Torque Optimization In Rack And Pinion Pneumatic Actuator

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Abstract

Pneumatic actuators are used for converting pressure energy of compressed air into the mechanical energy to rotate the valves. In other words, Actuators created the displacement of pistons due to force exerted by compressed air leading to conversion of linear motion into rotary motion. The pressurized air from storage is supplied to pneumatic actuator to do work. The air cylinder is a simple and efficient device for providing linear thrust or straight line motions with a rapid speed of response. Friction losses are low, seldom exceeds 5 % with a cylinder in good condition, and cylinders are particularly suitable for single purpose applications and /or where rapid movement is required.

The elastic nature of the compressed air is the chief limitation that makes them unsuitable for powering movement where steady forces or motions are required applied against a fluctuating load, or where extreme accuracy of feed is necessary. The air cylinder is also inherently limited in thrust output by the relatively low supply pressure so that production of high output forces can only be achieved by a large size of the cylinders. The objective is to focus the design, analysis and optimization of critical components of pneumatic actuator to achieve the improved yield or output in terms of torque. This dissertation gives detailed study of different mechanism and optimization of pneumatic actuators. Generally, selection of materials, modifications in mechanism and controlling the variable parameters is the point of focus for the improvement in actuators.

Keywords: - Pneumatic actuator, Torque optimization, Design and optimization of actuator, Rotary actuator, Rack and pinion actuator, Scotch yoke mechanism

1. Introduction

It should be noted that the torque output from rotary actuators is not always constant. As torque equals the force applied multiplied by the distance from the pivot point, actuator design is important. In a rack and pinion type actuator the distance from the pivot point is constant throughout the stroke and so, therefore, is the torque. With a scotch yoke design however, the distance from the pivot point varies throughout the stroke and so, therefore, does the torque. As the torque requirement of most valves also varies throughout the stroke, an attempt is made to match the operating characteristics of valve and actuator as closely as possible. Increasing the torque output of actuator is the need of time. Also, along with reliability, the weight and cost of the actuator has to be optimum. Aim involves the study of the different options of optimizing the Rack and Pinion actuator so the output torque will be increased. Also, its torque output characteristic shall be brought closer to valve torque.

Automated valves are important capital equipment components of many industries. Wherever goods and materials are manufactured, processed, or packaged, the process more frequently than not relies on fluid automation components. Process industries (including chemicals, petroleum refining, food and beverages, pulp and paper), resource industries (including crude petroleum and natural gas production and mining), public utility industries (including electric, gas, co-generation, water, sewage and sanitation), as well as construction industries, bottling and dispensing, laundry, and countless more rely on a variety of valves to control both their process flow and their profits.

Valves account approximately between 5 and 10% of capital spending in most end-use sectors. This critical investment requires proper engineering optimization. Selecting a valve best suited for the unique application at hand can result in greater production efficiency, lower emissions and leakage, decreased maintenance and downtime, lower installation costs, and overall productivity improvement.

2. Actuators

Pneumatic rotary actuators provide high torque output, durability and repeatability suitable for applications in process industries food industries petrochemical industries bottling plants, and remote flow manipulating operations with the help of valves. They are also use in unstructured environment such as ground and sea applications. There is a growing need for such actuators to perform with improved precision and high torque output and repeatability or manipulation tasks such as remote assembly, repair, and nuclear remediation.

2.1 Actuators are used for the following requirements stated below :-

1. Inaccessibility (Remote Operation)
2. Continuous Valve Operation
3. Sequence Control
4. Ease of Operation
5. Operation in hazardous environment
6. Reduction in operating costs
7. Fail safe requirement

2.2 Types of actuators :-

1. Pneumatic
2. Electric
3. Hydraulic

The above actuators are further classified into rotary and linear depending on the rotational torque output or linear thrust output.

