 ISSN 2797-7889

Efficiency Analysis of A 3-Phase Induction Motor using a Variable Speed Drive as a Speed Controller at PT. Indonesia Asahan Aluminum

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This paper analyzes the efficiency performance of a 7.5 kW three-phase induction motor controlled by a Variable Speed Drive (VSD) for industrial speed regulation applications. The motor is rated at 380 V, 50 Hz, four poles, with a nominal speed of 1440 rpm. A constant voltage-to-frequency (V/f) control strategy is implemented with operating frequencies varying from 30 Hz to 50 Hz. Simulation-based analysis is conducted to evaluate electrical input power, mechanical output power, rotational speed, torque, and efficiency under different operating conditions. The results show that the motor input power decreases from approximately 8.0 kW at 50 Hz to 4.0 kW at 30 Hz, indicating significant energy-saving potential during partial-speed operation. Motor efficiency increases with frequency, ranging from 80.0% at 30 Hz to a maximum of 88.8% at the rated frequency. The reduced efficiency at lower frequencies is mainly attributed to the dominance of constant losses such as core and mechanical losses. The study confirms that VSD-based speed control improves operational flexibility and enhances energy efficiency of three-phase induction motors, making it suitable for industrial applications with variable load and speed requirements.
Keywords: Three-phase induction motor, variable speed drive, energy efficiency, V/f control, industrial, motor drive.

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1. Introduction

Three-phase induction motors are one of the most widely used electrical machines in industry due to their simple construction, low maintenance costs, and high reliability. Nearly all production processes in large industries, including PT. Indonesia Asahan Aluminum, utilize induction motors as the primary drive for equipment. However, induction motors that operate directly on mains voltage typically operate at a fixed speed. This often doesn't meet varying load requirements, leading to energy inefficiencies. Energy efficiency is crucial at PT. Indonesia Asahan Aluminium, as the industry is one of the largest consumers of electricity in Indonesia. The aluminum production process requires high-power motors that operate continuously. If motors operate at a fixed speed without considering load variations, excessive electrical energy consumption will occur and operational costs will increase. This highlights the need for more efficient motor speed control technology that adapts to the needs of the production process.

With advances in power electronics technology, Variable Speed Drives (VSDs) have emerged as a solution for regulating induction motor speed by controlling the frequency and input voltage. With a VSD, motor speed can be adjusted according to load requirements, resulting in more efficient energy use. Furthermore, the use of a VSD also contributes to extending motor life, reducing mechanical shocks to the system, and improving the overall quality of the production process. The application of VSD to induction motors in large industrial environments such as PT. Indonesia Asahan Aluminium has the potential to significantly impact electrical energy savings. With higher efficiency, the company can reduce operational costs, increase competitiveness, and support government programs in energy conservation. An in-depth analysis of the effect of VSD on induction motor performance is essential to determine the extent to which

ISSN 2797-7889

this technology can improve drive system efficiency. Based on the description, this research will focus on the efficiency analysis of a three-phase induction motor using a Variable Speed Drive as a speed controller at PT. Indonesia Asahan Aluminum. It is hoped that the results of this study can provide a real picture of the differences in motor performance with and without a VSD, as well as become practical recommendations in efforts to optimize the use of electrical energy in the industrial sector.

2. Theoretical Study

Three Phase Induction Motor

A three-phase induction motor is one of the most widely used types of alternating current (AC) electric motors in the industrial sector due to its simple construction, low maintenance costs, and high reliability. The working principle of this motor is based on electromagnetic induction, namely the three-phase current flowing in the stator coils produces a rotating magnetic field. This magnetic field then cuts the conductor bars in the rotor, creating an induced current, which produces an electromagnetic force that rotates the rotor (Chapman, 2011). The rotational speed of the magnetic field generated by the stator is called synchronous speed (N_S),), which is expressed by Equation 1.

$$n_s = \frac{120\,f}{P} \quad (1)$$

with:
n_s = synchronous speed (rpm)
f = source frequency (Hz)
P = number of stator poles

However, the rotor never reaches synchronous speed, but is always slightly slower. The difference between synchronous speed (n_s) and rotor speed (n_r) is called slip (s), which can be seen in Equation 2.

$$s = \frac{n_s - n_r}{n_s} \times 100\% \quad (1)$$

This slip is important because without it, induced current would not be generated in the rotor, preventing the motor from producing torque. A low slip value indicates a motor operating at high efficiency, while a large slip indicates heavy loading and increased energy losses.

