

# A higher level of efficiency

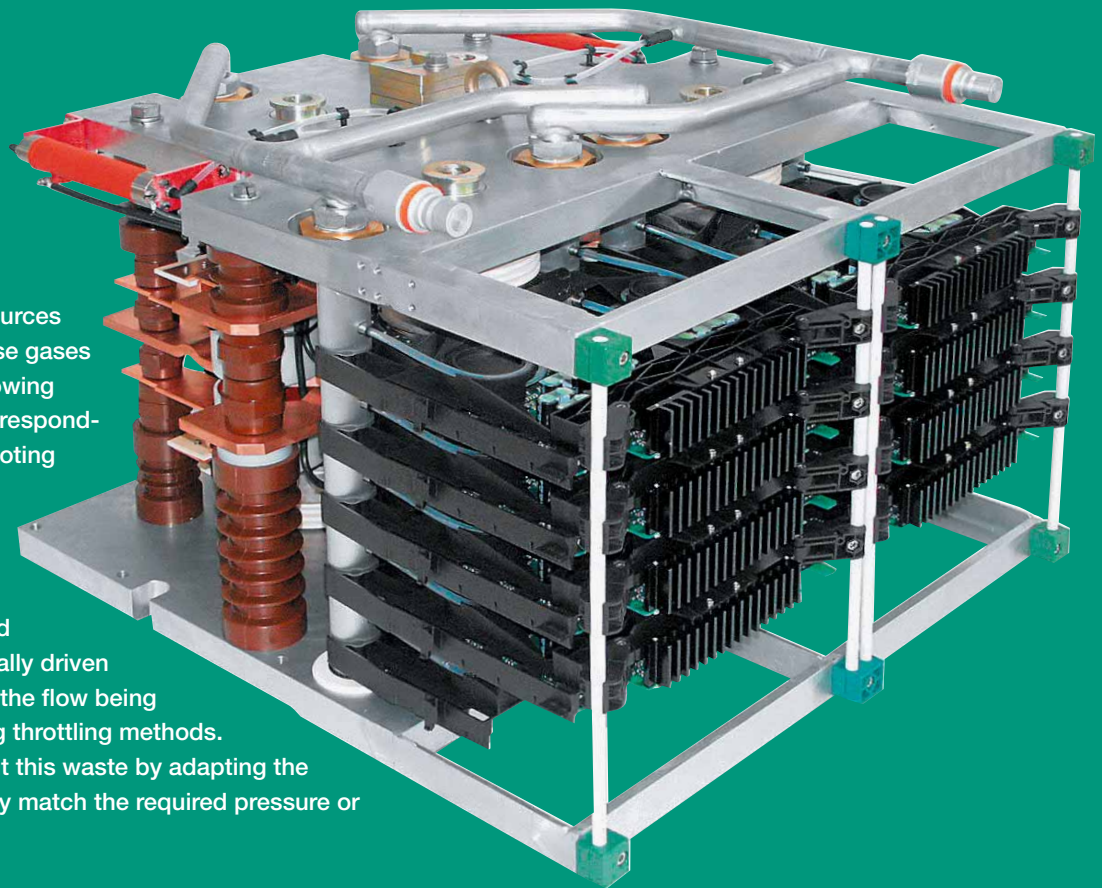
Five-level frequency converters for medium voltage  
Pieder Jörg, Gerald Scheuer, Per Wikström

The depletion of energy resources and the release of greenhouse gases into the atmosphere is of growing concern to mankind. ABB is responding to the challenge by promoting energy efficiency.

One area with huge potential for savings is in motors that operate fans, pumps and compressors. These are usually driven by fixed-speed motors, with the flow being controlled by energy-wasting throttling methods. Frequency converters cut out this waste by adapting the speed of the motor to directly match the required pressure or flow.

So is the problem solved? Not totally. There are two basic problems to be overcome in designing frequency converters for medium voltage: These are reaching the voltage of the motor and getting closer to an ideal sinusoidal voltage. ABB's innovative solution lies in the re-combination of existing solutions to solve both of these problems.

