Adjustable Speed Drives and Power Quality

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Abstract. The aim of this article is to increase the understanding of the problems arising when using ASD in relation to its environment. To accomplish this, a description of the ASD hardware and the electrical environment will be made, analysing the most sensitive elements. After critical points have been identified, mitigation equipment to increase the system immunity will be discussed.

Keywords

Power Quality, Adjustable Speed Drive, Voltage Dips, Short Interruption

1. Introduction

The utilization of Adjustable Speed Drives (ASD) has increased very quickly in the last years. In industry ASD now control directly the speed of induction motor, with precision up to 1% or more depending on the control system, taking the place of mechanical systems that previously controlled the drive speed. In offices and at home they control the motors of heating, ventilation and refrigeration systems and some home appliances as washing machines. Thus more flexible and improved control on the process is achieved and also the efficiency is increased. On the other hand ASD are more sensitive to their environment than older mechanical systems. The relationship between ASD and their environment is in the two ways: on one side the use of ASD carries some adverse effects on the environment as harmonics, dielectric break down, premature bearing failure, vibration, noise… On the other side there are the effects of the environment on the ASD that usually result in a malfunction or a process shutdown. These are the electrical disturbances of the public power supply system. Lack of customer knowledge about the number and kind of disturbances that can be expected leads to a bad specification of immunity of the new equipment. A good definition of the electrical environment where the ASD will be installed will allow the specification of immunity goals against disturbances adding, if necessary, mitigation equipment.

2. ASD Structure

An adjustable speed drive is an equipment designed to control the speed of an induction motor, generating sinusoidal voltages and currents with the necessary frequency and magnitude. The common ASD structure for medium and low power equipments is an indirect converter. This device first converts the power supply ac voltage, of fixed magnitude and frequency, into dc voltage by a rectifier. This dc voltage is then converted by the inverter in three-phase adjustable ac voltage with adjustable frequency and magnitude. Insulated Gate Bipolar Transistors (IGBT) are the power switches most used in the inverter. IGBT allow high switching frequencies resulting in a high dynamic control of the current, which is not possible with lower switching frequencies. In the control system, totally digital control, realized by high performance Digital Signal Processors (DSP), has replaced the previous analog control systems.
To analyse the sensitive elements an ASD will be divided in four main sections (Figure 1):

- AC/DC Rectifier
- DC link and precharge circuit
- DC/AC Inverter
- Control system

The different methods applied in each of these sections by the manufacturers of ASD, affect the susceptibility of the converter in relation to its electrical environment, its performance and also its cost, although the most expensive is not necessarily the least susceptible.

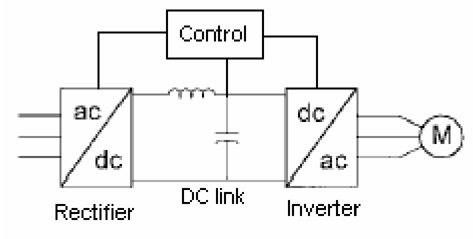

Figure 1- Basic sections of an ASD

A. AC/DC Rectifier

The rectifier converts the power supply ac voltage into dc voltage with a certain ripple. The power supply can be single-phase or three-phase, although the latter is preferred in applications over 1KW.
Non-controlled rectifier (Figure 2a) is formed by a six diode bridge in three-phase applications. It is the most commonly used, due to its simplicity and low cost since no additional control is needed. It is an important source of line current distortion thus an attenuation filter is necessary in medium power devices. This rectifier works only in the first quadrant so power flows only from the supply line to the motor. Therefore energy delivered by the motor must be dissipated in the DC link, typically by means of a resistor. Rectified dc voltage has mean voltage slightly less than peak voltage line ($1.42 \cdot V_{line, RMS}$), due to voltage drops in the power switches, and ripple frequency of 300Hz. It is to be noted that the mean voltage only depends on the line voltage.
Semicontrolled rectifiers and totally controlled rectifiers are also used in ASD. The former (Fig 2b) provides a DC voltage output ranging from 0 to the maximum value ($1.42 \cdot V_{line, RMS}$) but also works only in the first quadrant, so regenerative braking is not possible. It's used typically to control the charging current of the dc bus capacitors until maximum voltage is reached and works as a non-controlled rectifier after. The latter (Figure 2c) is capable of controlling DC voltage output from $-1.42 \cdot V_{line, RMS}$ to $+1.42 \cdot V_{line, RMS}$ though current flows only from power supply to converter. Its use is generally restricted to current source inverters where it is possible to change the output voltage sign to make a regenerative braking. On the other hand it increases reactive power consumption and current harmonics mainly for low output dc voltage.