The characteristic relationship between slip and torque in an induction motor is known as the torque-slip curve. At small slips, torque increases almost linearly with slip, then reaches a maximum torque (breakdown torque), and finally decreases at larger slips. This characteristic explains why induction motors can operate stably under a wide range of loads.

Induction Motor Efficiency

Induction motor efficiency is an important parameter in assessing motor performance, especially in industrial applications that require large electrical energy consumption. Efficiency (η) is defined as the ratio between the mechanical output power (P_{out}) produced by the motor with electrical input power (P_{in}) which can be seen in Equation 3.

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \quad (1)$$

Output power (P_{out}) is calculated based on the torque (T) produced by the motor multiplied by the angular velocity of the rotor (ω) shown in Equation 4.

$$P_{out} = T\omega \quad (1)$$

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While the input power (P_{in}) is determined from the product of voltage (V), current (I), power factor ($\cos\varphi$) and the number of phases (√3 for a three-phase motor), are shown in Equation 5.

$$P_{in} = \sqrt{3}\, VI \cos\varphi \quad (1)$$

The efficiency of an induction motor is affected by various power losses that occur during operation, including copper losses in the stator and rotor windings, iron losses due to hysteresis and eddy currents in the core, mechanical losses from bearing friction and air resistance, and other additional losses. Due to these losses, the efficiency of an induction motor never reaches 100%.

At full load, induction motors typically operate at high efficiency (85–95%), but at partial load, their efficiency decreases. Therefore, in industrial systems with varying operating loads, the use of a Variable Speed Drive (VSD) is essential to regulate motor speed to match load requirements. This not only increases efficiency but also significantly reduces electrical energy consumption.

Variable Speed Drive (VSD)

A Variable Speed Drive (VSD) is a power electronics device used to control the speed of an induction motor by changing the frequency and voltage of the power supply. By using a VSD, the frequency (f) can be varied, so that the motor rotation speed (N_r) can be adjusted according to load requirements. To keep the magnetic flux constant and the motor from saturating, the most commonly used control principle is the V/f Control (Volts per Hertz Control) method, where the ratio between voltage (V) and frequency (f) is kept constant. The stator flux of an induction machine is equal to the ratio of the stator voltage to the frequency because

$$\varphi(t) = \int v(t)\mathrm{d}t \quad (1)$$

Where,

$$v(t) = V_m \sin(\omega t) \quad (1)$$

so that,

$$\varphi(t) = \sqrt{2}\frac{V_m}{\omega}\cos(\omega t) \quad (1)$$

Motors are supplied with varying AC source voltage and frequency. When the frequency is lowered to slow the motor, the voltage is also reduced proportionally. Conversely, if the frequency is increased to speed up the motor, the voltage is also increased to keep the magnetic flux constant. V/Hz control is used in low-dynamic applications such as pumps or fans where small variations in motor speed with load can be tolerated. The application of VSD in industry provides several benefits, including: increasing energy efficiency by adjusting motor speed to load requirements, reducing electricity consumption under partial load conditions, extending equipment life by reducing transient voltages during starting, and reducing overall operating costs. If the slip(s) of the motor is taken into account, the rotor speed (N_r) with VSD settings can be written in Equation 9.

$$n_r = (1 - s)\frac{120f}{P} \quad (1)$$

Where:
n_r= rotor speed (rpm)
s = motor slip
f= VSD output frequency (Hz)
P= number of motor poles

ISSN 2797-7889

Thus, VSD is a very relevant technology in this research because it is able to increase the flexibility of three-phase induction motor operation while reducing electrical energy consumption.

