Voltage sags in industrial systems

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Abstract

This paper presents results relating to the effect of voltage sags in industrial systems on adjustable speed drives. The influence of the source impedance, dc link capacitor, characteristics of voltage sags and the effect of the utility is computed. The results from the analysis can be used during the design task of the power system protections and in order to improve the susceptibility of the adjustable speed drives (ASD´s) under sags. Simulation and experimental results are provided.

Keywords: sags, PWM drives, effects

1. Industrial distribution system under study

The power system components for voltage sag studies have been modelled and simulated by using a transients program [14]. The simulated power system under study includes the following components:

- Utility transmission impedance
- Distribution transformer
- AC line inductors
- PWM adjustable-speed drive
- Induction motor driven by the ASD
- Vector control system
- Controlled short-circuit connection to establish voltage sag phenomena

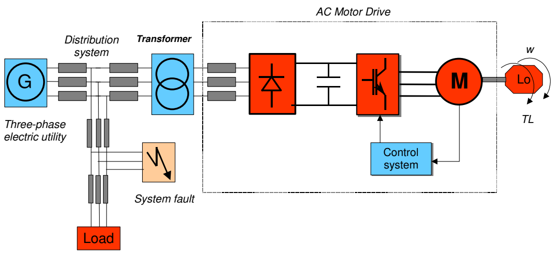

Fig 1. Industrial distribution system

2. Characterization of voltage sags

The recorded results are shown for a sag due to a distribution line fault at 22 kV and propagates down to 400 V system. The monitoring equipment is installed at the low voltage line side of the circuit. The voltage sag is characterized by [1], [2], [3], [4]:

- Voltage waveform record
- Magnitude and duration
- Sequence components of the voltage
- Phase angle shift associated

Both unbalance and phase angle shift are likely to have an important influence on nuisance tripping of equipment.

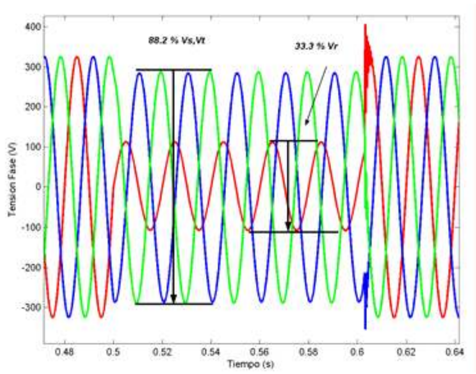

Fig. 2. Voltage waveform.

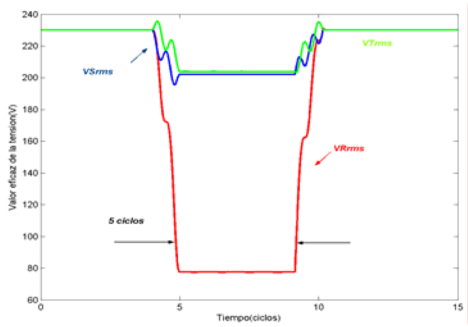

Fig. 3: Magnitude and duration

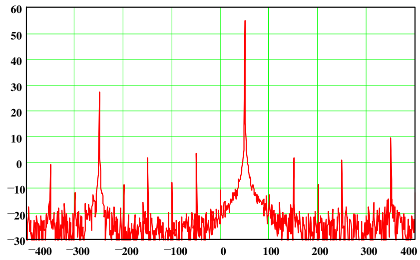

Fig 4. Sequence components of the voltage harmonic spectrum

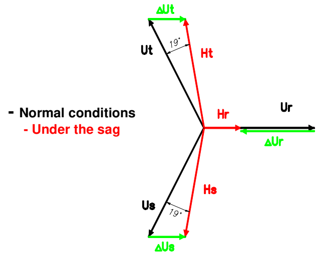

Fig. 5. Three-phase phasor diagram during and before the sag

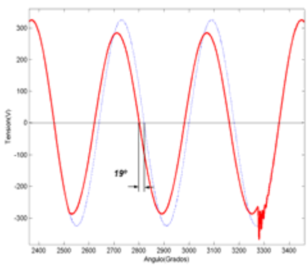

Fig 6. Phase angle between the voltage during the sag and during the normal evolution

3. Voltage sags

Three cases have been studied.

