

White Paper

## Unbalanced voltage supply

The damaging effects on three phase induction motors and rectifiers

Power and productivity  
for a better world™



# Electronic control systems are the cornerstone of efficient, modern industrial processes. The performance and reliability of instruments, sensors, relays, actuators and electric motors can all be affected by the quality of power supplied to them.

Variable Speed Drives (VSD) that trip, programmable logic controllers (PLC) that suddenly experience faults, motors that overheat and erroneous sensor signals can all cause interruption and shutdown of industrial processes. This can result in major restart delays, product scrapping, customer dissatisfaction, consequential losses and significant costs to business.

## Unbalanced voltage causes

All electrical networks suffer from power quality issues in varying degrees and frequencies. Brief sags and surges are common but networks can exhibit voltage supply irregularities that may be present for prolonged periods of time, or are constantly present on the network. Where a voltage imbalance exists on a supply network, it is usually due to generation faults, unmatched impedance on transformer banks, or large single phase loads on the three phase network.

Customer installation produced voltage imbalances are most commonly the result of single phase loads not connected evenly across the 3 phase system. Single phase motors, heating and cooling loads are very commonly connected in such a manner that one phase conductor carries significantly more current than the other two. The Line to Neutral Voltage of one phase is lower than the other two. Similarly, where the majority of the load is connected over only two phases, one Line to Neutral voltage is higher than the other two. In either case, Line to Line voltages are affected.

Figure 1 demonstrates an over voltage on one line, and an under voltage on another at the Medium Voltage (MV) or High Voltage (HV) transformer, while the third is at specified voltage. On the Low Voltage (LV) secondary, not only are the Line to Neutral voltages on two phases clearly over and under by 10% respectively, measuring the Line to Line vectors (dashed lines) shows voltage varying from specification.

This white paper deals only with the simple over and under voltage and the influence on motors and electronic rectifiers and the consequential effects of those devices. Further reading is available in other papers referencing phase angle shift that occurs with unbalanced voltage in three phase installations.

## Unbalanced voltage and induction motors

The effect of unbalanced voltage on induction motors is widely known by most technicians and plant engineers. Motor torque and speed are negatively affected and the motor may produce excessive noise. The voltage imbalance can also cause an increase in current imbalance and a temperature rise far greater than the voltage imbalance percentage.<sup>2</sup> We can calculate the increased temperature in an induction motor winding as a result of voltage imbalance.

Voltage imbalance in a 3 phase system is expressed as a single percentage. As in Figure 1, there may exist an under voltage and an over voltage.

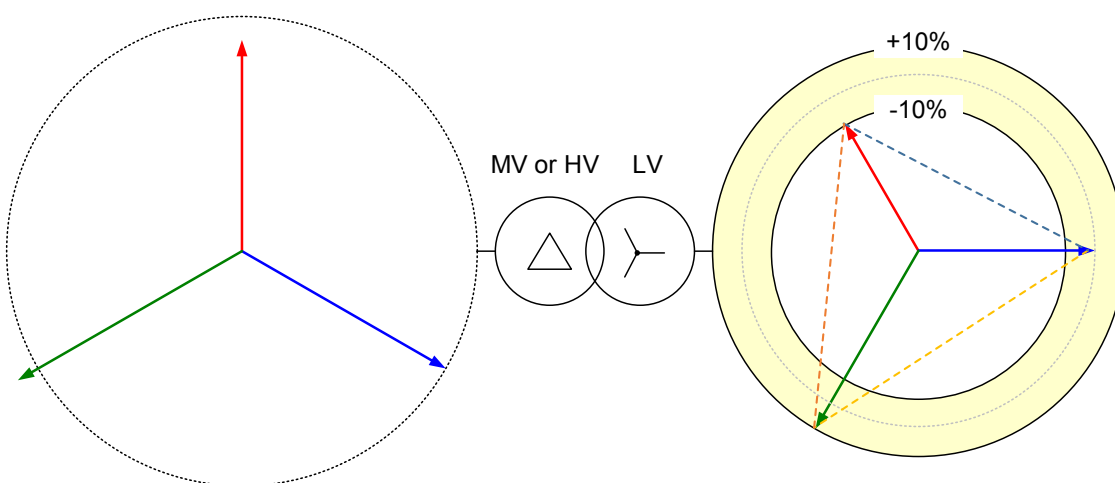


Figure 1

To calculate the system imbalance and the resulting temperature rise in the winding, the following formulae are used:

| Voltage imbalance % = (Maximum imbalance/Average voltage) * 100    |   |                             |
|--|---|-----------------------------|
| Example:   |   |                             |
| Measured line to line voltages                                     |   |                             |
| L1 - L2 = 392V (-2%)   |   | Largest imbalance = 12V     |
| L2 - L3 = 400V (0%)  |   |                             |
| L3 - L1 = 412V (+3%)   |   | Average voltage = 401.33V   |
| Voltage imbalance % = (12/401.33) * 100                            | → | Voltage imbalance % = 2.99% |
| Temperature rise % = 2 x (voltage imbalance % <sup>2</sup> ) * 100 |   |                             |
| Temperature rise % = 2 x 2.99 <sup>2</sup> * 100                   | → | Temperature rise % = 17.88% |

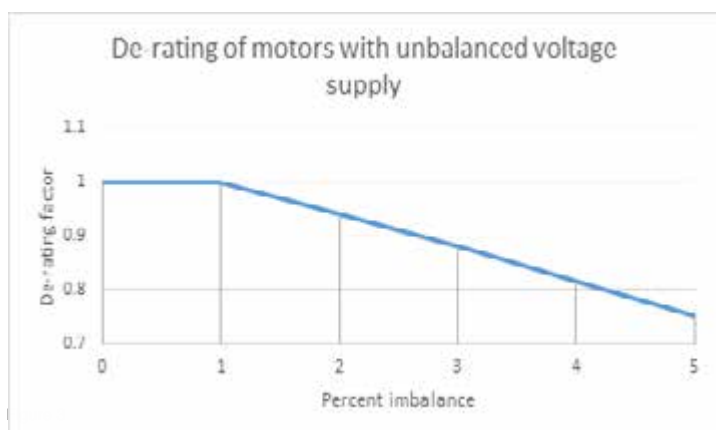
Figure 1

The table in Figure 2 demonstrates the formula above outlining the exponential winding temperature increase compared with the increase in voltage imbalance. An imbalance greater than 2% is unacceptable<sup>2</sup> as it results in a temperature rise in the winding that will be beyond the motors specification; the life of the motor may be decreased. NEMA limits require no more than 5% unbalanced voltage. Studies show that the average life expectancy of insulation halves with every 10° of temperature increase.<sup>3</sup>

| Effect of unbalanced voltage on winding temperature for 3 phase induction motors |                    |
|--|--------------------|
| % Voltage imbalance  | % Temperature rise |
| 2%   | 8%                 |
| 3%   | 18%                |
| 4%   | 32%                |
| 5%   | 50%                |

Figure 2

Three phase induction motors should be de-rated according to the chart in Figure 3.<sup>5</sup>



Not only does the increased operating heat induce premature expiration of the motor, excess current is also drawn with no additional power output, therefore over-stressing the supply cables and potentially reaching levels where the current overloads and the Variable Speed Drives (VSD) over current protection will trip.

VSD diodes, DC link capacitors and rectifier power supplies will experience additional thermal stress as a result of the increased AC line currents-to compensate for the voltage imbalance. Triplen harmonics can also be produced as a result of the increased stress to the rectifier diodes.

### Unbalanced voltage and rectifiers

Any electronic equipment that converts AC to DC will have a rectifier; computers, PLC's, Uninterruptible Power Supplies (UPS), and VSD's. Rectifiers are a non-linear load where the current output waveform is not linear to the voltage input waveform.