Relationship between VSD and Induction Motor Efficiency

The efficiency of an induction motor is greatly influenced by how electrical energy is converted into mechanical energy. Without control, induction motors typically operate at a constant speed at the grid frequency (50 Hz or 60 Hz), even when the driven load doesn't always require full speed. This wastes energy because the input power doesn't match the load's power requirements. The use of a Variable Speed Drive (VSD) allows an induction motor to operate at variable speed by adjusting the frequency and input voltage. By adjusting the frequency (f) according to the load torque requirements, the motor speed (n_r) can also be adjusted, so that power consumption becomes more proportional to the load. Motor efficiency under these conditions can be increased because losses due to core losses and copper losses are reduced. The formula for induction motor efficiency is shown in equation.

With the application of VSD, the output power (P_{out}) can be adjusted according to load requirements without causing excessive energy losses. In addition, the V/f Control method used by VSDs keeps the motor flux constant, so that the motor's electromagnetic performance remains optimal even when operating at low frequencies.

In general, the graph of induction motor efficiency versus load shows an increase in efficiency with the use of a VSD, especially at partial loads, because the input power can be adjusted to the output power. Thus, the VSD functions not only as a speed controller but also as an energy-saving device that increases the operational efficiency of induction motors, especially in industrial applications with variable loads such as conveyor systems, pumps, and fans.

Applications in the Aluminum Industry

The aluminum industry is one of the industrial sectors that requires significant electrical energy consumption, particularly in electrolysis, bauxite processing, casting, and utility systems such as pumps, fans, and conveyors. Three-phase induction motors are widely used due to their reliability, low maintenance costs, and ability to operate under harsh operating conditions. However, induction motors operated directly at a constant frequency (50 Hz) often result in energy waste, as the aluminum industry's loads are dynamic and do not always require full speed. The use of a Variable Speed Drive (VSD) allows the speed of an induction motor to be adjusted according to the needs of an industrial process. For example, in a cooling blower system, the cooling air requirement varies depending on the temperature of the melting furnace. Without a VSD, speed control is achieved by a damper (mechanical valve), which still consumes full energy even when air flow is restricted. With a VSD, the motor speed can be reduced when air flow requirements are low, significantly reducing electrical energy consumption. In the aluminum industry, energy efficiency is crucial, as electricity consumption accounts for more than 30–40% of production costs. With the implementation of VSDs, electrical energy savings in induction motors can reach 20–50%, depending on load variations. This not only increases productivity but also reduces operational costs and carbon emissions, thus supporting green industry principles.

3. Research Methods

This research is an applied research with a quantitative approach, which aims to provide a technical solution to the problem of low efficiency of three-phase induction motors in the production process at PT. Indonesia Asahan Aluminum (INALUM). The main focus of this research is to analyze changes in induction motor efficiency before and after the application of Variable Speed Drive (VSD) as a speed controller, based on actual measurement data in the field.

The scope of this research includes the collection, processing, and analysis of operational data of induction motors used in certain process units at PT. Indonesia Asahan Aluminium, especially on equipment that has variable load characteristics such as cooling pumps, blowers, and conveyors. The analysis is carried out based on electrical and mechanical parameters, including input power (kW), current, voltage, rotational speed (rpm), output power, and motor efficiency calculated using the ratio of output power to input power. In addition, this study evaluates the effect of speed control through VSD on reducing electrical energy consumption and improving motor operational performance.

This research is limited to three-phase induction motors equipped with VSDs and within the production process of PT. Indonesia Asahan Aluminium. The analysis focuses on changes in energy efficiency without considering the overall electrical protection system aspects, the in-depth influence of harmonics, or a complete economic analysis of the investment in installing VSDs. The research only uses technical measurement data obtained from operational units and does not include physical modifications to the equipment or controlled laboratory testing.

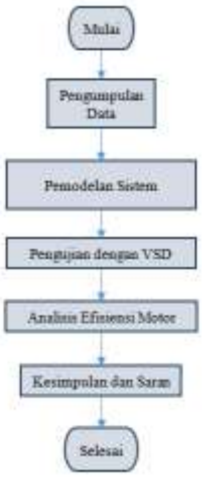

Figure 1. Research Flowchart

The data collection technique in this study was carried out through secondary data collection obtained from the results of operational records and technical measurements at PT. Indonesia Asahan Aluminum. This data is routine data collected by the maintenance and operations unit, including important information related to the performance of induction motors used in the production process, such as input power (kW), voltage (V), current (A), VSD output frequency (Hz), motor speed (rpm), and the type of load served. In addition, this study also utilized technical documentation such as motor nameplates, Variable Speed Drive specifications, process diagrams, and equipment operation reports. This data served as the basis for analyzing the motor's existing condition, particularly in comparing motor efficiency before and after VSD implementation.