Case A: System under type A sag voltage. The first one is a sag under a three-phase fault. The voltage during the event is equal in the three phases.

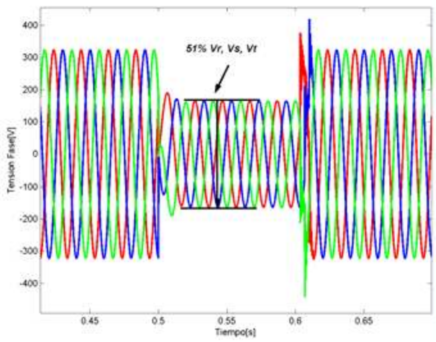

Fig. 7. Phase voltages during a type A sag

Case B: System under type C sag voltage. Sags type C are dips with the main drop between two phases. A subscript identifies the less sagged phase. Hence C_R would be a sag with the main drop between phase S and T.

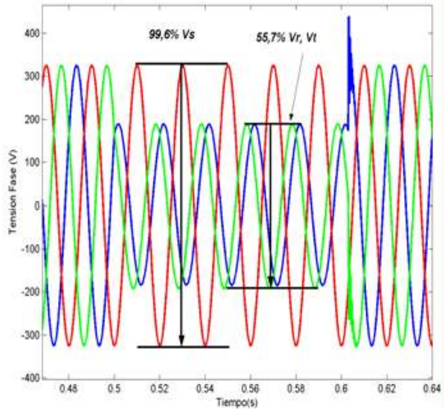

Fig. 8. Waveforms of the phase voltages during a type C_S sag

Case C. System under type D sag voltage. Sags type D are dips with the main drop in one phase. To identify the sagged phase a subscript is added, hence D_R would be a dip with the main drop in phase R.

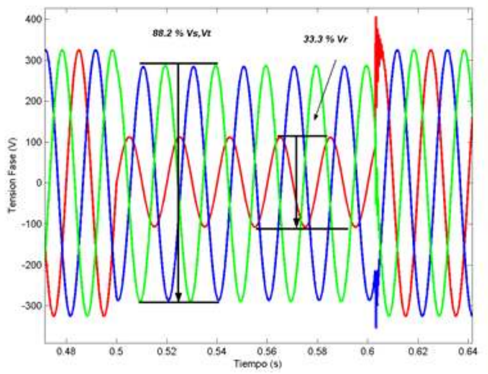

Fig. 9.Phase voltages during a type D_R sag

4. Effect of power system utility

The effect of the transformer and the location of the fault point have been studied [5], [6], [7], [8], [9].

A- Influence of the transformer winding connection

Depending on the winding connections of the transformer the retained voltages seen at secondary side due to an unsymmetrical fault at the primary side may be modified. This means that the dip type may change when going through the transformer.

The transformer between the faulted point and the observation bus is a Dyn transformer. The recorded results are shown for a sag due to a transmission line fault at 22 kV and propagates down to 400 V. In this case the load and the fault point are at different sides of a transformer with delta winding. The positive-sequence impedance-matrix is equal to the negative-sequence.

Case I: Three-phase fault

A three-phase fault causes a balanced sag, type A. There is neither negative nor zero-sequence voltage. The sag is characterised by its phase-retained voltage, which is of positive-sequence.

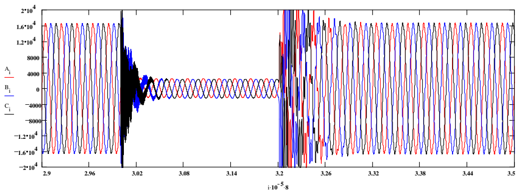

Fig.10.Phase voltages during a type A sag at the 22 kV bus

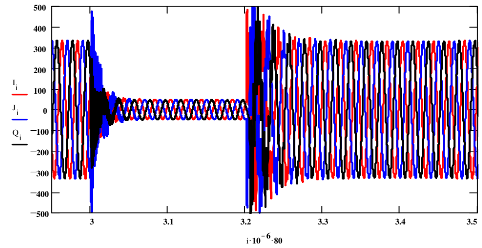

Fig.11.Phase voltages at the 400 V bus. Sag A propagated down from 22 kV bus is an A sag at 400 V

Case II- Phase to phase fault

During this fault, the non-faulted phase does not see any change in the voltage. The change in the voltages of the faulted phases is equal in magnitude but opposite in direction. In the analysed example, the voltage sag is a C sag. A single phase to phase fault involving phase R and S causes a C_T sag.

