Economic analysis of variable speed drive control through profinet technology on distributed control system: A case study in essential oil processing factories

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Abstract: Electrical equipment in essential oil processing plants is generally dominated by electric motor loads. In today's digital era, global competition and technological advances encourage factories to increase the efficiency and reliability of their production equipment. One way of efficiency is to use a variable speed drive (VSD). The existence of Profinet technology as a network protocol between the control equipment and the VSD allows users to increase system reliability while increasing energy use efficiency. Even so, there are still many factories that are hesitant to use this technology in their automation systems. Many low to medium-sized factories still use traditional control methods such as hardwired. This method is considered more reliable, and inexpensive compared to using Profinet technology. Cost-benefit analysis is carried out to prove this paradigm. At the same time provides certainty that the investment costs incurred in building the system provide added value for production equipment. From this research, it is proven that the use of Profinet technology in addition to providing savings on investment costs also provides benefits from a technical perspective. This technology also allows the implementation of condition-based monitoring systems for electric motors in production equipment. Which in turn can increase the performance and service life of the machine.

Keywords*:* Variable speed drive; Profinet; Efficiency; System reliability; Cost-benefit analysis

1. Introduction

In an era where energy prices are getting higher, the efficiency of energy use is very important. Electrical equipment in essential oil processing plants is generally dominated by induction motor loads. Thus the efficiency of energy use in induction motors becoming an important aspect (Kumar et al., 2015). One way to maximize the use of this energy is to install a variable speed drive (VSD) for an induction motor. The use of VSD in induction motor installations aims not only for the efficient use of energy but also to control the production process itself. Barnes (2003) described it as an analogy of someone controlling the speed of a vehicle. It is to adjust the vehicle speed with traffic conditions on the highway (process). In an addition, it will also directly impact the vehicle's fuel consumption. Finally, process control is an important aspect of product creation on a factory production line.

Energy use efficiency, as well as safe process control, are among the important aspects of an essential oil processing plant. The advancement of digital technology opens up the possibilities for industrial facilities to operate more efficiently. One example of digital technology in industrial facilities is factory automation. Automation systems enable the controlled equipment to work safely and efficiently (Persechini & Jota, 2013). The need for safe process control is crucial within industrial production facilities. In an essential oil processing plant, electric motors are usually to drive the tank mixer and also the transfer pump. The need to control the speed of the mixing process and also the transfer flow rate is a common application. In addition, there are additional benefits in the form of the cost efficiency of electrical energy. However, this added benefit seldom to be the main reason behind such applications.

The VSD control method through Profinet technology offers several advantages compared to traditional methods such as hardwired. However, this technology has not been fully adopted by most factories and industrial facilities (Mahalik & Yen, 2009). Most of the parties consider the Profinet technology to be more expensive than the hardwired method. It is often to be the main reason for using the much simpler hardwired method as the default approach in controlling the VSD. Economic studies and analysis are deemed necessary to determine how well the Profinet technology can play a role in increasing operational efficiency and the reliability of production equipment control systems. Therefore this study and analysis can also be used as a reference in designing and determining the right method to control the VSD.

2. Methods

Controlling the VSD

There are two types of methods for controlling induction motors using VSD. These are scalar control and vector control. Scalar controls are used to control fan loads as well as air ventilation systems, where the need for speed control alone is sufficient. Vector control on the other hand offers additional features in the form of controlling the speed and torque generated by the electric motor. However, this usually requires additional sensors or parameter data from the motor used (Vadi et al., 2022). In general, scalar control methods are more widely used in essential oil processing plant applications. It is because mechanical loads (agitators and pumps) in essential oil processing plants usually have static characteristics. This means that the speed control alone is sufficient to meet the process requirements.

Figure 1 shows a typical VSD block diagram. The controller or interface part of the VSD usually has input and output modules. Similar to PLC or DCS, this input and output module is used to communicate with control systems outside the VSD. Also with this module, VSD can be controlled remotely through controlling equipment in the form of PLC or DCS. In a small or medium-sized factory, the interconnection between the control equipment and the VSD is usually done by hardwired. Whereas one pair of cables represents one function or one control parameter. If a VSD requires at least four to six control functions/parameters (for start and stop functions, fault status, running status, remote operation status, speed set point, and speed status) so controlling a VSD requires at least six pairs of control cables. If there are several VSDs in one system, the number of control cables increases by that number (Barnes, 2003b).