A five-level arrangement means there are five output levels instead of the usual two or three. This step delivers a considerable improvement in the waveform, while at the same time achieving a higher output voltage. And to crown the success, the innovation was realized by drawing largely on proven concepts, reducing risk and bolstering reliability.



Traditional control strategies for flow control usually rely on wasteful “throttling methods.” To use a simple analogy, this is like driving a car by placing a brick on the gas pedal (fixed supply) and using the brake pedal for speed control (friction-based throttle). Frequency converters are the variable gas pedals of motor control, and represent a huge potential for energy savings.

Motors consume around 30 percent of all the electric energy produced in the world. About three-quarters of all motors power pumps, fans or compressors used in applications where energy consumption can be reduced through speed control. An ABB estimate shows that the worldwide adoption of such frequency converters in medium voltage drives can deliver savings of 227 TWh – in other words, the output of 144 fossil fuel power plants or the total energy consumption of a country such as Spain<sup>1)</sup>.

At present, less than ten percent of all motors sold every year are equipped with the most efficient speed control that exists: the frequency converter. Despite also being the least maintenance-intensive means of motor control available, customers are still opting for other means of control in the majority of cases. Why? The most frequently mentioned barriers for adopting the technology are:

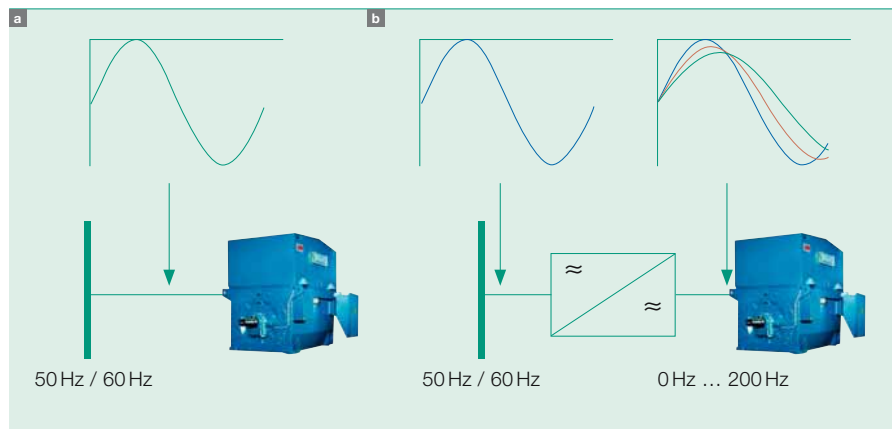
- reliability
- harmonics
- cost and/or very short payback requirements

ABB’s innovative five-level switches address all of these challenges.

### Better waveforms, higher voltages

Electricity generated in the traditional manner using a synchronous generator has a sinusoidal output voltage. Electric motors that are connected directly to the mains grid (direct-on-line connection) and hence operated at fixed speed are optimized for this type of waveform. If the same motor

1 A motor connected direct-on-line **a** and with a frequency converter inserted between the main grid and the motor **b**



design is to be used for a variable speed application, the frequency converter should deliver a waveform that is as close to the ideal sinusoidal shape as needed. Deviations from the ideal waveform lead to additional heating of the motor. This in turn means the motor cannot be used to its full power and must be de-rated. Another negative implication is that a superimposed torque ripple can cause torsional oscillations in the drive-chain and machinery.

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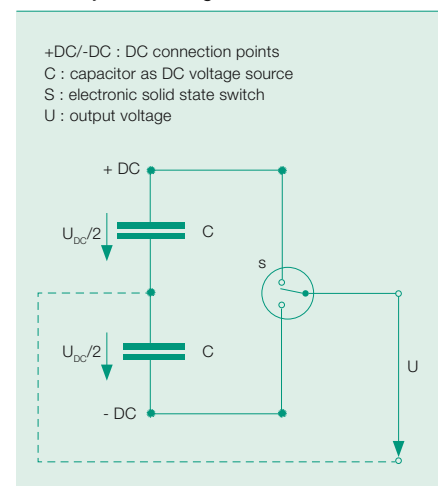
Furthermore, motors come in standardized voltage classes. For the medium voltage (MV) range of motors for powers of up to about 7000 kW, the most frequent voltages found on industrial sites are 6 kV/50 Hz and 4 kV/60 Hz. This means that, in order to use the same range of motors in both direct-on-line connections **1a** and with frequency converters **1b**, the output of the frequency converters has to be able to attain similar voltage values.

