CHAPTER 2
Voltage Sags

2.1 Definition of Voltage Sags

The European norm EN 50160 (2000-01-24) "Voltage characteristics of electricity supplied by public distribution systems" [13] applies to distribution systems in Europe. This norm also has the status of a Finnish national standard (SFS). In the publication, a voltage sags (or dip) is defined as a sudden reduction of supply voltage down to 90 % to 1 % of nominal followed by a recovery after a short period of time. A typical duration of a sags is, according to the standard, 10 ms to 1 minute.

IEEE Std. 1159-1995, the IEEE recommended practice for monitoring electric power quality [14], gives somewhat similar values (magnitude 90 % to 10 %, duration 10 ms to 1 minute) as a definition of voltage sags. IEEE Standard 1159 is presented in Fig. 2.1 where disturbances are classified based on both their magnitude and duration.

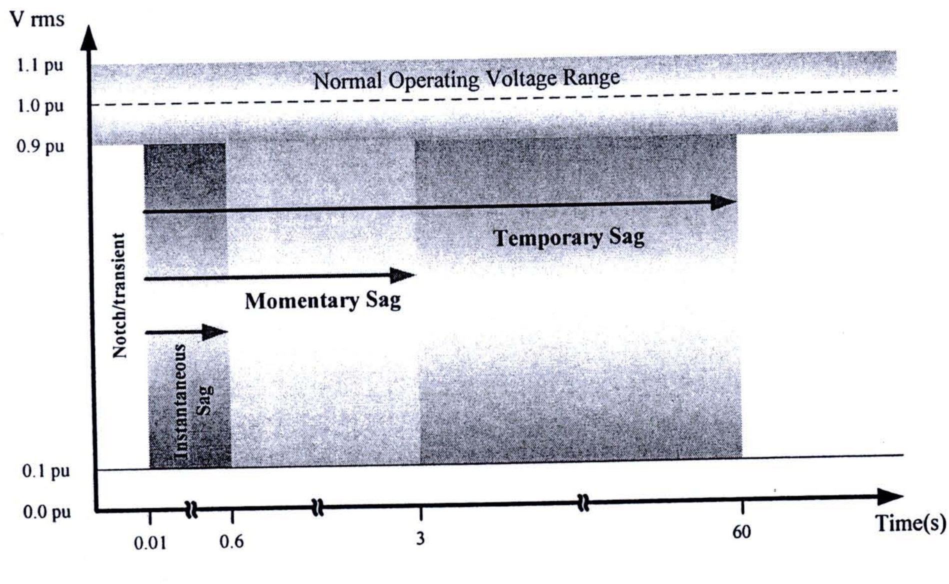

Figure 2.1 Definitions of voltage magnitude events as used in IEEE-1159-1995[14]

2.2 Causes of Voltage Sags

Generally, voltage sags are produced by faults in the electric power system and by starting of large loads. Faults are due mainly to lightning strokes on overhead lines. The effect of a lightning stroke is to induce a large overvoltage on the line. If this voltage exceeds the insulation withstand level, it results in a short circuit, otherwise the voltage peak will start to propagate through the system. If the peak voltage is not high enough to cause a flashover on the line, it might still trigger a spark gap on a varistor. A spark gap mitigates the overvoltage by creating a temporary short circuit, which in turn causes a voltage sags of one or two cycles. Data analysis from surveys shows that there is a strong correlation between sags and lightning[15]. It is believed that lightning is the main cause of voltage sags in U.S. distribution systems.

Starting of large induction motors or other loads will cause voltage sags. During start-up, an induction motor takes a larger current than normal, typically five to six times as large. This current remains high until the motor reaches its nominal speed, typically between several seconds and on minute. The drop in voltage depends strongly on the system parameters. Fig 2.2 shows the equivalent circuit used to analyze the aforementioned phenomena, where: Z_s is the source impedance and Z_m is the motor impedance.

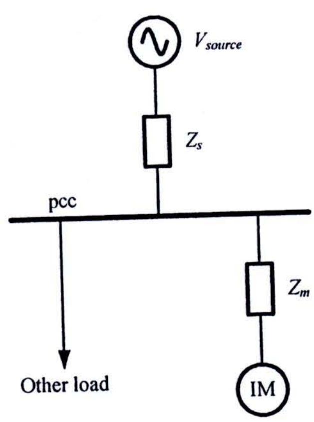

Figure 2.2. Equivalent circuit of an electric system showing the point of common coupling(PCC) for an induction motor and other sensitive loads.