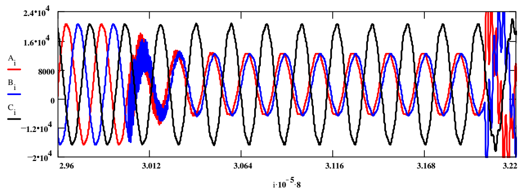

Fig.12.Phase voltages during a type C_T sag at the 22 kV bus

However the Dyn transformer change the character of the unbalanced sag. Sag C_T propagated down from 22 kV bus is a D_R sag at 400 V.

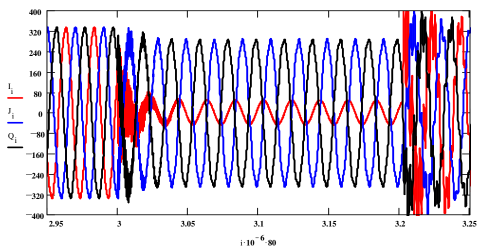

Fig.13.Phase voltages at the 400 V bus.

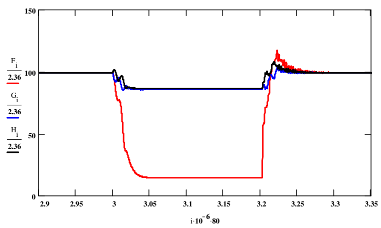

Fig.14 .Shape of the sag in the secondary side

Case III- Single Phase to ground fault

The phase voltages will not contain a zero sequence component because the transfer impedance is null. The non-faulted phases show the same magnitude and direction in their voltage change. These voltage changes are half of the value of the magnitude of the voltage change in the faulted phase.

In this case, the voltage sag is a D_R sag. A single phase to ground fault involving phase R causes a D_R sag. However the Dyn transformer change the character of the unbalanced sag.

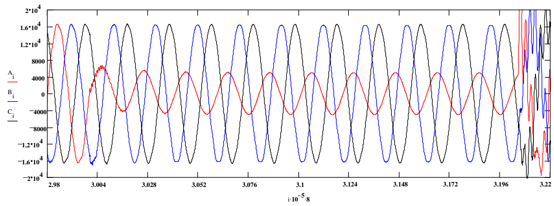

Fig.15.Phase voltages during a type D_R sag at the 22 kV bus

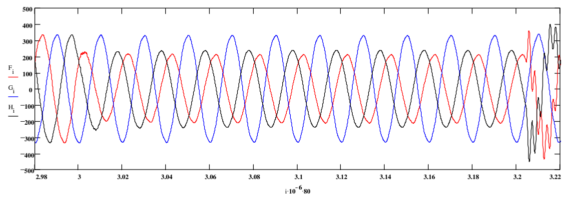

Fig. 16.Phase voltages at the 400 V bus. Sag D_R propagated down from 22 kV bus is a C_S sag at 400 V

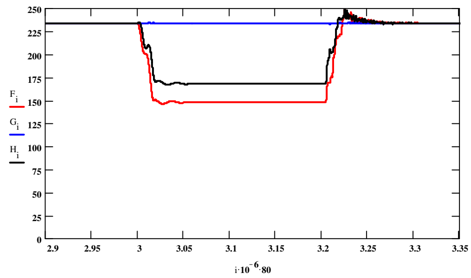

Fig.17.Shape of the sag in the secondary side

5. Effect of voltage sags on adjustable speed drives

The responses of ASDs to voltage sags conditions can significantly affect the industrial processes that use them. The general layout for PWM ASDs has a rectifier, a DC bus and an inverter. During a voltage sag, the response of the electronic ASDs depends on the hardware design, the controller software, and the control system response time.

