An analysis of quarter-turn valve drive transmission mechanisms

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Abstract. This article addresses problems of optimization of power specifications and efficiency improvement of electric drives for quarter-turn valves. What is proposed is a quad-link transmission mechanism having a variable transmission function matched with the ball valve torque specification. Using the elaborated and proven methodology of comparing technical solutions at the design phase, based on the qualitative-quantitative assessment and analysis of engineering and manufacturing parameters, two alternatives of the transmission mechanism construction were compared. Advantages and disadvantages of the proposed technical solutions are being analyzed. Preferable embodiments of the high-efficiency quarter-turn valve electric drive with the proposed transmission mechanism were determined.

1. Introduction
The development of the valves drive technology over the last decade has been more focused on the electrical drive [1], [2]. The advancement in power electronics, sensors and magnetic materials lays an extensive ground for improvement of the electrical drive technology, which, in practice, allows it to compete successfully with the pneumatic and hydraulic drive in the totality of functionality provided, cost efficiency and performance [3], [4].

The electric drive is becoming more and more versatile, reliable, energy-efficient and easy to operate [4 – 6]. The mentioned trends in development of the electrical drive found their reflection in the concepts of the “all electric ship”, “more electric aircraft”, “all electric aircraft” [7 – 12], and there is no doubt that the development of electrical drive technologies will only expand in the near future. However, the transmission mechanism necessary for matching angular velocities and torques of the motor and the load, presently being an integral part of a modern electric drive, has its own characteristics and limitations, which has a substantial effect on the electric drive specifications. The improvement and optimization of transmission mechanism specifications is an important direction in the development of driving technologies, and it allows substantially improving the electric drive power performance, specifically in the ball valve control systems.

2. Ball valve control specifics
One of the most widely spread valve types are ball valves [13]. Generally, the ball valve designs are similar and have close technical and operating features. The highest closing member resistance moments are known to occur in the ball valve closed position – Figure 1, curve#1, when the ball valve has been exposed to the fluid pressure for a long time.
To ensure breakaway (assurance of initial movement) at the maximum pressure difference upstream and downstream the ball valve, the torque developed by the control drive should be 2 to 3 times higher than the torque on other portions of the operating range. Moreover, an increased torque occurs on closing the ball valve owing to interaction between the ball and the seal.

The modern quarter-turn electric valve control drives in most cases feature a reducer with a constant gear ratio between the high-speed and the low-speed (output) shaft and adjustable mechanical or electronic torque-limiting systems. The straight line #2 Figure 1 shows the torque developed by the drive with a constant gear ratio, necessary to break away the valve rotary member.

For valve drives, and specifically for ball valve drives, it is generally accepted to use torque safety factors, for instance, [1], [3] and more. Curve #3 corresponds to the torque with safety factor of 1, 3 relative to the torque occurring at the valve rotary member. Straight line #4 shows the torque of a drive with a constant gear ratio providing the safety factor of 1, 3. Hence, it can be seen that the developed drive torque, except the initial and final portions, is significantly higher than required for the reliable turn of the valve rotary member. The need in ensuring the reliable valve control in heavy operating environment calls for introduction of significant safety factors. This result in the electric drive using only a small part of its torque capabilities across the most part of the operating range, which prevents the electric drive from being used with maximum efficiency. Attempts to resolve the mentioned controversy in order to ensure optimal power specifications of the ball valve electric drive can be traced down from issued patents aiming to ensure increased torques for breaking away the closing member from the open and closed positions. The most interesting ideas are brought down to building two-stage reducers, for instance, “Double-speed driving device”, USSR Certificate of Authorship 323989, F 16 H 1/28, (bulletin №35 1981); U.S. Patent 5507469, F16K 31/53 [14]. One reducer with increased transmission ratio is used for breakaway, and the other reducer with nominal transmission ratio is used for moving between initial and end portions of the working travel. Disadvantages of the mechanical systems like the above may not only consist in the complexity of design and operating algorithm, but also in the possibility of shock loads occurring at the time of transition from one mechanism transmission ratio to the other, which may result in shorter operating life and lower reliability.

