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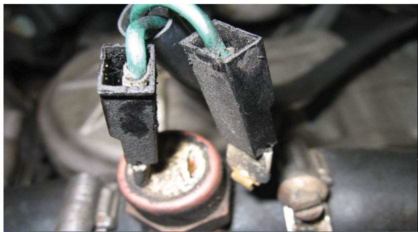

Electric Motors and Power Quality Disturbances

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Contents

Satish Rajagopalan, PhD, EPRI

EXECUTIVE SUMMARY

Electric motors and motor-driven systems form the backbone of the industrial sector, but these systems are susceptible to several power quality–related problems. Unbalanced voltages; voltage sags, swells, and interruptions; and overvoltages or undervoltages can cause havoc with motors, including premature motor failure from increased heating, motor inefficiency, poor power factor, and decreased starting and full-load torques.

Because motor failures often result in loss of revenue, industries need to take action to mitigate the effects of these power quality issues. This *PQ TechWatch* discusses in detail the impact of these power quality disturbances on the performance of electric motors and the various mitigation techniques that can be implemented to improve their immunity to such events.

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Motor failures often result in significant loss of revenue for industries.

INTRODUCTION

Electric motors consume about one-quarter of the energy generated in the United States. About 90 million motors are in use in the United States today, out of which over 40 million are in the industrial and commercial sector.

Several power quality disturbances can affect electric motor operation: unbalanced voltages; voltage sags, swells, and interruptions; and overvoltages and undervoltages. The impact of these disturbances is usually negative, resulting in increased heating and premature motor failure, decreased efficiency, poor power factor, and decreased starting and full-load torques. Motor failures often result in significant loss of revenue for industries due to a combination of repair or replacement costs, removal and installation costs, and costs due to loss of production. Consequently, any impact on electric motor performance due to power disturbance is of utmost importance to both the industry as well as the utility.

Voltage unbalance is one of the leading power quality problems that results in motor overheating and premature motor failure.

VOLTAGE UNBALANCE

Voltage unbalance is one of the leading power quality problems that results in motor overheating and premature motor failure. Unbalanced voltage conditions on utility distribution circuits can be caused by a number of conditions:[1,2]

- Unequal single-phase loads on different phases
- Open delta connections
- Open circuit on the distribution primary (open transformer connections)
- Unequal transformer tap settings
- Differences in impedances of single-phase transformers on the utility
- Faulty or malfunctioning power factor correction equipment such as capacitor banks
- Unidentified single-phase to ground faults
- Heavy reactive single-phase loads such as welders

Voltage unbalance can be defined in several quantitative ways. One of the definitions, also accepted by IEC 60034-26 and used by the power systems and utility community, is the ratio of negative sequence voltage to positive sequence voltage. This definition involves the calculation of sequence voltages using phasor relationships and is presented as follows:

$$V_{pos} = \frac{V_{ab} + a.V_{bc} + a^2.V_{ca}}{3}$$

$$V_{neg} = \frac{V_{ab} + a^2.V_{bc} + a.V_{ca}}{3}$$

where $a = -0.5 + j0.866$

and V_{ab}, V_{bc}, and V_{ca} are three-phase motor line-line voltages.

$$\%unbalance = \frac{V_{neg}}{V_{pos}}100$$

The other commonly used definition is from National Electrical Manufacturers Association (NEMA) MG1.1993 and is much simpler:

$$\%unbalance = \frac{MaxVoltageDeviationFromAverage}{AverageVoltage}100$$

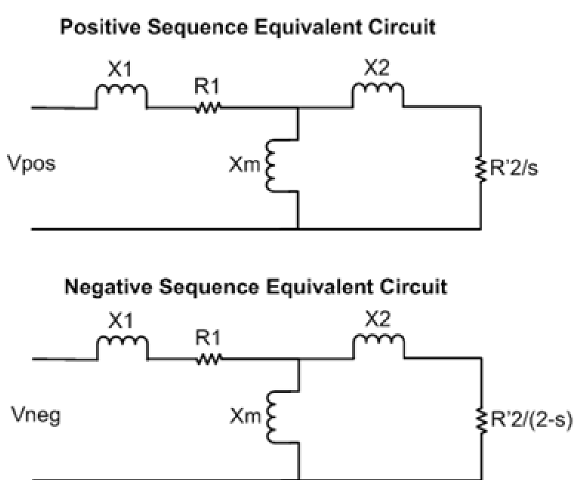
Either can be used. However, both the definitions diverge significantly at large unbalances (~20%).

