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DISCONTINUOUS PWM TECHNIQUES IN THREE-PHASE POWER CONVERTERS

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ABSTRACT

Johannes Kujala: Discontinuous PWM techniques in three-phase power converters
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Discontinuous pulse-width modulation (DPWM) techniques are used three-phase power converters to improve their efficiency. When power losses are reduced, less cooling equipment is needed. Therefore, smaller devices can be manufactured with fewer expenses. In this thesis, various DPWM techniques are examined, and they are compared to other conventional PWM methods. The goal of this thesis is to research the advantages and disadvantages of using these DPWM techniques.

The first part of this thesis explains the operating principles of three-phase inverters and rectifiers. The concept of an active rectifier is also introduced. Inverters are used to convert direct current into alternating current, whereas a rectifier performs the opposite operation. As the production of renewable energy becomes more common, the demand for these power converters increases. For instance, the DC power produced with photovoltaic cells must be converted to AC power suitable for the power grid.

In a conventional three-phase inverter, a phase leg with two switches is connected to each phase. The switches in these phase legs are generally controlled with pulse-width modulation (PWM). With PWM, the input voltage of the inverter can be chopped into discrete pieces, and thus form a desired output signal. In general, the desired waveform resembles a sine wave. The modulation is often implemented by comparing the values of a carrier signal and a reference signal. While the reference signal value is greater than the carrier signal, the phase leg it is connected to is clamped to the positive DC rail of the inverter. In the opposite case, the phase leg clamps to the negative DC-rail.

The switching frequency of the PWM is often very high, leading to the switching losses making up a significant part of the power losses of the entire inverter. In DPWM techniques, each phase leg of the inverter is clamped to either the positive or the negative DC rail for one-third of each period of the reference signal. This results in a major reduction of the switching losses. The unmodulated period can be implemented in either one or multiple segments. The losses can be reduced the most by positioning the unmodulated periods close to the peak current values.

The drawback of using the DPWM methods is the increased total harmonic distortion as well as the increased motor leakage current in motor drive applications. In this thesis, adjustable PWM (APWM) and near state PWM (NSPWM) are presented as possible solutions to this problem.

Keywords: Three-phase inverter, Active rectifier, Pulse-width modulation, Discontinuous PWM

TIIVISTELMÄ

Johannes Kujala: Epäjatkuvat PWM-tekniikat kolmivaiheisissa konverttereissa
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Huhtikuu 2020

Epäjatkuvia pulssinleveysmodulaatiotekniikoita (DPWM) käytetään kolmivaiheisissa konverttereissa niiden hyötysuhteen parantamiseksi. Tehohäviöitä vähentämällä konvertterin jäähdytyslaitteisto, ja täten myös itse konvertteri sekä sen kokonaiskustannukset saadaan pienemmiksi. Tässä kandidaatintyössä tarkastellaan useita DPWM-menetelmiä ja verrataan niiden suorituskykyä muihin tavanomaisesti käytettyihin PWM-tekniikoihin. Kandidaatintyön tavoitteena on tutkia näiden DPWM-menetelmien käytön hyötyjä sekä haittoja esimerkiksi harmonisen kokonäissärön ja tehohäviöiden osalta.

Työn ensimmäisessä vaiheessa tarkastellaan kolmivaiheisen invertterin ja tasasuuntaajan toimintaperiaatetta sekä esitellään aktiivisen tasasuuntaajan käsite. Invertteriä käytetään muunnettaessa tasavirtaa vaihtovirraksi, kun taas tasasuuntaaja suorittaa päinvastaisen toimenpiteen. Uusiutuvan energian käytön yleistyessä tarve näille laitteille lisääntyy, sillä tuotettua energiaa ei usein voida suoraan liittää sähköverkkoon. Esimerkiksi aurinkovoimalla tuotettava tasavirta täytyy juuri invertterillä muuntaa verkkoon sopivaksi kolmivaihevirraksi.

Tavanomaisessa kolmivaiheinvertterissä kuhunkin vaiheeseen on liitetty kaksikytkiminen vaihejalka. Useimmiten vaihejalkojen kytkimiä ohjataan pulssinleveysmodulaatiolla (PWM). PWM:llä invertterin sisäänmenojännite voidaan pilkkoa diskreeteiksi palasiksi ja näin muodostaa toivottu ulostulosignaali. Yleensä haluttu aaltomuoto muistuttaa sinisignaalia. PWM-ohjaus toteutetaan useimmiten vertailemalla kantoaallon ja referenssiaallon arvoja keskenään. Referenssiaallon hetkellisen arvon ollessa kantoaaltoa suurempi siihen kytketty vaihejalka on kytketty invertterin positiiviseen DC-kiskoon. Päinvastaisessa tapauksessa vaihejalka kytkeytyy negatiiviseen DC-kiskoon.

PWM-ohjauksen kytkentätaajuus on usein hyvin suuri, minkä vuoksi transistorien kytkentähäviöt muodostavat merkittävän osan koko invertterin tehohäviöistä. DPWM-menetelmissä invertterin kukin vaihejalka on yhden kolmasosan referenssisignaalin jaksonajasta lukittuna joko positiiviseen tai negatiiviseen DC-kiskoon. Kytkentähäviöitä voidaan näin vähentää huomattavasti. Moduloimaton osuus voidaan toteuttaa joko yhtenä tai useampana osana. Häviöitä voidaan alentaa eniten sijoittamalla moduloimattomat jaksot lähelle virran huippukohtia.

DPWM-menetelmien haittapuolena on harmonisen kokonaissärön sekä moottorikäytössä maavuotovirran kasvaminen verrattuna muihin tavanomaisiin PWM-tekniikoihin. Tässä kandidaatintyössä näihin ongelmiin esitetään eräinä mahdollisina ratkaisuina ”adjustable discontinuous” PWM ja ”near state” PWM.

