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Electric Motor Drive for Natural Gas Compression in Pipeline: Techno-economic Analysis

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Abstract:The transportation of natural gas requires more compressors than any other sector of the oil and gas market due to the long distances the gas must travel between gathering, processing and distribution sites. Electric drive is one of the major prime movers used for these compressor stations in order to maintain the gas flow and to deliver at a set pressure. To maintain a minimum transportation cost, a techno-economic module which will guide the drive and pipe selection is important. This paper presents a techno-economic tool which can be used to rapidly assess the profitability or otherwise of a natural gas pipeline project employing an electric motor drive as a prime mover. The techno-economic tool is made of modules which are integrated together by a FORTRAN code called wrapper. This controls the running of each of the modules. The modules which make up the techno-economic tool are pipeline and compressor station module, electric motor and economic modules. As a case study for this analysis, a 24 inch 512km pipeline with a natural gas throughput of 4.54 million cubic meters per day (160.3 MMscfd) requiring a drive power of 34 MW was employed. From the results and analysis, for a throughput of 0.5 Mm^3/day, the transportation cost is $0127, $0.192 and $0.249 for pipe sizes of 304.8 mm, 609.6 mm and 1219.2 mm respectively. The results presented also shows that the economic pipe size for a 4.5 million cubic meter per day of natural gas is 609.6 mm (NPS 24) with transportation cost of $0.043 which is equivalent to $1.13 per GJ.

Keywords:Electric drive, Techno-economic, transportation, natural gas, pipeline, compressor

I. Introduction

Increase in world's population and advancement in technology has led to tremendous rise in energy demand. Natural gas is the most used fossil fuel and will remain the preferred fuel to meet the ever growing energy demand for the foreseeable future. It is expected that global consumption of gas will double by 2030 [1]. For natural gas to meet the energy demand, it is required to be transported from the production region through processing plant to the customers. This process certainly requires compressor stations along a pipeline which requires a prime mover in order to keep the gas flowing and maintain a set delivery pressure.

Other than gas turbine, another viable prime mover option for natural gas compressor is the electric drive. Natural gas pipeline deregulation is causing pipeline operators to evaluate electric drives **as** an alternative to gas driven equipment [2]. In the last decade, electric motor driven compression has become more common in the natural gas industry. Many of the components of an electric motor drive system have undergone technological changes to meet the needs of gas compressor applications. The evolving of variable frequency drives (VFD), variable speed drives (VSD), and motors with advance bearing technologies has provided pipeline compression a more efficient drive system, with larger and more flexible operating envelopes [3]. There is better energy conversion efficiency in electric motor than in gas turbine, with over 95% of the electrical energy coming in being converted into mechanical energy going out. This high electric motor efficiency can further be improved with VSD which modulate motor output by varying the speed of the motor itself, rather than through the use of control valves.

The use of electric drive for pipeline compressors has come to stay because of its inherent advantage over some other drive option. These advantages include the lower maintenance cost and very importantly lack of on-site emission. This paper presents the techno-economic evaluation of electric drive for pipeline compressor using a model developed for rapidly assessing the profitability or otherwise of the system.

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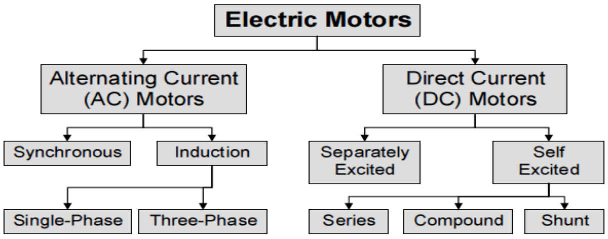
II. TYPES OF ELECTRIC MOTOR AND DRIVE TRAIN CONFIGURATION

Electric motors can be either alternating current (A.C.) or direct current (D.C.) motors. Figure 1 shows the classification of electric motors. Amongst the numerous types of electric motor, induction motors are the most commonly employed as prime movers for various industrial equipment. Theirpopularity is due to their simple design, ruggedness, low cost and easy maintenance and can bedirectly connected to an AC power source.The induction motor works by inducing current in the rotor through the small air gap between the stator and the rotor



