The five-level converter

ANPC-5L technology and the ACS 2000 drive

FREDERICK KIEFERNDORF, MICHAEL BASLER, LEONARDO SERPA, JAN-HENNING FABIAN, ANTONIO COCCIA, GERALD SCHEUER – Modern power electronics have revolutionized the delivery and usage of electrical power. In the area of drives, the ability to arbitrarily select and even continuously vary the output voltage frequency and amplitude of an inverter has permitted significant gains in energy efficiency and controllability. Inverters synthesize AC voltage by switching between different levels of DC voltage at a high frequency using semiconductors. The waveform created thus differs from an "ideal" sinusoidal waveform because of this rectangular switching pattern. The difference can be sufficient to bar the use of drives from many applications requiring a higher "quality" of AC voltage. One way to make the energy-efficient advantages of drives available to a broader range of applications is to increase the number of DC voltage levels available. ABB's ACS 2000 breaks beyond the commonly used three voltage levels and works with five. Furthermore, through its ingenious topology, it avoids many of the issues that otherwise make five-level converters complex.

An inverter (a circuit that converts DC to AC) works on the principle of switching between different levels of DC voltage. The output is thus not a sine-shaped AC wave but a pattern of high-frequency rectangular pulses that are made to resemble the sine wave as accurately as possible ➔ 1c. One analogy would be to consider a digital photograph taken at low resolution. The photograph does not accurately resemble the object it depicts because the low number of pixels limits the level of detail that can be represented. The ability to approximate an ideal sine wave with rectanglar pulses is similarly restricted by the number of available voltage levels. In contrast to the photograph, however, the differences are not just an aesthetic problem: The non-ideal sine shape causes harmonics (currents and voltages at higher frequencies) that can have repercussions ranging from stress on the insulation and bearings of motors to interference with other equipment. Harmonic filters can be used to smooth the output by absorbing problematic harmonics, but these are both a cost factor and a cause of additional losses. To deal with the effects of these harmonics, either motors must be designed to handle the extra stresses (which then excludes the use of many standard catalog motors) or such converters cannot be added to existing applications. There is therefore a strong case for a converter that can produce a more ideal sine output.

Inverter levels

The simplest inverter is the two-level converter. It is called two-level because it can apply only two voltage levels: the DC supply voltage and the reverse of that voltage. The three-level neutral-point clamped (NPC) converter is an extension of this concept that can additionally apply the neutral point voltage ➔ 1a and produce switching patterns of the type shown in ➔ 1c.

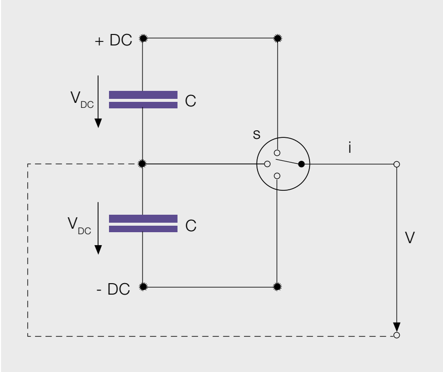
Converters have been designed that take a step beyond this and output five voltage levels. However, such circuits often come at the price of far higher complexity. For example, if the DC supply were to be built with five rather than three voltage levels, it would require additional clamping diodes and capacitors and the corresponding control and charging circuitry. An alternative approach is to connect converters in series. This again adds to the complexity of the DC supply circuit due to the need for galvanic separation of the supplies and thus costly transformers. Such solutions may be acceptable at high power levels, but the lower end of the medium-voltage drive range calls for simpler solutions.

ABB set out to address these issues, and found a solution that can output five power levels without adding complexity to the DC supply. A three-level DC supply alone cannot supply five voltage levels, and so the circuit does require an additional capacitor per output phase. But the solution ABB created ingeniously keeps this capacitor charged without the need for dedicated control circuitry.