2.3 Key factors in actuator selection :-

1. Energy source available
2. Fail safe requirement
3. Control requirement
4. Response time
5. Operating cycle
6. Valve orientation in pipeline
7. Area classification
8. Valve characteristics and torque

2.4 Features of pneumatic actuators :-

1. Simple Construction
2. Quick Response
3. Fail Safe Option
4. Material Options- Aluminum, Steel, Polymers

5. Travel Stops Arrangements available
6. Preferred in hazardous locations
7. Cost effective

2.5 Rotary motions can be obtained by two mechanisms :-

1. Rack and Pinion Mechanism :-

It consists of rack that moves linearly when pinion is rotated with the help of motor.

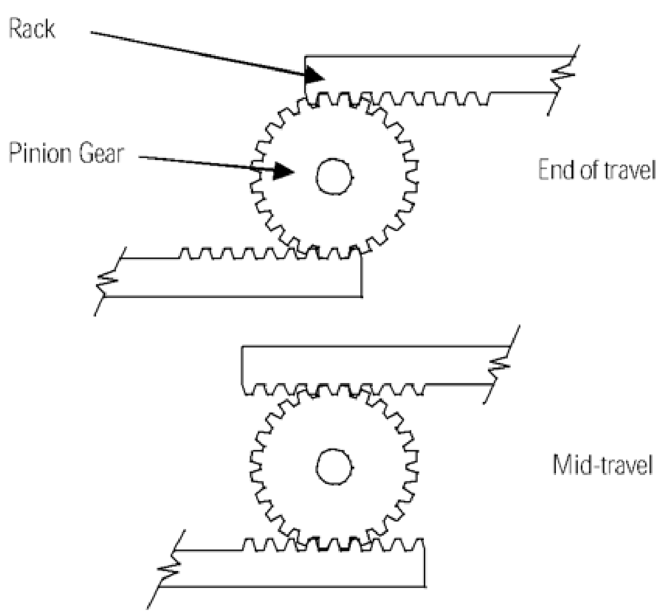

Figure no.1 : Rack and Pinion Mechanism.

Moment arm is constant at all travel positions.
Rotation is proportional to rack travel.
Hence the torque output is always constant throughout the travel.

2. **Scotch Yoke Mechanism :-**

Scotch yoke mechanism is used to convert linear to rotary motion and also vice versa.
This mechanism consists of a slotted yoke with a linearly traveling piston rod. The pin is fit into the piston rod and rolls inside the yokes slot.

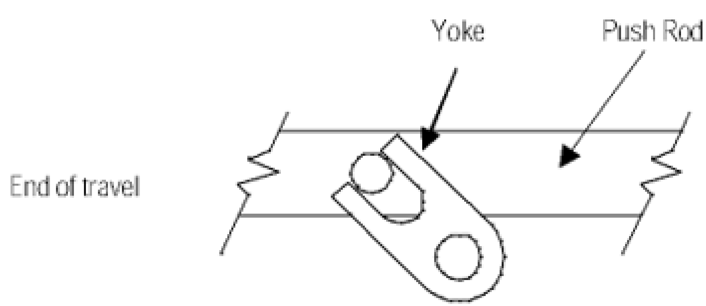

Figure no.2 : Scotch yoke mechanism

Longer moment arm and angle increases the output torque at the end of travel relative to the torque produced at the mid of travel. Rotation is not proportional to the push rod travel.

3. Development

3.1 The Proposed Scotch Yoke mechanism:

The proposed actuator consists of two pistons with extended projections along with the pin, rollers, slotted yoke and torque-transmitting shaft.
The objective is that this mechanism shall give higher break torques and run torques for same pressure and same piston diameters.

