COMPARATIVE ANALYSIS OF ENERGY-SAVING CAPABILITY OF DIRECT-ON-LINE, STAR/DELTA AND VARIABLE-SPEED DRIVE STARTER UNDER DIFFERENT OPERATIONAL PHASES

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Abstract: A significant amount of energy is being expended during different phases of the operation of air compressors in the manufacturing or processing industries. The expended energy comes with its cost implication which consequently contributes to the mammoth operational cost incurred in the smooth running of industries in the face of the current hyperinflation. Against this background, this study aimed to investigate the energy-saving capabilities of different starting methods such as Direct-On-Line (DOL), Star/Delta, and Variable Speed Drive (VSD) for an Atlas Copco AB screw air compressor. Field observations, inspection of the nameplate, and fundamental laws of energy form the backbone of this analysis. The outcome of this research showed that during the starting phase, loading phase and unloading phase the VSD starter achieved significant savings in energy consumed which translated to significant savings in the cost expended in making the air compressor stay in service. The outcomes of this study not only provide a concise guide in selecting the appropriate starting method based on the specific operational requirements and energy-saving objectives for air compressor systems but also highlight the energy-saving potential of VSD during different operational phases.

Keywords: Direct-On-Line, Star/Delta, Variable Speed Drive, Energy Savings, Loading Phase, Unloading Phase

Introduction

Air compressors play a vital role in ensuring a reliable supply of compressed air required for the smooth operation of pneumatic tools, equipment, and processes for various industrial applications such as manufacturing, construction, and energy production (Dindorf *et al.,* 2023; Okelola, and Olabode, 2018). However, air compressors consume a significant amount of energy, contributing to high operational costs and environmental impact (Herrera *et al.,* 2021). The need to optimize the energy consumption of air compressor systems has become a critical objective for many industries (Mascarenhas *et al.,* 2019; Olabode, *et al.,* 2017).
One area of interest in achieving energy savings is the selection of the appropriate starting method for air compressors and the prominent methods of starting air compressors for many applications in real-world industries of today entail Auto-transformer, DOL, Star/Delta, VSD, Stator Resistance Starter, and Rotor Resistance Starter among others. Each of these methods has its strengths and weaknesses in terms of energy efficiency and power consumption during different operational phases such as the start-up phase, loading phase, and off-loading phase.
For instance, the DOL starting method is the simplest and most commonly used technique, it involves applying the full supply voltage to the motor, resulting in a sudden surge of current during start-up (Akbaba, 2021). While this method is straightforward, it can lead to high energy consumption and potential stress on the electrical network. Also, the Star/Delta starting method is an alternative approach that reduces the initial surge in current during start-up (Osita *et al.,* 2017) It achieves this by initially connecting the motor in a star configuration with reduced voltage and then switching to a delta configuration for full voltage operation. This method offers some energy-saving benefits compared to DOL starting (Osita *et al.,* 2017). The VSD starting method provides the greatest potential for energy savings, and with the variable frequency drive, the motor speed can be adjusted to match the compressed air demand, resulting in optimized energy consumption (Schibuola *et al.,* 2018). The VSD starting methods gradually increase the motor speed during start-up and allow for speed reductions during periods of low demand, thereby reducing energy consumption. The auto-transformer starting has its pros and cons, it can potentially limit the starting inrush current by gradually reducing the supplied voltage during the start-up of induction and synchronous motor. Its major weakness boils down to issues of lower power factor, high-cost implication, and bulkiness in size (Ajewole *et al.,* 2020).
On the premises of the ever-increasing cost of energy in the world, industries across the globe are constantly seeking ways to reduce energy consumption and cost of production to continue to maintain maximum production levels and stay competitive through energy-efficient practices. One of such promising initiative is the consideration of energy consumption during the starting and operation of 3-phase induction electric motor characteristics using electric motor starters. It is against this premise that this current paper seeks to focus on the comparison of the commonly used starters; Direct-On-Line (DOL), Star/Delta, and Variable Speed Drive (VSD), and to establish a niche for this current study, the previous efforts in this regard were carefully reviewed.
For instance, Ibrahim, (2007) used a 3-phase, 380/480V variable speed drive to energize a pumping system having a single unit 3Hp, 460/400 volts, motor. The point of emphasis in this work centers on the comparison of the VSD-controlled system, and a traditional method, the performance of the VSD was found to be satisfactorily better than the traditional approach for starting the pumping machine. Similarly, Burt *et al.*, (2008) investigated motor performances under varying speeds induced by a VFD controller and loads. The specific goal of the study is to furnish the designers with the essential information required