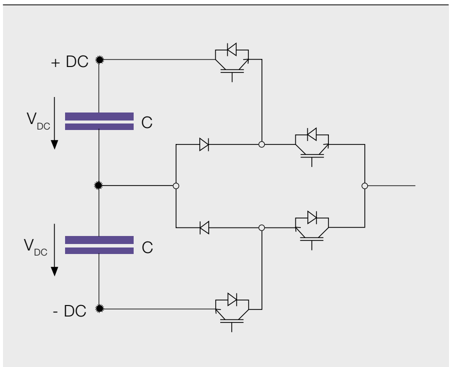
The ANPC-5L

The basics of the active neutral point clamped five-level (ANPC-5L) converter are shown in ➔ 2a. The phase capacitor C_{ph} is kept charged to half the voltage of the capacitors in the DC link, ie, one quarter of the total DC-link voltage. The overall principle of the circuit can be considered as a three-level NPC converter plus an additional capacitor. This phase capacitor is switched in series with the three-level converter as required and provides two additional intermediate output levels.

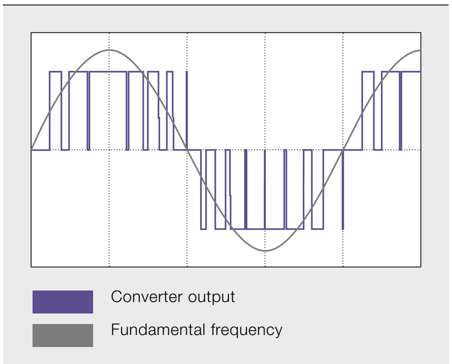
1 The basics of an NPC converter (only one phase shown)



1a Principle of operation



1b Circuit



1c Voltage waveform (sample)

The ANPC-5L requires only one more capacitor per phase than a NPC three-level converter.

The DC supply is identical to that of a three-level NPC converter. Cell 1 in → 2b is clearly similar in its topology to a NPC three-level converter → 1b. Similarly to such a circuit, the IGBT (insulated gate bipolar transistor) switching devices in cell 1 are rated for half the DC link voltage. Because the additional capacitor is charged to a quarter of the DC-link voltage, the IGBTs in cells 2 and 3 are rated for this lower voltage. This use of devices with lower ratings contributes to the simplicity of the converter. The elegance of the design becomes even more apparent when it is considered that it requires only one additional capacitor per phase than does an NPC three-level converter. The converter provides full four-quadrant functionality (power can be converted in both directions).

Operation of the ANPC-5L

The switching devices in cell 1 (of → 2b) are operated in complementary fashion, with S1 and Snp2 being operated together (and likewise S4 and Snp1). The devices in cell 2 are operated in opposition as are those in cell 3. The total number of switching states per phase is shown in → 3. In total, eight states are possible. As the converter has only five output levels, some states are redundant. However, rather than implying that certain converter states are never used, the study of → 3 reveals that for two of the three redundant state pairs, ie, V1/V2 and V5/V6, opposite effects can be made on the charging of the phase capacitor. → 4 compares V5 and V6, and shows how V6 subtracts $V_{DC}/2$ from the DC-link voltage whereas V5 adds it to the neutral point voltage. As a result the current through the phase capacitor is in the opposite direction. This feature can be used to maintain the required voltage in the phase capacitor without any further charging circuitry.

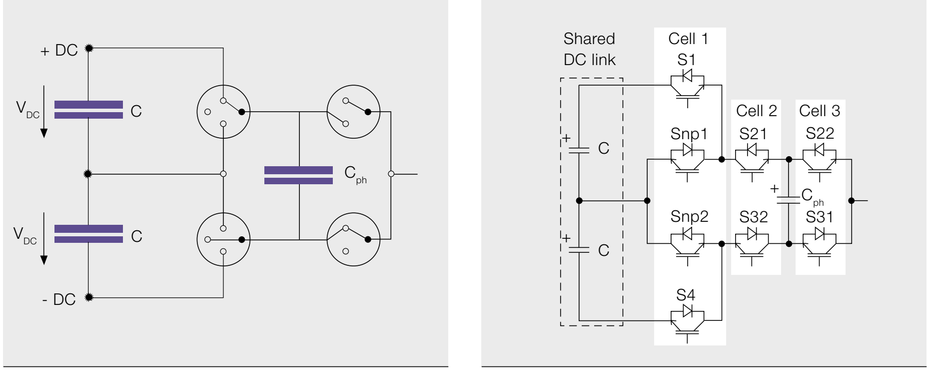
The ACS 2000

The ACS 2000 drive uses two five-level converters in a back-to-back (B2B) configuration. The basic layout of the ACS 2000 is presented in → 5.