Avainsanat: Kolmivaiheinvertteri, Aktiivinen tasasuuntaaja, Pulssinleveysmodulaatio,
Epäjatkuva PWM

TABLE OF CONTENTS

ABBREVIATIONS

ADPWM	Adjustable discontinuous pulse-width modulation
AFE	Active front end
BJT	Bipolar junction transistor
CMV	Common-mode voltage
CPWM	Continuous pulse-width modulation
DPWM	Discontinuous pulse-width modulation
IGBT	Insulated-gate bipolar transistor
MOSFET	Metal-oxide-semiconductor field-effect transistor
NSPWM	Near state pulse-width modulation
PV	Photovoltaic
PWM	Pulse-width modulation
RMS	Root-mean-square
SPWM	Sinusoidal pulse-width modulation
SVPWM	space vector pulse-width modulation
THD	Total harmonic distortion
VFD	Variable-frequency drive
VSI	Voltage source inverter

1. INTRODUCTION

Global energy trends are continuously focusing more and more on energy efficiency and renewable energy. Typically, renewable energy sources are connected to the electrical grid through an inverter. Wind power is generated usually with asynchronous generators, which require a variable-frequency drive (VFD) between the grid and the generator. Solar power produced with photovoltaic (PV) cells, on the other hand, is DC power, which needs to be transformed into AC power for grid-connection. Since a large part of renewable energy production is not only seasonal but also dependent on the time of day, battery storage systems are also becoming more important. To connect these battery systems to the grid, stored energy must be converted from DC to AC power. Altogether, the common factor in these cases is the need for an inverter. [1]

An inverter is a device that can be used to convert DC into AC. A common strategy to control its output voltage waveform is pulse-width modulation (PWM). In a typical three-phase full-bridge inverter, there are six switches. At any given moment, three of the switches conduct while the other three switches are open. The PWM is used to adjust the time (duty cycle) during which the switches are closed and open. By changing the duty cycle at a fast rate, the desired output voltage can be achieved. [2] Most often, the PWM is implemented by utilizing insulated-gate bipolar transistors (IGBT).

When using a PWM in an inverter, a triangular signal is often used as a modulation signal. In a common method, the modulation is controlled with a sinusoidal signal with the desired output frequency. [3] The transistor is then alternately switched on and off at each intersection of these two signals. The control signal can also be discontinuous, meaning that the signal remains unswitched for up to 120° during each cycle [4]. Discontinuous pulse-width modulation (DPWM) can thus be used to reduce the switching losses of a transistor, and thereby optimize the inverter efficiency in some applications [5]. This bachelor’s thesis will study the pros and cons of a DPWM and compare its operation to other PWM techniques.

The rest of the thesis is organized as follows. In Chapter 2, the basic principle and the components of a three-phase inverter are introduced. In Chapter 3, a three-phase rectifier is introduced, and active rectifiers are compared to the more common diode rectifiers. In Chapter 4, two common methods, sinusoidal PWM (SPWM) and space vector PWM (SVPWM) are presented. In Chapter 5, the DPWM is presented: Its basic principle and some common waveforms are explained. The DPWM is also compared to other PWM techniques in terms of power losses, total harmonic distortion (THD), and common-mode voltage (CMV). Chapter 7 draws conclusions.

2. THREE-PHASE INVERTER

Three-phase inverters are used to convert DC power into AC power. Since the power grid usually utilizes three-phase AC power, three-phase inverters are needed in many applications. Inverters can be used on their own, for example, to connect PV cells to the grid. They can also be used in VFDs with many useful applications. In addition to wind power grid-connection, inverters can be used with industrial induction motors, which consume a significant part of all electricity produced in the world [6].

2.1 Operation Principle

A three-phase inverter converts DC voltage to three-phase AC voltage by using transistors to chop the voltage. A conventional three-phase voltage source inverter (VSI) contains six transistors, usually IGBTs. By controlling these switches in a particular way, the output line-to-line voltages can be made to resemble a sinusoidal waveform. A conventional three-phase two-level VSI is depicted in Fig 2.1.

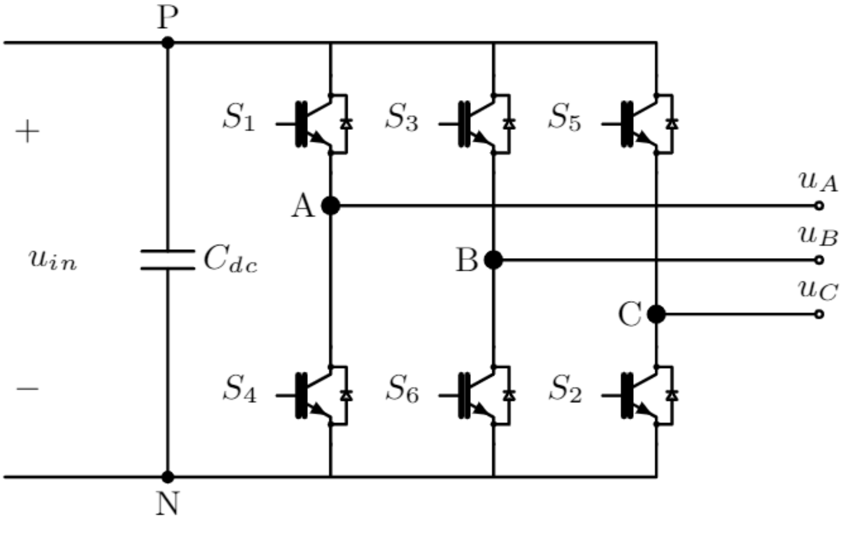


Figure 2.1. *A conventional three-phase voltage source inverter*

The inverter shown in the figure has three phase legs. Each terminal (A, B, C) can either be connected to the positive or the negative DC-rail (P or N). To avoid short-circuiting the input capacitor C_{dc}, both switches in one phase leg can never be conducting simultaneously. This means that there are eight possible switching states, which are shown in Fig. 2.2.

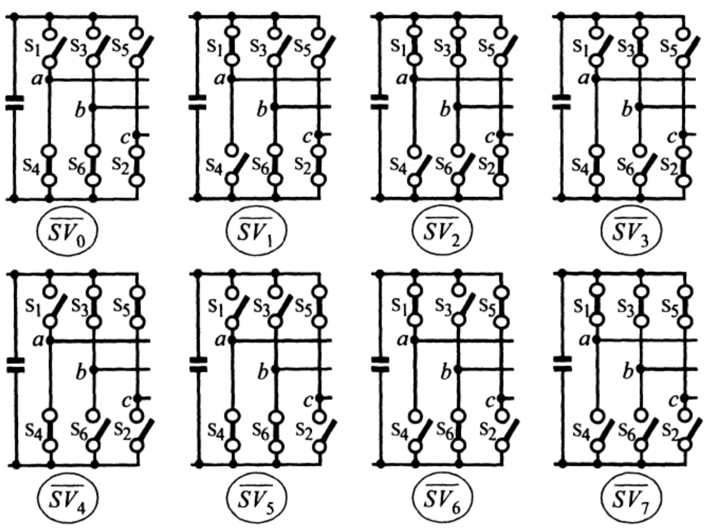


Figure 2.2. *The possible switching states for a three-phase VSI [3]*

The states 1 through 6 are the essential switching states that produce the AC voltage to terminals A, B, and C. The switching between the states varies by the mode of which the inverter is operated in. Usually, a three-phase inverter is run either in square-wave or PWM operation.