The described controversies does not affect drives using the Scotch-Yoke transmission mechanism [15] that has a torque performance corresponding to the ball valve power curve – maximum torque reached by the mechanism in the closed position and increased torque reached in the open position. Design of such a mechanism allows the mechanism carrier to be coupled with the pneumatic or hydraulic cylinder rod easily enough. However, an additional mechanical converter of rotary to translational motion – a screw-nut – is required for coupling with the electric motor. The efficiency factor of the screw-nut sliding converter depends on many factors and may be within broad limits [16], [17], but in practice does not exceed 45%. A relatively low efficiency factor of the screw-nut converter (30% and less) ensures static retardation of the resulting Scotch-Yoke transmission mechanism,
however, the conditions for persistence of the static retardation can be disturbed by external factors, such as vibration [18]. Therefore, the static retardation cannot be regarded as a reliable method of the valve closing member position retention. To prevent the valve closing member from changing position, the electric drive with a Scotch-Yoke transmission can be equipped with a special blocking means, for example, Auma LMS anti-back drive device [19]. Thus, it can be asserted that the Scotch-Yoke mechanism has a deficiency, that being a low efficiency factor, which not only necessitates the use of a more powerful motor, but can also affect the total life of the transmission mechanism due to increased wear in sliding friction couples, as well as necessitates, in heavy duty conditions, the use of electric drive forced cooling systems.

The efficiency increase of the Scotch-Yoke screw transmission mechanism can be achieved by replacing the sliding friction with the rolling friction. A transmission with idle rolling elements can be used as the screw-nut converter, for example, a ball-screw or a roller-screw transmission with an efficiency factor of 80-90%. Sliding bearings (sliding blocks) can be replaced by linear ball or roller guides [20]. However, such converters and bearings are precise mechanical devices setting fairly high requirements for manufacturing accuracy of other elements of the mechanism, for in-service maintenance quality, and are relatively expensive. For that reason the linear or roller guides, as well as rotary-to-translational converters with idle rolling elements have not been used in Scotch-Yoke screw mechanisms, as far as the authors are informed. Also known are technical solutions for increasing the efficiency of quarter-turn drive transmission mechanism for big ball valves by replacing the Scotch-Yoke mechanism with wire transmission [21], [22]. However, the wire transmission, as well as rack and pinion mechanisms, despite higher efficiency factor, do not offer the advantages of the Scotch-Yoke mechanism being the non-linear transmission function repeating the shape of change of the ball valve torque characteristics.

3. Kinematic chain of the quad-link transmission mechanism proposed

A substantial increase of a quarter-turn drive transmission mechanism efficiency factor while retaining the non-linear transmission characteristic is possible by using a special quad-link transmission mechanism [23]. The mechanism consists of two levers interconnected by a crank rod. Shown on Figure 2 is a scheme of the quad-link mechanism and its operation in several phases, wherein $a$ is the first lever arm, $c$ is the second lever arm, $d$ is a distance between rotation axes of the levers, $b$ is a distance between the crank rod hinges. The first lever is connected with the motor or intermediate reducer, while the second one is connected with the output shaft. The levers rest on bearing supports, the crank rod is connected with the levers by means of pins resting in bearings. The mutual position of rotation axes of the levers, lever lengths to crank rod lengths relation are chosen so as to ensure that the second lever pivot angle during mechanism operation is 90°, the first lever performing an incomplete turn.

The transmission ratio behavior of such a mechanism is shown on Figure 3. It can be seen that in the “closed” position the mechanism develops the maximum transmission ratio, gradually decreasing as the second lever rotates and increasing again when the second lever takes the “open” position, while the minimum transmission ratio value can be within 1,7-1,9.