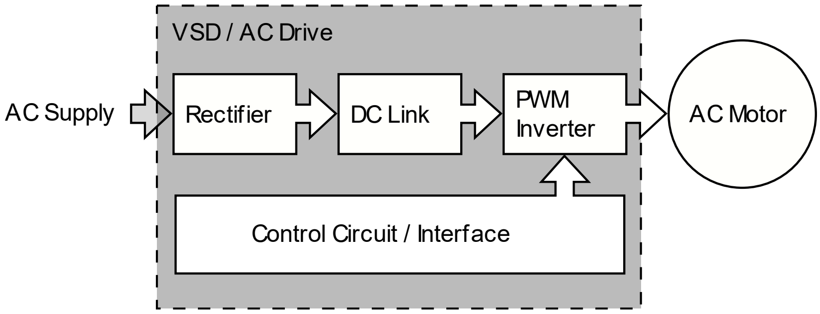

Figure 1. A typical VSD block diagram

With the increasing technological advances and competition between companies, more and more factories are adopting the smart factory idea. Where production equipment is equipped with sensors and a condition-based monitoring system. To fully take advantage of the features of these smart devices, many control parameters are required. Thus, traditional methods such as hardwiring are no longer relevant for use. Other methods such as field bus to ethernet are considered superior to be used in cases like this. Apart from being simpler in terms of installation, this technology also allows users to retrieve or send more information data from the VSD in real-time. Figure 2 and Figure 3 show a typical hardwired and networked control system installation schematic respectively.

Field bus and ethernet

The field bus is a communication medium between control equipment (PLC / DCS) with sensors, actuators, or other equipment (Cena et al., 1995). The term field bus in the world of automation is not a new thing. One of the main criteria that a field bus must have is being able to provide real-time information to the controlling device.

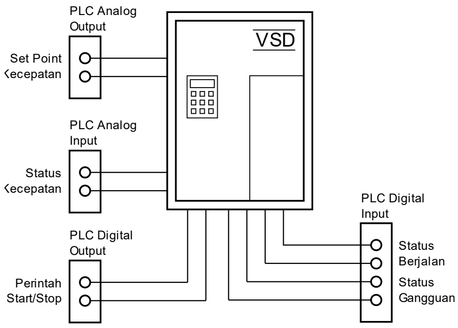

Figure 2. Typical schematic of hardwired control method

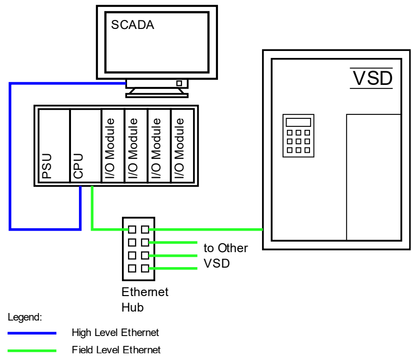

Figure 3. Typical schematic of networked control method

On the other hand, Ethernet communication technology is used as a communication link between control devices at a higher level. In contrast to field buses, ethernet offers several advantages thanks to standardization which allows equipment from various manufacturers to interoperate with each other (Huynh et al., 2010). With the development of digital technology, from field bus technology to ethernet, more and more practitioners and researchers are testing this new technology. Several studies have been conducted to test the capabilities of this fairly new technology. Flammini, Ferrari, Sisinni, Marioli, & Taroni, 2002) compared the traditional hard-wired, field bus, and also ethernet methods, in terms of the resources required to perform the process. Ethernet-based communications technologies are proving to be comparable to field bus technologies in terms of cost, data handling capabilities, and complexity. This opens up opportunities for this technology to develop and be accepted by end users. Plus the fact that this technology is very easy to implement because it has standardization and also the same interface from one manufacturer to another adds to the attractiveness of implementing this technology.

