INSTALLING VARIABLE SPEED DRIVES: ENERGY EFFICIENCY PROFITS VERSUS POWER QUALITY LOSSES

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INTRODUCTION
Replacing conventional motors by Variable Speed Drives (VSD's) can yield considerable energy savings at some industrial applications (such as pumps or compressors). However, in some cases, these savings are decreased or even entirely eliminated by process outages due to VSD-trippings on voltage dips due to short circuits in the grid. Many industrial companies and even energy efficiency consultants do not know the exact impact of voltage dips when installing a VSD in an industrial process. This paper gives a methodology to integrate poor Power Quality when considering to buy a VSD and provides guidelines on when voltage dips can have a significant impact on the energy efficiency profits. To derive such guidelines, it is taken into account that the shut down of a VSD due to a dip mainly occurs by the tripping of the undervoltage protection on its DC-bus. Next to this, the derived guidelines are validated in a practical case study.

DECISION MAKING PROCESS
To determine whether costs due to the lack of Power Quality outweigh the benefits of energy efficiency profits when installing a VSD, a Total Cost of Ownership (TCO) analysis has to be performed. In this case, the following components are taken into account in the TCO-analysis:
− Purchase and installing cost of the VSD
− Energy costs
− Costs due to the lack of Power Quality
− Maintenance costs. These will not be analysed within this paper.

Furthermore, an appropriate decision making criterion has to be chosen. According to several corporate finance handbooks (e.g., [4]), the Net Present Value is the appropriate criterion and will therefore be applied in this paper.

Taking the installation of a VSD on a centrifugal pump as an example, the next section discusses how to calculate the profits by comparing the power consumption of a conventional motor versus a VSD. Subsequently, the cost of poor power quality is calculated. Finally, the method is validated by a case study of adding a VSD to a compressor.

ENERGY EFFICIENCY PROFITS
To calculate the energy efficiency profits when installing a VSD on a centrifugal pump, three basic parameters have to be known:

− Pump characteristic: head (in m) as a function of flow rate (in m³/h)
− System characteristics: static head and friction head as a function of flow rate
− Flow requirement profile throughout the year

Additionally, the losses of the valve and the VSD can be used to obtain more accurate results.

The energy efficiency profits are calculated in two steps:
1) Calculation of the power saving as a function of the required flow

Figure 1 shows both the pump curve and the system characteristic of a given application. When operated at full capacity, the resulting flow (Q) and head (H) are determined by crossing point A. To calculate the power saving of applying a VSD instead of a throttle valve for a reduced flow is illustrated with Figure 1 where the required flow is reduced from Q₁ to Q₂.

Figure 1 Operating points of pump system

In general, the power consumption of a centrifugal pump can be calculated with:

\[ P_p = c \times \frac{Q \times H}{\eta_p} \quad (1) \]

p used power
Q flow
H head
c constant depending on the gas or fluid
\( \eta_p \) pump efficiency.

It should be mentioned that pump efficiency\( \eta_p \) itself depends on Q. Usually \( \eta_p \) decreases with decreasing values of Q. If the flow is reduced by a throttle valve, the system characteristic
will change as indicated by the dash-dot line in Figure 1 and B will be the new operating point. Reducing the flow by a VSD changes the pump characteristic as indicated by the dotted line in Figure 1 after which C is new operating point. The power saving of using the VSD consists of two parts. Firstly, there is a power saving due to prevention of losses at the throttle valve, which can be calculated by the surface of the striped area in Figure 1. Secondly there can be a power saving by operating the pump at higher efficiency. This saving can only be calculated knowing the efficiency at the different operating points of the pump. The power saving of the use of a VSD at all flows can be obtained by extrapolating the above-described methodology at all flows. This results in a typical picture as shown in Figure 2.

![Figure 2 Power gain when using a VSD instead of a mechanical throttle](image)

2) Once the power saving is known at all flow rates, the energy saving can be calculated if the required flow rate profile throughout the year is known. The energy saving is obtained by integrating the power saving over the year as shown in the following equation:

\[
\text{Eg (kWh)} = \int_{t=\text{Jan}}^{\text{Dec31}} P_g(Q_t) \, dt
\]

\[\text{Eg} \quad \text{saved energy} \]
\[P_g(Q_t) \quad \text{saved power at t}\]

**COST OF POOR POWER QUALITY**

The cost of poor Power Quality at an industrial facility when only voltage dips are taken into account, can be calculated by the number of process outages due to dips multiplied by the average cost of a process outage. In this paper, a typical grid structure in Western Europe (Figure 3) is used as an example. In this configuration, the facility containing the sensitive process is directly connected to a Medium Voltage (MV)-substation. The sensitive process is located at Low Voltage (LV), which on its turn is connected to MV by a delta-wye (also called delta-star) transformer. On the same MV-busbar, several other feeders are connected, in which all MV-cables are assumed to be underground cables. In the High Voltage (HV)-substation, one or more Wye-delta transformers connect the HV-busbar to these MV-busbars. The HV-busbar is integrated in the HV-grid by overhead lines.

