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ENERGY DEVELOPMENT AND POWER GENERATING COMMITTEE

PANEL SESSION: GLOBAL POWER SYSTEMS FOR SUSTAINABLE ENERGY DEVELOPMENT

Sponsored by: International Practices for Energy Development and Power Generation Subcommittee

IEEE 2004 General Meeting, Denver, 6-12 June 2004
Wednesday, June 9, 2004, Plaza Ballroom F, 2:00 p.m.

E XTENDED PANEL SESSION SUMMARIES

Chairs: Ambra Sannino, Chalmers University of Technology, Gothenburg, Sweden,
E-mail**:** ambra.sannino@ieee.org
Tom Hammons, Chair International Practices for Energy Development and Power Generation, University of Glasgow, Scotland, UK;
E-mail: T.Hammons@ieee.org

Track 4: Sustainability and Global Change

This Panel Session discussed Global Power Systems for Sustainable Energy Development.

Sustainability must be the goal when building power systems of the future. Often this concept is identified with the use of renewable energy sources, but there are other aspects that have to be taken into account to build a fully sustainable power system.

Sustainability can be significantly improved by reducing losses in power transmission and distribution that can be done by applying direct current based systems. Use and proper control of energy storage becomes of crucial importance when renewable sources with stochastic behavior account for a large amount of the total generation. However, introduction of renewable-based generation, energy storage, and dc transmission and distribution are made possible by increased use of power electronics, which in turn also causes losses.

This panel session highlighted some of these aspects and made clear that sustainability can and should be applied throughout the power system – at all levels: not only generation but also transmission, distribution and utilization.

Presenters and Titles of their Presentations are:

1) Ambra Sannino, Chalmers University of Technology, Gothenburg, Sweden. “Global Power Systems for Sustainable Development--An Introduction.”
2) Kundur, PowerTech Laboratories, Canada. “Sustainable Electric Power Systems in the 21st Century: Requirements, Challenges, and the Role of New Technologies.”
3) Gunnar Asplund, ABB Power Technologies, Ludvika, Sweden. “Sustainable Energy Systems with HVDC Transmission.”
4) Göran Andersson, ETH Zurich, Switzerland. “Power Electronics Solutions for Sustainability.”
5) Robert B. Schainker, EPRI, USA. “Executive Overview: Energy Storage for a Sustainable Energy Future.”

6) Daniel Nilsson, and Ambra Sannino, Chalmers University of Technology, Gothenburg, Sweden. "Efficiency Analysis of Low and Medium-Voltage DC Distribution Systems."
7) Math Bollen, STRI AB, Ludvika, Sweden; Stephen R. Connors, Massachusetts Institute of Technology, Cambridge, MA, USA; and Jimmy Ehnberg, Chalmers University of Technology, Gothenburg, Sweden. "Generation Reliability for Small Isolated Power Systems Entirely Based on Renewable Sources."

Each Panelist spoke for approximately 20 minutes. Each presentation was discussed immediately following the respective presentation. There was a further opportunity for discussion of the presentations following the final presentation.

The Panel Session was organized by Ambra Sannino (Chalmers University of Technology, Sweden), Jim McConnach (Castle Hill Engineering Services, Ontario, Canada) and Tom Hammons (University of Glasgow, UK).

Ambra Sannino and Tom Hammons moderated the Panel Session

1) . The first presentation was a brief Introduction to the Panel Session was entitled: "Global Power Systems for Sustainable Development". Ambra Sannino, Chalmers University of Technology, Gothenburg, Sweden made it.

The concept of sustainability is not limited to the use of renewable energy sources; rather it extends to all levels in a power system. Critical issues like use and control of energy storage and application of power electronics in the sustainable grid were introduced. In an attempt at treating these issues in a global perspective, the situation of developing countries and solutions for their electrification was also introduced.

Ambra Sannino is with the Department of Electric Power Engineering, Chalmers University of Technology, Sweden. She obtained her MSc degree and her PhD degree from the University of Palermo, Italy, in 1997 and 2001, respectively. Her interests include applications of power electronics in power systems and power quality. From August 1999 to September 2000 she was a guest researcher at the Department of Electric Power Engineering at Chalmers University of Technology.

2). The second presentation was entitled: "Sustainable Electric Power Systems in the 21st Century: Requirements, Challenges, and the Role of New Technologies." It was made by Prabha Kundur, PowerTech Laboratories, Canada.

Prabha Kundur holds a PhD in Electrical Engineering from the University of Toronto and has over 30 years of experience in the electric power industry. He is currently the President and CEO of Powertech Labs Inc., the research and technology subsidiary of BC Hydro. Prior to joining Powertech in 1993, he worked at Ontario Hydro for 25 years and was involved in the planning, design and operation of power systems.

He has served as Adjunct Professor at the University of Toronto since 1979 and at the University of British Columbia since 1994. He is the author of the book Power System Stability and Control. He has delivered technical courses for utilities and universities around the world.

Dr. Kundur is currently Chair of the Power System Dynamic Performance Committee of the Power Engineering Society. He is also very active in CIGRE and is currently the Chair of the Study Committee C-4 on "System Technical Performance". He is the recipient of the 1997 IEEE Nicola Tesla Award and the 1999 CIGRE Technical Committee Award.

3). The third presentation was on Sustainable Energy Systems with HVDC Transmission and was made by Gunnar Asplund, ABB Power Technologies, Ludvika, Sweden. It concerned efficient electric transmission of electricity to make sustainable generation of energy possible. In this respect, High Voltage Direct Current has an important role.

Gunnar Asplund obtained his MS in Electrical Engineering from the University of Lund, Sweden, in 1969. His employment has been with ASEA and later ABB Power Technologies, Ludvika, Sweden. He has worked in the fields of high voltage testing, thyristor valve development, project management, commissioning of the Itaipu HVDC project in Brazil, system studies, engineering, and for the last ten years he has been manager of development of HVDC within ABB. Asplund received the Polhem prize and gold medal from the Swedish academy of engineering science for development of HVDC based on voltage source converters.

4). The fourth presentation was on Power Electronics Solutions for Sustainability and was made by Göran Andersson, ETH Zurich, Switzerland. It assessed the possibilities of power electronic solutions to enhance the sustainability of electric energy systems. The concept of sustainability was discussed and a definition was proposed. This definition emphasizes the flexibility of the system to be able to incorporate future innovations and engineering achievements. For the electric energy system, power electronics offers such flexibility in different ways, for the end users, distribution and transmission systems, as well as the connection of primary energy sources. In the presentation, the technical solutions of the different applications was reviewed.

Göran Andersson is with ETH Zurich, Switzerland.

5). The next presentation was entitled: ”Executive Overview: Energy Storage for a Sustainable Energy Future.” Robert B. Schainker, EPRI, USA prepared it. Ambra Sannino and Tom Hammons presented it.

Sustainability of electric power systems involves massive use of renewable energy sources for the production of power. Some of these sources, for example wind and sun, have a characteristic stochastic behavior, which makes output power production from these sources difficult to predict. Energy storage will be needed at different locations in the power system to level the mismatch between power generation and consumption and/or to store the surplus of power from renewable sources during periods of light load. The presentation gave an overview of different storage technologies and how they can be used in a sustainable power system.

Robert B. Schainker is a Technology Fellow in the Delivery and Markets Division of the Electric Power Research Institute (EPRI) in Palo Alto, California, USA. He joined EPRI as a Project Manager in Advanced Power Systems in 1978, and moved to his present position in 2001. He has authored over 50 publications on Flexible AC Transmission Schemes (FACTS) technologies, energy storage technologies (including compressed air energy storage, super conducting magnetic energy storage, battery storage, and pumped hydro storage), economic benefits analyses for electric utilities, optimal control theory, and commitment to dispatch, dynamic benefit analysis applied to utility operations and planning, adaptive control, estimation and information, statistical sensitivity analysis and two-phase flow. He received a BSc degree in Electrical Engineering in 1966, and a PhD degree in Applied Mathematics in 1969, both from Washington University, St. Louis, Missouri.

6). The penultimate presentation was on efficiency analysis of low and medium-voltage DC distribution systems. Daniel Nilsson and Ambra Sannino, Chalmers University of Technology, Gothenburg, Sweden prepared it. Daniel Nilsson presented it.

Here, sustainability aspects connected to the use of DC for power delivery in low- and medium-voltage distribution systems wasexamined. The efficiency of an AC system, a DC system, and a hybrid AC-DC system were calculated and compared. The presenter showed that with the assumption of a substantial reduction in semi-conductor losses, the total system losses decrease using DC. This was discussed and evaluated.

Daniel Nilsson received the MSc degree from Chalmers University of Technology, Gothenburg, Sweden in 2002. Since December 2002 he has been working towards his PhD degree in the Department of Electric Power Engineering of Chalmers University of Technology, Sweden.

Ambra Sannino received her MSc degree and her PhD degree from the University of Palermo, Italy in 1997 and 2001, respectively. She is with the Department of Electric Power Engineering, Chalmers University of Technology, Sweden.

7). The final presentation was entitled: “Generation Reliability for Small Isolated Power Systems Entirely Based on Renewable Sources.” Math Bollen, STRI AB, Ludvika, Sweden; Stephen R. Connors, Massachusetts Institute of Technology, Cambridge, MA, USA; and Jimmy Ehnberg, Chalmers University of Technology, Gothenburg, Sweden prepared it. Math Bollen presented it.

The presentation examined generation reliability for power systems that are entirely based on renewable energy sources. Stochastic models for solar and wind power is used together with simpler models of small-scale hydropower and storage. The load model is deterministic and based on industrial activities with a maximum load of 28 kW. Discussed were 38 different cases where different supply configurations were simulated using Monte-Carlo simulation. The presenter showed that a system with only wind power has better availability than a system with only solar power. However, solar power is more regular which allows for more efficient use of storage. To obtain high availability, large storage capability is needed or a combination of sources. This was discussed and evaluated.

Math H. J. Bollen is currently manager EMC and power quality at STRI AB, Ludvika, Sweden. Before joining STRI in December 2003, he was Research Associate at Eindhoven University of Technology, The Netherlands; Lecturer at the University of Manchester Institute of Science and Technology, Manchester, UK; and Professor in Electric Power Systems at Chalmers University of Technology, Gothenburg, Sweden. He received the MSc and PhD degrees from Eindhoven University of Technology, The Netherlands in 1985 and 1989, respectively.