Some of the benefits that come from having this smart equipment include increasing equipment reliability and also enabling equipment self-diagnostic function. It is proven to provide benefits to the operational efficiency of the equipment. In research conducted by (Dias et al., 2021), an electric motor condition monitoring system was built without any additional sensors. With programming algorithms as well as the information received from the VSD through Profinet technology, a comprehensive analysis of the condition of the electric motor can be made. Profinet is an ethernet-based automation equipment communication technology.

Profinet Technology

Profinet is a communication standard for factory automation from the non-profit organization PROFIBUS & PROFINET International (PI). Within Profinet, data exchange can be carried out in real-time through data provider and consumer schemes. Equipment is divided into three different classes, namely IO Controller, IO device, and also IO Supervisor. The IO Controller is in charge of managing the course of process control and giving orders in the form of input data to IO devices. On the other hand, IO devices execute commands on-field equipment such as VSDs. The IO device can also send actual information on the condition of the equipment in the field to the IO Controller. Meanwhile, the IO Supervisor is usually only used temporarily in the program development process, equipment testing, or during the problem-finding process (PROFINET System Description Technology and Application, 2014). Figure 4 shows the communication path from the Profinet installation.

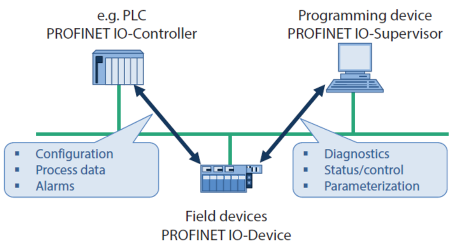

Figure 4. Communication path of profinet IO

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Profinet technology allows an IO Device to be used simultaneously by more than one IO Controller. Therefore equipment built using this technology has a high degree of flexibility. In addition, data exchange cycles can also be set individually for each IO device in the system. Making it easier for system designers to determine the priority of data exchange. For VSD control applications, where control cycle time is critical, it is only natural that an IO device such as a VSD will usually have the highest data cycle priority in the system.

A case study

The research was conducted to show the added value of using Profinet technology as a VSD control medium. An economic feasibility study was carried out on a project where twenty-five induction motors will be controlled via a VSD. These twenty-five induction motors are used in several production equipments that belongs to two separate production processes. One of the production process flowcharts is shown in Figure 3. The research begins by determining the architecture of the system to be built. As Profinet technology is part of ethernet technology, network topology has an important role in designing the whole system. Several network topologies can be used such as line, star, ring, or tree topologies. Line topology is commonly used to connect IO devices in the field. The star topology is used to connect IO devices and also IO controllers. Ring topology is used when the system requires redundancy features. While the tree topology is a combination of the topologies above.

The architecture of the system will greatly affect its performance. In addition, the topology of the system also has a direct impact on the costs required to build it. For example, a line topology may reduce the cost of using network switching equipment. However, as a result, the system becomes vulnerable and its performance will decrease as the size of the system increases. On the other hand, using only the star topology will increase the cost of using network switching equipment. For a large system, a mix of line and star topologies is usually preferred. Ring topology can be used if redundancy is a criterion required by the system. The tree topology was chosen for this project because it has the advantages of the star topology but still considers the simplicity of the line topology. The line network is divided in the system based on the conditions of the production process. This division is done to reduce the need for network connecting channels within the switching equipment. In addition, dividing the line network according to process conditions will make it easier to isolate the network when a problem occurs. The red-striped box in Figure 5 shows an example of the line network communication in the system, while Figure 6 shows the topology of the system.