Such output voltages are not easy to attain with traditional two- and three-level converters as the maximum output voltage is determined by the voltage ratings of the power semiconductors.

### Inside a frequency converter circuit

The energy conversion in a converter is realized in two steps: In the first, the energy supply in the form of a sinusoidal voltage at fixed frequency and constant amplitude is “rectified” into a DC-voltage or DC-current. This DC-quantity is then, in a second step, “inverted” into an AC-voltage or current whose frequency and amplitude are variable. Both the rectifier part and the inverter part of this conversion are realized by electronic circuits built up of electronic switches. This article is primarily about the

2 Phase representation of a two-level voltage source inverter by means of an ideal switch, fed by a DC-voltage source

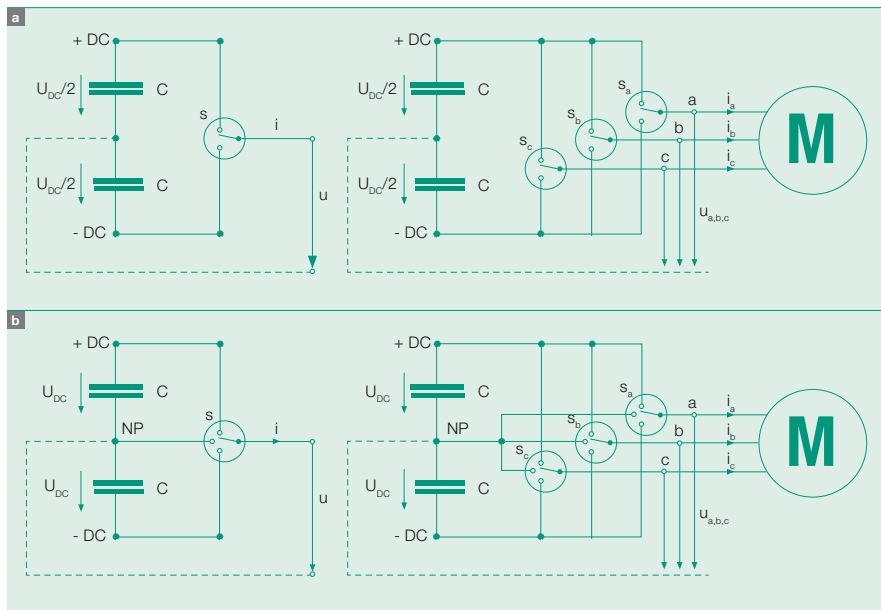


### Footnote

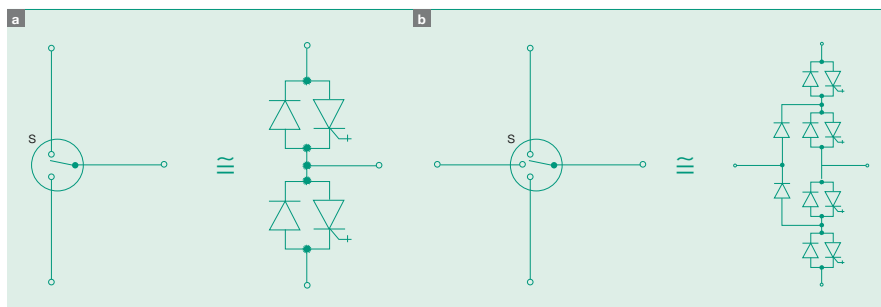
<sup>1)</sup> See also Wikstroem, P., Tolvanen, J., Savolainen, A., Barbosa, P., Saving energy through drive efficiency, ABB Review 2/2007, 73–80 (especially pages 74–76).

Product innovations

3 Two-level inverter with split capacitor **a** and three-level inverter **b** (conceptual drawings)



4 Although the switches in converters are often represented as simple contacts (left), they do in fact integrate a larger number of semiconductor components (right). **a** shows a two-level phase leg and **b** its three-level equivalent



Factbox 1 Semiconductors: 50 years of development in switching

In the past 50 years, ABB has established and maintained a leading position in the field of power electronics. Frequency converters for motors are an essential part of this business.

