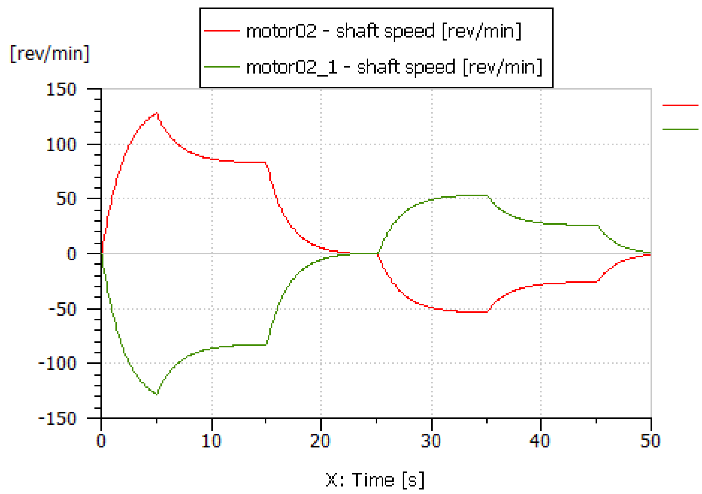

Fig. 23. Shaft speed in the case of rotating the vehicle around his vertical axle

4. Electrohydraulic skid-steering vehicles with electric motors

The new "green target" of cleaning the environment by the aid of hybrid drives generated many experimental construction equipment which keep the split hydrostatic transmission, replacing the internal combustion engines. Promising examples are offered by PARKER, MOOG and REXROTH [18-20], which are developing the whole electric hydraulic and control chain for some widely used mobile equipment's. A modern servopump is presented in figure 24 [18].

Fig. 24. High pressure swash plate axial piston pumps driven by a three phase AC brushless motor

The main components of a hybrid transmission are included in the simulation network from figure 25. The main parameters of the hydraulic components were the same as in the previous case. However, the variations of some hydraulic and mechanical parameters, shown in the following figures are different from the previous case (figures 26, 27 and 28).

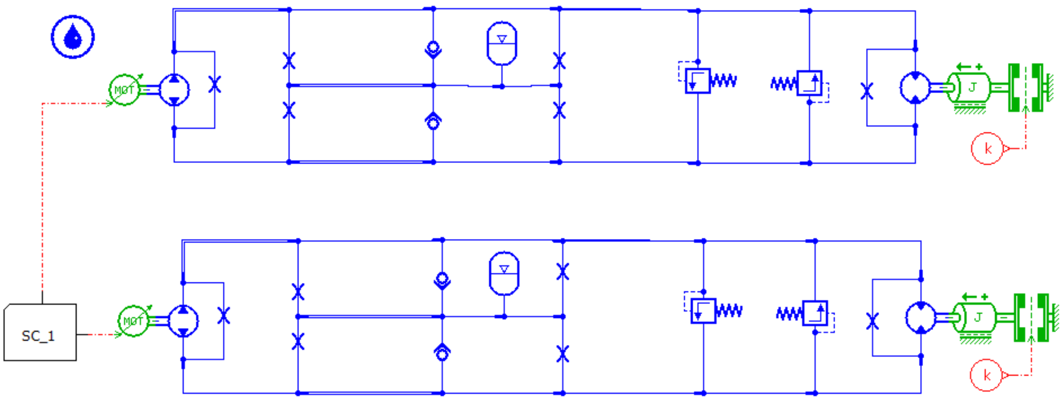

Fig. 25. Simulation network for the hybrid transmission of a skid front loader

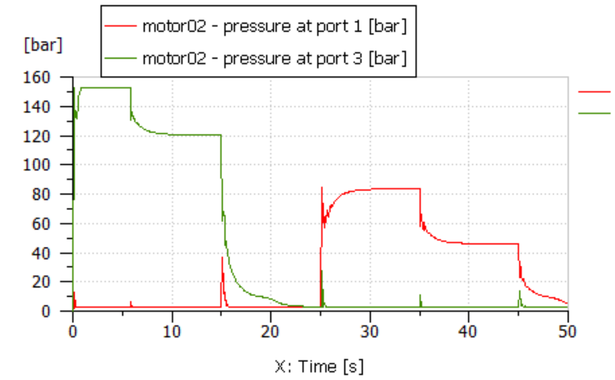

Fig. 26. Pressure variations in the ports of the first hydraulic motor during a common skid steering