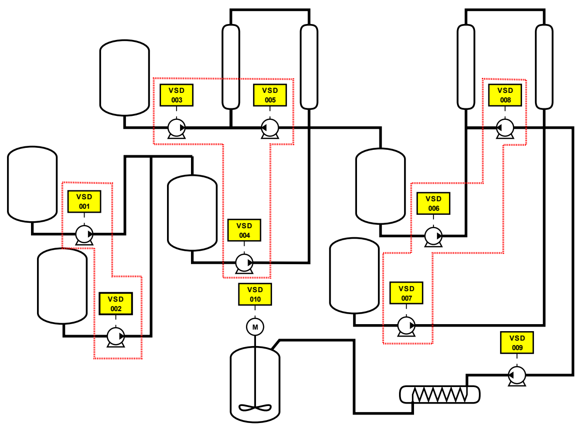

Figure 5. Typical flow diagram of the process

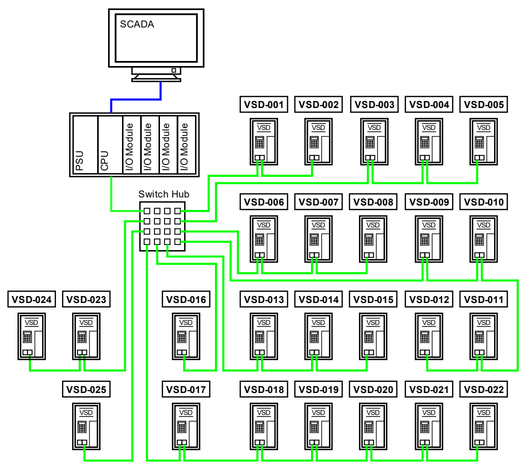

Figure 6. The architecture of the system built

From the system architecture, a list of the installation equipment and accessories can be generated. From this list, an estimate of the required costs can be obtained. Economic analysis is performed on the same system using Profinet and hardwired method. To obtain the correct analysis results, the components that are compared are only components that are truly specific for the Profinet and hardwired installation. For example, components such as the central processing unit (CPU) of a PLC are not compared. This is because these components are equally needed in both the Profinet and hardwired methods. Table 1 shows the cost components being compared between the Profinet and hardwired methods. The nature of the cost components in the table shows that the estimated cost may vary depending on other external matters than the number of VSDs installed (in this case 25 units). For example, the number of VSD communication modules required for the Profinet method is only affected by the number of VSDs installed in the system. Thus this cost component has a nature of direct and fixed cost. The cost of manpower required may vary depending on several items other than the number of VSDs installed, such as the distance between the VSD's panel and the PLC's panel, the number of control connections required, or the topology used by the system. Thus this component has a nature of indirect and varying.

Table 1. Cost components of VSD installation using Profinet and Hardwired

Profinet	Hard-wire	Nature of Cost
Equipment cost		
PLC Communication module	PLC Input/Output module	Direct and fixed cost
VSD Communication module	VSD Input/Output module	Direct and fixed cost
Installation cost		
Man Power	Man Power	Varying cost
Installation material	Installation material	Varying cost
Supporting equipment	Supporting equipment	Varying cost

The benefits analysis from the use of Profinet technology is then to be carried out after the cost analysis. The difference in installation costs using Profinet and hardwired can be categorized as a benefit. In some cases, the difference in installation costs alone cannot be used as the only reason for making a decision. Other benefits derived from using Profinet technology are also presented in the form of a currency unit. It is to facilitate the cost benefits analysis. In the end, the benefits obtained must be greater than the costs incurred, as the main criterion for decision-making. Some of the benefit components analyzed are shown in Table 2. The relation column in the table shows the connection between the benefit acquired within the cost spent. The nature of benefit shows the value of the benefit within the system built.

Table 2. Benefits of VSD installation using Profinet

Benefit	Relation	Nature of Benefit
Installation		
Man power	Direct	Varying
Installation material	Direct	Varying
Information		
More information can be acquired	Indirect	Fixed
Interoperability		
Interoperability between the different controllers (PLC)	Direct	Fixed

3. Results

The installation and the initial investment costs are divided into several parts according to Table 1. In this study, the VSD and PLC used were from the Siemens brand. The selection of this brand is based on consideration of familiarity and also the population of this brand in the existing factories. It is to reduce the number of spare parts needed and also to make interconnection with the existing system easier. It is also worth mentioning that the calculation of investment and installation costs is carried out based on estimated prices. The data is taken from the historical data held from previous vendor offers. The cost calculation of each part according to Table 3 is as follows.

Main equipment

The main equipment used in the cost calculation is shown in Table 3. In installations using Profinet, only the PLC communication module and VSD communication module are needed. As the PLC communication module is included in the CPU, so this component is considered as freely obtained in the cost component.

While in installations using hardwired, the input and output modules of the PLC are calculated based on the number of control parameters needed. The number of control parameters used as a reference is as follows:

- Three digital input signals (for remote operation status, running status, fault status)
- One digital output signal (for start and stop commands)
- One analog input signal (for current speed status)
- One analog output signal (for speed set point value).

