VOLTAGE SAG RIDE THROUGH IMPROVEMENT OF MODERN AC DRIVES: REVIEW OF METHODS AND A CASE STUDY

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ABTRACT

Modern solid-state induction motor drives are highly sensitive to voltage sags. Their nuisance tripping can cause long re-start delays and production losses. Although it is the supply utility's responsibility to maintain a good quality supply system, drives manufacturers also have to take steps to harden the performance so that a drive stays on line as long as possible during a voltage sag provided the resulting performance of the drive can be tolerated. This paper reviews the approaches that can be used to improve the sag behaviour of a drive and presents the results from an experimental study in relation to a modern drive [8].

1. INTRODUCTION

Many industrial processes are now very much dependant on solid-state AC motor variable speed drives (VSD). Their reliable operation demands an AC supply of high quality. While there is an increasing demand on the electricity supply utilities to improve the supply quality, at the equipment level the drives manufacturers and the application engineers also have to take steps to improve the behaviour of a drive system so that it can ride through short periods during which the supply quality is not adequate. A common and most concerning supply quality situation arises during voltage sags in AC supply systems.

Voltage sags

Voltage sags are short duration reductions in the supplied RMS voltage [1]. They are normally classified as a reduction of the RMS voltage to between 0.1pu and 0.9pu, for a time period of less than 60 seconds. A study of unbalanced fault types has shown that there are seven types of voltage sags for three phase systems [1], however discussions in this paper is limited to balanced three phase voltage sags.

Impact of voltage sags on variable speed drives

With correct application design and parameter settings, damage to equipment from voltage sags is minimised, but can lead to the disruption of continuous production processes. This is a result of not being able to adequately control the process during a voltage sag or a nuisance trip of an inverter. When this occurs, it is often a lengthy task to remove all the damaged process material, and then repair or replace process equipment to allow start-up. This is especially evident in thin strip processing (such as mills producing strip steel or paper) and fibre thread processing.

Voltage sags cause a decrease of the DC Bus voltage in the VSD. During very brief sags it may be possible to supply the energy from the DC Bus capacitor. During longer sag periods, the DC Bus voltage will drop to a lower level. If this falls below the DC Bus trip voltage then the inverter will trip.

There are two standard ways in which a VSD can be configured to function in the case of an undervoltage condition as shown in Figure 1. Curve 1 shows the drive tripping and coasting to a stop where manual interaction is required to restart. Curve 2 shows the drive tripping and coasting. The voltage supply then returns to normal and it restarts with auto recovery.

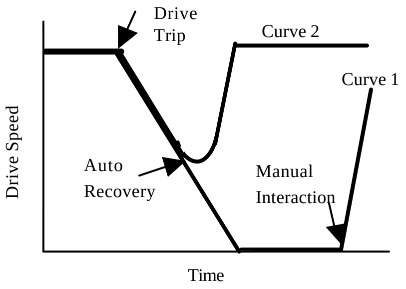

Figure 1 Drive recovery from an under voltage trip.

A voltage sag can cause most of its damage to equipment and circuit protection devices when it is cleared. At this point, large voltage and current transients are present, as the system returns to normal. The DC Bus voltage is low (due to the preceding sag), and once full AC voltage is available, the DC Bus capacitor will draw a large currents as it recharges. Pre-charging circuits to reduce initial current when the VSD is first switched on are normally timed out. This recharging current may even be sufficient to burn out the diodes in the rectifier if the incoming circuit protection does not trip first. There are many different types of mitigation techniques available to control or mitigate the effect of a voltage sag on a VSD. They are based around software control (such as kinetic and magnetising energy recovery), hardware (such as increasing the DC bus capacitor size), or a combination (such as a boost converter). In this paper these techniques will be reviewed briefly.

This paper also gives a detailed review of results from a simulation study of a software based mitigation technique utilising both kinetic and magnetising energy recovery, and a detailed account of the effect of balanced voltage sags on a commercially available VSD.