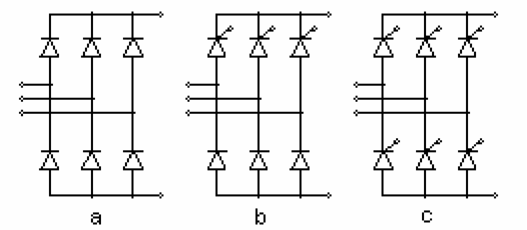

Figure 2- AC/DC Rectifiers

B. DC Link and Precharge Circuit

The DC link is commonly called DC Bus. It has two main objectives: filtering the rectifier output with ripple, to provide a smoother voltage or current, and acting as an energy reserve, to supply the inverter when the power supply fails. ASD immunity against disturbances depends therefore on the energy stored in this circuit and the energy demanded by the load.
Generally ASD can be divided in current source inverter (CSI) and voltage source inverter (VSI). The first has an inductor in the DC link providing a smoother current whereas the latter filters the voltage output by means of paralleled capacitors. In low and medium power ranges the most commonly used is the voltage source inverter ASD with a non-controlled or semicontrolled rectifier. The DC Bus of this ASD is formed by big electrolytic capacitors in series, to increase the maximum voltage permissible, and in parallel to increase the energy stored. An inductor is sometimes present in the bus forming a LC filter, to reduce the harmonic distortion of the input current. The capacitance on the DC Bus varies from 75 to 360uF/kW according to the manufacturer [3]. When an electrical disturbance reduces power line voltage under its nominal value, the rectifier doesn't conduct so the inverter is supplied by the capacitors connected on the DC Bus. Problems will appear if this voltage drops seriously. Since many inverter controls assume a constant dc voltage in their calculations to obtain the magnitude voltage output, a significant drop will cause an error in the output voltage desired. Therefore ASD performance will be very different whether DC Bus voltage is sensed or not. On the other side, all ASD have a built-in undervoltage protection. It disconnects the inverter when the dc voltage decreases below a security level, about 85% commonly. This protects the power switches of the rectifier from overcurrents when the supply line voltage recovers. Thus the immunity of the ASD should be increased as the undervoltage security level decreases, but it must be high enough to prevent any damage on the ac voltage recovery.
The DC Bus precharge circuit is very important. In the power on the high charge current of the capacitors, initially discharged, will blow the fuses, or damage the rectifier diodes, if no precaution is taken. All ASD have a built-in precharge circuit that keeps the current limited until the capacitors are charged. There are many methods to limit the input current. When the rectifier is semicontrolled or totally controlled current is limited by slowly increasing the dc bus voltage. In non controlled rectifiers the method employed most often is a resistor in series, generally in the DC Bus, disabled when the nominal dc voltage is reached.

C. Inverter

The inverter converts filtered dc voltage into three-phase ac voltage of adjustable magnitude and frequency, allowing the control of the speed of an induction motor. The structure most used is a six IGBT bridge with two IGBT in each branch switching complementarily to avoid short circuits. Two basic switching strategies are used to control the voltage output:

- Six pulse inverter: the IGBT of each branch conduct during 180º each one, and the branches closes sequentially every 120º, producing a six pulse voltage waveform at the desired frequency. This inverter can not control the ac voltage output magnitude thus DC Bus voltage must be controlled using either a controlled rectifier or a chopper.

