

**Advanced Architectures and  
Control Concepts for  
  
MORE MICROGRIDS**

**Contract No: PL019864**

**WORK PACKAGE C**

**Deliverable DC3: Alternative Microsource interfaces**

**FINAL Version**

**30-11-2009**

# Document Information

**Title:** Cost-effective power electronic interfaces for three-phase four-wire microgrids.

**Date:** 30-11-2009

**Task(s):** TC3. Alternative Microsource interfaces

<b>Coordination:</b>	Coordinator's name	e-mail
<b>Authors:</b>	Staffan Norrga	staffan.norrga@se.abb.com

**Access:**     — Project Consortium  
                  — European Commission  
                  X **PUBLIC**

**Status:**     — For Information  
                  — Draft Version  
                  — Final Version (internal document)  
                  — Submission for Approval (deliverable)  
                  X Final Version (deliverable, approved on.\_)

**TABLE OF CONTENTS**

- 1. INTRODUCTION ..... 6**
  - 1.1. Microgrids ..... 6**
  - 1.2. Needs for power electronic interfaces ..... 7**
    - 1.2.1. Photovoltaics ..... 7
    - 1.2.2. Microturbines ..... 10
    - 1.2.3. Battery storage units..... 11
  - 1.3. References ..... 12**
  
- 2. NOMENCLATURE AND FUNDAMENTAL CONCEPTS ..... 13**
  - 2.1. Symbols..... 13**
  - 2.2. Abbreviations..... 13**
  - 2.3. General concepts concerning three-phase systems ..... 14**
    - 2.3.1. Fourier series expansion of periodic signals ..... 14
    - 2.3.2. Harmonics in three-phase Systems ..... 15
  - 2.4. References ..... 15**
  
- 3. LOW VOLTAGE THREE PHASE DISTRIBUTION SYSTEMS ..... 16**
  - 3.1. Introduction..... 16**
  - 3.2. Grounding ..... 17**
  - 3.3. Standards and International Regulations for grid connected distributed sources..... 20**
    - 3.3.1. Voltage Quality ..... 21
    - 3.3.2. Power Quality ..... 22
    - 3.3.3. Anti-islanding requirements ..... 23
    - 3.3.4. Imbalance ..... 24
  - 3.4. Microgrid in Distribution..... 25**
  - 3.5. Conclusion ..... 26**
  - 3.6. References ..... 27**

<b>4. INVERTER TOPOLOGIES FOR CONNECTION TO THREE-PHASE LV GRIDS .....</b>	<b>28</b>
4.1. Required functionality.....	28
4.2. Overview of basic voltage source converter topologies.....	29
4.3. Inverter configurations for connection to four-wire three-phase systems .....	30
4.4. References .....	32
<b>5. CONTROL AND MODULATION OF INVERTERS.....</b>	<b>33</b>
5.1. Modulation of voltage source inverters .....	33
5.1.1. Definitions, PWM for Voltage Source Converters .....	33
5.1.2. Reference Common Mode Injection .....	34
5.1.3. Space Vector Modulation .....	35
5.2. General control of grid-connected inverters .....	38
5.2.1. Current and voltage controllers .....	38
5.2.2. Control measures to achieve coordination between several sources .....	39
5.3. References .....	39
<b>6. INVERTERS UNDER UNBALANCED LOAD CONDITIONS.....</b>	<b>41</b>
6.1. General definitions and relations .....	41
6.2. Differential mode frequency domain modelling.....	42
6.3. Common-mode frequency domain modelling .....	44
6.4. Consequences for VSC with whye-delta coupled transformer.....	45
6.4.1. General .....	45
6.4.2. DC ripple compensation possibilities.....	46
6.5. Consequences for the four-phase-leg VSC .....	47
6.6. Consequences for the VSC with grounded DC link midpoint.....	47
6.6.1. General .....	47
6.6.2. DC ripple compensation possibilities.....	48
6.6.3. DC capacitance versus DC voltage requirements.....	48
6.7. References .....	49

<b>7.</b>	<b>COMPARISON OF THE STUDIED INVERTER CONCEPTS .....</b>	<b>51</b>
7.1.	Reference system data .....	51
7.2.	Galvanic isolation.....	51
7.3.	DC voltage level and DC capacitor storage size requirements .....	51
7.4.	Semiconductor rating requirements .....	54
7.5.	References .....	55
<b>8.</b>	<b>CONCLUSION.....</b>	<b>56</b>
<b>9.</b>	<b>APPENDIX A: MULTIPLICATION OF PERIODIC SIGNALS IN THE TIME DOMAIN .....</b>	<b>58</b>
9.1.	General .....	58
9.2.	Three-phase systems.....	59

# 1. INTRODUCTION

## 1.1. Microgrids

Power systems currently undergo considerable change in operating requirements – mainly as a result of deregulation and due to an increasing amount of distributed energy resources (DER). In many cases DER include different technologies that allow generation in small scale (micro-sources) and some of them take advantage of renewable energy resources (RES) such as solar, wind or hydro energy. Having micro-sources close to the load has the advantage of reducing transmission losses as well as preventing network congestions. Moreover, the chance of having a power supply interruption of end-customers connected to a low voltage (LV) distribution grid (in Europe 230 V and in the USA 110 V) is diminished since adjacent micro-sources, controllable loads and energy storage systems can operate in the islanded mode in case of severe system disturbances (in fact a power delivery can be fully independent of the state of the main grid). This is known today as a microgrid. The typical Microgrid has the same size as a conventional low voltage distribution feeder and will rarely exceed a capacity of 1 MVA and a geographical span of 1 km. Usually, more than 90% of low voltage domestic customers are supplied by underground cable when the rest is supplied by overhead lines. The Microgrid often provides both electricity and heat to the consumers by means of combined heat and power plants (CHP), gas turbines, fuel cells, photovoltaic (PV) systems, wind turbines, etc. The energy storage systems usually include batteries and flywheels.

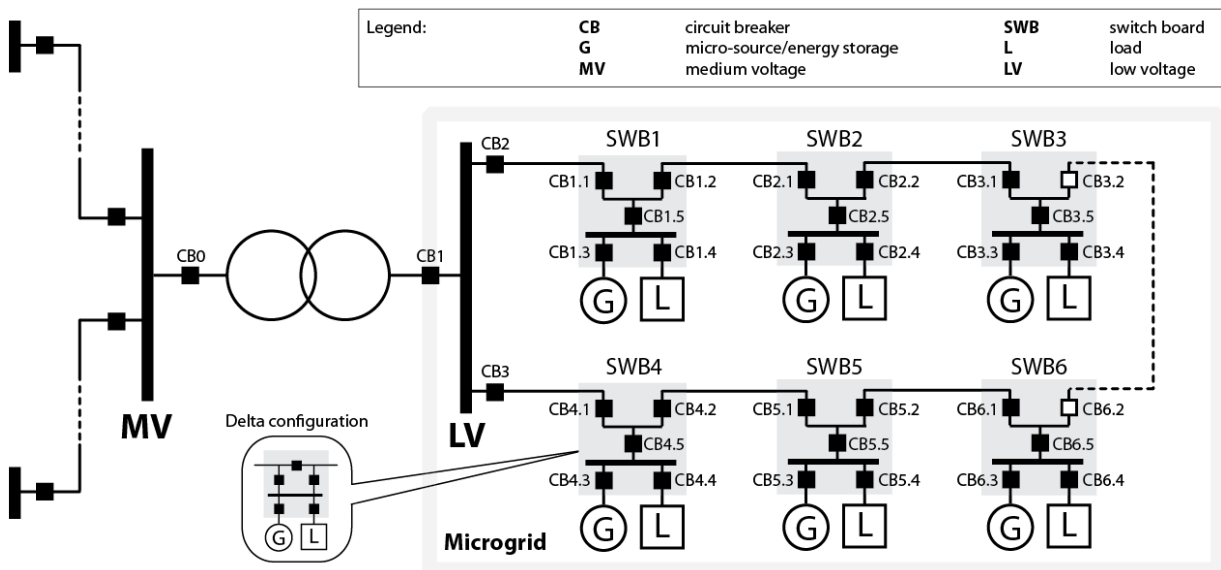


Figure 1. Typical microgrid layout.

A single Microgrid is depicted in

Figure 1 where the microgrid is connected to the main medium voltage (MV) grid when the circuit breaker (CB) CB1 is closed (the circuit breakers CB3.2 and 6.2 are normally open).

Microgrids offer various advantages to end-consumers, utilities and society, such as:

- improved energy efficiency,
- minimized overall energy consumption,
- reduced greenhouse gases and pollutant emissions,
- improved service quality and reliability,
- cost efficient electricity infrastructure replacement.

In light of these, the microgrid concept has stimulated many researchers and attracted the attention of governmental organizations in Europe, USA and Japan. Nevertheless, there are various technical issues associated with the integration and operation of microgrids.

## **1.2. Needs for power electronic interfaces**

This chapter gives a brief summary of distributed energy resources that may be used in microgrids. It is obvious that power electronic interfaces are required in most cases for grid connection.

### **1.2.1. Photovoltaics**

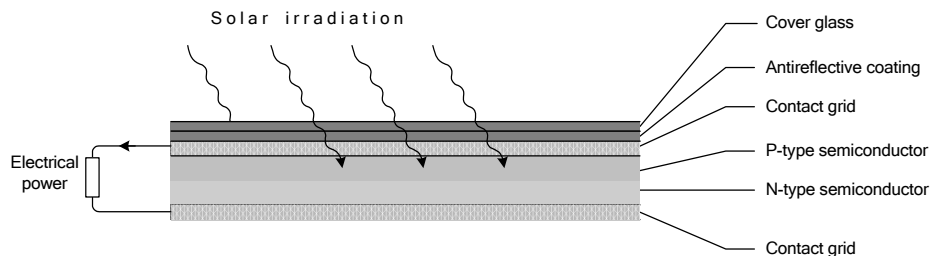
Photovoltaics (PV) is an environmentally beneficial means of producing electricity on site, directly from the sun, with limited maintenance, no emissions, and no depletion of materials[1]. Because they contain no moving parts, they are durable, reliable and easy to maintain. PV cells are assembled into flat plate systems that can be mounted on rooftops or other sunny areas.

Interest in building integration of photovoltaics (BIPV), where the PV elements actually become an integral part of the building, often serving as the exterior weather skin, is growing worldwide. An important benefit of such technology is that no additional land area is required.

#### ***Photovoltaic cell***

A photovoltaic cell is composed of several layers of different materials. The top layer is a glass cover or other encapsulant to protect the cell from weather conditions. This is followed by an anti-reflective layer to prevent the cell from reflecting the light away. Two semiconductor layers in the solar cell create the electron current. Materials, such as silicon and compound semiconductors are suitable for making these semiconducting layers.

In addition to the semiconducting materials, solar cells consist of two metallic grids, forming electrical contacts. One is placed above the semiconducting material and the other below. The top grid contact collects electrons from the semiconductor and transfers them to the external load. The back contact layer is connected to complete the electrical circuit.



**Figure 2: PV cell schematic description**

Connected together in series, solar cells form *modules* that can generate substantial amounts of power. Modules are the building blocks of solar electric systems, which can produce enough power for a house, a rural medical clinic, or an entire village. Large arrays of solar electric modules can even provide electricity for utilities.

### ***Crystalline silicon cells***

Crystalline silicon solar cells are used in more than two thirds of all solar electric devices currently. Like most semiconductor devices, they include a positive layer (on the bottom) and a negative layer (on the top) that create an electrical field inside the cell. When a photon of light strikes a semiconductor, it releases electrons. The free electrons flow through the solar cell's bottom layer to a connecting wire as direct current (DC) electricity.

Some solar cells are made from polycrystalline silicon, which consists of several small silicon crystals. Polycrystalline silicon solar cells are cheaper to produce but somewhat less efficient than single-crystal silicon.

### ***Thin film cells***

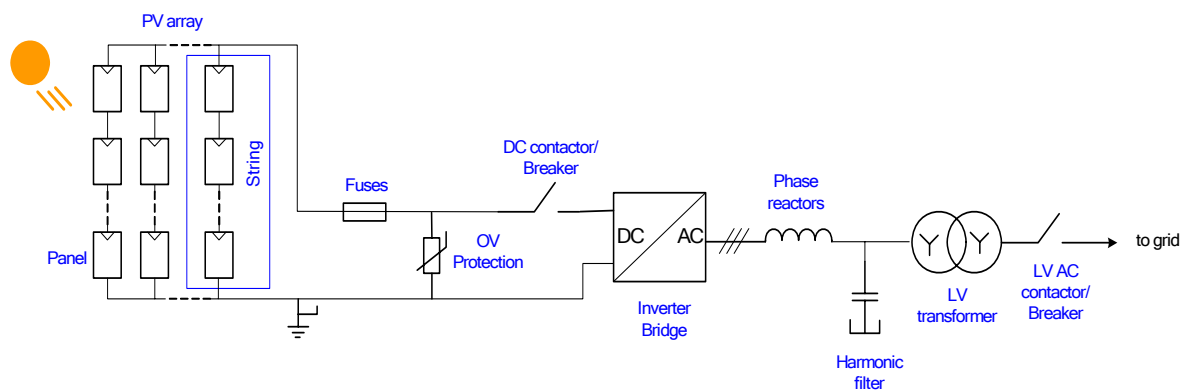
Solar electric thin film cells are lighter, more resilient, and easier to manufacture than crystalline silicon modules. The best-developed thin-film technology uses amorphous silicon, in which the atoms are not arranged in any particular order as they would be in a crystal. Other thin-film materials include cadmium telluride and copper indium diselenide. Substantial cost savings are possible with this technology because thin films require relatively little

semiconductor materials. Among disadvantages should be mentioned that the efficiency is considerably lower (5%-10%) than that of crystalline or polycrystalline silicon cells.

Thin films are produced as large, complete modules, not as individual cells that must be mounted in frames and wired together. They are manufactured by applying extremely thin layers of semiconductor material to a low-cost backing such as glass or plastic. Electrical contacts, antireflective coatings, and protective layers are also applied directly to the backing material. Thin films conform to the shape of the backing, a feature that allows them to be used in such innovative products as flexible solar electric roofing shingles

### **Solar Electric System Components**

In a PV-based system for energy production the PV modules are firstly connected in series to achieve appropriate voltage. The series connected strings are then connected in parallel to form an array, see Figure 3. In addition to PV modules, a grid-connected PV system requires a power conversion system for converting the unregulated DC voltage from the PV array into a single-phase or three phase AC voltage that can be connected to the grid. This conversion system is made up from an inverter bridge, usually based on IGBT transistors, followed by harmonic filters and in some cases a transformer for stepping up the voltage, in case the grid voltage level cannot be achieved otherwise. In other cases, particularly for single-phase systems the voltage adaptation is made on the DC side by means of a DC/DC boost converter. Complete systems usually include switchgear, fuses, and a grounding circuit as well. In some cases equipment for automatically aligning the panels to the sun is also used (sun trackers, sun followers). This adds cost to the system, but can significantly increase power yield.

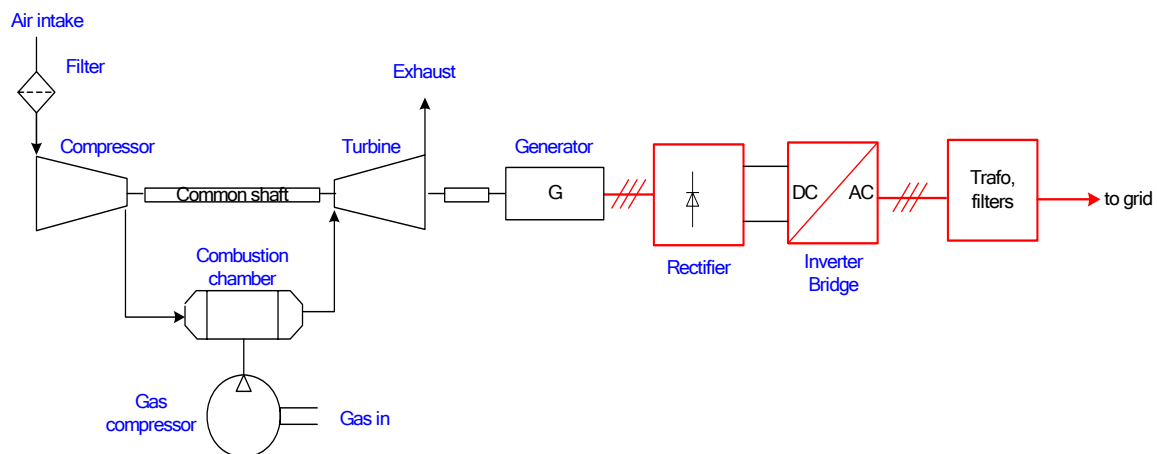


**Figure 3: Components of a typical grid-connected PV system**

### 1.2.2. Microturbines

Microturbines are a relatively new distributed generation technology [2]. They were introduced in the market in 1998 by Capstone and Elliot Energy Systems. The initial systems were with lower capacity units - 30 kW (Capstone) and 45 kW (Elliott). Eventually, with the market development, new higher capacity units were introduced, as for example Ingersoll Rand's 250 kW microturbine.