![Figure 2. Mechanism operation phases: 1-1 "closed" position; 2-2 intermediate position; 3-3 "open" position.](image-url)
The function of pivot angle $\beta$ depends on the initial angle $\alpha$ and has the following appearance:

a) $\beta(\alpha) = \arccos \lambda + \arccos \varphi$, in the range $0^\circ < \alpha \leq 180^\circ$, thereat:

$$\lambda = \frac{d - a \cos \alpha}{\sqrt{a^2 + d^2 - 2ad \cos \alpha}}$$ (1)

$$\varphi = \frac{a^2 + c^2 + d^2 - b^2 - 2ad \cos \alpha}{2c\sqrt{a^2 + d^2 - 2ad \cos \alpha}}$$ (2)

b) $\beta(\alpha) = \arccos \varphi - \arccos \lambda$, in the range $180^\circ < \alpha \leq 360^\circ$, where $\varphi$ and $\lambda$ have the same dependencies. The transmission function $i(\alpha)$, as a ratio of angle $\beta$ increment to increment $\alpha$, is a first derivative of the pivot angle: $i(\alpha) = \beta'(\alpha)$. Figure 4 shows an example of the quad-link mechanism design. The arm length from the second lever should be greater than the arm length $a$ of the first lever, since the second arm is to make a quarter-turn, while the first lever is making no more than three fourths of a turn. In total, such a mechanism allows obtaining a high efficiency factor, low breakaway torque, long life, simple design.

The quad-link transmission mechanism addressed can be used as an output stage of a mechanical converter in a quarter-turn electric drive, which would allow the requirements for power characteristics of the motor, intermediate reducer and control electronics to be substantially reduced.
To enable control and limitation of the torque developed by the drive, it is reasonable to equip the control system with mechanism output lever angular position sensors and motor phase current sensors. A structural diagram of such an electric drive is presented in Figure 5.

![Figure 5. Structure of an electric drive with the quad-link mechanism.](image)

It should be noted that the proposed quad-link mechanism allows expanding the power specification range of ball valve control drives and is independent of the physical motor operation principles (motion system) and motion type of the motor output link (rotary, translational). The motor may have not only the electromagnetic functioning principle but also the pneumatic, hydraulic or a different one. Figure 6 is an example of the quad-link mechanism linking with a pneumatic cylinder and return spring through rack and pinion pair. This will provide high developed torques and the valve emergency shutoff function at the same time.

![Figure 6. Kinematic chain of the pneumatic drive with the quad-link mechanism](image)

Of the greatest practical interest for the electric drive, in the authors’ opinion, is a combination of the worm gear-based intermediate reducer and the quad-link mechanism. The worm gear has relatively high operating and technical specifications, low cost, and is widely used in modern electric drives, therefore its application seems most reasonable. Thus, the worm-quad-link mechanism can be regarded as a direct alternative to the Scotch-Yoke screw transmission mechanism of the quarter-turn valve drive.

4. A methodology for assessment and comparison of technical solutions

In order to compare and correlate the quad-link worm mechanism and the Scotch-Yoke screw transmission mechanism, assess their features, advantages and disadvantages when used in a quarter-turn valve drive at the schematic diagram level, the authors have used the elaborated and proven methodology of design-phase qualitative-quantitative assessment of technical solutions [24]. This methodology is intended for designers of mechanical systems, making a justified choice of technical solutions from a variety of alternatives in objective uncertainty and subjective choice environment. The methodology is aimed at increasing the quality of decisions taken specifically at early design phases when the design has not yet been defined, and the designer is to choose between several alternatives at the schematic solution level. The methodology allows conducting a tentative analysis and comparing several alternative technical solutions by the totality of chosen criteria, and justifiably identifying the preferable solution at the design phases while choosing one or another design
implementation of the mechanical system, i.e. without final designing, prototyping and calculative study of all alternative variants. The methodology is aimed at increasing the quality level of the technical products laid down on the design phases, by increasing the objectivity of summarized diverse information.