![Figure 3 Typical Western European grid configuration](image)

Neglecting dips due to starting currents of large loads, dips mainly originate from two sources:

1) Short circuits in the meshed HV-grid. These phenomena, which among others include lightning strikes and trees growing into an overhead line, dominantly cause single phase short circuits.

2) Short circuits in the radial (or open loop) MV-grid. In most areas, the MV-grid consists of underground cables. Examples of phenomena causing dips are contractor digging and spontaneous cable failures. Since the MV-grid is operated in an isolated mode (as shown in Figure 3), only two- and three-phase short circuits lead to a dip. Since three-phase short circuits occur more often than two-phase ones, only this type is discussed.

The next two subsections discuss both of the above origins of voltage dips in detail.

**Single phase short-circuits in the meshed HV-grid**

Single-phase short circuits in the meshed HV-grid result in a two-phase dip in the line-to-line voltages at LV. This can be argued by taking into account the different transformer connections between HV and LV and using a dip propagation scheme such as discussed in [2]. To determine whether or not the VSD will trip on a pre-defined two-phase dip, the cause for drive tripping has to be analysed in detail. Tripping of a drive due to a dip is mainly initiated by an undervoltage protection on its DC-bus (Figure 4).
This protection initiates tripping of the drive whenever the voltage of the DC-bus crosses a pre-defined level. This level is set by the drive manufacturer and can be expressed as a percentage of the rated voltage at the DC bus. Typical values of the voltage decrease at which the drive trips vary between –10 and –30%. Figure 5 shows both the course of the DC-voltage during a two-phase voltage dip and the minimum voltage level of the DC-bus (\(U_{DC,min}\)).

Whether or not the DC-bus voltage reaches the level \(U_{DC,min}\) at which the drive will trip, depends on the decrease of the voltage between two sinuses where the capacitor is charged (e.g. between \(t_1\) and \(t_2\) in Figure 5). Assuming the torque demand and frequency to remain constant during the dip, this decrease can be calculated by an energy balance between \(t_1\) and \(t_2\):

\[
E_C = E_L
\]

(3)

\(E_C\) energy taken from in the DC bus capacitance
\(E_L\) load energy demand

The DC bus voltage \(U_{DC}\) at the end of the dip \(t_2\) can be calculated by:

\[
\frac{C}{2} [U_{DC}^2(t_2) - U_{DC}^2(t_1)] = \int_{t_1}^{t_2} \omega_L P_L dt = \int_{t_1}^{t_2} P_L dt
\]

(4)

\(C\) DC bus capacity
\(P_L\) Power demand
\(T_L\) Torque
\(\omega_L\) Frequency

Assuming the power demand \((P_L)\) to remain constant and the level of the minimum voltage protection is known, the time after which the DC-bus voltage crosses the minimum voltage level can be calculated with the following formula:

\[
t_{trip} = \frac{C}{2P_{Load}} [U_{DC,rated}^2 - U_{DC,min}^2]
\]

(5)

(Note that the initial assumptions of constant load torque and speed lead to a pessimistic evaluation of \(t_{trip}\)).

The drive trips if the actual duration between two charging periods of the capacitor \((= t_2 - t_1)\) is longer than the calculated \(t_{trip}\). In Figure 5 for example, \((t_2 - t_1)\) has a shorter duration than \(t_{trip}\) and consequently the drive will not trip. For a better understanding, a short quantitative example is given, in which following typical values are considered:

\(C=100\mu F/kW\), \(U_{DC,rated}=565\)V and \(U_{DC,min}=0.8U_{DC,rated}=450\)V and the load is operated at rated power. Using (5), \(t_{trip}\) is calculated to be 5.8 ms. It can also be calculated that \(t_2 - t_1 = 7.95\)ms, which can be goniometrically determined from Figure 5, when knowing that \(U_{DC,min}=0.8U_{DC,rated}\). In this case, the drive would trip on a two-phase dip having a decrease of 20% or more.

However, if the load would only be operated at half of the rated power, both the factor \(C/2P_{load}\) and \(t_{trip}\) doubles. This would result in a \(t_{trip}\) of 11.6 ms. Since this duration is longer than \(t_1 - t_2\), the drive would not trip.