Definition: *Microturbines are small combustion turbines approximately the size of a refrigerator with outputs of 25-500 kW. They evolved from automotive and truck turbochargers, auxiliary power units for airplanes, and small jet engines and are composed of a compressor, combustor, turbine, alternator, recuperator, and generator.*



**Figure 4: Simplified sketch of microturbine system [2].**

Microturbines offer a number of potential advantages compared to other technologies for small-scale power generation. These advantages include their small number of moving parts, compact size, light weight, greater efficiency, lower emissions, lower electricity costs, and ability to use waste fuels. They also have the potential to be located on sites with space limitations for the production of power.

Recuperated units use a sheet-metal heat exchanger that recovers some of the heat from an exhaust stream and transfers it to the incoming air stream. The preheated air is then used in the combustion process. If the air is preheated, less fuel is necessary to raise its temperature to the required level at the turbine inlet. Recuperated units have a higher thermal-to-electric ratio than unrecuperated units and can produce 30% to 40% fuel savings from preheating. In

addition, waste heat recovery can be used with these systems to achieve efficiencies greater than 80%.

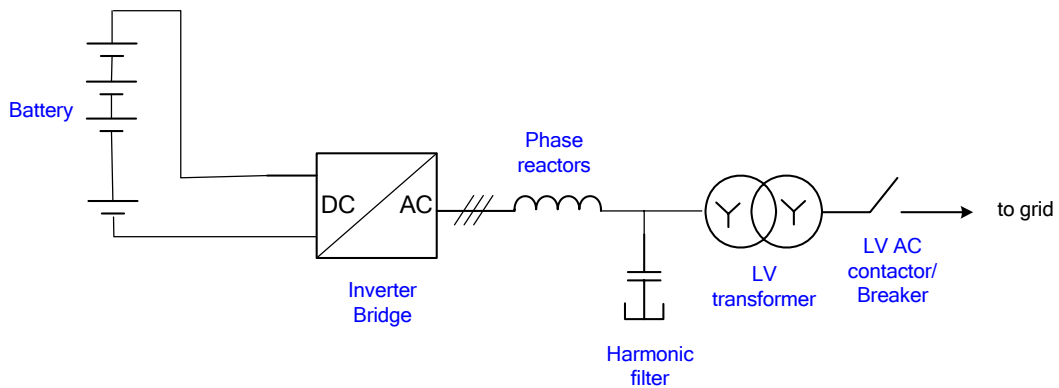
<b>Characteristics of microturbines [3]</b>	
Size Range	25-500 kW
Fuel	Natural gas, hydrogen, propane, diesel, landfill gas, biogas
Efficiency	15 % (Unrecuperated) 20-30% (Recuperated) Up to 85 % - CHP
Environmental	Low (<9-50 ppm) NO <sub>x</sub>
Other Features	Cogeneration (50-80°C water)
Capital Cost (\$/kW)	700 – 1 100
Maintenance Interval (hours of operation)	5 000 – 8 000

### **1.2.3. Battery storage units**

In stand-alone power systems as well as in microgrids there is frequently a need for temporary energy storage. In case renewable energy sources, such as wind and solar, are used this need emanates from the fact that the energy production is not constant over time. For this reason a temporary storage is required to bridge the gap between the instantaneous load demand and the generation capacity.

The battery type that is the most common in small scale energy storage systems is *lead-acid* batteries, which are the most mature among all batteries. They are the prime storage choice for power quality, UPS, spinning reserve and some energy management applications. Key features of lead acid battery technology are a high degree of maturity and lowest initial storage cost (in \$/kWh) of all batteries [4]. The main drawback of Lead acid batteries is their limited cycle life and that they show poor resilience to deep discharge. The cycle life of stationary VRLA batteries in a controlled environment (20°C) is typically 800 – 1500 cycles.

A battery energy storage system requires a power electronic interface to be connected to an AC grid, see Figure 5. The purpose is to turn the varying DC voltage from the batteries into regulated AC voltage that can be fed into the grid. To allow for both charging and discharging of the batteries the grid interface needs to be bidirectional in terms of power flow.



**Figure 5: Schematic view of battery storage unit**

### 1.3. References

- [1] Luque, A; Hegedus, S; "Handbook of photovoltaic science and engineering"; John Wiley, 2002.
- [2] Malmquist, Anders, Ola Aglen et al, "Microturbines: speeding the shift to distributed heat and power", ABB Review, pp 22-30 (Mar. 2003, ABB, Baden, Switzerland).
- [3] "Advanced Microturbine System: Market Assessment", Energy and Environmental Analysis, Inc., May 2003.
- [4] C.D. Parker, "Lead-acid battery energy storage systems for electricity supply networks", Journal of Power Sources, vol. 100, p. 18-28, 2001.

## 2. NOMENCLATURE AND FUNDAMENTAL CONCEPTS

### 2.1. Symbols

#### Symbol Conventions for Time-varying Quantities

<i>Symbol</i>	<i>Meaning</i>
$u, u(t)$	Instantaneous value
$U$	DC or RMS AC value
$\hat{U}$	Peak AC value
$\vec{u}$	Space vector, instantaneous value
$\underline{U}$	Complex phasor ( $u(t) = \text{Re}(\underline{U}e^{j\omega t})$ )
$\hat{U}_k$	Magnitude of the harmonic of order $k$

#### Specific Symbols

<i>Symbol</i>	<i>Quantity</i>	<i>Unit</i>
$e$	Natural base ( $\approx 2.7182818\dots$ )	-
$\pi$	Constant ( $\approx 3.14159265\dots$ )	-
$j$	Imaginary unit ( $j^2 = -1$ )	-
$f$	Frequency	Hz
$t$	Time	s
$\tau$	Time constant	s
$u, v$	Voltage	V
$u_i$	Phase voltages ( $i=1,2,3$ )	V
$u_{ij}$	Line-to-line voltages ( $u_{ij} = u_i - u_j$ )	V
$U_d$	DC link voltage, pole to midpoint	V
$i$	Current	A
$i_i$	Phase currents ( $i=1,2,3$ )	A
$\varphi, \phi$	Load angle	rad
$N_{tr}$	Transformer turns ratio	-
$s_i$	Coupling function for phase leg $i$	-
$\omega$	Angular frequency	rad/s
$\omega_0$	Fundamental angular frequency	rad/s
$\omega_c$	Carrier angular frequency	rad/s
$T_c$	Carrier cycle time	s
$T_s$	Modulation interval for space vector modulation	s
$M$	Modulation index (modulation depth)	-
$p$	Pulse number, frequency ratio	-
$f(t)$	Modulated function	various
$D_k$	Coefficients of the Fourier series expansion	various
$C_{mn}$	Coefficients of the double Fourier series expansion	various
$\delta$	Duty cycle	-

### 2.2. Abbreviations

VSC	Voltage Source Converter
DEG	Distributes energy Generation
RES	Renewable energy sources
PWM	Pulse width modulation
PS	Positive sequence
NS	Negative sequence
ZS	Zero sequence

### 2.3. General concepts concerning three-phase systems

In this section a few mathematical concepts related to periodic systems and three-phase systems are described. They will be needed for the subsequent discussion of grid-connected inverter interfaces for distributed power resources.

#### 2.3.1. Fourier series expansion of periodic signals

A periodic signal  $f(t)$ , such as a PWM voltage waveform, with cycle time  $T$  may under certain circumstances be described by a Fourier series expansion.

$$f(t) = \sum_{k=-\infty}^{\infty} D_k e^{jk\omega_0 t} \quad (1)$$

Here  $\omega_0$  is the angular frequency of the fundamental oscillation of the signal, i.e.

$$\omega_0 = \frac{2\pi}{T}.$$

The Fourier coefficient  $D_k$  corresponds to the harmonic component with angular frequency  $k\omega_0$  and can be determined by the integral:

$$D_k = \frac{1}{T} \int_0^T f(t) e^{-jk\omega_0 t} dt \quad (2)$$

Under condition of linearity the frequency domain description of the signal given by the Fourier series is valuable in the sense that it enables a frequency-oriented circuit analysis. For instance, if the harmonic components of the phase voltages are known the corresponding phase current harmonics may be computed. To see this more clearly the complex Fourier series can be rewritten as a cosine series. When  $f(t)$  represents a voltage or current waveform it is real-valued, whereby  $D_{-k} = \overline{D_k}$  applies, which is easily verified from Eq. (2). Using this identity and rearranging the sum, Eq. (1) can be rewritten as

$$f(t) = D_0 + 2 \sum_{k=1}^{\infty} |D_k| \cos(k\omega_0 t + \arg[D_k]). \quad (3)$$

Thus  $2D_k$  can be interpreted as a *phasor* containing information about the amplitude and phase shift of the harmonic component with order  $k$ .

In case the waveform exhibits half-wave symmetry, i.e. it fulfils the relation,

$$f(t) = -f\left(t \pm \frac{T}{2}\right), \quad (4)$$

which is often the case in the context of power systems, only odd harmonics will appear in the Fourier series expansion, which can easily be verified from (2). Thus

$$D_k|_{k \text{ even}} = 0$$

applies in this case.

### 2.3.2. Harmonics in three-phase Systems

The general properties of three phase systems makes it possible to predict which harmonics in the phase voltages that will influence a source or load connected to a three-phase converter. In order to do this it is firstly recalled that a general sinusoidal three phase system can be separated into two symmetric sequences and a zero sequence.

$$\begin{pmatrix} \mathbf{U}^+ \\ \mathbf{U}^- \\ \mathbf{U}^0 \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 1 & e^{j2\pi/3} & e^{-j2\pi/3} \\ 1 & e^{-j2\pi/3} & e^{j2\pi/3} \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} \mathbf{U}_1 \\ \mathbf{U}_2 \\ \mathbf{U}_3 \end{pmatrix} = \mathbf{C}\mathbf{U}_p \quad (5)$$

$$\begin{pmatrix} \mathbf{U}_1 \\ \mathbf{U}_2 \\ \mathbf{U}_3 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ e^{-j2\pi/3} & e^{j2\pi/3} & 1 \\ e^{j2\pi/3} & e^{-j2\pi/3} & 1 \end{pmatrix} \begin{pmatrix} \mathbf{U}^+ \\ \mathbf{U}^- \\ \mathbf{U}^0 \end{pmatrix} = \mathbf{C}^{-1}\mathbf{U}_s \quad (6)$$

Here  $\mathbf{U}_1$ ,  $\mathbf{U}_2$  and  $\mathbf{U}_3$  are the phasors corresponding to the three phase voltages. For the zero-sequence the waves of each phase are identical and it therefore can not drive any currents in a connected load or source without connected midpoint.

Now consider an arbitrary three-phase system with non-sinusoidal symmetrically shifted, periodical, phase voltages,  $u_1(t)$ ,  $u_2(t)$  and  $u_3(t)$ , such as in the output of a three-phase pulse width modulated VSC:

$$u_1(t) = u_2(t + T/3) = u_3(t + 2T/3), \quad (7)$$

Then it can be shown that the set of phasors corresponding to these voltages of a certain harmonic order,  $\mathbf{U}_{1,k}$ ,  $\mathbf{U}_{2,k}$  and  $\mathbf{U}_{3,k}$ , will form either symmetrical or zero-sequence systems, see e. g. [1]. Depending on the harmonic order, these systems can be characterised as follows:

$$k = 1 + 3r \quad \text{pure positive sequence}$$

$$k = 2 + 3r \quad \text{pure negative sequence}$$

$$k = 3 + 3r \quad \text{pure zero sequence}$$

where  $r = 0, 1, 2$  etc.

Thus it can be concluded that if the phase voltages are periodical and phase-shifted by one third of a cycle with respect to each other no components at integer multiples of three will appear in the line-to-line voltages. This circumstance is of vital importance to several three-phase modulation schemes.

## 2.4. References

- [1] Reed M. B., "Alternating-Current Circuit Theory", Harper & Brothers, New York, 1948.

### 3. LOW VOLTAGE THREE PHASE DISTRIBUTION SYSTEMS

#### 3.1. Introduction

The electrical power system is mainly composed of three separate parts; generation, transmission and distribution (**Figure 6**). Most of the distribution systems are low voltage three phase 4 wire systems. In Europe, the distribution system voltage is 400 V three-phase or 230 V single-phase. There are different international regulations and standards regarding LV distribution system supply. Most of the European low voltage distribution system uses up to 16 A current per customer with a short circuit capacity of 200 A or higher for equipments connected to the LV grid. The typical topology of the LV distribution system in Europe is radial in nature. A typical distribution system in Europe has few number of MV-LV transformers for supplying a whole neighbourhood which is generally of the rating of 1 MVA. The higher voltage at distribution level (230V/400 V) provides acceptable loss for longer distribution wires. In recent times, the cable distribution is also becoming more usual especially in cities. The micro-grid concept with more and more distributed generation resources are becoming popular due to its inherent reliability and efficiency with more concern on green technology. With the radial distribution system, some of the common protection and regulation requirements need to overview for connection of such distributed energy resources (DER). This chapter provides some overview of the existing regulations mostly regarded in European standards for grounding, harmonics, voltage quality, power quality and unbalance.

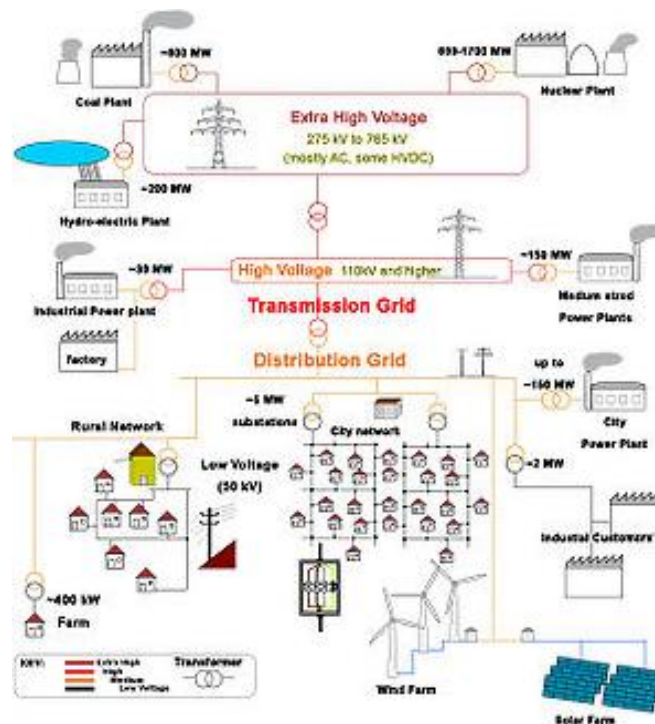


Figure 6 Present electric grid configuration.

### 3.2. Grounding

International standard IEC 60364 specifies three families of grounding or earthing arrangement in the distribution level using two letter codes TN, TT and IT. The first letter indicates the connections between ground and the power supply equipments (generator or transformer). 'T' denotes a direct connection between a point and the earth; 'I' denotes no point of connection between the point and the earth. The 2nd letter denotes the connection between the earth and the electrical device. Here, 'T' denotes direct connection with earth and 'N' denotes that the connection with earth is via supply system.

**TN network:** In TN grounding system, one point in the generator or transformer, typically the star point of the three phase system is grounded. The body of the electrical device is connected to the ground via this ground connection. There are three families of TN grounding network.

**TN-S:** Protective grounding and the neutral conductor of the system are separate and only grounded at the supply side (Figure 7).