Apart from PLC input and output modules, several other pieces of equipment are also needed and the amount is adjusted according to the number of existing VSDs. From the main equipment list below, the total cost of equipment using Profinet is IDR 112,500,000.00 while using hardwired is IDR 177,520,000.00. So the cost difference of main equipment between Profinet and hardwired is IDR 65,020,000.00.

Table 3. The list of main equipment

Equipment	Quantity	Unit	Unit quantity formula
Profinet			
PLC Communication Module	1	Unit	Equal to the number of CPUs in the system
VSD Communication Module	25	Unit	Equal to the number of VSDs in the system
Hardwired			
Digital input module (32-channel)	3	Unit	$\frac{(Number\ of\ VSD\ *\ 3)}{32}$
Digital output module (32-channel)	1	Unit	$\frac{Number\ of\ VSD}{32}$
Analog input module (8-channel)	4	Unit	$\frac{Number\ of\ VSD}{8}$
Analog output module (8-channel)	4	Unit	$\frac{Number\ of\ VSD}{8}$
Digital output interfacing relay	32	Unit	Equal to the number of digital output channel
Terminal block	160	Unit	Equal to the total number of PLC input/output channel
VSD input/output module	25	Unit	Equal to the number of VSDs in the system

Supporting Equipment

Supporting equipment is the equipment used to support the installation. The supporting equipment required for the installation is usually very dependent on the design of the system. For example, to install using Profinet, an Ethernet switch hub is needed as a bridge to form the network topology. As the number of channels required for the ethernet switch hub, is very dependent on the topology used, and also the number of VSDs in the system. And so these kinds of equipment are considered supporting equipment in this paper. Again, the supporting equipment used in each project may vary, depending on how large the system is built, the topology used, and the control method chosen. Table 4 shows the supporting equipment in the installation using Profinet and Hardwired.

Table 4. The list of supporting equipment

Equipment	Quantity	Unit	Unit Quantity Formula
Profinet			
Relay	25	Unit	Equal to the number of VSDs in the system
16-ch Ethernet switch hub	1	Unit	As per system architecture Figure 6
Profinet communication cable (shielded twisted pair / STP CAT 6)	50	Meter	As per system architecture Figure 6
Industrial RJ45 connector	50	Unit	Two units for each VSD
Hardwired			
Relay interface	150	Unit	As per the control schematic diagram
Terminal block	300	Unit	Equal to the number of control parameters required

From the supporting equipment list above, the equipment cost of using Profinet is IDR 14,500,000.00, while using hardwired is IDR 14,400,000.00. So the cost difference between supporting equipment using Profinet and hardwired is IDR 100,000.00, whereas the cost of Profinet supporting equipment is more expensive than hardwired.

Installation material

The PLC and VSD modules are located on two different panels, so a control cable is needed to connect the two. The distance between the PLC panel and the VSD panel is about 25 meters. Using the Profinet, the only control cable required is an Ethernet cable to connect between the two pieces of equipment, the PLC's CPU, and also the ethernet switch hub within the VSD's panel which all the VSDs are connected to. While in installations using hardwired, each control parameter of each VSD must be connected using separate cables between one parameter and another. Table 5 shows the installation materials using Profinet and Hardwired. From the installation material listed below, the cost of using Profinet is IDR 1,365,000.00, while using hardwired is IDR 38,155,000.00. So the cost difference between installation material using Profinet and hardwired is IDR 36,790,000.00.

Table 5. The list of installation material

Equipment		Quantity	Unit	Unit Quantity Formula
Profinet				
	Profinet communication cable (STP CAT 6)	25	Meter	One connection from the PLC's panel to VSD's panel
	Industrial RJ45 connector	2	Unit	One for each end of the communication cable
Hardwired				
	Digital input cables (24x0,75mm^2 unscreened)	125	Meter	Equal to the number of the control parameter
	Digital output cables (24x0,75mm^2 unscreened)	75	Meter	Equal to the number of the control parameter
	Analog input cables (24x0,75mm^2 screened)	75	Meter	Equal to the number of the control parameter
	Analog output cables (24x0,75mm^2 screened)	75	Meter	Equal to the number of the control parameter
	Other installation accessories	1	Lot	As required