Stephen R. Connors is with Massachusetts Institute of Technology, Cambridge, MA, USA.

Jimmy S. G. Ehnberg received his MSc degree from Lund University of Technology in 2000. Since then he has been working for his PhD degree in Electric Power Systems at Chalmers University of Technology. His research interests include power system reliability and renewable energy sources.

The final EXTENDED PANEL SESSION SUMMARIES follow

EXTENDED PANEL SESSION SUMMARIES

1. GLOBAL POWER SYSTEMS FOR SUSTAINABLE DEVELOPMENT—AN INTRODUCTION

Ambra Sannino, *Member, IEEE*

Abstract-- This paper serves as an introduction to the panel session on "Global power system for sustainable development". The concept of sustainability is not limited to the use of renewable energy sources; rather it extends to all levels in a power system. In the panel, sustainable development in the generation, transmission, distribution and consumption of electric energy will be discussed. Crucial issues like use and control of energy storage and application of power electronics in the sustainable grid will be discussed. In an attempt at treating these issues in a global perspective, the situation of developing countries and solutions for their electrification will also be discussed.

Index Terms—environment, sustainable development, power system, renewable energy sources, power electronics.

Introduction

The concept of sustainable development, more and more discussed in the latest years, is often identified with preserving the environment. However, according to the official definition issued by the Brundtland Commission (about 1983), sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [ref]. Later in the same document, it is specified that the concept of sustainable development involve three dimensions: environment, economy, social development (which also includes cultural aspects).

Sustainability is thus clearly a very broad concept covering very different aspects. Energy plays a very important role in all these aspects: CO_2 emissions due to power production from non-renewable sources affect the environmental aspect, while access to energy makes a number of activities possible, thus affecting the economical growth and the social and cultural development, e.g. by improving health and education. Still, sustainability is identified by the broader public with environmental issues linked to global warming and the greenhouse effect. The widespread use of renewable energy sources is generally indicated as the solution to the problem, and sometimes very unrealistic scenarios involving renewable sources are drawn. A number of renewable energy sources are known to date, but this does not always mean that their application is yet technically and/or economically viable. A system that is heavily based on renewable energy sources will need a different way of design and operation because of the peculiar characteristics of these sources as compared to traditional oil and coal or nuclear. Moreover, sustainable production of energy is only part of the solution to the problem: how to bring this energy to the end-user in a sustainable way is also important.

The purpose of the panel session on "Global power system for sustainable development" is to discuss how power systems change in a sustainable scenario. It will be shown that sustainability in power system is not limited to energy production from renewables, rather it is broader concept that must be applied at all levels in a power system. Sustainable development in generation, transmission, distribution and consumption of electric energy will be discussed, in an attempt at treating these issues in a global perspective. Although in some cases reference is made to EU countries, issues related to electrification of developing countries will be specifically discussed.

Greenhouse Effect and Global Warming

Global temperature increase is the most widely understood aspect of climate change. According to IPCC's Third Assessment Report [1] the global recorded temperature has increased by about 0.6°C since the middle of the 19th century, despite considerable year to year variations. Globally the 1990s have been the warmest decade on record and 1998 the warmest year. The global mean temperature since 1900 is shown in Figure 1. IPCC also states that global average temperature is projected to rise under all IPCC emission scenarios from 1990 to 2100 by 1.4 to 5.8°C, as well as that the sea levels will rise by 0.1 to 0.9 meter. Glaciers, icecaps and sea-ice extent are projected to continue to decrease further and climate change will persist for centuries [1]. The EU Council of Ministers proposed already in 1996, based on the results of IPCC's Second Assessment Report, that global temperatures should not exceed 2°C above pre-industrial levels of year 1900 [2]. Taking into account the present increase of approximately 0.5 °C, this means a maximum additional 1.5 °C temperature increase.

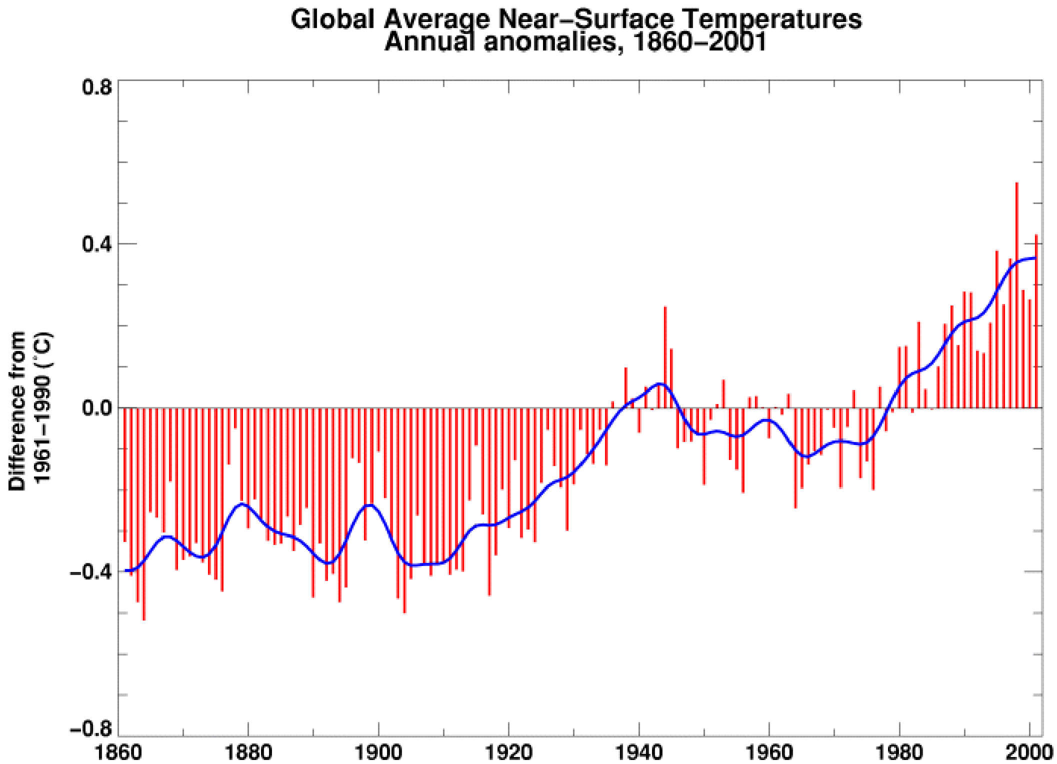

Figure 1. Global mean temperature from 1860 (source: *).**

There is evidence that the cause of the increase in global temperature resulting in climate change is the increase in concentration of greenhouse gases (GHG, mainly CO_2) in the atmosphere, which causes the radiation from the sun reflected on earth not to be sent back out of the atmosphere, resulting in the so-called greenhouse effect. The solar rays remain trapped near the surface of the earth and increase its temperature. This temperature increase is only one of the many aspects of climate change related to GHG emissions. Other important aspects include rising sea levels, change in precipitation patterns, floods, changes in food productivity and increase of infectious diseases. These effects can have impact on e.g. agriculture and water resources.

CO_2 contributes around 65% to total GHG emissions, mainly from fossil fuel combustion due to activities in the industry and transport sectors, heating systems and energy production, see Figure 2. CO_2 emissions are thus strongly linked with the level of industrialization of a country, as shown in Figure 3. United States alone are responsible for a level of CO_2 emissions that is 20 times the level of emissions for Africa or Asia (excluding China). Note that Figure 3 shows annual emissions per capita: if total annual emissions are considered, China is the second main responsible, accounting to a total amount of emissions that is about the same as for the whole EU. The average level for the EU is around 8 tonnes per capita, but even within the EU there are considerable variations, with among others Germany, Belgium and the Netherlands definitely above the average level, while Sweden and France are well below. Geographical distribution of climate change policies is another key issue. The global average annual per capita emissions of CO_2 is due to the combustion of fossil fuels is at present about 4 tonnes, in developed and transitional economy countries about 10 tonnes and in developing countries about 2 tonnes.

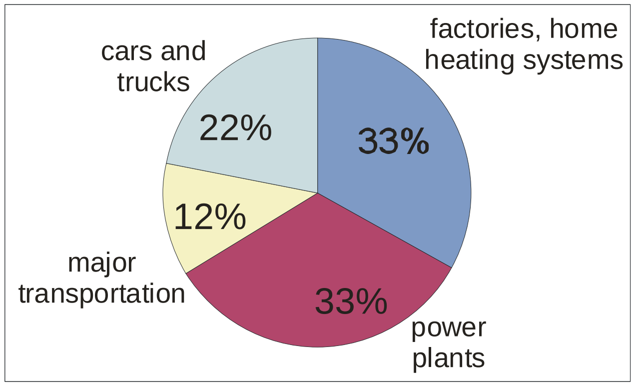

Figure 2. Share of renewable energy in gross electricity consumption for the EU countries (source: European Environment Agency http://www.eea.eu.int/).

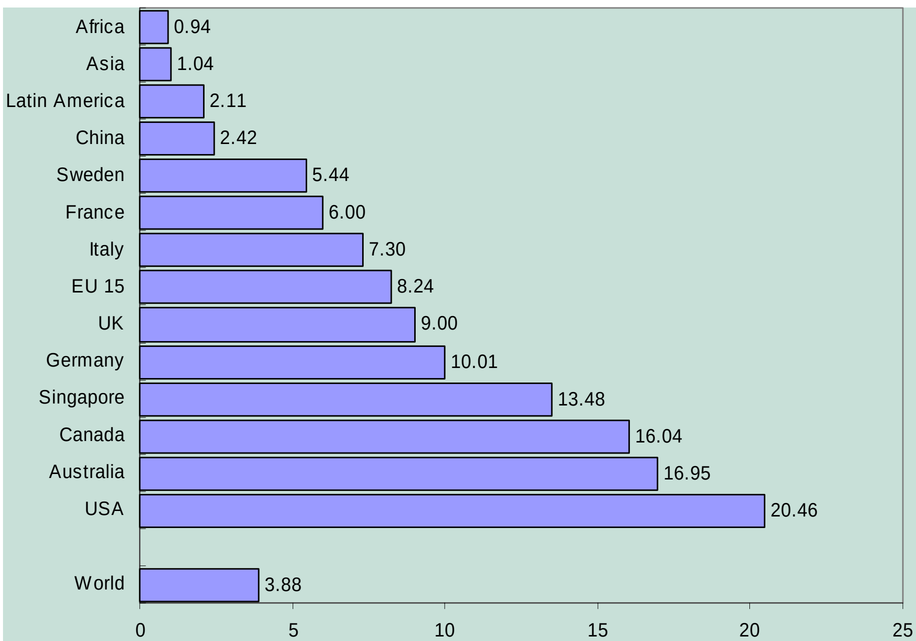

Figure 3. Share of renewable energy in gross electricity consumption for the EU countries (source: European Environment Agency, http://www.eea.eu.int/).