Electronic switches are at the heart of every frequency converter. The story of the emergence of five-level switching, is best introduced by a brief tour of the evolution of these devices.

Readers who have been following the development of these devices long enough will remember that the first high-power electric drives were based on line-commutated thyristors. These thyristors can be designed for high currents and high blocking-voltages (present-day versions reach values of

8–10 kV). Their major drawback is that they can be switched on at any given point but cannot be switched off (they remain on until an external effect causes the current to stop flowing). This feature limits the available switching strategies, and by consequence the suitability of such circuits from a power quality point of view (see two-level switching in **7a**).

Converters using these switches create harmonics of high magnitude and relatively low frequency. Such harmonics cause problems both on the supply and the motor side. Moreover, the power factor on the network side varies over the operating range of the frequency converter. Line side problems have been addressed by using filters. The motor side problems are dealt with by dimensioning the motor to cope with the additional heating and to

design the shaft and couplings according to the requirements called for by torsional oscillations. At the time, this was considered acceptable because there was no other solution that could compete. In fact, it is still the preferred solution for very high power applications (20 MW and above) because of its reliability. However, with the arrival of new switching components, new topologies that provide voltage waveforms much closer to the ideal sinusoidal shape can be implemented. The new components, all of them differently optimized transistors such as IGBTs (Insulated Gate Bipolar Transistors) and IGCTs (Integrated Gate Commutated Thyristors), are characterized by the fact that they can be switched off arbitrarily.

Most ABB converters are so-called Voltage Source Inverters (VSIs). **2** shows the simplest topology of a VSI: A single output phase of the frequency inverter is alternatively connected to one or the other pole of a large DC-capacitor. It is the purpose of the rectifier circuit (not shown) to ensure that this capacitor is kept charged to a fixed DC-voltage. If an AC-voltage is to be generated, the switch in the inverter circuit needs to change positions (ie, change the output voltage) at least once every half cycle. If an output of 50 Hz is required, for example, the switch should change to each of its two positions at least 50 times per second.

In practice, the switch is usually “flipped” much faster than this. A digital controller is used to direct its switching status. The switching strategy of this controller determines not only the frequency but also the average voltage across the load. These levels are modified by adjusting the input values of this unit as desired. This control strategy is known as Pulse Width Modulation (PWM).

In reality, the switch is not a moving contact as the diagrams suggest, but is

built up from power semiconductor devices **4a**. The development and capabilities of such switches has, since the first emergence of such converters, been dependent on progress in power semiconductors

**Factbox 1.**

### Ready for the next level

Although the two-level VSI voltage waveform as shown in **7a** can be varied in amplitude and frequency by means of PWM, the shape of the output is far from sinusoidal. As a result, the harmonic current distortion, and hence additional losses and the resulting heat generation in the motor, are high. One way to render the voltage waveform more desirable is to introduce more voltage levels. To introduce another simple analogy, this is similar to increasing the resolution on a computer monitor to make the graphics sharper.