2. MITIGATION TECHNIQUES

2.1 Software

Kinetic energy recovery

Sisa examines the kinetic ride through ability of drives in his article [2]. Kinetic ride through is the regeneration of power from the energy stored in the rotating mass of the rotor and load, to keep the DC Bus voltage at a predetermined level. This is done as a coordinated sequence, where the drive (or set of drives if they are on the same DC Bus), act regeneratively by reducing speed and transferring the energy back to the DC Bus. Figure 2 shows curves for kinetic energy assisted ride through versus non-ride-through. The drive system with ride-through ability will be able to withstand much deeper and longer sags than the non-ride-through system, at the expense of drive speed.

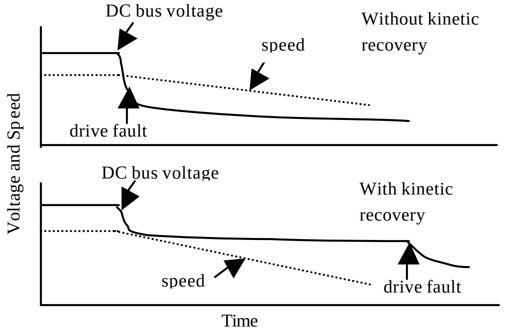

Figure 2 Drives with kinetic ride through versus non ride through during a voltage sag.

It is envisaged that by using kinetic ride-through, a controlled stop can be made, reducing down time created by product breaking during a voltage dip, as caused by an uncontrolled stop. Whilst the product during the kinetic ride through may be of low quality, it will prevent the need to re-thread production machines. If there is a common DC Bus in use, it is possible to regenerate from non essential systems first (ie cooling fans, lubrication pumps), in the hope that the voltage sag will be small enough to prevent the production process motors noticing the dip.

Magnetising energy recovery

It is possible to recover a small amount energy from the stored energy due to the magnetising currents (flux) in the motor. Narayanan [3] describes this type of recovery as forcing the inductance of the motor windings to act as a current source, feeding this stored energy back into the DC Bus. The motor requires flux to act in regenerative mode and hence this type of recovery is normally possible only after kinetic energy recovery. There will be a point where it is inefficient for the system to recover kinetic energy, and the control system should then switch to magnetising energy recovery.

2.2 Hardware

Increasing the DC bus capacitor size

The simplest way to improve a VSD's voltage sag ride through ability is to increase the DC Bus capacitor size. Bollen and Zhang have undertaken studies relating to the size of the DC Bus capacitor [1]. They assume a balanced sag on all phases and that the capacitor will supply the energy for as long as possible. Their studies produced a graph as shown in Figure 3. Modern VSDs typically have between 75 and 360 µF of capacitance per kW of drive rating.

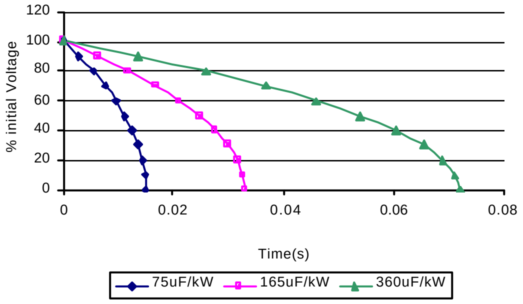

Figure 3 Voltage tolerance of an adjustable-speed drive for different capacitor sizes.

The graph in Figure 3 assumes that the voltage level of the incoming supply has dropped to zero. The vertical axis is the undervoltage setting for the DC Bus trip expressed as a percentage of initial Bus voltage. The horizontal axis is the time to trip. If the AC supply voltage does not drop to zero, the DC Bus will fall to a new voltage along the curve, but then be maintained by the supply. This shows that the larger the capacitance per kW rating, the longer the DC Bus capacitors are able to supply the energy during a voltage sag.

Duran-Gomez, Enjeti and Von Jouanne discuss similar methods to the DC Bus capacitor [4]. They discuss the use of batteries to supply the required power during a voltage sag, but noted that "such rapid deep-cycle electric demands is harmful to the battery". The maintenance cost of such a system would be high in order to have a constantly ready system. This is similar to an

Uninterruptable Power Supply (UPS) of the VSD's supply side, however the cost of such a system for the critical drives in a continuous process would be unacceptable. Super capacitors are the emerging technology ready to take over from the normal capacitor on the DC Bus. Super capacitors are high power density capacitors that can store a large charge, however at the moment they are relatively expensive.