The stator current generates a rotating magnetic field in the air gap between the stator and rotor. The interaction of the induced rotor current with the rotating magnetic field generates a torque on the rotor. The synchronous speed which is the rate of rotation of the rotating magnetic field created by the stator is given by the equation (1);

$$n_s = \frac{60 \times f}{p} \qquad (1)$$

where f is the frequency of the AC supply current in Hz and p is the number of magnetic pole pairs per phase.

A major characteristic of the induction motor is the presence of slip (S) which is the difference between the rotating speed of the magnetic field (synchronous speed) and the rotating speed of the rotor. This determines the motor's torque and can be calculated from equation (2).

$$\%S = \frac{n_s - n_r}{n_s} \qquad (2)$$

where n_s is stator electrical speed and n_r is rotor mechanical speed.

The induction motor speed can be controlled to suit natural gas compressors requiring variable speed operation. The speed control can be achieved by varying input voltage, varying input frequency, changing the winding pole number or by varying input frequency and voltage together. Compressor variable speed requirement can also be met by a constant speed motor, utilizing a variable speed gearbox. The rotor speed, which is the speed delivered to the pipeline compressor if it is a direct coupling or to a gear arrangement if this exists, can be obtained from equation (3) with the knowledge of the percentage slip and synchronous speed [4].

$$n_r = (1 - s)n_s (3)$$

I. MODULE DEVELOPMENT AND INTEGRATION

The procedure follows the development of a techno-economic module (TEM) architecture which can be employed to assess quickly the economic and technical profitability of a pipeline system using electric motor as a prime mover. Figure 2 shows the architecture for TEM for pipeline. The electric motor, pipeline, compressor station and economic modules were developed in FORTRAN codes. All the modules were integrated by a code called wrapper which controls the running of all the modules with results written into separate files.The development of the pipeline and compressor station modules have been described in earlier publication by the author, this relates to the use of gas turbine as prime mover [5]. The economic module developed considers the cost components of electric motor drive and the economic appraisal was done using net present value methodology. The electric motor module takes into cognisance the speed-torque relationship of electric motor vis-à-vis the operating speed of the compressor.

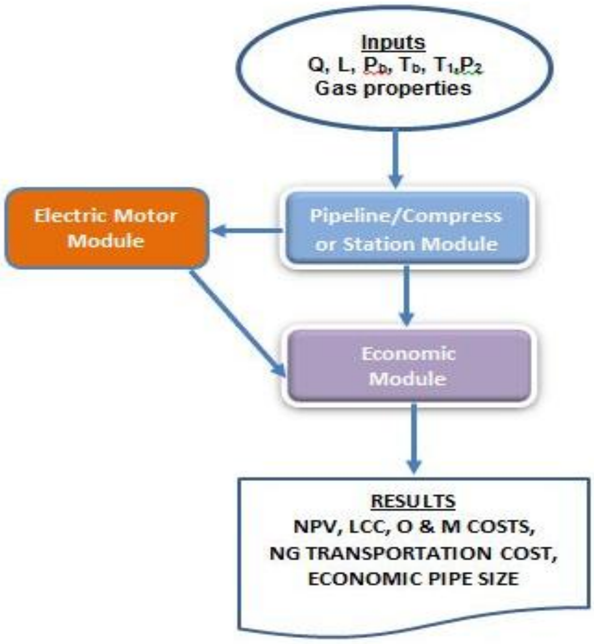


Figure 1: Techno-economic Module Architecture

A. *Development of Equivalent Circuit of an induction Motor*

In developing an equivalent circuit of an induction motor, the similarity between a transformer and induction motor is considered. The primary of the transformer is similar to the stator of the induction motor and the rotor corresponds to the secondary of the transformer. It follows from this analogy that the stator and the rotor have their own respective resistances and leakage reactance. A magnetizing reactance exists because the rotor and the stator are magnetically coupled. The air gap in an induction makes the magnetic circuit relatively poor, thus the corresponding magnetizing reactance will be relatively smaller than that of transformer. The hysteresis and eddy current losses in an induction motor can be represented by a shunt resistance, as was done for the transformer.