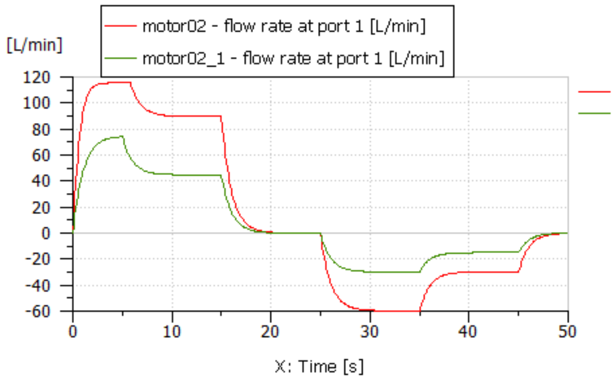

Fig. 27. Variations of the flow rates in the input ports of the hydraulic motors

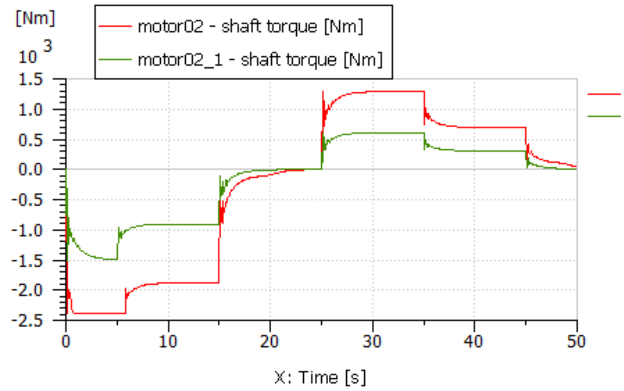

Fig. 28. Variation of the shaft torques of the hydraulic motors

The real turning radius R of the equipment with skid-steering for both types of transmissions depends on the relation between the speeds of the "internal" hydraulic motors n_i and the "external" ones, n_e (Fig. 29) . The classical relations established long time ago by Jo Yung Wong for the kinetics of the steel tracks [9-

10, 14], are still completed by many research for different contact materials and guiding roller configurations.

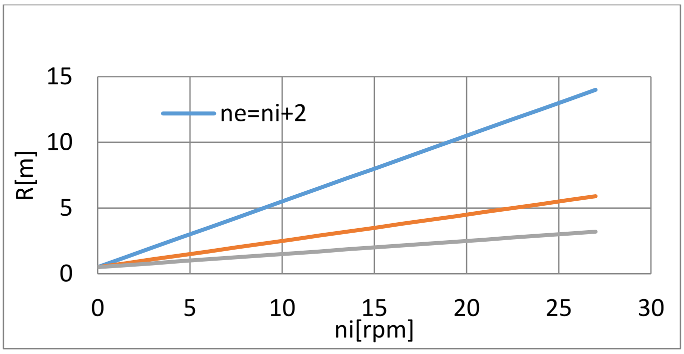

Fig. 29. Relation between the speed of the hydraulic motors and the turning radius

5. The future of the hybrid and full electric construction equipment's

The rapid extension of the electric and hybrid car generated a lot of attempts for eliminating the combustion engines and even the hydraulic actuators from wide categories of equipment (Figs. 30 and 31). The collaboration between the advanced suppliers of actuators, as MOOG, and the integrators of hybrid components into construction equipment as DOOSAN generated some modern achievements as the world's first all-electric Bobcat compact track loader (Fig. 32) successfully tested in 2022 [21]. VOLVO successfully tested this year the first hybrid excavator (Fig. 33) with energy recovery system by 25-30% using hybrid actuators and digital radial piston pumps [22].

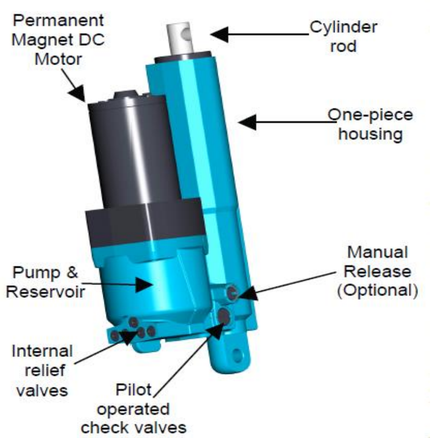

Fig. 30. Main components of a hybrid servomotor used on mobile equipment's [18]

Fig. 31. Snow plough with electric propulsion and hybrid actuators for the front blade

Fig. 32. The world's first all-electric compact track loader (DOOSAN)

Fig. 33. The world's first all-electric excavator with energy recovery system by electrohydraulic servomotors based on DANFOSS digital pumps (VOLVO)

5. Conclusions

Many specialists have shown an enthusiastic position to the idea of electric construction machines, but the mature users remain neutral observers of the practical problems concerning the reliability of the heavy-duty electromechanical actuators. The huge electric energy crisis already created a lot of negative reaction to the full electrification of the skid-steering machines [16-17]. The future of the batteries is already a big problem with a strong economic impact on the technical decisions. Another problem becoming critical everywhere in the world is the chronical lack of skilled technical staff capable to identify and to solve interdisciplinary problems "on the spot". The exploitation of the new generation of self-guided tractors by GPS systems pointed out the need of a special qualification for the technical staff, which is time consuming and expensive.

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