The net effect of unbalanced voltage is unbalanced current that is significantly large (combined positive and negative sequence currents) in the motor.

Impact on Motor Operation and Performance

From a motor's point of view, a voltage unbalance is equivalent to running the motor with two voltage sources—one with a positive sequence source and the other with a negative sequence source, each of which produces a balanced set of currents in the electric motor. This in turn represents two sets of current vectors representing the actual currents produced in the three stator phases by the original unbalanced voltages. The motor, therefore, behaves as the equivalent of the sum of two motors, one (with the positive sequence voltage source) running as a normal motor would do at a slip *s*, and the other (with the negative voltage sequence voltage) running with a reverse field at a slip of 2 – *s*. The net effect of unbalanced voltage is unbalanced current that is significantly large (combined positive and negative sequence currents) in the motor. As an example, a 1% voltage unbalance may result in up to 6% to 10% unbalance in the motor currents. The two equivalent circuits are shown in the figure below.[3]

Induction Motor Positive and Negative Sequence Equivalent Circuits



Source: Pillay, Hofmann, and Manyag [3].

From the equivalent circuits, the total power and torque output of the motor in this case can be given as

$$P_m = I_p^2 r_2 \left[\frac{(1-s)}{s}\right] - I_n^2 r_2 \left[\frac{(1-s)}{(2-s)}\right] N_s$$

$$T = r_2 \frac{\left[\frac{I_p^2}{s} - \frac{I_n^2}{(2-s)}\right]}{N_s}$$

where

T is the motor torque,

r_1 and r_2 are stator and rotor resistance, respectively,

N_s is the synchronous speed of the motor,

s is the slip,

I_p and I_n are the equivalent positive and negative sequence currents per phase, and

P_m is the electrical output of the motor.

And from the equivalent circuits:

r_2' is the rotor resistance referred to the primary,

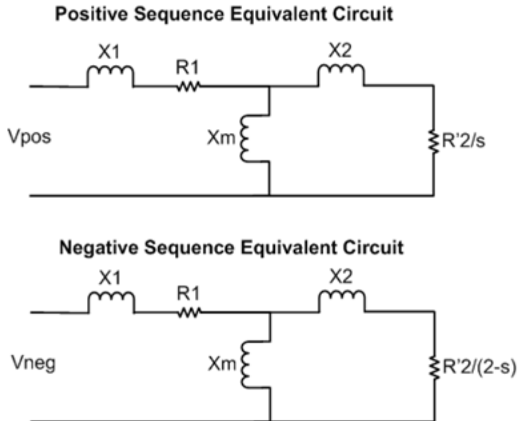
x_1 and x_2 are stator and rotor reactance, respectively,

x_2' is the rotor reactance referred to the primary, and

x_m is the magnetizing reactance.

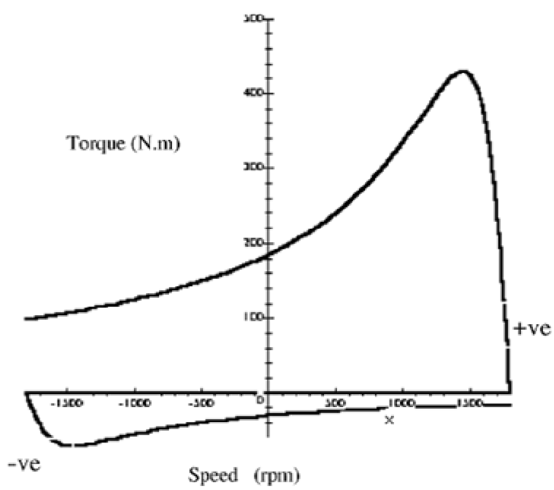
The positive and negative torque-speed curves created by each of the sequence components are shown in the figure below.[4] The positive sequence torque is representative of what the motor would normally produce. However, the counter-rotating magnetic field in the motor produced by the negative sequence voltage results in a negative torque. This results in a net shaft torque that is lesser than the rated torque that would be produced by the balanced supply. This can also be observed from the above equations.[5] In addition, the negative sequence

Induction Motor Positive and Negative Sequence Equivalent Circuits



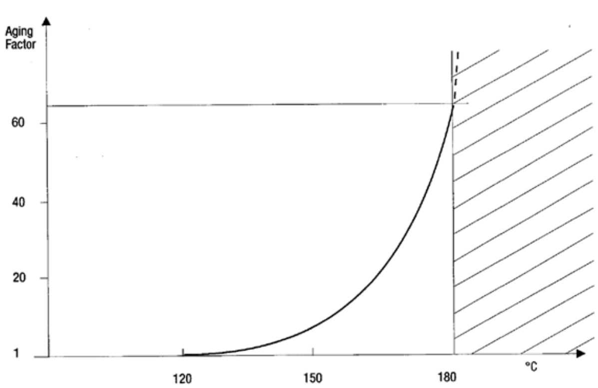
Source: Pillay, Hofmann, and Manyag [3].