Mechanical design

The transformerless ACS 2000 → 6, is designed to maximize uptime through its modular construction. Components are sized to fulfill the expected lifetime and easy front-side access is provided for all critical components. The drawer design

2 Principle of the ANPC-5L converter (only one phase shown)



2a Principle of operation

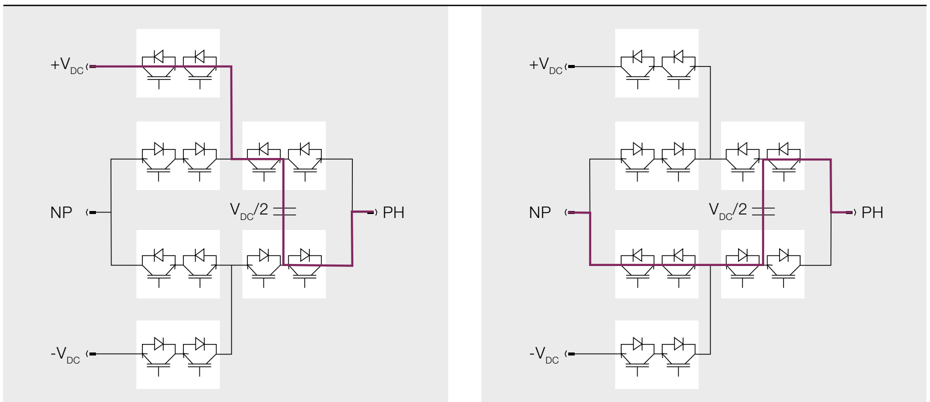
2b Circuit

The capacitor C_{ph} is kept charged to half the voltage of a DC-link capacitor.

3 Phase states of ANPC-5L converter

Cell 3 S4	Snp2	Snp1	S1	Cell 2 S32	S21	Cell 1 S31	S22	Output level	Phase output voltage	Effect on Cph i>0	i<0	Effect on Vnp i>0	i<0	Switching vector
1	0	1	0	1	0	1	0	–2	–V	0	0	0	0	V0
1	0	1	0	1	0	0	1	–1	–V/2	–	+	0	0	V1
1	0	1	0	0	1	1	0	–1	–V/2	+	–	–	+	V2
1	0	1	0	0	1	0	1	0	0	0	0	–	+	V3
0	1	0	1	1	0	1	0	0	0	0	0	–	+	V4
0	1	0	1	1	0	0	1	+1	V/2	–	+	–	+	V5
0	1	0	1	0	1	1	0	+1	V/2	+	–	0	0	V6
0	1	0	1	0	1	0	1	+2	V	0	0	0	0	V7

4 Two different current paths both producing the same output voltage.

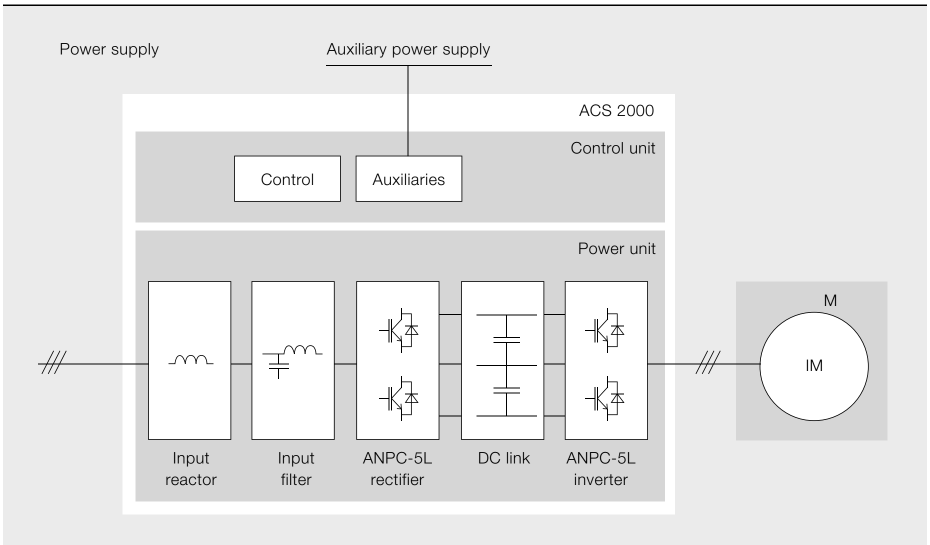


4a Switching state V6 from → 3

4b Switching state V5 from → 3

The opposite direction of the current in C_{ph} permits the charge of this capacitor to be maintained.