The voltage drop experienced by a load fed from the same bus as the motor is found from the following expression in (2.1):

$$V_{pcc} = V_{sag} = \frac{Z_m}{Z_s + Z_m} V_{source} \tag{2.1}$$

From monitoring it is known that voltage drops due to induction motor starting are seldom deeper than 85%.

2.3 Classification of Voltage Sags

The voltage sags are caused mainly by short-circuit faults and starting of large induction motors. Various types of faults can cause the voltage sags: single-phase-to-ground faults, phase-to-phase faults, and phase-to-phase-ground faults. The voltage at the PCC can be expressed by equations (2.1). However, the expressions must be carefully interpreted, as the voltages at the PCC, are not equal to the voltage at the load terminals. Typically, the three-phase loads are connected in delta connection, however, star connection can be also used.

The single-phase-to-ground fault and the phase-to-phase fault lead to four basic types of voltage sags, that is voltage sags types A, B, C, and D [16].

1) Voltage Sag Type A

This type of voltage sag is caused by three-phase-to-ground faults. It is considered as symmertric three-phase voltage sag with a low-frequency occurrence disturbance [17]. The voltage sag type A can be expressed as in equation (2.2).

$$\left.\begin{aligned} V_a &= \bar{V} \\ V_b &= -\frac{1}{2}\bar{V} - j\frac{\sqrt{3}}{2}\bar{V} \\ V_c &= -\frac{1}{2}\bar{V} + j\frac{\sqrt{3}}{2}\bar{V} \end{aligned}\right\} \qquad (2.2)$$

where $\bar{V}$ = voltage phasor of phase A

2) Voltage Sag Type B

This type of voltage sag is caused by single-phase-to-ground faults and affects the primary side of the star-to-star transformer at the PCC. The voltage sag type B can be expressed as in equation (2.3).

$$\left.\begin{aligned} V_a &= \bar{V} \\ V_b &= -\frac{1}{2}\bar{V} - j\frac{\sqrt{3}}{2} \\ V_c &= -\frac{1}{2}\bar{V} + j\frac{\sqrt{3}}{2} \end{aligned}\right\} \qquad (2.3)$$

3) Voltage Sag Type C

This type of voltage sag is caused by phase-to-phase-to-ground faults. In this type of sag, a phase angle-jump is observed as the voltage in the two-faulted voltage phase move toward each other. The voltage sag type C can be expressed as in equation (2.4).

$$\left.\begin{aligned} V_a &= 1 \\ V_b &= -\frac{1}{2} - j\frac{\sqrt{3}}{2}\bar{V} \\ V_c &= -\frac{1}{2} + j\frac{\sqrt{3}}{2}\bar{V} \end{aligned}\right\} \tag{2.4}$$

4) Voltage Sag Type D

This type of voltage sag is caused by phase-to-phase-to-ground faults. The load is connected in delta and three phases experience a drop. One phase could be down to zero in this type of sag with delta-connected load. The voltage sag type D can be expressed as in equation (2.5).

$$\left.\begin{aligned} V_a &= \bar{V} \\ V_b &= -\frac{1}{2}\bar{V} - j\frac{\sqrt{3}}{2} \\ V_c &= -\frac{1}{2}\bar{V} + j\frac{\sqrt{3}}{2} \end{aligned}\right\} \tag{2.5}$$

Fig. 2.3 shows four types of voltage sags in phasor diagram form for the classification of voltage sags defined previously.

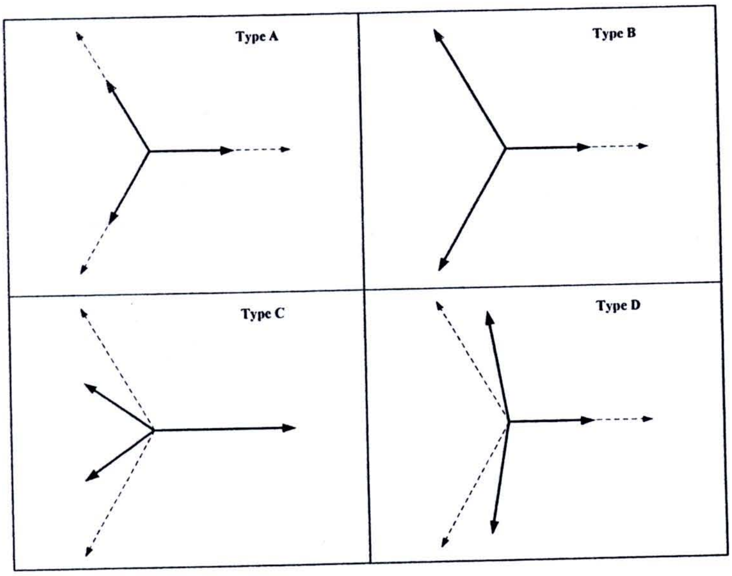

Figure 2.3 Phasor diagram of four types of voltage sags[14].