Sustainable Energy Production

A. Some statistics

A big portion of CO_2 emissions is due to energy production from fossil fuels, i.e. oil and coal. One way to reduce the emissions linked with the production of energy is thus to use “clean” ways to produce energy, which do not produce emissions. In the EU, oil accounts for the largest share of the total energy supply (42% in 1994) and it has remained relatively stable since the 1980s. The trend on the share of energy supply by coal (18% in 1994) has been falling over the period 1985-1994 [3], while the share by natural gas (19% in 1994) is slowly increasing. Nuclear power accounts for about 15% of the total energy supply.

The share of renewable energy has remained stable in the period 1985-1994 at about 5%.

Natural gas also produces CO_2 emissions, but is definitely less dangerous than coil or oil. The increase is in the use of natural gas has not been so much due to policy incentives, rather to the fact that where, as in the UK, liberalization of the electricity market occurred at the same time as the gas market was deregulated, many power producers chose natural gas for its flexibility and low cost.

Nuclear power does not produce emissions, however, it is not a sustainable alternative because of the problem with nuclear waste. In many countries in the EU, the decision has been taken not to build new nuclear power plant and even, e.g. in Sweden, to phase out nuclear power in the long run. At present, Finland is the only country in the EU that has recently decided to build a new nuclear power plant.

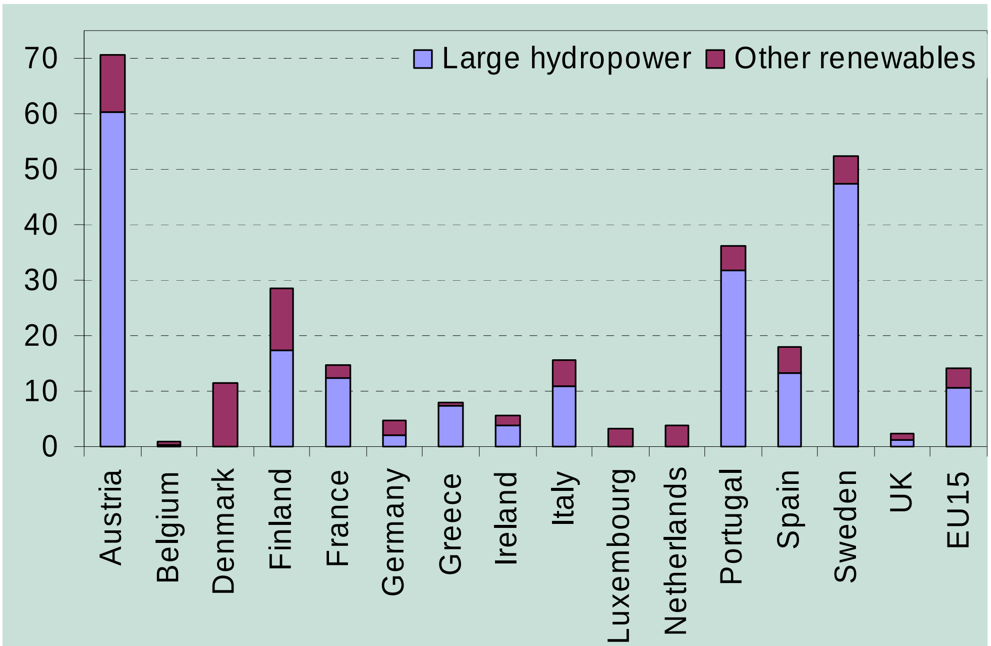

Figure 4. Share of renewable energy in gross electricity consumption for the EU countries (source: European Environment Agency http://www.eea.eu.int/). Note: An initial political agreement on the target levels presented here was reached among the Member States at the December 2000 meeting of EU Energy Ministers (Energy Council). Gross electricity consumption equals domestic generation, plus imports minus exports.

The share of renewable energy sources in gross electricity consumption shown in Figure 4 is still relatively low, compared to the proposed indicative targets decided in 2000. In 1998, renewable sources contributed 14.1% of electricity generation: 10.6% from large hydropower installations (with capacity of more than 10 MW) and 3.5% from all other renewables. The proposed EU indicative target is for 22.1% of gross electricity consumption in 2010 to come from renewable sources.

Due to geographical site limitations and environmental considerations, the share of large hydropower is expected to remain approximately constant until 2010. The contribution from renewables other than large hydro renewables grew rapidly between 1996 and 1998, but significantly faster growth will be needed if the 2010 target is to be reached.

B. Technical challenges with renewables

One of the problems with renewables is that they are often not located where the energy should be used. This is especially true for production of large quantities of energy from renewables. Large wind power parks will more and more be located offshore at a consistent distance from land, in order to take advantage of the high speed of the wind offshore. Another example is the oft-cited possibility of establishing large

PV-arrays, which occupy very large areas, in Saharan regions, which are anyway not used. In Sweden, large hydropower plants are located in the North of Sweden, while energy is mostly consumed in the South, where most of the population lives. This requires large amounts of energy to be transported from the production site to the place where they are actually used.

Another problem with renewables is that they are often producing when the energy is not used. It is not possible to control when the wind will blow or the sun will shine, and even forecasting the output of solar and wind plants with sufficient reliability is not easy. One of the areas in which PV-cells are often used is the supply to isolated houses that are located far away from the grid. In this case, the solar cells produce energy during the day if the sun shines, while the energy is needed more in the evening for lighting. This problem is solved by storing energy in batteries during the day to use it later. But if a consistent amount of the energy that is used everyday in the grid is produced by renewable sources, much higher amounts of energy will have to be temporarily stored. One option in countries that have hydroelectric power plants with basins is to use these basins for pumped energy storage. This means that in a windy night, the turbines will run and produce energy that is used to pump big volumes of water up into the basins. In the morning, these big quantities of water can be released to produce energy.

Sustainable Energy Transmission

Improving sustainability of power transmission mainly translates into decreasing power transmission losses. Due to transmission losses, more than one kWh has to be produced for one kWh consumed. If the energy is produced from non-renewable sources, emissions of CO_2 are associated also to the production of the fraction of power that is then dissipated along the transmission lines. Power losses, which are due to heating of conductors because of the current flowing through them, are unavoidable. However, all measures that can be taken to reduce losses to a minimum will have a beneficial impact on the environment.

One way to improve sustainability of the transmission is to use dc for transmitting power over long distances by using high voltage overhead lines in HVDC transmission. It should be said that HVDC is chosen for long distance transmission not because of loss reduction, but rather due to the possibility to increase the transmission capacity over what is normally possible for a traditional ac line. It is well known that, for an ac transmission line of given length and operated at given voltage, the maximum power that can be transmitted is proportional to the square of the line voltage and to the inverse of the length. However, in practical conditions it is never possible to transmit this maximum power because of stability concerns. Moreover, to charge the distributed reactive elements composing an ac line a certain amount of reactive power is required by the line in all cases but one (when the line is transmitting the natural or characteristic power), and as a consequence the voltage profile along the line is not flat. Problems with dynamic stability and voltage control with ac transmission lines can be solved by using power-electronic devices to improve the controllability of the power flow and voltage profile. However, this increases the costs. No such problems arise when using dc transmission, which makes HVDC normally economical, in spite of the cost of the converter stations at the line terminals, for long transmission distances.

Due to the high capacitance of high-voltage cables, HVDC has been in most cases the only viable option for submarine power transmission. The reactive power required by a high-voltage cable becomes already for moderate lengths (about 50 km) so high that it must have a much bigger cross section and still transmit a very low active power.

Combining HVDC technology with underground cable transmission also allows reducing the visual impact of power transmission on the landscape, which improves sustainability. This will become an important application now that, because of the visual negative impact of overhead transmission lines, together with concern from the public for possible negative effects of electromagnetic fields, it is more and more difficult for utilities to obtain right-of-way to build new transmission lines.

Sustainable Energy Distribution and Consumption

A considerable portion of the total losses in households is due to stand-by losses of consumer electronic equipment, i.e. electricity consumed by the equipment when it is powered but not operating. Energy consumption of consumer electronic equipment has steadily increased over the latest years, due to increased use of devices like TVs and VCRs, introduction of new entertainment equipment (like DVD players), and use of more battery powered equipment (especially mobile telephones). The total EU domestic power consumption of consumer electronic equipment in stand-by mode has been estimated to around 36 TWh and is predicted to increase to 62 TWh by year 2010 [11]. By removing or reducing these losses, a reduction of the negative effects of electric energy consumption on the environment may be achieved.

Stand-by losses are normally due to the fact that most single-phase electronic-based devices use low-voltage dc obtained by means of a transformer followed by a single-phase rectifier. When the equipment is not operating but is still powered, the primary winding of the transformer is absorbing a small open-circuit current that creates the losses.

To force manufacturers to improve their design in order to produce more efficient apparatuses, policy options should be applied such as tax incentives or regulations. In Europe, one option being discussed is the introduction of a labeling initiative for energy-efficient consumer electronic equipment following the example of the US Energy Star program [11].