Labor cost (Man hours)

Installation time is one of the important components of a project. By using Profinet, the installation time can be finished in no time. It can be shown directly from the amount of installation material used in installations using Profinet compared to using hardwired methods. The length of installation time is calculated based on estimation. The multiple linear regression (MLR) method has been widely used to predict installation time, as in research conducted by (Hur et al., 2015) and also (Ishii et al., 2014). The dependent variable to be estimated is the man-hour required to finish the installation. While the independent variables are the number of cables to be installed, the number of connections to be terminated, and also the distance between the PLC's panel and VSD's panel. The installation time then can be quantified into a cost by multiplying the total installation time by the labor cost per unit of time. From the installation time calculation, the labor costs of using Profinet were IDR 1,153,125.00 while using hardwired was IDR 15,290,625.00. So the cost difference between the labor costs of using Profinet and hardwired is IDR 14,137,500.00. The overall cost comparison of using Profinet and Hardwired is shown in Table 6.

Table 6. Cost comparison between VSD installation using Profinet and hardwired

Cost of	Profinet	Hard-wire	Cost Difference
Main Equipment	Rp 112.500.000,00	Rp 177.520.000,00	Rp 65.020.000,00
Supporting Equipment	Rp 14.500.000,00	Rp 14.400.000,00	Rp 100.000,00
Installation Material	Rp 1.365.000,00	Rp 38.155.000,00	Rp 36.790.000,00
Labor Cost (Man hours)	Rp 1.153.125,00	Rp 15.290.625,00	Rp 14.137.500,00
Total	**Rp 129.518.125,00**	**Rp 245.365.625,00**	**Rp 115.847.500,00**

From the above table, the comparison of the required investment costs is shown. The use of Profinet on the system built proved to be more economically competitive than the hardwired methods.

4. Discussion

As previously explained, the difference in costs from using Profinet compared to hardwired can be considered a benefit. However, beyond the cost issue, there are several additional benefits to be gained from Profinet technology. Some of these benefits include additional information or data and parameters obtained, as well as interoperability between control systems.

The value of an information

Through Profinet technology, various types of data can be exchanged between VSD and PLC. Table 7 shows the data that can be exchanged through the Profinet. Of course, this data can be processed into a new feature that is useful during the operation of production machines. (Dias et al., 2021) at their research proved that an equipment condition-based monitoring feature can be built without any additional sensors. The data obtained through Profinet communication can be processed with a certain algorithm to produce a diagnostic accuracy of up to 90%. As a result, it can reduce the time of unexpected interruptions, and at the same time extend the service life of the machines themselves.

Table 7. Information obtained by using Profinet

Information Description	Information Flow	Comparison to Hardwired method
Control WORD 1 (16-bit of data)	PLC → VSD	1-bit data for start/stop command
Speed set-point (16-bit of data)	PLC → VSD	Using an analog output module
Status WORD 1 (16-bit of data)	VSD → PLC	3-bit data for remote, running, and tripped status
Actual speed value	VSD → PLC	Using an analog input module
Actual current value	VSD → PLC	Not available
Actual torque value	VSD → PLC	Not available
VSD Alarm code (16-bit of data)	VSD → PLC	Not available
VSD Fault code (16-bit of data)	VSD → PLC	Not available

In this term, a piece of information then can be assessed as a commodity, where its value will increase along with the increasing amount of data and information collected at a time (Glazer, 1993). To measure the value of information, three main methods can be used:

- With this information available, the income earned is greater than before this information was available.
- With this information available, the costs incurred are lower than before this information was available.
- The information can be directly traded and generate income directly.

In this case, the second method is more suitable for use as an analysis method. From Table 7 it can also be seen that in installations using hardwired, only a small amount of information can be obtained. If at least one additional piece of information is needed (for example the actual current value data), it will incur additional costs as shown in Table 8.