There are drawbacks in the use of extra capacitors on the DC bus. Bulkiness and redesign of pre-charging and discharging are some of the concerns in addition to added costs.

2.3 Hardware and Software combinations. Boost converters.

There are many types of boost converters that have been experimented with, to varying degrees of success. The boost converter circuits that Gomez and Enjeti [5] describe are designed to improve sag ride through performance with minimal cost. In this approach as shown in Figure 4 there is only the addition of a few extra components (4 diodes and an inductor), utilising the VSD's dynamic braking (DB) semiconductor. The main benefit of such an approach is that there are no additional power semiconductors within the main current path, and the additional components are only rated to a small proportion of the inverter.

During a sag the current is drawn from the rectifier circuit and the boost converter circuit. This helps to limit the tripping due to over currents in the rectifier components. When a sag is detected, the control circuit starts to switch the dynamic braking semiconductor. This is at a constant frequency with a varying duty cycle as determined by the feedback from the DC Bus voltage. During the on-period, current builds up in the inductor, and then during the off-period this current flows to the DC Bus.

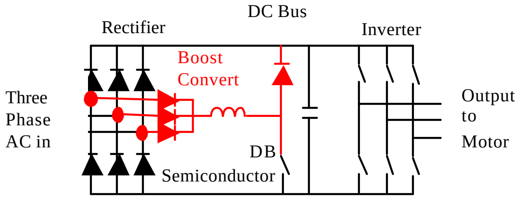

Figure 4 Inverter circuit with a 'Boost Converter circuit'.

The boost converter ride through has the extra advantages that it is easy to add to existing variable speed drive units, and is low in cost compared to other improvement possibilities for sag ride through. However, it does require the use of the dynamic braking semiconductor, and source code modifications.

3. MODELLING OF VECTOR DRIVES, AND SIMULATION RESULTS

To investigate the sag behaviour a vector controlled induction motor drive has been modelled using PSCAD/EMTDC™ [6] version 3.0.3.

Figure 5 shows the function blocks of the system simulated.

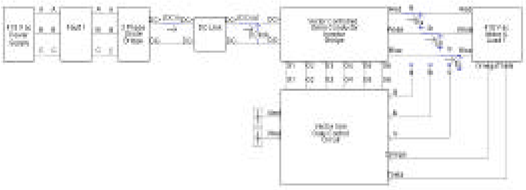

Figure 5 Functional blocks of the vector controlled induction motor drive using PSCAD/EMTDC™.

Simulation results for balanced three phase sags for the drive with no sag mitigation technique in place.

A three phase voltage sag of 0.5 per unit on each phase was applied as shown in Figure 6 (DC Bus voltage, current in and RMS supply voltage) and in Figure 7 (speed, with electrical and load torques).

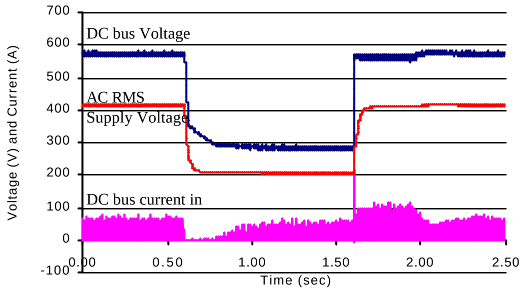

Figure 6 Voltages and currents when all three phases drop to 0.5 pu of normal supply voltage for one second.

The drop in the DC bus voltage level would certainly cause a low DC Bus voltage trip. During the initial drop in the voltage, the diodes in the rectifier circuit are reversed biased, thus the capacitor supplies the current to the inverter and there is no current drawn from the AC supply. As the DC Bus voltage level starts to recover, current is again drawn from the AC supply. When the AC supply voltage returns to 1 per unit at 1.6 seconds, a large current transient occurs as the capacitor recharges and the drive accelerates. Figure 6 shows that this inrush current transient is in the range of 200A. This is sufficient to trip circuit protection devices rated for this application.