For a three-phase inverter, the theoretical maximum of the root-mean-square (RMS) value of the output line-to-line voltage is u_{in}. If power losses are not considered, this is always achieved when operating the inverter in square-wave mode. Therefore, the magnitude of the output voltage cannot be controlled with an inverter in square-wave operation. However, the output voltage frequency can be controlled by changing the switching frequency of the transistors. Therefore, square-wave operation is acceptable only if the inverter input voltage is controllable. [2]

In square-wave operation, each switch in the inverter is on for 180°, or half a period, and then off for another 180°. Additionally, at any given moment, one switch from every phase leg conducts, while the other one does not. [3] The line-to-line voltage can have three different values with the square-wave operation. For the VSI in Fig. 2.1, these are $+u_{in}$, 0, and $-u_{in}$. The voltage waveforms with 120° phase shifts are presented in Fig. 2.3.

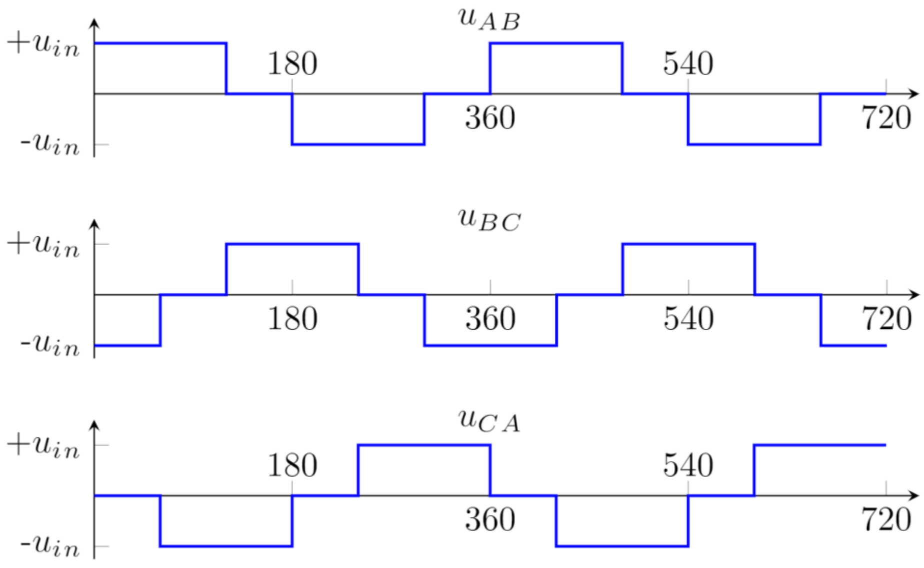


Figure 2.3. *Line-to-line output voltages*

The output current of an inverter in square-wave operation contains a significant amount of harmonic currents. They are undesired currents whose frequency is a multiple of the fundamental current. The harmonic currents originate from the fact that a square-wave is comprised of sinusoidal waves with different harmonic frequencies. The most notable harmonics for a three-phase VSI are the 5th, 7th, and 11th. A high THD can cause, e.g., increased heating and higher power losses in induction motors. [3] These harmonic currents can be filtered, for example, with an LCL filter.

Often the application of the inverter requires a good power quality, i.e. low THD. For example, when operating grid-connected converters, the amount of THD allowed is regulated [7]. In these instances, the inverter is usually operated with PWM which is presented more precisely in the following chapters of this thesis.

2.2 Insulated-gate bipolar transistor

IGBT is a voltage-controlled semiconductor device which is a combination of a metal-oxide-semiconductor field-effect transistor (MOSFET) and a bipolar junction transistor (BJT). By combining these two in a Darlington configuration, the low on-state resistance of a BJT and the short switching times of a MOSFET can be achieved. [8] Therefore, an IGBT is a three-terminal device where the MOSFET controls the gate signal, but the collector and emitter are a part of the BJT. The equivalent circuit of an IGBT is presented in Fig. 2.4.

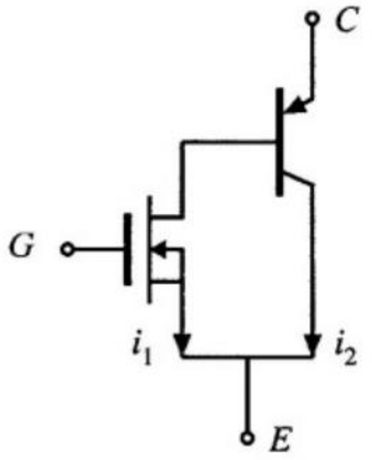


Figure 2.4. *The equivalent circuit of an IGBT [9]*

IGBTs have a high current handling capacity and blocking voltage, as well as high maximum switching frequency [9]. Due to these superior characteristics, they are widely used in high-voltage applications, e.g. grid-connected power converters.

When the voltage between the gate and the emitter of the IGBT is positive, and it exceeds a certain threshold, a path is provided for current to flow from the collector to the emitter. The magnitude of the current depends on the voltage between the collector and the emitter as well as the gate drive voltage. However, the current cannot grow infinitely while the collector voltage increases. For each gate drive voltage, the current is saturated after reaching a certain value. The IGBT can only be operated in active region, i.e. the linear region where collector current stays constant [8]. This is presented in Fig. 2.5.