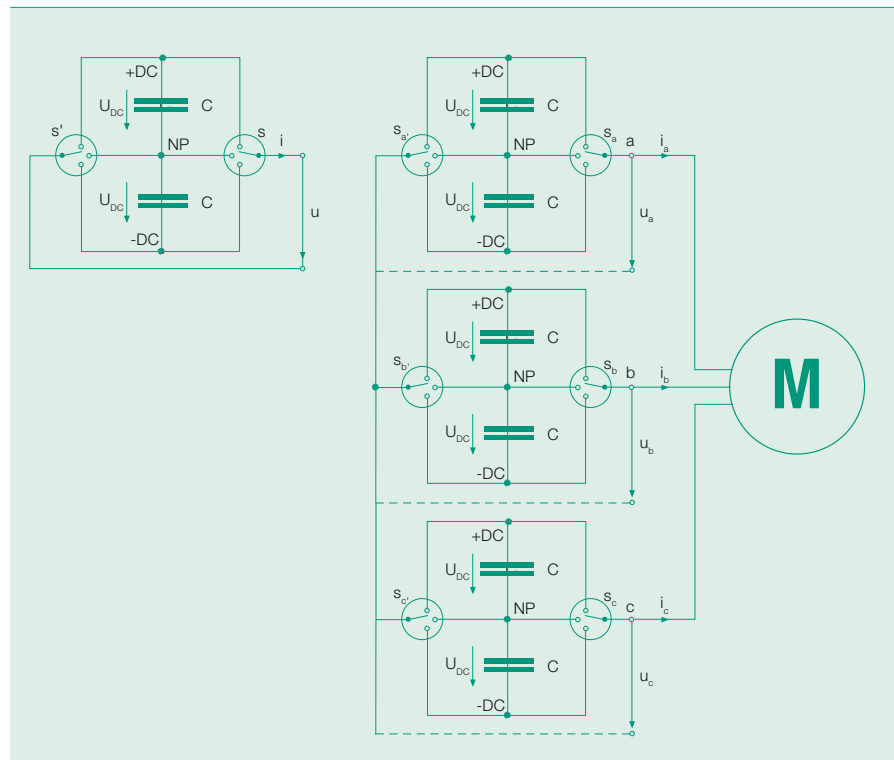
## ABB's ACS 5000 converter uses five-level technology

A further reason for wishing to move away from the two-level arrangement is that the highest output voltage that can be achieved with the two-level

VSI topology and modern power semiconductors is 2.3 kV. This is not enough for the standard range of medium voltage motors.

The topology with two capacitors and an electronic three-position switch, which is also referred to as the three-level inverter because of the number of output voltage combinations per

**5** Concept of the new innovative five-level inverter phase (left) and the complete three-phase motor drive with nine-level phase-to-phase voltage



**6** ABB's ACS 5000 converter uses five-level technology, delivering a nine-level phase-to-phase voltage to the motor



Product innovations

phase, has been known for some time. **3b** shows a conceptual schematic with a three-position switch. This circuit has to switch any of the three connection points of the capacitors to the output for both current directions<sup>2)</sup>. For specific voltage and current ratings, ABB has standardized this electronic three-position switch **4b** as a Power Electronic Building Block (PEBB). This standardization provides the advantage that the same building blocks are used in different applications, permitting ABB to collect field experience much more quickly and so fine-tune the design, providing higher reliability for the customer.

Increasing the number of levels drastically improves the waveform.

For about a decade, these building blocks have been used for different products and systems, including converters for variable speed drives (eg, in the ACS 1000 and ACS 6000 drive units), energy storage systems and power quality systems.

The five-level evolution

Combinations of a higher number of capacitors and increasingly complex electronic circuits have been discussed in academia for some time. Usually, however, such suggestions did not fit established technologies for capacitor energy storage, nor were they compatible with the properties of the semiconductor switches the market had to offer. Furthermore, such