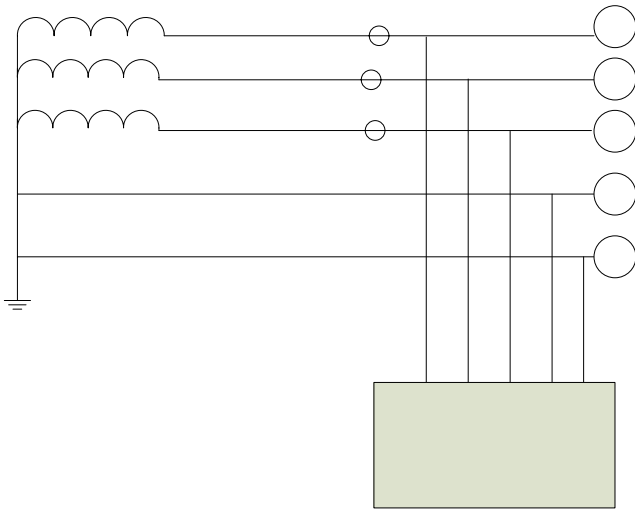
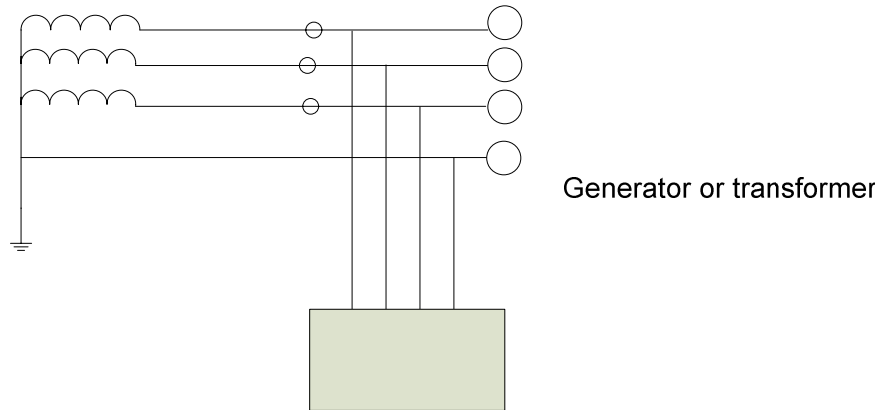


Figure 7 TN-S grounding system.

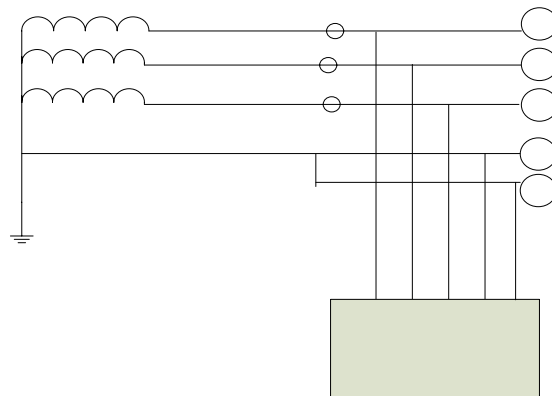
**TN-C:** A combined PEN conductor is used. It saves cost of one additional conductor but it needs multiple grounding at different point to avoid risk of broken neutral or ground (Figure 8).

Generator or transformer



**Figure 8 TN-C grounding system.**

**TN-C-S:** Part of the system uses combined PEN conductor while at some points PE and N conductors are separated ( like inside house wiring) (Figure 9). The combined PEN conductor can be grounded at different points providing multiple grounds. This reduces the risk of broken neutral or ground conductors.

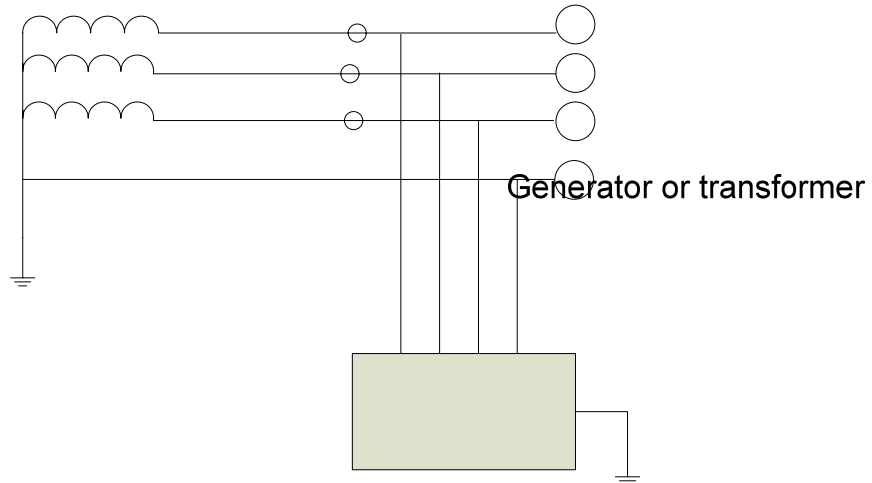


**Figure 9 TN-C-S grounding system.**

**TT Network:**

In TT grounding system, the earth connection of the consumer is provided by a separate ground at the customer premise irrespective of the grounding in the supply system (Figure 10). This is advantageous, if the ground connection of the supply becomes weak.

Generator or transformer

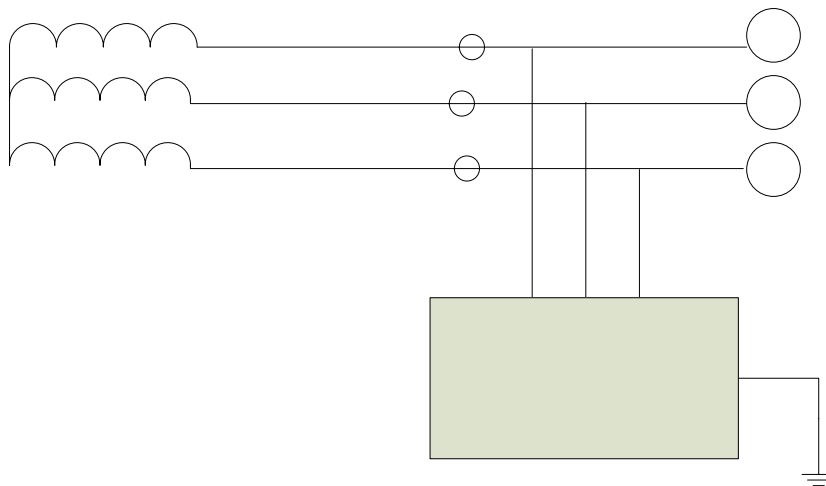


**Figure 10 TT Grounding network.**

**IT Network:**

In IT system, there is no connection to the earth at the supply terminal. The grounding of consumer premises is done locally (Figure 11).

Most of the European distribution systems use TN-S or TN-C-S system for reliable grounding.



**Figure 11 IT grounding.**

The summary of the characteristics of different types of earthing or grounding system can be summarized in the following table. Table 1 may help to identify individual requirements and related schemes.

**Table 1 Characteristics of Grounding Schemes.**

Electrical Characteristics	TT	TN-S	TN-C	IT1	IT2
Fault Current	High	Very high	Very high	Low	Very high
Fault voltage	High	High	High	Low	High
Touch voltage	Low/very high (low if equipotential)	High	High	Low	High
Protection of persons with generating set	Good	Bad	Bad	Good	Bad
Continuous overvoltage	Good	Good	Good	Bad	Good
Transient overvoltage	Good	Bad	Bad	Good	Bad
Immunity to nearby lightning strike	Bad	Good	Good	Good	Good
Continuous emission of an electro-magnetic field	Good	Good	Bad	Good	Good
Interruption after first fault	Bad	Bad	Bad	Good	Good
Cost of repair	High	Very high	Very high	High	Very high
Installation damage	Less	More	More	Very less	more

### **3.3. Standards and International Regulations for grid connected distributed sources**

#### **“Low Voltage” Directive 2006/95/CE**

The Low Voltage Directive refers to any electrical equipment designed for use at a rated voltage from 50 to 1000 V for alternating current and from 75 to 1500 V for direct current. In particular, it is applicable to any apparatus used for production, conversion, transmission, distribution and use of electrical power, such as machines, transformers, devices, measuring instruments, protection devices and wiring materials.

The following categories are outside the scope of this Directive:

- electrical equipment for use in an explosive atmosphere;
- electrical equipment for radiology and medical purposes;
- electrical parts for goods and passenger lifts;
- electrical energy meters;
- plugs and socket outlets for domestic use;
- electric fence controllers;

- radio-electrical interference;
- Specialized electrical equipment, for use on ships, aircraft or railways, which complies with the safety provisions drawn up by international bodies in which the Member States participate.

The most common LV distribution voltage supplies in the European Union is 3-phase 4-wire 230/400 V. An international standard IEC 60038 is the recommended practice for the 3-phase 4-wire distribution system. The variation of frequency and voltages varies from country to country. But the most common regulation for frequency variation is between 0.1 % to 2 %. The quality of LV network supply voltage implies that the service should be compliant with statutory limits of magnitude and frequency, uninterruptible power supply except for scheduled maintenance or as a result of system faults or other emergencies and preservation of near sinusoidal waveform.

There are many international regulations regarding the grid connected distributed generation resources. Some of the important regulations are referred in this section.

### **3.3.1. Voltage Quality**

Voltage regulation guidelines (EN 50160 [12]) demand a maximum voltage unbalance for three phase inverters of 3 %. Voltage amplitude variation is maximum permitted  $\pm 10\%$ . Frequency variation should be within  $\pm 1\%$ . Voltage dips are restricted to less than 1 sec. and less than 60%. Maximum THD level for voltage harmonics are recommended to be less than 8%. Some guidelines on the harmonic content permitted for different harmonics are given in Table 2.

**Table 2 Permitted Harmonic Contents.**

Odd Harmonics		Even Harmonics	
Order h	Relative voltage (%)	Order h	Relative voltage (%)
3	5	2	2
5	6	4	1
7	5	6-24	0.5
9	1.5		
11	3.5		
13	3		
15	0.5		
17	2		
19	1.5		
21	0.5		
23	1.5		
25	1.5		

The voltage deviations are permitted to vary within specified limits according to different IEEE and IEC regulations. In Europe, mostly IEC 61727 regulations are recommended. For 230/400 V, disconnection of DG is recommended as follows (Table 3).

**Table 3 Disconnection of DG according to voltage deviation.**

Voltage range (%)	Disconnection time (s)
$V < 50$	0.1
$50 \leq V < 85$	2
$110 < V < 135$	2
$V \geq 135$	0.05

The delay in disconnection is allowed to provide ride-through capability against short term disturbances. Similar regulations also exist for frequency deviation from IEC 61727. If frequency is beyond the range of  $\pm 1$  Hz from the nominal frequency of 50 Hz, the disconnection time is recommended to be 0.2 seconds. The same IEC 61727 guidelines provide minimum delay in reconnection after trip. If voltage is greater than 85 % or less than 110% and frequency limit is within  $\pm 1$  Hz then the minimum reconnection time is 3 minutes.

### 3.3.2. Power Quality

According to both IEEE 1574 [1] and IEC 61727 [5], the dc component of the current should be less than 1% of the rated RMS current. The harmonic content should be measured by

using harmonic analysis using FFT and there is no maximum trip time. The current harmonics are limited according to following guidelines in Table 4. Also, according to the testing guidelines, the current harmonics should be measured using a voltage source with less than 2.5% THD. To-date, IEC 61727 has not been approved in Europe and the general practice is adhere to requirements specified by IEC 61000-3-2 [8] for Class A equipments as given in Table 5. The current limits in IEC 61000-3-2 are given in amperes and typically higher than the ones in IEC 61727. For equipments with a higher current than 16 A but less than 75 A, a similar standard exists in IEEE 61000-3-12 [10].

**Table 4 Current harmonic content requirement.**

IEEE 1574 and IEC 61727						
Harmonic order (odd)	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$h \geq 35$	THD (%)
%	4.0	2.0	1.5	0.6	0.3	5.0

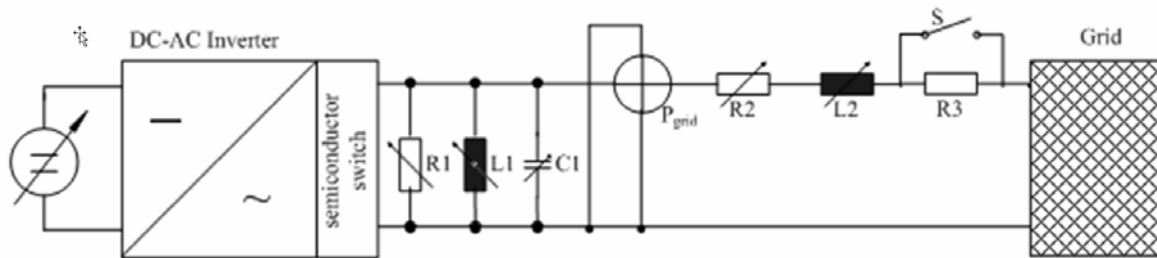
**Table 5 IEC 61000-3-2 for Class A harmonic requirements.**

Odd Harmonics		Even Harmonics	
Order h	Current (A)	Order h	Current (A)
3	2.30	2	1.08
5	1.14	4	0.43
7	0.77	6	0.30
9	0.40	$8 \leq h \leq 40$	$0.23 \cdot 8/h$
11	0.33		
13	0.21		
$13 \leq h \leq 39$	$0.15 \cdot 15/h$		

**3.3.3. Anti-islanding requirements**

Islanding for grid connected DG system occurs if the DG is not disconnected within a very short time after the grid is tripped. It is continuing to operate with local load. If the DG system does not disconnect after the grid trips, there can be consequences due to reconnection of the grid out-of-phase closure as well safety hazard to the utility workers. In order to avoid these serious consequences safety measures called anti-islanding requirement has been in place. Anti-islanding requirements under IEC 62116-2006 [6] (which is similar to the IEEE 1547) provide guidelines to check whether a DER (Distributed Energy Resource) equipment is capable of detecting tripping of grid. The DER (mostly inverter) is tested at three levels of power output (A 100-105%, B 50-66% and C 25-33% of inverters rated output). The DER

inverters have also specific voltage conditions. In Germany, the anti-islanding testing method is stricter and is regulated by VDE-0126-1-1. The typical test circuit is shown in Figure 12.



**Figure 12 Anti-islanding test circuits for detection of impedance change.**  
Reference: Power Electronics for Renewable Energy Systems Course, 25-28 Nov 2008, R. Teodorescu, M. Liserre, P. Rodriguez, J Guerrero

In recent years, IEEE 1547 [1] standard has included grid requirement not only for PV inverters but also for any distributed resources under 10 MVA. But, different countries yet to have a common regulation policy regarding anti-islanding. Hence, there are still differences between requirements specified by local utility and grid operations.

### 3.3.4. Imbalance

One part of power quality is the voltage imbalance in the supply. The regulation on the imbalance can be found in EN 50160 and it is valid in European Union. A significant part of the equipment in use today, especially electronic and computer devices requires good power quality (PQ). However, the same equipment often causes distortion of the voltage supply in the installation, because of its non-linear characteristics, i.e. it draws a non-sinusoidal current with a sinusoidal supply voltage. Thus, maintaining satisfactory PQ is a joint responsibility for the supplier and the electricity user. According to standard EN 50160 [12] the supplier is the party who provides electricity via a public distribution system, and the user or customer is the purchaser of electricity from a supplier. The unbalance calculation uses the ratio between negative sequence component and positive sequence component of the supply voltage or current [13]. If  $V_p$  is the positive sequence and  $V_n$  is the negative sequence voltage then the percentage unbalance is given by,

$$U_V = \frac{V_n}{V_p} * 100\%$$

The current unbalance can be similarly calculated for the positive sequence current ( $I_p$ ) and negative sequence current ( $I_n$ ) as follows.

$$U_I = \frac{I_n}{I_p} * 100\%$$

The general requirement for LV system is that the unbalance should be less than 2% for 95% of the week. The unbalance is calculated over a mean of 10 minutes RMS values. The restrictions can be up to 3% in some locations. According to EMC standards for low voltage distribution from EN 61000-2-2 and IEC 61000-2-12 provides the same regulation of having up to 2% of unbalance.

### 3.4. Microgrid in Distribution

Recent developments in renewable resources and small generation units have initiated distributed generation based power system architecture. The renewable resources can be connected to transmission and distribution level. But, microgrid architecture is typically present a self-sustained distribution system. But there are many issues involving the integration of asynchronous and small synchronous generation units in the traditional distribution system. Some of the traditional requirements for distribution system in Europe as have been summarized in the previous sections relates to grounding requirement, harmonic contents in the supply voltage and current, anti-islanding and unintentional islanding requirements and unbalance due to single phase loading. Another aspect of such microgrid configuration is in the change of protection devices of the distribution system. The protection devices in general, are designed for radial system for one way power flow. In the presence of distributed generation, these protection devices need to account for power flows in reverse direction as well. Several of microgrid architectures have been configured in Europe in recent years. The general form of such microgrid is shown in **Figure 13**. The regulations of protection equipment as specified in different European standards [14] can be summarized in **Table 6**. The protection requirements along with the requirements of quality and islanding scheme are being the main focus of today's utilities and governments.