Positive and Negative Sequence Torques of an Induction Motor



Source: Pillay, Hofmann, and Manyag [4].

Temperature vs. Thermal Aging



Source: Allen Bradley/Rockwell Automation Application Note [9].

voltage decreases the starting and breakdown torques of the motor. This means that the motor would have increased difficulty in riding through voltage dips and sags, which in turn would affect the system stability.

If full load is demanded, the electric motor would have to be operated at high slip, increasing rotor losses and heat produced. The increased heat in turn causes premature motor failure. The percent additional temperature rise is equal to two times the percent voltage unbalance. As an example, a motor with 2% unbalance would result in a temperature increase of 8°C. The winding insulation life is typically reduced by one-half for each 10°C increase in operating temperature. The increased losses also directly impact the efficiency of the motor as shown in the table on the next page.[6] The effect of voltage unbalance on the insulation life of a typical T-frame motor having Class B insulation, running in a 40°C ambient temperature, loaded to 100%, is shown in the next table.[7] Motors with a service factor of 1.0 are less capable of withstanding voltage unbalance than motors with a higher service factor.[8] The effect of insulation aging versus temperature is shown in the figure below.[9] It can be seen that as temperature increases, the life of the insulation deteriorates exponentially.

The effects of voltage unbalance on an electric motor can be summarized as:

- Increased motor losses and reduced efficiency
- Decreased full load, starting, and breakdown torque
- Increased heating and loss of insulation life resulting in premature motor failure
- Increased operating noise
- Nuisance tripping of current or voltage unbalance protection resulting in loss of production or output
- Longer time to run-up

Impact on Motor Efficiency due to Voltage Unbalance

	Motor Efficiency (%)		
Motor Load (%rated)	**Voltage Unbalance**		
	Nominal	1%	2%
100	94.4	94.4	93.0
75	95.2	95.1	93.9
50	96.1	95.5	94.1

Source: DOE Motor Tip Sheet [6].

Impact on Motor Insulation

	Insulation Life	
Voltage Unbalance (%)	**Service Factor**	**Service Factor**
	1.0	1.15
0	1.00	2.27
1	0.90	2.10
2	0.64	1.58
3	-	0.98
4	-	0.51

Source: Cooper Bussmann [7].

Special protective relays can be used to detect voltage unbalance, and protect equipment from the degrading effects of unbalance.

NEMA standard MG-1 recommends that motors not be operated with a voltage unbalance of more than 5%.

Restoring Voltage Balance

Single-phase loads could be redistributed uniformly across the phases. Any indication of voltage unbalance must first be followed by a close inspection of loading across each phase. System impedances due to transformers and lines must be checked to make sure that each phase has similar impedance. Static volt-ampere-reactive (VAR) compensators and line conditioners can also be used to correct the unbalance. These solutions can be applied at the utility level as well as at the panel level.[10] An example of a line conditioner is an automatic voltage regulator (AVR). AVRs are commonly used to correct undervoltage and overvoltage, as well as voltage unbalance. The AVR automatically compensates for all voltage fluctuations, provided that the input voltage to the AVR is within its range of magnitude and speed of adjustment. An effective scheme is to use a number of small AVRs distributed throughout the plant at critical equipment locations.