The phase-to-phase-to-ground faults lead to three additional types of voltage sags, that is voltage sag type E, F and G, thus resulting in a total of seven types of voltage sags. These three sag types are different from the four types defined earlier. These types of sags cannot be translated one to the other.

5) Voltage Sag Type E

This type of voltage sag is caused by two-phase-to-ground faults. The voltage sag type E cannot occur in Adjustable Speed Drives(ASD) equipment terminals due to the zero-sequence component of the voltages are assumed not to propagate down to the ASD-equipment terminals. The voltage sag type E can be expressed as in equation (2.6).

$$\left.\begin{aligned} V_a &= 1 \\ V_b &= -\frac{1}{2}\overline{V} - j\frac{\sqrt{3}}{2}\overline{V} \\ V_c &= -\frac{1}{2}\overline{V} + j\frac{\sqrt{3}}{2}\overline{V} \end{aligned}\right\} \qquad (2.6)$$

6) Voltage Sag Type F

This type of voltage sag is caused by two-phase-to-ground faults in a delta-connected load configuration. The voltage sag type F can be expressed as in equation (2.7).

$$\left.\begin{aligned} V_a &= \overline{V} \\ V_b &= -\frac{1}{2}\overline{V} - j\sqrt{3}\left(\frac{1}{3}+\frac{1}{6}\overline{V}\right) \\ V_c &= -\frac{1}{2}\overline{V} + j\sqrt{3}\left(\frac{1}{3}+\frac{1}{6}\overline{V}\right) \end{aligned}\right\} \quad (2.7)$$

7) Voltage Sag Type G

This type of voltage sag is caused by two-phase-to-ground faults(load connected via a non-grounded transformer removing the zero-sequence the component). The voltage sag type G can be expressed as in equation (2.8).

$$\left.\begin{aligned} V_a &= \frac{2}{3}+\frac{1}{3}\overline{V} \\ V_b &= -\frac{1}{3}\left(1+\frac{1}{2}\overline{V}\right) - j\frac{\sqrt{3}}{2}\overline{V} \\ V_c &= -\frac{1}{3}\left(1+\frac{1}{2}\overline{V}\right) + j\frac{\sqrt{3}}{2}\overline{V} \end{aligned}\right\} \quad (2.8)$$

Fig. 2.4 shows three types of voltage sags due to two-phase-to-ground faults defined previously.

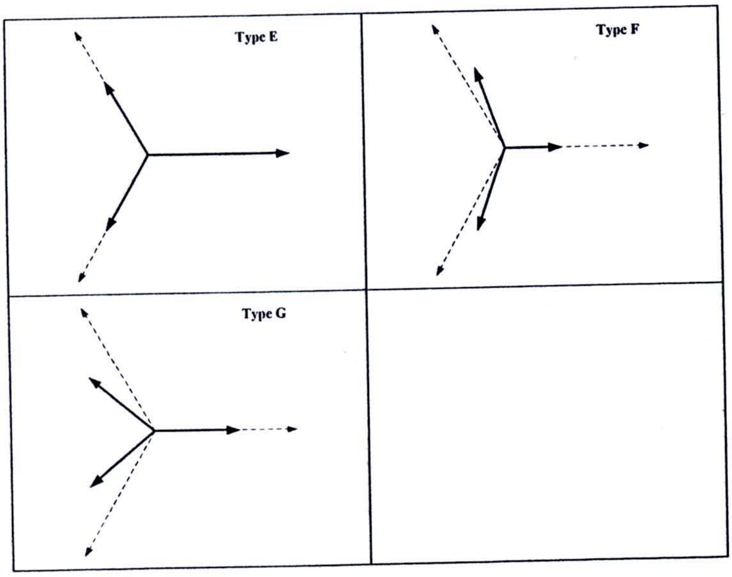

Figure 2.4 Three types of voltage sags due to two-phase-to-ground faults.