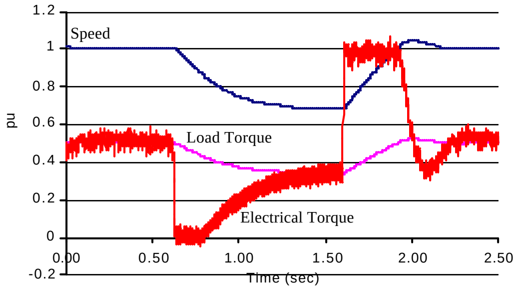

Figure 7 Speed and torques when all three phases drop to 0.5 pu of normal supply voltage for one second.

It is clearly evident that the speed drops off as the DC Bus Voltage drops. During this period the electrical torque supplied by the motor is less than the required load torque. An equilibrium speed is reached where the supply voltage can provide the required power to sustain the motor speed. When the sag is cleared the drive quickly accelerates back to set speed.

Simulation results for the balanced three phase sags for the drive with sag mitigation technique in place.

To allow Narayanan's [3] control mitigation techniques to be tested the simulation circuit was modified. The new simulation circuit used for the sag ride through testing has the DC Bus voltage fed into the vector selection block. This reference voltage is used when kinetic energy recovery is implemented.

This circuit confirmed that it is possible to utilise this technique to keep the DC Bus voltage at a nominal level. As shown in Figure 8 the RMS supply voltage sags to 0.5pu on all three phases at the 2 second point. There is a sudden drop in the DC Bus voltage. However unlike in Figure 6 this drop is controlled and it only drops marginally below the setpoint voltage of 520 Volts, before kinetic regeneration takes place and the setpoint voltage is maintained. This voltage level is maintained until the speed reaches 0.10pu, where magnetising energy recovery is used. At this point the DC Bus voltage begins to fall.

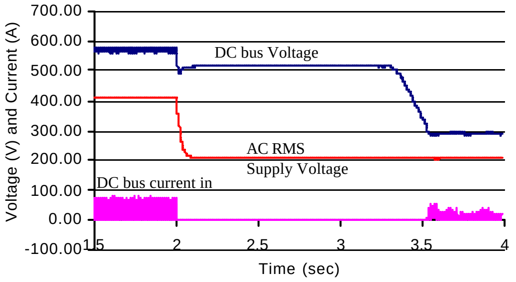

Figure 8 Voltage and current when a three phase sag of 0.5pu is applied with control mitigation in place.

Figure 9 shows additional results of the test above. Comparing this with Figure 7 (where the speed was maintained at a lower value), the speed now continues to falls as regeneration occurs. The electrical torque is driven negative (regenerates) when the mitigation technique is implemented, and as speed is reduced it is driven further negative to maintain the voltage setpoint. Once the speed reaches 0.10pu magnetising energy recovery begins, as observed at approximately 3.4 seconds. The setpoint for the quadrature axis current i_q is given a value of zero, and direct axis current i_d setpoint is controlled to regenerate the required energy. As expected, there is very limited energy stored in the form of magnetising energy compared to the kinetic energy component, and the DC Bus voltage begins to fall.

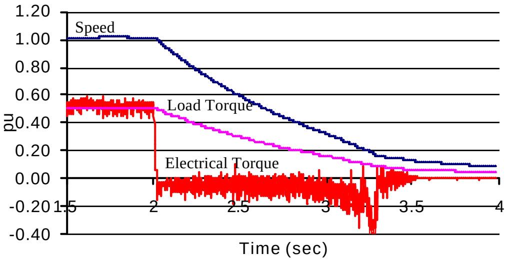

Figure 9 Speed and torques when a three phase sag of 0.5pu is applied with control mitigation in place.