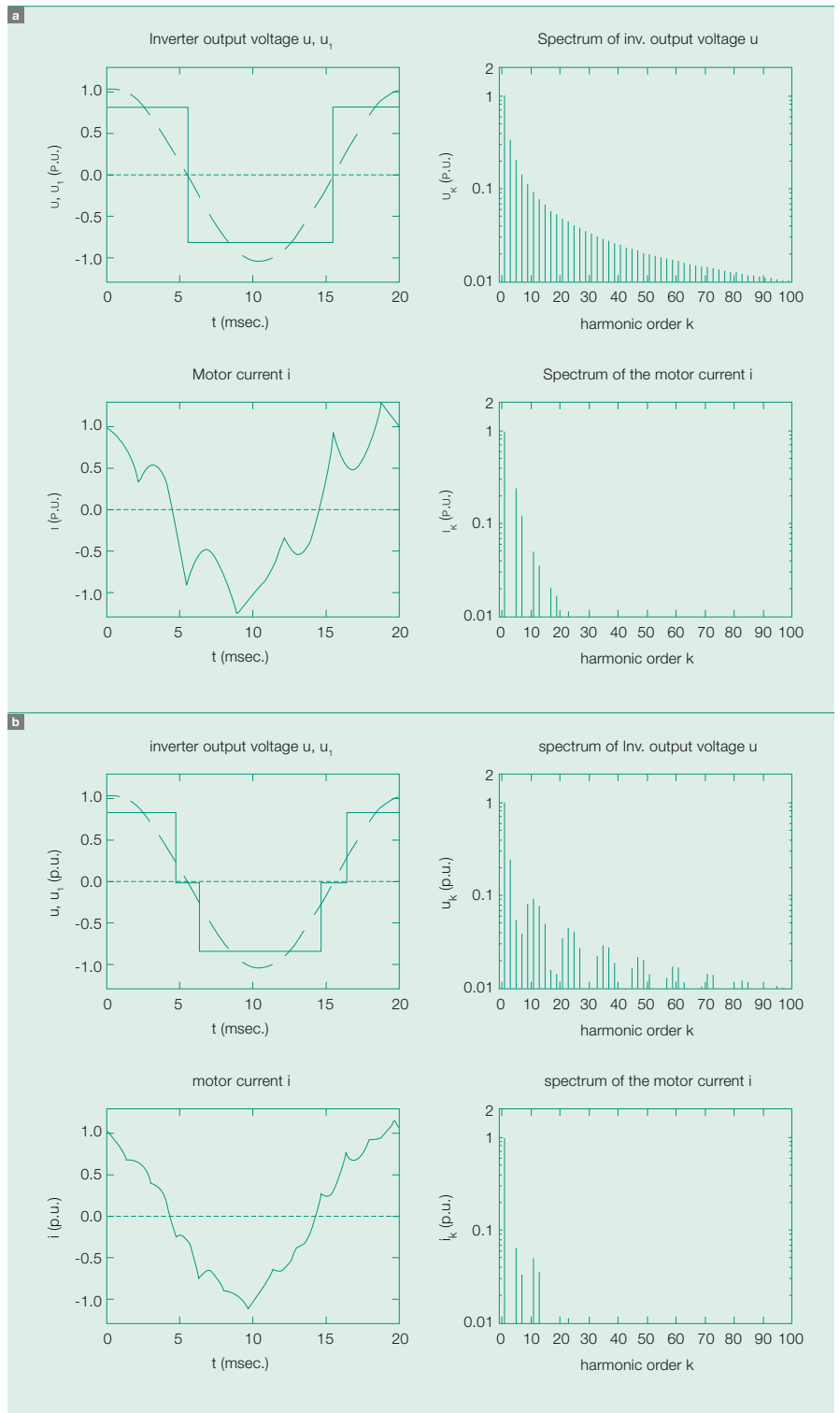
Factbox ABB drives product range

ABB, as the leading supplier of drives, offers the complete range of variable speed drives for applications in the power range of 0.12kW to over 100MW.

The company serves utilities and industrial customers in the cement, mining & minerals, chemical, oil & gas, marine, metals and pulp & paper industries.

For further information, visit [www.abb.com/drives](http://www.abb.com/drives)