For type F and G, the voltages drop along both axis. During a two-phase-to-ground fault, the voltages are lower at the ASD-equipment terminals. Sag types F and G are derived with the assumption of equal positive, negative and zero-sequence impedances. With the assumption that zero-sequence component of the voltages will not propagate down to the ADS-equipment terminals, only five type of three-phase voltage sags can be found at the ASD-equipment terminals [16], they are:

- Type A due to three-phase faults
- Type C and type D due to single-phase and phase-to-phase faults.
- Type F and type G due to two-phase-to-ground faults.

2.4 Effect of Voltage Sags

Many sensitive loads cannot discriminate between a sag and a momentary interruption. The severity of the effects of voltage sags depends not only on the direct effects on the equipment concerned, but also on how important the function carried out by that equipment is. Modern manufacturing methods often involve complex continuous processes utilizing many devices acting together. A failure of one single device, in response to a voltage sags, can stop the entire process. This may be one of the most serious and expensive consequences of voltage sags. However, such damage or loss is a function of the design of the process and is a secondary effect of the voltage sags. Some of the most common direct effects are described in this section;

2.4.1 Information Technology(IT) and Process Control Equipment

The principal units of this category of equipment require direct current (DC) supplies. These dc supplies are provided by means of modules that convert the alternating current (AC) supply from the public power supply system.

It is the minimum voltage reached during a voltage sags that is significant for the power supply modules. A simplified configuration of a DC power supply is shown in Fig. 2.5.

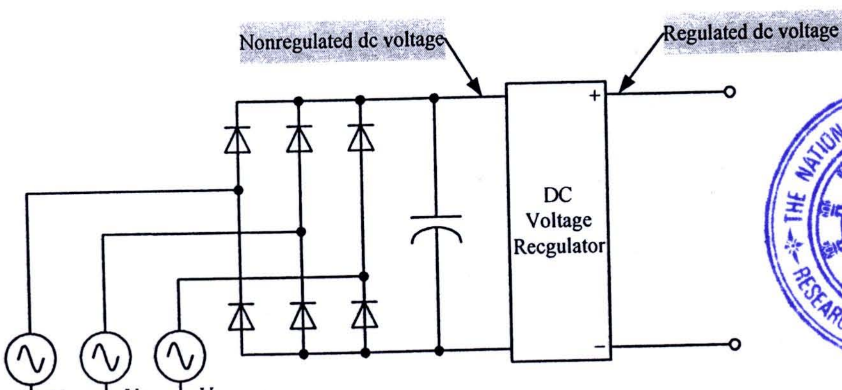

Figure 2.5 Regulated DC power supply.

The capacitor connected to the non-regulated DC bus reduces the ripple at the input of the voltage regulator. The voltage regulator converts the non-regulated DC voltage into a regulated DC voltage of a few volts the feeds sensitive digital electronics. If the AC voltage drops, so does the voltage at the dc side. The voltage regulator is able to keep its output voltage constant over a certain range of input voltage. If the DC voltage becomes too low, the regulated dc voltage will start to drop and ultimately errors will occur in the digital electronics.

2.4.2 Contactors and Asynchronous Motors

AC contactors (and relays) can drop out when the voltage is reduced below about 80% of the nominal for a duration of more than one cycle, i.e. a sags to 80%. A recent paper [18] has presented test results for contactor sensitivity. The main conclusion states that most of the contactors open when the voltage drops below 50%, but the most sensitive ones tolerate only a 30% voltage depression. It is also stated that sag duration does not have a practical relevance but the point-on-wave of sag initiation affects the contactor performance significantly.

The point of operation of an asynchronous motor is governed by the balance between the torque-speed characteristic of the motor and that of the mechanical load. The torque-speed characteristic of the motor depends on the square of the voltage. During a voltage sag, the torque of the motor initially decreases, reducing the speed, and the current increases until a new point of operation can be reached. Severe sags are equivalent to short interruptions in their effects on the operation of the motor. Depending on the ratio of the total inertia to the rated torque, two different behaviours of the mechanical time constant are found:

- Mechanical time constant is low compared with the duration of the sag. The speed decrease is such that the motor virtually stops.
- Mechanical time constant is high compared with the duration of the sag. In this case, the motor speed decreases slightly. However, there is the possibility of the back electromotive force (emf) being in phase opposition to the supply voltage during the recovery, resulting in an inrush current greater than the normal starting current. The high inrush current at the voltage recovery can produce a second voltage drop retarding the re-acceleration of motors to normal speed.