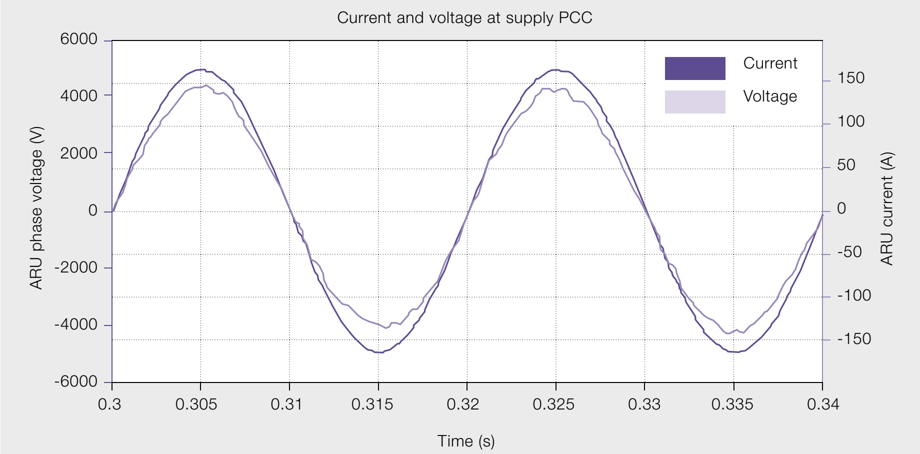
5 Basic configuration of ACS 2000 drive



6 800kW 6kV transformerless ACS 2000 drive

7 ACS 2000 phase module

8 Voltage and current of drive input showing unity power-factor operation



The transformer-less ACS 2000 drive is designed to maximize uptime through its modular construction.

of the phase modules facilitates quick and safe replacement in case of faults.

A key component of the modular concept is the phase module ➔ 7. The module comprises the main components of one phase leg of the converter (as shown in ➔ 2b), including the power semiconductors, the gate unit and the phase capacitor. The module additionally contains an interface board to the upper-level control as well as current and voltage measurement equipment. This allows a simple interconnection as only a power connection and a fiber-optic link need to be established. The current-carrying connections are realized as contact plugs.

Thanks to this simplicity, the end user can replace a module within minutes.

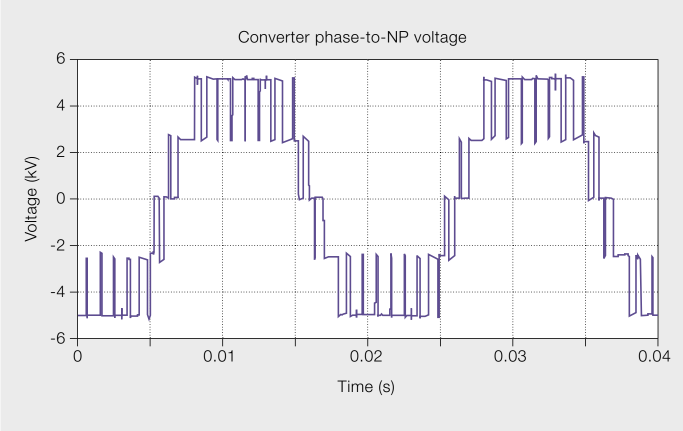
Testing

The ACS 2000 was tested in a B2B configuration. Two ACS 2000 drives were installed: the DUT (device under test) and a load inverter. Both drives were supplied from a common three-phase network connection and were connected to their respective electric machines (which were on a common shaft). One practical result of this interconnection is that only the losses in the drive system have to be covered by the supply. As both drives (DUT and loading inverter) were ACS 2000, it was possible to observe the motoring and regenerating modes simultaneously. Long-term B2B tests were also performed to verify the high reliability of the drives.