A solution is the use of dc for powering the equipment. This will not only eliminate the stand-by losses, but also reduce losses during normal operation, because both the transformer at the input of low-voltage equipment and the following single–phase rectifier would be removed. This makes also the equipment lighter and more compact, and improves its reliability due to a reduction in the number of components. Producing dc-supplied equipment will not require major changes in the design if a proper voltage level can be used, i.e. the voltage required by the dc circuit at the output of the rectifier in the original apparatus. Otherwise, a dc-dc converter is needed at the input, to adjust the voltage to a proper value for the low-power electronic circuits in the equipment.

But the advantages of a low-voltage distribution system are not limited to the reduction of losses in the end-user equipment. Due to the absence of a reactive current component, for the same active power drawn by the load, current magnitude is lower, and so are the losses. Another expected advantage is easier integration of distributed generation units: photovoltaic systems [12], as well as fuel cells [13] generate energy at dc and therefore could be directly connected to a low-voltage dc network. Connection to today's ac network requires one dc/ac conversion. A two-stage conversion (ac/dc and back, similarly as in ac drives) is necessary for connecting to the ac grid variable-speed wind turbines and natural-gas micro turbines. The use of dc would save one conversion, with a consequent reduction in losses. A dc distribution system also allows direct connection of battery blocks for back-up energy storage, which are used for avoiding supply interruptions in hospitals or office buildings with high power quality demands and presently require two conversions (from ac to dc and back). A direct connection to a dc network would save two conversions.

A dc distribution system may be even used in factories for powering process-control equipment, which has the same input stage as consumer electronics. If the production is heavily based on ac motor drives, a higher-power dc network may be built in the factory to supply the dc-bus of the drives' inverters, again saving one conversion for each drive system.

A feasibility study of low-voltage dc distribution systems for homes and offices was carried out in [14]. An existing office was considered as case study, because of the high penetration of low-power electronic loads. From the study, it was concluded that the use of dc in offices leads to a simplified system and to consistent savings. The same conclusion can probably be obtained for other type of systems with high reliability requirements like hospitals, data centers and large commercial centers.

Sustainable Power in Developing Countries

Electrical energy is of utmost importance for any modern economy. In developing countries, the availability of a reliable power supply at a reasonable cost is a key factor for economic growth and development [4]. Still, about two billion of the world's population has no access to modern forms of energy, such as electricity or fossil fuels [5]. The majority of these people depend on burning biomass, like wood or waste from agriculture, for cooking, heating and lighting. Availability of domestic appliances and electrical machinery for various activities increases productivity. Electric lighting in homes increases the time that can be spent on recreation, work and study [5,6].

Rural electrification in these countries is often extremely low because many villages are far away from existing grids, which makes the cost of providing connection to the grid too high for the utility. Within the village itself, houses are often scattered, making distribution to individual houses very costly and maintenance and repair costly and time-consuming. Moreover, even if the utility can make the investment for the connection, the cost of electricity can become too high for the household.

because of the high costs of grid connections and large investments needed for building big power plants, traditionally-designed power systems, based on a small number of nodes with large generators and a "tree structure" with a few long transmission lines and a radial distribution system, are not suitable to electrification of rural areas. Alternative solutions can be provided by decentralized power generation. Local generation, using small sources, removes the need for long and costly transmission lines that often also provide very low-quality supply due to instability of voltage and frequency. Moreover, renewable energy sources can be used for these purposes, which make these solutions environment-friendly [8]. Different sources may be used depending on local needs (power demand) as well as on locally available resources. A small number of loads, for example a few houses, may be supplied by a small photovoltaic array or a small wind turbine [5,7]. Due to the inherent variability of wind and sun, some kind of energy storage must also be included to store energy during the day or during windy hours and release it to the loads during the night or when the wind stops. Such a small, isolated system may be called a "micro-grid". Many examples of "naturally" isolated systems can be found in Europe, e.g. Crete and other smaller Greek islands [9.10]. However, these systems have a connection with the power system on the mainland and use a mixture of renewable sources and diesel-based generation. Additional challenges are introduced here by the absence of a connection to a larger grid and the exclusive use of renewable sources.

Micro-grids using different sources may be operated in different ways. The most suitable frequency can be chosen, according to the energy source used and the technology applied. A micro-grid powered by solar cells, which produce direct current, can be operated as an isolated dc system. To provide energy during the night, batteries directly connected to the dc network can be used. On the other hand, operating at power frequency of 50 or 60 Hz may still be the most suitable solution for a micro-grid powered by a small wind turbine. Several solutions for storage are available, depending on the size of the grid: capacitors, flywheel systems, and batteries but in this case connected to the network via a converter. In principle, any frequency could be used, provided that the loads can operate correctly at that frequency. Operating at dc, for example, does not pose any problems for lighting and heating, but this is not valid for all types of loads. The same freedom of choice holds for the voltage levels.

Normally, the micro-grids will be designed and set up to operate as isolated systems. However, this does not exclude the possibility of interconnecting them, to build up a bigger power system. On the contrary, micro-grids can be seen as "modules" with similar structure that can be interconnected to form bigger structures. To tie together micro-grids operated with different voltage and frequency, dc tie lines are obviously most suitable. An example with three micro-grids (representing villages or groups of sparse houses equipped with local generation and energy storage) connected by two dc tie lines is shown in Figure 5.

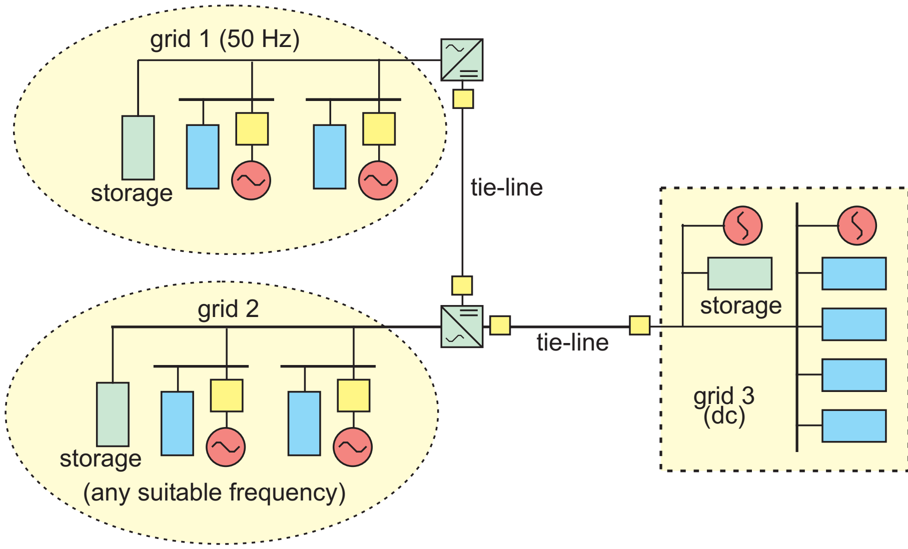

Figure 5. Micro-grids operated at different frequencies interconnected by dc tie lines.

Conclusions

Sustainability must be the goal when building power systems of the future. Often this concept is identified with the use of renewable energy sources, but there are other aspects that have to be taken into account to build a fully sustainable power system.

Sustainability can be significantly improved by reducing losses in power transmission and distribution that can be done by applying direct current based systems. Use and proper control of energy storage becomes of crucial importance when renewable sources with stochastic behavior account for a large amount of the total generation. However, introduction of renewable-based generation, energy storage, and dc transmission and distribution are made possible by increased use of power electronics, which in turn also causes losses.

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Biography

Ambra Sannino (S'99, M'01) received the M. Sc. degree and the Ph.D. degree from the University of Palermo, Italy in 1997 and 2001, respectively. From August 1999 to September 2000 she has been a guest researcher at the Department of Electric Power Engineering of Chalmers University of Technology, Gothenburg, Sweden, where she is currently working as Assistant Professor. Her interests include applications of power electronics in power systems and power quality.

2. SUSTAINABLE ELECTRIC POWER SYSTEMS IN THE 21ST CENTURY: REQUIREMENTS, CHALLENGES AND THE ROLE OF NEW TECHNOLOGIES

Prabha Kundur, *Fellow IEEE*

Abstract-- Electricity has indeed become a basic necessity in modern society. While the industry has done a good job of meeting the energy needs of the 20th Century, generally it has had an adverse impact on the natural environment. The industry is now undergoing a period of major restructuring: a shift from a monopolistic to a competitive structure. It is facing new economic and social pressures to refocus its business so as to meet the energy needs of the society in a way that is "sustainable" in the long run. Sustainability requires balancing economic growth and prosperity with the preservation of the natural environment.

Index Terms— sustainability, environment, hydrogen economy, distributed generation**.**

The electric power supply industry, with its humble beginning in the 1880s, has evolved into one of the largest industries. Electricity has indeed become a basic necessity in modern society. While the industry has done a good job of meeting the energy needs of the 20th Century, generally it has had an adverse impact on the natural environment. The industry is now undergoing a period of major restructuring: a shift from a monopolistic to a competitive structure. It is facing new economic and social pressures to refocus its business so as to meet the energy needs of the society in a way that is "sustainable" in the long run.

Sustainability requires balancing economic growth and prosperity with the preservation of the natural environment. Business practices have to be built on "three pillars" of sustainability:

- *environmental sustainability,*
- *economic sustainability, and*
- *social sustainability.*

This will have a profound impact on how power systems will be planned, built and operated in the future. The challenges for the industry are to:

- produce, transmit and use energy in an environmentally responsible manner,
- reduce costs by improving operating efficiency and business practices, and
- enhance the reliability and quality of power supply.

A wide range of new technologies is likely to play a major role in meeting the challenges and shaping the future directions of power systems.

Environmental sustainability requires integrating "green thinking" into our business practices. This involves minimizing the environmental impact of power plants as well as all other equipment. With regard to power generation, the concern is for greenhouse gas emissions, global warming issues, and local emissions. Renewable sources of generation are unable to cover a substantial part of the base load. The use of natural gas is a step in the right direction; however, the key question is what is the best form of its use. The use of clean coal technologies and nuclear generation are important options in some regions. The general trend will be towards a *carbon-free electricity/hydrogen energy economy*. Hydrogen could be used to complement electricity as an energy carrier. Hydrogen and electricity form an ideal "energy currency pair", and are likely to dominate the energy delivery and transportation systems in the 21st century [1,2].