The main principle of the methodology consists in a qualitative and relatively-quantitative comparison of technical solution options using a points system as against the solution selected as a basic one. The methodology is based on a modified expert assessments method offering a relative simplicity of implementation and a sufficient credibility of the assessment with a high skill of practicing experts [25] - [28]. Criteria are assessed using the integer ordinal scale from 1 to 9. In this respect, the average value of "5" is taken as neutral and regarded as a reference point in the assessment. Values less than "5" characterize the negative assessment gradually decreasing to "1", while values higher than "5" characterize the positive assessment, which increases to 9. In this case it is possible to point out specifically both the negative assessment and the positive one in points (differentiation of assessments). The average «5» is given by the expert in case of difficulties in assessing due to lack of specific knowledge and competences. This ensures correlation of results from an expert to an expert and increases credibility of the eventual (total) assessment.

Experts connected with different phases of the product lifecycle (design, production, operation) should be involved in order to increase the objectivity of the assessment. It can also be noted that a characteristic feature of this methodology is that the product major quality index (MQI) and basic quality indices (BQIs) are determined first. The index characterizing the product’s functional features and determining its application range (application index) is taken as the MQI, while technical, technological, economic and other indices affecting the MQI should be related to BQIs. The methodology comprises four major phases performed sequentially. A generalized functional diagram of the proposed methodology is shown on Figure 7.

**Figure 7.** Functional block diagram of the technical solutions design-phase assessment methodology (S1, S2 are technical solutions under consideration; S1 is the basic solution; P1, P2 are preferable solutions).

At the preparatory (first) phase, the developer of the mechanical product determines the initial selection task data, including optional solutions, the basic technical solution, the expert group, the initial review procedure. Next, tentative lists of design limitations and priorities, set of criteria and their weight factors, assessment counting procedure are formed. Another characteristic feature of the procedure is that the initial data for the technical solutions review are originally handed over to the experts for correction and supplementing. Owing to that, the procedure’s effectiveness and further credibility of the designed products assessment are remarkably increased.

At the second stage, a group of practical experts performs a qualitative scoring assessment of the solutions being compared. The analysis of the expert assessments results in the second-phase preferable technical solution P1 being determined.
The third phase includes a relative-quantitative assessment and a comparison of technical solutions basing on the analysis of design and technology parameters (DTPs) affecting the MQI/BQI, and that effect is determined in relative units. The analysis results in the third-phase preferable technical solution P2 being determined.

At the fourth phase, the results obtained at previous phases are analyzed and compared. If the results obtained at the second and third phases coincide (P1=P2), the final technical solution for implementation in practice is chosen. In cases when P1≠P2, the obtained results can be used as source data in the search for a new technical solution, for example, using the theory of inventive problem solving [29 - 34].

Applying the methodology for comparison of the quad-link worm transmission mechanism with the Scotch-Yoke screw mechanism. The quad-link worm transmission mechanism and the Scotch-Yoke screw transmission mechanism have been analyzed and compared following the considered procedure (Figure 8).

The Scotch-Yoke screw mechanism was taken as the basic technical solution (S1), relatively to which the quad-link worm transmission mechanism (S2) was assessed. Since the compared design variants of the valve drive transmission mechanism have similar dependencies of the transmission function on the rotation angle and, correspondingly, the same application indices, it is reasonable to use a different characteristic having a significant practical value, as the MQI. Basing on the above, the processability was chosen as the MQI. The processability is one of the integrated characteristics of a technical unit that expresses ease of its manufacturing, maintainability and operating performance. The processability of a transmission mechanism can be integrally characterized through the manufacturing cost and operational expenses. The manufacturing cost (prime cost) of the unit in this case is defined via two BQIs: ease of its manufacturing and specific torque of the transmission mechanism. The specific torque is defined as \( Q=T/m \), wherein \( T \) is a developed torque, N·m; \( m \) is a weight of the transmission mechanism, kg. This parameter allows assessing the technical level of the solution being addressed. The cost of operation is defined by two BQIs: the transmission mechanism life and efficiency factor. Four experts were involved to carry out a qualitative assessment of the valve drive transmission mechanism – two design engineers, a process engineer and a metrology engineer. Prior to the assessment, the experts studied the technical materials and conducted the mechanisms analysis. To rule out cross-influence on individual assessments, the experts did not exchange opinions before solution review. Results of the transmission mechanisms qualitative expert assessment are visible in Table 1.

