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Modeling, Control and Protection of Low-Voltage DC Microgrids

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Cover:
DC circuit board, arc-lighting distribution system, Halmstad, 1890
Photo: Bo Johansson

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To My Father

"My personal desire would be to prohibit entirely the use of alternating currents. They are as unnecessary as they are dangerous. I can therefore see no justification for the introduction of a system which has no element of permanency and every element of danger to life and property."

Thomas A. Edison, "The Danger of Electric Lighting," *North American Review* 149 (Nov. 1889), pp. 625–633

Abstract

Current trends in electric power consumption indicate an increasing use of dc in end-user equipment, such as computers and other electronic appliances used in households and offices. With a dc power system, ac/dc conversion within these loads can be avoided, and losses reduced. AC/DC conversion is instead centralized, and by using efficient, fully controllable power-electronic interfaces, high power quality for both ac and dc systems during steady state and ac grid disturbances can be obtained. Connection of back-up energy storage and small-size generation is also easier to realize in a dc power system.

To facilitate practical application, it is important that the shift from ac to dc can be implemented with minimal changes. Results from measurements carried out on common household appliances show that most loads are able to operate with dc supply without any modifications. Furthermore, simple, and yet sufficiently accurate, load models have been derived using the measurement results. The models have been used for further analysis of the dc system, both in steady state and during transients.

AC microgrids have gained research interest during the last years. A microgrid is a part of power systems which can operate both connected to the ac grid, and autonomously in island mode when the loads are supplied from locally distributed resources. A low-voltage dc microgrid can be used to supply sensitive electronic loads, since it combines the advantages of using a dc supply for electronic loads, and using local generation to supply sensitive loads. An example of a commercial power system which can benefit from using a dc microgrid is data center. The lower losses due to fewer power conversion steps results in less heat which need to be cooled, and therefore the operation costs are lowered.

To ensure reliable operation of a low-voltage dc microgrid, well-designed control and protection systems are needed. An adaptive controller is required to coordinate the different resources based on the load-generation balance in the microgrid, and status of the ac grid. The performance of the developed controller has been studied and evaluated through simulations. The results show that it is possible to extend use of the data center dc microgrid to also support a limited amount of ac loads close to the data center, for example an office building.

A protection-system design for low-voltage dc microgrids has been proposed, and different protection devices and grounding methods have been presented. Moreover, different fault types and their impact on the system have been analyzed. The type of protection that can be used depends on the sensitivity of the components in the microgrid. Detection methods for different components have been suggested in order to achieve a fast and accurate fault clearing.

An experimental small-scale dc power system has been used to supply different loads, both during normal and fault conditions. A three-phase two-level voltage source converter in series with a Buck converter was used to interconnect the ac and the dc power systems. Together the converters have large controllability, high power quality performance, and allow bi-directional power flow. This topology can preferably be used together with energy storage. The tests confirm the feasibility of using a dc power system to supply sensitive electronic loads.

Index terms: circuit transient analysis, dc power systems, dispersed storage and generation, load modeling, power conversion, power distribution control, power distribution faults, power distribution protection, power electronics

List of Selected Publications

I D. Nilsson and A. Sannino, "Efficiency analysis of low- and medium-voltage dc distribution systems," in *Proc. IEEE Power Engineering Society General Meeting*, vol. 2, Denver, CO, June 6–10 2004, pp. 2315–2321

II D. Salomonsson and A. Sannino, "Load modelling for steady-state and transient analysis of low-voltage dc systems," *IET Electric Power Applications*, vol. 1, no. 5, pp. 690–696, Sep. 2007

III D. Salomonsson, and A. Sannino, "Comparative design and analysis of dc-link-voltage controllers for grid-connected voltage-source converter," in *Conf. Rec. IEEE Industry Applications Society Annual Meeting*, New Orleans, LA, Sep. 23–27 2007, pp. 1593–1600

IV D. Salomonsson and A. Sannino, "Centralized ac/dc power conversion for electronic loads in a low-voltage dc power system," in *Proc. IEEE Power Electronics Specialists Conference*, Jeju, Korea, Jun. 18–22 2006, pp. 3155–3161

V D. Salomonsson and L. Söder, "Comparison of different solutions for emergency and standby power systems for commercial consumers," in *Proc. IEEE International Telecommunications Energy Conference*, Providence, RI, Sep. 10–14 2006, pp. 579–586

VI D. Salomonsson, L. Söder, and A. Sannino, "An adaptive control system for a dc microgrid for data centers," in *Conf. Rec. IEEE Industry Applications Society Annual Meeting*, New Orleans, LA, Sep. 23–27 2007, pp. 2414–2421. A revised version will appear in *IEEE Transactions on Industry Applications*

VII D. Salomonsson, L. Söder and A. Sannino, "Protection of low-voltage dc microgrids," *Submitted to IEEE Transactions on Power Delivery*

VIII D. Salomonsson and A. Sannino, "Low-voltage dc distribution system for commercial power systems with sensitive electronic loads," *IEEE Transactions on Power Delivery*, vol. 22, no. 3, pp. 1620–1627, Jul. 2007

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Finally, Lina, my beloved wife: I am happy for being able to share the moment with you. Especially, this right now!

Daniel Salomonsson
Stockholm, Sweden
February 2008

Contents

Chapter 1

Introduction

This chapter gives an introduction to dc power systems, and the motivation and the aims with this thesis. The historical background is based on [1–5] and the motivation on Publications I and II.

1.1 Historical Background

One of the first commercial applications in the world using electric power was arc lighting systems. Light is created by an arc between two carbon tips giving a glaring white light with an open flame and noxious fumes. The carbon tips needed periodically to be renewed, which resulted in a lot of maintenance. This system was demonstrated in the beginning of 19^{th} century and was powered by batteries. However, it became practical first in the 1850s when instead dynamos were used, and was suitable for street lighting and in industrial and commercial buildings. The systems were powered with single-phase high-voltage (HV) (3.5 kV) ac transmitted through overhead lines.

The inventor Thomas A. Edison was shown an arc light system in Boston in 1878, and he was convinced that he could built a better system, which could be used both outdoors and indoors, and required less maintenance. Since Edison wanted to use the electricity to power both lights and machines he chose dc instead of ac. Edison developed all necessary components for a complete low-voltage (LV) dc distribution system, including the feeder system. The first Edison system was built around Pearl Street, downtown Manhattan, New York and served about one square mile (2.6 km^2). In September 1882 about 1200 light bulbs were connected to the Pearl Street station. However, his first incandescent lighting system with a central dc generating station was demonstrated on a temporary basis in January 1882 at Holborn Viaduct in London, England.

The drawback with Edison's dc system was the low voltage, which limited the distance of the feeders. In 1885 George Westinghouse incorporated the patents of the Gaulard and Gibbs ac transformer with his company, and started to build ac power systems, which utilized both HV transmission and LV distribution. Soon the number of ac power systems exceeded the number of dc power systems. However, there were still no available ac machines.

In 1887 Nikola Tesla, a former Edison employee, sent in a numbers of patent applications for his poly-phase ac power system, including a two-phase induction machine. Westinghouse also bought Tesla's patents to his electrical company, and Tesla became a Westinghouse employee. At the world fair in Chicago 1893 Westinghouse used Tesla's poly-phase ac power system for the first time to distribute power to both lights and machines.

The first large-scale long-distance power transmission was built between the Niagara Falls and Buffalo. An ac system was chosen due to its capability to transmit power long distances. Westinghouse together with General Electric (merger of Edison General Electric Company and Thomson-Houston Electric Company in 1892) were contracted to set up the power system. Ironically, the first customers were local industries and they required dc power! However, a year later, in November 1896, ac power was transmitted 26 miles (42 km) from Niagara Falls to Buffalo using three-phase HV (10.7 kV) ac. The transmitted voltage was transformed down to 440 V ac, and loads requiring dc (for example street cars) were supplied with 550 V dc through rotating converters.

Even though the use of ac power systems increased at the beginning of the 20^{th} century, dc power systems remained in operation. For example in Stockholm, Sweden, the last residential dc distribution systems were converted into ac in the mid 1970s.

1.2 Industrial and Commercial DC Power Systems

Direct current power systems are still today used in different industrial and commercial applications, due to both historical and practical reasons: the simplicity of speed control of dc machines, and the possibility to build reliable, yet simple, power systems by use of directly-connected batteries.

Telecommunication systems are today supplied with 48 V dc through converters connected to the ac grid. In case of a power outage the loads are supplied from batteries directly connected to the dc bus. In some telecommunication stations a standby diesel generator can also be used to support the batteries. A similar solution is also used to supply control and protection equipment in power plants and substations. However, a higher voltage level (110 or 220 V dc) is used due to longer distances between sources and loads, and higher load power ratings [6–8].

Historically, dc has been used in LV drive systems where speed control has been required, and ac in applications where it has not. In the latter case simpler and more robust induction machines have been used. Speed control of dc machines can be obtained by changing the supplying voltage or the magnetic flux. In the early age of dc machines this was obtained by using a variable resistor in series with the machine, or a variable resistor in the excitation circuit. This is a simple solution, but results in high losses and a poor speed-torque characteristic. By use of power electronics better, faster, and more precise control of both ac and dc machines can be obtained. Today dc-powered machines can be found in traction applications such as subways, trams and trains, but also in industrial drive systems [9].

Although ac made a big breakthrough in the beginning of the 20^{th} century dc solutions have been adopted by a number of relatively new applications such as electric vehicles, hybrid electric vehicles [10], electric ships [11, 12] and HV dc transmission [13, 14].

1.3 Motivation

When ac was introduced, loads were mostly resistive. Today, however, many loads require ac power supply to be converted to a voltage with different amplitude and frequency [15]. This conversion is in most cases obtained with a diode rectifier and a dc/dc converter. The diode rectifier introduces non-sinusoidal currents in the ac grid, which may give rise to electromagnetic compatibility (EMC) and power quality problems, e.g. reactive power consumption and low-frequency current harmonics, causing both increased losses and protection malfunction [16]. The maximum total harmonic distorsion allowed to be generated by these loads is regulated by power quality standards [17, 18]. To reduce the impact of non-sinusoidal currents on the ac grid, many power-electronic loads are equipped with a power factor correction (PFC) circuit [19]. The load current and its harmonic content of an electronic load is shown in Fig. 1.1. This can be compared with Fig. 1.2, showing the load current and its harmonic content of an electronic load with PFC. By using an appropriate dc voltage to supply electronic loads, the rectifier and the PFC circuit can be removed from the loads, reducing energy losses and saving money without reducing power quality. For these reasons use of LV dc distribution is once again attracting interest [20–23].