2.4.3 Programmable Logic Controller

Programmable Logic Controllers(PLC) are solid-state control systems that monitor the status of the devices connected as inputs of a process, e.g. relays, switches, sensors, etc. According to the acquired information, the implemented software in the PLC memory calculates the status of the devices connected as outputs, e.g. alarms, lights, fans, etc. The power supplies of PLCs and computers may be sensitive to short voltage sags that can stop the entire process being controlled.

2.4.4 Adjustable Speed Drives

Adjustable Speed Drives(ASD) are reported to be the most critical equipment regarding voltage sags and momentary interruptions. Its common circuit diagram is shown iN Fig. 2.5, consisting of a rectifier and a voltage-source inverter. The rectifier bridge is only responsible for keeping the DC link capacitor charged with a sufficient voltage to assure the proper operation of the inverter. In order to reduce the harmonic currents on the DC side, a smoothing reactor is connected on the rectifier DC terminal (L_s). With the same purpose, a small reactor can also be connected between the network and the rectifier (L_N), but this reactor causes even further voltage drops on the DC voltage.

It can be mentioned that larger AC drives and DC motor drives use commonly thyristor-controlled rectifiers and their firing control system may be affected by phase-angle shifts during unbalanced sags, especially if the synchronization system is based on the zero-crossing of the voltages. In order to avoid damage of thyristors, the drives are stopped when an abnormal network voltage is detected.

The inverter is responsible for the main task of the ASD, which is the speed control of motor loads, e.g. pumps, fans and compressors. High switching frequency using pulse-width modulation (PWM) is employed for a fast control of speed/torque. The voltage and current that the inverter can supply to the motor is dependent on the DC link voltage, which in its turn depends on the AC network voltage. Faults in AC system cause the reduction of the DC link voltage and as a consequence, the inverter may not be able to produce the required voltage on its terminal for certain speeds, i.e. speed/torque full control of the motor is lost. The drive controller detects a lower voltage on DC link and it may trip the drive as a safety but in most of cases unnecessary measure.

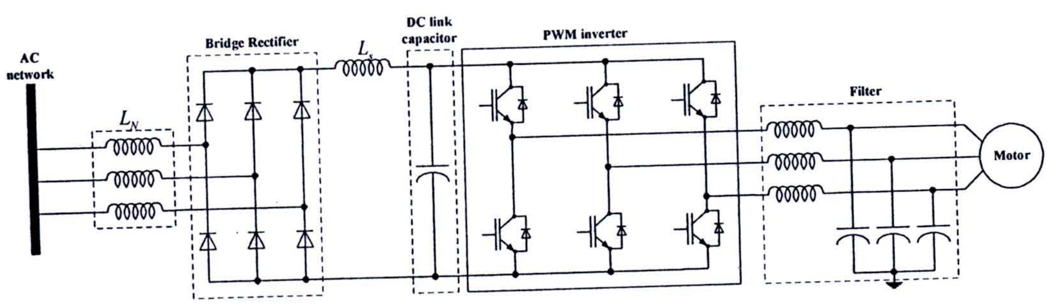

Figure 2.6 Adjustable Speed Drive(ASD) configuration.

A voltage sag in the AC network may stop the rectifier diodes conduction since the AC voltage is lower than the DC voltage. In order to supply the motor load, energy is drawn from the DC capacitor, making the DC voltage decrease. This drop depends thus on the load and the size of the capacitor. It is concluded that the use of larger capacitors would in theory, avoid the reduction of the DC voltage to levels that could trip the drive off, causing a misoperation of the inverter control. Nevertheless, the size of the capacitors required for achieving a ride-through capability to a three-phase balanced sag with typical duration of 100 ms would be too expensive and unfeasible [19].

2.5 Conclusion

Voltage sag may cause problems to low-power rating and high-power rating equipment that is based on power electronics devices. Low-power equipment involves programmable logic controllers (PLCs), IT equipment and process control equipment. Examples of high-power equipments are adjustable speed drives; both AC and DC drives. Not only power electronic based equipment is sensitive to voltage sag; also electromechanical relay and motor contractors are reported to open their contacts when voltage drops below 0.5 to 0.7 pu.

Several solutions providing ride-through to solve the voltage sag problem will be treated in the next chapter.