Protection Relays

Motors should be protected with voltage and/or current unbalance protection, particularly as supply conditions cannot be guaranteed. Such periods include when connections burn off in the high- or medium-voltage networks or if a distribution substation primary fuse blows. Special protective relays can be used to detect voltage unbalance and protect equipment from the degrading effects of unbalance. Unbalance relays are usually of the microprocessor type and are available with numerous features. Typically, these devices are small, relatively inexpensive, automatic or manual reset, and offer programmable trip time and unbalance limit settings. They also can be connected to activate an alarm, trip a circuit, or both when unbalance exceeds a predetermined limit. In addition, these versatile relays can be retrofitted into a motor control circuit or any portion of a power distribution system. Another type of protective relay, the negative sequence voltage relay, can detect single-phasing, phase voltage unbalance, and reversal of supply phase rotation. These relays sense anomalies only upstream of their location in a circuit. Therefore, this type of relay will not be able to detect an internal problem in a motor or other load downstream.[11] If an unbalanced supply is a possible condition, then a central supervising relay should alert the attention of personnel to the fact that certain limits are exceeded, permitting them to take corrective measures before motor overheating becomes critical.

Derating

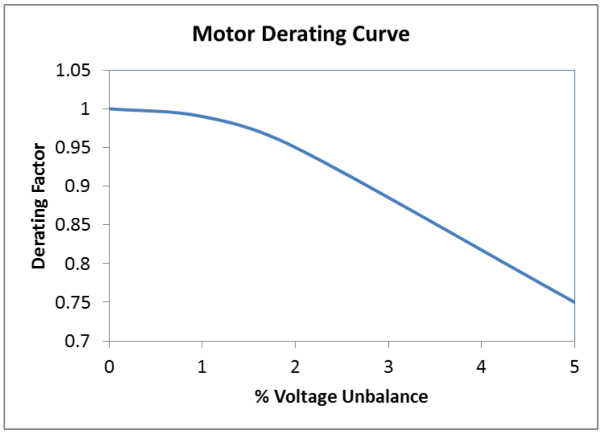
NEMA standard MG-1 recommends that motors not be operated with a voltage unbalance of more than 5%. While undesirable, motors can be derated to reduce the possibility of damage. Several methods exist for derating a motor. Research by NEMA indicated that the percentage increase in temperature is proportional to twice the square of the percentage voltage unbalance, and can be mathematically expressed as:

$$1 + \frac{2(percentunbalance)^2}{100} = \left(\frac{percentload}{100}\right)^{-1.7}$$

The NEMA MG-1 deration curve is shown in the figure at the top of the next page.[12] No derating is necessary for unbalance up to 1%.The curve shows that at 5% unbalance, as much as 75% derating may be needed to operate a motor safely. It must be kept in mind that the voltage unbalance definition used is as per NEMA. Derating a motor is undesirable and is used as an option of last resort, because the unbalance situation still exists and the motor cannot operate at its full potential.

It must be kept in mind that the derating curve shown is applicable only to motors with normal starting torque and normal locked-rotor current. Examples of such motors include centrifugal pumps, fans, and compressors. In these applications, the required starting torque is less than 100% of rated full-load torque. For all other cases, the motor manufacturer must be contacted.

Motor Deration Curve



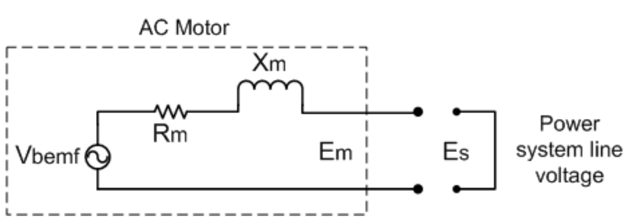
Source: NEMA MG-1 2010 [12]

Unsupervised reclosing of contactors while a motor is still rotating can cause severe problems, including destruction of the motor.

VOLTAGE SAGS AND INTERRUPTIONS

Line-connected three-phase AC motors in industrial installations are often subjected to momentary voltage sags and interruptions. During such an event, the three-phase motor contactors may open, disconnecting the motor from the line. After the event, when the line voltage returns to normal, automatic reclosing of the motor contactors is the preferred action to bring the motor back on-line. However, unsupervised reclosing of contactors while the motor is still rotating can cause severe problems, including destruction of the motor. Certain conditions must be present before a rotating AC motor can be safely reconnected to the three-phase AC line,[13] especially for motors larger than 30 hp.