In Figure 9 from 2 to 3.4 seconds the system uses kinetic energy recovery. When magnetising current recovery is enabled the voltage level starts to fall from the setpoint of 520Vat the 3.402 second point. By the 3.424 second point the voltage level has dropped to 510V. For that rate of decay of voltage across the capacitor, it must only be supplying approximately 1A of the required 2.6A (known system current draw). Hence we must be recovering magnetising energy. This magnetising energy recovery only lasts for a few cycles, before all the current required is drawn from the capacitor. At this point the DC Bus voltage begins to decrease at a more rapid rate.

4. BEHAVIOUR OF A COMMERIAL VSD

Description of the test equipment

The voltage sags were produced using the University's 20kVA programmable power quality disturbance generator [7]. This supplied a 7.5kW induction motor connected to a load. The load device was a 10kW DC generator connected to a resistor bank. Only balanced three phase sags were used of which the depth and duration can be conveniently controlled.

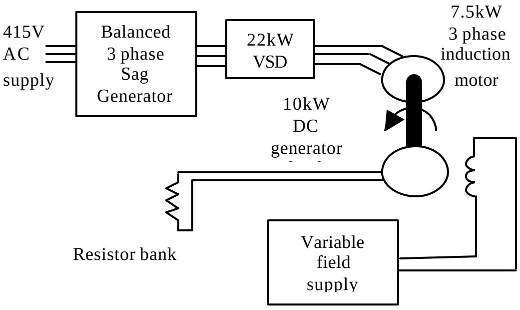

Figure 10 Test setup for voltage sag testing.

To avoid damage to the VSD the low DC bus voltage trip was enabled, thus the inverter will shut itself down when it senses a low voltage on the DC bus. This will help prevent damage as a result of the high transient currents when the sag is cleared. As such, the current transients shown in the simulation would not be observed, and the currents were not recorded.

Behaviour of a commercial VSD results during voltage sags

The test VSD was subjected to voltage sags of varying depths for a duration of 10 seconds per test. This allowed both the immediate and long term effects of the sags to be observed. During this period the motor speed, DC bus voltage, and one phase of the AC voltage waveform were recorded.

These tests were repeated for three different torque loadings.

LOAD 1: A no load test where the only load was the motor and attached generator armature.

LOAD 2: A loaded test with a field current of 0.1A in the field windings of the generator.

LOAD 3: A loaded test with a field current of 0.2A in the field windings of the generator.

The VSD is capable of maintaining set speed for a short period during a voltage sag. As expected, the length and the depth of the voltage sag effect the ride through ability of the drive. A shallow sag can be ridden through for a longer period than a deeper sag. The load inversely affects how long the drive can ride through a voltage sag, (ie the larger the load, the smaller the ride through ability).

Figure 11 shows the natural (without any additional control mitigation) ride through ability of the VSD tested for the test loads. The graph presents the new voltage level during the sag against the ride through period (time that speed remains at approximately 1pu after the voltage sag is applied). The drive is able to ride through a voltage sag provided it remains on the left hand side of the ride through curve. If the length of the sag is sufficient to be on the right hand side of the ride through curve, then the VSD response varies depending on the sag depth.

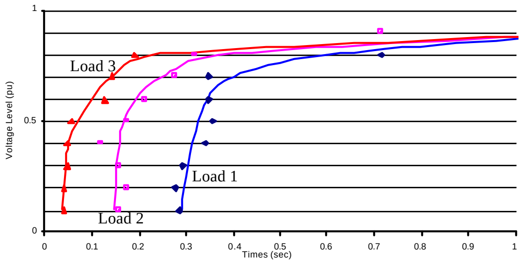

Figure 11 Ride through curves for the test VSD with no additional control mitigation.

For deep sags the VSD typically tripped out, and coasted to a stop. It appears that the VSD utilised regenerative braking to provide power back to the DC bus, but the severity of the sag resulted in the inverter tripping nearly instantaneously. It is interesting to note that the DC bus voltage decreases steeply initially as the drive maintains near set speed. There is a slight increase in the DC Bus voltage as what seems to be minimal regeneration occurs before the drive shuts down, and then coasts to a stop. If the voltage returns to normal after the trip, the inverter requires manual interaction before it will start. Figure 12 is representative of this situation.