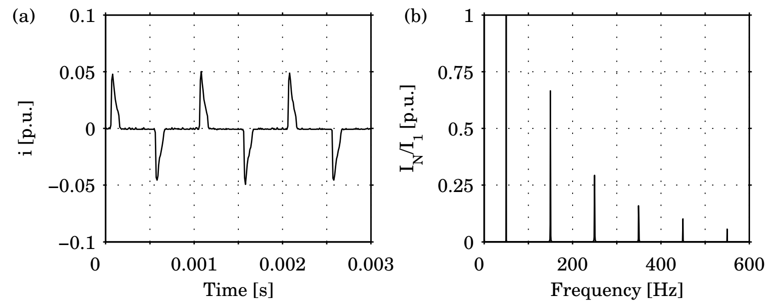

Fig. 1.1. Electronic load with diode rectifier.

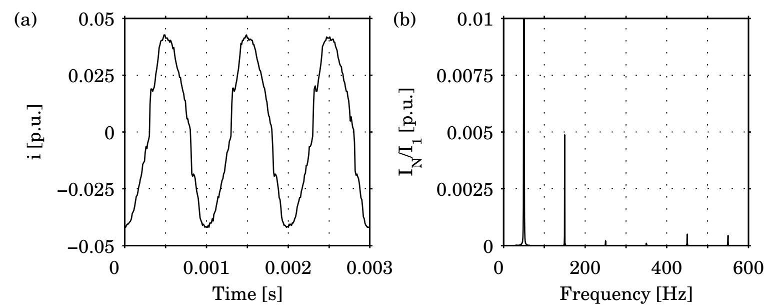

Fig. 1.2. Electronic load with diode rectifier and PFC.

An LV dc system is well suited for photovoltaic systems and fuel cells, which both produce dc [24, 25]. Microturbines, small hydro plants and variable speed wind turbines produce ac with a different frequency than the grid, and hence need an ac/dc/ac converter. These sources can benefit from connection to a dc system, since the dc/ac converter can be removed or replaced by a simpler and cheaper dc/dc converter. Also battery blocks can be directly connected to the system without any converters, resulting in saved money and reduced losses [26, 27].

In [28–35] the benefits with use of LV dc distribution have been discussed, and different layouts have been proposed. Control issues of such systems have been addressed in [36–40], and power quality improvements have been addressed in [19, 41–44].

1.4 Aim and Outline

Based on the motivation in the previous section the aims with this project are:

- to test if existing LV residential loads can be supplied with dc, and derive load models which can be used in simulation tools,
- to analyze different ac/dc interface topologies and their operation control,
- to build a small-scale LV dc system which can be used to make experimental tests,
- to identify new applications which can benefit from use of LV dc distribution, and
- to develop operation control and protection system for LV dc systems.

This thesis is a summary of a collection of published or submitted scientific papers. The body of this thesis is divided into the following chapters:

Chapter 2 summarizes the results from the work on load measurement and load modeling.

Chapter 3 briefly discusses different ac/dc interface topologies and presents a topology which was used in this project.

Chapter 4 presents operation control and protection of a dc microgrid. Results obtained from the experimental setup are also discussed.

Chapter 5 contains conclusions and ideas for future work.

1.5 Scientific Contributions

- Existing residential and commercial ac loads have been tested to investigate the possibility to supply these loads with dc and within which voltage range.
- New models of existing residential and commercial ac loads which can be used for steady-state and transient analysis of LV dc systems have been developed and compared with measurement data.
- Different ac/dc-converter topologies suitable to use for interconnecting ac and dc power systems have been evaluated.
- The performance of the selected converter topology during both steady-state operation and transients has been studied through simulations, and experimental tests.
- The performance of different dc-link-voltage controllers for grid-connected voltage-source converters has been analyzed and compared.

- The structure of ac/dc and dc microgrids has been analyzed, and an overview of different systems which could benefit from using such a system has been presented.
- An analysis of a suitable control system for a data center dc microgrid has been presented. The performance of the proposed control system has been studied through simulations.
- Suitable protection devices and grounding methods for an LV dc microgrid have been described. An LV dc microgrid protection-system design has been proposed which ensures a fast and reliable fault clearance. The design has been applied on a small test system, and its behavior during faults has been studied through simulations.
- An experimental setup has been built and used to show the feasibility of using a dc power system to supply sensitive electronic loads in order to reduce the number of converters.

Chapter 2

Load Modeling

Based on Publication II, this chapter presents load modeling for steady-state and transient analysis of LV dc systems.

2.1 Motivation

Standards describing component modeling and calculation methods are necessary in order to analyze a power system. Available standards today for LV dc systems are IEEE Std. 399-1997 [45, 46] and IEC 61660 [47], which both cover load flow and short-circuit calculations of dc auxiliary power systems. These are used for example, in power plants and substations. Loads in these standards are modeled as constant-resistance (CR), constant-current (CC) or constant-power (CP) loads, depending on the load characteristic. These models are adequate for load-flow calculations and simplified short-circuit calculations.

However, simple, and yet sufficiently accurate, models are required when performing thorough system studies, for example in simulations of systems which involve power electronics. The models will be used in large system studies and therefore they cannot be as detailed as when studying a single load only, as it would require too many computational resources.

If the use of LV dc for residential power system gains interest, there will be a transition time when both ac and dc will be used in parallel. During this time it is important that existing loads, without any modifications, will work equally well independent on the supplying voltage. It is also of interest to study within which voltage range existing loads will operate with dc. Both 230 and 325 V, the rms and the peak value of a 230-V ac voltage, respectively, have been mentioned as possible voltage levels [23]. Taking into account a ±10% deviation of the voltage results in the voltage range 200–360 V dc, within the loads should operate.

2.2 Results

Depending on construction and operation existing loads were divided into three groups:

- resistive loads (further divided into heating and lighting loads),
- rotating loads (split into induction machine-based and universal machine-based), and
- electronic loads (comprising power supplies and lighting appliances).

Samples from each group, 63 all together, were used in this two-fold test. The first part of the test was to determine the steady-state characteristic of the loads. This can be done using

$$P(U) = A_{\mathrm{CR}}U^2 + A_{\mathrm{CC}}U + A_{\mathrm{CP}} \tag{2.1}$$

where A_{CR} is the CR coefficient, A_{CC} is the CC coefficient and A_{CP} is the CP coefficient [48]. This test also showed the operating range of the tested load.

The second part of the test was to analyze the transient response of the loads. A fast voltage drop in the load supply voltage was applied, and both voltage and current were recorded.

From the measurement data simple models were derived. The models were verified by comparing measurement and simulation results.

Resistive Loads

Resistive loads can be divided into two subcategories depending on the function of the load. Heating loads are used for heating, such as stoves, kettles, and coffee makers. Measurement results together with (2.1) show that these loads have a constant resistive characteristic. However, lighting loads (incandescent lamps) do not have a constant resistance. In these cases measurements show that the resistance is temperature dependent, and that the model in (2.1) was not adequate for all resistive loads. Hence a new model for resistive loads, which takes into account that the resistance is an affine function of the load current, was developed:

$$U = (R_0 + R_1 I)I = R_0 I + R_1 I^2. \tag{2.2}$$

Using (2.2) to calculate the power $P = UI$ as a function of the voltage yields

$$P(U) = U\left(-\frac{R_0}{2R_1} + \sqrt{\frac{U}{R_1} + \frac{R_0^2}{4R_1^2}}\right). \tag{2.3}$$

In Fig. 2.1(a), which shows the steady-state measurement result of one 60-W incandescent lamp, both a constant resistance and a current-dependent resistance have been used. In Fig. 2.1(b) (2.3) has been used instead of (2.1).

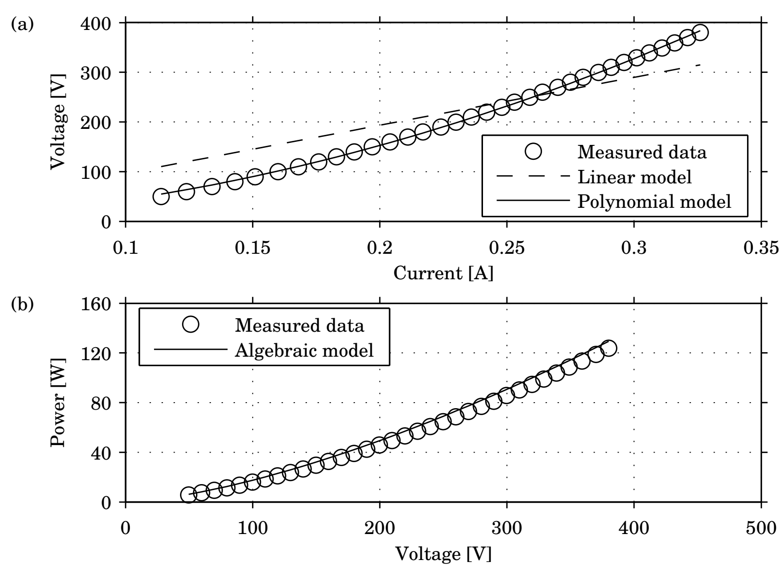

Fig. 2.1. Steady-state measurement of 60 W incandescent lamp: (a) resistance characteristic, and (b) power characteristic.

The transient measurement of the same lamp is shown in Fig. 2.2. Fig. 2.2(b) shows that the current starts to increase directly after the step is applied. The reason is that the reduced load current results in a lower filament temperature, which in turn results in a lower resistance. The lower resistance then makes the current higher. A proposed expression to calculate the resistance during the transient is

$$\hat{R}[k+1] = \hat{R}[k] + \frac{\tau}{\Delta t}(R[k+1] - \hat{R}[k]) \tag{2.4}$$

where τ is a time constant, Δt the time step of the simulation, k the number of time steps and $R[k]$ the steady-state resistance value at time step k. The estimated time constant of the filament of an incandescent lamp, $\hat{\tau}$, is linked to the rated power of the lamp.