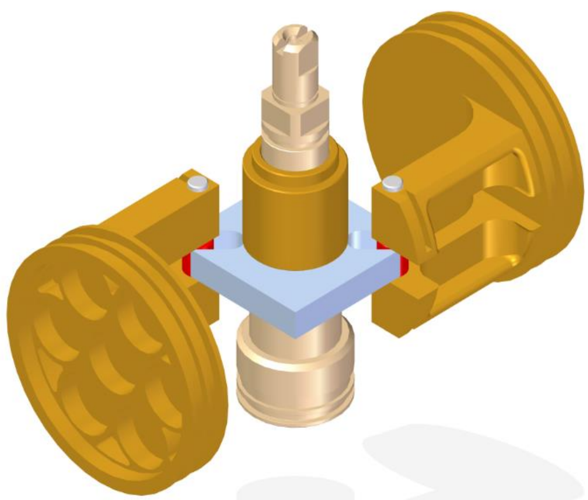

Figure no.3 : Scotch Yoke Mechanism

3.2 Torque of Rack and Pinion Actuator by calculations :

Calculated theoretical torque values :-

ACT SIZE	3 bar	3.5 bar	4 bar	4.5 bar	5 bar	5.5 bar	6 bar	7 bar
100	76	89	102	115	127	140	153	178
115	125	145	167	189	210	231	252	294
125	166	193	221	249	276	304	331	387

Below graph shows the values of output torque of actuator along its travel from 0° to 90° rotation.