for estimating power usage in pumping plant installations with the use of VFD-controlled systems. The approach used in their work involves testing motors with both VFD and across-the-line (ATL) configurations to evaluate and compare the performance of the motor's efficiency. It was found that the VFDs can adjust speeds to match the specific requirements of the application, thereby allowing for overall energy savings.

Furthermore, Saurabh *et al*., (2012) focused on the starting analysis of an induction motor using the DOL and Sinusoidal Pulse Width Modulation (SPWM) as a thyristor-based advanced mechanism. The metrics evaluated in their work include the behavior of the speed, torque, and current during the starting period while the simulation was conducted in the MATLAB environment. Also, the comparative performance of these two techniques was done and SPWM outsmarts the DOL technique based on these metrics. In a similar vein, Alvarez and Ronquillo, (2013) investigated the behavior of voltage, current, and torque during the starting operation of an Induced Draft Fan (IDF) motor in Batangas Sugar Central Inc. Their work aimed at identifying the causes of operational problems and proposed a more effective auto-transformer motor starter for the IDF motor. In their methodology, the characteristics of various starting methods for three-phase induction motors were observed closely based on parameters such as voltage, current, and torque. Also, the design requirements based on relevant standards like the National Electrical Manufacturers Association (NEMA), Philippine Electrical Code (PEC), and National Electrical Code (NEC) were equally investigated. The voltage, current, and torque values are then computed and analyzed based on the actual motor specification on the nameplate.

In addition, Bhase and Lathkar, (2015) investigated the effect of VFD on energy conservation with induction motor based on the concept of affinity law. Of interest in their work are parameters such as variable torque loads and constant torque type loads. With the VFD, the characteristics obtained during start-up and load were comparatively in tandem with the manufacturer's specifications. Also, Bokde *et al.,* (2017) presented the utilization of the star-delta starter in terms of power saving, the approach proposed entails the integration of a delta-star converter with the conventional star-delta starter. When the motor load is below 30% of the full load, the motor connection is switched to operate in star mode to save electrical energy and once the load exceeds 30% of the full load, the motor connection automatically changes to delta mode without disrupting the motor's operation. Implementing this module enables energy savings, reduction in maximum demand, kVA reduction, and an increase in power factor, contributing to the efficiency of the power system. However, the arrangement lacks specific details about the technical implementation of the proposed approach and the testing or validation procedures employed. Similarly, Schibuola *et al*., (2018) used a VSD for a high voltage alternating current system which consists of a primary air system with an air handling unit in the library of a building. A quasi-steady state calculation procedure based on a spreadsheet-style model was implemented with a certain monitoring time interval to provide accurate information about the numbers and distribution of the fan coils in action. The collated data records of electric consumption showed the display energy performance of the system. Also, the comparison of the approach proposed with the conventional constant flow rate system was done and the study shows that the integration of VSD technology into the fan coil system resulted in a massive annual energy saving of about 38.9% in the electric consumption. The work of Suraj & Mahesh, (2019) focused on the performance evaluation of DOL, Auto-Transformer, and Star-Delta for starting an induction motor. The work compared these starting methods based on curves of currents, torque, and speed under a constant power load condition while using MATLAB/SIMULINK as simulation software. Conclusively, the outcome of the study adjured Star-Delta as being mostly preferred to other techniques.