Equivalent Circuit Representation (Per Phase) of a Disconnected Three-Phase AC Motor



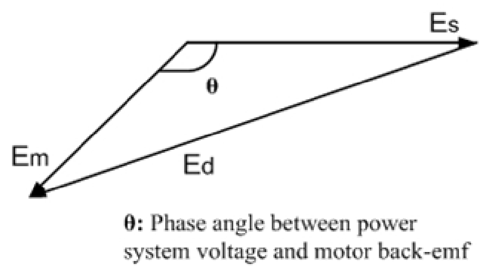
When power to a three-phase motor is interrupted, the motor inertia causes the motor to continue to spin at a decreasing rate. This spinning motor generates a back-EMF (electromotive force), which appears at the motor terminals. This back-EMF voltage decays exponentially at a rate proportional to the motor open-circuit time constant as the rate of spin decreases. Typical time constants may be as long as 5 seconds, with large synchronous machines having the larger time constant. The motor load also affects the rate of motor slowdown. The higher the load on the motor, the more quickly the motor will slow down. However, the presence of power-factor-correction capacitors extends the rate of the slowdown.[14]

As the motor slows, the phase angle between the back-EMF and the power system voltage changes. When the power returns to normal and the motor contactors apply the line voltage to the motor, the motor will experience a terminal voltage equal to the vector difference of the system voltage and the internal back-EMF of the motor. This terminal voltage could be as large as twice the nominal voltage, depending on the instant of contactor reclosure.

The figure at bottom left shows the equivalent circuit diagram for a three-phase motor when the motor contactors open during a voltage sag or interruption. The motor back-EMF, V*bemf*, is equal to the motor open-circuit terminal voltage, *Em*, at the instant when the motor is disconnected from the three-phase supply, *Es*.

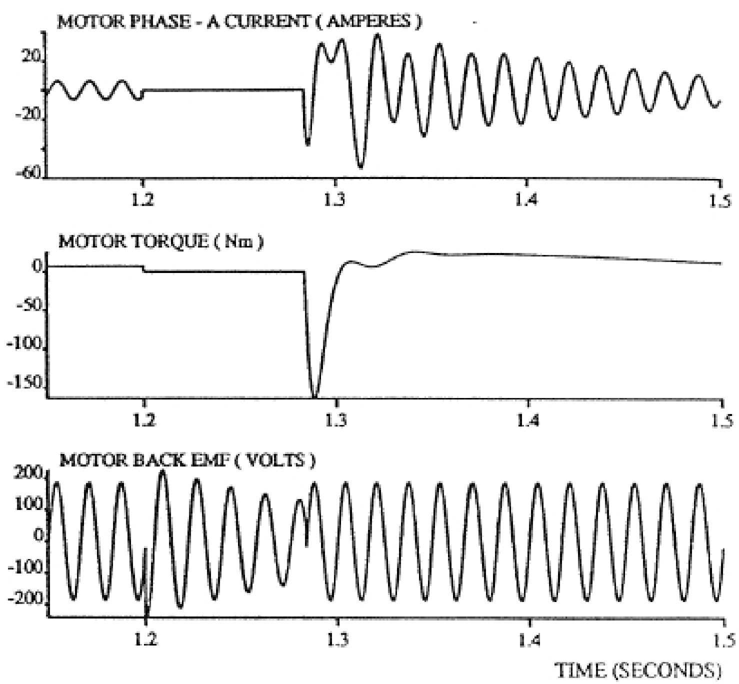
The figure at the top of the next page shows the phasor diagram of the motor voltage (*Em*) and supply voltage (*Es*) for the worst-case scenario where the motor is disconnected after an interruption.[15] The scalar magnitude of the voltages shortly after the interruption (say after about five cycles) are approximately equal. Moreover, under worst-case conditions as shown in this figure, the phase angle (θ) between *Em* and *Es* may be large (in the range of 120–180 degrees), resulting in a large vector magnitude

Vector Representation of AC Motor Voltages Representing Worst-Case Scenario



Source: Working Group on Fast Transfer of Motors, IAS-PSPC [15].

Simulated AC Motor Trip and Out-of-Phase Motor Reclosure After Five Cycles, Resulting in a Large Torque Transient

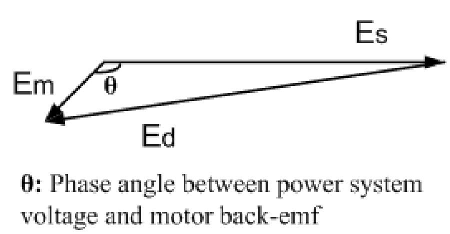


Source: S. Chattopadhyay and T. S. Key [16].

of voltage, *Ed*. This large voltage is applied to the motor terminals when the motor contactors reclose after five cycles. Because the back-EMF is comparable in magnitude to the supply voltage and significantly out of phase with the supply voltage, the resulting effective voltage (*Ed*) could approach twice the nominal voltage if the phase angle (θ) is close to 180 degrees. This sudden application of a large voltage to the motor would likely cause a large inrush current and torque transient, as shown in the figure below left.[16] If the torque transient exceeds the motor's design specifications, the motor may be damaged.