The overall generating capacity will include a significant proportion of distributed generation [3]. This includes renewable sources, such as wind and ocean energy, as well as non-renewable sources, such as micro turbines and fuel cells. The former form an important primary source of clean energy, but present significant technical challenges which need to be effectively addressed in their integration with existing power systems; these however, are not insurmountable problems [4,5]. The latter, in addition to reducing adverse impact on the natural environment, contribute to reduction in transmission costs and offer significant security benefits, as they are less vulnerable to failure in power grids due to natural calamities or system blackouts.

Fuel cells, in particular, have a wide range of potential applications as a source of stationary electric power in different sizes and as a source of electric energy for automobile applications. A fuel cell combines hydrogen with oxygen from air to generate electricity with water and heat as by-products. Hydrogen may be supplied from an external source or generated inside the fuel cell by reforming a hydrocarbon fuel. The capacity of fuel cells range from 3 kW to 3 MW with efficiencies ranging from 35% to 60%. With co-generation, a carbonate or solid oxide fuel cell can achieve an efficiency of 80%, and can generate electricity directly from a hydrocarbon fuel. Fuel cells thus form an environmentally friendly alternative power generation source that can potentially yield lower cost electricity, using a non-combustion and non-mechanical process. They are quieter and have lower fuel and maintenance costs than conventional power plants.

Efficiency and economy are of greater importance in the new electricity supply industry environment. These are achieved by more effective use of equipment and the integrated power system. In addition, it is necessary to have an infrastructure that will support the reliability and service quality demands of a digital economy.

More effective use of individual equipment is achieved through use of new technologies such as: automated pro-active monitoring systems for maintenance and prevention of failures; intelligent systems technology for equipment diagnostics; assessment of remaining life, life extension and upgrading; and dynamic equipment rating.

Electric power quality will be of increasing importance. End-use equipment are more sensitive to disturbances that arise both on the utility supply system and within the customer facilities Power quality problems are many: impulsive transients, voltage sags, flicker, harmonics, imbalance, and frequency control problems. These problems are somewhat compounded by the new forms of distributed generation. Power quality disturbances can have significant economic consequences for many facilities. A wide variety of technologies exist for mitigating the causes and consequences of such disturbances. Investigation of power quality problems and analysis of measured data for diagnostics requires expertise in several areas. The required new tools for diagnosis are ideally based on artificial intelligence techniques: expert systems, artificial neural networks, and adaptive neuro-fuzzy systems.

Modern electric power systems are large complex systems, with many processes whose operations need to be optimized and with millions of devices requiring harmonious interplay. Efficient and secure operation of such systems presents many challenges in a competitive, disaggregated business environment. Power system security problems, in particular, will pose new and increased challenges. This is increasingly evident from the many major disturbances experienced by power systems in different parts of the world in recent years. More effective use of integrated power system is achieved through use of new technologies such as: intelligent systems; on-line security assessment; coordinated emergency controls and real-time system monitoring and control leading to "self-healing" systems [6,7,8].

Finally, widespread "smart" energy efficient use of electricity will have a significant impact on sustainability. It contributes to resource conversation leading to environmental as well as economic benefits.

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Prabha Kundur holds a Ph.D., in Electrical Engineering from the university of Toronto and has over 30 years of experience in the electric power industry. He is currently the President and CEO of Powertech Labs Inc., the research and technology subsidiary of BC Hydro. Prior to joining Powertech in 1993, he worked at Ontario Hydro for 25 years and was involved in the planning, design and operation of power systems.

He has served as Adjunct Professor at the University of Toronto since 1979 and at the University of British Columbia since 1994. He is the author of the book Power System Stability and Control (McGraw-Hill, 1994(, which is the standard modern reference for the subject. He has performed extensive international consulting and has delivered technical courses for utilities and universities around the world.

Dr. Kundur was elected a Fellow of the IEEE in 1987. He is currently Chair of the Power System Dynamic Performance Committee of the Power Engineering Society. He is also very active in CIGRE and is currently the Chair of its Study Committee C-4 on "System Technical Performance". He is the recipient of the 1997 IEEE Nicola Tesla Award and the 1999 CIGRE Technical Committee Award.

The University Politechnica of Bucharest, Romania honored Dr. Kundur with the title “Doctor Honoris Cause” in 2003.

3. SUSTAINABLE ENERGY SYSTEMS WITH HVDC TRANSMISSION

Gunnar Asplund, ABB Power Technologies, Ludvika, Sweden

Abstract—Article on the necessity of efficient electric transmission on electricity to make sustainable generation of energy possible. In this respect High Voltage Direct Current has an important role.

Index Terms—Sustainable energy, electric generation, electric transmission, HVDC, VSC, hydropower, wind power, solar power, cables, converters

Introduction

Sustainable energy generation like hydro, wind, sun and waves are normally not located close to the consumption. This fact makes transmission of the power as almost as essential as the generation.

Non-sustainable ways of generating electricity does not normally have this problem. Boat or train can transport coal. Oil is transported around the world by tankers and shorter distances by pipeline. Gas is normally transported by pipeline but can also be transported by boat in liquid form. Of the sustainable resources truck or train can transport only biomass. Hydro, wind, sun and wave energy have to be transmitted as electricity.

Electricity has been used for more than 100 years mainly by alternating current. However, transmission of large amounts of power over long distances the use of high voltage direct current, HVDC has in many cases been found very economical.

What is HVDC

HVDC was first used commercially 50 years ago. Since then a growing number of transmission schemes have been constructed around the world.

HVDC differs from high voltage alternating current, HVAC, that the voltage is not alternating 50 or 60 cycles per second but is constant. The advantage of HVDC is that long distance transmission is more efficient as there is no need to charge the capacitance of a transmission line with the alternating voltage. The drawback of HVDC is that one needs more expensive terminals at the line ends.

The HVDC converter station is made up of a number of equipment known from ac transmission schemes. It also contains some special features of which the most important one is the converter valves. In the beginning the converters were equipped with mercury arc valves. Later thyristor valves have been developed and have made the design of HVDC more flexible and also increased the power that is possible to transfer.

Gunnar Asplund is with ABB Power Technologies,
Power Systems, HVDC (email: gunnar.asplund@se.abb.com)

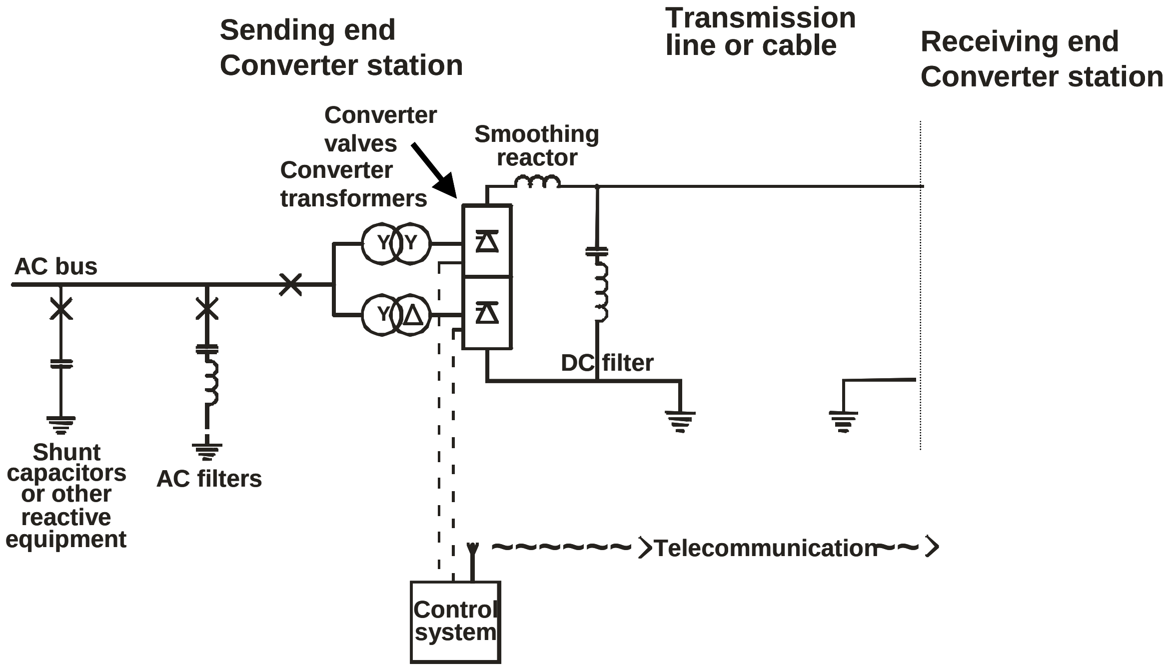

Figure 1. Typical HVDC converter station using thyristor valves

HVDC has a number of properties that makes it different from ac- transmission. The most important are:

- The two stations can be connected to networks that are not synchronized or does not even have the same frequency
- Power can be transmitted over very long distances without compensation for the reactive power. Reactive power is power that does not add to the transmitted power, but is a byproduct at ac-transmission as the line or cable capacitances has to be charged 50 or 60 times per second. As HVDC has constant voltage it does not generate reactive power. See also figure 2.
- Only two conductors are needed (or even one conductor if the ground or the sea is used as return) for HVDC compared to three conductors for alternating current.