Table 8. The additional cost of installation for one additional piece of information in the hardwired method

Equipment	Quantity before add. information (unit)	Quantity after add. information (unit)	Cost difference
Analog input module (8-channel)	4 (unit)	7 (unit)	Rp 29.400.000,00
Analog input cables (24x0,75mm2 screened)	75 (meter)	125 (meter)	Rp 6.250.000,00
Other installation accessories	1 (lot)	1 (lot)	Rp 400.000,00
Total			**Rp 36.050.000,00**
Additional cost / VSD			Rp 1.442.000,00

The table above shows that the benefits derived from using Profinet are more than only the lowered investment cost. In addition, the use of Profinet is also proven to provide additional information on the controller device (PLC). It can then be utilized further as an equipment condition-based monitoring system. Although, the value of this feature is yet explicitly shown in this paper.

Interoperability

A VSD device is generally only controlled through one controller device (PLC). But in some cases, a distributed control system may control the same device simultaneously. An example of the frequent application within the essential oil processing factory is when a transfer pump for certain chemicals is used to transfer the material to machine A and machine B. Where machine A and machine B have their respective control devices. Then the control device from machine A and machine B can be connected directly to the transfer pump's VSD, and control the pump directly. With Profinet, any configurations like this can be done without additional installation costs. Configuration can be done through the software, and the function can be used immediately. An example of the architecture of such a system is shown in Figure 7.

Although this control scheme can also be done with the hardwired method, it will require some additional equipment and installation material. It is then will directly increase the cost of installation. Thus with the hardwired method, one VSD is usually only controlled through one control device (PLC). Limiting the flexibility of the production equipment.

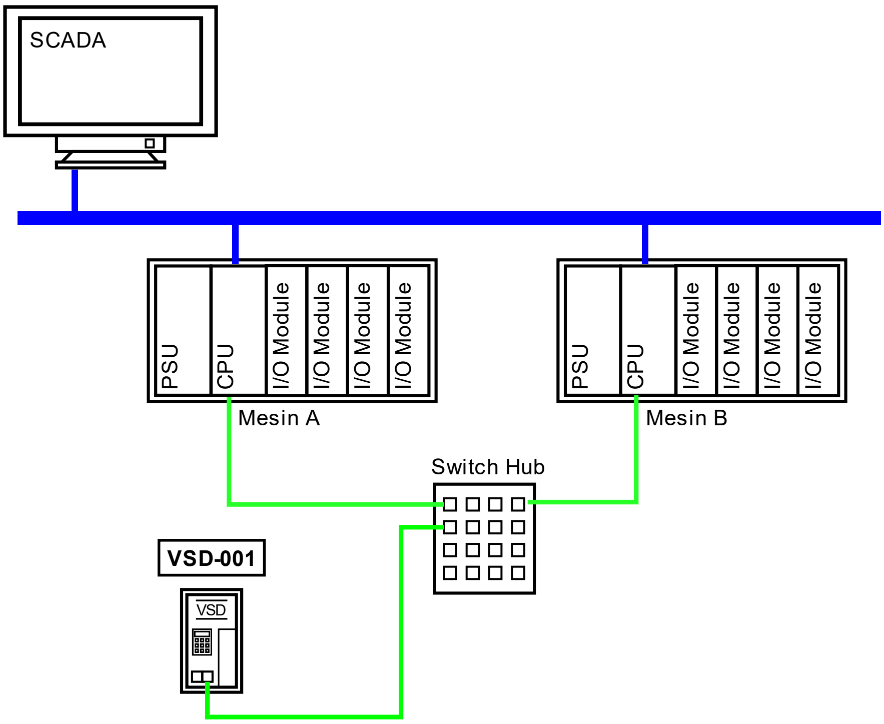

Figure 7. Typical architecture of a system using interoperability feature

5. Conclusion

VSD control through Profinet has proven to have a positive impact from an economic and technical standpoint. Installation costs with Profinet on the system built, provide savings of up to 47% compared to using the hardwired method. It is sufficient to provide confidence in using Profinet technology as a VSD control medium. In addition, Profinet technology also has a positive impact from a technical perspective. More information can be obtained from the use of this technology. This information eventually provides additional value to the system. What's more, the information can then be used as a database in building an equipment condition-based monitoring system. Although, it is not explained directly in this study, building such a system is not an impossible task. Further, the value of this system can be analyzed so that the economic impact of building it can also be shown for the sustainability of this research.

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