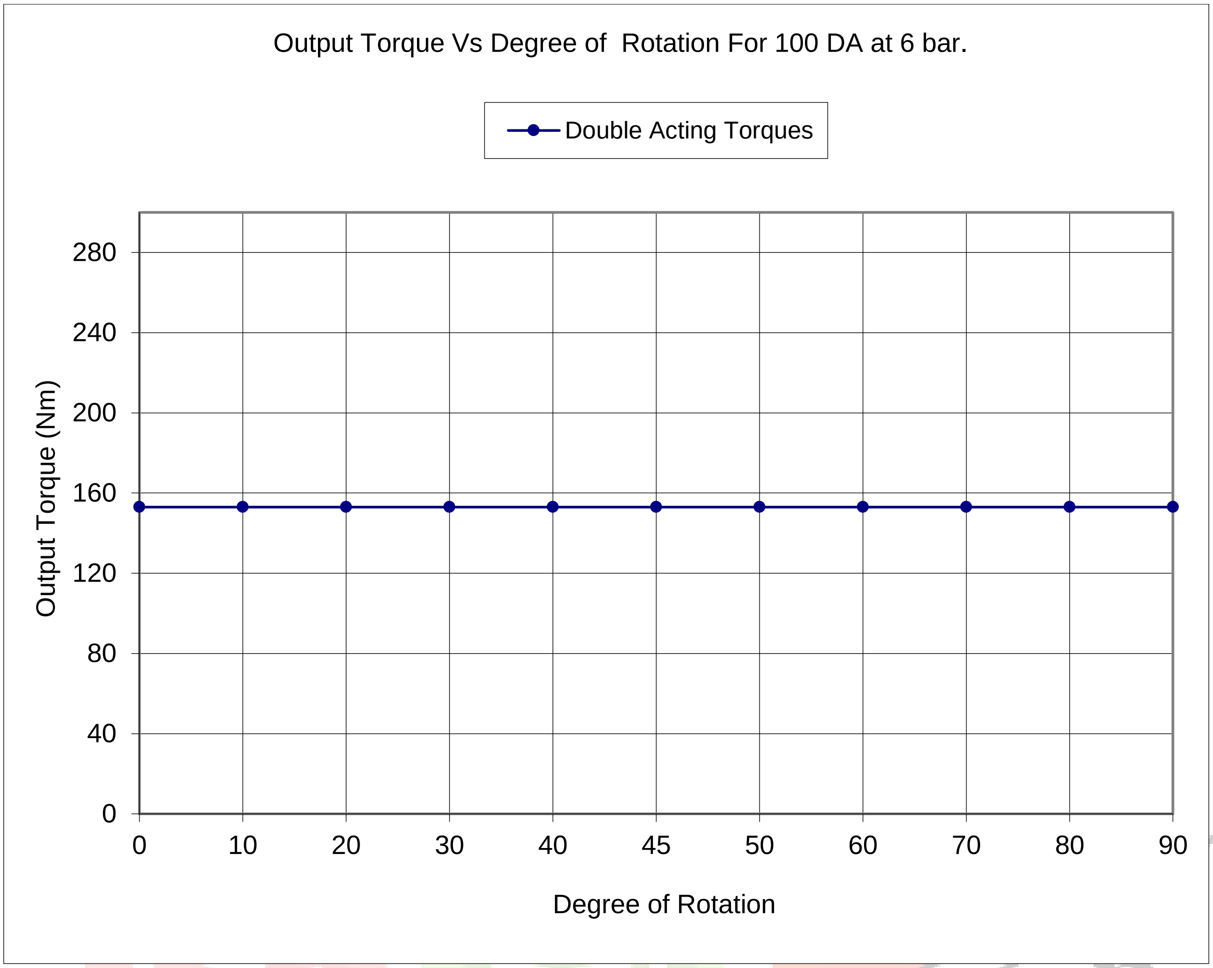

Figure no.4 : Graph of Output Torque vs. Degree of Rotation

3.3 Torque of Scotch Yoke Mechanism Actuator by calculations :-

Projected Theoretical Torque values :-

Torque	3 bar	3.5 bar	4 bar	4.5 bar	5 bar	5.5 bar	6 bar	7 bar
Break	171.5	200.1	228.7	257.3	285.9	314.5	343.1	400.2
run	110.3	128.6	147.0	165.4	183.8	202.2	220.5	257.3

Below graph shows the values of output torque of actuator along its travel from 0° to 90° rotation.

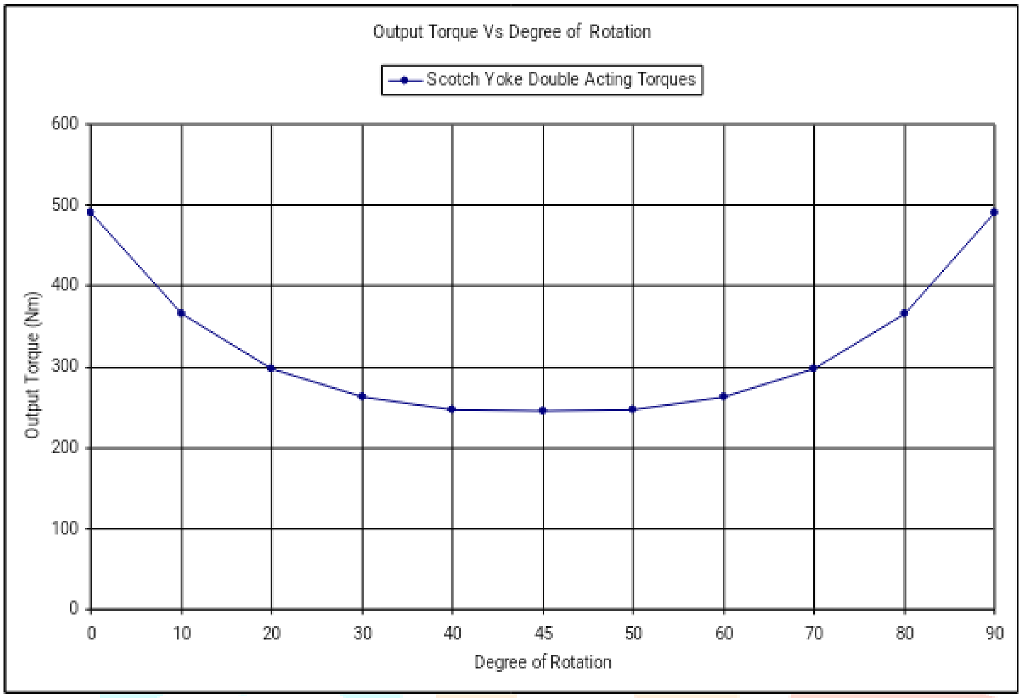

Figure no.5 : Graph of Output Torque vs. Degree of Rotation

$$\text{Total torque improvement} = \frac{\text{Scotch yoke mechanism torque}}{\text{Rack and pinion mechanism torque}}$$

$$= 343.061 / 152.51$$

$$= 2.25 \text{ times}$$

3.4 Following tables shows the torque comparison for rack and pinion and scotch yoke mechanism at different pressures.

Torque Output for Scotch Yoke Mechanism (Nm)