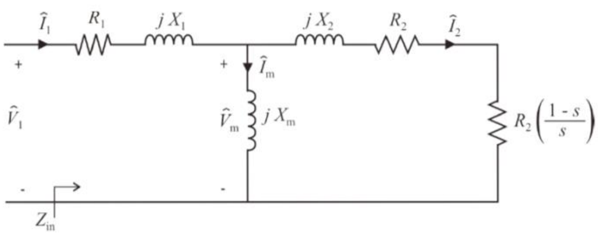


Figure 2: Equivalent circuit of an induction motor

Figure 3 shows the equivalent electric circuit of an induction motor which consists of the traditional five parameters (i.e. stator resistance R_1, stator leakage reactance X_1, magnetizing Reactance X_m, rotor leakage reactance X_2, and rotor resistance R_2. Once the slip is calculated, the input impeadance can be obtained from equation 4.

$$Z_{in} = R_1 + jX_1 + jX_m || \left(\frac{R_2}{s} + jX_2\right) \qquad (4)$$

This can be further expressed mathematically as $Z_{in} = R_1 + jX_1 + \frac{jX_m\left(\frac{R_2}{s}+jX_2\right)}{\frac{R_2}{s}+j(X_m+X_2)}$ (5)

With the knowledge of the motor source voltage, $\widehat{V}_1$, the stator current can be computed using equation 6.

$$\hat{I}_1 = \frac{\widehat{V}_1}{Z_{in}} \qquad (6)$$

The rotor current can be determined from current divisions as

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$$\hat{I}_2 = \left(\frac{jX_m}{\frac{R_2}{s} + jX_2 + jX_m} \right) \hat{I}_1 \tag{7}$$

The rotor current is flowing through the term $R_2/2$, which may be represented as the series of combination of a pure resistance R_2 and a back-emf term $R_2\left(\frac{1-s}{s}\right)$. The mechanical torque can then be computed as the power into the back-emf term divided by the mechanical speed. This results in

$$\tau_m = \frac{3I_2^2 R_2}{\omega_m} \left(\frac{1-s}{s} \right) \tag{8}$$

Figure 4 shows the percentage torque and synchrous speed characteristic for an induction motor.

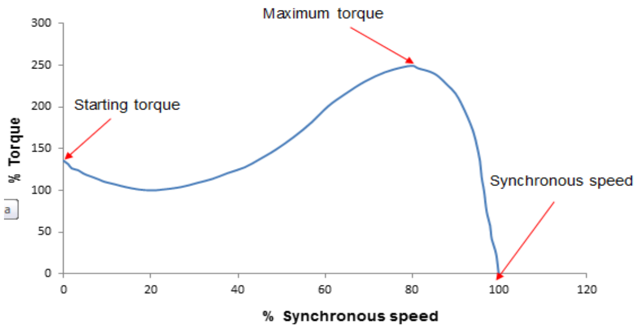

Figure 3: %Torque- % Synchronous speed curve of induction motor

The torque versus speed relationship for the induction motor must be analysed carefully to ensure that all compressor required operating points may be met. The torque produced by an induction motor is a function of shaft power and the shaft speed, where the torque reduces with speed for constant power. This can be expressed as

$$\tau = 9.5493 \frac{P_m}{n_r} \tag{9}$$

B. *Motor Life Cycle Cost (LCC)*

Life cycle cost is the systematic economic consideration of all whole life costs and benefits of the motor over a period of analysis or expected motor life while fulfilling the performance requirements. This analysis is recommended to assess the large cost items in the motor installation and operation project. LCC is the capital cost (purchase and installation), plus maintenance and operation costs (based on energy prices) over its life time. This computation was done bearing in mind the life expectancy of the motor.