The figure below also shows the scenario where the motor back-EMF has decayed significantly.[17] In this case, the effective voltage difference (*Ed*) is almost equal to the nominal voltage of the motor (*Es*). Therefore, the motor can be safely powered. A common rule of thumb used in the industry for reclosing motors after momentary sags or interruptions is to avoid reconnection if the vector difference (*Ed*) exceeds 125% to 135% of the nominal motor voltage.

Vector Representation of AC Motor Voltages with Back-EMF Appreciably Diminished



Source: Working Group on Fast Transfer of Motors, IAS-PSPC [17].

Automatic motor reclosers synchronize the motor back-EMF with the input supply voltage prior to reclosing.

The American National Standards Institute (ANSI) standard C37.96 and NEMA standard MG-1 permit a maximum 1.33 per unit voltage on the motor voltage and frequency base for out-of-phase reclosing.[18] If the residual back-EMF is almost equal to the voltage rating of the motor, reclosing must be done only if the phase angle difference is less than 80 degrees.[19] With the voltages out of phase, safe reclosing can be done only if the residual back-EMF is less than 0.33 per unit of the rated motor voltage.[20]

Besides damage to the motor caused by a torque transient, the large inrush currents may cause system unbalance if several motors are operating on the same line. However, such system unbalance is usually uncommon because the transmission line dampens out these inrush current disturbances.

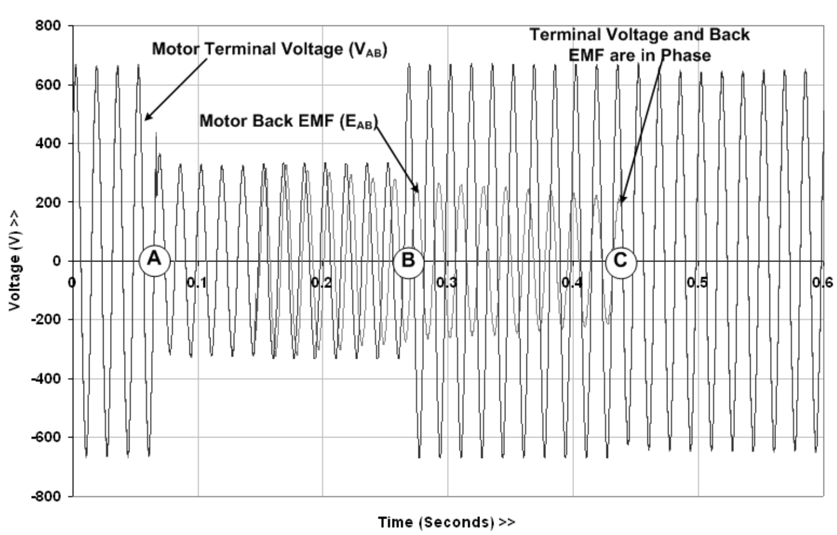
Use Automatic Motor Ride-Through Controllers/Reclosers

Automatic motor reclosers synchronize the motor back-EMF with the input supply voltage prior to reclosing. One example of such a recloser, used for illustrative purposes here, is the WaveSync.[21] The WaveSync ride-through controller is an electronic device intended to address the costly problem of AC motors shutting down due to momentary power interruptions and voltage sags. Controllers of this type are designed to safely disengage and reengage supply voltage in phase with the decaying back-EMF of the motor. Where successfully applied, this approach applies a safe operating voltage to the motor such that transient effects including large momentary peak torques do not occur or are minimized.