Actuator size 100 DA	3 bar	4 bar	5.5 bar	6 bar	7 bar	8 bar
Break	171.5	228.7	314.5	343.1	400.2	457.4
Run	110.3	147.0	202.2	220.5	257.3	294.1

Torque Output for Rack and Pinion Mechanism (Nm)

Actuator size	3 bar	4 bar	5.5 bar	6 bar	7 bar	8 bar
160 DA	326.0	434.0	597.0	651.0	760.0	869.0
125 DA	166.0	221.0	304.0	331.0	387.0	442.0
115 DA	125.0	167.0	213.0	252.0	294.0	337.0
100 DA	76.0	102.0	140.0	153.0	178.0	204.0

3.5 Finite element analysis

In stress analysis of scotch yoke analysis mechanism, the stress levels were high at yoke, roller and pin elements. The stress plot for other elements was not clear since the other elements are less stressed. Hence individual components are analyzed for stresses.

Summary of stress analysis :-

Part	Material	Tensile strength (MPa)	Induced stresses from FEA analysis (MPa)
Piston	LM24PDC	250	212.54
Pin	En 24 Through hardened (40-45 HRC)	1275-1460	760.7
Rollers	En 24 (40-45 HRC) Hard chrome plating 60-62 HRC	1275-1460	910.8
Yoke	En 24 (40-45 HRC) Hard chrome plating 60 -62 HRC	1275-1460	579.62
Torque shaft	En 8 Hardened and tempered Nickel plating	1030-1155, 594-666 (Shear Strength)	263.7 Shear Stress

Summary shows that induced stresses on all components is within limit and so they are safe.

4. Experimental testing

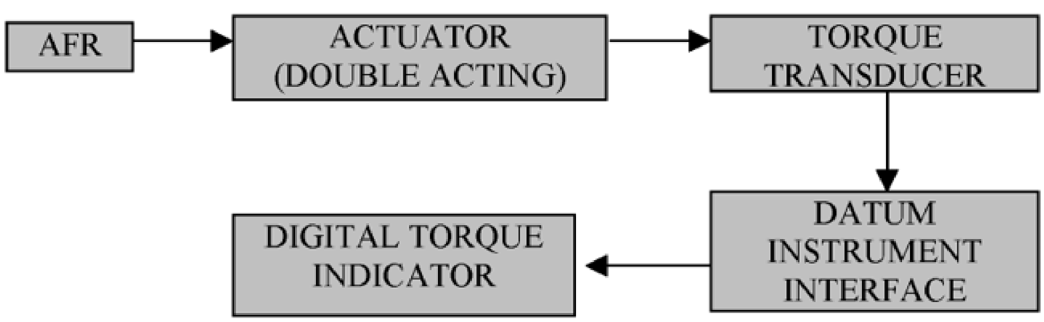

Figure no.6 : Block Diagram for Torque Testing

Torque test rig consists of coupling rigidly fixed to a frame.

Strain gauge transducers are mounted on the coupling to measure the torsional strain.

This torsional strain is measured and converted to electrical signal ranging from 4 to 20 milli Ampere. Electrical signal is then calibrated in terms of torque. The torque is displayed on the digital panel.

Air filter regulator is used to control and set the pressure applied to the actuator.