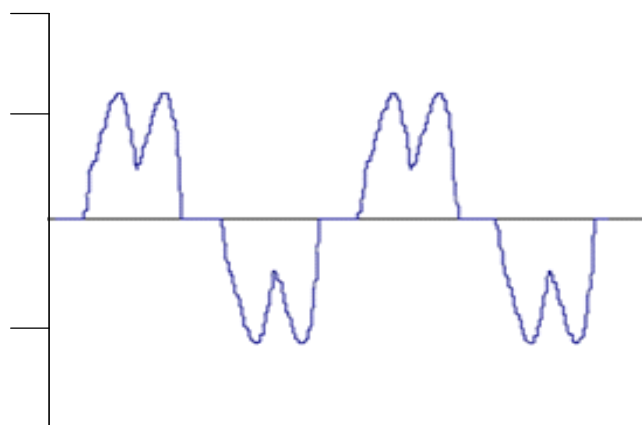


Figure 4: Normal line current for 1 phase of a three phase rectifier

The diodes in a typical rectifier switch when the switching threshold voltage is exceeded in the positive direction. During each half cycle, two phases will exceed the switching threshold voltage, as one is decaying another is rising and vice versa-thus producing two peaks in the line current draw.

When operating correctly and the voltage is balanced, the AC supply current waveform has a double pulse per half cycle shape, as shown in Figure 4. The area under the graph is effectively power, in watts, required to operate the connected DC load.

Current flow cannot transfer or commute immediately from one diode to another in a rectifier due to supply inductance. The rectifier begins to exhibit differing conducting modes where varying numbers of diodes are simultaneously conducting. Further supply imbalance results in overlap of these modes, where more varying quantities of diodes are conducting. The angle of overlap is determined by the time taken to complete commutation.<sup>4</sup>

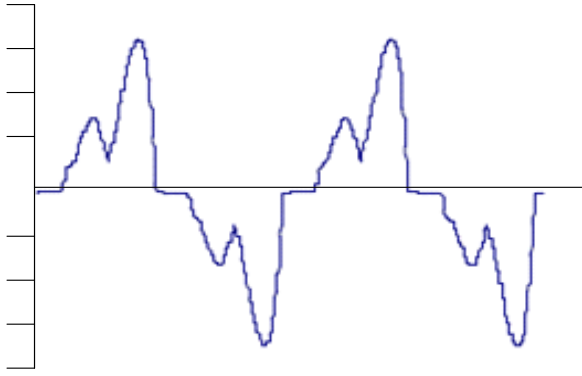


Figure 5: Line current with 5% voltage imbalance

The AC input line current waveform in Figure 5 represents an AC voltage supply imbalance of 5%. The line current waveform starts to look like a single pulse indicating an increased switching of the diodes and an increase in current through the diodes. The same amount of power still needs to be supplied, therefore the area under the graph must remain the same as in Figure 4, hence the AC line current peak is larger.

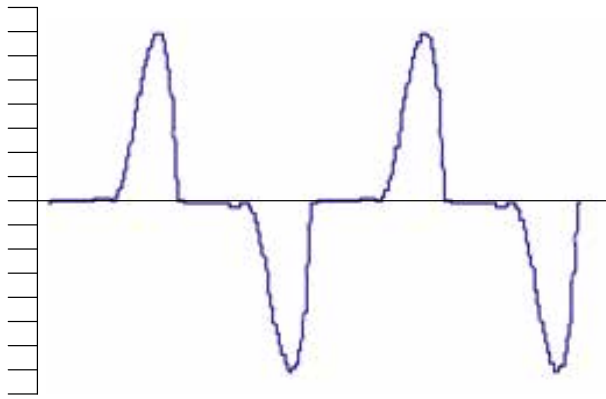


Figure 6: Line current where one phase of the rectifier is no longer conducting

The larger the voltage supply imbalance, the more single pulse shape the AC line current waveform becomes. Again, the same amount of watts is required so the amplitude of the waveform needs to increase as the duration decreases to maintain the area. Line current significantly increases with larger voltage imbalance as shown in Figure 6.