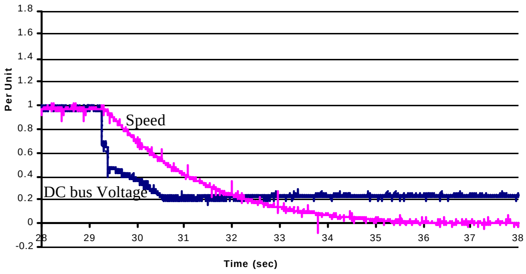

Figure 12 A representative curve of the effects of a large depth voltage sag on the test VSD.

For medium depth sags the VSD typically used regenerative braking to near zero speed, and then accelerated back to an equilibrium speed below the set speed. Similar to the previous case, the DC Bus voltage decreased quickly as the drive tried to approximately maintain the set speed. Regeneration again appears to occur as indicated by the rate of the decrease in speed and the increase in the DC bus voltage. Once the system has regenerated all the energy it can, the DC bus voltage drops again. When the DC bus voltage level has stabilised, the motor then accelerates back to an equilibrium speed. If the voltage level returns to normal the drive will accelerate back to set speed. Figure 13 is representative of this situation.

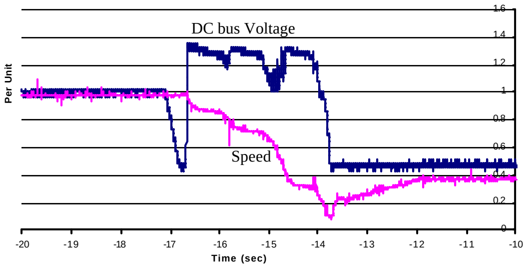

Figure 13 A representative curve of the effects of a medium depth voltage sag on the test VSD.

For shallow sags the VSD typically decelerated to the equilibrium speed from the set speed. During this deceleration, regenerative braking appears to be used and results in large fluctuations in the DC bus voltage level. If the voltage level returns to normal the drive will accelerate back to set speed. Figure 14 is representative of this situation.

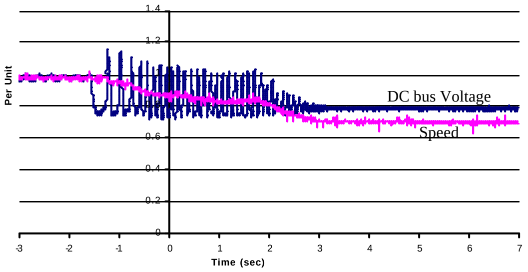

Figure 14 A representative curve of the effects of a small depth voltage sag on the test VSD.

For all loading levels the VSD appears to have regenerative abilities, but the control is very coarse and results in a rapid drop in speed, associated with a rise in the DC Bus voltage.

5. CONCLUSIONS

This paper has given a review of methods for voltage sag ride through mitigation techniques. There is no one mitigation technique that will suit every application, and whilst the power supply utilities strive to supply improved power quality, it is up to the applications engineer to minimise power quality issues, with one or a combination of these.

A vector drive simulation during a balanced three phase sag was provided. This demonstrates the danger of large current transients that may be present in the system when a voltage sag is cleared, highlighting the dangers if appropriate actions are not taken to shut the VSD down or somehow maintain the DC Bus voltage level. The simulation is also used to prove that by using the kinetic and magnetising energy of the system it is possible to maintain the DC bus voltage level. This is a trade-off for speed, which for some applications may be acceptable. Recovery of kinetic energy is seen to be worthwhile whilst the recovery of magnetising energy makes only a marginal improvement.

A case study of how a commercially available VSD reacts with balanced three phase sags of different depths with varying loads has been given. The complex sequence of events following a voltage sag were illustrated. The typical outcome is dependant on the depth of the sag. As such it would be particularly difficult for a VSD manufacturer to produce voltage tolerance trip curves for a VSD with a known load. Of course the type of loads used within industry are widely varied and it would be almost impossible for a manufacturer to produce tolerance curves for every possible load, especially given a range of different power quality issues facing today's applications engineers.

6. REFERENCES

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