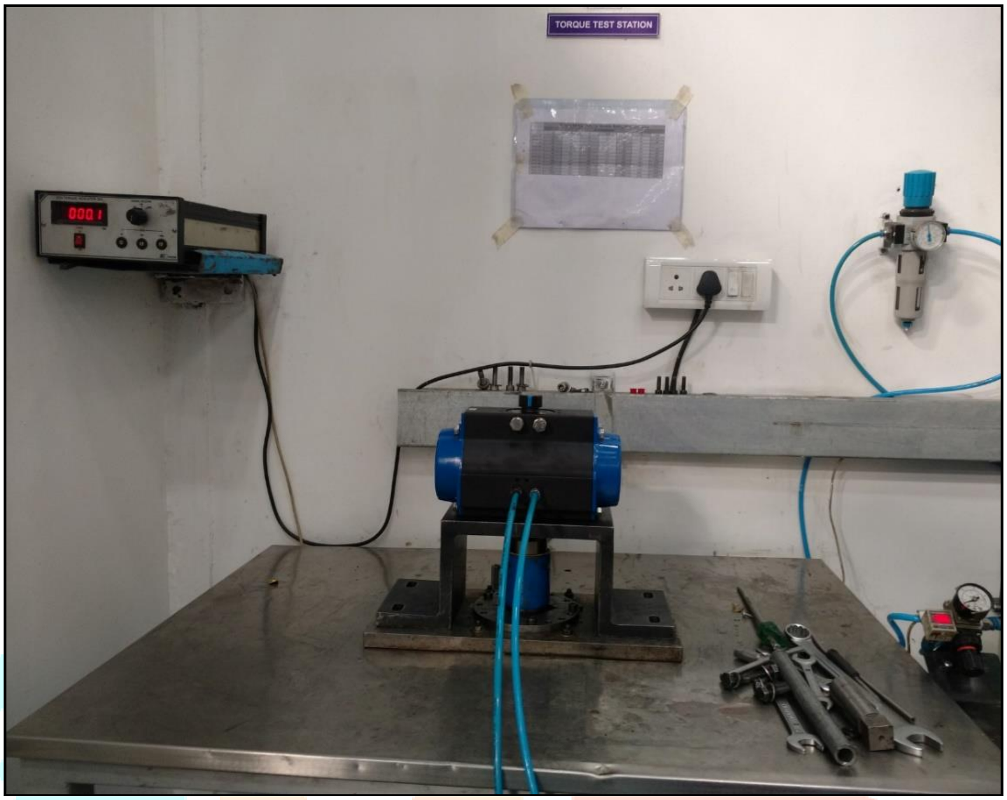

Figure no.7 : Torque Test Rig Setup

Since the torque shaft is rigidly coupled to coupling the torque transmitted is read by strain gauge and displayed on digital reading panel.

5. Experimental results

Torques obtained from experiments :-

Torque	3 bar	3.5 bar	4 bar	4.5 bar	5 bar	5.5 bar	6 bar	7 bar
Break	133	163	194	225	252	279	297	324
run	89	108	127	146	165	184	203	238

1. Scotch yoke actuator torque improvement is around 1.8 to 1.9 times of Rack and pinion actuator torques.
2. The practical break torques is less than theoretical torque. This is due to loss of torque due to friction at four sealing areas (2 piston O-rings and 2 pinion O-rings) and load loss at bearing reaction.
3. The practical run torques is less than theoretical torques. This is due to loss of torque due to friction at sealing areas.
4. The pressure drop at pipe joints could also be the reason for torque loss.
5. Any small leakage from pressure gauge to actuator could also lead to torque loss.

6. Conclusion

The scotch yoke mechanism functionally satisfies all the requirements of a rotary actuator.
As compared to Rack and Pinion we can see that the torque output of Scotch Yoke Mechanism is 1.9 times higher.

$$\text{Percentage improvement} = \frac{\text{Improved value - Initial value}}{\text{Initial value}} \times 100$$

$$= \frac{297-153}{153} \times 100 \qquad \text{(Values considered at 6 bar)}$$

$$= 94.12\ \%\ \text{Improvement}$$

Now same actuator can operate a higher size valve with Scotch Yoke Mechanism.