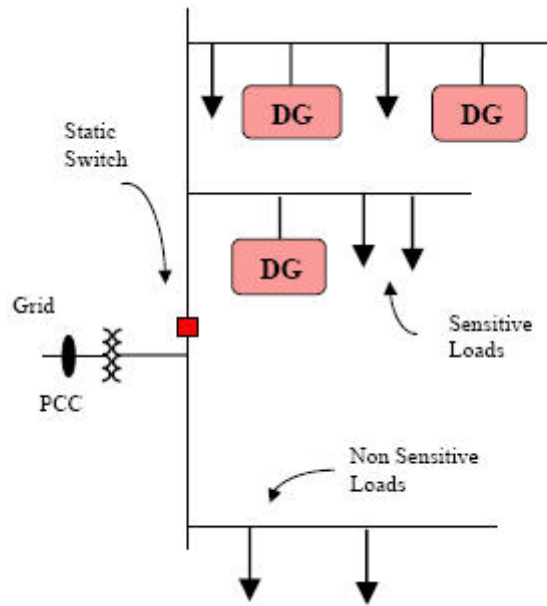


Figure 13 Typical Microgrid Architecture.

Table 6 Protection requirement for online LV generators.

Protection Requirement	Permanent parallel operation for LV generators			Short term parallel operation (% min. max) for LV generators		
	<150 KVA	150-250 KVA	>250 KVA	<150 KVA	150-250 KVA	>250 KVA
Under/over voltage and frequency	Yes	Yes	Yes	Yes	Yes	Yes
Loss of Main		Yes	Yes			
Overcurrent	Yes	Yes	Yes	Yes	Yes	Yes
Earth fault		Yes	Yes		Yes	Yes
Reverse Power			Yes			
Directional overcurrent			Yes			
Neutral voltage displacement		Yes	Yes		Yes	Yes
Parallel limit timer					Yes	Yes

### 3.5. Conclusion

This chapter summarizes the existing requirements regarding protection, grounding and qualities of supply in the distribution system in Europe. The major portion of European distribution grid is radial and hence has strict requirements on interconnection of distributed

resources. Some of the existing protection and quality constraints also applies to the small generating units that can be connected according to microgrid initiatives. Though the requirements vary from country to country, an overall picture has been presented in this short chapter such that it provides inputs to the microgrid initiative and can provide a general basis for control, protection and quality requirements.

### 3.6. References

- [1] IEEE 1547-2003 Standard for Interconnecting Distributed Resources with Electric Power Systems
- [2] IEEE 1547.1- 2005 Standard for Conformance Tests Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems
- [3] IEEE 929-2000, Recommended Practice for Utility Interface of Photovoltaic (PV) Systems – incorporated in IEEE 1547
- [4] UL 1741, Standard for Inverters, Converters, and Controllers for Use in Independent Power Systems - elaborated by Underwriters Laboratories Inc. – compatible with IEEE 1547
- [5] IEC61727 [6] Photovoltaic (PV) systems - Characteristics of the utility interface - December 2004
- [6] IEC 62116 Ed.1 2005: Testing procedure of islanding prevention measures for utility interactive photovoltaic inverter (describes the tests for IEC 61727) – approved in 2007
- [7] VDE0126-1-1 2006 Automatic disconnection device between a generator and the public low-voltage grid” – Safety issues- applied on German Market

### EMC

- [8] IEC 61000-3-2, Ed. 3.0 – “Electromagnetic compatibility (EMC) –Part 3-2: Limits – Limits for harmonic current emissions (equipment input current  $\leq 16$  A per phase)”, ISBN 2-8318-8353-9, November 2005
- [9] EN 61000-3-3, Ed. 1.2 —“Electromagnetic compatibility (EMC) –Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current  $\leq 16$  A per phase and not subject to conditional connection”, ISBN 2-8318-8209-5, November 2005
- [10] IEC 61000-3-12, Ed. 1 – “Electromagnetic compatibility (EMC) –Part 3-12: Limits – Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current  $>16$  A and  $\leq 75$  A per phase” , November 2004
- [11] IEC 61000-3-11, Ed. 1 —“ Electromagnetic compatibility (EMC) – Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current  $\leq 75$  A and subject to conditional connection” , August 2000
- [12] Standard EN 50160 – “Voltage Characteristics of Public Distribution System”, CENELEC: European Committee for Electrotechnical Standardization, Brussels, Belgium, November 1999

### Utility Voltage Quality

- [13] Voltage disturbances- Introduction to unbalance, Power quality application guide, Copper Development Association.
- [14] Hassan Mansir, “Distributed Generation comparison of the American and European interconnection”.

# 4. INVERTER TOPOLOGIES FOR CONNECTION TO THREE-PHASE LV GRIDS

## 4.1. Required functionality

As discussed in section 1.2 the connection of microsources to a low voltage microgrid generally requires a power electronic interface. The objective of the work will be to evaluate possible concepts regarding such interfaces. The ability of these concepts to handle the frequently unbalanced loading conditions present in microgrids will be studied in particular.

Figure 14 shows various possible pathways for interfacing low voltage microsources, such as PV panels, to an LV distribution network with three phases and a neutral. Many of these have been documented in the literature. The system mainly has to accomplish three tasks:

**Voltage adaptation and regulation.** In many cases the output voltage of the microsource is considerably lower than that of the AC grid. Furthermore the voltage may be varying, as in the case of batteries, fuel cells and photovoltaic cells. For these reasons the possibility of boosting and regulating the voltage is often required.

**Galvanic isolation.** In several applications it is required that that the grid should be galvanically separated from the source e. g. by a transformer. Furthermore, on several markets such separation is mandated by grid codes or norms.

**AC-DC conversion.** This is necessary since a sine voltage with acceptable harmonic content should be produced on the AC side. In some cases the conversion has to be bidirectional. This applies for instance to battery storage, where charging as well as

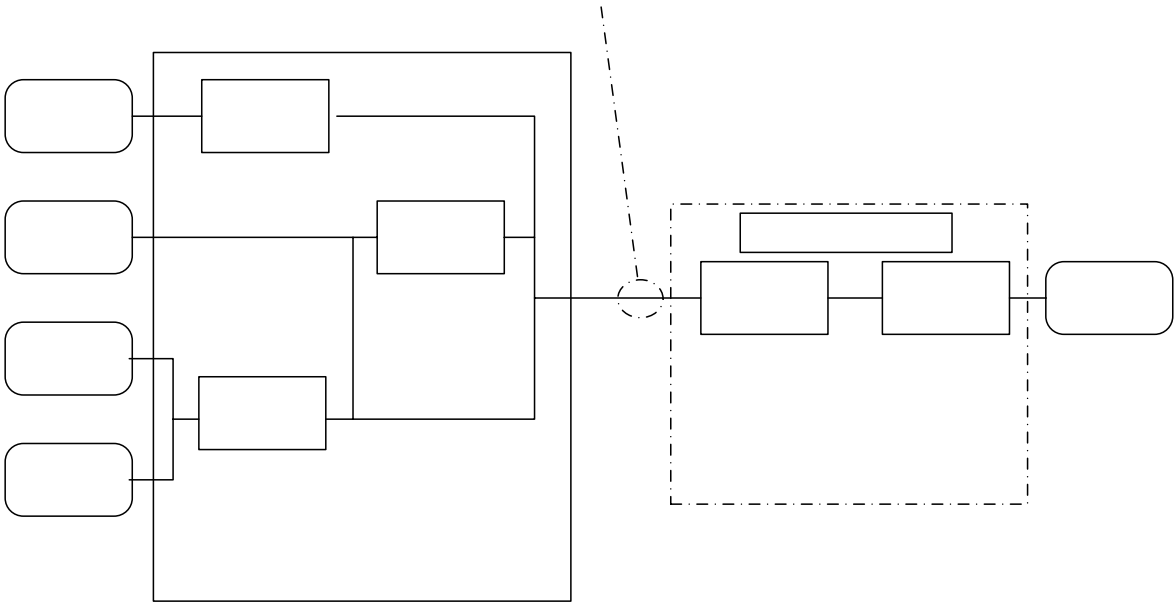


Figure 14. General scheme for microsource grid interfaces

discharging should be possible.

The basic topology that should be the focus of this work can be seen in Figure 14. It consists of two stages. The first steps up and regulates the voltage. The output is a regulated DC voltage. The second stage converts this DC voltage into a four-wire three-phase AC voltage that can be connected to the grid. The work should mainly be concerned with this latter stage. One specific issue that will be addressed is how to handle unbalanced conditions resulting from single-phase loads connected in the AC grid. These could e. g. be electrical appliances in households.

#### 4.2. Overview of basic voltage source converter topologies

The basic two-level voltage source converter, see Figure 15, can convert a DC voltage into an AC voltage of arbitrary frequency and magnitude. VSCs operate in all four quadrants and the power flow may thus be directed from the AC side to the DC side or vice versa. The semiconductor valves need to be able to conduct voltage in both directions and to block voltage in one direction by gate command. They are generally implemented by switches such as IGBTs or MOSFETs with diodes connected in anti-parallel.

The operation of a phase leg in a VSC during a modulation interval is outlined in Figure 16. A modulation interval generally constitutes a small fraction of a fundamental cycle of the AC side (typically 10% or less). During this interval the voltage on the DC side and the current on the AC side can be assumed to be approximately constant. The commutation process causes the phase outlet to alternately be connected to the positive and the negative DC rail. Thereby a desired pulse pattern can be achieved in the phase voltage. This also implies that

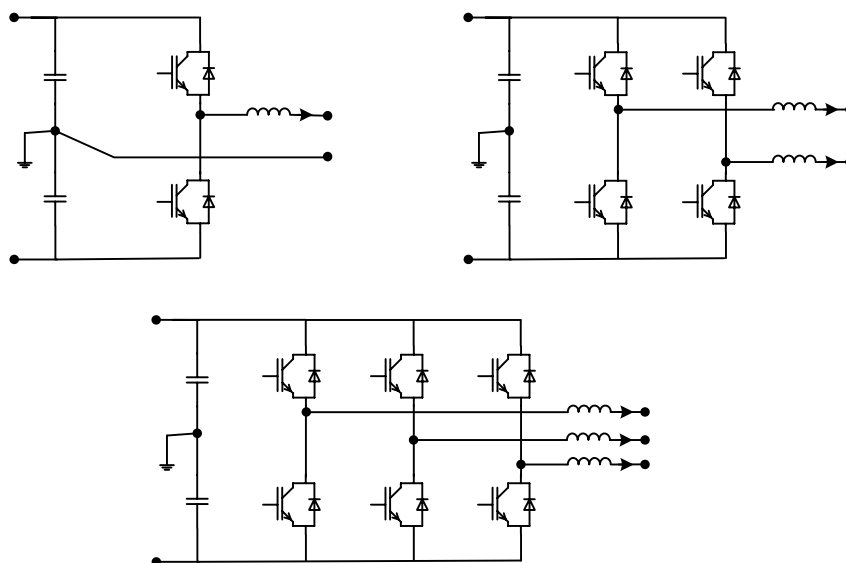


Figure 15. Voltage source converters with various number of phase legs.

the AC side current commutates between a switch in one valve and the diode in the other valve as shown in the figure. In case the phase current is directed in the opposite direction the commutation would occur between the other diode-switch pair.

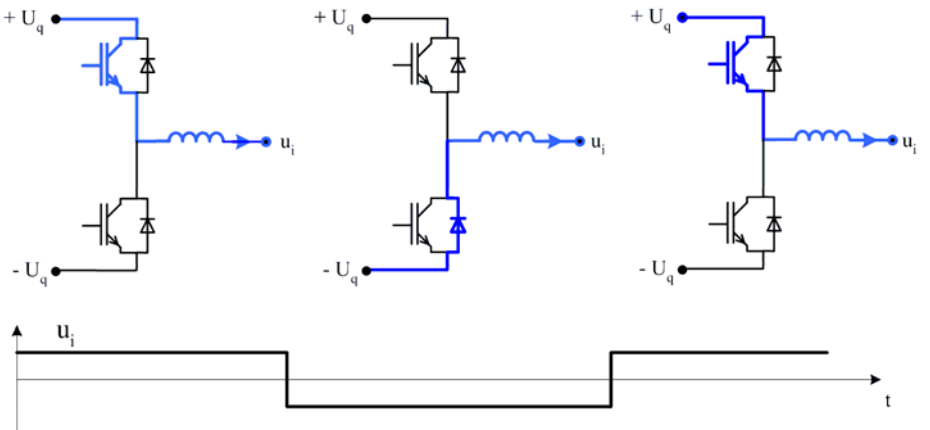
The mode of switching employed is generally referred to as *hard switching* i.e. the development of current and voltage during the commutations are governed by the properties of the involved semiconductor devices, their drive circuits, and the parasitic elements of the circuit such as the inductance of the DC side capacitors.

A number of factors have contributed to the widespread use of this class of topologies. Among these are the good controllability, a relatively simple protection concept and the availability of suitable semiconductor devices (IGBT, MOSFET). VSC systems are currently used in e.g. industrial drives, electric railway traction systems, distributed energy generation systems and even in very high power converters for HVDC and SVC applications.

**4.3. Inverter configurations for connection to four-wire three-phase systems**

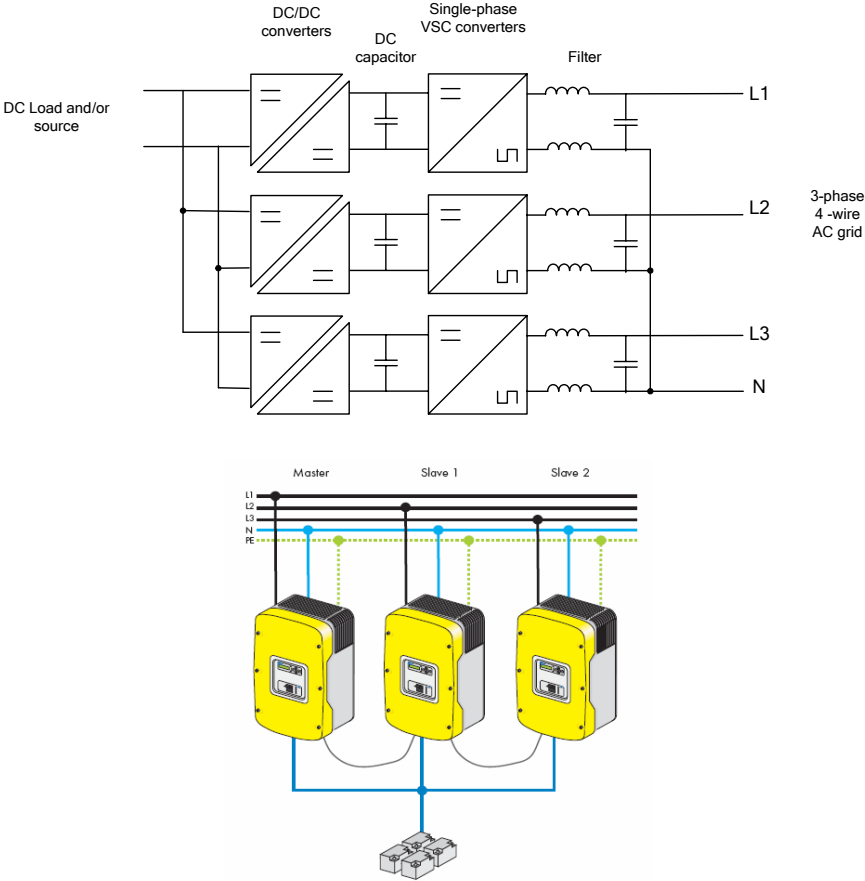
A straightforward solution to the problem of interfacing a DC microsource to a three-phase system with neutral is to use three complete single-phase inverter units, see Figure 17. This approach [1] is however likely to be costly, especially since each single-phase unit has its own DC side voltage conditioning.

