Effects of Voltage Sags on AC Motor Drives

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Abstract - Voltage sags are normally described by magnitude variation and duration. In addition to these quantities, sags are also characterized by unbalance (asymmetry), non-sinusoidal waveshapes, and phase angle shift (phase jump). These factors are important for determining the behavior of ac motor drives during sags. Voltage unbalance and phase angle shifts cause large unbalanced source currents to, excessive voltage ripple in the dc-link, and reduced dc-link average voltage. The response of the motor and drive to these varies considerably. Experimental results clearly show the load-dependent behavior of a typical drive. The ability of the drive to ride-through a voltage sag is dependent upon the energy storage capacity of the dc-link capacitor, the speed and inertia of the load, the power consumed by the load, and the trip point settings of the drive. The control system of the drive has a great impact on the behavior of the drive during the sag and after recovery. The trip point settings of many drives can by field-adjusted and greatly improve many nuisance trips resulting from minor voltage sags.

I. INTRODUCTION

A voltage sag is defined as a momentary decrease (0.5-30 cycles) in rms voltage magnitude, usually caused by a fault in the utility transmission or distribution system or within a customer facility. Voltage sags are the most frequent cause of disrupted operations for many industrial processes, particularly those using modern electronic equipment which are very sensitive to short duration supply voltage variations. To quantify the effect of sensitive equipment to voltage sags, it is necessary to characterize the parameters of voltage sags. Most often, voltage sags are characterized by a duration and depth parameter and are usually represented in a two dimensional rms voltage magnitude versus duration plot. This simplified representation of voltage sag characteristics does not take into account the difference in individual phase voltages (voltage asymmetry or unbalance) and the associated phase angle shift during a voltage sag. Furthermore, it does not take into account the non-sinusoidal nature of the voltage waveform during the sag.

Many sags are caused by a single-line-to-ground fault (SLGF). Double and three-phase symmetrical faults occur relatively infrequently on many systems in the United States (usually less than 20% of the time), but may occur more frequently on other systems. Asymmetrical faults will cause unbalance in voltage magnitude and phase shift from the nominal and among phases. Large motor starting can also cause sags, but these tend to have a balanced effect on all three phases. Depending on the type of equipment and associated control circuit, a voltage sag may lead to mal-operation, tripping, or permanent damage to the load.

AC motor drives are among the most common power electronic-based industrial equipment. The typical ac drive has a three-stage topology: diode rectifier, dc link or bus (filtering), and a PWM inverter as shown in Fig. 1. The drive normally supplies variable frequency ac power to a three-phase induction motor.

![Fig. 1. Typical AC motor drive topology.](image-url)

The ac drive has some energy storage in the dc link capacitor and most use passive diodes on the “front end.” AC drives are often touted as having better ride-through behavior than dc drives due to the energy storage. The ac drive can be made somewhat tolerant to voltage sags, but most drives are rather sensitive. This paper will discuss the effects of voltage sags on ac drives and explore the impact of phase jump and unbalance on the operation of the drive.

II. THE NATURE OF VOLTAGE SAGS: MAGNITUDE AND PHASE JUMP

A majority of faults on a utility system are single-line-to-ground faults. During a SLGF, the voltage on the faulted phase goes to nearly zero volts at the fault location. The corresponding voltage at a customer bus depends on the system configuration, location of the fault, the impedance of the system upstream of the fault, the feeder impedance, the distance of the fault and the transformer connections between the faulted system and customer bus. Obviously, it is
very difficult to predict the voltage that will result at a particular load as the result of a SLGF, but it is clear that the voltage will change.

A. Transformer Connection

Transformer connections have an interesting effect on the ultimate line voltage seen at the load during an asymmetric fault. Most ac motor drives are fed from a three-wire delivery without a neutral. As a result, the input rectifier stage only sees line-to-line voltages. At the fault location, disregarding impedances, a SLGF will yield a voltage of zero on one phase to neutral voltage, but the other two phases are essentially unaffected. However, if a Y-Δ transformer is between the fault and load, then two of the phase voltages on the Δ-side are affected by the SLGF. But, none of the line-to-line voltages go to zero. Therefore, even a zero phase voltage on the Y-side will not result in zero voltage at the drive; instead the drive will see a voltage sag on two of the line voltages. A table of transformer secondary voltages resulting from a SLGF on the primary is shown in Table 1[1]. The lowest voltage at the customer bus will be no lower than 33% of nominal voltage even for a SLGF on the primary of the transformer. Note that this table does not show the phase shift that will often accompany the sag.