4. Results and Discussion

Research Data

This study discusses the effect of using Variable Speed Drive (VSD) on the working efficiency of three-phase induction motors used in industrial process systems at PT. Indonesia Asahan Aluminium (PT INALUM). The focus of the discussion is directed at changes in the characteristics of power, current, power factor, torque, and motor efficiency at various operating speed variations regulated by VSD. Data

ISSN 2797-7889

were obtained from technical documentation and factory specifications, as well as parameter estimates based on industry standards. Table 1 shows the main parameters of the induction motor used as the basis for the simulation.

Table1. Induction Motor Specifications

Parameter	Mark	Information
Nominal voltage	400 V	Three-phase working voltage
Motor power	10 hp	Motor capacity
Frequency	50 Hz	Industry standard supply frequency
Nominal speed	1440 rpm	Speed at full load
Nominal torque	47 Nm	Torque capability according to motor load
Type of motorbike	Squirrel cage	Used in Simulink blocks

Simulations were performed on a three-phase induction motor at PT. Indonesia Asahan Aluminium using MATLAB/Simulink as shown in Figure 2. The modeling includes the interaction between the motor and the load to observe changes in the characteristics of power, current, power factor, torque, and motor efficiency at various operating speed variations regulated by the VSD.

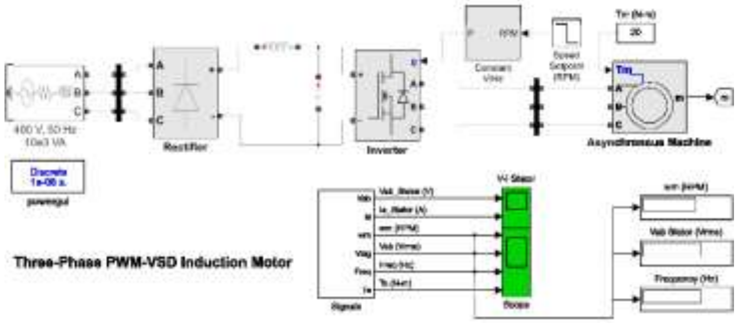

Figure 2. MATLAB/Simulink Simulation

Speed control is performed using a Variable Speed Drive (VSD) with a constant voltage to frequency ratio (V/f) control method. The frequency variations used are 30 Hz, 35 Hz, 40 Hz, 45 Hz, and 50 Hz. The simulation results are presented in Tables 2 to 5. presenting the simulation results of the electrical, mechanical, and efficiency parameters of the motor at each frequency variation.Table2presents the electrical parameters of the simulation results including stator voltage and motor speed, it can be seen that increasing the frequency causes the motor to rotate faster which is followed by a proportional increase in stator voltage.

Table2. VSD Operating Parameters

No	*f*(Hz)	(V)	(rpm)	
1	30	228	860	60
2	35	266	1000	70
3	40	304	1140	80
4	45	342	1290	90
5	50	380	1440	100

Table 3 provides simulated motor input data. This table shows an increase in power factor when power consumption increases due to increased frequency and motor speed.

Table 3. Motor Input Data

No	*F* (Hz)	(A)	*pf*	(kW)	Q (kVAR)	S (kVA)
1	30	15	0.7	4	4.1	5.7

No	*F* (Hz)	(A)	*pf*	(kW)	Q (kVAR)	S (kVA)
2	35	17	0.74	5	4.6	6.8
3	40	19	0.78	6.2	5	8
4	45	21	0.82	7.2	5.3	8.8
5	50	22	0.85	8	5	9.4

The simulated motor output data is shown inTable4. This data shows a relatively small change in torque as rpm is increased despite a significant increase in output power.

Table4. Motor Output Data

No	*f*(Hz)	*Torque*(Nm)	*Pout*(kW)	Efficiency (%)
1	30	44	4	80
2	35	45	4.7	82
3	40	46	5.5	83.9
4	45	47	6.3	86.1
5	50	48	7.2	88.8

Data analysis

The relationship between motor input power and VSD frequency is shown inFigure 2The graph shows that the input power increases almost linearly with increasing frequency. At a frequency of 30 Hz, the motor input power is recorded at 4.0 kW, while at a nominal frequency of 50 Hz the input power increases to 8.0 kW.