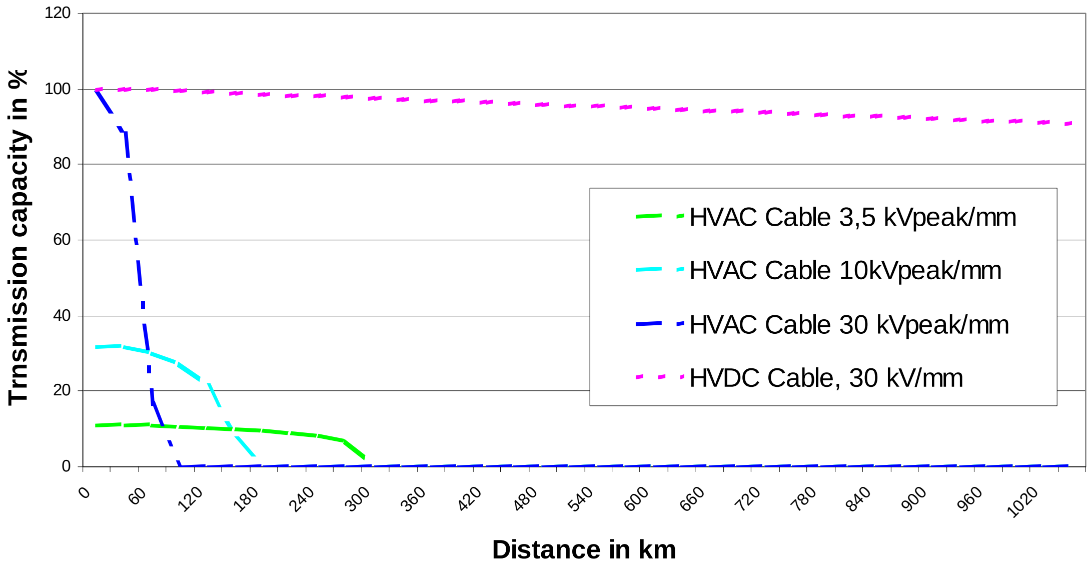

Figure 2. Shows the power that is possible to transmit as a function of the distance for ac- cables of various voltage stress compared to HVDC. With ac high power can be transmitted short distances or low power long distances. HVDC cables can transmit high power over long distances.

The same situation is valid for lines, but here the effect is seen at longer distances than with cables.

C. Voltage source converters

A new type of HVDC using transistors for the AC/DC conversion has been developed. By using components that can not only switch on the current but also switch it off, making it possible to build voltage source converters (VSC)

This type of converters offers many advantages when it comes to transmission of power especially from sustainable energy systems.

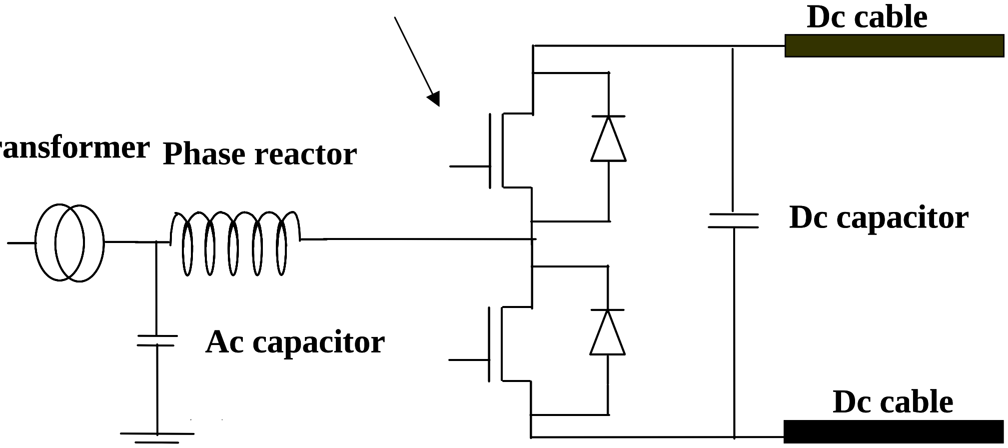

Figure 3. VSC converter valve

VSC HVDC has the following additional advantages:

- Simultaneous control of both active and reactive power. The ac- voltage can be controlled at both stations. See also Figure 4.

- No need for short circuit power for commutation. Can operate against even black networks.

- Can operate without communication between the stations

- Can operate from control the power continuously from one direction

- No change of voltage polarity when the power direction is changed. This makes easier to build multi terminal schemes

- Possibility to use robust and economical extruded cables both for land and sea.

- Small converters that reduce the requirement for space

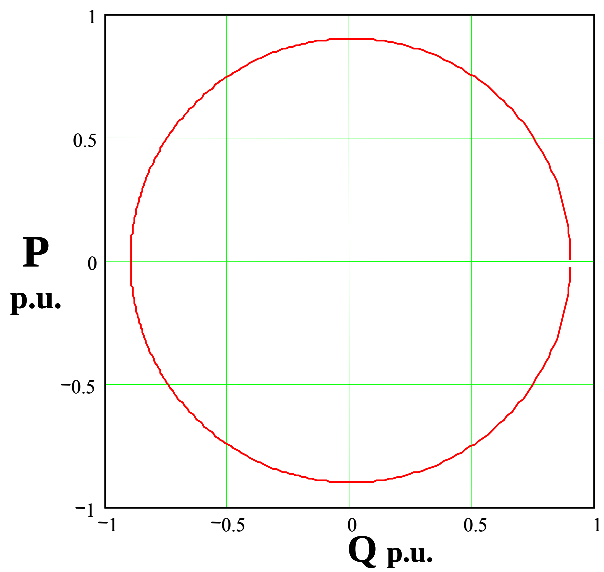

Figure 4. In a voltage source converter the active and reactive power can be controlled at the same time like in a synchronous converter, but the control is much faster, in the millisecond range.

Hydropower

The by far most important generation of sustainable energy comes from hydropower. This has been the situation from the very beginning of electric generation. The result of this is that most hydropower close to consumption areas is already utilized.

D. Present situation

During the last 50 years many HVDC projects utilizing converters with thyristor valves have been constructed in order to transmit power from hydro plants. Some of the most important of these transmissions are listed below.

Project	Power MW	Distance km	Voltage +/- kV
Cabora Bassa, South Africa, Mozambique	1930	1420	550
Inga- Shaba, Republic of Congo	560	1700	500
Nelson River Canada	4000	940	500
Itaipu Brazil	6300	790	600
Quebec- New England	2000	1480	450
Pacific Intertie USA	3000	1360	500
Geszuba- Shanghai	1200	1000	500
New Zealand	560	600	350
Skagerrak Denmark	440	240	250/350
TSQ China	2000	800	500
Three Gorges- Changzhou	3000	890	500
Three Gorges- Guandong	3000	940	500

E. Future situation

There is a tendency that new project are situated further away but also have more available power. We here talk about more than thousand kilometers of lines transporting several thousand megawatts of power

This is the situation in China where hydro resources are located in the middle of the country and the consumption is in the east and in the south.

Another country where long distance transmission has been discussed is Brazil where the affluences of the Amazon River have grand potentials of hydropower. Also here the main consumption areas are located several thousand kilometers away.

Another country is India where large hydro resources in Assam are only possible to explore if much of the power could be transmitted to other states several thousand kilometers away.

Still another area of interest is Africa and the Congo River, which has the largest potential worldwide for hydropower. Also here the population situation is such that very long transmission is needed if exploration should be possible.

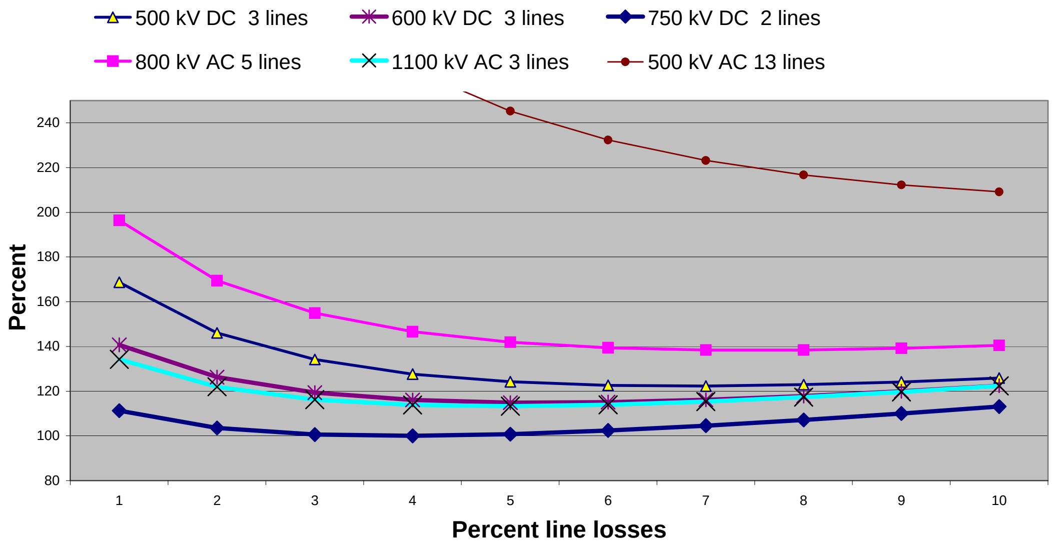

Figure 4. The cost of transmitting 10000 MW of power over 2000 km. AC and DC at various voltages is compared. All costs including cost of losses are included. As can be seen 750 kV dc is the most cost efficient alternative. However, this voltage level is still not in use.

Wind Power

The second most important sustainable type of energy where electricity is needed for the transportation is wind power. Until today most wind power has been small scale generation connected to the most nearby ac grid. This constitutes no problem as long as the wind power in feed is small compared to the total power installed in the network. However, if wind shall constitute a more substantial part of the power in the network, big wind parks will have to be constructed. To construct such big parks on land will both meet big opposition as well as problems to find sites with good wind conditions. Most probably new big sites will have to be constructed at shallow sites at the sea.

As long as the distances are a few tenths of kilometers and the powers are up to some hundred megawatts, ac cable connections will be sufficient. But with increasing power and distance, dc-connections will be more competitive. In this case HVDC with voltage source converters seems to be best suited for the transmission.

F. Present Situation

Already a couple of projects have been constructed where the suitability of VSC HVDC in conjunction with wind power has been demonstrated.

Project	Power MW	Distance Km	Voltage +/- KV
Gotland Sweden	60	70	80
Tjaereborg Denmark	7	4	10

G. Gotland VSC HVDC Project

The Swedish island of Gotland is situated in the middle of the Baltic Sea and the island earlier got all its power though two HVDC- cables from the Swedish mainland. Actually, Gotland had in 1954 the first commercial HVDC project in the world.

As the wind conditions on the island are excellent a large number of wind power stations were built on the southern part of the island. This made it possible to reduce the need for import of power. However, the ac- network on the island was not designed for feeding power from the south to the center of the island. Normally, constructing a new ac- line could have solved this, but due to the crossing through a bird protection area it was judged to be less suitable with overhead lines. Instead a VSC HVDC system using underground-extruded cables was built. This solved the problem to transmit the power and made very important contributions to stabilize the voltage in the ac network on the whole island.