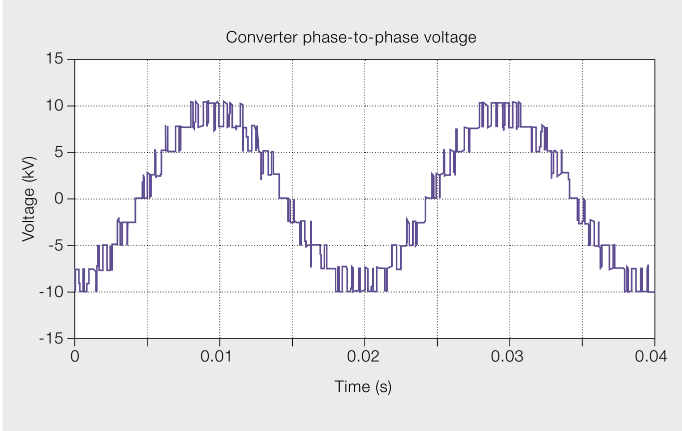
Input and output performance

The rectifier performance is illustrated in ➔ 8. The five-level inverter delivers a nine-level phase-to-phase voltage to the

9 Voltage waveforms from measurements



9a five-level waveform (phase to neutral point)



9b nine-level waveform (phase-to-phase)

motor. Typical voltage and current waveforms are shown in ➔ 9. The new five-level inverter produces an output that is pleasingly close to sinusoidal and meets the requirements for driving motors that were designed for direct-on-line (DOL) connection without needing to derate them.

Riding through outages

The combination of multilevel ANPC-5L technology and the dynamic performance of direct torque control can be used to prevent a trip of the drive, even in the case of a mains power outage lasting several seconds. Operation can also continue when certain auxiliary supplies fail for a limited time. The maximum sustainable duration of a power outage depends on the load, the machine and the operating point before the occurrence of the outage.

During ride-through operation, the voltage of the DC link is kept at a specified level to maintain the magnetization of the machine. For this purpose, energy from the rotating mass of the motor and the load is fed back through the inverter to compensate the losses and maintain the DC-link voltage. The ride-through mode can be maintained as long as the rotating mass has sufficient energy to supply these needs. When the main supply voltage is restored, the acceleration of the machine back to the desired speed commences immediately.

Field measurements made on an actual customer installation are illustrated in ➔ 10. The grid power outage lasted one second. ➔ 10a shows the grid voltage and input current dropping to zero. In ➔ 10c, the motor torque regenerates during the outage to maintain the DC-link voltage ➔ 10b. When the grid voltage returns, the torque quickly reverts to motoring mode.

The combination of multilevel ANPC-5L topology and the dynamic performance of direct torque control can be used to prevent a trip of the drive, even in the case of a mains power outage lasting several seconds.

Applications and success

The ACS 2000 is designed for diverse fields of application in various industries within the general purpose drives market as shown in ➔ 11.

Award winning drive

In December 2010, the consultancy company, Frost and Sullivan, recognized the ACS 2000 with the 2010 European Medium-Voltage Drives New Product Innovation Award. Frost and Sullivan said “the product offers benefits such as flexible line supply connections, lower harmonics, reduced energy consumption,