Increased line current flows through the diodes and associated capacitors of the rectifier, increasing the stress on these components and the heat generated as a result of the increased switching load. Ripple on the supply line appears due to the high switching frequency, which leads to the existence of uncharacteristic triplen harmonics.<sup>1</sup>

Most modern VSD's found in today's industrial plants have a Pulse Width Modulator (PWM) rectifier, where unbalanced voltage supplies will produce increased line current—a 100Hz ripple on the DC bus of the VSD and a reactive power (kVAR) increase. These phenomena can cause the VSD to trip on over current, or under voltage on the DC bus. Technicians may have difficulty tracing a fault as the connected load may not show any immediate or obvious faults.

### Correcting unbalanced voltage supply

It is near impossible to supply industrial plants with a perfectly balanced voltage. As single phase loads are distributed unevenly or switched unpredictably, the power supply system will always contain a degree of asymmetry and there is little to no control of events on the transmission or distribution network.

The PCS100 AVC-20 designed and manufactured by ABB, is purpose built to provide continuous balanced voltage at the utility supply level. Whether the unbalanced voltage is a result of an unstable network supply or unbalanced single phase loading within the plant, the PCS100 AVC-20 will correct up to a 20% unbalanced voltage continuously, even if the voltage imbalance is permanently present on the supply.

Where the unbalanced voltage continually and randomly fluctuates due to either network issues, or loads and faults within the customers' installation, the PCS100 AVC-20 will correct the unbalanced voltage within 20 milliseconds, or less than one cycle, and continue to correct and adjust the level of correction as necessary to  $\pm 1\%$  of the set nominal voltage.

The presence of an appropriately sized PCS100 AVC-20 on the low voltage supply to your industrial plant can help to eliminate all the issues, process interruptions, premature aging and costs that unbalanced voltage supply to 3 phase induction motors and 3 phase rectifiers found in industrial plants can cause.

To find out more about ABB's PCS100 AVC-20 solutions:  
[www.abb.com/ups](http://www.abb.com/ups)

## References

1. **Bollen, M. H.** (2000). Understanding Power Quality Problems: Voltage Sags and Interruptions (1 ed.). (P. M. Anderson, Ed.) Gothenburg, Sweden: IEEE Press
2. **Christopherson, N.** (n.d.). Protecting Motors From Improper Voltages and Amperages. Retrieved October 20, 2015: <http://web.fscj.edu: http://web.fscj.edu/Mark.Bowman/handouts/Protecting%20Motors%20From%20Improper%20Voltages%20and%20Amperages.pdf>
3. **Gosbell, V., Perera, S., & Smith, V.** (2002). Voltage Unbalance. University of Wollongong, School of Electrical, Computer & Telecommunications Engineering. Wollongong: University of Wollongong. Retrieved October 20, 2015: <http://www.elec.uow.edu.au/apqrc/content/technotes/technote6.pdf>
4. **Kazem, H., Zahawi, B., & Giaouris, D.** (2009, February). Modelling of Six-Pulse Rectifier Operating Under Unbalanced Supply Conditions. ARPJ Journal of Engineering and Applied Sciences, 4(No. 1), 71-75. Retrieved October 21, 2015: [https://www.staff.ncl.ac.uk/damian.giaouris/pdf/Papers/jeas\\_860.pdf](https://www.staff.ncl.ac.uk/damian.giaouris/pdf/Papers/jeas_860.pdf)
5. **Pillay, P., Hofmann, P., & Manyage, M.** (2002, December). Derating of Induction Motors Operating With a Combination of Unbalanced Voltages and Over or Undervoltages. IEEE Transactions on Energy Conversion, 17(4), 485 - 491. Retrieved October 19, 2015: <http://users.encs.concordia.ca/~pillay/12.pdf>

## Author

Bruce Bennett  
 ABB Limited, DMPC  
 Napier, New Zealand

## Note:

We reserve the right to make technical changes or modify the contents of this document without prior notice. With regard to purchase orders, the agreed particulars shall prevail. ABB does not accept any responsibility whatsoever for potential errors or possible lack of information in this document. We reserve all rights in this document and in the subject matter and illustrations contained therein. Any reproduction, disclosure to third parties or utilization of its contents – in whole or in parts – is to aggregate the load shedding capabilities of multiple facilities forbidden without prior written consent of ABB.