For this reason, the focus of this work is instead inverter topologies based on a three-phase converter bridge of the same kind as used in industrial motor drives. In Figure 18 through Figure 20 different such topologies, which can also provide the neutral connector required in the four-wire system, are shown. In the first, a delta-whye coupled transformer is used to form the neutral. This way the zero-sequence resulting from unbalanced loading is decoupled from the converter. With such a system a part of the voltage adaptation could be made by the transformer, whereby a lower DC link voltage could be feasible. In the second alternative the neutral is formed by the midpoint of the DC link, Figure 19. This is a simple solution. One drawback is however that imbalances on the AC side will result in a voltage

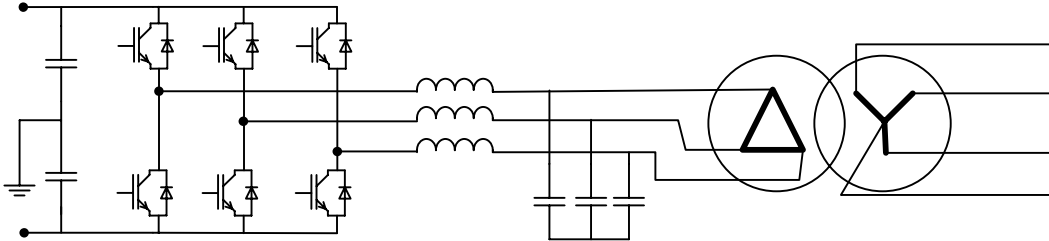


**Figure 16. Operation of a phase leg in a voltage source converter during a modulation interval.**

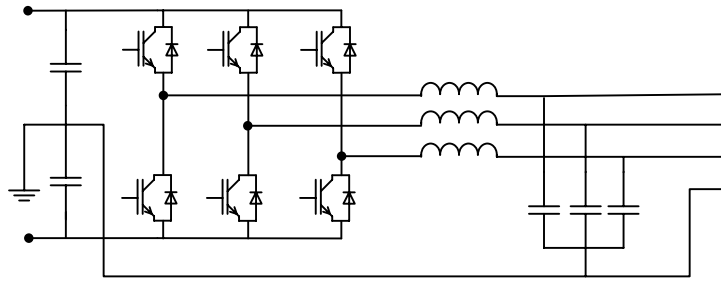
ripple on the DC side which may imply that a larger DC capacitor is required. The third alternative uses an additional phase leg in the converter to form the neutral, see Figure 20, ref [3]. This solution has the advantage of independent control of the neutral voltage, but is likely to be more expensive and complex than the other solutions.



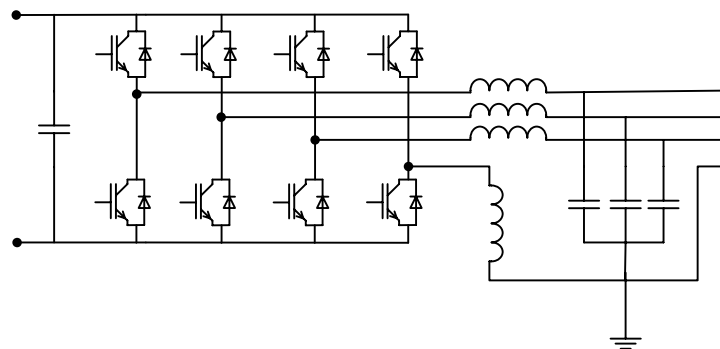
**Figure 17. Inverter system for connection to three phase four-wire system. The system is made up of three single-phase inverters [2]**



**Figure 18. Converter system with delta-wye coupled transformer used to decouple zero-sequence and form the neutral connector**



**Figure 19. Converter system where the DC link midpoint forms the neutral connector.**



**Figure 20. Converter system where a fourth converter leg is used to form the neutral connector.**

#### 4.4. References

- [1] Mohan N., Undeland T. M., Robbins W. P., "Power Electronics, Converters Applications and Design", Second Edition, John Wiley, 1995.
- [2] SUNNY ISLAND 5048 datasheet, SMA Solar Technology AG, Germany.
- [3] Richard Zhang, Dushan Boroyevich, V. Himamshu Prasad, Hengchun Mao, Fred C. Lee, Stephen Dubovsky, "A Three-phase Inverter with A Neutral Leg with Space Vector Modulation", ., Twelfth Annual Applied Power Electronics Conference and Exposition Conf Proc, 1997.

## 5. CONTROL AND MODULATION OF INVERTERS

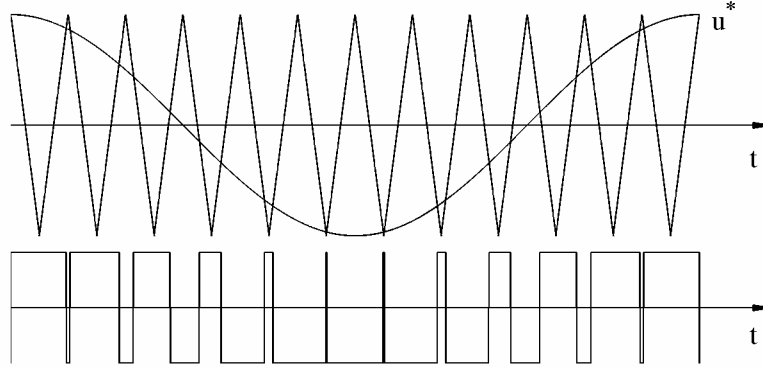
This chapter concerns general aspects of control and modulation of two-level inverters.

### 5.1. Modulation of voltage source inverters

#### 5.1.1. Definitions, PWM for Voltage Source Converters

Since the output from a voltage source converter can not be varied continuously but only be switched between discrete levels the only means of control is to appropriately choose the switching instants. The purpose of the modulation method is therefore to decide the switching instants so that the voltage-time area over time of the switched pulse pattern coincides with that of the desired reference (target) waveform.

An important class of modulation methods is the so called *carrier-based* methods. According to these methods the switching instants occur at the intersections between the reference voltage waveform and a carrier waveform. The carrier is typically a triangular with angular frequency  $\omega_c$ , considerably higher than the frequency of the reference waveform,  $\omega_0$ . For a two-level converter the output is connected to the upper level when the reference waveform exceeds the carrier and to the lower level otherwise, see Figure 21. The quotient between carrier and reference frequencies equals the number of pulses per fundamental cycle and is denoted *pulse number* or *frequency ratio*,  $p$ . The above described practice where the carrier is compared to a time-continuous sinusoidal reference is referred to as *natural sampling*. This can be practically implemented by analogue electronic circuits (function generators, comparators etc). Currently modulators, at least for moderate switching frequencies, are generally implemented in digital hardware. Under such circumstances a continuous sinusoidal reference becomes impractical as the switching instances correspond to solutions of a transcendental equation. For this reason generally a sampled version of the reference is used, where the sampling instances coincide with the peak values of the carrier. This practice is referred to as *regular sampling*. Another reason for using a sampled reference is that the reference generally is provided by some sort of higher level controller, which is also digitally implemented and thus only delivers its outputs at discrete points in time. With regular sampling the task of determining the switching instants in principle simply amounts to a multiplication of the sampled reference with the cycle time of the carrier  $T_c$ .



**Figure 21. Carrier-based modulation with triangular carrier (both leading and trailing edge modulated).  $M = 1$ ,  $p = 12$**

The normalised value of the fundamental component of the phase voltage is labelled *modulation index* ( $M$ ). As normalisation factor the magnitude of the phase voltage pulses  $U_d$  is often used.

$$M = \frac{\hat{U}^{(1)}}{U_d} \quad (8)$$

This choice of normalisation is adopted in this work. For a phase leg in a two level converter  $U_d$  amounts to half of the pole to pole DC link voltage. In the literature, the fundamental component obtained with square-wave switching is sometimes instead used as normalisation factor.

$$M' = \frac{\pi \hat{U}^{(1)}}{4 U_d} \approx 0.7854M \quad (9)$$

In the linear region, i.e. when the reference never exceeds the carrier, under idealised conditions the fundamental components of phase voltage and reference voltage are equal.

$$\hat{U}^{(1)} = \hat{U}^* \quad (10)$$

A modulation scheme where the magnitude of the reference exceeds the magnitude of the carrier is termed *overmodulation*. In this case Eq. (10) no longer holds.

### 5.1.2. Reference Common Mode Injection

A basic modulation scheme for a three-phase VSC, as shown in Figure 22, can be achieved by applying a carrier-based modulation as described in Section 5.1.1, with sinusoidal references and common carrier, to the three phase legs. Under such circumstances the maximum possible modulation index in the linear range equals one, which corresponds to a peak output voltage equal to half the DC link voltage. The addition of a common-mode third

harmonic component to all the references makes it possible to use a higher reference fundamental without overmodulating the converter.

The third harmonic reduces the peak envelope of the reference so that it does not exceed the carriers, see Figure 23. As the midpoint of the source or load is not connected it is not affected by the zero-sequence which does not appear in the line-to-line voltages. In e. g. [1] it is explained that a sinusoidal zero-sequence with amplitude of 1/6 of the fundamental is optimal with respect to increasing the maximum modulation index. With this choice  $M$  can be increased to  $2/\sqrt{3}$  which approximately amounts to a 15% increase. The zero-sequence does not need to be sinusoidal as long as its period is one third of the fundamental period.

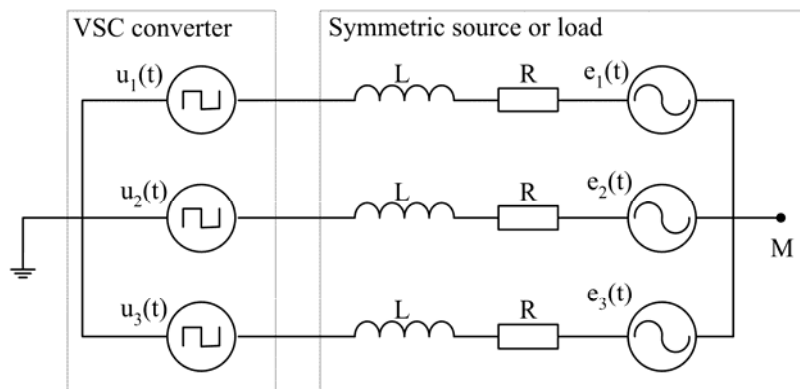
The addition of a zero sequence as described is highly attractive as it implies that higher output voltage and thereby more power can be achieved with a given converter. It is therefore widely used e. g. in drives applications.

### 5.1.3. Space Vector Modulation

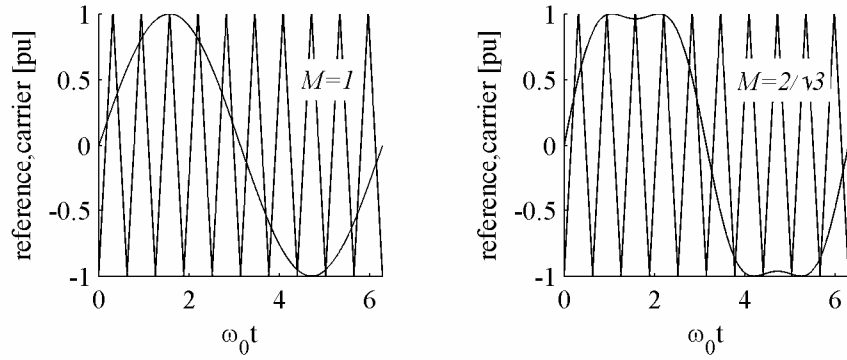
A three-phase modulation algorithm that has gained great popularity is the so called *space vector modulation (SVM)* [3]. The main reasons hereof are that it is simple to implement and furthermore is inherently compatible with modern torque and current control schemes. To describe the method the concept of a voltage space vector is firstly defined as

$$\bar{u} = K(u_1 + u_2 e^{j2\pi/3} + u_3 e^{-j2\pi/3}) \quad (11)$$

where  $u_1$ ,  $u_2$  and  $u_3$  are the three phase voltages. Other three-phase quantities such as current may also be transformed into their space-vector equivalents in the same manner. The constant  $K$  can be chosen arbitrarily. In this work the value  $K = 2/3$  is chosen which gives an amplitude-invariant transformation. The space vectors corresponding to the switching states that the converter can assume are called *base vectors*. There are six active



**Figure 22. Principal circuit diagram of a three-phase load or source with unconnected midpoint connected to a voltage source converter.**



**Figure 23. Zero-sequence addition to the reference waveforms. Left: no zero sequence, right: one sixth third harmonic added to the reference.**

base vectors where the phase legs have different switching states ( $\bar{v}_1$  through  $\bar{v}_6$ ) and two zero vectors ( $\bar{v}_0$  and  $\bar{v}_7$ ), in which all phase legs are switched to the same DC terminal, see Figure 24.

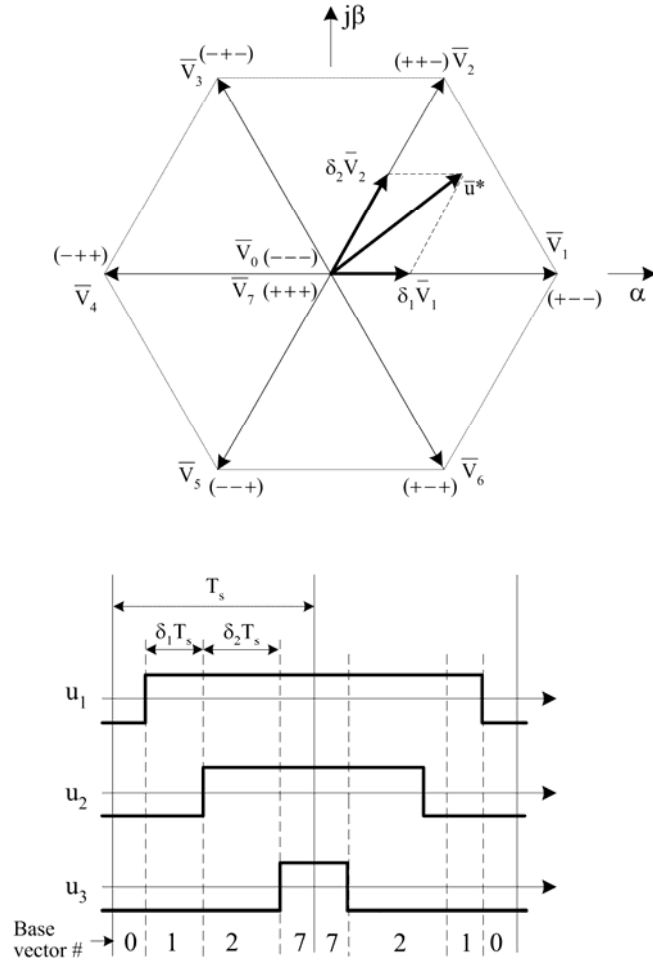
The six active vectors are symmetrically distributed, as seen in the figure, and can be described by the following expression:

$$\bar{v}_p = \frac{4}{3} U_a e^{j(p-1)\pi/3} \text{ for } p=1, \dots, 6. \quad (12)$$

The space vector modulation algorithm is based on having the reference defined in terms of its space vector,  $\bar{u}^* = u_\alpha^* + ju_\beta^*$ , and choosing the base vectors and their duty cycles during the modulation interval so that their average over the interval coincides with this reference vector. In a modulation interval the initial state is always one of the zero vectors. As the three phase legs are switched at different instants during the interval two active vectors are imposed and finally the system arrives at a zero vector, opposite to the initial one. The switching sequence is chosen in such way that the active vectors will be the ones adjacent to the reference vector.

With a sampled reference vector the determination of the duty cycles of the active states can be made by solving an equation of the type

$$\delta_1 \bar{v}_{p_1} + \delta_2 \bar{v}_{p_2} = \bar{u}^* \quad (13)$$



**Figure 24. Space-vector modulation.**

which is readily done by splitting it into real and imaginary parts. The variables  $p_1$  and  $p_2$  represent the indices of the two base vectors to be used in the concerned modulation interval whereas  $\delta_1$  and  $\delta_2$  are the corresponding duty cycles. The duty cycles are defined as

$$\delta_i = T_i / T_s . \quad (14)$$

The total zero vector duration is then given by the remains of the modulation interval as

$$\delta_z = 1 - (\delta_1 + \delta_2) . \quad (15)$$

A degree of freedom that remains is the relative distribution of  $\delta_z$  on the two zero vectors  $\bar{V}_0$  and  $\bar{V}_7$ . In most cases the preferred choice is to let the zero vectors have equal duration, i. e.

$$\delta_0 = \delta_7 = \frac{\delta_z}{2} , \quad (16)$$

although several other alternatives are conceivable.

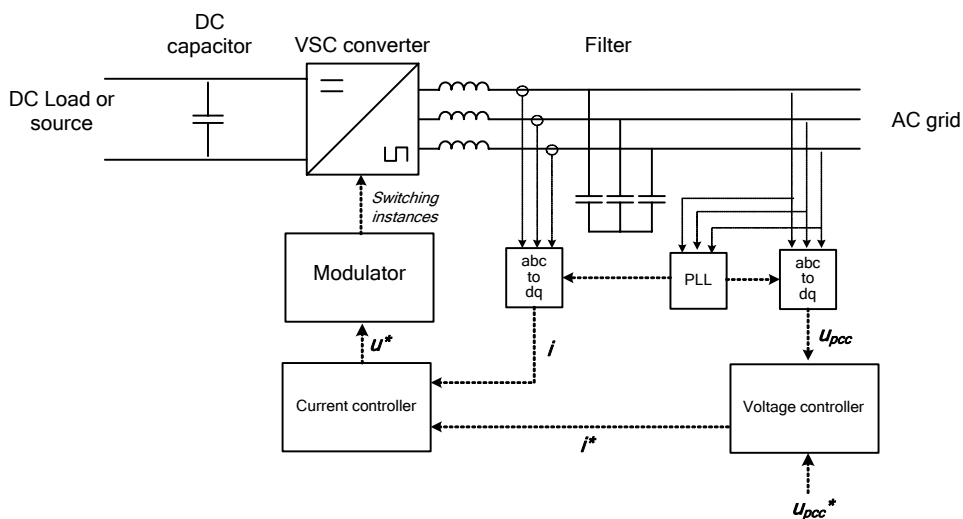
In [1] it is explained that space-vector modulation can be viewed as a regularly sampled carrier-based method with zero-sequence injection. The algorithm thus merely amounts to an efficient way of choosing the zero-sequence signal.