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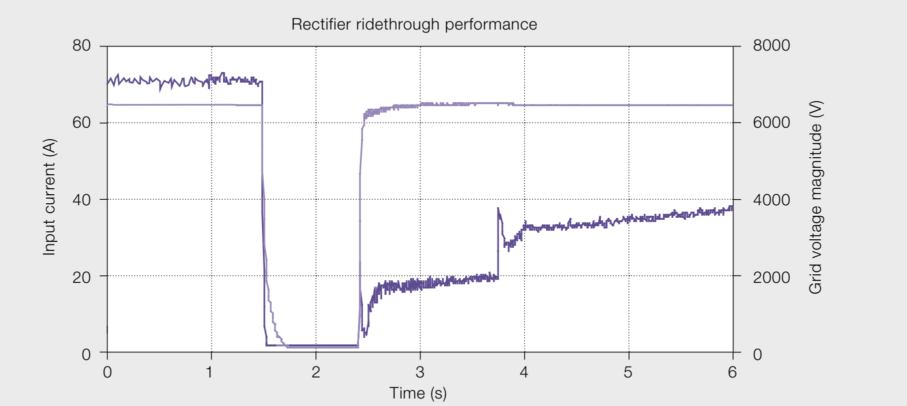
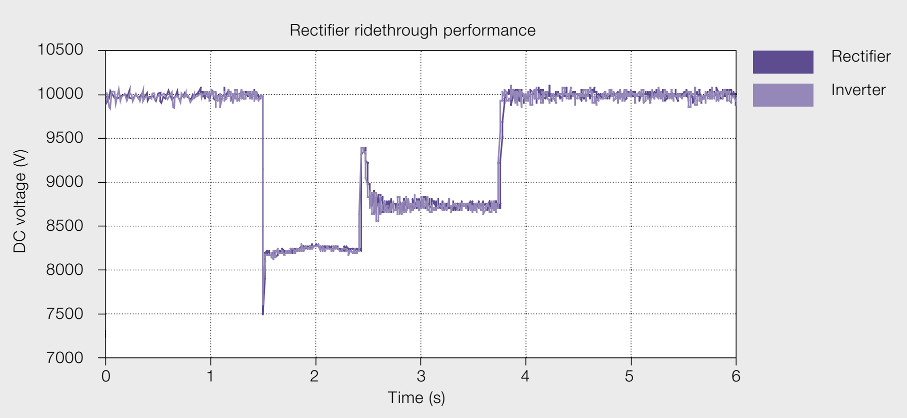
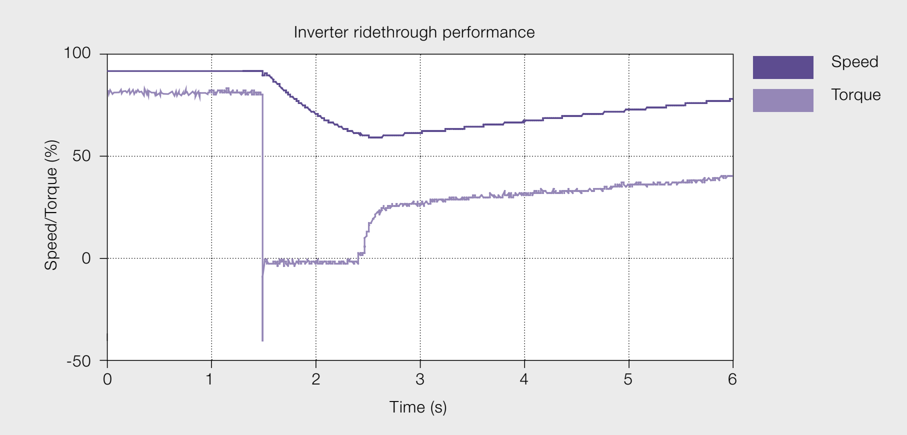
10 Surviving a short power outage: measurement of ride-through mode



10a Supply



10b DC link voltage



10c Output performance

11 Target industries and applications of the ACS 2000

Industries	Applications
Cement, mining and minerals	Conveyors, crushers, mills, fans and pumps
Chemical, oil and gas	Pumps, compressors, extruders, mixers and blowers
Metals	Fans and pumps
Pulp and paper	Fans, pumps, refiners, vacuum pumps and chippers
Power generation	Fans, pumps, conveyors and coal mills
Water	Pumps
Other applications	Test stands and wind tunnels

ease of installation and commissioning, high reliability and lower cost of ownership. The only drive with voltage source inverter (VSI) topology, transformerless design and patented multi-level IGBT control, ACS 2000 marks a milestone in the medium-voltage (MV) drives segment [. . .] The product offers a range of value added features, including simple installation, commissioning and operation. Such attributes are critical from the end-user perspective."

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Further reading

The technical part of this article is based on a paper presented at a symposium in Pisa in June 2010. Due to space constraints, the present article was shortened considerably with respect to the original paper and readers interested in further details are recommended to read the original version [1].

The authors would like to acknowledge the contributions of current and former colleagues in the development of this technology: P. Barbosa, N. Celanovic, M. Winkelnkemper, F. Wildner, C. Haederli, P. Steimer, J. Steinke, and many others.

Reference

[1] Kieferndorf, F., Basler, M., Serpa, L. A., Fabian, J.-H., Coccia A., Scheuer, G.A. (2010, June). ANPC-5L technology applied to medium-voltage variable-speed drives applications. Paper presented at the International Symposium on Power Electronics, Electrical Drives, Automation and Motion, Pisa, Italy. CD-ROM Proceedings.

Title picture

Drives are ubiquitous in plants and industries and come in all power classes ranging from small fans to large crushers. The cover picture shows the Torrevaldaliga Nord power plant in Italy.