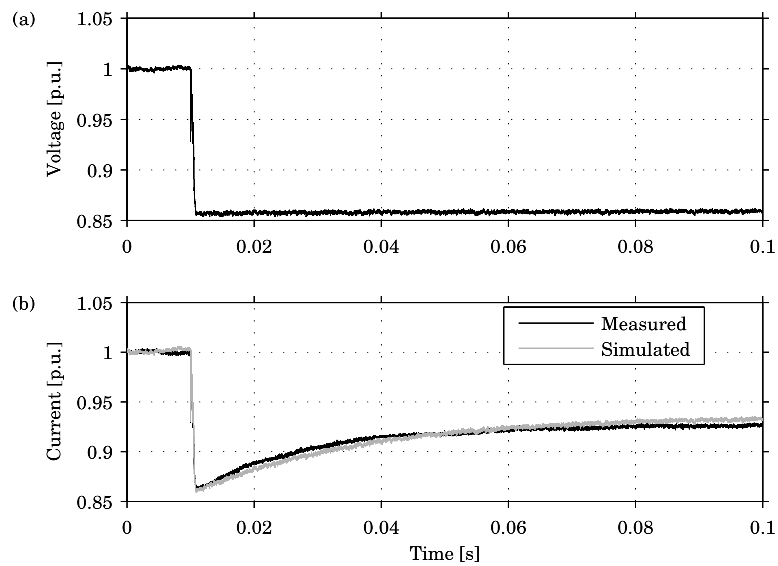

Fig. 2.2. Transient measurement and modeling of incandescent lamp: (a) voltage, and (b) current.

Rotating Loads

Universal machines are usually used in small household appliances, such as mixers, food processors and vacuum cleaners. A universal machine has the same construction as a series-magnetized dc machine, and therefore operates equally well with ac as dc [9]. However, larger household appliances such as washing machines and tumble dryers are instead using induction machines. These machines are often supplied from a power-electronic converter, which will be treated in the next section.

The analysis of the steady-state measurements shows gives that a universal machines can be modeled as a voltage-dependent current source

$$I = Y_0 U + I_0 \tag{2.5}$$

where I is the load current, Y_0 is the conductance, U is the load voltage and I_0 is the constant load current. The steady-state measurement of a vacuum cleaner is shown in Fig. 2.3.

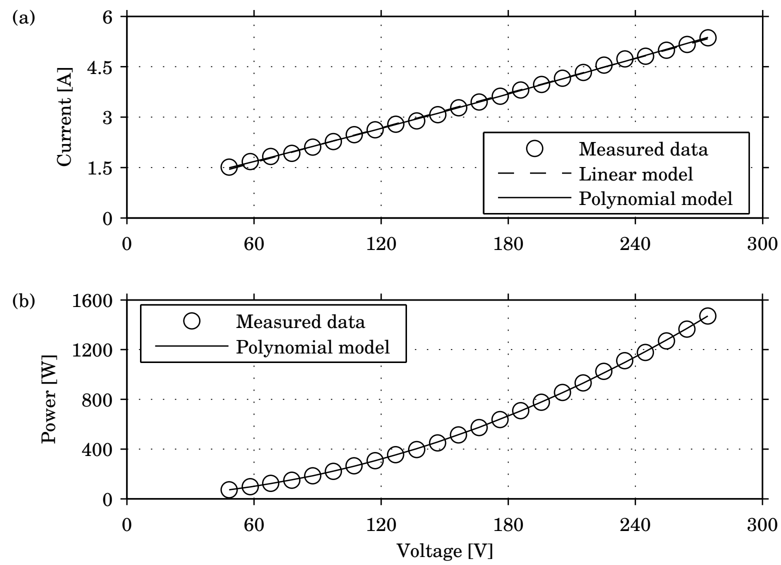

Fig. 2.3. Steady-state measurement of vacuum cleaner: (a) conductance characteristic, and (b) power characteristic.

The transient response of a universal machine has two parts. One electrical transient and one mechanical transient, where the electrical transient is approximately 100 times faster than the mechanical one. In order to fully model the transient behavior of the universal machine it is necessary to also measure the rotational speed of the machine, which in this particulary study was not possible.

Electronic Loads

The number and size of home electronic products has increased fast the last few years. Example of such loads are computer equipment, flat screen monitors and televisions, and battery chargers. Common for all these products are that they are supplied through power electronic converters. Furthermore, lighting appliances such as compact fluorescent lamps and fluorescent tubes with HF ballasts also utilize power-electronic converters.

A power-electronic converter adjusts the grid voltage to a voltage with an amplitude and a frequency which is required by the load. In most cases the grid voltage is first rectified by a diode rectifier and then adjusted by a power-electronic converter, which together are called a switch mode power supply (SMPS). The SMPS has a wide range input which means it can be supplied with 100–240 V/50–60 Hz, which in reality menas 90–265 V in the range 47–63 Hz and dc. A suggested simplified model of an electronic load is shown in Fig. 2.4. It consists of two diodes and an input filter, and the steady-state load model.

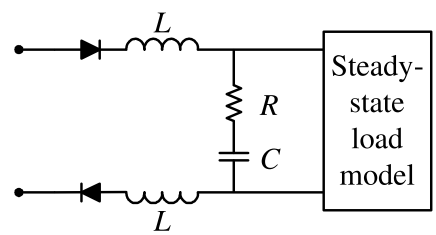

Fig. 2.4. Electric model of electronic load.

The steady-state measurement of a computer power supply is shown in Fig. 2.5. Fig. 2.5(b) clearly shows that the computer power supply has a CP characteristic in the tested voltage range, which is logic since the computer will consume the same power regardless of the supplying voltage.

The power supply used in compact fluorescent lamp usually have a simple design and can in most cases be modeled as a CC load. Some compact fluorescent lamps are designed to used as emergency lights, and therefore can be operated with both ac and dc. However, HF ballast can have varying designs depending on its application. Fig. 2.6 shows the steady-state measurement of a HF ballast, which has two characteristics. In the lower voltage range it has a CC characteristic and in the upper voltage range it has a CP characteristic. Dimmable lamps must not have a CP characteristic.

The transient response of a computer power supply is shown in Fig. 2.7. Fig. 2.7(b) shows that the load current becomes zero directly after the voltage step, which can be explained by looking at Fig. 2.4. When the supply voltage becomes lower than the capacitor voltage, the diodes block the load current until they become equal, but then the current reaches a higher value due to its CP characteristic.

The transient response of compact fluorescent lamps and HF ballasts depends on their input rectifier design and their load characteristic. Fig. 2.8 shows the transient response of a HF ballast with CC characteristic. The fast transient is due to the input filter and the slower transient is due to the response of the internal current controller.

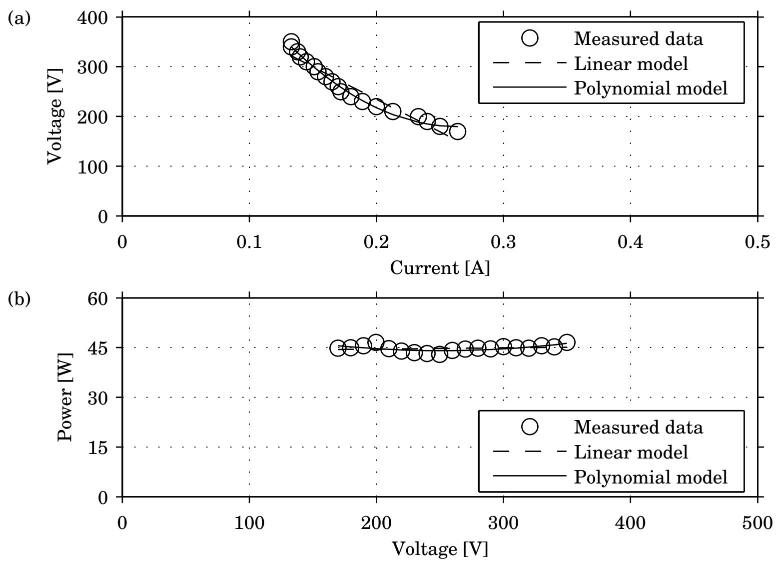

Fig. 2.5. Steady-state measurement of computer: (a) resistance characteristic, and (b) power characteristic.

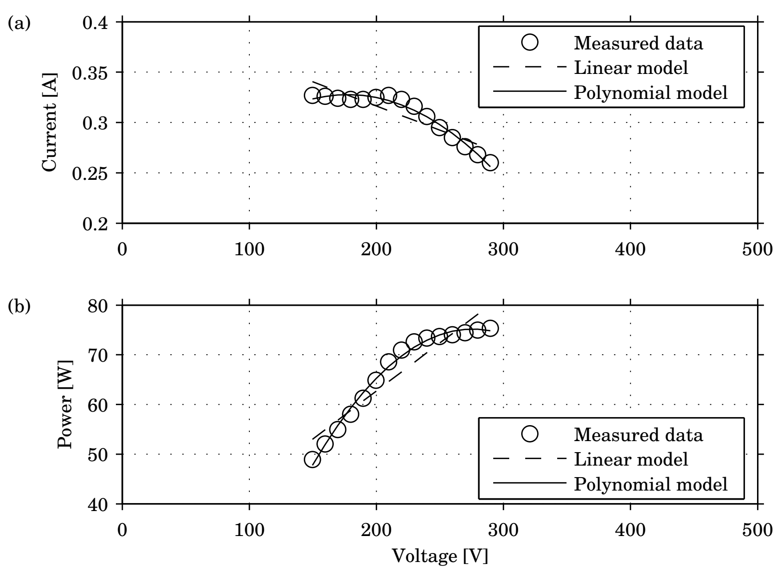

Fig. 2.6. Steady-state measurement of HF ballst: (a) conductance characteristic, and (b) power characteristic.

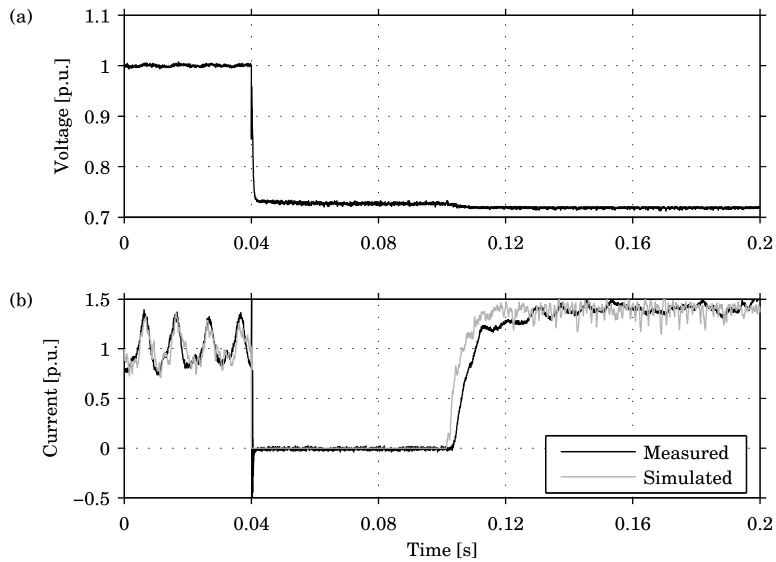

Fig. 2.7. Transient measurement, and modeling of computer: (a) voltage, and (b) current.

