Techno-economic analysis of slip ring motor replaced by standard squirrel cage induction motor with VSD

H Dewi¹, F H Jufri¹ and C Hudaya¹²,∗
¹ Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, 16424, Indonesia
² Energy System Engineering Master Study Program, Faculty of Engineering, Universitas Indonesia, Depok, 16424, Indonesia

*c hudaya@eng.ui.ac.id

Abstract. Induction motor slip ring-type technology has been widely used in industrial as one of the crucial electrical components to convert energy mechanically. The construction of this motor is more complex than other standardized induction motors such as squirrel cage. The complexity lies in the connection between the rings and brushes which requires more maintenance. Meanwhile, Squirrel cage motor that is supported by a Variable Speed Drive allows its user to start motor smoothly and adjusts the speed more efficiently. In this study, we exclusively investigate the possibility of the outdated technology replacement by using squirrel cage standardized induction motor based on its compatibility and the financial perspective as well. To prevent any coming up problems, the selections of new motor and VSD must fulfill the requirement of the existing system. Technical data were collected from customer’s SCADA and nameplates. While the financial calculation was made based on the payback period. In this case, the payback period is projected within two years and the energy saving could reach 69% that basically depends on operation patterns. According to our perspective, standard squirrel cage motor potentially replaces the slip ring motor in which it is not only having a simple operation but also less maintenance and energy cost.

1. Introduction

Slip ring-type induction motor has been widely used in industries as one of the crucial electrical components to convert electrical energy into a mechanical one. The slip ring technology uses external resistance to adjust motor speed and to provide starting current requirement that is connected to the induction motor rotor. The complexity lies not only on the external resistance contactor but also the connection between the rings and brushes, which require intensive maintenance. Furthermore, the slip ring brushes should be changing out regularly at least every two months. In addition, even though the external resistors are robust enough, its contactors which open and close the resistor to control the slip ring motor’s speed need to replace or maintenance annually or even more frequently, depending on its utilization [1]. On the other hand, standard squirrel cage induction motor that is supported by a Variable Speed Drive (VSD) technology allows its user to start motor smoothly and adjusts the speed more efficiently.

In this study, we exclusively investigate the techno-economic analysis of 2422 kW slip ring motor replaced by identical standard squirrel cage induction motor equipped with VSD. The main object of this study is an induction slip ring motor which was used as an induced draft fan driven at the cement
industry. Through this study, we provide the complete consideration to select a replacement squirrel cage motor and VSD combination correctly to obtain better operation than the existing system. Then, the economic outlook will also be established in the form of investment capital schemes and payback period by considering operational and maintenance cost.

2. **Induction motor as a load drive**

There are two types of induction motor’s rotor that could be placed inside the stator. One is called a cage rotor or squirrel cage motor while the other is called a wound rotor or slip ring motor. A slip ring motor has a complete set of three-phase winding that is similar to the winding on the stator. The windings of the rotor are shortened by brushes on the slip rings. Therefore, the rotor currents of the slip ring induction motor are accessible at the stator brushes, where they can be examined and where additional resistance can be inserted into the rotor circuit to modify the motor’s torque and speed-current characteristics. The prototypes of slip ring induction and squirrel cage rotors are shown in Figure 1 and Figure 2, respectively. The squirrel cage rotors consist of a series a conductor bars laid into slots carved in the face of the rotor and shorted at either end by large shorting rings. This design is referred to as a cage rotor because the conductors look like the exercise wheel that squirrels run on. Slip ring induction motor is more expensive than squirrel cage induction motor, and it requires much more maintenance because of the wear associated with its brushes and slip rings [2].

Induction motors are designed to apply for various load characteristics such as transportation, material handling, and most production process. In general, there are three types of load characteristics, such as variable torque, variable power, and constant torque. Meanwhile, slip ring motor is particularly used to start a high inertia load or a load that requires a very high starting torque across the motor’s full speed range. The motor could produce high torque by applying a resistor to the motor’s slip ring with low locked rotor current relatively. This is one conventional method that allowed an induction motor to produce overload torque [1]. In the other hand, there have been substantial technological advancements of variable speed drive. Furthermore, squirrel cage motor and VSD installation not only increases energy efficiency, saves energy consumption, improve power factor and process precision soft start-up and over speed capability, but also eliminates throttling mechanisms to control air flow and frictional losses affiliated with electromechanical adjustable speed technologies [3].