Figure 5. The Gotland VSC HVDC project in the foreground. Wind power in the background

With this reinforcement of the ac grid on Gotland the wind power can continue to be expanded on the island. In fact, already today it happens that the windmills on the island produce more power than what is consumed (there are around 50 000 inhabitants) and the surplus is exported to the mainland. So Gotland already today could be taken as an example of what might happen in the future more generally.

H. The Tjaereborg Project

In Denmark wind power has grown more and more important over the last decades. Today, Denmark is one of the countries in the world with the largest proportion of wind power. This has also led to problems to find new sites for new wind farms and locating them at the sea has attracted a lot of interest. Also VSC HVDC has attracted interest of several reasons. Both for transmitting the power from sea to shore, but also to supply the wind generators with reactive power. As most wind generators are asynchronous machines, they consume a lot of reactive power and this can cause voltage stability problems in the generator end.

In the other end where the transmission line is connected to the ac grid, there might also be problems in the short circuit power of that point is not very strong.

It is also favorable if one can adopt the frequency of the wind generator to the speed of the wind. By this it is possible to get more power out of the wind.

All this together led to the construction of a demonstration plant in conjunction to a small park of four wind generators. This plant has demonstrated operation with variable frequency and serves as a demonstrator for a bigger wind park far out at sea.

Figure 6. The Tjaereborg VSC HVDC transmission Solar Energy

Today solar generation is not explored in a large scale, but the installed power is growing at a high rate each year. When the development of solar panels gets to a certain efficiency and cost, solar energy might become a very important contribution to the electricity generation. As with other sustainable energy, suitable sites for solar plants are most certainly located in deserts where the efficiency will be the best and the land is not used for agriculture, forestry or urban settlement. In this case it becomes even more important to be able to transmit very large power of energy from sites with very good sunlight to consumption areas. The desert often has a very difficult environment for overhead lines this risk of salt contamination of the insulators. In this case underground cables would be very advantageous. As was mentioned above, VSC HVDC is very suited for cable transmission on land and with a further development of extruded cables there are possibilities to transmit very large amounts of power over long distances even to supply whole continents with power.

Future Scenario

If one looks into the future fossil fuels will be scarcer and more power will have to come from sustainable energy systems. This will pose new requirements on not only generation of this power but also on transmission and storage of the energy as both wind and solar energy is not available when the wind blows or when the sun shines and not when there is a need for electricity. In order to illustrate a possible future situation when there only sustainable generation a scenario has been made showing how Europe could be supplied by electricity.

In this scenario all Europe is connected with a very efficient transmission network with capability to transmit power all over Europe. The backbone of this network could be HVDC. Power is supplied by hydropower (already existing), wind power along the coasts and finally big bulk generation of solar energy from the Sahara desert.

In the best areas of Sahara the energy that reach the surface is around 300 Watts per square meter. With an efficiency of 30 percent and a covering of 30 percent of the area with solar panels the total installed power of Europe (700 GW) need a space of 26000 square kilometers. As Sahara has a surface of 10 million square kilometers the power plants would only occupy 03 percent of the area.

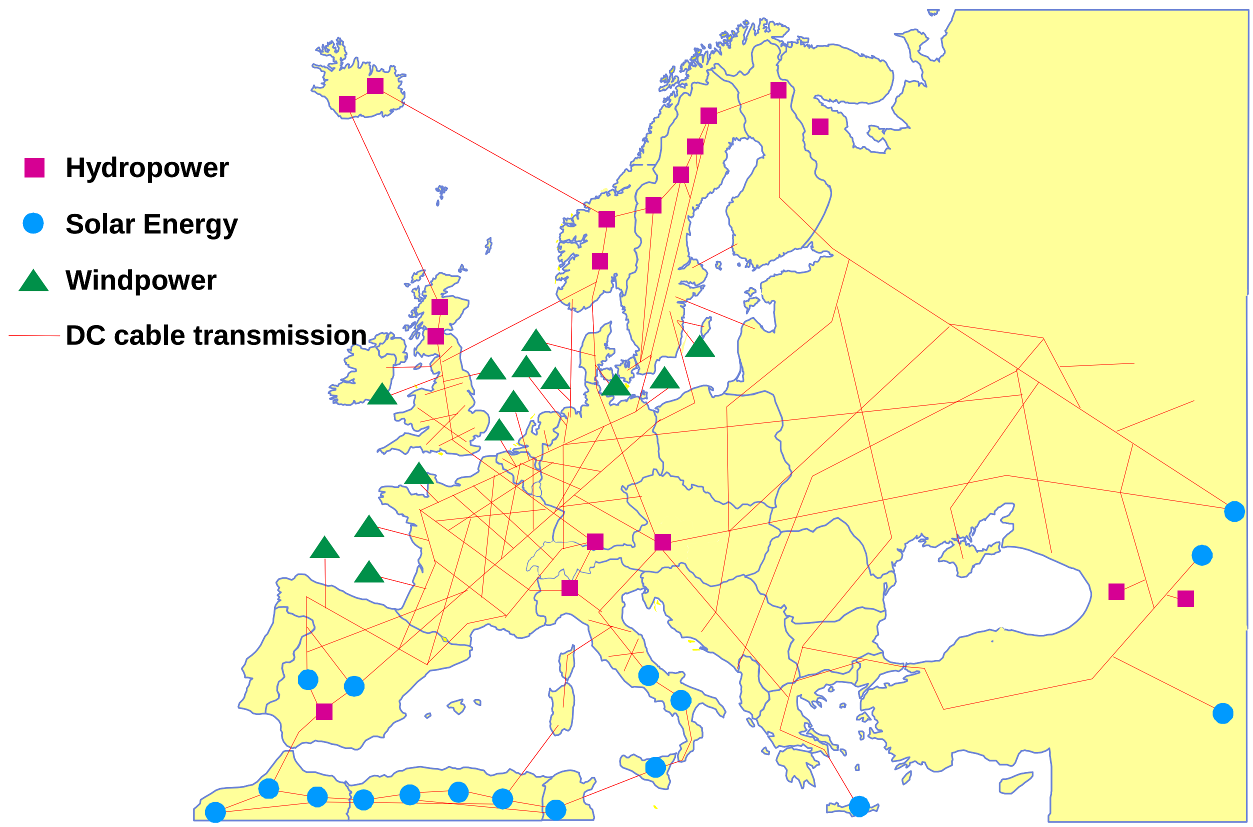

Figure 7. A scenario showing the possible transmission of solar power from the Sahara, wind power from the sea and hydropower with storage capability in Scandinavia and the Alps to consumption areas in Europe.

Conclusions

Even if we still produce most of our electric power by fossil fuels, there will come a day when this is no longer possible. Then sustainable energy generation will be needed. Characteristic of such generation is that it is often located in very sparsely inhabited areas and normally very far from the place where the energy will be consumed. Here it will be very important to find efficient ways to transport large amounts of electricity long distances. Today, HVDC seems to be the best solution to this problem.

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Biography

Gunnar Asplund was born in Stockholm, Sweden on September 23, 1945. He got his MS in Electrical Engineering at the University of Lund in 1969.

His employment experience is with ASEA and later ABB. He has worked in the fields of high voltage testing, thruster valve development, project management, commissioning of the Itaipu HVDC project in Brazil, system studies, engineering and since ten years he is manager of the development of HVDC within ABB.

Asplund has received the Polhem price and the gold medal from the Swedish academy of engineering science for the development of HVDC based on voltage source

4, POWER ELECTRONICS SOLUTIONS FOR SUSTAINABILITY

Göran Andersson, ETH Zurich, Switzerland.

***Abstract*—**This paper presents an attempt to assess the possibilities of power electronic solutions to enhance the sustainability of the electric energy system. Firstly, the concept of sustainability is discussed and a definition is proposed. This definition emphasizes the flexibility of the system to be able to incorporate future innovations and engineering achievements. It is shown that for the electric energy system, power electronics offers such flexibility in different ways. This applies to the end users, distribution and transmission systems, as well as the connection of primary energy sources. In addition to flexibility, also controllability is offered, which is important for the energy management, incorporating load management and energy savings. The technical solutions of the different applications mentioned are reviewed. It is argued that power electronics solutions could give an important contribution to the sustainability of electric energy systems.

Keywords: Power electronics, sustainability, HVDC, FACTS, mixtribution, de-centralized generation

I. Introduction

The title of this paper contains two terms that not too often are discussed in the same context, i.e. *power electronics* and *sustainability*. This is understandable since power electronics is a highly technical concept and most often discussed in strictly technical conditions among engineers, while the concept of sustainability is more frequently used when discussing energy policies or long term development of the energy system or other long term critical infrastructure systems. In this paper the two are brought together and it is argued that power electronics offers in many situations solutions that will contribute to the highly desirable sustainability of the energy supply in general and the electric energy supply in particular.

A. Sustainability

Sustainability in the energy sector is quite often used to classify primary energy sources. An almost synonymous word frequently used is *renewable*, which strictly speaking is rather meaningless since one of the fundamental laws of physics says that the energy in a closed system is constant. A more precise definition is thus needed, and one was suggested already in 1978 in the Public Utility Regulatory Policies Act (PURPA), by DOE in USA:

A renewable resource is an energy source that is regenerative or virtually inexhaustible.

Instead of renewable the, from physics point of view, more appealing word *regenerative* is used, indicating that the energy is not renewed but rather regenerated from the primary source. Energy sources we denote as regenerative are hydro, wind, and solar power, and in all these cases the energy that is extracted in these sources is regenerated by the solar radiation. In the time scales we are talking about it is reasonable to assume that solar radiation will persist, but it is not obvious that with possible future meteorological changes on earth, that these primary energy sources could be utilized to the same extent, in the same way, or at the same locations as today. What is interesting in the above definition by PURPA is the last part on “virtually inexhaustible” energy sources. This opens up a whole new range of energy sources such as geothermal, fusion based nuclear, and some researchers also claims that new generations of fission based nuclear power could fall in this category of renewable energy sources according to the PURPA definition.