## 5.2. General control of grid-connected inverters

This section briefly deals with closed-loop controllers used for the AC-side voltage and current used in grid-connected inverters. The control structure is influenced by a number of considerations such as the nature of the DC source and the grid requirements.

### 5.2.1. Current and voltage controllers

Typically, the current and voltage controllers operate in a dq-system rotating with the positive sequence of the grid voltage. This is made by transforming the measured three-phase signals by a dq-transformation whereby the positive sequence will be a DC signal. The control system generally has an inner loop acting on the phase currents. Depending on the application there may also be an outer loop, controlling the grid-side voltages, see Figure 25.



**Figure 25. Cascaded control of grid-connected inverter with inner current loop and outer voltage control loop. Simplified schematic**

During so called **grid-forming** operation the inverter (possibly together with some other inverters or other sources) sustains the grid voltage. It thus handles voltage level and frequency regulation. In a microgrid this mode of operation is used when the grid operates in island mode and there is no connection to the external AC grid. Electrically, the inverter should ideally act as a stiff voltage source during this mode of operation, regardless of the nature of the loads in the grid.

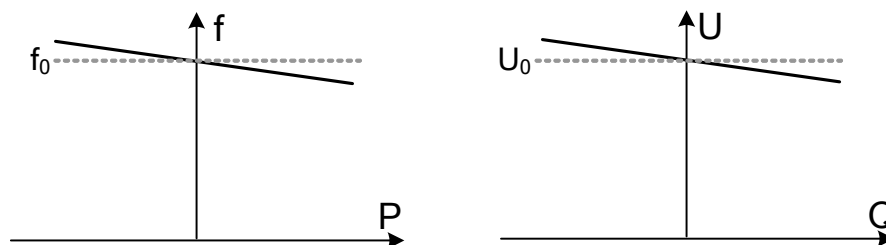
During **grid-feeding** operation the inverter is assumed to be connected to a functioning AC grid. In the case of a microgrid this implies either that the external grid is connected, or that the voltage and frequency regulation is carried out by other microsources in islanded mode. An inverter operating in grid-feeding mode synchronises to the grid voltage and injects active

power. The inverter may also inject various degrees of reactive power into the grid if this is desired from a grid perspective (also referred to as grid-supporting operation). Especially during grid fault conditions the injection of reactive power may be desired in order to help stabilise the grid voltage. Grid feeding is generally the only possible mode of operation for uncontrollable microsources such as PV panels. Electrically, an inverter should act as a stiff current source in this mode of operation.

With respect to imbalances in the grid voltage different strategies exist for the control of inverters in grid-feeding mode.

### 5.2.2. Control measures to achieve coordination between several sources

In case several inverters in the system act as grid-forming, i.e. they take part in voltage and frequency control, it becomes necessary to coordinate their operation. A methodology for achieving this, which is similar to the coordinated operation of several synchronous generators in the main grid, is described in [4]. The basic idea of the methodology is that the grid frequency and voltage are used to convey the information about active and reactive power need via droop functions. The frequency droop is related to active power whereas the voltage droop is related to reactive power, see Figure 26.



**Figure 26. Droop functions for inverter control in order to achieve coordination between several inverters. Left: frequency vs. active power. Right: Output voltage vs. reactive power.**

### 5.3. References

- [1] Holmes D. G., Lipo T. A., "Pulse Width Modulation for Power Converters – Principles and Practice", IEEE Press, 2003.
- [2] Malesani L., Tomasin P., and Toigo V., "Space Vector Control and Current Harmonics in Quasi-Resonant Soft-Switching PWM Conversion", IEEE Transactions on Industry Applications, Vol. 32, No. 2. March/April 1996.

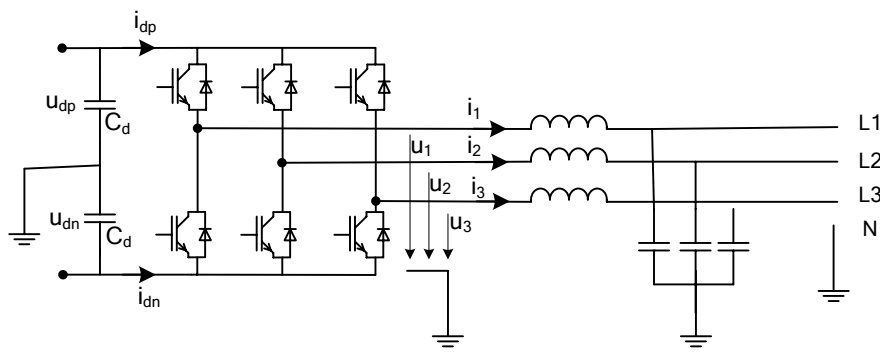
- [3] Van Der Broeck H. W., Skudelny H.-C., and Stanke G. V., "Analysis and Realization of a Pulsewidth Modulator Based on Voltage Space Vectors", IEEE Transactions on Industry Applications, Vol. 24. No.1 January/February 1988.
- [4] D. Georgaki, S. Papathanassiou, N. Hatziargyriou, A.Engler, Ch. Hardt, "Operation of a prototype Microgrid system based on micro-sources equipped with fast-acting power electronics interfaces", 35th IEEE PESC Conf. Proc., Aachen Germany, 2004.

## 6. INVERTERS UNDER UNBALANCED LOAD CONDITIONS

This chapter will cover certain aspects of the modelling of three-phase two-level voltage source converters, with special emphasis on the coupling between AC and DC side at operation under unbalanced conditions. In the later sections of the chapter this modelling is applied to the three studied converter systems for connection to four-wire three-phase systems.

### 6.1. General definitions and relations

Figure 27 contains the circuit schematic of a three-phase two-level voltage source converter with symbols for the most important quantities shown.



**Figure 27 Three-phase voltage source converter.**

In order to create models for the coupling between AC and DC side we first make the following definitions:

For the AC side:

$$u_{cm} = \frac{1}{3}(u_1 + u_2 + u_3) \quad \text{Common-mode AC side voltage}$$

$$u_{i,dm} = u_i - u_{cm} \quad \text{Differential-mode AC side voltage, phase } i.$$

$$i_{cm} = \frac{1}{3}(i_1 + i_2 + i_3) \quad \text{Common-mode AC side current}$$

$$i_{i,dm} = i_i - i_{cm} \quad \text{Differential-mode AC side current, phase } i.$$

For the DC side:

$$i_{d,pm} = \frac{1}{2}(i_{dp} - i_{dn}) \quad \text{Pole mode DC side current}$$

$$i_{d,gm} = \frac{1}{2}(i_{dp} + i_{dn}) \quad \text{Ground mode DC side current}$$

$$u_{d,pm} = \frac{u_{dp} - u_{dn}}{2} \quad \text{Pole mode component of the DC link voltage}$$

$$u_{d,gm} = \frac{u_{dp} + u_{dn}}{2} \quad \text{Ground mode component of the DC link voltage}$$

Note that both of these latter quantities may be time-varying.

Furthermore, the **switching function**  $s_i(t)$  is defined, which tells whether the converter connects the phase outlet  $i$  to the upper ( $s_i=1$ ) or the lower DC rail ( $s_i=-1$ ). It changes sign whenever the phase leg is commutated.

**The following expressions can now be derived for linking the currents and voltages on both sides of the switching matrix.**

1. For the **common mode voltage**

$$\begin{aligned} u_i(t) &= \frac{1}{2} \{ (s_i + 1)u_{d,p} + (s_i - 1)u_{d,n} \} = \frac{1}{2} \{ (s_i + 1)(u_{d,pm} + u_{d,gm}) + (s_i - 1)(u_{d,pm} - u_{d,gm}) \} = \\ &= s_i u_{d,pm} + u_{d,gm} \end{aligned} \quad (17)$$

and thus:

$$u_{cm}(t) = \frac{1}{3} [s_1(t) + s_2(t) + s_3(t)] u_{d,pm} + u_{d,gm} \quad (18)$$

2. For the **pole mode current** into the DC link we get

$$i_{d,pm} = \frac{1}{2} (s_1 i_1 + s_2 i_2 + s_3 i_3), \quad (19)$$

which is easily verified as follows.

$$\begin{aligned} i_{dp} &= \frac{1}{2} \{ (s_1 + 1)i_1 + (s_2 + 1)i_2 + (s_3 + 1)i_3 \} \\ i_{dn} &= -\frac{1}{2} \{ (s_1 - 1)i_1 + (s_2 - 1)i_2 + (s_3 - 1)i_3 \} \\ i_{d,pm} &= \frac{1}{2} (i_{dp} - i_{dn}) = \dots = \frac{1}{2} (s_1 i_1 + s_2 i_2 + s_3 i_3) \end{aligned}$$

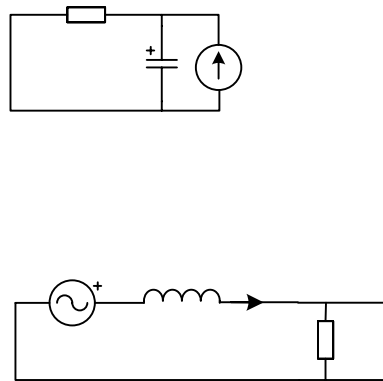
3. Finally, for **ground mode current**, the following trivially applies:

$$i_{d,gm} = \frac{i_1 + i_2 + i_3}{2} = \frac{3}{2} i_{cm} \quad (20)$$

## 6.2. Differential mode frequency domain modelling

The equivalent circuits with regard to differential mode (positive and negative sequence harmonics) are shown in Figure 28 for both DC and AC side. The impedance  $Z_{sh}$  in this circuit applies to differential mode.

Eq.(19) defines the pole mode current into the DC link. As is evident from this expression this current results from the sum over all phase legs of the products of the switching functions and phase currents. In App. A. the nature of the three-phase systems resulting from such phase-by-phase multiplication is treated. As regards the harmonic currents injected into the DC link, only the cases where the products related to each phase leg form a zero sequence at a certain harmonic order are of interest. In other cases the contributions from the phase legs will cancel out.



**Figure 28. Differential mode (positive/negative sequence) circuits. (a) DC side, (b) AC side.**

*DC side (one pole)*

The case where the fundamental frequency phase current is unbalanced is the most important and will be treated in detail.

Assume that both the phase currents,  $I_{p,i}^{(l)}$  and the phase switching functions  $S_i^{(l)}$  have both positive, negative and zero sequence components at the fundamental frequency. From the discussion in app. A it is clear that this may result in second harmonic and DC component in the modulation products. In Table 7 the various combinations that may arise are summarised. This table was compiled from Table 11 and Table 12 and the symbols are the same as in these tables.

**Table 7. DC link pole mode current harmonics generated as modulation products for different phase sequences in the switching functions and AC side currents**

$I_{p,i}^{(l)}$	$S_i^{(l)}$	P	N	Z
P		DC 2(N)	0 2(Z)	0 2(P)
N		0 2(Z)	DC 2(P)	0 2(N)
Z		0 2(P)	0 2(N)	DC 2(Z)

$L$

$i_{i,dm}$

$Z_{sh}$

We see that a zero sequence second order harmonic can result from a combination of a positive and a negative sequence or from two zero sequences. In quantitative terms the second harmonic current injected into the DC link can be computed as follows.

$$\mathbf{I}_{d,pm}^{(2)} = \frac{3}{4} \left( \mathbf{I}_{p,p}^{(1)} \mathbf{S}_n^{(1)} e^{j(\theta_{ip,p}^{(1)} + \theta_{k,n}^{(1)})} + \mathbf{I}_{p,n}^{(1)} \mathbf{S}_p^{(1)} e^{j(\theta_{ip,n}^{(1)} + \theta_{k,p}^{(1)})} + \mathbf{I}_{p,z}^{(1)} \mathbf{S}_z^{(1)} e^{j(\theta_{ip,z}^{(1)} + \theta_{k,z}^{(1)})} \right) \quad (21)$$

In deriving this expression it should be kept in mind that a factor of two differs between the Fourier coefficients and the corresponding phasors. The coefficient of three emanates from the fact that the current into the DC link gets contributions from all three phase legs.

Focussing on the impact of a negative sequence component in the phase current (the second term in eq. (21)) we can estimate the second harmonic pole mode ripple caused as follows:

$$\mathbf{U}_{d,pm}^{(2)} = \frac{3 \mathbf{I}_{p,n}^{(1)} \mathbf{S}_p^{(1)}}{8 \omega_0 C_d}. \quad (22)$$

### 6.3. Common-mode frequency domain modelling

Based on equations (18) and (20) above, a common-mode (zero sequence/ground mode harmonics) equivalent schematic of the system can be drawn, as shown in Figure 28, see also [2]. This is made by firstly deriving the circuits for AC and DC side and then joining them. In this figure  $Z_{d,gm}$  is the total ground mode DC side impedance per pole, whereas  $Z_{shz}$  is the AC filter shunt impedance for common mode per phase.

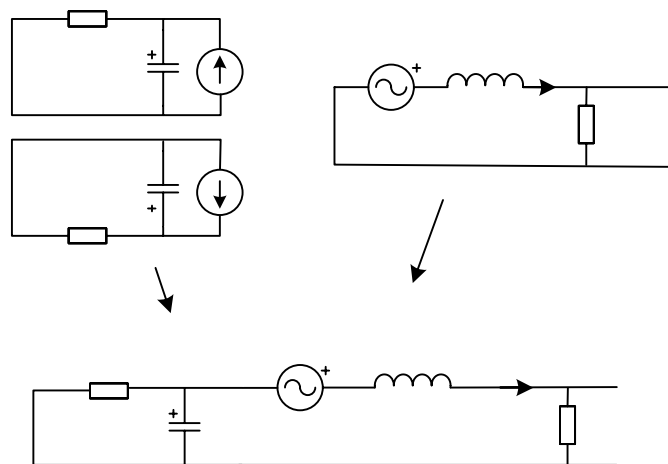


Figure 29. Common mode (zero sequence) circuits. (a) DC side, (b) AC side, (c) combined circuit showing the circulating common mode current.

## 6.4. Consequences for VSC with whye-delta coupled transformer

### 6.4.1. General

In the case of a transformer-coupled inverter (Figure 18) the neutral connector is formed by the whye-point of the primary (grid-side) winding. Thereby a zero-sequence current can flow on the grid side. The corresponding secondary side current will circulate among the delta-coupled windings and not be visible in the transformer secondary terminals. To understand the linkage of all symmetric components between whye and delta windings the following analysis can be made.

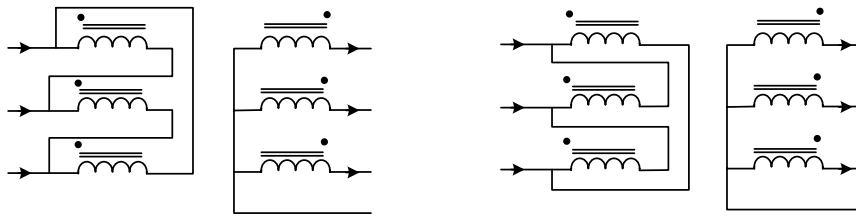


Figure 30. Whye-delta coupled transformer.