$$Electricity\ cost = \left(\frac{Motor\ power\ rating}{conversion\ efficiency} + P_{Loss} \right) \times electricity\ tariff \tag{10}$$

$$Transmission\ loss, P_{Loss} = \frac{P_T^2}{V^2} \left(\frac{\rho_{wire} \times L_{wire}}{A_{wire}} \right) \tag{11}$$

$$LCC = \sum_{1}^{n\ years} (Electricity\ cost + capital\ cost + O\&M\ cost) \tag{12}$$

II. RESULTS AND DISCUSSION

The results obtain from the simulation of the integrated TE modules are presented in this section. This result shows the economic appraisal of using electric motor drive as prime movers for pipeline compression. The results from the pipeline and compression station modules have been presented by the author in [5].

A. *Effects of Throughput on the Operating Cost*

Figure 5 presents the effect of throughput on the operating cost for electric motor drive option. The operating cost increased from \$0.0615 billion to \$0.623 billion as the throughput increased from 0.5 Mm^3/day to 2.5 Mm^3/day for a pipe size of 304.8 mm and electricity tariff of \$0.05/kWh. This amounts to a difference of \$0.562 billion. For 609.6 mm pipe size the operating cost increased from \$0.0472 billion to \$0.285 billion as the throughput increased from 0.5

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Mm^3/day to 2.5 Mm^3/day which amounts to a difference of $0.237 billion. The rise in operating cost as a result of increase in throughput reduces with increase in pipe size. The sensitivity shows that the higher the electricity tariff, the higher the operating cost. Pipe size 1219.2 mm is seen to have the least rise in operating cost as drive power is minimal with flow through it. Figure 5 also shows that the operating cost tends to zero as the throughput reduces to zero.

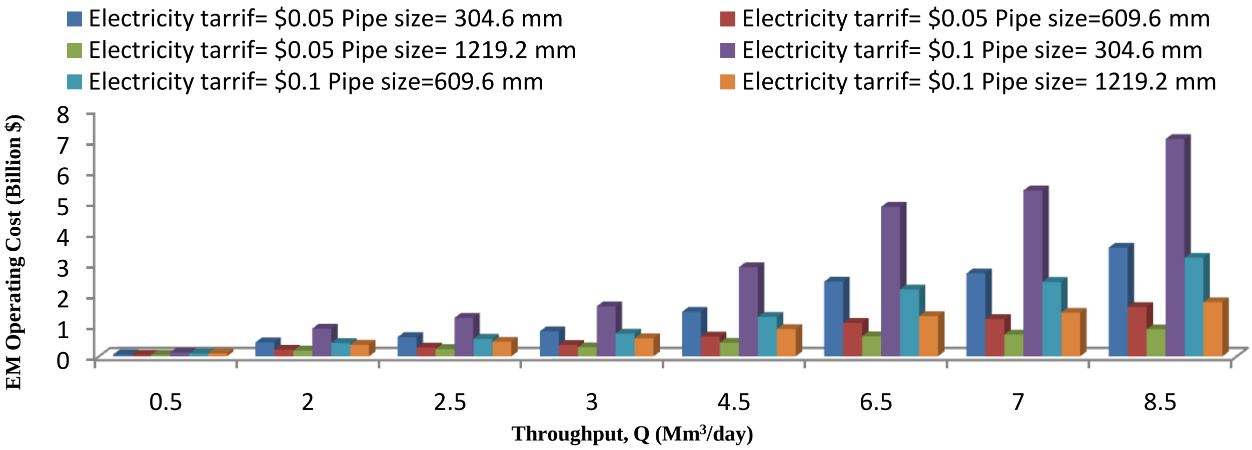

Figure 5: Operating cost variation with throughput for different pipe size

B. Effect of Pipe Size on Operating and Pipe Material Cost

Figure 6 presents a comparative analysis of the effect of pipe size on pipe cost and operating cost.