- PWM inverter: allows an adjustable magnitude and frequency output voltage with a constant dc link. In this case the switching frequency, constant, is higher than the output ac voltage frequency, adjustable. There are two main techniques to calculate the pulse width each period. In the direct sine PWM the pulse width is modulated comparing a sinusoidal voltage reference, of desired magnitude and frequency, with a high frequency carrier waveform. The second technique is the Space Vector PWM and it the most used nowadays thanks to the high performance of DSP. It is based in a special switching scheme for the power switches depending on the output voltage vector desired, resulting in sinusoidal currents in the stator phases of the motor. Generates less harmonic distortion and uses more efficiently the DC Bus voltage than the direct sine technique.
  For both techniques the power devices of the inverter must switch at high frequencies. This causes higher losses and more complexity of the control circuits of the power devices. On the other hand high frequency harmonics generated are easier to eliminate, less harmful to motor torque and a low-cost non controlled rectifier can be used.

The PWM voltage source inverter is employed most often in low and medium power ASD. Power devices are IGBT which allows switching frequencies up to 20kHz though limited in maximum power up to 1700V and 400A approximately. To work in the four quadrants a power diode is connected in antiparallel with each IGBT. Thus energy returned by the motor, when braking or acting as a generator, flows to the DC Bus. The driver is the device that transforms control signals from the DSP into the voltage and current levels necessary to control the IGBT. Moreover most drivers feature IGBT overcurrent and undervoltage protection.

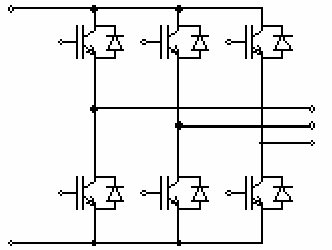

Figure 3- IGBT Inverter

D. Control System

ASD control system is made of one or more circuit boards and performs four main functions:

- Digital speed control
- Voltage conditioning of feedback variables, typically, the current, DC Bus voltage, position or speed and temperature.
- Control and protection of power devices
- Communication

It is important to note the significant changes the control system has seen in the recent years. In the first place, the advances in building and designing technologies of circuit board in addition to the superficial mounting technique, lead to an important size reduction. In the second place the “revolution” in the microcontrollers field as a whole and particularly the arrival of DSP (Digital Signal Processor) in industrial control applications, leads to a totally digital control: from signal treatment and filtering to the ac actual sophisticated control techniques without forgetting the traditional PID regulators. Analog electronics have been practically relegated to signal conditioning of feedback variables to admissible voltage levels for the analog to digital converter integrated in the DSP. Finally, communications significance has grown very much in the last years and is a field with continuing innovations and changes. ASD connectivity with other field devices, such as PC or programmable logic controllers, and enhanced performance including self-diagnostic abilities are in increasing demands.

3. ASD Environment

The ASD environment is formed by the power supply, the electrical environment, and on the other side by the cable-motor-load system governed by the ASD. This article is focused in the relationship between ASD and its electrical environment where a power quality issue arises in two ways. On one hand power supply disturbances can produce a process interruption. On the other hand ASD itself is a disturbance source.

Power supply system

Consumer concern with power quality has increased in the last years since the use of susceptible equipment has grown and interruptions caused by disturbances imply a high economical cost. A power quality problem is manifested through voltage, current or frequency variations that are not normalized. These disturbances can be generated in the electric utility or in the consumer facility: large motor starting, short-circuits, harmonics produced by electronic equipment… Conducted disturbances include harmonic distortion, due to non-linear loads, interharmonics (harmonics not integer multiples of fundamental frequency, 50Hz), phase-angle jumps, frequency fluctuation, high frequency noise produced by high frequency switching and voltage variation, with variable duration. The last group includes voltage dips (or sags) and short interruptions as slow voltage variations and transient voltage variation, and are the most important concerning ASD.

A. Overvoltage transients

Overvoltage transients are also known as voltage spikes. They are high energy waves characterized by fast rise and decay times (dv/dt), high magnitude added to the fundamental voltage, and duration from nanoseconds to a few milliseconds. They can be generated by lightning, circuit breakers or capacitor switching.