Voltage sags cause a decrease of the DC bus voltage in the ASD. During very brief sags it may be possible to supply the energy from the DC bus capacitor. During longer sags periods, the DC bus voltage will drop to a lower level. If this falls bellow the DC bus trip voltage then the inverter will trip [10], [11], [12], [13].

Case I- Three-phase sag

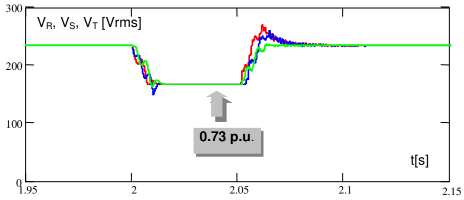

Fig.18.Shape of the sag in the secondary side

At the occurrence of a three-phase or balanced sag, no energy is supplied from the AC-supply into the DC bus because of the reverse biased diode rectifier. All the energy needed to drive the load is taken from the electric energy stored in the DC bus capacitor. As a result, the dc bus voltage starts to decay according the dc bus capacitor, the load torque, the mechanical speed and the inverter and motor efficiency [15], [16], [17], [18], [19].

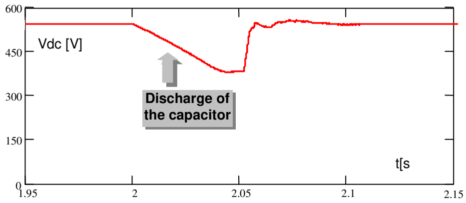

Fig 19. Decrease of the DC bus voltage under sag

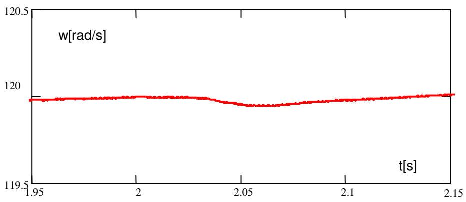

Fig 20. Speed of the motor during the sag event under the effect of the vector control system

If the supply voltage recovers before the dc bus voltage reaches the under-voltage protection level, a high charging current is drawn from the supply.

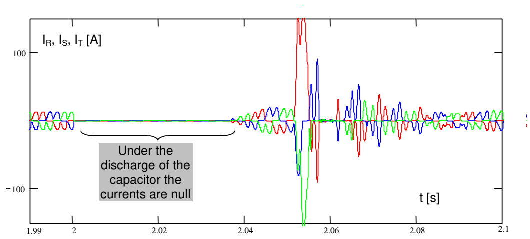

Fig 21. Line currents during the sag event

Case II- Sag due to a phase-to-ground fault

Sag D_R propagated down from 22 kV bus is a C_S sag at 400 V.The dc-link voltage under a voltage sag event is directly dependent on both the output power and the effective inductance (including two source inductance and dc-link inductance).

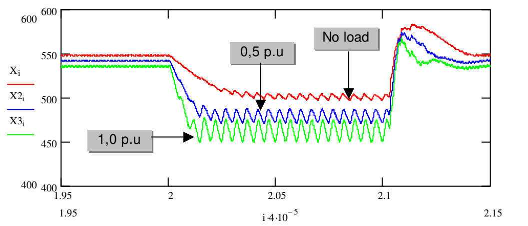

Fig 22. Decrease of the DC bus voltage under different load conditions (1.0 p.u., 0.5 p.u. and no load)

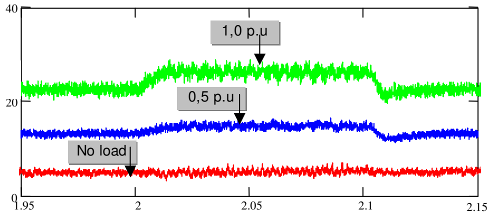

Fig 23. Increase of the DC bus current under different load conditions (1.0 p.u., 0.5 p.u. and no load)

Case II- Sag due to a phase-to-phase fault

Sag C_T propagated down from 22 kV bus is a D_R sag at 400 V. Under these conditions the three-phase rectifier is single phased during the voltage sag event. Since the output power has to be supplied via two phases, this mode increases the rms input current of the ASD during the sag event.