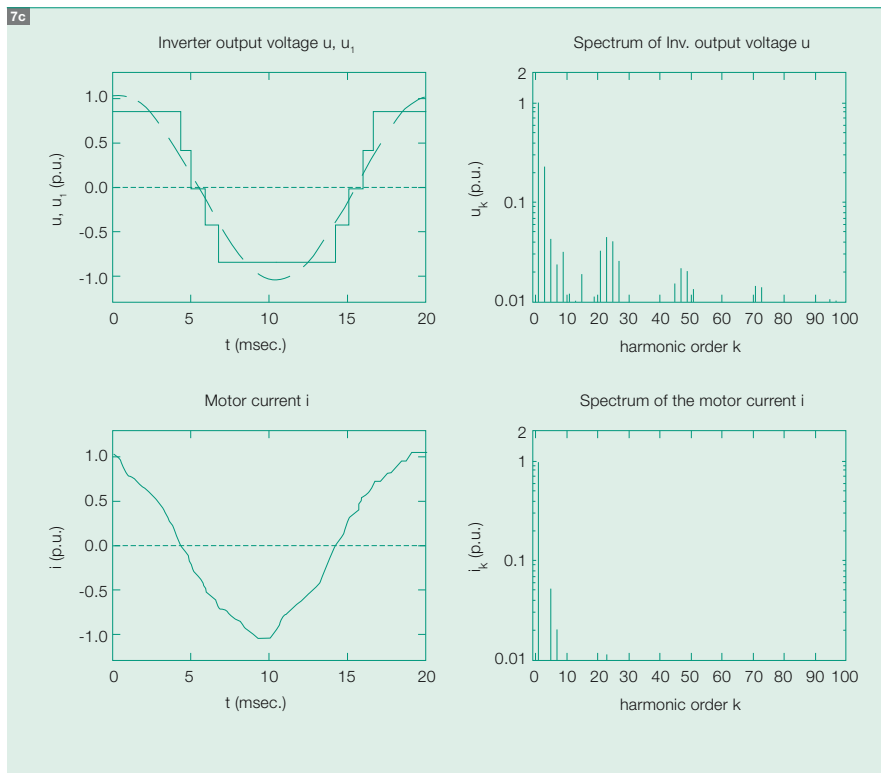
7 Increasing the number of levels from two **a**, through three **b** to five **c** drastically improves the waveform, even for the minimal switching frequency as shown



solutions allowed little re-use of existing building blocks, and their reliability figures were questionable due to a high parts count.

For the latest addition to its family of medium voltage drives, the ACS 5000,

ABB engineers looked back at traditional thyristor-based products such as cycloconverters and – with the available three-level building block of **4b** in mind – came up with an astonishingly simple solution for a product with five output voltage levels (and



A 5-level power electronic building block easily slides into the drive on rails



hence nine levels phase-to-phase) **8**. This was achieved by applying the proven three-level technology in relation to the star point of the electrical system independently for each phase.

The conceptual circuit **5** is derived from identical existing building blocks S and S' respectively.

The well-established technology of the three-level inverter is re-used in an innovative configuration.

**Why five levels?**

The phase-to-phase voltage waveform of a two-level inverter and a three-level inverter are compared with that of the new five-level converter **7c**. The five-level inverter used in the ACS 5000 **6** delivers a nine-level phase-to-phase voltage to the motor **8**. Just from looking at the waveform, it already becomes obvious that the new five-level inverter produces an output that is much closer to the ideal sine wave. In fact, the result is so convincing that it is

now possible to use motors designed for direct-on-line connection without needing to de-rate them. This presents the optimal solution for a 6 kV converter today.

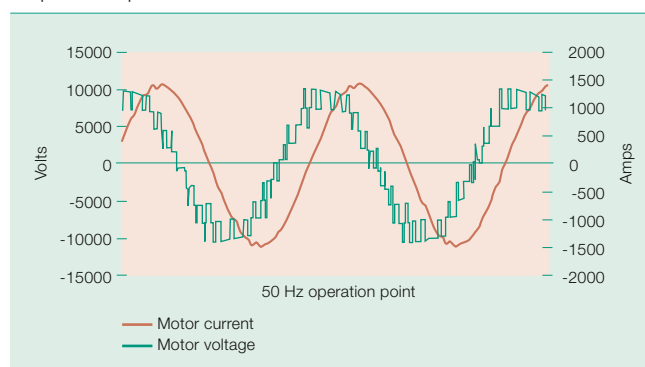
Would adding further switching levels be a goal to further improve waveforms? Such attempts would significantly add to complexity without delivering proportional benefits. In particular, the reliability of the drive would get worse due to the higher parts count.

**Proven solutions**

ABB has found a surprisingly simple way of creating near-sinusoidal volt-

age waveforms with a frequency converter largely based on proven, existing components. The well established technology of the three-level inverter is re-used in an innovative configuration, providing five-voltage levels per phase, or even nine-voltage levels phase-to-phase. The full re-use of basic power electronic building blocks allows these excellent output waveforms to be achieved with proven reliability. The goal to use standard motors is reached while maintaining high efficiency with a low parts count.

**8** Using a five-level converter, the output voltage reaches nine levels phase-to-phase



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**Footnote**

<sup>2)</sup> Most high-power semiconductor devices can conduct current in only one direction.