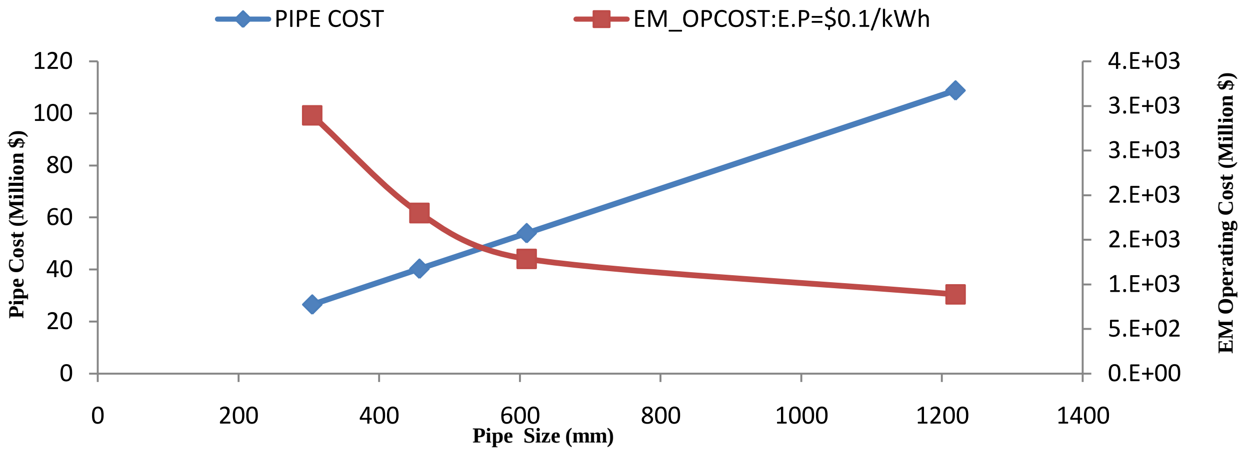

Figure 6: EM Operating cost & Pipe cost against with Pipe diameter for varying electricity price

The pipe material cost for the usage of 609.6 mm size is $53.9 million and $26.5 million for a pipe size of 304.8 mm. This gives a savings of $27.4 million in material cost. On the other hand the operating cost for an estimated electricity tariff of $0.05/kWh is $641.9 million using a pipe size of 609.6 mm and for a pipe size of 304.8 mm and the same electricity tariff, the operating cost is $1.4 billion. This amounts to an increase of $804 million. It shows that although under-sizing of pipe apart from technical issues has negative economic impact on the natural gas pipeline project. The saving in pipe cost is only about 3.4 % of the increase in the operating cost.

C. Effect of Throughput on NPV

Figure 7 presents the effect of throughput on the Net Present Value for the Electric Motor for varying pipe sizes. For a throughput of 4.5 Mm^3/day through a 609.6 mm pipe size the NPV is $2.7 billion and for a throughput of 7.0 Mm^3/day, the NPV is $4.2 billion. This is an increase of about 55 % in NPV. But for a 4.5 Mm^3/day through a

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304.8 mm pipe size, the NPV is $2.6 billion and $4.0 billion for a throughput of 7.0 Mm^3/day. This gives a percentage increase of 53.8%.