![Figure 1. Slip ring rotor type.](image1)

![Figure 2. Squirrel cage rotor type.](image2)

Induction motor selection is based on the torque requirement. Therefore, squirrel cage motor selection has to match with the existing system’s characteristic or application’s torque requirement [2-5]. In order to control torque production in the slip ring motor, resistor banks are switched in and out by means of high-current electrical contactors. These resistors are called external resistor or a rheostat and are sized based on rotor current and the application’s torque requirements. In general, if the load works under 50% speed for a high percentage of its operational cycle, it could be a good chance to upgrade to a VSD as the way to energy saving. If the speeds of motors are gradually decreased during its operation, therefore the resistors banks would absorb abundant energy to produce the torque. The energy saving in the motors would be in the order hundreds of kWh, depending on the power and its duty cycle [1].
VSD can be applied to a wide variety of loads. In the cement industry, a fan is used as the drive of airflow, so that rested dust during the production could be removed through the chimney. The object of this study is induced draft fan which is a variable torque type load. Figure 3 illustrated the savings potential with a VSD versus common throttling methods such as damper control and inlet vane control. These mechanisms waste high amounts of energy compared to the adjustable speed drive. Due to large power of the fan (2422 kW), a small change of fan’s speed could provide the difference in energy consumption, making user could achieve large energy saving with even small speed adjustments only [4]. The observed fan follows the affinity law [6]:

\[
\text{Power} \propto \text{pressure} \times \text{flow} \tag{1} \\
\text{Pressure} \propto \text{speed}^3 \tag{2} \\
\text{Flow} \propto \text{speed} \tag{3} \\
\text{Power} \propto \text{speed}^3 \tag{4}
\]

Bhase et al. found that for variable torque type motor, a decrease of 20% speed contributed to the reduction of 45% energy consumption [6]. A similar trend was also observed in the study of Siroyv et al. about medium-voltage drive fan [7]. Furthermore, energy saving calculation using affinity law could be employed if the fan does not consider a minimum pressure of air flow. Otherwise, there should be other constant value should be taken into account [8].

3. Research methodology

3.1. Data collecting of the existing slip ring motor

The technical specifications of the existing slip ring motor need to determine in order to seize new motor and to meet the requirement of the application. Those data are used to provide the existing load profiles that will then be utilized as standard in the next motor duty application. Table 1 describes the fan’s characteristic and slip ring motor’s capability that was taken from its nameplate. Meanwhile, Table 2 is the summary of monthly average load profiles that was taken from the customer’s SCADA data.
Table 1. Existing load application and motor technical data

| Fan specification                          | Value       |
|--------------------------------------------|-------------|
| Specific air density at inlet (kg/m³)      | 1.41        |
| Airflow at inlet (m³/s)                    | 669,600     |
| Static pressure at inlet (Pa)              | -10,300     |
| Speed (rpm)                                | 990         |
| Power demand at normal operating (kW)      | 2,202.5     |
| Air flow control mechanism                 | damper      |

| Motor specification                        | Value       |
|--------------------------------------------|-------------|
| Rated Output (kW)                          | 2422        |
| Speed (rpm)                                | 993         |
| Current (A)                                | 156         |
| Voltage (V)                                | 11,000      |
| Duty type                                  | S1 (Continuous) |
| Rated Torque (Nm)                          | 23,301      |

Table 2. Summary of monthly load profile of the existing system.

| Annual Running Motor | Annual Air Flow | Air Flow Flow |
|----------------------|-----------------|--------------|
| Hours               | Total Power     | Energy       | (%)         |
| (hours)             | (kW)            | (kWh)        |             |
|                     |                 | (m³/s)       |             |
|                     |                 |              |             |
| 6,000               | 1,769.45        | 10,616,700   | 404,539.93  | 60%         |