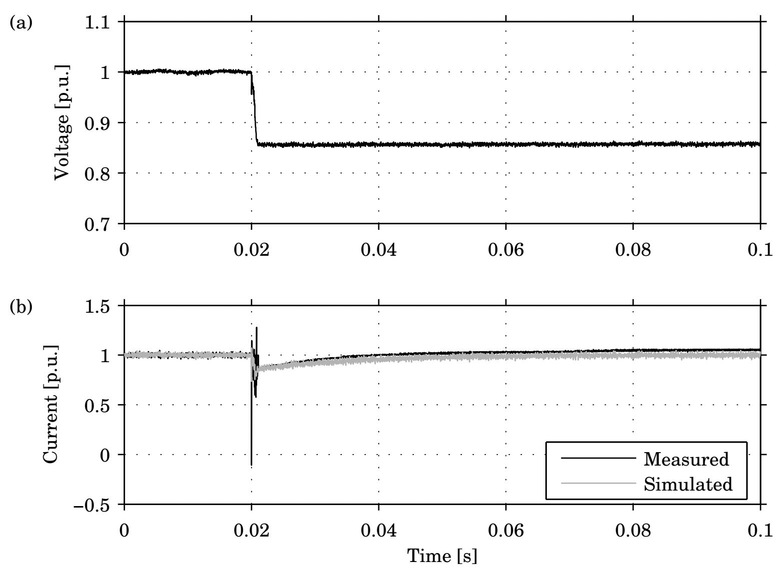

Fig. 2.8. Transient measurement, and modeling of HF ballast: (a) voltage, and (b) current.

2.3 Conclusions

All resistive loads can operate with dc in the full tested range without any modifications. Problems may arise with switches inside the load, which are not designed to interrupt a dc current. Furthermore, these loads are dependent on the rms-value of the voltage, and will therefore require at most 230 V dc, otherwise they will exceed their thermal limits. Furthermore, incandescent lamps are sensitive to overvoltages which decrease the life of the lamps. Resistive loads can be modeled either as a pure resistance (heater loads) or as a current-dependent resistance with a time constant (lighting loads).

The universal machines were tested in the range 50–300 V dc, where the rotational speed of the machine increases with increased voltage. These loads can be modeled as a voltage-dependent current source. Finally, electronic loads can also be operated with dc, at least in the range 200–300 V, without any modifications. These loads are modeled as a diode rectifier with an input filter together with the steady-state load characteristic.

If an existing ac system were to be replaced with a dc system, 230 V would be a suitable voltage level to recommended. However, a higher voltage level is preferable since it reduces the load currents and the equipment cost. In a new dc system with special designed dc loads a voltage level in the range 300–400 V would be recommended.

Chapter 3

AC/DC Interface

Based on Publications III and IV, this chapter presents analysis of ac/dc interfaces.

3.1 Motivation

An interface is required when interconnecting a dc power systems with an ac system. The design of the interface has great significance on the operation of the dc system and the impact on the ac system. A well-designed ac/dc interface shall provide a controllable dc-link voltage, high power quality and high transient performance during faults and disturbances. It must also have low losses and low cost. Moreover, bi-directional power-flow capability may be desired if generation is present in the dc system, in order to transfer power from the dc system to the ac system during low-load, high-generation conditions in the dc system. Finally, galvanic isolation is necessary to prevent having a current path between the ac system and the dc system in case of a fault.

Different designs of ac/dc converters and their control algorithms have been studied for many years. However, little research has been presented regarding converters which can be suitable to interconnect an ac system with an LV dc power system.

In this thesis, some of the most common types of ac/dc converters using power electronics will be briefly described with respect to the above mentioned design options in order to find a suitable interface design. The selected interface will be further analyzed.

3.2 Different Topologies

A diode bridge is a very cheap and simple device for rectification of ac to dc. It can, depending on its power rating, be made for both single-phase and three-phase connection, as shown in Fig. 3.1 [49]. The diode bridge can be modified by adding a few components, as shown in Fig. 3.2, which will give it either buck or boost characteristics with controllable dc-link voltage and PFC [50]. For high-power applications, three single-phase rectifiers can be connected one to each phase, with their dc-links in series.

A two-level three-phase voltage source converter (VSC) utilizes six switches instead of three, as in a three-phase diode rectifier with PFC. The scheme of a two-level VSC is shown in Fig. 3.3. The three additional switches make it possible to have bi-directional power flow [49]. The two-level VSC operated as a rectifier has a boost output characteristic. The minimum level of the output dc-link voltage is determined by the ac voltage, and equals twice the peak value of the phase-to-ground voltage [50]. A transformer can be connected between the VSC and the ac grid to adjust the minimum output dc-link voltage. The transformer will also provide galvanic isolation between ac system and the dc system, and its leakage inductance will serve as grid filter. Finally, a two-level VSC also has controllable power factor [50].

A combination of a two-level VSC and a dc/dc Buck converter is shown in Fig. 3.4 [51]. Combining two converters by connecting them in series gives increased controllability of the output dc-link voltage. The voltage of the dc link between the two-level VSC and the Buck converter is allowed to vary in a wider range, for example in case of faults in the ac grid, since the output dc-link voltage is controlled by the Buck converter. Furthermore, an energy storage besides the capacitor can be installed between the two converters, as a protection against interruptions. By controlling the power flow through the converters individually, the charge of the energy storage can be controlled. Observe that connecting energy storage to the dc system with any other converter solution would require an additional charger. However, the configuration uses eight switches instead of six, which increases the losses. Also, the configuration has bi-directional power flow but no galvanic isolation.

The configuration of a three-phase three-level VSC, shown in Fig. 3.5, uses 12 switches instead of eight [52]. Compared with the two-level VSC, it results in two, instead of one, controlled dc links from the same ac supply: u_{dc1} and u_{dc2}. This can be useful for replacing existing ac installations with three-phase cables. In a dc system application, it means that loads can be connected to either of the two dc links, and it is still possible to maintain balanced dc-link voltage, which would not be possible with a two-level VSC.

All five described configurations are possible choices, with different trade-offs between price and performance. Table 3.1 gives, the range of the output dc-link voltage, the number of switches, and says whether the interface allows bi-directional power flow for the different types.

TABLE 3.1
AC/DC INTERFACES

Interface type	Output dc-link voltage u_{dc} Min	Max	Number of switches	Bi-directional power flow
Diode	-	$\hat{u}_{\mathrm{ac}}$	0	No
Diode PFC (Buck)	0	$\hat{u}_{\mathrm{ac}}$	3	No
Diode PFC (Boost)	$\hat{u}_{\mathrm{ac}}$	∞	3	No
Two-level VSC	$2\hat{u}_{\mathrm{ac}}$	∞	6	Yes
Two-level VSC and Buck	0	∞	8	Yes
Three-level VSC	$\hat{u}_{\mathrm{ac}}$	∞	12	Yes

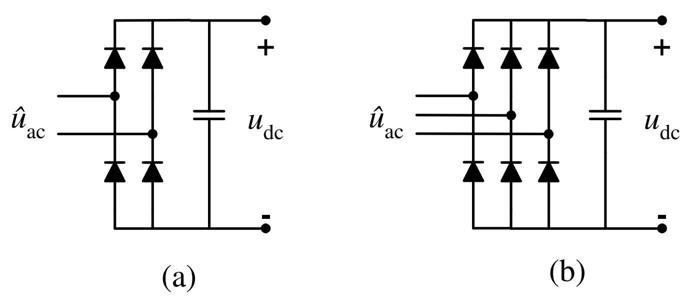

Fig. 3.1. Diode rectifier: (a) single phase, and (b) three phase.

3.3 Selected AC/DC Interface

The two-level VSC with Buck converter is selected as the ac/dc interface to use to interconnect ac and dc power systems since it has a wide range output dc-link voltage, can be designed to have a high transient performance during faults and disturbances, and it is suitable to be used with energy storage. Galvanic isolation can be achieved by adding a transformer with unity ratio before the VSC. A detailed scheme of the interface is shown in Fig. 3.6. The control system of the ac/dc interface consists of two independent parts: one for the VSC and one for the Buck converter.

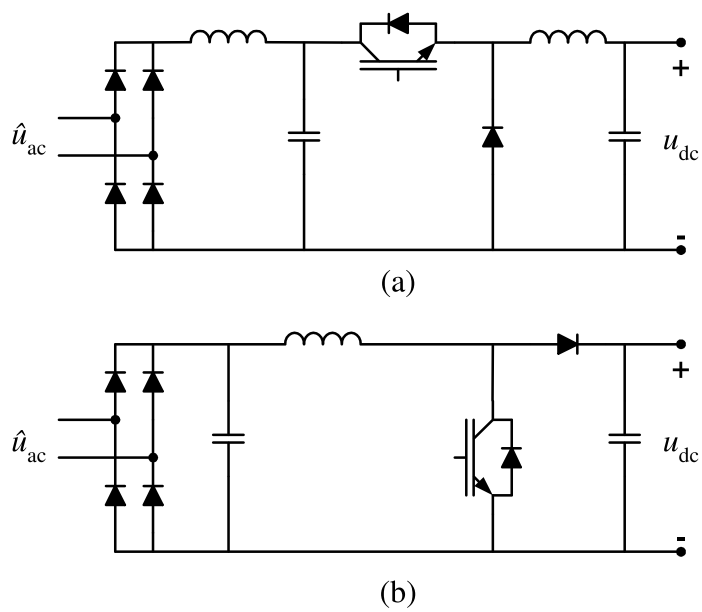

Fig. 3.2. Single-phase diode rectifier with PFC: (a) Buck, and (b) boost.

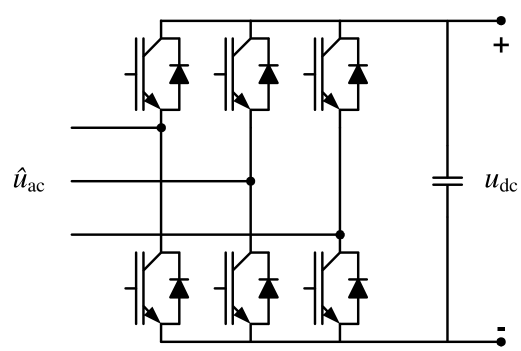

Fig. 3.3. Three-phase, two-level VSC.