<table>
<thead>
<tr>
<th>Transformer Connections</th>
<th>Line-to-line Voltages on the Secondary Side of the Xfmr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( V_{ab} )</td>
</tr>
<tr>
<td>Y-Y</td>
<td>0.58</td>
</tr>
<tr>
<td>Δ-Δ</td>
<td>0.58</td>
</tr>
<tr>
<td>Y-Δ</td>
<td>0.33</td>
</tr>
<tr>
<td>Δ-Y</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Table 1. Effect of transformer connections on rms magnitude during a SLGF [1].

Similarly, a line-to-line fault will cause phase shifting and can cause a zero voltage condition on the secondary of a transformer. Transformer connections and impedance ultimately determine the voltage available at the load bus.

B. Unbalanced sags: magnitude and phase angle jump

A sag is usually defined as a momentary reduction in rms voltage [1,2,3]. A recent publication [4] dealt with the issue of phase-angle shift during voltage sags. One reason that the phase angle jump during voltage sags has been neglected is because this parameter is not quantified in any digital monitoring equipment currently available in the market. Also, the consequences of the phase shift on equipment operation is not well understood.

The origin of phase jumps associated with voltage sags is well explained in [4]. The two main reasons for difference in phase angle of pre-fault and during-fault voltage are the difference in \( X/R \) ratios of the source and the faulted feeder, and the propagation of voltage sags due to single-phase faults through a transformer.

An example of phase shift on the voltages of a three-phase system after a line-to-line fault is shown in Fig. 2. In this figure, a 60° phase shift of the \( b-n \) voltage occurs and the magnitude drops to about 50% of nominal until the fuse clears the fault a few cycles later. The rms plot, using a conventional one-cycle moving window, shows the magnitude variation.

It is significant to note that the line voltage \( V_{bc} \) is zero during the event, \( V_{ab} \) is unaffected, \( V_{ba} = V_{ca} \), and \( V_{ab} = -V_{bc} \). Voltages \( V_{bn}, V_{cn}, V_{ca} \), and \( V_{ab} \) all suffer changes in magnitude and phase angle. This is more easily visualized in the phasor diagram of Fig. 3.

Similarly, a line-to-line fault will cause phase shifting and can cause a zero voltage condition on the secondary of a transformer. Transformer connections and impedance ultimately determine the voltage available at the load bus.
The phase angle is affected in two ways. The phase relationship among the three phases (i.e., 120° between the three phases) and the phase shift or “jump” from the pre-event phase angle to the angle during the fault are both important. It is clear from Figs. 2 and 3 that the phase angle of the $V_{bn}$ voltage jumps by -60 degrees and the angle of $V_{cn}$ jumps by +60° at the initiation of the sag. The voltages $V_{ab}$ and $V_{ca}$ jump by ±30° respectively. But, the relationship among the three-phase voltages during the event are not 120°. Examination of Fig. 3 shows phase-to-neutral voltage angles of 180°, 0°, 180° of an, bn, and cn voltages and line-to-line voltage angles of 150° and 150° for the ab and ca voltages and an undefined amount for bc (this voltage magnitude is zero). The effect on an ac motor drive with a diode front end is “single-phasing” since the rectifier only responds to line-to-line voltages. The ac motor drive will only “see” these highest line-to-line voltages.

C. Example of a recorded unbalanced sag

A digital recording from the field, representative of many sags, is shown in Fig. 4. This figure shows the rms voltage variation from line-to-neutral at customer bus during a voltage sag which resulted in a minimum 79% rms voltage in one phase. The magnitude of fault voltage on the other two phases were 92% and 96% respectively. This unbalanced voltage condition during a SLGF is typical and, depending on the equipment under consideration and the control circuit algorithm that is programmed into the equipment, this momentary unbalanced voltage condition may initiate a trip command that will take the equipment off-line and thereby disrupt the process.

III. EFFECT OF VOLTAGE SAGS ON AC DRIVES

A. Phase angle shift effect on AC Drives

Fig. 1 shows the configuration of a typical ac PWM drive. The first stage consists of a three-phase diode bridge rectifier with a dc-link capacitor and inductor to filter the incoming ac voltage to a low ripple dc voltage. (The dc-link filter inductor is often not included in the standard ac drive.) The inverter section converts the dc voltage back to a variable frequency and variable magnitude ac voltage using a pulse width modulated (PWM) control scheme.

A previous publication reported that the phase shift in voltage during a sag does not significantly impact a diode bridge rectifier [6]. As discussed in Section II, phase shift is a prevalent characteristic of voltage sags. Further analysis has shown that the phase shift has a direct bearing on the response since the diode bridge responds to the maximum difference between any two of the line voltages, which phase affects. The momentary unbalance in the supply voltage (magnitude and/or phase angle) during sags may lead to mal-operation of the drive or operation of protective devices due to excessive current unbalance in the line side of the drive.
discharges slightly as energy is transferred from the capacitor through the inverter to the motor.