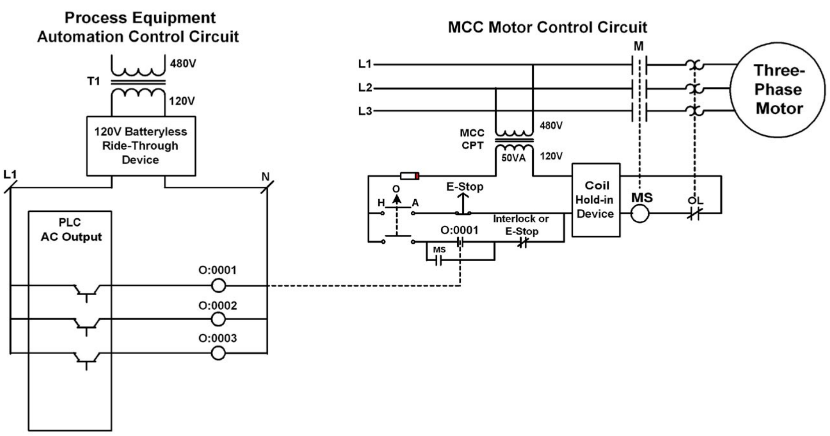
Such controllers are typically installed inside of the motor starter enclosure. In cases where this is not practical, the controller can be installed in a separate enclosure. When a momentary power interruption occurs, the controller opens the motor starter contactor and waits until the supply power is restored, or until 3 seconds have elapsed (default value). If the power is restored within the configurable time, the controller will re-engage the starter contactor at the appropriate time so that the motor field and supply voltage are in phase. If the motor field collapses below 5%, the starter is re-engaged without regard to phase relationship.

The figure below left illustrates how the WaveSync operates to avert the possible shutdown of a 50-hp electric motor that is subjected to a voltage sag. The illustration shows a three-phase, 12-cycle voltage sag where the supply voltage decreased to 50% of its normal value. The WaveSync senses the voltage sag at point A and disengages the motor contactor. During the voltage sag, the WaveSync monitors the supply voltage and the motor's back-EMF. At point B, the supply voltage returns to normal. However, the WaveSync does not close the motor contactor at this point because the back-EMF of the motor (E_{AB}) and the terminal voltage (V_{AB}) are not in phase with each other. Instead, the WaveSync continues to monitor both voltages until they are in phase. At point C, the two voltages align, and the WaveSync energizes the motor contactor. Therefore, the applied effective voltage is minimized, averting a motor shutdown and a high torque transient.

WaveSync Operation During a 12-Cycle Voltage Sag to 50% of Normal Voltage



Conditioning a Programmable Logic Controller and Motor Control Circuit



Providing power conditioning on the controller and motor starter circuit is a proven method to keep a process up and running during voltage sags.

A proven method for keeping an industrial process up and running through a typical voltage-sag event involves providing power conditioning for the associated control circuits.

Ensure That the Motor Starters Drop Out During the Interruption

If an interruption truly occurs (versus a voltage sag), taking the motor completely off-line is an option. Choosing voltage-sag ride-through schemes that will hold above the "interruption" level (i.e., 10%) but allow for typical voltage-sag ride-through for durations up to 1 second is typically recommended. Standards such as SEMI F47 from Semiconductor Equipment and Materials International define voltage sag levels that should be safe for system ride-through.

A proven method for keeping an industrial process up and running through a typical voltage-sag event involves providing power conditioning for the associated control circuits. Through EPRI's power quality research and hundreds of service-related power quality testing and power quality auditing jobs, this approach has been proven effective many times over. By keeping the machine or process controller and associated control circuits protected from the voltage sag, the system can ride through many of the events that would have normally led to process shutdowns. A typical approach for conditioning a programmable logic controller (PLC) and associated motor control circuit is shown in the figure at left.

In some cases, protection of a motor starter coil or contactor down to the 25% level is applicable, as can be done with coil hold-in devices. Constant-voltage transformers are also commonly used on many motor/compressor control circuits where the customer wants to drop the motor load when there is an interruption of very deep sag.

Trip the Plant Main Breaker as a Result of the Interruption

This sounds like the most extreme response. However, if the main breaker can be reclosed at a time in which the interruption occurs, then the voltage can be brought back on either manually or automatically if the residual voltage has decayed significantly (common value is 25% nominal voltage). Taking the plant off-line can also help extinguish the fault arc and allow for minimum recloser times. Options for signaling to the plant that it should trip off the motor or main breaker include a transfer-trip signal from the utility or interruption sensing on the plant side. With this approach, the plant systems are likely to all drop off-line unless an uninterruptible power supply or interruption coverage power conditioning is in place.

The utility recloser time should be set beyond the open-circuit time constant of the largest motor in the plant. This is the amount of time for the residual motor voltage to decay to 36.8% of the initial value. This assumes the customer has always on two-wire control through hardwired or via PLC, and so on, in various places where the contactor may stay engaged or come back on immediately when the power is restored.