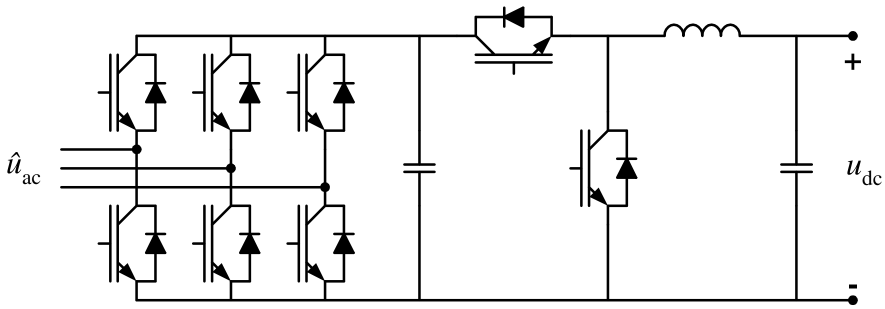

Fig. 3.4. Three-phase, two-level VSC in series with a Buck converter.

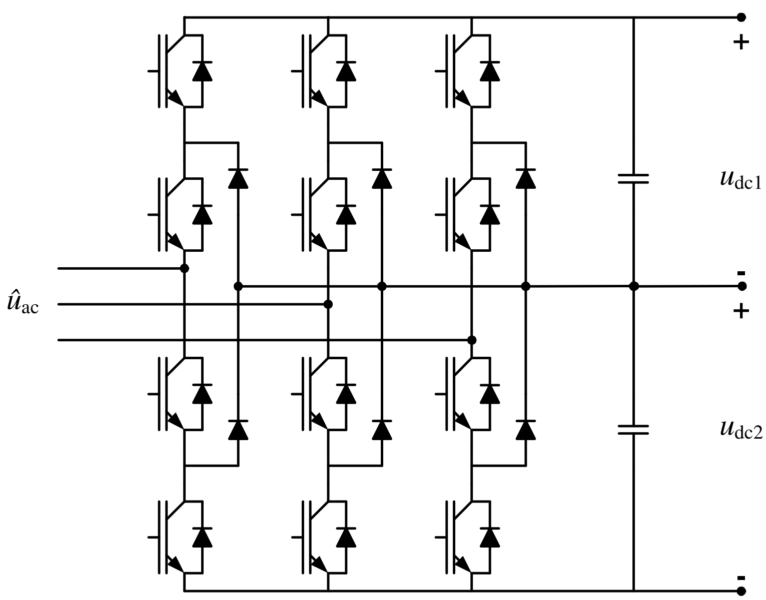

Fig. 3.5. Three-phase, three-level VSC.

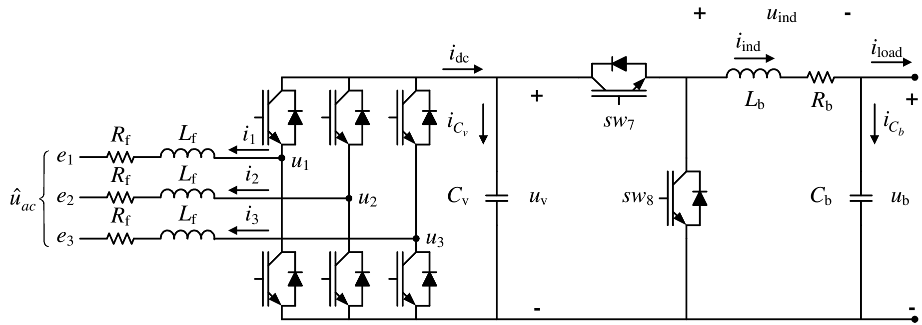

Fig. 3.6. Detailed scheme of a three-phase, two-level VSC in series with a Buck converter.

Control of Three-Phase Two-Level Voltage Source Converter

By using pulse width modulation (PWM) the output voltage of the VSC can be controlled, and hence the voltage across the grid filter. This means that the current through the filter can be controlled, and in turn the power flow between the grid and the VSC [50]. The power flow can be bi-directional, and active and reactive power can be individually controlled. Different current-control techniques are described in [53]. The VSC current control system adopted here uses a vector controller implemented in the synchronous dq-coordinate system, where the positive sequence ac components appear as dc quantities [54]. From Fig. 3.6, the following equation for the system can be derived as

$$L_{\mathrm{f}}\frac{\mathrm{d}\boldsymbol{i}_{dq}(t)}{\mathrm{d}t} = \boldsymbol{u}_{dq}(t) - (R_{\mathrm{f}} + \mathrm{j}\omega L_{\mathrm{f}})\boldsymbol{i}_{dq}(t) - \boldsymbol{e}_{dq}(t). \quad (3.1)$$

More details about the current controller are found in Publication III.

The voltage across the dc-link capacitor can be kept at a constant value by controlling the active power flow on the ac side of the VSC to equal the power required to maintain the charge of the capacitor and to supply the Buck converter connected to the dc side of the VSC [55–60]. The relation between the dc-link voltage u_{v} and the current $i_{C_{\mathrm{v}}}$ flowing into the capacitor C_{v} is

$$i_{C_{\mathrm{v}}}(t) = C_{\mathrm{v}}\frac{\mathrm{d}u_{\mathrm{v}}(t)}{\mathrm{d}t}. \quad (3.2)$$

This equation is used when deriving a controller for the dc-link voltage.

In Publication III two different designs of dc-link-voltage controllers have been compared and analyzed with respect to stability, voltage control and load-disturbance rejection. The analysis shows that having the same voltage-control characteristic results in different load-disturbance rejections. One of the designs was shown to be more sensitive to incorrect parameters. Furthermore, it was shown that using feed forward, either measured or estimated, increases the response of the controller. The results have been verified in an experimental setup.

Control of Buck Converter

The output dc-link voltage of the Buck converter, which is shown in Fig. 3.6, can during continuous-conduction operation be calculated as

$$u_{\mathrm{b}} = u_{\mathrm{v}} \frac{t_{\mathrm{on}}}{T_{\mathrm{s}}} = u_{\mathrm{v}} D \tag{3.3}$$

where u_{v} is the input voltage, t_{on} is the time during one switching period when sw_7 is on (sw_8 is off), T_{s} is the duration of the switching period, and D is the duty ratio [50]. However, if the output voltage of the converter should be stable in spite of load variations, a voltage controller must be designed. The idea of the controller is to have one inner controller of the current through the inductor L_{b}, that will charge the output capacitor C_{b} and supply the load, and one outer loop that controls the needed inductor current to charge the capacitor C_{b} to the voltage reference level. The derivation of the controllers can be found in Publication IV.

A laboratory prototype of the selected interface was built and used to verify its performance during both steady-state and transients, such as load connection and grid disturbance. Fig. 3.7 shows the dc voltages at the output and intermediate stages and the grid currents during connection of a resistive load. The interface maintains the dc-link voltage almost at its reference level, and the grid currents are sinusoidal. The small deviation between the dc-link voltage and its reference levels is the result of the dc-link-voltage-controller design. Finally, in Fig. 3.8 the grid voltages, and the dc-link voltages during a phase-to-phase fault are shown. The grid voltages during the fault have a 0.79 p.u. retained voltage, 27% unbalance and undergo a 11°-phase shift. The fault affects the intermediate dc-link voltage only, and not the voltage seen by the loads.

3.4 Conclusions

An interface is required when interconnecting ac and dc power systems. The converter design affects the performance of the converter with respect to controllability, power quality and safety. A VSC in series with a Buck converter was selected, since the converters can easily be used together with energy storage connected at the intermediate dc link, and no additional converter for the energy storage is required.

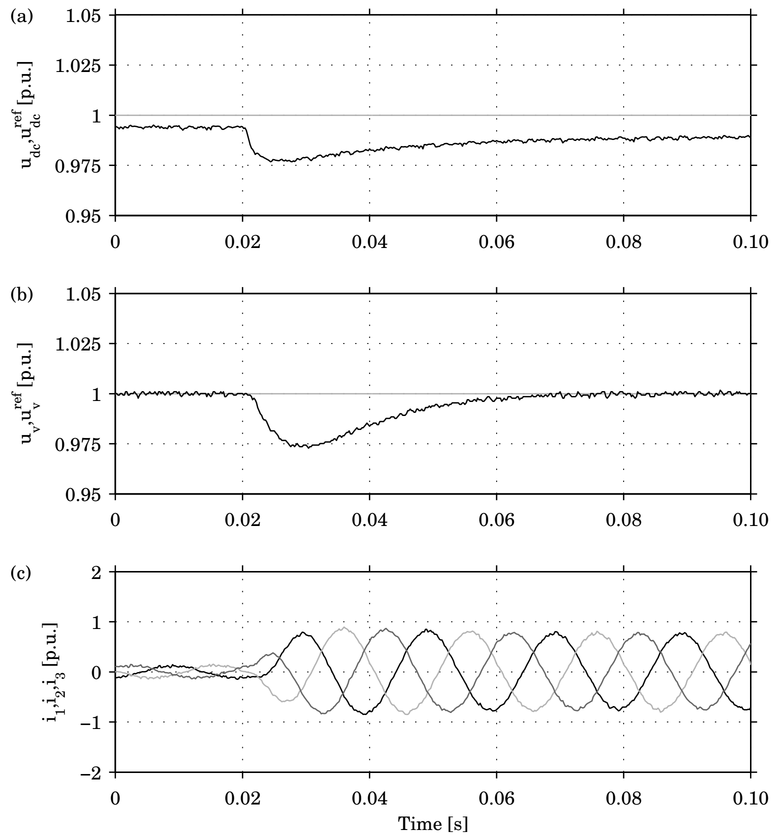

Fig. 3.7. Measurement result of the selected interface when connecting a 0.67 p.u. resistive load: (a) Buck dc-link voltage, (b) VSC dc-link voltage, and (c) three-phase grid currents.

Different designs of the VSC dc-link voltage controller have been analyzed and compared with respect to stability, voltage control, and load-disturbance rejection. It was shown that different designs have different characteristics which affects its performance. Furthermore, the response of the controller can be improved by using feed forward. Finally, both the VSC and the VSC with Buck converter were experimentally tested.