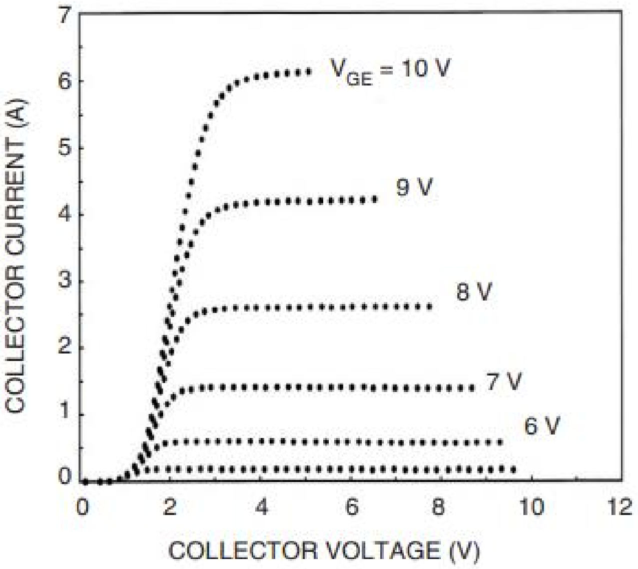


Figure 2.5. *The forward characteristics of an IGBT [8]*

3. THREE-PHASE RECTIFIER

A Three-phase rectifier is a device that rectifies a three-phase AC voltage, i.e. converts it into pulsating DC voltage. A VFD, on the other hand, is a device that converts AC voltage into AC voltage with a different frequency or magnitude. This is implemented by first rectifying the input voltage, and then inverting it back to AC voltage. Therefore, rectifiers are often used alongside inverters. The output of a three-phase rectifier can be modified by using different semiconductor devices in them. The basic types of three-phase rectifiers are uncontrolled, semi-controlled, fully controlled, and an active rectifier [10].

3.1 Diode rectifier

A conventional diode rectifier, or an uncontrolled rectifier, consists of a three-phase voltage source, six diodes, and a load. A diode is a semiconductor in which current can only flow in one direction. In a three-phase rectifier depicted in Fig. 3.1, current can only flow through the upper diodes from the source to the load. Therefore, the voltage over the load must always be positive.

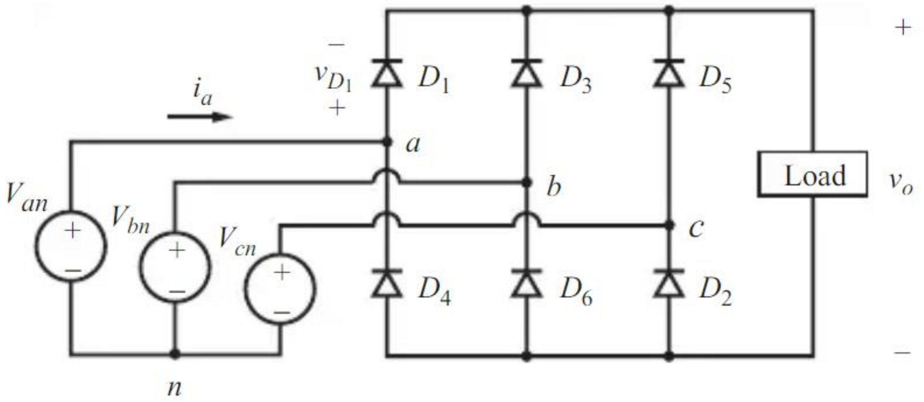


Figure 3.1: *A conventional three-phase diode rectifier [11]*

At each moment, two of the diodes in the circuit conduct. From the upper diodes, the one with the highest positive voltage conducts. Accordingly, the diode from the lower ones with the highest negative voltage conducts. Both diodes in the same phase leg cannot, however, be conducting simultaneously. The output voltage waveform with the corresponding conducting diodes is shown in Fig. 3.2.

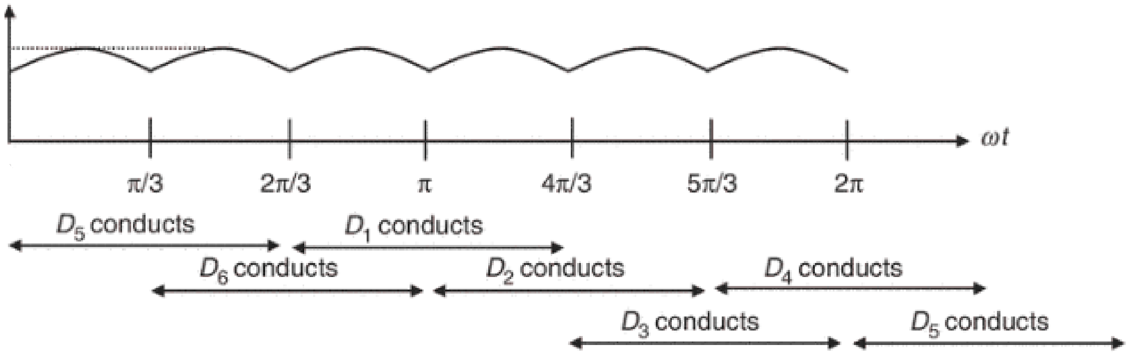


Figure 3.2. *The output voltage waveform of a three-phase rectifier [8]*

As presented in the figure above, the output voltage waveform is not completely constant but pulsating. The magnitude of these pulses can be reduced for example with a capacitor connected parallel to the load. The rectifier in Fig. 3.1 is called a six-pulse rectifier, as there are six of these pulses in each period of the input voltage. Therefore, the length of one pulse is π/3, and the average value of the output voltage is

$$V_{o,ave} = \frac{3}{\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \sqrt{3}V_m \sin(\omega t)\, d\omega t = \frac{3\sqrt{3}}{\pi}V_m \approx 1.65V_m \tag{5.1}$$

where V_m is the RMS value of the input phase voltage. [8]

Either some or all diodes in a rectifier can be replaced with thyristors to create a controlled rectifier. A Thyristor is a semiconductor component like a diode. The difference between them is that a thyristor can be turned on with a short current pulse in its gate. The thyristor then stays conducting until the current flowing through it drops to zero. [10] The thyristor is controlled by a firing angle α, and the output voltage of a fully controlled rectifier is

$$V_{o,ave} = 1.65V_m \cos(\alpha)\,. \tag{5.2}$$

Since $\cos(\alpha) \leq 1$, the output voltage of a rectifier can only be decreased with the use of thyristors. Therefore, the use of fully controlled rectifiers often results in significant power losses. However, using them in VFDs enables generated braking power to be fed back to the supply grid [8].

3.2 Active rectifier

In some VFD application, the driven motor should be able to be utilized also as a generator. This requires bidirectional power flow and thus, active rectifiers can be used. [10] An active rectifier, i.e. active front end (AFE) is a rectifier in which diodes are replaced with transistors, e.g. IGBTs. In addition to the gate turn-on capability of the fully controlled rectifiers, an active rectifier also has the capability for gate turn-off. Therefore, the switches in an active rectifier can be turned on and off multiple times each period with a PWM signal. Active rectifiers can be used, for example, to modulate the output voltage and current, or to reduce the THD of the output waveforms [8]. A schematic for an AFE is presented in Fig. 3.3.