Sourabh *et al*., (2019) focused on DOL and star-delta starter methods for starting induction motors. The methodology involves a combination of hardware experimentation and MATLAB Simulink simulation to analyze and compare the performance of these starting methods while the central goal was to establish which of these methods is the most appropriate method for the induction motor during both start-up mode and on-load condition phase. In a similar work by Ayibapreye *et al*., (2020), the focus was on designing an automatic star-delta starter for induction motors to provide a low-voltage start and reduce starting current surges. Their technique involves using electrical relays and an electronic timer to control the voltage supplied to the motor, the arrangement is to initially start the motor in a star connection to reduce the voltage, and after a certain time, it is switched to a delta connection to apply the full supply voltage. The perceived weakness of this work is that no comparison was made relative to other techniques to ascertain the superior performance of the approach proposed.

Similarly, Sukarma *et al*., (2020) investigated the comparison of three-phase induction motor start using DOL, Star/delta, and VSD Altivar61 to analyze the starting of a 1.1 kW, 380/400 voltage three-phase induction motor when using each of the starters. The methodology used in their works entails recording the voltages (Line-to-Neutral, Line-to-Line, Total Harmonic Distortion Line-to-Neutral, Total Harmonic Distortion Line-to-Line, and the Total Harmonic Distortion current) during starting for each motor starter, DOL, Star/Delta and VSD Altivar61. The work concluded that the VSD starter outsmarted the other two starters. Also, Deesor *et al*., (2021) focused on comparing the starting methods of three-phase squirrel cage induction motors: DOL, Star Delta, and Autotransformer starters. The approach adopted in their work entails a laboratory experimental setup to evaluate the performance of these starting methods relative to their output responses for the voltage, current, speed, and torque. The experimental performance was benchmarked with the simulation results obtained from the MATLAB Simulink environment. For clarity and easy interpretation, the obtained results were presented using tables and bar charts for these different starting methods.

The foregoing showed that while the energy-saving benefits of VSD and Star/Delta starting methods have been acknowledged in the literature, there is a need for further investigation and comparative analysis specific to different types of air compressors and operational scenarios. This study aims to address this research gap by focusing on the energy-saving capabilities of these starting methods for an Atlas Copco AB screw air compressor, a widely used and representative compressor in industrial settings. By examining the energy consumption patterns during different operational phases, such as starting, loading, and unloading, this study seeks to provide valuable insights for industrial operators and system designers. The findings will contribute to informed decision-making regarding the selection of starting methods, allowing for improved energy efficiency, reduced operational costs, and enhanced sustainability in air compressor systems.

Materials and Methods

Description of GA22 Atlas Copco Air compressor

The GA22 compressor from Atlas Copco Airpower is a powerful and efficient machine designed to deliver reliable compressed air for various applications. With a maximum allowable working pressure of 10 bar (145 psi), this compressor ensures consistent and stable performance even under demanding conditions and is widely used in many manufacturing industrial applications. The parameters and their corresponding rating as found in the nameplate as described in Table 1.

Table 1: Specification on the nameplate of GA22 Atlas Copco Air compressor

Name: Atlas Copco Airpower Type: GA22 Serial Number: API463666		
S/N	**Parameters**	**Ratings**
1	Maximum Allowable Working Pressure	10 bar (145 psi)
2	Unloading pressure	6.5 bar
3	Loading pressure	5.5 bar
4	Volumetric Flow Rate	51.7 I/s (109.5 cfm or 3.1 m^3/min
5	Voltage	400 V
6	Frequency	50 Hz
7	Motor Power	22 kW
8	Motor Speed	2940 r/min
9	Mass	535 kg

Mathematical Modelling of Energy Consumption

a). The Direct-On-Line Starter: The energy consumed during the starting phase of the compressor can be computed with the Eqn. (1) thus;