The delta side currents phasors link to the whye side phasors in the following way for the configuration in Figure 30(a)

$$\begin{pmatrix} \mathbf{I}_a^\Delta \\ \mathbf{I}_b^\Delta \\ \mathbf{I}_c^\Delta \end{pmatrix} = N \begin{pmatrix} 1 & 0 & -1 \\ -1 & \mathbf{(a)} & 0 \\ 0 & -1 & 1 \end{pmatrix} \begin{pmatrix} \mathbf{I}_a^Y \\ \mathbf{I}_b^Y \\ \mathbf{I}_c^Y \end{pmatrix}$$

and for the configuration in Figure 30(b)

$$\begin{pmatrix} \mathbf{I}_a^\Delta \\ \mathbf{I}_b^\Delta \\ \mathbf{I}_c^\Delta \end{pmatrix} = N \begin{pmatrix} 1 & -1 & \mathbf{b} \\ 0 & 1 & -1 \\ -1 & 0 & \mathbf{c} \end{pmatrix} \begin{pmatrix} \mathbf{I}_a^Y \\ \mathbf{I}_b^Y \\ \mathbf{I}_c^Y \end{pmatrix}$$

$i_a^D$        $i_a^Y$       a  
 $i_b^D$        $i_b^Y$       b  
 $i_c^D$        $i_c^Y$       c  
n

Combining these expressions with the matrices for transforming to and from a system of symmetric components (eqs. (5) and (6)) we obtain the following relationship between the currents of the whye and delta sides

$$\begin{pmatrix} \mathbf{I}_+^\Delta \\ \mathbf{I}_-^\Delta \\ \mathbf{I}_0^\Delta \end{pmatrix} = N\sqrt{3} \begin{pmatrix} e^{j\pi/6} & 0 & 0 \\ 0 & e^{-j\pi/6} & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \mathbf{I}_+^Y \\ \mathbf{I}_-^Y \\ \mathbf{I}_0^Y \end{pmatrix}. \quad (23)$$

As expected there is no linkage from the whye-side zero sequence currents. Furthermore, the Y-side positive and negative sequences are phase-shifted by 30 degrees. Whether this shift is leading or lagging depends on which of the connection types (a) or (b) from Figure 30 is chosen.

In conclusion, the use of a whye-delta connected transformer will block zero-sequence current completely, whereas the negative sequence will pass through with a phase shift of 30 degrees.

#### 6.4.2. DC ripple compensation possibilities

The second harmonic pole mode harmonic resulting from an AC side negative sequence current is inevitable as long as a balanced output voltage should be produced, since it relates to a fluctuation in the power between AC and DC sides. However, the output AC voltage can be compensated for this ripple by adapting the duty cycles with regard to the instantaneous value of the pole mode DC voltage. In terms of a simple carrier-based modulator this is described in Figure 31, as long as the modulator is not saturated, i. e. none of the voltage references exceed the instantaneous value of the DC voltage. The theoretical limit for the point where overmodulation may start to occur, at least during part of the time, is given by the following expression.

$$U_{d,nom} \geq \hat{U}_p^{ps,(1)} + \hat{U}_d^{pm,(2)} \quad (24)$$

By inserting eq. (22) and noting that  $\hat{U}_p^{ps,(1)} = MU_{d,nom}$  the following inequality may be obtained for defining the possible operating range:

$$C_d U_{d,nom} \geq \frac{3}{8} \frac{1}{\omega_0} \frac{M \hat{M}_p^{ns,(1)}}{1-M} \quad (25)$$

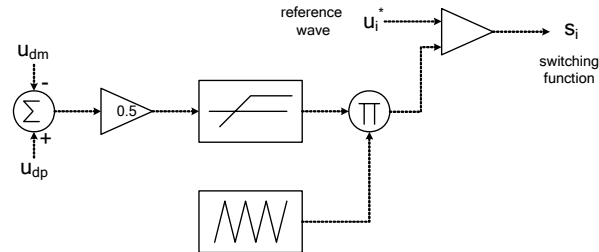
This applies to the case without third harmonic injection.

For the case where third harmonic zero sequence injection is used, the limiting equation can be modified as follows;

$$U_{d,nom} \geq \frac{\sqrt{3}}{2} \hat{U}_p^{ps,(1)} + \hat{U}_d^{pm,(2)} \quad (26)$$

In this case the limit for the operating range is defined by

$$C_d U_{d,nom} \geq \frac{3}{8} \frac{1}{\omega_0} \frac{M_p^{\hat{ns},(1)}}{1 - \frac{\sqrt{3}}{2} M} \quad (27)$$



**Figure 31 Compensation of pole-mode ripple**

## 6.5. Consequences for the four-phase-leg VSC

For an inverter with a fourth phase leg for providing the neutral connector, the impact of AC side imbalances will be similar to that of an inverter with a delta-whyne-coupled transformer. Since there is no connection to the midpoint of the DC link there will be no ground mode harmonics in the DC link. The fourth leg will in the steady state be operating with zero reference voltage, implying that it will produce a square wave at the switching frequency. The absence of any low order harmonics in the switching function means that no low order harmonics will be coupled to from the AC side to the DC link, refer to app A.

In case third harmonic injection is used to allow for increased modulation index the fourth leg may be used to compensate the neutral point for the added zero sequence. In this case the fourth leg will have a third harmonic as reference identical to the third harmonic added to the references of the three conventional phase legs.

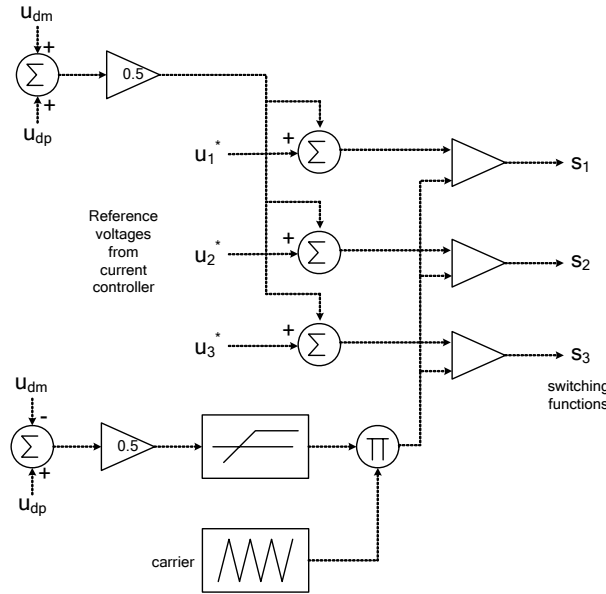
## 6.6. Consequences for the VSC with grounded DC link midpoint

### 6.6.1. General

For the inverter configuration where the DC link midpoint is used to form the AC side neutral the DC link will be affected both by the negative and zero sequence components of the AC side current. A zero sequence will result in a DC side ground mode ripple at the fundamental, whereas a negative sequence will result in a DC side pole mode ripple at the second harmonic order if the AC side voltage should be symmetric.

### 6.6.2. DC ripple compensation possibilities

As discussed in the previous section DC side pole mode imbalances can be compensated for by adapting the modulation to the instantaneous DC pole mode voltage. Observing the zero sequence/ground mode equivalent schematic in Figure 29 it is obvious that the term  $(s_1+s_2+s_3)u_{d,pm}$  can be used to compensate for the ground mode ripple. This term links the pole-mode DC voltage to the common-mode AC side voltage.



**Figure 32. Outline of modulation scheme including simultaneous compensation for ground mode and pole mode DC link ripple.**

### 6.6.3. DC capacitance versus DC voltage requirements

Assuming the use of the DC ripple compensation method described in the previous section the required DC link capacitance as a function of the nominal DC link voltage can be computed. Firstly, we state the pole mode second harmonic ripple and the ground mode fundamental ripple magnitude as follows:

$$U_d^{pm,(2)} = \frac{3 M_p^{ns,(1)}}{8 \omega_0 C_d} \quad (28)$$

$$U_d^{gm,(1)} = \frac{3 I_p^{zs,(1)}}{2 \omega_0 C_d} \quad (29)$$

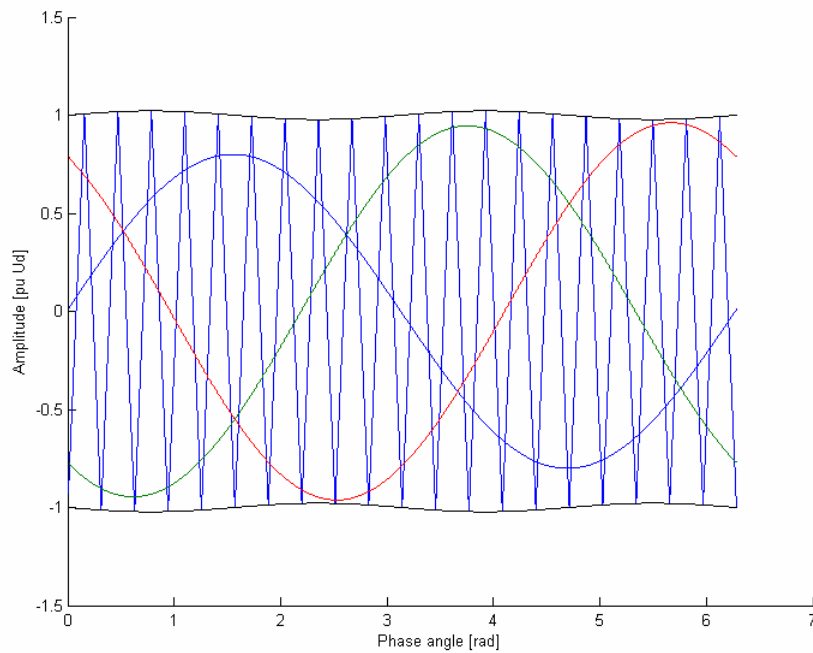
Furthermore, from Figure 32 it is obvious that these two ripple components limit the allowable phase voltage reference in equal measure. Thereby, we get the following expression for defining the limit for overmodulation, see also Figure 33:

$$U_{d,nom} \geq \hat{U}_p^{ps,(1)} + \hat{U}_d^{pm,(2)} + \hat{U}_d^{gm,(1)} \quad (30)$$

Inserting expressions (28) and (29) we can find the limit for the minimum product of DC link nominal voltage and capacitance at a certain level of imbalance and a certain modulation index.

$$U_{d,nom} C_d \geq \frac{3}{8} \frac{1}{\omega_0} \frac{M_p^{ns,(1)} + 4\hat{I}_p^{zs,(1)}}{(1-M)} \quad (31)$$

In order to avoid overmodulation despite a DC link ripple induced by AC side unbalances we can either use high DC link voltage or low DC link impedance i.e. a large DC capacitor. The expression further states that a modulation index close to unity can not be used whenever there is a DC ripple.



**Figure 33. Carrier and reference waves (normalised) in the case of simultaneous compensation for pole mode and ground mode DC link voltage ripple. Principle diagram.**

## 6.7. References

- [1] Mohan N., Undeland T. M., Robbins W. P., "Power Electronics, Converters Applications and Design", Second Edition, John Wiley, 1995.
- [2] Lianxiang Tang, Boon-Teck Ooi, "Impact of Zero Sequence Component on Voltage-Source Converters", PCC-Osaka, 2002.

- [3] Prasad N. Enjeti, "A New Technique to Reject DC-Link Voltage Ripple for Inverters Operating on Programmed PWM Waveforms", IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. I, NO. 1. JANUARY 1992
- [4] Y.-K. Lo, C.-L. Chen, "Three-phase four wire voltage controlled AC line conditioner with unity input power factor and minimised output voltage harmonics", IEE Proc.-Electr. Power Appl, Vol. 142, No. 1, 1995.

## 7. COMPARISON OF THE STUDIED INVERTER CONCEPTS

This chapter provides a qualitative and, to some extent quantitative comparison of the three studied inverter topologies.

### 7.1. Reference system data

This section provides a specification for a converter system to be used in a microgrid. This serves as a basis for the comparison of the three converter concepts made in the subsequent sections. In terms of harmonics requirements the studied inverters are supposed to comply with the applicable norms, such as IEC 61000-3-4.

Rated power AC side	100 kW
Grid voltage line to line	400 V
Grid voltage variation	±5%
Grid frequency	50 Hz

**Table 8. Main data for the reference system.**

### 7.2. Galvanic isolation

Certain applications require the AC grid to be galvanically isolated from the DC source. The normative requirements for such galvanic isolation furthermore vary between different countries. The only concept to inherently offer galvanic isolation is the inverter system equipped with a delta-wye transformer. In order to provide isolation using the two other concepts it will be required to for instance connect an isolated DC/DC converter between the inverter and the DC source. Such a DC/DC converter may be required also for other reasons, such as to step up and regulate the DC voltage, see next section. However, typically the step-up function can be achieved in a more cost-effective manner by using an unisolated DC/DC converter.

### 7.3. DC voltage level and DC capacitor storage size requirements

As discussed in the previous chapter, the requirements with regard to the minimum DC link voltage required to produce a certain AC grid voltage differs between the concepts.

Firstly, for the transformer-coupled inverter there is no firm inherent requirement concerning the DC voltage since the transformer turns ratio can be adapted to provide the desired grid side voltage out of any DC voltage.

However, the two directly coupled inverter types will impose inherent limitations on the required DC link voltage. To produce a certain required AC voltage a corresponding DC voltage has to be present. The required nominal DC voltage may be further increased in the

presence of AC side imbalances since these causes DC voltage ripple, according to eqns. (25) and (27).

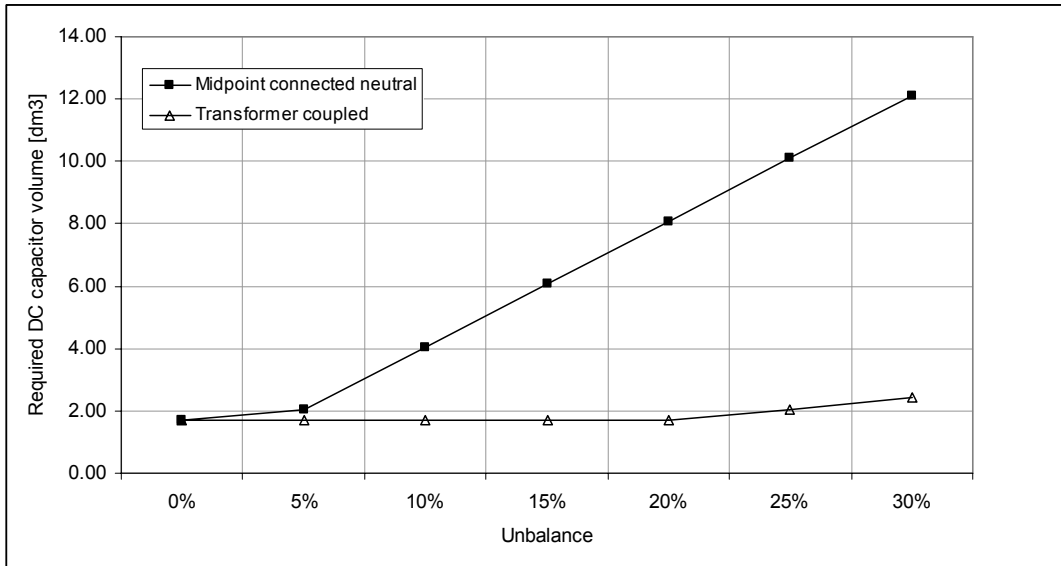
In this regard the midpoint-coupled inverter differs from the four-leg inverter in the sense that it does not permit the use of zero-sequence injection in the PWM pattern which implies a further limitation of the modulation index. Table 9 shows representative and feasible DC link voltage values for the studied inverters. It is assumed that the overall DC link voltage ripple can amount to 10% of the nominal DC link voltage. In the table the crest voltages pole-to-pole and pole-to-ground, including ripple, are also displayed. The former of these is important in the sense that it is the maximum voltage the semiconductors have to switch whereas the latter contributes to the DC capacitor voltage rating. Note that the ripple and crest levels in this case will be independent of the unbalance level since the modulation index and thus the available margin for ripple was fixed. In Figure 34 the estimated physical volume of DC capacitors is shown versus the unbalance level. The negative and zero sequence components in the AC side currents are assumed to be equal, and the unbalance level is defined as

$$\text{unbalance} = \frac{I_p^{\text{ns,(1)}}}{I_p^{\text{ps,(1)}}} = \frac{I_p^{\text{zs,(1)}}}{I_p^{\text{ps,(1)}}}.$$

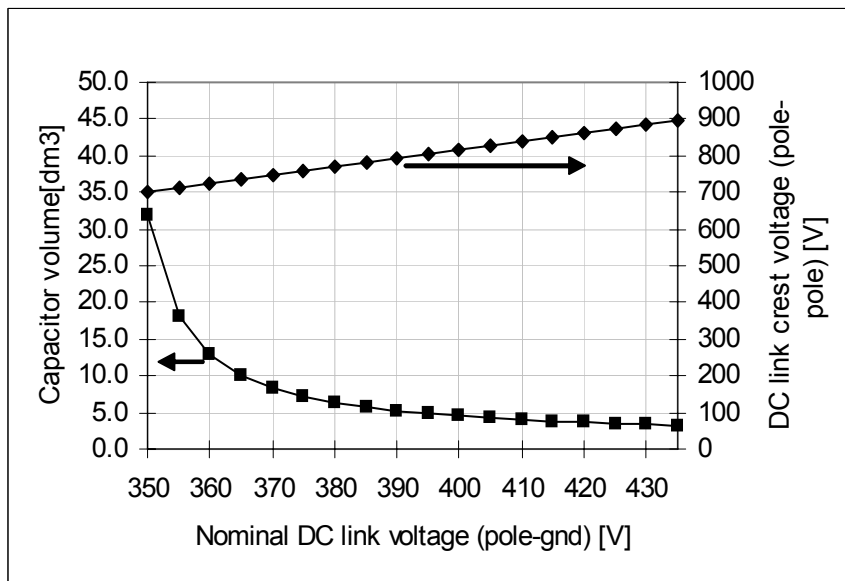
A certain minimal DC capacitor energy is assumed to be required, regardless of the ripple level. This level is set to 2 ms times the rated power, i.e. 200 J for a 100 kW inverter. This is manifested in the curves which are flat for low degrees of unbalance. However, above a certain limit the DC link capacitance needs to be increased to limit the voltage ripple. This is particularly the case for the inverter where the neutral is connected to the DC link midpoint since the zero sequence in this case causes a significant ground mode DC link ripple. The energy density at rated voltage for DC capacitors is assumed to be 120 J/dm<sup>3</sup>. This value is typical for DC polypropylene capacitors used in these applications, see e.g. [5]. Electrolytic capacitors have higher energy density, but suffer from poor lifetime and reliability, which makes them less attractive in grid connected applications. It is obvious from the graph that a high degree of unbalance, corresponding to near single-phase operation will require large DC capacitor. However the cost, weight and volume of the capacitors are still likely to be lower than that of a transformer. Figure 35 shows the impact of variation of the nominal DC voltage on the DC capacitor size as well as the crest pole-to-pole DC voltage. It is obvious that increasing the DC link voltage can allow for reduced DC capacitor size since the ripple amplitude can be higher.