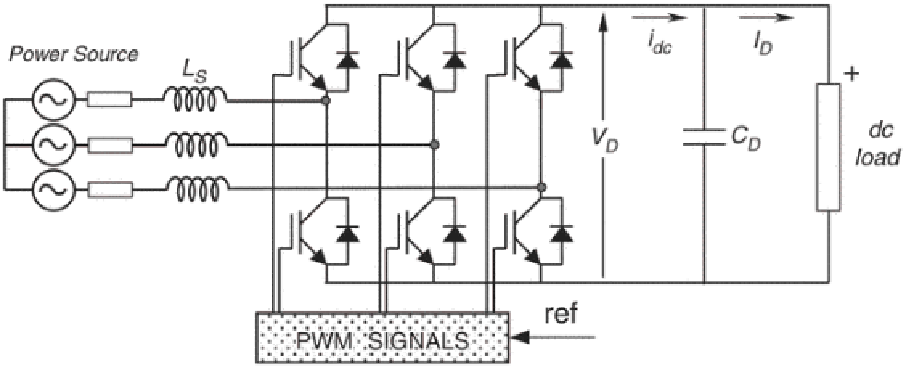


Figure 3.3. *A three-phase active voltage source rectifier [8]*

When operating the active rectifier, its DC-link voltage, i.e. the voltage over the capacitor C_D, is kept at a desired reference value. This is implemented by using a feedback control loop. The voltage over the capacitor is measured and compared to the reference value. The difference in the values can then be used to adjust the modulation in the control block of the rectifier. [8]

Compared to a diode rectifier, an active rectifier has a more complicated structure, making it bigger and more expensive to manufacture. In addition to that, an LCL filter is a critical part of a high-power active rectifier [12]. A three-phase LCL filter is presented in Fig. 3.4.

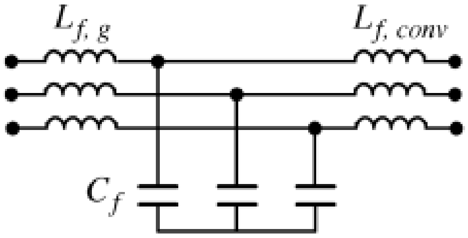


Figure 3.4. *A three-phase LCL filter [13]*

The LCL filter is placed between the input voltage source and the transistors of an active rectifier. They are practically always used in active rectifiers due to their capabilities of damping current harmonics in high frequencies, e.g. around the switching frequency of the rectifier [14]. In very high switching frequencies, the LCL filter can be replaced with a simpler L filter. However, since the crucial size for the L filter inductor increases rapidly as the switching frequency decreases, an LCL filter is generally the smaller and cheaper filter solution. [3]

4. PULSE-WIDTH MODULATION

Pulse-width modulation is the most common strategy for controlling the output AC voltage of an inverter. It is a method used to reduce the average power of a signal by chopping it into discrete parts. The name pulse-width modulation originates from the fact that the width of these discrete parts, i.e. pulses, is modulated to create a desired output signal.

The objective of PWM is to achieve a desired low-frequency output voltage by varying the duty cycle of the converter switches. The duty cycle denotes the portion of a period during which the corresponding switch is conducting. In most applications, the preferred approach is carrier based PWM due to its low harmonic distortion characteristics and simple implementation [15]. The general process of PWM is quite simple: A reference signal is compared to a carrier signal. Every time these two signals cross, the switch is turned on or off.

The carrier signal is either a sawtooth or a triangular signal with the desired switching frequency. Generally, one triangular carrier signal is used to modulate all three phase legs in a three-phase VSI since its symmetrical switching sequence results in lower power losses and lower THD. [15] For the reference signal, on the other hand, there are many alternatives. The most conventional methods are SPWM and SVPWM [16].

The magnitude and frequency of the inverter output voltage can be calculated if the input DC voltage, along with both the reference signal and carrier signal waveforms are known. First, the amplitude modulation index is calculated as [2]

$$m_a = \frac{\hat{v}_{control}}{\hat{v}_{tri}} \tag{4.1}$$

where $\hat{v}_{control}$ is the peak amplitude of the control signal, and $\hat{v}_{tri}$ is the peak amplitude of the carrier signal. If $m_a \leq 1$, the inverter operates in the linear region, and the output voltage and the modulation index vary linearly. In the linear operating region, the peak output phase voltage for a two-level three-phase inverter, like the one depicted in Fig. 2.1, can be calculated as [2]

$$\hat{v}_{phase} = m_a \frac{V_{in}}{2} \tag{4.2}$$

where V_{in} is the input DC voltage of the inverter.

If, on the other hand, m_a ≥ 1, the inverter is in overmodulation, and the output voltage does not increase proportionally with the modulation index [11]. If the amplitude modulation index keeps increasing, the inverter will eventually reach square-wave operation, and thus the maximum RMS-value for the output voltage.

4.1 Sinusoidal PWM

In SPWM, a sinusoidal wave is utilized as the reference signal. The basic bipolar scheme for a single-phase SPWM with a triangular carrier signal is depicted in Fig. 4.1.

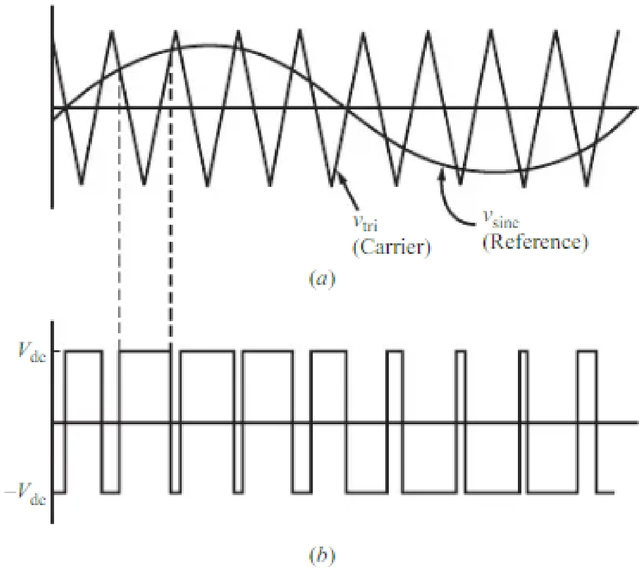


Figure 4.1. *(a) Triangular carrier and sinusoidal reference signal; (b) A single-phase output voltage waveform [11]*

When the value of the reference signal is higher than the carrier signal, the upper switch of a phase leg is conducting, and the phase leg is thus connected to the positive DC-rail. Again, when the carrier signal value is higher, only the lower switch conducts, and the phase leg is connected to negative DC-rail.