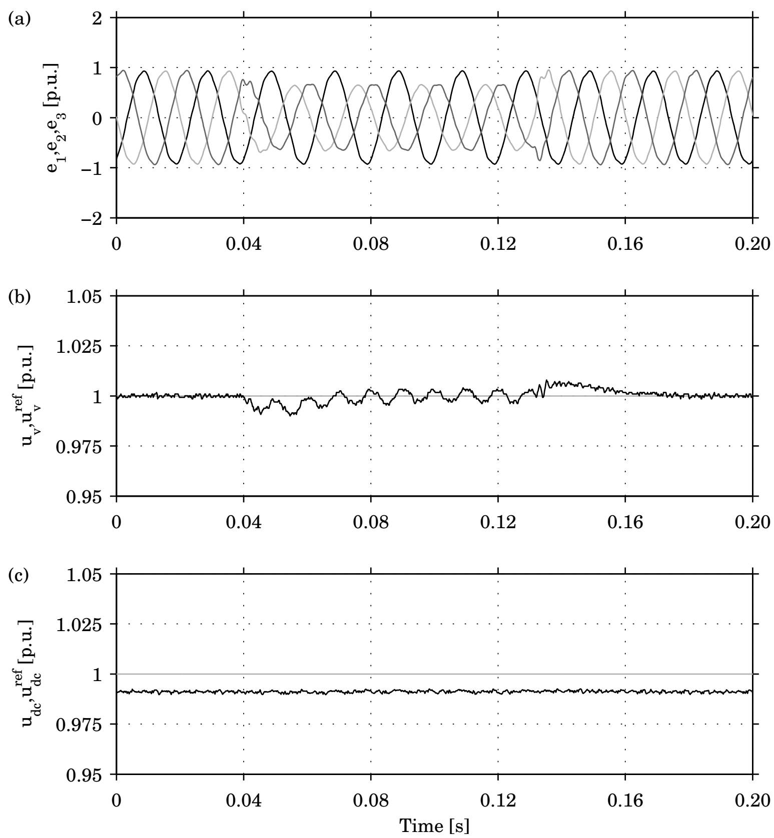

Fig. 3.8. Measurement result of the selected interface during a phase-to-phase fault: (a) grid voltages, (b) VSC dc-link voltage, and (c) Buck dc-link voltage.

Chapter 4

Control and Protection of Low-Voltage DC Microgrids

Based on Publications V, VI, VII and VIII, this chapter presents control and protection systems for LV dc microgrids.

4.1 Motivation

Increasing the amount of distributed resources (DRs) in the electric power system can enhance its operation. Instead of having most of the power produced in large power plants and then transmitted to the customers via the transmission system, it can be locally produced in the distribution system by DRs [61]. These are often small (<500 kW) and use renewable energy. Examples of DRs are small wind and hydro turbines, PV arrays, fuel cells and micro turbines [62].

A part of the distribution system together with its sources and loads can form an isolated electric power system, a microgrid [63–65]. During normal operating conditions, the microgrid is connected to the ac grid at the point of common coupling (PCC), and the loads are supplied from the local sources and, if necessary, also from the ac grid [61]. If the load power is less than the power produced by the local sources, the excess power can be exported into the ac grid.

Commercial and industrial LV power systems often have a large amount of sensitive non-linear loads, which in some cases must be protected from disturbances and outages in order to operate correctly. Examples of such loads are lighting, data and communication systems, control systems, safety systems and equipment for heat, ventilation and air conditioning (HVAC) [66]. A common way to ensure reliable power supply is to install online un-interruptible power supplies (UPSs) and standby diesel-generator sets [66]. The UPSs are used to protect the loads from transients and short interruptions with a duration up to approximately half an hour. Within this time the diesel generators are automatically started to support the UPSs.

A microgrid is well suited to protect sensitive loads from power outages and in some cases also disturbances, e.g. voltage dips [67]. An isolated power system with high reliability can be obtained by utilizing the local sources together with fast protection systems [66, 68, 69]. To be able to operate the microgrid in island mode it is necessary to have an island detection system, which safely disconnects the microgrid when an ac grid outage occurs, to prevent energizing the ac grid [70, 71]. If a blackout in the ac grid occurs which also includes the microgrid, the microgrid can be disconnected from the ac grid and used for service restoration [72].

An LV dc microgrid can be preferred over an ac microgrid in cases where most of the sources are interconnected through power-electronic interfaces and are sensitive electronic equipment [23–25, 27]. The advantages are that loads, sources and energy storage then can be connected through simpler and more efficient power-electronic interfaces [73].

Having multiple sources sharing the voltage control can be solved by using a centralized master-slave configuration or implementing a local voltage-droop characteristic in each of the source controllers. Both local and centralized control of the sources connected to the microgrid during steady state have been treated earlier in [24, 25, 27]. However, to ensure reliable operation of the LV dc microgrid, it must also be studied during faults. Little research has been presented about this so far. In this thesis, the designs of both a control system and a protection system are proposed, and their performance during faults are studied and evaluated.

4.2 AC/DC Microgrids

In a dc microgrid, energy storage and a large portion of the sources and the loads are interconnected through one or more dc busses. However, there will still be a need for ac microgrids since some sources and loads cannot be directly connected to dc. Moreover, as long as ac is used for distribution, the dc microgrid will at some point be connected to the ac grid. Therefore, it is proposed that the ac and dc microgrids should be considered as two parts of a mixed ac/dc microgrid, which is connected to the ac grid at the PCC.

Power can flow between the ac microgrid and the dc microgrid through power converters, but also between the ac microgrid and the ac grid. The power direction depends on the balance between load and generation. An example of an ac/dc microgrid is shown in Fig. 4.1, where Zone 1 is the dc microgrid, Zone 2 the ac microgrid, and Zone 3 the rest of the ac grid.

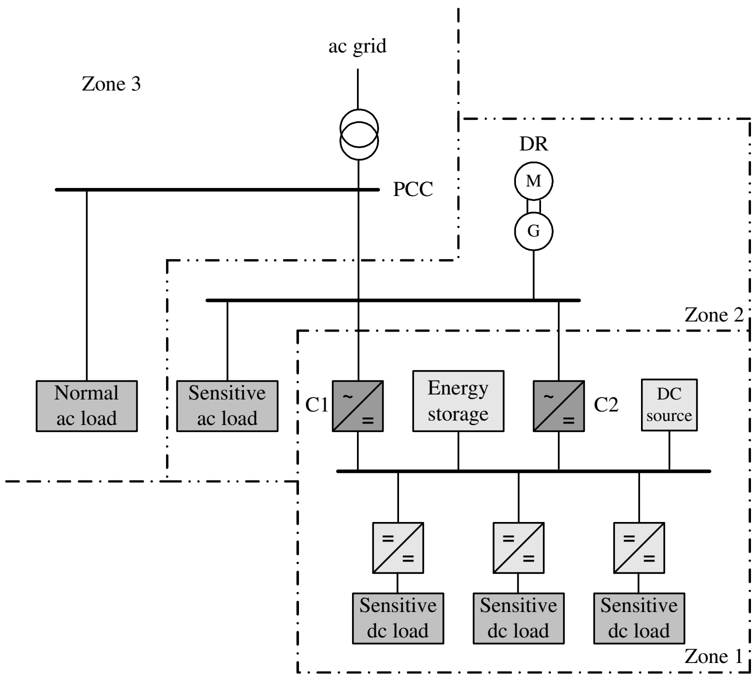

Fig. 4.1. Example of an LV ac/dc microgrid.

In Publication V four different commercial power systems with sensitive electronic loads were analyzed: an auxiliary power system for substation and generating station, a hospital, a voice and data communication facility, and a data center. The result shows that a data center has a possibility to greatly improve its operation performance by using an LV dc microgrid. The main improvements identified were power quality, efficiency, and consequently operation cost.

4.3 DC Microgrid for Data Centers

Data centers are an example of commercial power systems with sensitive electronic loads. They provide management for various types of server applications, such as for web hosting, Internet, intranet, telecommunication, and information technology. The large power consumption of data centers (up to tens of MW [74]) together with a high price of electricity result in high cost for the owners of data centers. One possibility to reduce the cost is to lower the losses in the system. This will also reduce the need for cooling.

Fig. 4.2 shows a typical scheme of a data center power system with sensitive computer loads (together with their internal SMPS with PFC) and HVAC equipment [75, 76]. The power system has a connection to the ac grid, which normally supplies the loads. If an outage occurs in the ac grid, the loads can be supplied from a standby diesel generator. During the time it takes to detect the outage, disconnect the ac grid and start the diesel generator, the sensitive loads are supplied from an ac UPS. One way for data centers to combine the need for high reliability and the possibility to reduce the losses is to use a dc microgrid.

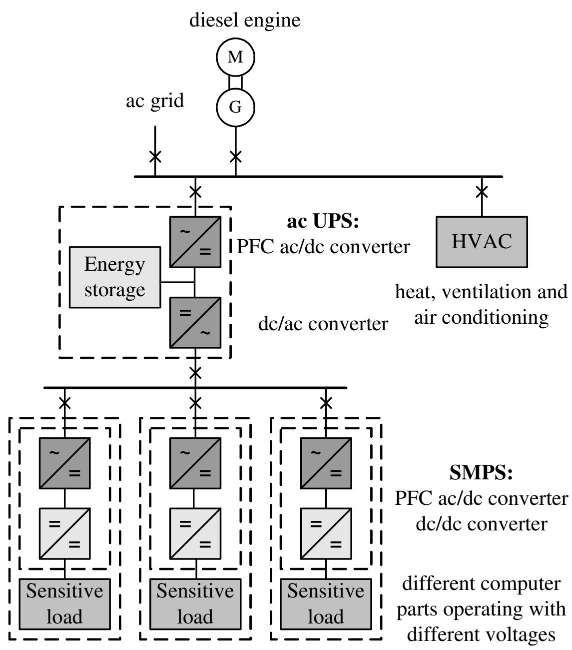

Fig. 4.2. Data center power system.

Fig. 4.3 shows a scheme of a proposed dc microgrid for data centers connected to the ac grid, which is one special case of the LV ac/dc microgrid. The dc microgrid is indicated as Zone 1. Zone 2 is prioritized ac loads which are located close to the data center dc microgrid, for example cooling equipment or an office building. Finally, Zone 3 is the ac grid and the loads connected to it.