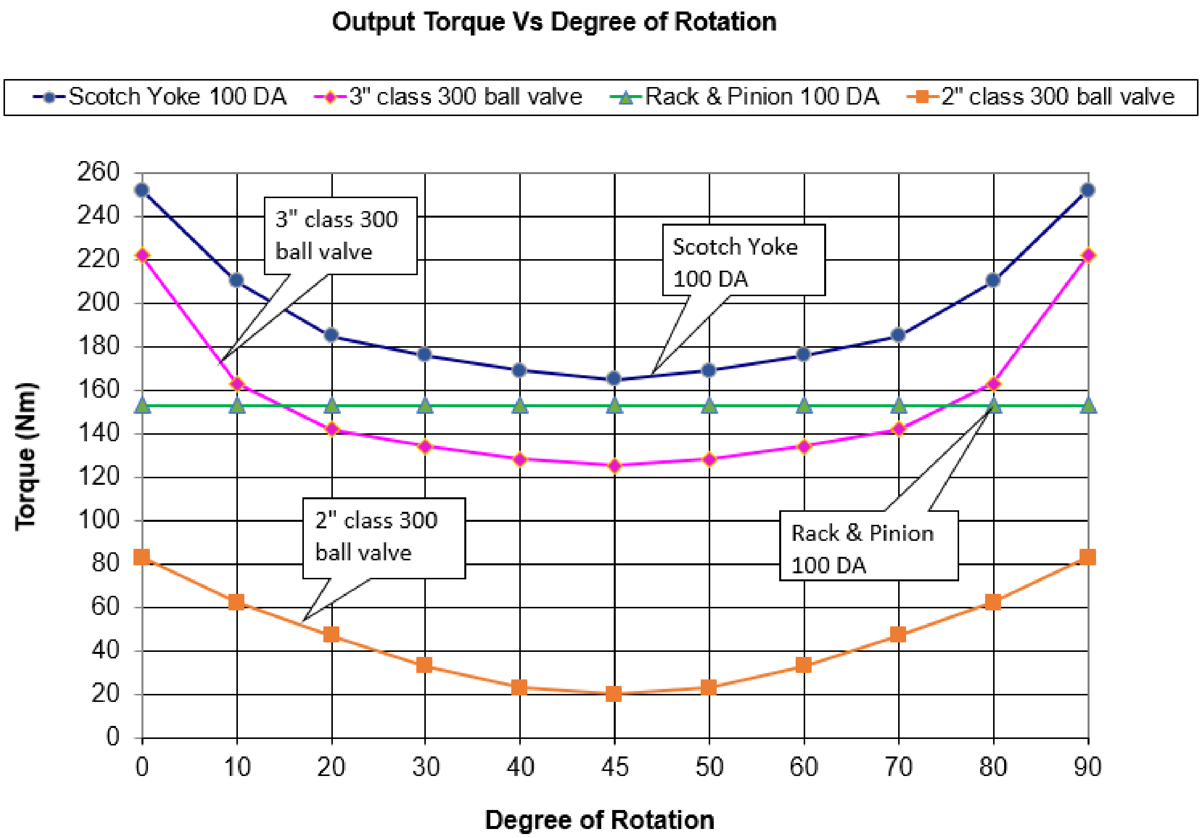

Figure no.8 : Actuator Selection Curves

Referring to actuator selection curves, we see that 100 DA actuator with optimized torque can now operate 3" class 300 in place of 2" class 300 valve i.e. one size higher valve. This will lead to considerable reduction in valve automation cost. Also, weight of automation package will be less leading to further cost reduction in pipeline fabrication cost.

Also, considerable cost saving has been achieved when compared with rack and pinion actuator giving same output torque.

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