In a three-phase inverter, each phase leg can be modulated by its own reference signal. The reference signals have the same waveforms, but with 120° phase shifts, as always in three-phase systems. As in square-wave operation, there are three possible line-to-line output voltage values. However, the switches between these voltages happen far more frequently in SPWM.

4.2 Space vector PWM

As presented in Fig. 2.2, there are eight possible switching states in a three-phase two-level inverter. In states $\overline{V_0}$ and $\overline{V_7}$, current cannot flow from the input to the output since either all upper or all lower switches are open. These states are called zero vectors, while the rest are known as switching vectors. All states are shown as space vectors in Fig. 4.2.

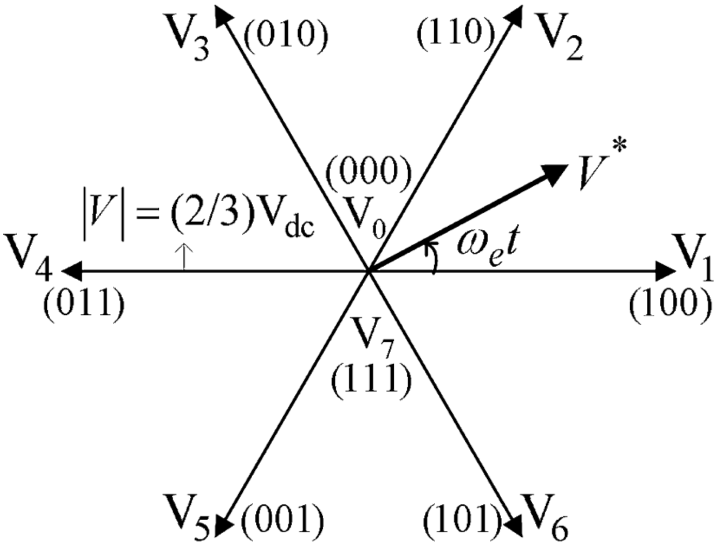


Figure 4.2. *Vectors corresponding to all eight switching states [15]*

The principle of SVPWM is to assemble a reference vector from different state vectors. Each reference vector is a combination of its two nearest switching vectors and the two zero vectors. For instance, the vector V^* in Fig. 4.2 is a combination of the switching vectors V_1 and V_2, and the zero vectors V_0 and V_7. Therefore, the reference vector V^* can be presented as

$$V^* = d_1 V_1 + d_2 V_2 + \frac{d_0}{2} V_0 + \frac{d_0}{2} V_7 \qquad (3.3)$$

where d_1 and d_2 are the duty cycles of the corresponding switching vectors. The rest of the time is divided between the zero vectors, with their total duty cycle being d_0. Similarly, all voltage vectors on the complex plane can be denoted with their corresponding vectors and duty cycles over a sampling period.

5. DISCONTINUOUS PWM

DPWM is a modulation technique in which the modulating signal is clamped to DC-rail for one-third of each period. With DPWM, the switching losses of a power converter can thus be significantly reduced, especially with high switching frequencies. With better power efficiency, less cooling equipment is needed for the converters. Therefore, the devices can often be made smaller and cheaper with the use of DPWM.

5.1 Operation principle

It has been shown that the properties of a three-phase inverter can be improved by adding an appropriate zero-sequence signal to the reference voltage waveform [17]. For all carrier-based PWM techniques, this reference signal can be presented as

$$v_i^{**}(t) = v_i^{*}(t) + v_0(t) \tag{5.1}$$

where $v_i^{*}(t)$ is the fundamental component of the signal, $v_0(t)$ is the zero-sequence component, and *i* in all terms is one of the three phases (A, B, or C). The fundamental component of the signal is the three-phase continuous sinusoidal signal. [18]

The zero-sequence signal can be used to alter the duty cycle of the inverter switches. For the upper switch in each phase leg, the duty cycle can be presented as

$$d_+ = \frac{1}{2}\left(1 + \frac{v_i^{**}}{V_{DC}/2}\right) \tag{5.2}$$

where V_{DC} is the input voltage of the three-phase inverter [15]. Since one of the switches in each leg is always conducting while the other one is not, the duty cycle for the lower switch is

$$d_- = 1 - d_+. \tag{5.3}$$

If the zero-sequence component equals zero, the method in question is SPWM. When, however, the added zero-sequence signal is such that the phase legs are clamped to either the positive or the negative DC rail for a part of each period, the method is called DPWM. A block diagram, depicted in Fig. 5.2, presents the injection of the zero-sequence signal for an approach with one common triangular carrier signal.

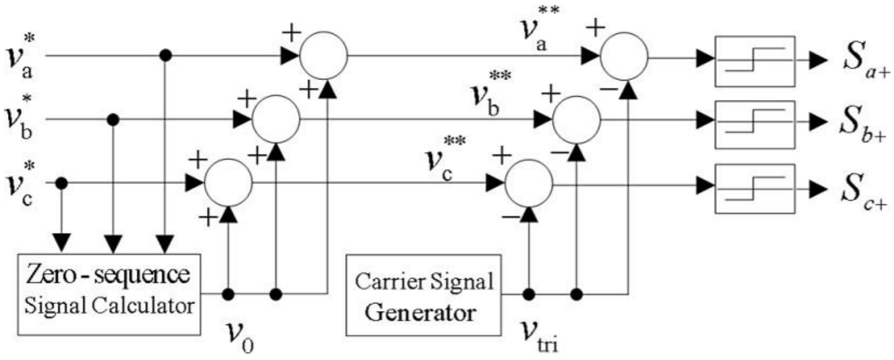


Figure 5.1. *A block diagram of the zero-sequence signal injection [15]*

In three-phase DPWM, a zero-sequence signal is injected in a way that one phase is always clamped to either the negative or the positive DC-rail. The clamped phase is altered throughout each period. If the same zero-sequence signal is added to each phase leg of a three-phase inverter, the average value of the output line-to-line voltage stays constant [19]. The single-phase modulation waveform and the zero-sequence signal for the most common waveform, DPWM1 modulation wave, are presented in Fig. 5.2. [15].