B. Voltage dips

Voltage dips are defined, in EN 50160, as “a sudden reduction of the supply voltage to a value between 90% and 1% of the declared voltage, followed by a recovery after a short period of time. Conventionally the duration of a voltage dip is between 10ms and one minute”. They are caused by large currents typically involved in short-circuits or produced by connection of large loads. Those currents produce large voltage drops through supply system impedances affecting the supply of other consumers.

Voltage dips are characterized by their duration and magnitude, the latter expressed as a percentage of the nominal voltage. Voltage dip severity depends on the network structure of the supply system, radial or interconnected for example, and the observation point. The voltage magnitude of the dip, known as residual voltage, will depend on the number of phases involved, the impedance between the observation point and the source of the short circuit, and on the transformers between the two points. According to the connection of its windings, a single line to ground fault in the primary side can result in a voltage dip on two or three phases in the secondary side. The duration of the dip will depend on the speed of operation of the circuit protections, such as fuses, circuit breakers and differential protections, with a typical clearance time in the range of 100 and 500ms.

In addition phase-angle jump and phase unbalances must be considered. In [3] voltage dips are classified in four types (A to D). This classification is based on the resulting voltage magnitude, unbalances and phase-angle jump produced by single line to ground faults, line to line faults or three-phase faults.

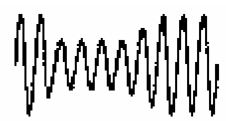

Figure 4– A voltage dip

C. Short Interruptions

When there is short-circuit, circuit protection devices disconnect the faulted circuit from the power supply network. To minimize interruption time these devices apply automatic reclose at pre-set time intervals and, after a number of open-reclose operations pre-set, the faulted circuit is disconnected definitively if the fault has not disappeared. Thus depending on the network structure and the observation point with respect to the point of the short-circuit, some consumers will experience a series of supply interruptions of brief times while others may have to wait for repairs of the supply system. It is considered a short interruption when the duration is up to 1 minute and the residual voltage is below 1% of the nominal voltage.

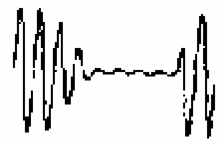

Figure 5– A short interruption

4. Susceptibility of ASD

When power supply voltage is below DC Bus voltage, power flowing to the ASD is interrupted and the DC Bus capacitors will have to supply the load. Therefore, the DC Bus voltage will decrease to a voltage level at which ASD inverter will be disconnected. The dc voltage drop depends on the characteristics of the disturbance, its magnitude, duration, unbalances and phase-jump, on the capacity available at the DC Bus and on the power consumed by the load. If the dc voltage drop is not limited can cause the following problems on the ASD:

- Power switches of the inverter can be damaged if power supplied to the load remains constant, since the voltage decrease will produce a current increase.
- To provide a maximum torque across the speed range, and avoiding motor saturation, the ratio voltage to frequency must remain constant. If a voltage drop is detected, output frequency has to decrease proportionally, and consequently does load speed. In some process this drop in the speed may be unacceptable.
- In many cases, control electronics and IGBT drivers can be powered off, since they are supplied from the DC Bus through a buck DC-DC converter.
- Rectifier power switches can be damaged or the fuses blown, due to charge overcurrents of capacitors on the ac line voltage recovery.

To avoid these problems all ASD have an undervoltage protection that disconnects the inverter when DC Bus voltage drops below a pre-set value. This doesn’t means that the process is stopped in all cases. When nominal ac voltage is recovered, some ASD re-start immediately, others re-start after a certain time, and others only admits a manual re-start operation. Automatic re-start is not necessary in all cases but it is very interesting in those processes where a limited drop in the speed is admitted. In those cases, the problem consists in the synchronization of the inverter output with the actual motor speed, to avoid important electrical and dynamic transients that can damage the equipment. Different solutions are available depending on the drop of speed admissible by the process. Naturally the solution chosen will have an effect on the cost of the equipment. One solution would be to disconnect the inverter for 1 or 2 seconds, to assure that no induced voltage remains in the stator phase, and, after this time, re-starting the motor from zero speed. This solution will suppose no extra cost to the equipment. On the other extreme, voltage transducers can be used to sense the induced voltage in the stator, to generate with the inverter a synchronized voltage. This solution needs more transducers and thus ASD cost will be much higher. Another method, only adding one voltage transducer to monitor DC Bus voltage, consists in using the mechanical energy stored in the load inertia to maintain constant the DC Bus voltage. Thus the rectifier is protected from ac line recovery, since no charge currents will occur, and there is no loss of synchronization between the inverter and the motor speed.