**Table 9. DC side representative parameters for the different inverter types**

Quantity	Unit	Midpoint neutral	Transformer coupled and four-leg inverter
Maximum modulation index	-	0.9	1.05
Nominal modulation index	-	0.86	1.00
Nominal DC voltage pole-ground	V	380	330
Pole-pole DC link crest voltage	V	775	718
Pole-midpoint DC link crest voltage	V	417	359



**Figure 34. Estimated required DC capacitor volume vs. the rated unbalance handling capability.**



**Figure 35. Estimated required capacitor volume and pole-to-pole crest voltage for the midpoint-connected inverter. 15% AC side unbalance assumed.**

#### 7.4. Semiconductor rating requirements

IGBT modules, comprising the switching as well as the antiparallel diode function, is commonly the choice of semiconductor device for inverters of the rating treated in this report. Different types of modules exist in the market, containing either a single IGBT-diode pair, two such pairs forming a phase leg, or even an entire three-phase inverter bridge comprising complete valves. Furthermore, market offerings differ in terms of the voltage and current rating of the devices. Table 10 shows the currently available single IGBT modules in the blocking voltage classes 1200V and 1700V. As is visible a multitude of devices is available with current ratings from 200A to 3600A. In addition, at lower current ratings components integrating a phase leg, or even an entire three-phase bridge are available.

Manufact↓ BV→	1200 V	1700 V
<b>ABB</b>	none	1600, 1800, 2400
<b>Infineon</b>	400(10), 600(7), 800(4),900(2), 1200(5), 1600(4),1800(3),2400(5)	400(2), 600, 800(2), 1200(5), 1600(4), 1800(4), 2400(8), 3600(3)
<b>Fuji El.</b>	200, 300(2), 400(2), 600(4), 800, 1200, 1600, 2400, 3600	1200, 1600, 2400, 3600
<b>Hitachi</b>	400,600,1200	1200(2), 1600, 1800(2), 2400, 3600
<b>Dynex</b>	400, 600, 800(2), 1200(2), 1600(2),1800(2), 2400(2)	400, 600, 800, 1200, 1600, 2400
<b>IXYS</b>	none	1800,2400
<b>Powerex</b>	400 (2), 600(3)	400, 500, 800, 1200, 1800(2), 2400

**Table 10. Current IGBT module market offerings (single switch + antiparallel diode). Figures refer to current ratings. Figures within parentheses refer to the different varieties offered by a manufacturer within a certain voltage and current rating.**

In some cases different variants of a device with a certain current rating are available, differing in terms of the trade-off between switching losses and on-state losses. These differences are achieved during processing by different types and degrees of irradiation, which affects the charge carrier lifetime.

For the treated inverters with 400VAC grid connection typically IGBT modules with 1200V blocking voltage are used. An important matter is whether the midpoint connected inverter will need a higher voltage rating for the IGBTs, 1700V, considering the higher required DC

link voltage as well as the larger ripple amplitude. As is evident from Table 9 the pole-pole DC link crest voltage can be kept below 800V, although this may require a large DC capacitor. As regards current rating two factors have the most influence. The first is the max current the device has to turn off, which must be matched to the SOA capabilities defined by the manufacturer. The instantaneous current rating will be defined by the AC side current and any additional current ripple. This is not likely to differ considerably between the inverter types. The only exception is if the transformer-coupled inverter is dimensioned for a lower output voltage which is later adapted by the transformer. The other main dimensioning factor for the current rating is the thermal requirement that the device junction temperature should be kept below the maximum allowed level in all operating points. All in all, it is not likely that the semiconductor requirements will cause significant cost differences between the three inverter concepts. One notable exception concerns the four leg inverter. The fourth leg, connecting the neutral, can theoretically have a lower current rating than the other three. However for sourcing and spare parts inventory reasons most likely the fourth leg will likely have the same semiconductor elements. This implies a 33% increase in silicon area requirements, as well as gate drive units and other valve-related equipment, for this inverter concept.

## **7.5. References**

- [5] Unlytic UL30 film capacitors, Bulletin No. L96-134 Rev. 4, Electronic Concepts Inc.

## 8. CONCLUSION

In microgrids, like in other LV distributions grids, significant unbalances may be present. This is mainly the result of single-phase loading where the effects of the loads are not evened out due to the small size of the grid. The imbalances amount to negative and zero sequence currents being drawn by the loads. In microgrids these imbalance currents have to be contained within the grid itself. In islanded mode there is no external grid to absorb the imbalances. Since the microgrid is supposed to be grid friendly when connected to the external grid, the imbalance currents should preferably be handled within the microgrid also in this case. The implication is that in either case the microsource power electronic interfaces have to provide the zero sequence and negative sequence currents. As discussed in section 6, such imbalance currents on the AC side inevitably leads to DC link voltage ripple in the inverter. Negative sequence current leads to pole mode (differential mode) ripple whereas zero sequence may lead to ground mode (common mode) ripple if there is a connection to the DC link midpoint. The DC link ripple may lead to a distortion of the AC side voltages produced by the inverter, if proper measures are not taken.

Three inverter topologies suited for connection to four-wire three-phase grids were selected for further study. These were all simple two-level topologies that can be derived from inverters types used for industrial motor drives. The inverters differ in terms of the method for producing the neutral. For all inverter types means for modifying the modulation method in order to compensate for the DC link ripple were described. Thereby undistorted phase voltages can be produced even at unbalanced loading.

The main outcome of the comparison of the topologies in section 7 is that the means employed for handling the neutral connection will affect the cost and complexity of the inverter in different ways. For the midpoint connected inverter the DC capacitor will need to be large, if unbalanced loads are to be handled, in order to smoothen the ground-mode ripple. For the four-leg inverter the cost of the additional phase leg will have to be considered. Finally, for the transformer-coupled inverter the cost of the transformer will make

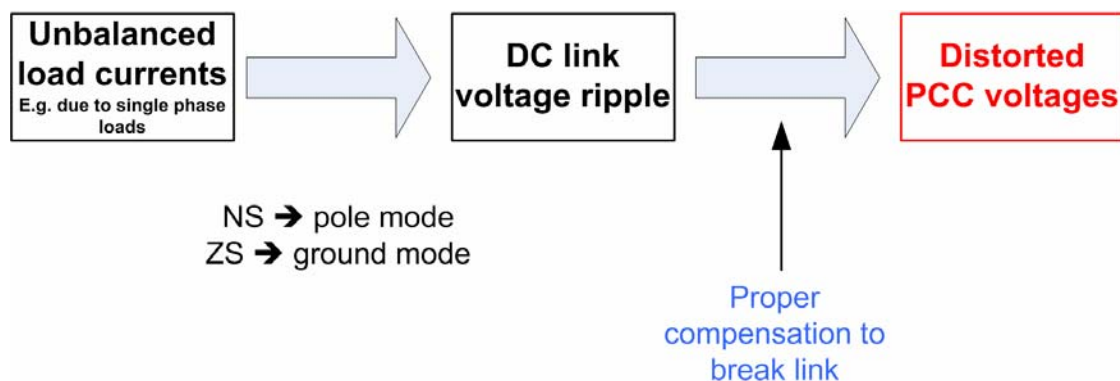


Figure 36. Impact of unbalanced loading.

up a significant portion of the overall system cost. However, the transformer offers several benefits apart from producing the neutral connection, which may be attractive, or even necessary, in many applications.

## 9. APPENDIX A: MULTIPLICATION OF PERIODIC SIGNALS IN THE TIME DOMAIN

### 9.1. General

When dealing with voltage source converters multiplication of time domain signals is often encountered. This Appendix gives an overview of some mathematical concepts required to understand the consequences of such multiplication in the frequency domain.

Assume  $x(t)$ ,  $y(t)$  are periodic with the same cycle time and have the complex Fourier series coefficients  $X_n$  and  $Y_m$ . Then their product

$$f(t) = x(t)y(t) \quad (32)$$

has the Fourier coefficients

$$F^{(h)} = \sum_{k=-\infty}^{\infty} X^{(k)}Y^{(h-k)} \quad (33)$$

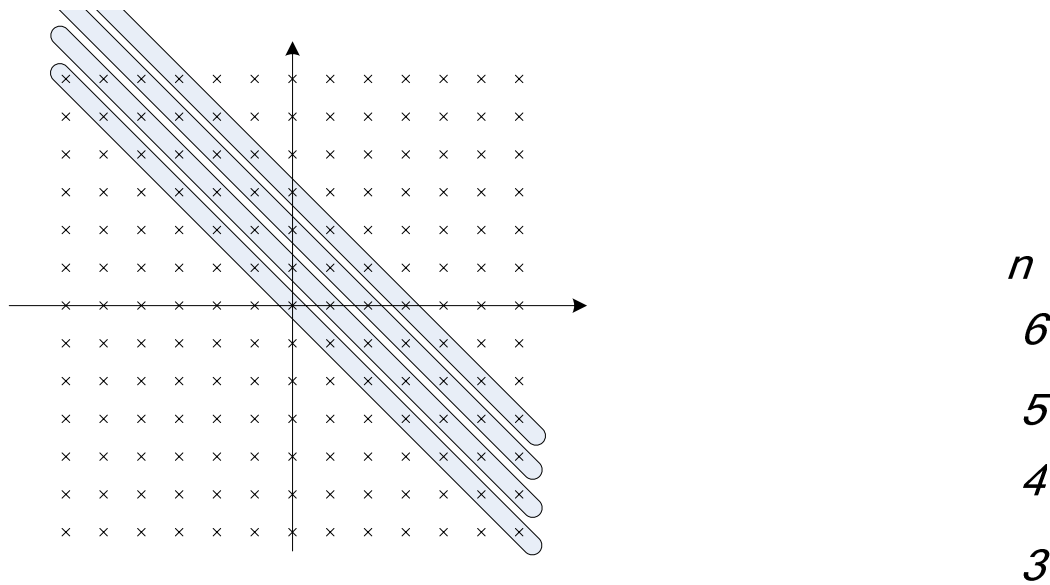
i.e. a **convolution** of the two Fourier series. In Figure 37 this circumstance is visualised, showing which harmonics of the multiplied signals that will be part of a certain harmonic of the resulting signal. Now consider a single harmonic of order  $h_1$  in the signal  $x$  and a single harmonic of order  $h_2$  in the signal  $y$  with the corresponding phasors.

$$\begin{aligned} \mathbf{X} &= \frac{1}{2} X e^{j\theta_x} \\ \mathbf{Y} &= \frac{1}{2} Y e^{j\theta_y} \end{aligned}$$

In the convolution sum the following combinations of the two harmonic orders will result in nonzero terms:  $h_1-h_2$ ,  $h_2-h_1$ ,  $h_1+h_2$ ,  $-h_1-h_2$ . Two of these will be negative. Thus, there will always be two physical harmonics formed in the product, at orders  $|h_1-h_2|$  and  $h_1+h_2$ . Their corresponding Fourier coefficients will be as follows.

$$F^{(h_1+h_2)} = \frac{1}{4} X^{(h_1)} Y^{(h_2)} e^{j(\theta_x^{(h_1)} + \theta_y^{(h_2)})} \quad (34)$$

$$F^{(|h_1-h_2|)} = \frac{1}{4} X^{(h_1)} Y^{(h_2)} e^{j|\theta_x^{(h_1)} - \theta_y^{(h_2)}|} \quad (35)$$



**Figure 37. Graphical interpretation of the convolution sum for the resulting harmonics when two periodic signals  $x(t)$  and  $y(t)$  with Fourier coefficients  $X^{(n)}$  and  $Y^{(m)}$  are multiplied.**

**9.2. Three-phase systems**

In this section the issue of multiplication of all three phase quantities of a three phase system with those of another three-phase system is treated. In particular nature of the resulting three-phase system when the two multiplied systems are balanced or zero sequences is considered.

Make the following initial assumption:

Signals  $x_1, x_2, x_3$  form a sinusoidal three-phase system at harmonic order  $h_1$ .

Signals  $y_1, y_2, y_3$  form a sinusoidal three-phase system at harmonic order  $h_2$ .

Multiplying these signals phase by phase in the time domain will, according to (34) and (35) above, yield three signals with two harmonics each. The following Fourier coefficients correspond to these harmonics:

$$F_i^{h_1+h_2} = \frac{1}{4} X_i^{h_1} Y_i^{h_2} e^{j(\theta_{x,h_1} + \theta_{y,h_2})}, i = 1, 2, 3 \quad (36)$$

$$F_i^{|h_1-h_2|} = \frac{1}{4} X_i^{h_1} Y_i^{h_2} e^{j|\theta_{x,h_1} - \theta_{y,h_2}|}, i = 1, 2, 3 \quad (37)$$

Now consider the case where both  $X_{h1,i}$  and  $Y_{h2,i}$  form either positive, negative or zero sequence systems. By inspecting expressions (36) and (37) we can understand the nature of the three-phase systems formed by the multiplication. In Table 11 the phase sequences

resulting from a certain combination of phase sequences in the multiplied signals  $x_i$  and  $y_i$  are shown. In the tables P represent positive sequence, N negative sequence and Z zero sequence. We see for instance that a zero sequence at order  $h_1+h_2$  and a positive sequence at order  $h_1-h_2$  will result when the multiplied signal sets contain a positive sequence at order  $h_1$  and a negative sequence at order  $h_2$ .

**Table 11. Resulting phase sequences from multiplication of two three-phase systems**

(a) For the harmonics at order  $h_1+h_2$

	X	P	N	Z
Y				
P		N	Z	P
N		Z	P	N
Z		P	N	Z

(b) For the harmonics at order  $(h_1 - h_2)$

	X	P	N	Z
Y				
P		Z	N	P
N		P	Z	N
Z		N	P	Z

The special case where the considered harmonics in signals x and y are of the same order ( $h^1=h^2=h$ ) deserves some extra attention. Under these circumstances the formed harmonic at order  $|h_1-h_2|$  will be a DC component with magnitude as follows.

$$F_i^0 = 2 \operatorname{Re} [X_{i,1} Y_{i,1}] = \frac{1}{2} X_{i,1} Y_{i,1} \cos(\theta_{x,1} - \theta_{y,1}) \quad (38)$$

In a power converter context it is of interest to understand whether these DC components sum to zero or not, depending on the nature of the three-phase systems of the two multiplied signals at the given harmonic orders. Inspection of eq. (38) and some thought reveals that a non-zero value will result whenever the two systems follow the same phase sequence as shown in Table 12. This value amounts to

$$\sum_{i=1}^3 F_i^0 = \frac{3}{2} X_i^h Y_i^h \cos \varphi \quad (39)$$

where  $\varphi$  is the phase angle difference between the two signals at the given harmonic. This parameter is the same for all three phases since they are of the same sequence.

The harmonics at  $h_1+h_2=2h$  on the other hand will form balanced or zero sequences just like in the case where  $h^1 \neq h^2$ , i.e. they will follow Table 11(a).

**Table 12. Multiplication of two three-phase systems at the same harmonic order.  
Sum of the resulting DC component.**

	X	P	N	Z
Y				
P		$\neq 0$	0	0
N		0	$\neq 0$	0
Z		0	0	$\neq 0$