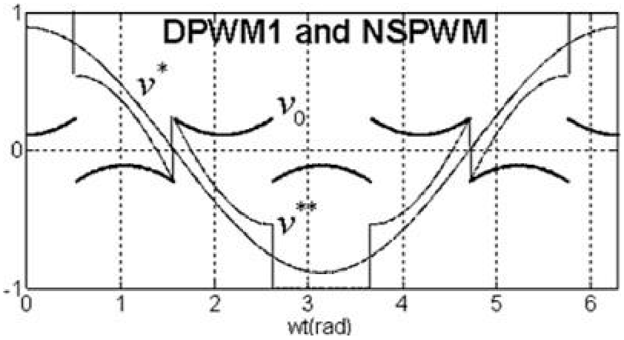


Figure 5.2. *DPWM1 modulation waveform [15]*

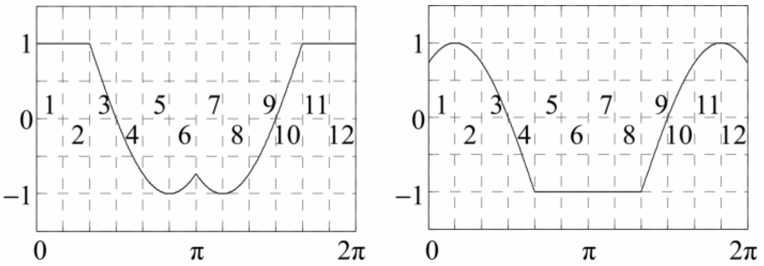
When the DPWM1 zero-sequence signal v_0 is added to the sinusoidal reference signal v^*, the resulting signal clamps alternatively to both the positive and the negative DC-rails. In DPWM1, the width of the two unmodulated periods is 60°, and they are positioned around the minimum and maximum points of the sinusoidal reference signal. Theoretically, a limitless number of zero-sequence signals, and thus DPWM methods, could be generated. However, the performance and simplicity requirements of practical VSIs limit the number of possibilities. [20] Some other conventional DPWM methods are presented in Chapter 5.2.

5.2 Different modulation waveforms

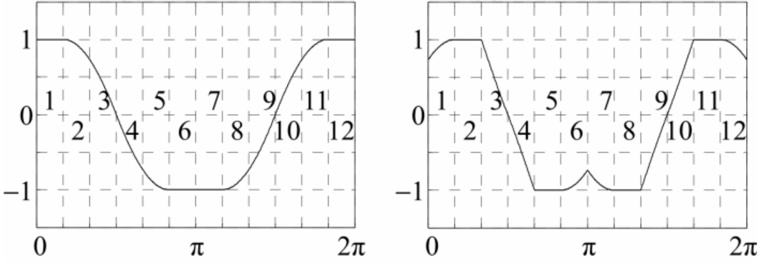
There are six common ways of implementing DPWM to a device. In all of them, each phase leg of a three-phase inverter remains unswitched for 120° during each period. The different methods can be divided by the length of each saturated period, and they are:

- 120° discontinuous modulation where each phase leg is continuously clamped to either the positive or the negative DC-rail for one-third of a period. These methods are called DPWMMAX and DPWMMIN.
- 30° discontinuous modulation where during every period each phase leg is alternatively locked to each DC-rail for 60° at a time. These methods include DPWM0 and DPWM1 and DPWM2.
- 120° discontinuous modulation where there are four unmodulated 30° periods in each cycle. DPWM3 is this kind of a method.

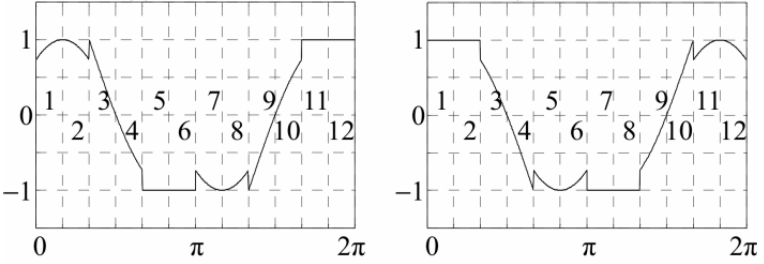
The reference signals for each of these DPWM techniques are presented in Fig. 5.1. Each graph is divided into 12 sectors, one being 30°. Presuming that the amplitude of the carrier signal $\hat{v}_{tri}$ = 1, the switches remain unswitched for 120° per period in all methods.



(a) DPWMMAX (b) DPWMMIN



(c) DPWM1 (d) DPWM3



(e) DPWM0 (f) DPWM2

Figure 5.3. *The reference signals of six common DPWM methods [21]*

In DPWMMAX and DPWMMIN, the voltage can only be clamped to one of the DC rails in the phase leg. Naturally, DPWMMAX is clamped to the positive, and DPWMMIN is clamped to the negative rail for 120°. Since the reference waveforms are asymmetrical, also the output voltage waveforms for the 120° discontinuous modulation methods will be asymmetrical. These methods can also cause disproportionate wear to the switches in a phase leg since the conducting losses are not divided equally across them. [3]

When using a 60° discontinuous modulation method, the reference signals, and thus also the output voltages, are symmetrical. As seen in Fig. 5.1, each of the reference waveforms, DPWM0, DPWM1, and DPWM2, are all alternatively switched to the positive and negative DC rails for the periods the phase leg is unmodulated.

The difference between the three waveforms is the location of the saturated period. In DPWM1, the 60° unmodulated periods are centered around both the positive and the negative peaks of the fundamental reference voltage. This arrangement functions best for a resistive load when the peak currents match the peak voltage. [3]

DPWM0 is the best arrangement for a capacitive load since the saturation period is centered at 30° before the peak reference voltage. Correspondingly, DPWM2 is centered 30° after the peak reference voltage and is thus the best arrangement for an inductive load. 60° saturated periods can be positioned anywhere between the ones in DPWM0 and DPWM2. By positioning the saturated period as close as possible to the peak currents, the switching losses can be minimized. [3] DPWM3, on the other hand, has its four 30° saturation periods positioned with 60° intervals between them. Of the six methods presented, DPWM3 has the lowest harmonic distortion, while DPWM1 has the highest [21].