At the same time problems caused by overvoltage transients are more limited. All ASD incorporates overvoltage suppressors, snubbers, or other filters that, with a suitable design, will protect the equipment against these disturbances. If no protection exists, the rectifier will be the most affected: DC Bus voltage will remain practically constant, due to the large capacitors, but a sudden voltage raise on the ac side will produce overcurrents that can blow the fuses, or worse, can cause the destruction of the power switches if the maximum blocking voltage is exceeded.

5. Mitigation

Voltage dips and short interruptions are caused mainly by faults in consumer installations connected to the power supply system. Because they are an unpredictable and a random phenomenon, their frequency of occurrence and probability of occurrence is highly variable depending on the point where the installation is connected, even from one year to another. On the other hand research and surveys have shown that voltage dips and short interruptions can occur in any place, at any moment, and with voltage drops up to zero and durations over 1 second. According to EN 50160 the number of voltage dips that can be expected in one year, as an indicative value, can vary from some tens to a hundred, with a duration below one second and a residual voltage higher than 40% of nominal voltage. However voltage dips with higher duration or less residual voltage can occur. Therefore all equipment connected to the power supply system is subjected to these disturbances.

At the same time, it can be said that these disturbances are intrinsic of the power system supply, so the change is that modern electronic equipment is more susceptible to the electrical environment. As the use of this equipment increases the problem increases too. There are two solutions: improve the power supply or improve the connected equipment. Here is the origin of electromagnetic compatibility (EMC): all equipment must be compatible with the power supply where it is connected. Thus an electromagnetic emission and immunity limits are fixed to electronic equipment to prevent, on one hand, an excessive emission of disturbances and, on the other hand, to provide equipment with a suitable immunity level. IEC 61000 (parts 6-1 and 6-2) specifies that all equipment must ride-through a voltage dip of a residual voltage of 70% for 10ms, and must not be damaged for a voltage dip of a residual voltage of 40% for 100ms.

In many cases, this will be enough since the equipment will be not damaged. But critical process, as continuous process in which a shut-down is not admissible, will need mitigation devices to increase the immunity level of susceptible equipment like ASD. There are many methods to achieve a higher immunity, and the selection of one will depend on the type of disturbance, on the cost of the mitigation device and on the cost caused by the disturbance. The problem of voltage dips and short interruptions is energetic and most of the solutions consist in increase the energy stored. There are also other methods, such as active rectifier and boost converters on the dc side.

A. Methods additional energy storage

The aim is to store enough energy to supply the inverter when the power system doesn't do it due to a disturbance. These methods will be useful for voltage dips and short interruptions. There are several methods of energy storing available nowadays: additional electrolytic capacitors, battery back-up, motor-generator systems with flywheel, uninterruptible power supplies (UPS), super condensers, superconducting magnetic energy storage (SMES) and energy cells. Whereas UPS and motor-generator systems can supply the ASD from ac line, the other systems must be connected directly to the DC Bus. This last group can not be applied in ASD in which the DC Bus is not accessible or the line voltage protection can not be disabled. This protection stops the ASD when three phase voltages are not correct.

The most important parameters that must be considered when choosing an energy storage system are the amount of energy that it has to store, and the volume necessary to do it, whether additional equipment is required, such as battery charging devices, maintenance, recharge time and life time.