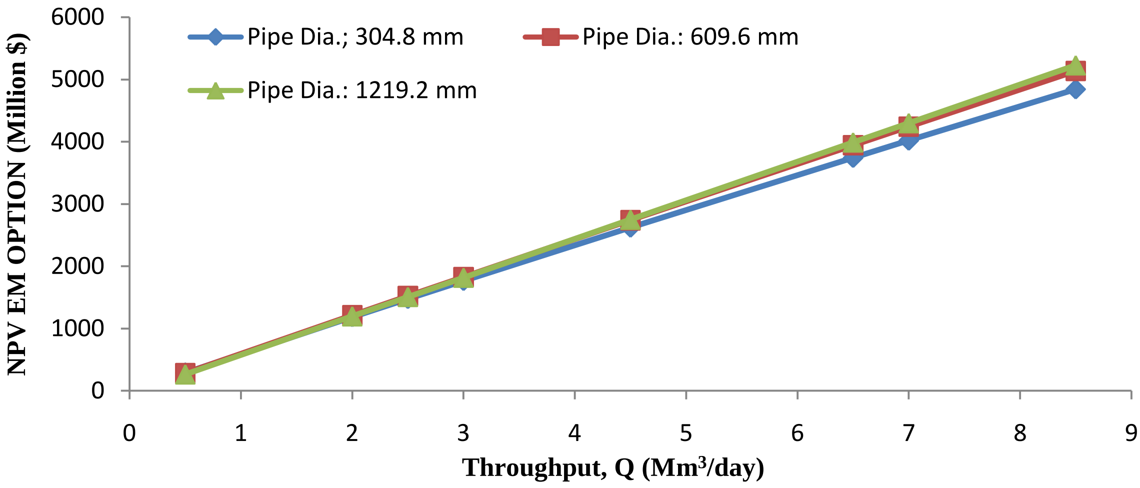

Figure 7: NPV Variation with throughput for different pipe sizes

The increase in throughput undoubtedly increases the compressor drive power required, as shown in Figure 8. This rise in drive power will also cause an increase in the capital and operating costs.

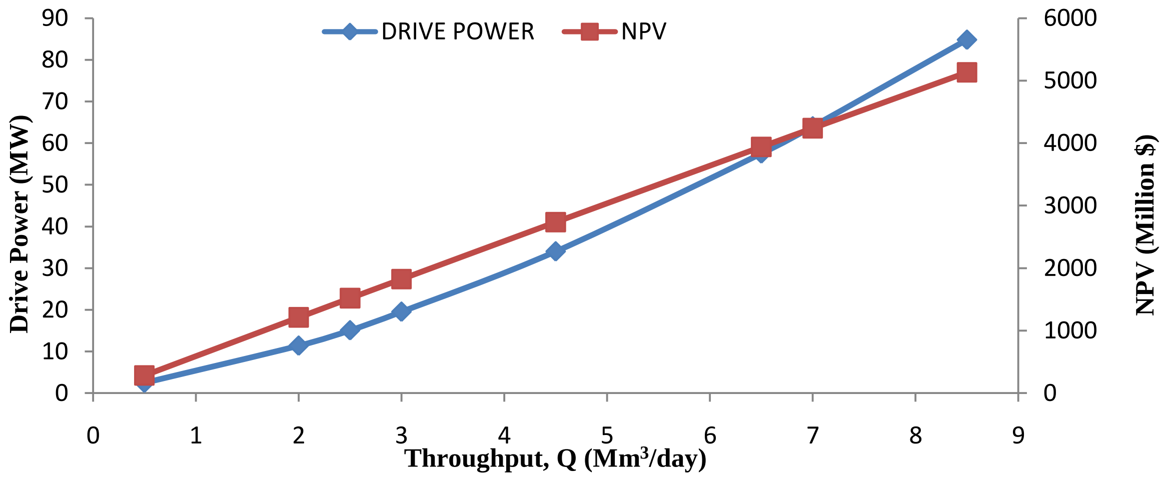

Figure 8: Drive power and NPV against throughput

Figure 8 shows the trend of variation of drive power and NPV as the throughput changes. The increase in NPV, which puts together all the cost components and cash flows over the project life, despite the increase in capital and operating costs, further confirms the possession of economies of scale by pipeline transportation systems [6].

D. Effect of Throughput on Natural Gas transportation Cost

Figure 9 presents the effect of throughput on gas transportation cost for varying pipe sizes using electric motor as driver. For a throughput of 0.5 Mm^3/day, the transportation cost is $0.127, $0.192 and $0.249 for pipe sizes of 304.8 mm, 609.6 mm and 1219.2 mm respectively. It is seen that 304.8 mm presents the lowest cost at an electricity tariff of $0.05/kWh. This amount is equivalent to $3.34 / GJ, which is higher than what is expected of pipeline transportation cost and this suggest that 0.5 million cubic meter per day is not economical to be transported over long interstate pipelines.