5.3 Advantages and disadvantages of DPWM

5.3.1 Power losses

Since each phase leg of a three-phase inverter is unswitched for 120° each period, the switching frequency can be multiplied by 3/2 without increasing the switching losses of an inverter. Therefore, often the power losses of a three-phase inverter can be reduced by using DPWM instead of continuous PWM (CPWM) techniques. In general, the switching losses can be reduced the most when the unmodulated periods are positioned close to the current peaks.

The differences in power losses between SPWM, SVPWM, and DPWM2 have been analyzed in [16]. The DPWM2 method was chosen due to the inductive nature of the inverter load. The test conditions are presented in Table 5.1, and the results in Fig. 5.4.

Table 5.1. *Inverter test conditions*

Load 1		Load 2	
V_{DC}	400 V	V_{DC}	400 V
Modulation index	0.99	Modulation index	0.67
I_{RMS}	1.90 A	I_{RMS}	6.35 A
V_{RMS}	216 V	V_{RMS}	139.5 V
Switching frequency	20 kHz	Switching frequency	20 kHz

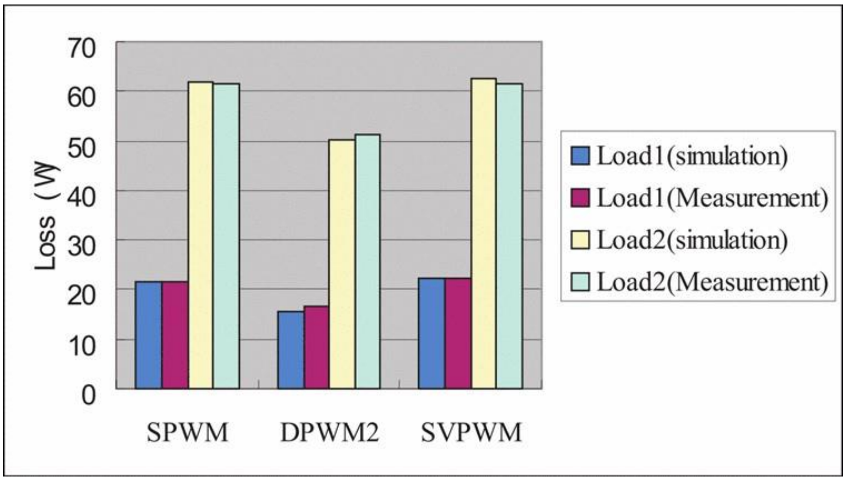


Figure 5.4. *Inverter losses with different PWM techniques [16]*

A significant difference in power losses between the three methods was found. The power losses between these modulation methods in an electrical machine were also examined with the assumption that the poorer waveform quality of DPWM2 leads to higher power losses in the machine. However, the assumption was discovered false. A conclusion was then reached that the poorer waveform quality of the DPWM was insignificant when compared to power loss reduction. [16]

5.3.2 Total harmonic distortion

As stated in the previous chapter, the unmodulated period in DPWM techniques results in poorer waveform quality, e.g. higher output current THD. The choice between DPWM and CPWM techniques can be difficult, as it must be determined whether the reduced power losses or the lower THD is more crucial. In general, the amount of power losses is more important in high speed and heavy load applications, whereas in low speed and light load applications, low THD is often preferred [22].

Adjustable DPWM (ADPWM) offers a tradeoff between the CPWM and DPWM methods with the capability of adjusting the length of the unmodulated periods. It can be used in electric machine drive systems, e.g. fans and pumps, that are operated in altering speeds. Therefore, in low-speed region, the modulator could operate like conventional SPWM whereas, in high-speed region, the improved efficiency of DPWM could be benefitted from. As the required power is proportional to the cube of speed, fulfilling the THD and loss requirements in both the low and high speeds becomes easier with the use of ADPWM. [22]

5.3.3 Common-mode voltage

The use of DPWM techniques also causes a high CMV, i.e. a high voltage difference between the voltage source and the neutral point of the load in a three-phase inverter. The neutral point voltage can be presented as

$$V_n = \frac{V_{ab} + V_{bc} + V_{ca}}{3} \tag{5.4}$$

where V_{ab}, V_{bc}, and V_{ca} are the line-to-line output voltages of the inverter. In motor drive applications, a high CMV is related to increased motor leakage currents and reduced life expectancy for the bearings. [23]

One method proposed to reduce the CMV is near state PWM (NSPWM) in which the reference signal is the same as in DPWM1. However, NSPWM utilizes two triangular carrier waves instead of one in DPWM1. Since the two carrier waves have a phase shift of 180°, they can be denoted as V_{tri} and $-V_{tri}$. The general switching rule in NSPWM is that while the reference signal is higher than the carrier signal they are compared to, the upper switch in the corresponding phase leg is conducting. The signal that each phase reference is compared to is dependent on the phase region of the reference signal. In essence, the signal with the highest voltage is at any given moment compared to the carrier signal $-V_{tri}$ whereas the other two reference signals are compared to V_{tri}. NSPWM has been shown to have superior performance characteristics in the high modulation range where the amplitude modulation index m_a > 0.6. [24]

6. CONCLUSION

The goal of this thesis was to research DPWM techniques and present their advantages and disadvantages in comparison to other conventional PWM methods. A general operating principle for DPWM was presented, and different modulation techniques were introduced. The operating principles of a three-phase inverter and an active rectifier were also examined to establish a base for understanding the use of different PWM techniques in them.

The development of discontinuous PWM techniques in three-phase inverters and active rectifiers has allowed power electronics manufacturers to achieve significant improvements in the efficiency of the devices. The reduction in power losses is caused by an unmodulated period in the phase legs of a three-phase power converter. Although these methods can result in poorer output waveform quality, improved efficiency is often deemed more essential.

Different DPWM techniques are designed to have diverse benefits. The different layout possibilities of the unmodulated periods can be exploited when the type of load is altered. For a capacitive load, DPWM0 is considered a suitable method, whereas an inductive load functions better with DPWM2. If the amount of motor leakage current needs to be reduced, a good modulation option is NSPWM. If, on the other hand, the device in question is used in altering speeds, ADPWM might offer a good tradeoff between the low-speed and high-speed requirements regarding power losses and waveform quality. Thus, the various DPWM methods can be stated to be very versatile, and they are therefore used whenever possible.

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