B. Boost converter

A DC-DC boost converter is a device that maintains the DC Bus voltage constant. It is connected at the output of the rectifier and before the capacitor filter. The converter can be integrated in the ASD supplied by the manufacturer, or it can be an add-on module in ASD with the accessible DC Bus. In the first case, the rectifier must be sized properly since the current will be doubled when the voltage dip has a depth of 50%. Therefore the maximum depth the ASD can ride-trough with this system is limited. In the second case the ASD needs no modification since the add-on boost converter can be supplied by a different rectifier or even by an energy storage system as those mentioned before.

C. Active rectifier

This device is hardware equivalent to that of the pwm inverter but it performs the inverse function: it converts an ac fixed voltage into a dc adjustable voltage.

Replacing the diode rectifier by an active rectifier has three main advantages. The first is that DC Bus voltage is controlled so it can remain constant in presence of voltage dips and voltage transients. The second is that input current has a sinusoidal waveform, without harmonics and with unitary power factor. Finally this converter works in the four quadrants, thus regenerative braking can be made.
The ability of active rectifiers to ride-through voltage dips at full load will depend on the nominal current of the power switches. In addition, it must be considered that three inductors in series are needed to filter the current input, and that DC Bus voltage is higher than with a diode rectifier, so higher dv/dt are produced.

6. Testing ASD

Negative effects caused by voltage disturbances have been shown and some mitigation methods have been presented. Thus a method to characterize the susceptibility of the ASD against power supply disturbances is necessary. There are some standards establishing test procedures, measuring techniques and methods for evaluateing the test results. The IEC 61000 standard specifies emission measurement methods, sets emission limits, details immunity testing techniques and recommends protection methods either in general or for specific products to achieve the electromagnetic compatibility. Part 4 of that standard deals with tests and measurement techniques related with EMC, and part 4-11 specifically focuses on voltage dips, short interruptions and voltage variations immunity tests. To perform these tests a sag generator is necessary. This equipment should be capable of generating voltage dips with adjustable levels, which may be different for each phase, and adjustable phase shifts. Moreover, the change of voltage can be abrupt at zero crossings of the voltage or at additional angles considered critical by product committees or individual product specifications.
On the other side, IEC-61800 Part 3 is a standard specifically for adjustable speed drives and includes test methods and fixes immunity and emission requirements for this equipment. To perform the test the ASD has to be connected to a motor with the adequate power and the cable connections and grounding specified by the manufacturer. To describe the performance of the ASD subjected to disturbances, three classes, namely A, B and C, are defined. Class A is used when there is no variation in the ASD performance. Class B is used when there is a change in the performance but the equipment auto recovers when the disturbance disappears. Finally class C is used when the disturbance produces a trip and a disconnection of the protection, making a manual recovery necessary. In the case of voltage dips and short interruptions, this standard fixes a class C performance for the ASD. The consumer has to notify the manufacturer if higher immunity is necessary. This can be achieved adding ride-through capabilities or with mitigation devices as has been shown.

7. Conclusions

Adjustable speed drives are devices susceptible to power supply system disturbances as far as operation of the equipment can be interrupted. An ASD is formed by a rectifier, a DC Bus, an inverter and a control system which interfaces with the environment, formed by the power supply system and the motor-load system. A thorough knowledge of each element and its relation with the others is fundamental to integrate successfully an ASD in a critical industrial process. Progress in electronic systems in the recent years has lead to smart equipment of which even its performance against disturbance can be pre-set. In addition there are a great number of devices destined to increase the immunity of ASD, when power quality problems arise. At the same time, with actual monitorization and registering equipment of ac line, it is possible to perform detailed analysis of the electric environment in which the ASD will operate. Using the statistical results obtained, immunization objectives for the ASD can then be made. To achieve an optimal design of the drive, the cost resulting from the process shutdown, originated by the electrical disturbances of the power supply, can be compared to the cost of the mitigation devices required to achieve the specified immunization level.
On the other side, further research could be done on the use of modern ASD, formed by an inverter and an active rectifier, to improve the immunity of the whole process against power supply disturbances. This could be done by delivering the energy accumulated in high inertia loads to other equipments integrated in the process on the ac side, thus compensating for voltage dips.

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