Other considerations include the motor load torque and inertia of the motor and driven equipment. If the inertia of the system is high, reclosing back into the load causes potential problems. In general, where fast reclosing is used, a study should be conducted to look at

A large voltage has the potential to saturate the motor core, and once the motor enters saturation, its impedance drops, resulting in large winding currents that may be damaging.

the potential interactions of the motor, driven equipment, and power system. The plant can then decide whether to try to ride through the event or drop the motorized equipment off-line.[22]

OVERVOLTAGE AND UNDERVOLTAGE

While the behavior of electric motors exposed to voltage variations is application driven, some behavior of electric motors due to voltage fluctuations can be generalized. The table below shows the effect of 10% deviation in supplied voltage on key motor characteristics. A decrease in even 10% of name-plate voltage can result in a 19% loss of generated torque and a decrease in efficiency of up to 3%. Full load current may increase up to 10%. A consequence of the increased current is increased heat generation from the motor. The resulting temperature may increase by up to 15%. A similar effect is also seen in synchronous motors with constant field excitation. If the field voltage varies as the line voltage, the pull-out or maximum torque could be affected, as this torque is proportional to the square of the voltage.

General Effect of Voltage Variations on Induction-Motor Characteristics

Characteristic	Proportional to	Voltage variation	
		90% of nameplate	110% of nameplate
Starting and maximum running torque	Voltage squared	–19%	+21%
Percent slip	$(1/\text{voltage})^2$	+23%	–19%
Full load speed	Synchronous speed—slip	–0.2 to –1.0%	+0.2 to 1.0%
Starting current	Voltage	–10%	+10%
Full load current	Varies with design	+5 to +10%	–5 to –10%
No load current	Varies with design	–10 to –30%	+10 to +30%
Temperature rise	Varies with design	+10 to +15%	–10 to –15%
Full load efficiency	Varies with design	–1 to –3%	+1 to +3%
Full load power factor	Varies with design	+3 to +7%	–2 to –7%
Magnetic noise	Varies with design	Slight decrease	Slight increase

Source: IEEE Std. 141-1993 [26]

Overvoltages are longer sustained events than voltage swells. If the motor load is a constant, a sustained overvoltage results in decreased motor current. However, the outcome could be much different if the overvoltage is significant. A large voltage has the potential to saturate the motor core.[23] Once the motor enters saturation, its impedance drops, resulting in large winding currents that may be damaging. This scenario is especially likely with motors manufactured today. To offset the increase in cost that accompanies the manufacture of high-efficiency motors, motor manufacturers tend to design new motors close to saturation for more optimum use of the core material. This in turn makes them more susceptible to saturation from overvoltage. Another consequence of overvoltage is decreased motor power factor. Typically, the overvoltage trip must be set at 110% to protect the motor and also provide a robust operation during overvoltages.[24]

Sustained undervoltage results in increased motor currents that in turn result in increased heat. Increased heat can cause winding insulation degradation, very similar to what was explained under voltage unbalance earlier. While undervoltage improves power factor, any advantage is usually nullified due to the heat generated by increased currents. This is especially the case when the motor is close to fully loaded and any undervoltage can cause motor currents to push beyond the nameplate values. In addition, the slip and starting torque vary as the square of the voltage deviation.[25] As the voltage decreases, so does the starting torque.

All electric motors should be typically protected with an undervoltage protection element in addition to the overload trip. The trip point is typically set at 80% to 90% of nameplate voltage. When a motor is line-started, the

A power quality study or audit will aid in deciding the best possible electric system configuration, as well as help in choosing necessary power quality mitigation equipment.

motor draws a large inrush current that may result in a temporary undervoltage. This can be exacerbated if multiple motors are served off the same bus and started simultaneously. This may result in the motors not producing enough starting torque, and motor stalls can occur. In such scenarios, their starts should be staggered using a time-delay element.

In summary, slight undervoltages have a more detrimental effect on motor performance than slight overvoltages.[26]

CONCLUSIONS

This report presents the impacts of several power quality disturbances on electric motor performance. The industry user should carefully identify the power quality disturbances that are most likely to impact the facility. The respective motor manufacturers must then be contacted to ensure the best possible protection systems. Such a power quality study/audit should be conducted as early as in the planning phase for the facility. This will aid in deciding the best possible electric system configuration, as well as help in choosing necessary power quality mitigation equipment. In addition, the motor could be sized correctly for a given application. Derating factors and other design guidelines are also provided in the NEMA MG-1 standard.

NOTES

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3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
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