This demonstrates that the use of a VSD significantly reduces power consumption during partial-speed operation. In industrial applications such as conveyors at PT Indonesia Asahan Aluminum, where motors do not always operate at maximum speed, speed regulation using a VSD can avoid the excessive energy consumption common with conventional drive systems.

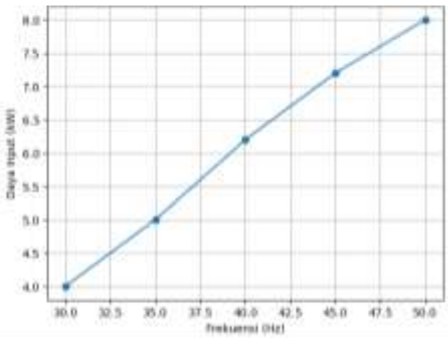

Figure 2. Relationship between Motor Input Power and VSD Frequency

The relationship between motor efficiency and VSD frequency is shown in

Figure **3**. Based on the graph, motor efficiency increases with increasing frequency and rotational speed. At 30 Hz, motor efficiency is 80.0%, while at 50 Hz, efficiency increases to 88.8%.

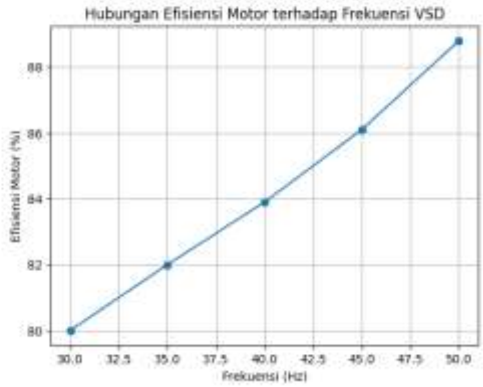

Figure 3. Relationship between Motor Efficiency and VSD Frequency

The relatively low efficiency at low frequencies is thought to be due to the dominance of fixed losses, such as iron and mechanical losses, whose values do not decrease significantly even though the output power decreases. As frequency and load increase, the motor output power increases more than the increase in losses, so that the motor efficiency increases. At a nominal frequency of 50 Hz, the motor operates close to its design conditions, so that the efficiency reaches its maximum value. This result is in accordance with the general characteristics of induction motors, where the highest efficiency is achieved when the motor operates at a load close to the nominal load.

Simulation results show that the use of a Variable Speed Drive offers two main advantages: flexibility in speed regulation and increased energy efficiency. At partial speeds, the VSD can significantly reduce motor input power, although motor efficiency decreases slightly due to the dominance of fixed losses. However, overall, total energy consumption remains lower than operating the motor at a fixed speed.

These findings are highly relevant to industrial applications at PT Indonesia Asahan Aluminum, which have variable load operating patterns. By operating the motor according to process requirements, the use of a VSD not only improves drive system efficiency but also contributes to electrical energy savings and lower operating costs.

5. Conclusion

Based on the simulation and analysis results, the application of Variable Speed Drive (VSD) on a 7.5 kW three-phase induction motor has proven effective in controlling the motor speed according to the process load requirements and contributing to electrical energy savings. This is indicated by a decrease in motor input power from 8.0 kW at a nominal frequency of 50 Hz to 4.0 kW at a frequency of 30 Hz. The analysis results also show that motor efficiency increases with increasing frequency and workload, namely from 80.0% at a frequency of 30 Hz to 88.8% at a frequency of 50 Hz, which indicates that the motor operates most optimally at conditions close to its design specifications. Although at low speeds the motor efficiency is relatively decreased due to the dominance of fixed losses, such as iron losses and mechanical losses, the total energy consumption remains lower than operating the motor without a VSD. Thus, the use of a VSD provides advantages in the form of increased operational flexibility and energy efficiency, making it suitable for application in industrial motor drive systems with varying load characteristics, such as conveyor systems at PT Indonesia Asahan Aluminium.

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