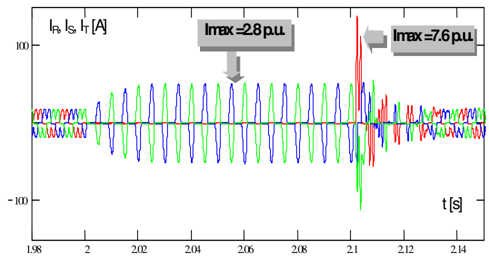

Fig 24. Line currents during the sag event

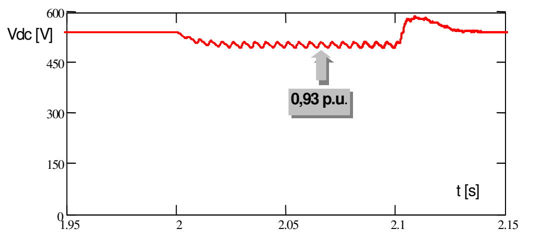

Fig 25. Decrease of the DC bus voltage under sag

6. Commercial ASD during voltage sags

Some experimental analysis were carried out to verify the results obtained by using the transients program. In this section, an experimental analysis is discussed for a commercial available 400 V, 50 Hz, 12 kVA PWM adjustable speed drive. The analysis platform includes 11 kW induction motor, three-phase and programmable supply voltage to produce the voltage sags and electrical brake to permit motor operation under different load levels.

Test A

For this evaluation test the ASD was subjected to D_R voltage sag for a duration of 100 ms ($U_R = 90\angle 0^\circ$, $U_S = 203\angle -101^\circ$, $U_T = 203\angle -100{,}46^\circ$). It is a no load test. During the sag the line currents are null. The rectifier diodes cease to conduct because are reverse biased due to reduction in the phase voltages.

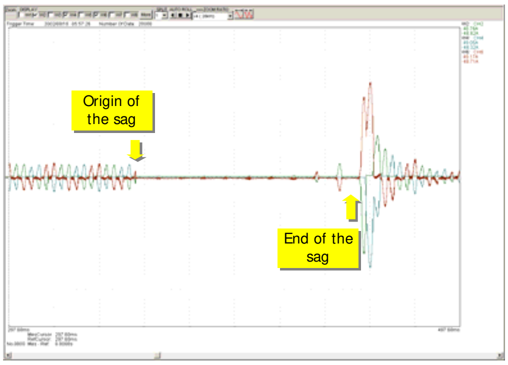

Fig. 26.Waveforms of the supply line currents during the sag

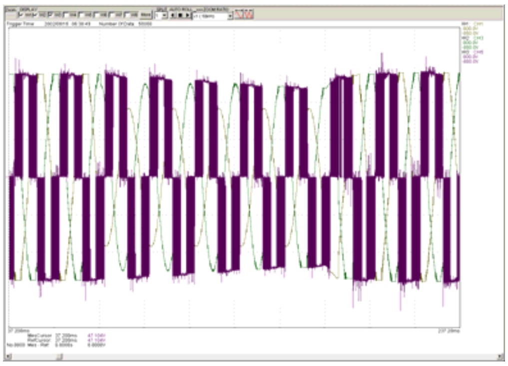

Fig. 27.Motor line voltages and supply line voltages

Test B

The ASD was subjected to D_R voltage sag for a duration of 100 ms ($U_R = 70\angle 0^\circ$, $U_S = 230\angle -101^\circ$, $U_T = 230\angle -100{,}46^\circ$). During the sag, the rectifier is single phased and the line currents are increased. The dc-link voltage reduction under no load and single phase behaviour is slight.