Energy Consumed $(kWhr) = \sqrt{3} \times I \times V \times cos\emptyset \times hrs / 1000$ Eq.(1)

Also, the total energy consumed at starting per day was calculated by multiplying the starting energy consumption by the number of times the compressor unloads (starts) per day which is four times per day given as;

Total kWhr per day at starting $= 4 \times starting\ kWhr$ Eq.(2)

Similarly, the total monthly energy consumed was computed by multiplying the daily energy consumption at starting by the number of days in operation (in this case 25 days was considered excluding the days the compressor is under maintenance) using Eqn. (3) thus;

Total monthly kWhr of energy consumed$= 4 \times starting\ kWhr\ per\ day$ Eq.(3)

Also, the cost of the energy consumed per month was computed by multiplying the cost of one unit of electricity by the total energy consumed per month at starting and as given with Eq.(4) thus;

Monthly cost of energy per month $=$ ₦$68 \times total\ energy\ per\ month\ at\ starting$ Eq.(4)

The energy consumed during the compressor's operation (running) was calculated using the given formula for the energy consumed at 100% efficiency.

Energy consumed during running $= \sqrt{3} \times V \times I \times cos\emptyset$ Eq.(5)

b). For Star/Delta Starter

The energy consumed during the starting phase of the compressor can be computed with the Eq. (6) while that of energy consumed during the loading operation of the air compressor is given by Eqn.(7) respectively. Equations (2), (3), and (4) are also applicable to star/Delta starters.

Energy Consumed at Starting $(kWhr) = \frac{\sqrt{3} \times \frac{V}{\sqrt{3}} \times \frac{I}{\sqrt{3}} \times cos\emptyset \times hrs}{1000}$ Eq. (6)

Energy consumed during the loading operation $= \sqrt{3} \times V \times \left(\frac{1}{\sqrt{3}}\right) \times I \times cos\emptyset$ Eq. (7)

c). For the Variable Speed Drive

The voltage applied to the compressor motor can be computed with the help of Eq. (8) thus;

$$V_{motor} = \frac{V_1}{F_{system}} \times F_1 \quad \text{Eq. (9)}$$

Where; $V_1 =$ voltage per phase at the motor terminal with a system frequency of 50Hz; F_{system} =system frequency (typically 50Hz) and F_1 =starting frequency of the VSD.

Similarly, the starting current of the VSD is influenced by the starting frequency, and for starting frequencies between 5Hz and 10Hz, the starting current ranges from 1.5 to 2.1 times the rated motor current. If the starting frequency is lower than 5Hz, the motor will require less than 1.5 times the rated current to start.

Description of experimental procedure in the methodology

DOL starter has provision for two push buttons designated with the colour green for starting and colour red for stopping the air compressor. The DOL starter begins with the connection to the three-phase main supply and the air compressor. On pressing the green button, an alternating current flows through the contactor coil and control circuit which gets the contactor coil energized thereby closing the contacts, and in this way, a three-phase main supply is made available to the air compressor. Also, on pressing the red button, the current through the contact becomes discontinued indicating the absence of supply to the air compressor. The procedure is repeated for the other two phases loading and unloading phase.

Star/Delta starting method

There are two contactors in the star-delta starting method; the star contactor and delta contactor. The star contactor is firstly energized at the startup position with the supply from the main and at switching to delta mode, the star contactor opens and the delta contactor closes and the time elapsed between the start and the switch-over from star to delta was measured to be approximately between 3 and 15 seconds. The cycle is repeated for the other two phases loading and unloading operational phase of the air compressor.

Variable Speed Drive

VSD is an intelligent drive system that has the potential to continuously change the speed motor relative to the air demand. With VSD air demand slows, the compressed air system reduces the speed of the motor, and thus the power consumed becomes reduced.

Sequence of the procedural flow

Step I: Start

Step II: Conduct a field inspection to obtain the parameters of GA22 Atlas Copco Air compressor from the nameplate

Step III: Carry out the mathematical modeling of the energy consumption of the compressor using fundamental laws of energy for each of the starting methods.