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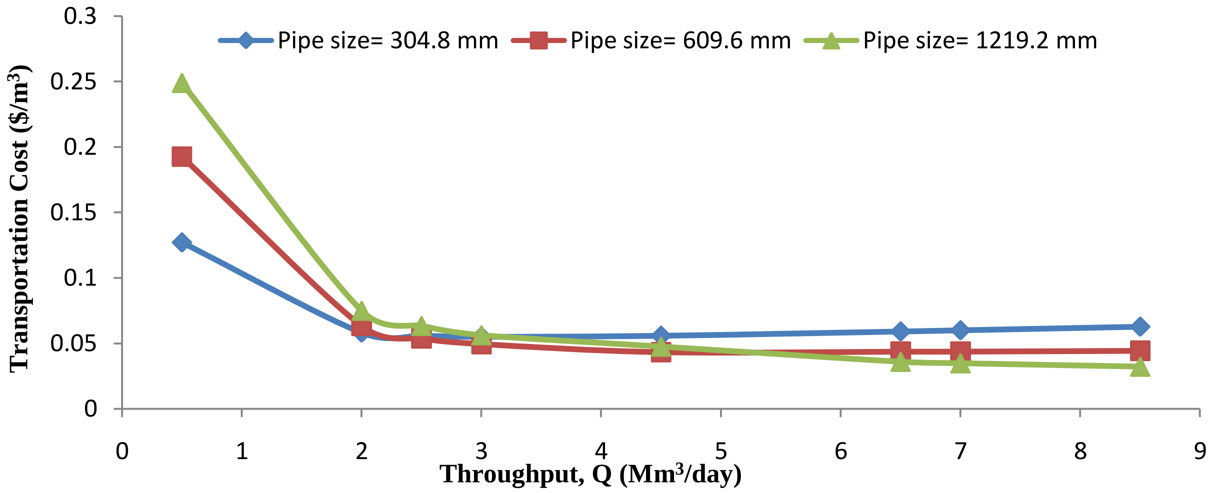

Figure 9: Gas Transportation cost

An increase in throughput from 0.5 Mm^3/day to 2.0 Mm^3/day gave rise to a sharp drop in the gas transportation cost across all the pipe sizes and 609.6 mm pipe size has the least transportation cost of $0.054 although that is not the optimum point for this pipe size. Beyond 2.5 Mm^3/day, an increase in transportation cost is noted for pipe size 304.8 mm. This implies that the optimum throughput for 304.8 mm is 2.5 Mm^3/day which yields $0.055 transportation cost. For a 609.6 mm pipe size and electricity tariff of $0.05/kWh, the transportation cost rise as the throughput goes beyond 6.5 Mm^3/day. For 1219.2 mm pipe size the transportation cost continues to drop all through the throughput studied for the studied electricity tariffs. It is believed that there will be an increase in the transportation cost at a point as the throughput continues to rise. This point will be the optimum throughput for 1219.2 mm pipe size. At a throughput of 8.5 Mm^3/day, 1219.2 mm presents the lowest gas transportation cost of $0.032.

III. CONCLUSION

This paper presents the development of a techno-economic tool which can be used to rapidly assess the profitability or otherwise of a natural gas pipeline employing electric motor drive as prime mover for pipeline compressors. The results could be used to guide the selection of economic pipe size which gives the minimum investment and operating cost for the pipeline system and consequently minimum natural gas transportation cost. The transportation cost for a 0.5 million cubic meter per day of natural gas through a pipe size of 304.8 mm (12 inch) is $0.127/$m^3$ which is equivalent to $3.34 /GJ. Although this is the minimum for this throughput, it is far higher than the transportation cost of about $1.4 /GJ found in confidential operators reports. This therefore, indicates that the transportation of natural gas of throughput of 0.5 Mm^3/day or below over long distance pipeline is uneconomical.

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