![Figure 8. The Scotch-Yoke screw (S1) and quad-link worm (S2) transmission mechanisms of a quarter-turn valve drive.](image)

| Type of mechanism | BQI1 Ease of Manufacturing | BQI2 Specific torque | BQI3 Life | BQI4 Efficiency | Σ score |
|-------------------|---------------------------|---------------------|-----------|----------------|---------|
| Scotch-            | E1 E2 E3 E4             | E1 E2 E3 E4       | E1 E2 E3 E4 | E1 E2 E3 E4 | 69      |
As follows from the qualitative expert assessment results, the preferable technical solutions P1 is the quad-link worm mechanism. For the quantitative comparison of the technical solutions, the design and technological parameters (DTP) affecting the MQIs/BQIs were determined. Quantitative assessment of transmission mechanisms are visible in Table 2.

**Table 2. Quantitative assessment of transmission mechanisms.**

| Type of mechanism            | DTP1 Number of parts and assemblies in the mechanism | DTP2 Number of manufactured parts | DTP3 Number of sliding friction pairs | DTP4 Number of rolling friction pairs | DTP5 Efficiency factor |
|------------------------------|------------------------------------------------------|-----------------------------------|---------------------------------------|---------------------------------------|------------------------|
| Scotch-Yoke screw mechanism  | 13                                                   | 9                                 | 3                                    | 2                                     | 30                     |
| Quad-link worm mechanism     | 15                                                   | 5                                 | 1                                    | 5                                     | 50                     |

As follows from the quantitative assessment results, the preferable technical solutions P2 is the quad-link worm mechanism.

Considering the obtained qualitative and quantitative estimates, it can be concluded that life and efficiency factor of the quad-link worm mechanism are nearly twice as greater than those of the Scotch-Yoke screw mechanism, other addressed specifications being comparable, and higher processability.

**5. Quarter-turn electrical valve drive**

To check the operation principle of the quad-link mechanism within the structure of the valve drive and to confirm the main technical specifications, a mock-up specimen of the quarter-turn valve drive was manufactured. The general view of the drive is shown on Figure 9.

![Figure 9. General view of the electric drive.](image-url)
The quarter-turn valve drive contains a high-torque motor mounted on permanent magnets, a quad-link transmission mechanism and control equipment. To implement the required power specifications of the drive, the main geometrical parameters of the mechanisms were selected as follows: length of lever a - 48 mm, length of lever c - 102 mm, distance between axes of levers d - 72 mm, length of connector rod b - 112 mm. The operation of the quad-link mechanism in different phases is shown on Figure 10.

![Figure 10. Operation of the quad-link mechanism in several phases.](image)

When the lever c turns at 90°, the lever a turns at an angle of 210°. The design chart of the transmission function of the mechanism is shown on Figure 11.