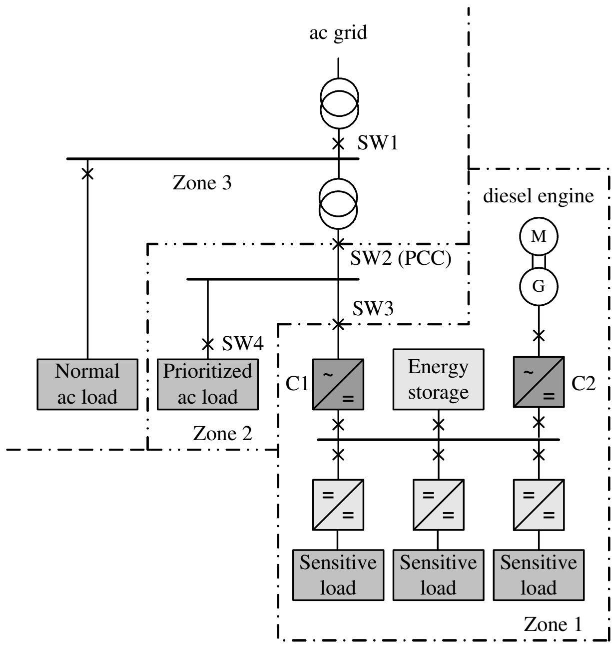

Fig. 4.3. Low-voltage dc microgrid for data centers.

Control of DC Microgrid for Data Centers

The data center dc microgrid has a number of components which can be controlled: converter C1, the energy storage unit, converter C2 (together with the diesel generator), switches SW2 and SW3. An adaptive control system is therefore required to coordinate the control of these components. Converter C1 can be operated in three different modes: controllable dc source (cdcs), controllable ac source (cacs) or controllable power source (cps). When it is operated as a cdcs it is regulating the dc-link voltage in the dc microgrid. When it is operated as a cacs it can be used to generate ac voltage and supply the loads in Zone 2 (switch SW2 must then be open). Finally, when it is operated as a cps it can inject a controllable amount of active power to the ac grid. Converter C2 can only be operated as a cdcs. Switch SW2 is used to disconnect the dc microgrid and the prioritized ac loads from the ac grid, and switch SW3 to disconnect Zone 1 from Zone 2.

Eight different operation modes have been identified, in which the data center dc microgrid can operate. These modes are further described in Publication VI. For each operation mode, the mode of the control variables of the converters C1 and C2, and the switches SW2 and SW3 are defined. The control variables for each operation mode are reported in Table 4.1.

TABLE 4.1
CONTROL VARIABLES FOR DIFFERENT OPERATION MODES OF THE DATA CENTER DC MICROGRID

No.	Operation mode	Control variables			
		C1	C2	SW 2	SW 3
1	Import mode	cdcs	off	closed	closed
2	Emergency support mode	cacs	off	open	closed
3	Emergency mode	off	off	closed	open
4	Standby support mode	cacs	cdcs	open	closed
5	Standby mode	off	cdcs	closed	open
6	Standby export mode	cps	cdcs	closed	closed
7	Emergency export mode	cps	off	closed	closed
8	Off	off	off	closed	open

The adaptive control system changes the control variables based on the input variables and the current operation mode. If any of the input variables change state, the adaptive control system will change the control variables, and this results in a transition from one operation mode to another. As previously stated, the dc microgrid for data centers has eight different operation modes which can be used. It can only change from one operation mode to another operation mode which is relevant from an operational and control perspective. Each transition from one operation mode to another operation mode is due to an event (planned or unplanned). In Fig. 4.4 the 23 identified transitions for the data center dc microgrid are shown, and these are further described in Publication VI.

The proposed adaptive controller was implemented and tested in the simulation software package EMTDC/PSCAD. Different cases were studied and analyzed. The most critical transitions, 1 and 22, are due to an outage in Zone 3. When it occurs it is important to quickly detect the outage and change the operation mode in order to keep the sensitive loads in Zone 2 online.

4.4 DC Microgrid Protection

Besides a control system, a well-functioning protection system is necessary to ensure reliable operation. It can be designed using techniques used in already existing protection systems for high-power LV dc power systems, for example protection systems for generating stations and traction power systems [8, 77–79]. However, these systems utilize grid-connected rectifiers with current-limiting capability during dc faults. In contrast, an LV dc microgrid must be connected to an ac grid through converters with bi-directional power flow, and therefore a different protection-system design is needed.

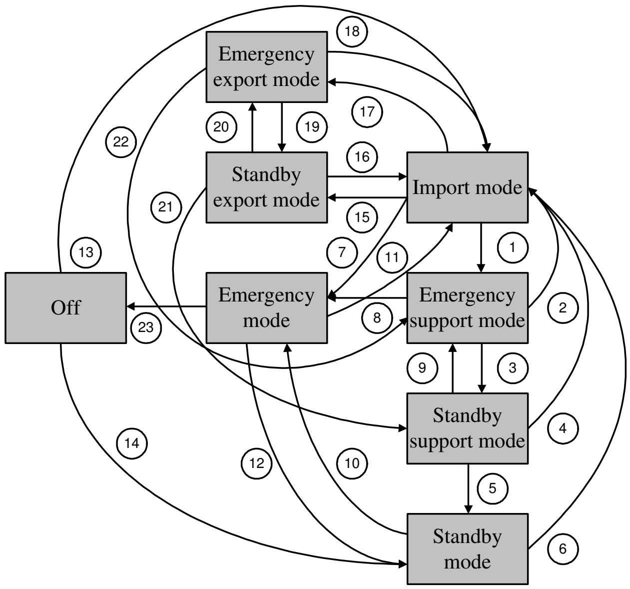

Fig. 4.4. Operation modes and transitions of the data center dc microgrid.

Short-circuit current calculations for LV dc systems have been treated in [80–82], and fault detection in [37, 83]. However, the protection devices have not been considered. So far the influence of protection devices on the system performance has only been considered in studies of HV dc applications such as electric ships and HV dc transmission systems [84, 85].

In this section, LV dc microgrid protection is presented. The protection system consists of grounding, protection (current interrupting) devices, protective relays, and measurement equipment.

Grounding

Grounding is a complex issue and there are many different approaches to designing grounding in an electric power system [86], and different solutions result in different performance [87, 88]. Grounding is used for detection of ground faults and for personnel and equipment safety [8]. An LV dc microgrid can be ungrounded, high-resistance grounded or low-resistance grounded. Moreover, the ground can be connected either to one of the poles or to the middle point of the converter and the battery. The two alternatives are shown in Fig. 4.5.

Fig. 4.5(a) shows a TN-S dc system. It has the middle point of the converter and the battery connected to ground (T), and separate (S) wires are used throughout the system for neutral (N) and protective earth (PE). The alternative in Fig. 4.5(b) is an IT dc system. It has the positive pole connected to ground through an impedance (I). The positive pole is preferably connected to ground compared with the negative one to reduce the impact of corrosion.

Using alternative (a) in Fig. 4.5 results in a large ground current and a large dc-link voltage transient in case of a low-resistance ground fault. The large voltage transient may affect other loads connected to the faulted pole, but not loads connected to the other pole. The fault is easily detected and can be quickly cleared. A TN-S dc system provides a well-defined pole-to-ground voltage and paths for leakage currents from noise filters.

An IT dc system has only a small current and voltage transient in case of a ground fault. This will ensure a stable operation of the loads during a ground fault. However, a ground in the system will change the pole-to-ground voltage, which may affect sensitive electronic loads. Due to the small ground-fault current it can be difficult to measure and detect the fault, and metal enclosures of loads may be energized. To further improve the system in case of a ground fault the line impedance of each load can be increased to limit the voltage transient. However, this results in increased losses. Alternative (b) is commonly used in telecom power systems [89].

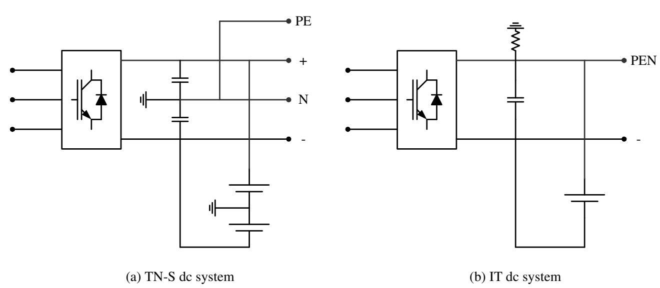

Fig. 4.5. LV dc microgrid grounding: (a) TN-S dc system, and (b) IT dc system.

Protection Devices

Protection devices commercially available for LV dc systems are fuses, molded-case circuit breakers (MCCB), LV power circuit breakers and isolated-case circuit breakers [77, 90, 91]. Some of these models are specially designed for dc, but most can be used in both ac and dc applications.

A fuse consists of a fuse link and heat-absorbing material inside a ceramic cartridge. When the current exceeds the limit of the fuse, the fuse link melts and an arc is formed. In order to quench the arc, the arc voltage must exceed the system voltage. This can be done by stretching and cooling the arc. There is no natural current zero in a dc system which helps to interrupt the fault current. Voltage and current ratings of fuses are given in rms values, and are therefore valid for both ac and dc.

A molded-case circuit breaker consists of a contactor, a quenching chamber and a tripping device. When an MCCB is tripped the contacts begin to separate, and an arc is formed between them. The arc is forced into the quenching chamber by air pressure and Lorentz magnetic forces. The quenching chamber consists of multiple metal plates which are designed to divide the arc into multiple smaller arcs. This will increase the total arc voltage and decrease the arc temperature, and the arc will in most cases extinguish [91]. To improve the voltage withstand capability multiple poles can be connected in series.

Molded-case circuit breakers are usually equipped with a thermal-magnetic tripping device, and the voltage and current ratings are given in rms values. The magnetic tripping senses the instantaneous value of the current, which means that the rated current for dc is $\sqrt{2}$ times higher than for ac. However, for the thermal tripping the values are the same [91].

For larger LV dc systems, for example a traction power system, special high-speed dc circuit breakers are available. These circuit breakers are designed to fully handle rated voltage and current. A high-speed circuit breaker starts to interrupt the fault current within 0.01 s. Problems may arise with low currents which can cause the circuit breaker contacts to weld together [79].

There are some known problems associated with fuses and circuit breakers in LV dc systems such as large time constants and long breaker operation time. By utilizing power-electronic switches such as gate-turn-off thyristors (GTOs) the operation speed decreases and the inductive current interruption capability can be increased [84, 92]. However, the losses of such a solution are much higher compared with a mechanical switch. Therefore a combination of one mechanical switch and one power-electronic switch has been proposed in [93].

Protective Relays and Measurement Equipment

High-speed dc circuit breakers are equipped with mechanical instantaneous over-current tripping devices, which can be set to trip the breaker if the current exceeds 1–4 p.u.. The electromagnetic force generated by the current is used to trip the circuit breaker. However, if the circuit breaker shall be tripped due to other events, a protective relay is required.