Step IV: Compute the behavior of GA22 Atlas Copco Air compressor at different operational phases (Starting phase, loading phase, and unloading phase) for each of the starting methods

Step V: Compare the performance of the DOL, SD, and VSD at different operational phases using energy consumption and cost of energy consumed as performance metrics.

Step VI: Make validate inferences based on the analysis carried out for each of the starting methods at different operational phases.

Step VII: Stop

Computational Assumptions

The following assumptions guide the performance analysis in terms of energy saving of the different starters employed in this present work;

i). According to the original equipment manufacturer (Atlas Copco compressor AB), a pressure of 1 bar reduction leads to 6% reduction in the compressor power reduction.

ii). Ambient temperature of the air compressor is typically 30℃. The temperature after compression is 30℃ + 10℃ (Atlas Copco AB; retrieved on 14/07/2023).

iii). the starting time of a Star/Delta starter for a 22kW electric motor is 10 seconds (field observation)

iv). the starting or ramp time of a 22kW air compressor is 10 seconds (proposed for this study)

v). the available starting current of a Direct-on-line starter for a 22kW motor: 6 × the rated current of the motor = 6 × 40.5 amps = 243 amps at start

vi). the available starting current of Star/Delta starting current of star/delta starter for the 22kW motor:

= 2.6 × rated current of motor
= 2.6 × 40.5
= 105.3 amps at starting

vii). the available starting current of a VSD for the 22kW motors.

= 1.5 × rated current of the motor
= 1.5 × 40.5
= 60.75 amps at starting

viii). the frequency of the unloading process or activity is 4 times per day.

ix).For the investigative work and easiness of the calculation, we have assumed an efficiency of 100% for each of the DOL, Star/Delta, and VSD starters.

x). the cost of one unit of electricity (KWhr) was assumed to be ₦68/kWhr.

Results and Discussion

Presented in Tables 2, 3, and 4 are the results summary for the performance evaluation of direct-On-Line Starter, Star/Delta, and Variable speed drive respectively.

Table 2: Energy saving performance evaluation of the DOL approach

S/N	Performance evaluation metrics	Computed Values
1	Energy consumed at the starting	0.7942 kWhr per day
2	Total energy consumed at starting per month	26.62 kWhr
3	Total energy consumed at starting in a year	288.86 kWhr
4	Total cost of energy consumed at the starting in a year	₦19,642.48k
5	Energy consumed during the loading operation	142.93 kWhr per day
6	Energy consumed during the unloading operation	3.022 kWhr per day
7	Total energy consumed during loading and unloading per day	146.74 kWhr per day
8	Total energy consumed during loading and unloading per month	3668.5 kWhr per month
9	Total cost of energy during loading and unloading per month	40,353.5 kWhr per year
10	The cost of energy consumed for loading and unloading per year	₦ 2,744,038.00 per year

Table 3: Energy saving performance evaluation of Star/Delta approach

S/N	Performance evaluation metrics	Computed Values
1	Total energy consumed at starting per day	0.3867 kWhr per day
2	Total energy consumed at starting per month	9.67 kWhr
3	Total energy consumed at starting per year	106.37 kWhr
4	Cost of the total energy consumed at the starting	₦ 7,233.16k
5	Energy consumed during loading operation per day	82.90 kWhr per day
6	Energy consumed during loading per year	22,797.50 kWhr per year
	Cost of energy loading per year	₦1,550,230.00k
7	Energy consumed during the unloading operation	0.4376 kWhr
8	Energy consumed during unloading per day	1.7504 kWhr
9	Energy consumed during unloading per month	43.76 kWhr per month
10	Energy consumed during unloading per year	481.36 kWhr per year
12	Total energy consumed in a year (starting energy + loading energy + unloading energy)	23,385.23 kWhr
13	Cost of total energy consumed in a year by star/delta starter	₦ 1,590,195.64k