![Figure 11. Design chart of the transmission function of the mechanism.](image)

The minimum value of the transmission function is 1.75 with such mechanism configuration. The maximum value of the transmission function is reached in the “closed” position (0°), and it is equal to 6. In the “open” position (90°), the value of the transmission function is 3.5. The specific feature of the quad-link mechanism is an increased load on the mechanism’s pivots in the area of the operating range corresponding to the “open” position, as well as the necessity for limiting the torque in the extreme sections of the operating range on the side of the drive control system. The dependence of responses in the pivots of the quad-link mechanism on the turn angle is shown on Figure 12.
The general technical specifications of the electrical drive are given in Table 3.

| Parameter                              | Value/Dimensions |
|----------------------------------------|------------------|
| Maximum torque of the drive            | 350 Nm           |
| Actuation time                         | 1...2 sec        |
| Operation mode                         | Intermittent     |
| Nominal speed of motor rotation        | 40 rpm           |
| Motor torque                           | 120 Nm           |
| Type of electrical motor               | Synchronous      |
| Power input in standby mode            | 10 Wt            |
| Dimensions, mm                         | 325x263x235      |
| Weight, kg                             | 37               |

6. Drive layout

The drive has the original layout pattern based on the quad-link transmission mechanism. Figure 13 shows the sectional view of the drive.

The lever a is structurally combined with the motor rotor mounted in two bearing pieces, the lever c is also mounted in a bearing unit on the rotating axis. The pins of the connector rod b are mounted in the levers on needle bearings. To prevent excess loads in the mechanism, mechanical stops are provided for the lever a, which stops are not reached by the lever with nominal operation of the drive. Inside the rotor pocket, a sensor of the rotor’s angular position is located, which sensor can be installed both on the rotating resolver and on the Hall transducers. The top of the drive is sealed with a cover equipped with a scale showing the angular position of the drive’s output rod.

Given that the quad-link mechanism has an extremely high efficiency (losses only in the bearings), it appears impossible to provide self-locking of the drive on its basis. To ensure reliable fixation of the
mechanism in the main operating positions (closed/open), magnet clamps – contactless devices fixing the rotor in the positions corresponding to the position of the output rod “open” / “closed” are offered for use in the drive.

7. Drive testing results
According to the results of measuring the drive parameters, low vibration of the drive was confirmed both at idle and under load. In the section 0...10°, the drive develops a torque of 600Nm. In the section 10...90°, the torque is 200Nm. In the original section, an increased torque relative to the design value was obtained due to the left shift on the transmission function curve (Figure3) in design engineering. The limiting parameter of the quad-link mechanism in the “open” position is the response value in the pivots, in the “closed” position – the torque developed by the motor.

During the drive design, production and testing processes, the following advantages and disadvantages were found:
+ Quietness
+ Fast response time
+ Simplicity and reliability of the mechanism
+ High efficiency of the quad-link mechanism
+ Possible shifts on the transmission function curve during operation for changing the power parameter
+ Long life
– Necessity for limiting the motor torque adjusted for the transmission function of the mechanism
– Necessity for introducing a special locking device for the rotor in the extreme positions and impossible self-locking in the in-between positions
– Low transmission ratio for most valve control tasks
– Necessity for introducing a special threshold device for limiting the torque developed by the drive in the extreme positions when operating the manual override

8. Conclusions
Basing on the completed analysis and comparison of the quad-link worm mechanism and the Scotch-Yoke screw mechanism in accordance with the proposed methodology, the following advantages and disadvantages of the former can be pointed out.

Advantages:

- High efficiency factor.
- Simplicity and dependability of the mechanism.
- Longer life.
- Good compatibility with quarter-turn electric drives, including quick-acting ones.

Disadvantages:
- The necessity to limit motor torque with regard to the mechanism transmission function.

Therefore, introducing the quad-link mechanism as an output stage of the quarter-turn electric drive mechanical transmission would allow 4 to 5-fold reduction in the maximum motor and intermediate reducer torques requirements, which would substantially increase economic effectiveness due to reduction of the electric drive dimensions by one or two sizes. It can be eventually noted that the quad-link transmission mechanism has a longer life, higher efficiency factor and offers a number of important advantages as compared to the Scotch-Yoke mechanism, which allows using it in building energy-efficient quarter-turn electric valve drives.

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