Protective relays use information from measured voltages and currents, and in some cases also information based on communication with other units. It is important to note that the measurement equipment must be able to handle dc quantities in order to work properly.

Besides overcurrent, protective relays can calculate time derivatives and step changes of currents to determine if the system is in normal operation or if a fault has occurred [79, 94]. More sophisticated numerical methods to detect faults and identify them from normal operation in traction applications, for example by using neural networks, have been treated in [95, 96].

Protection-System Design

The overall function of the LV dc microgrid protection system is to detect and isolate faults fast and accurately, in order to minimize the effects of disturbances. The design of the protection system depends on a number of issues: the type of faults which can occur, their consequences, the type of protection devices required, the need for backup protection, detection methods, measures to prevent faults, and finally, measures to prevent incorrect operation of the protection system.

Possible fault types in a dc microgrid are pole-to-pole and pole-to-ground faults. Pole-to-pole faults often have a low fault impedance, while pole-to-ground faults can be characterized as either low-impedance or high-impedance faults. The location of the faults can be on the bus or one of the feeders, inside the sources or the loads.

The main difference between an LV dc microgrid and other existing LV dc power system is the type of converter that is used to interconnect the dc system with the ac grid. Converters used for example in dc auxiliary power systems for generating stations and substations, and traction applications are designed to have a power flow only from the ac side to the dc side. Therefore, it is also possible to design the converters to be able to handle faults on the dc side by limiting the current through them. However, the power flow between an LV dc microgrid and an ac grid must be bi-directional. A different type of converter is then required, and it may not be possible to limit the current through the converter during a fault in the LV dc microgrid.

During a fault, all sources and energy storage units connected to the dc microgrid will contribute to the total fault current. The fault current from each DR is determined by its design and the total fault impedance. The converters used in the LV dc microgrid have a limited steady-state fault-current capability due to their semiconductor switches. However, they can provide a fault current with a high amplitude and a short duration from their dc-link capacitors. Energy storage, for example lead-acid batteries, can provide a large steady-state fault current. In contrast to converters, they have a long rise time.

The components within the dc microgrid must be protected from both overloads and short circuits. Depending on the sensitivity of the component different solutions exist. Power-electronic converters are very sensitive to overcurrents, and if they do not have internal current-limiting capability, they require very fast protection. Examples of such devices are fuses, hybrid circuit breakers, and power-electronic switches. Batteries and loads do not require such fast protection, and therefore simpler and cheaper devices can be used.

To achieve selectivity in the dc microgrid, it is necessary to coordinate the different protection devices. Feeders and loads are preferably protected by fuses since they are simple and cheap, and it is easy to obtain selectivity. However, it is common to use MCCBs closest to the loads due to their two-pole interruption. The protection devices protecting sources and energy storage devices must be able to separate a bus fault from a feeder or a load fault, in order to achieve selectivity. Different methods were studied and analyzed through simulations in Publication VII. The results show that a combination of the dc-link-voltage level and the derivative of the current is the best fault-detection method for converter protection, due to the converter fault-current characteristic. Batteries have a different fault-current characteristic so it is possible to use the instantaneous value of the current to detect a fault.

4.5 Experimental Results

A small-scale experimental setup of a dc microgrid was built to evaluate and compare the use of ac and dc for supplying sensitive electronic loads. In the experimental setup, shown in Fig. 4.6, the loads were arranged so that they could be supplied either with dc or ac. The tested loads were selected to represent a small office: a fluorescent lamp, a compact fluorescent lamp, a computer and a coffee maker. These are shown in Fig. 4.7. The loads were supplied with either ac from the grid, or with dc from the proposed ac/dc interface presented in Chapter 3. In the first case the steady-state behavior of the loads was studied, where the main focus lied on the contents of the current harmonics. The results show that dc may well be used to supply electric loads compared with ac. In a dc system there will not be any problems associated with current harmonics. In the second case different arrangements of protecting sensitive loads from transient disturbances were studied. The experimental test showed that a computer and a fluorescent lamp used in the test were affected by voltage dips in the ac grid; the computer restarted and the fluorescent lamp shut off. It was demonstrated that supplying the loads with the dc system connected to the ac grid through the interface can prevent disturbances to affect the loads. This solution has lower losses compared with a conventional ac

UPS, which is otherwise required to provide a disturbance-free power supply.

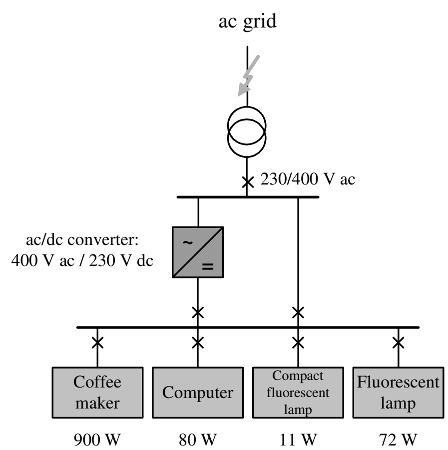

Fig. 4.6. Overview of the laboratory setup.

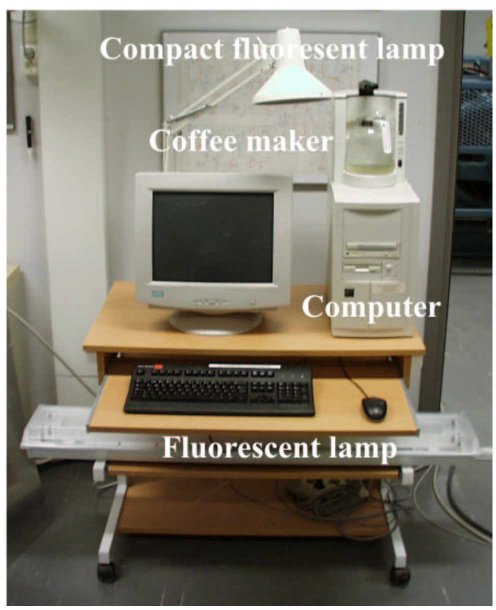

Fig. 4.7. Tested loads: a fluorescent lamp, a compact fluorescent lamp, a computer and a coffee maker.

4.6 Conclusions

An LV dc microgrid is proposed as a solution to use in power systems with a large amount of sensitive electronic loads, for example data centers. It is then possible to reduce operation costs since the losses are lowered due to fewer power conversions, and less cooling is required. In a power system with a mix of different types of sensitive loads and local generations, an ac/dc microgrid can be a better choice. A survey of four different commercial power systems with sensitive loads showed that a data center has a possibility to greatly improve its operation performance by using an LV dc microgrid. An adaptive controller was designed for the data center dc microgrid which coordinates the operation of the sources based on local information. The performance of the controller was studied and evaluated through simulations. It was shown that the data center dc microgrid can be used to support local loads. Furthermore, a protection-system design for LV dc microgrids has been proposed. Different protection devices and grounding methods which can be used in an LV dc microgrid have been presented. When designing the protection system it is important to consider the protection devices that are required to be used and where they should be placed. System studies are required to evaluate the overall system performance during faults. Finally, experimental tests have verified the feasibility of using LV dc to supply sensitive electronic loads.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this thesis modeling, control and protection of LV dc microgrids have been presented.

The historical background in Chapter 1 showed that even if ac conquered dc in the battle of currents, dc is stilled used to power loads. Furthermore, dc has in recent years been adopted by new applications. This thesis has shown the possibilities to further extend the use of LV dc power systems.

Chapter 2 described the results from load modeling for steady-state and transient analysis of LV dc systems. The first aim with the work was to investigate which existing LV ac loads that could operate with dc without any modifications and within which voltage range. The second aim was to develop simple models of the loads which can operate with dc. The measurement results showed that resistive loads operate equally well with dc as with ac as long as the rms-voltages are equal. However, problems may arise with load switches, which are not designed to interrupt dc current. Depending on the rated power, a resistive load is modeled either as a pure resistance or as a current-depending resistance. Rotating loads with a universal machine and electronic loads could also operate with dc without any modifications. The voltage range within the loads could operate varied among the different designs. A universal machine is modeled as a voltage-dependent current source, and electronic loads as a diode rectifier with a filter and the steady-state load characteristic.

Chapter 3 summarized the work on ac/dc interfaces. An interface is required in order to interconnect an ac and a dc power system. The design of the interface highly affects its performance with respect to controllability, power quality and safety. A VSC in series with a Buck converter was selected to be used, since these converters together have bi-directional power flow, generate no low-frequency harmonics, and can preferably be used together with an energy storage device. Galvanic isolation can be obtained by connecting them to the ac grid through a transformer with unity ratio. Different designs of the VSC dc-link voltage controller have been analyzed and compared with respect to stability, voltage control, and load-disturbance rejection. It was shown that different designs have different characteristics which affects its performance. Finally, both the VSC and the VSC with Buck converter were experimentally tested.

Chapter 4 presented the work on LV dc microgrids. An LV dc microgrid can be preferable to an ac microgrid, where most of the sources are interconnected through a power-electronic interface and most loads are sensitive electronic equipment. The advantage of an LV dc microgrid is that loads, sources and energy storage then can be connected through simpler and more efficient power-electronic interfaces. A survey on four different commercial power systems with sensitive loads showed a data center has a possibility to greatly improve its operation performance by using an LV dc microgrid. An adaptive controller was designed for the data center dc microgrid which coordinates the operation of the sources based on local information. System studies showed that the data center dc microgrid can be used to support loads in its close vicinity. Furthermore, a protection-system design for LV dc microgrids has been proposed. Different protection devices and grounding methods which can be used in LV dc microgrids have been presented. When designing the protection system it is important to consider which protection devices are required to be used and where they should be placed. System studies are also required to evaluate the overall system performance during faults. Finally, experimental tests have verified the feasibility of using LV dc to supply sensitive electronic loads.

5.2 Future Work

- Improve the model of the protection system so it also takes into account the time delay due to computation and communication, and the formation of arc.

- Development of a control system for a dc microgrid with different types of sources and energy storage, which in turn have different operation costs.

- Laboratory setup of a dc microgrid with different types of sources and energy storage where both the control and protection system can be tested.

- Development of international standards and guidelines for LV dc microgrids. Important issues are: voltage levels, component design (for example plugs, outlets, and switches), protection design, grounding methods and power quality.

- Investigate to what extent it would be possible to use mixed ac/dc microgrids in the power system, and how would it affect its stability and reliability.

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