### Three phase short circuits in the MV grid

Three phase short circuits in the MV grid cause a three-phase short circuit with the same magnitude at LV. During such event, the DC-bus is not charged every period. This means, that the energy in the capacitor should supply the power to the load during the entire incident.

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**FOOD SECTOR EXAMPLE**

This section provides a TCO-analysis of adding a VSD to a compressor of a refrigerator within a French fries production line (the methodology for calculations of savings is similar for compressors and pumps).

**Process outline**

Figure 7 shows the different steps in the process of making frozen French fries from raw potatoes. It should be analysed...
whether adding a VSD to the compressor within the freezer would be techno-economically interesting. At the moment, the flow is regulated by a throttle valve.

Washing and steaming
Brushing to remove skin
Cutting
Pre-backing
Freezing
Packaging and transport

Figure 7 Outline of the analyzed production process

The following information is required to calculate the retrofit:
- The motor power is 75 kW.
- The required flow is equally spread between 5% and 80% of the maximum flow during the entire year.
- If the freezer would halt for any reason (such as a voltage dip), a complete reset of 5 minutes should be executed. Meanwhile, the fries in the pre-backing oven preceding the freezer cannot go into the freezer and should be considered lost. Together with the cost for refilling the oven with new oil, such an event costs €2 500.
- Electricity rates are € 80 per MWh
- Investments are considered with the method of NPV, a project lifetime of 10a and a discount rate of 10%.

Figure 8 shows the number of expected 2ph and 3ph dips exceeding a certain depth level, which is obtained from previous years. Note that the duration of the dips is not mentioned, since this has no added value in the predicted outage behaviour of VSD’s. However, it could impact the outage behaviour of the compressor without VSD. In this paper it is assumed, that compressors without VSD’s are not vulnerable to dips.

Looking at the number of times at which the voltage drops with a minimum percentage of 10% or 30% (in literature, e.g. [6] often called the SARFI_{90} and SARFI_{70} value) it can be concluded that these are typical values in Europe or the US.

VSD-characteristics

The installation of a VSD of 75 kW with following characteristics is analysed:
- DC-bus capacity : 4 mF
- Cost of VSD: € 10 000 (incl. installation)
- The setting of the minimum voltage protection is – 20%

Energy efficiency profits

If the required flow-profile is taken into account as discussed previously, the total annual energy saving is 141 660 kWh, which equals an annual profit of €11 333.

Losses due to lack of Power Quality

The VSD trips for 3ph voltage dips having a depth exceeding 20%. From Figure 8, it can be read that this occurs in average 2.8 times annually. The VSD will also trip for 2ph dips for which \( t_{\text{trip}} \) is lower than 7.95 ms in (5). Calculating \( P_{\text{load}} \) for these conditions results in 50.9 kW. This means that the VSD will trip for all dips with a depth exceeding 20% during which the load is equal or larger than 50.9 kW. A 2 ph dip having a depth exceeding 20% occurs 3.5 times annually. From the load profile (equally spread between 5% and 80% of the maximum flow during the entire year) it can be calculated that 16.2% of the time the load exceeds 50.9 kW. In average the drive will trip 0.6 times due to two-phase dips at LV. The total annual number of process outages amounts to 3.4.
TCO-analysis

If both inflation and tax influence are neglected, (6) and Figure 10 show the NPV calculation when installing a VSD.

\[
\text{NPV} = -C_0 + \sum_{n=1}^{n_{\text{end}}} \left( C_a - f_n C_{\text{dip}} \right) \frac{1}{(1+r)^n}
\]

- \( C_0 \): Purchase cost VSD
- \( f_n \): number of dips causing process outages in year \( n \)
- \( C_a \): annual energy efficiency profit
- \( C_{\text{dip}} \): outage cost per dip
- \( f_n C_{\text{dip}} \): annual outage cost
- \( r \): discount rate
- \( n_{\text{end}} \): project duration

An alternative to installing a conventional VSD is to install a VSD with an active rectifier (also called Active Front End or AFE) instead of a diode rectifier. This active rectifier causes an additional investment, but protects against voltage dips with a certain maximum magnitude [1] [5]. The cost of a 75 kW VSD with AFE providing protection to dips of 50% is in the range of €20 000. The number of remaining process outages due to dips is 2.6 as can be read from Figure 8. In this case, the NPV is +€9600, which means that this project yields more benefit than installing a VSD with diode rectifiers.

CONCLUSIONS

This paper has shown how to take into account both energy efficiency and Power Quality aspects when considering to install a VSD. If a typical annual number of outages due to dips as reported by literature in Europe or the US (being in the range of 0-10) is considered, it can be concluded as a general guideline that voltage dips have to be considered if process outage costs exceed 5% of the annual savings due to energy efficiency.

REFERENCES