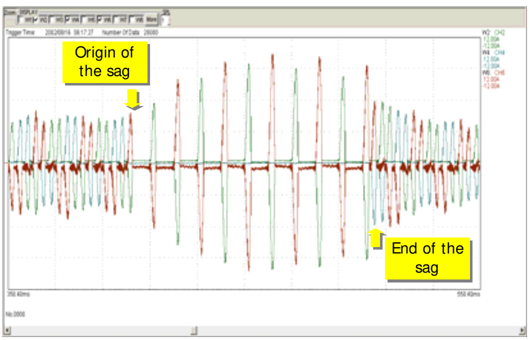

Fig. 28.Waveforms of the supply line currents during the sag

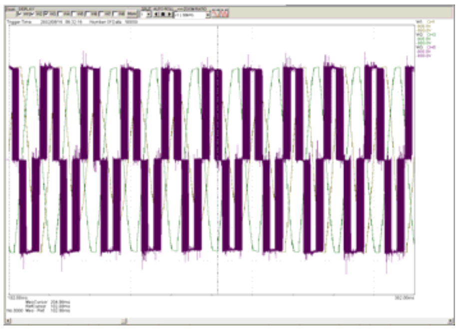

Fig. 29. Motor line voltages and supply line voltages

Test C

In this evaluation test the ASD was subjected to D_R voltage sag for a duration of 100 ms ($U_R = 90\angle 0^\circ$, $U_S = 203\angle -101^\circ$, $U_T = 203\angle -100{,}46^\circ$). Three intervals have been seen. 1)At the occurrence of the sag all the energy needed to drive the load is taken from the electric energy stored in the DC bus capacitor. The line currents are null. 2)When the dc bus voltage reaches the new steady state, the rectifier is single phased and the line currents are increased . 3)If the supply voltage recovers before the dc bus voltage reaches the under-voltage protection level, a high charging current is drawn from the supply.

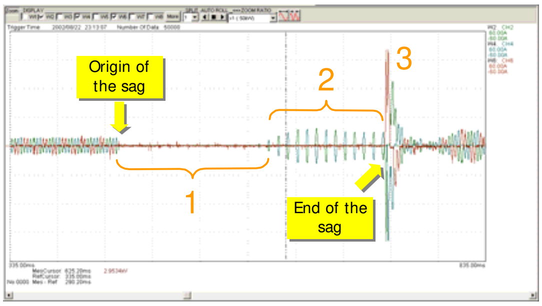

Fig. 30.Waveforms of the supply line currents during the sag

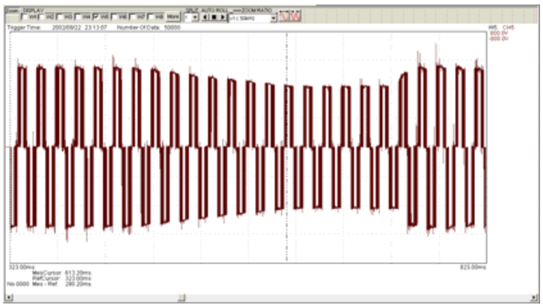

Fig.31 . Motor line voltage

Test D

The ASD is set to trip when the dc voltage drops 0,76 times the nominal value. This evaluation test was conducted to show how the ASD goes to stop as the dc voltage falls bellow the DC bus trip voltage. The response of the ASD can be seen in figure 32.

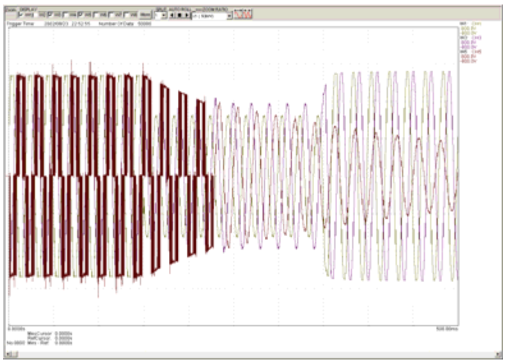

Fig.32.Motor line voltages and supply line voltages

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Conclusions

In this paper, the effect of voltage sag on ASD´s has been evaluated both experimentally and by simulation. The power system components for voltage sag studies have been modelled and simulated by using a transients program. This paper also gives a review of results from the effect of the winding connections of the transformer, the kind of fault, the resulting kind of sag and the load torque on the dc voltage and input current fluctuations. The model and the results can be used during the design task of the mitigation devices and ride-through alternatives.

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