Table 4: Energy saving performance evaluation of VSD approach

S/N	Performance evaluation metrics	Computed Values
1	Energy consumed at starting in a year	57.23 kWhr
2	Cost of the energy at starting	₦ 3,891.65k
3	Energy consumed at loading per year	2,8693.5 kWhr
4	Cost of energy consumed	₦ 1,951,158
5	Energy consumed at unloading operation per day	2.01 kWhr
6	Energy consumed at unloading operation per year	552.75 kWhr
7	Cost of energy consumed at unloading operation per year	₦ 37,587.0k

Observations of the results presented in Tables 2, 3, and 4 showed that during starting operation, both the VSD and Star/Delta starting methods offer energy-saving benefits compared to DOL. This justification for this energy reduction is not unconnected to the fact that with the adoption of either VSD or Star/Delta starting approach, the compressor motor experiences a gradual increase in rotational speed, which reduces the initial surge in current and subsequently lowers energy consumption. In contrast, DOL starting applies the full supply voltage to the motor, causing a sudden surge in current and resulting in higher energy consumption. Regarding energy-saving capabilities during the loading phase, the findings of this research revealed that both Star/Delta and DOL starting methods do not provide significant advantages over each other rather both methods operate the compressor motor at its rated speed and power, resulting in similar energy consumption levels. Also, it is pertinent to consider that the efficiency of the compressor itself plays a crucial role in overall energy consumption during this phase.

Also, during the unloading phase, the investigation carried out reveals distinct energy-saving capabilities among the different starting methods. For instance, Star/Delta and DOL, which continue to run at their full speed during unloading, do not offer any energy-saving benefits during this phase whereas, the VSD demonstrates a significant energy-saving potential as in Tables 2,3 and 4. The VSD system is programmed to operate at a reduced speed, typically 50% of its full speed, when there is no demand for compressed air output, except for the minimal air requirement within the compressor chamber for lubrication purposes (approximately 2.5 bar to 3.5 bar). This reduced speed operation leads to a corresponding reduction in power consumption, as predicted by the affinity laws.

To quantify the energy savings, the findings of this research reveal that a 1 bar reduction in pressure during unloading, achievable with DOL and Star/Delta starting methods, results in approximately 6% power consumption reduction and is not unconnected to the decrease in compressed air demand during unloading and the corresponding lower operating speed of the compressor, leading to reduced energy consumption. Furthermore, during the loading phase, the VSD starter is designed to run at a 10% speed reduction compared to its full speed, and according to the affinity laws, this speed reduction results in a significant 27% reduction in power consumption, highlighting the energy-saving potential of VSD during this operational phase.

Figures 1 and 2 show the performance of the three approaches at starting revealing its effect on the energy consumed and the corresponding cost implications per year. The energy consumed with the VSD at starting was found to have reduced minimally compared with what was obtained using the other two approaches. Also, the corresponding cost of energy expended at starting at the prevailing unit cost for energy consumed used in the analysis follows a similar trend adjuring VSD as the preferred approach for starting air compressors for many industrial applications.