3.2. Saving energy and economic calculation

Saving energy was calculated from affinity law, as described in Equation (5), that is proportional to the air flow \( Q_0 \) at 100%, \( Q_N \) at 60%, the nominal power at 100% \( P_0 \) and total efficiency system \( \eta \).

\[
P_N = \left( \frac{Q_N^3 \times P_0}{Q_0} \right) / \eta \quad (5)
\]

The economic parameter was estimated by calculating the payback period (PBP). In detail, the payback period calculation was carried out by comparing two factors which are saving energy and capital investment. While the direct comparison of the total amount consumed energy between the existing and new motor system represented the saving energy which has been made. Annual Energy saving AES is calculated from the difference of annual energy consumption of old system AEC\(_O\) and new system AEC\(_N\) then multiply by annual operation hours:

\[
AES = (AEC_O - AEC_N) \times AOH \quad (6)
\]

The payback period (PBP) is the function of the investment cost of the new system divided by annual energy cost saving:

\[
\text{Payback period (years)} = \frac{\text{Investment Cost}}{\text{Annual energy cost saving}} \quad (7)
\]

4. Results and discussion

4.1. Selection of squirrel cage motor and VSD

The selection of new motor combined with VSD has been carried out to accommodate the entire system requirements. This step is crucial to ensure that there is no technical obstacle once the new proposed system is integrated for operation. For instance, we have to look carefully on the motor torque and starting current through the motor torque vs speed curve and the load vs torque curve. The torque produced by the motor must be greater than the load torque under any conditions (starting, running at
rated, full speed and acceleration). On the other hand, VSD selection follows the specifications of the motor that has been chosen. The VSD used in this study is based on multi-inverter that uses LV-IGBT technology with 30 pulses, meaning that the waves generated by this inverter are close to sinusoidal waves so that they do not have the potential to produce harmonics that are harmful to the motor and the system [9].

4.2. Saving energy calculation

Power consumption calculations in the new proposed system refer to the affinity fan law in Equation (5) multiplied by the total system efficiency resulting in 544.78 kW. This calculation can be applied because VSD is able to regulate speed in the range required with power consumption based on affinity law. The values in Equation (6) refer to the operating conditions in the existing motor. Therefore, to obtain the output with the same velocity of air flow, we employed the identical assumptions used in the new proposed system. Once the velocity of air flow is known, we could predict the absorbed power of the new proposed motor. Based on the existing data, the nominal power needed to produce an airflow of 669,600 m³/s is 2202.5 kW, while in the ID fan operating data stated that the ID fan only operates at 60% rates. Therefore, the fan does not work at a nominal rating, or in other words, its capacity has been reduced.

\[
P_N = \left( \left( \frac{404.540}{669,600} \right)^3 \times 2202.5 \right) / 0.89 = 544.78 \text{ kW} \tag{8}
\]

Figure 4. Comparison of power consumption for the existing and new proposed system.

\[
\text{AES} = (1769.44 - 544.78) \text{ kW} \times 6000 \text{ h} = 7,347,982 \text{ kWh} \tag{9}
\]

\[
\text{PBP} = \frac{734,051}{507,010} = 1.45 \text{ years} \tag{10}
\]

Equation (9) shows the energy costs that can be saved are 7,347,982 kWh which equal to 6,000 hours’ annual operation. Assuming the electricity price for cement industry of US$ 0.069/kWh, the total energy saving cost for this project achieved US$ 507,010. Based on Equation (10), the payback period is achieved within 1.45 years by assuming the total expenditure for the first installation costs of US$ 734,051.
5. Conclusion
The techno-economic analysis of slip ring motor replaced by standard squirrel cage induction motor equipped with VSD has been assessed through its compatibility to the existing system demand, especially load torque requirement. Furthermore, in the matter of fact that standard squirrel cage induction motor is able to provide the same torque as the existing system and capable of starting smoothly with VSD capability. We found that the energy saving could achieve 69% and the payback period is estimated to be less than two years. Another advantage of squirrel cage integration is that there is no need for more frequent maintenance and replacement of slip ring brushes.

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