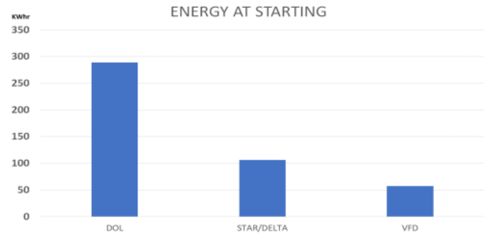

Figure 1: Energy consumed at the starting

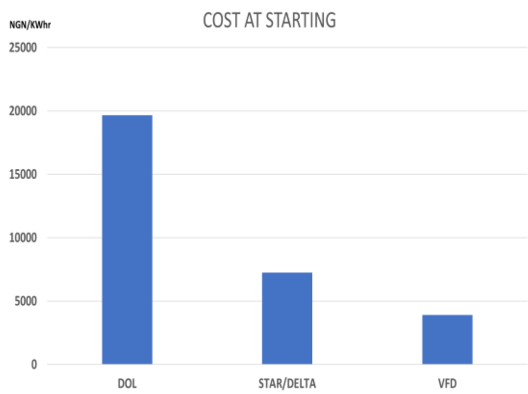

Figure 2: Cost of energy at the starting

Figures 3 and 4 show the performance of the three approaches during operation in terms of energy consumed and the corresponding cost implications per year. The energy consumed with the VSD and Start/Delta approach was comparatively smaller compared with that of DOL during operation. However, as small as it is, VSD was found to conserve a noticeable amount of energy relative to Start/Delta showing its superior performance over the two approaches. The corresponding cost implication showed that VSD achieved a significant cost saving at the prevailing unit cost of energy consumed which follows a similar trend as observed during the starting phase thereby adjuring VSD as a preferred approach for running air compressors for many industrial applications.

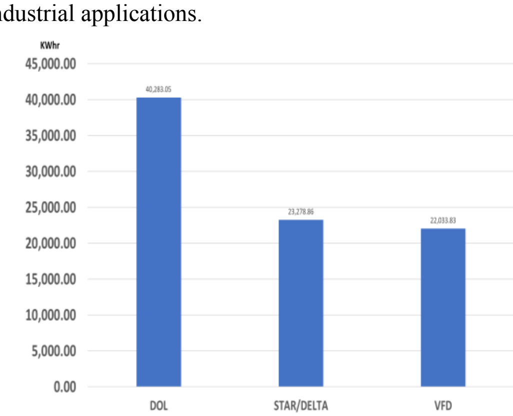

Figure 3: Energy consumed during operation

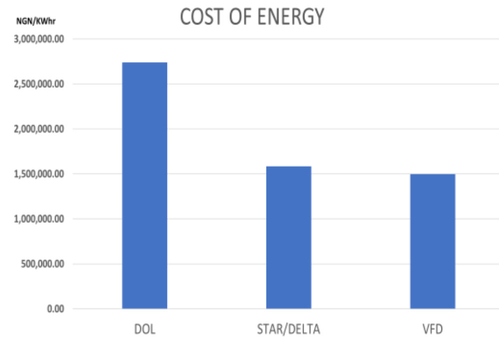

Figure 4: Cost of energy during operation

Conclusion

Optimizing the overall efficiency of the compressor system is one of the leading concerns in manufacturing industries around the globe in the face of the current reality of hyperinflation in the operational cost and procurement cost of equipment. This present study evaluated the performance of different compressor starter techniques such as Direct-on-line, Star/Delta, and Variable Speed Drive under different operational conditions such as starting, loading, and unloading conditions. The findings of this study provide valuable information for industrial applications and system design, aiding in the selection of the most appropriate starting method based on energy-saving goals and operational requirements. The main conclusions drawn from this investigation are as follows:

- Both VSD and Star/Delta methods demonstrated energy-saving benefits compared to DOL during the starting phase and are not unconnected to the gradual increase in motor speed with VSD and Star/Delta starting methods resulting in reduced energy consumption during the start-up period. In contrast, DOL starting, which applies the full supply voltage directly to the motor, led to higher energy consumption due to the immediate surge in current.
- At the loading phase, no significant differences were observed between the Star/Delta and DOL methods in terms of energy-saving capabilities as both methods operated the compressor motor at its rated speed and power, resulting in similar energy consumption levels.
- At the unloading phase, VSD demonstrated notable energy-saving potential with power consumption significantly reduced compared to Star/Delta and DOL methods, which continued to operate at full speed.

Future research could expand the scope of this study by investigating additional starting methods and exploring the influence of compressor design and control strategies on energy efficiency. Also, the implementation of VSD with varying voltage/ frequency ratios can also be researched to further validate the energy-saving capability of VSD.

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