Of course when discussing the energy supply one cannot ignore the transmission and distribution of energy or the use of energy in various forms by mankind. The energy sector must be analyzed as a system taking all the above activities into account and not only the supply side. This is a well-established fact, but quite often ignored in the public discussion.

A term that offers a broader connotation than what was discussed above is sustainability. With a sustainable energy system one does not necessary mean that all the primary energy sources are renewable according to the PURPA definition, but rather that it can be sustained or kept in operation at the desired quality level and if needed with the help of new innovations, technical and others. It is prudent to believe that coming generations will have their own wishes and desires about the society, including the energy system, and also that they will be as innovative as the preceding generations. A sustainable development presumes an active role of future generations, not only a passive administration of earlier achievements. However, it is important that we of the current active generation do not deprive the coming generations from the opportunity to enjoy a quality of life comparable to our own. With quality of life one should not only understand material factors, which are essential for a high quality social and cultural life, but also the possibility to form their own ways of life, of course without depriving their successors from this right. The concept of sustainability does then not only focus exclusively on foreseeable risks but also takes into account resources, creativity, and benefits.

The views expressed above are not new when discussing the future of man made systems of long duration. A human activity where the above aspects have been extensively researched and penetrated is the nuclear waste management. Individuals with quite different backgrounds, such as philosophers, theologians, psychologists, engineers, and scientists, have here worked out a number of principles that should guide the society and its decisions regarding these topics. The principles promoted in the previous paragraph are usually referred to as the *equal opportunity principle*, chapter 1 of ref. [1]. This principle emphasizes not only the risks with a certain development, but stresses also the possibilities to enhance the benefits.

The discussion above could be used to formulate a definition of a sustainable energy system, and the following is thus proposed:

An energy system *is said to be sustainable if its current operation and use do not deprive future generations of the opportunity to enjoy the benefits from it that we are doing. The future generations' options and freedom of action should be considered, and their possibilities to implement innovative improvements.*

With this definition sustainability is not a static condition, given by the needs, possibilities, and knowledge of our generation, but a dynamic process where our legacy to the next generation is not only risks, but also possibilities for further developments and improvements. A key ingredient in sustainability is that adopted solutions are flexible enough to allow new scientific findings and engineering solutions and innovations to be incorporated in existing systems.

It should be noted that this sustainability according to this definition includes environmental issues as one of its components. But an environmentally friendly solution is not automatically sustainable. The possibility for changes as wished by future generations must also be considered.

The above definition of sustainability is of course not unique and allows different interpretations. This is not a disadvantage *per se*. It has been argued that too precise definitions sometimes can actually be an impediment when it comes to create new solutions and find new development paths, [2].

The above mentioned and stressed flexibility is offered by power electronics as will be elaborated in the next subsection.

B. Power Electronics

The introduction of power electronics has been called the "silent electrical revolution" [4]. For many end users this introduction of power electronics can be recognized in higher efficiency, improved flexibility, and added features in many electrical appliances. Almost all pieces of electrical equipment used in modern homes contain some power electronics. For energy savings, or management, controllability is an important prerequisite, and this is to a very large extent offered by power electronics circuits.

In many power systems today one can see a clear trend from electric power systems where all the electric power is generated in relatively few large power plants connected to the transmission or sub-transmission system to systems where a substantial fraction of the power is generated by a large number of small power plants. The most evident examples are Denmark and northern Germany. In the western part of Denmark the generation from non-dispatch able power sources does during some loading conditions exceed the load in the system, [3]. This massive expansion of distributed generation is to a large extent a consequence of political decisions and initiatives, and due to agreements in the European Union. Similar developments can be expected, to a larger or lesser extent, in other member states. Also in other countries, similar political initiatives have been introduced in order to stimulate the introduction of small-scale regenerative electric power production.

In these new systems the traditional power flow direction, from the large centralized power plants through the transmission system to the sub-transmission and distribution systems to the end-users, will not persist anymore. Instead more mixed load flow patterns will be at hand, and sometimes one is talking about a "mixtribution" system. A schematic picture of a how such a system can be designed is shown in Figure 1. This picture shows some of the features of the "mixtribution" system, and particularly the power electronic interfaces are indicated. In this figure only the power electronic based devices in the generation, transmission, and distribution levels are shown. In the loads the power electronics devices in different forms play a very important role, as will be shown below, but these devices are not explicitly drawn in Figure 1. Even if the traditional roles of transmission and distribution systems will be different as compared with today, we will retain the old terminology. In practice the terms will denote systems at different voltage levels.

A completely new function of power electronics is provided by the interfaces between various new energy sources and the grid, in Figure 1 illustrated by interfaces to wind and solar power but not restricted to these. These power sources are providing dc voltage and current, e.g. solar and fuel cells, or ac power at varying frequencies, e.g. wind and hydro power, and an inverter or frequency converter is required to provide power at fundamental frequency.[1]

In the following of the paper these different applications of power electronics in possible future electric energy system will be discussed shortly. The aim is to give an overview of these applications and their properties and the requirements on these. This can be regarded as an introduction to the other presentations in this panel session.

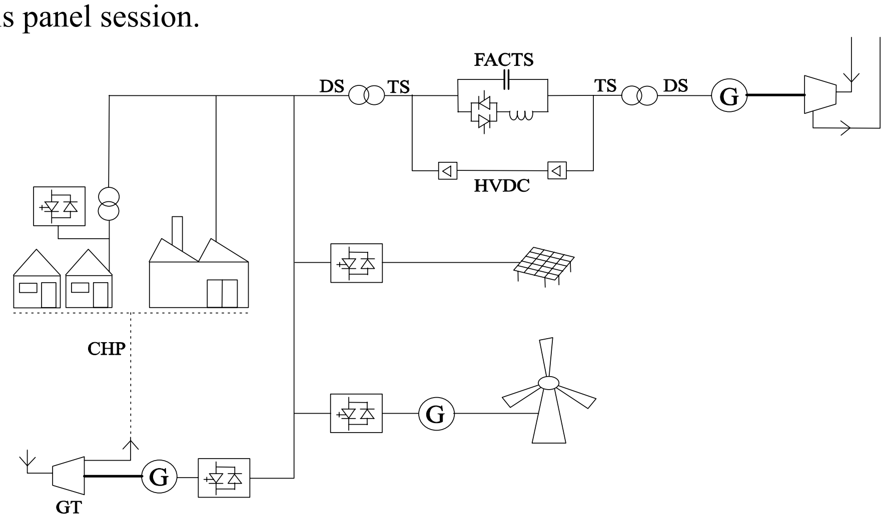

Figure 1. A power system with centralized and de-centralized power generation and integrated power electronics solutions.

[1] In general it is of course not obvious that a fundamental frequency of 50 or 60 Hz is optimal. One could think of different frequencies depending on system loading or different frequencies in different parts of the system. But the need for power electronic interfaces remains.

II. TECHNICAL SOLUTIONS

The development concerning power electronics has been very rapid and has had a significant influence on power system development during the last years. Many achievements can be seen as spin offs from the communication and IT applications, but some are driven by requirements within the energy sector. Particularly the control of power electronics have benefited a lot from the revolutionary development in microprocessors and integrated circuits, which has decreased the costs for these functions drastically. The development concerning the power handling components, i.e. traditional thyristors, GTOs, IGBTs, IGCTs, etc, has also been significant, but still the market for these devices is smaller, so the same developments have not been seen. During recent years the automobile industry has shown an increased interest in power electronics, and this huge market might increase the attraction to semiconductor manufacturers concerning higher power rating devices.

Below some applications are discussed in somewhat more detail.

A. End Users

When it comes to end users, consumers of different kinds, power electronics offer a number of attractive features. Important are of course the direct energy saving potential that can be achieved by more intelligent control, but also the enhanced quality that can be obtained in various ways. The possibilities to exercise load management in a step-less and flexible way will be greater with power electronics.

1) Residential Loads: Many home appliances use today power electronics as an integrated part. It is outside the scope of this paper to review these solutions but a few key features should be mentioned. Besides offering direct energy savings and increased quality, the possibilities for load management are obvious. Together with communication the power of heaters, air conditioners, and other type of loads could adjust to levels that are optimal from a system's point of view without lowering the quality of supply from these devices. This could reduce the peak loads considerably.

2) Non-residential Loads: There are a large variety of different non-residential loads. These include industries with high electricity consumption, e.g. steel and paper mills, manufacturing industries, offices, shopping centers, hospitals, etc. All of these have their special needs and possibilities. Many of these potential possibilities coincide with those of residential loads, but since the individual loads are of greater size for these consumers, the investments are often more attractive and have shorter payback times.

One important kind of load where power electronics has played an important role is electrical motors. In the industrialized countries it is estimated that about 50% of all electricity is used in the industry, and of this electrical motors consume some 65%. It is consequently important that this electricity is used in an efficient way. We all know that a lot of research and development efforts have been put into this topic, but there is still a huge potential for further developments. Not only energy savings can be achieved, but also quality improvements in various ways. This can be noise reduction, more efficient use of raw materials, etc.

3) Transportation Sector: In many countries the main emission of CO2 comes from the transportation sector, i.e. cars, buses, and trucks. A number of new concepts have been suggested aiming at reducing the use of fossil fuel in cars, and many of these include electrical motors. There is the all electrical car, having virtually zero emission, with chargeable batteries, but also hybrid solutions combining traditional car engines, using different fuels, and electrical systems. Also solutions with fuel cells are being developed and tested. In all these solutions power electronics is an important prerequisite.

Power electronics is since long an important and integrated part of rail based transportation systems, i.e. trains, subways, trams, etc. In many countries there are active policies aiming at increasing the percentage of transportation on rail. Power electronics systems have for a long time been a standard and important part of railway technology, and these solutions are continuously improved in different ways. Particularly in densely populated areas, rail based transportation, above and under ground, is believed to be of more and more importance.

B. Distribution Systems

While power electronics is more or less standard in different loads, i.e. in devices converting electrical energy into useful energy for the consumer, power electronics is today quite exclusive in distribution systems. As discussed above the role of the distribution system will probably change drastically in the future, so it is not possible to foresee all applications. There might be completely new ways of using power electronics in the future. With distribution systems we mean here system of typically 100 kV and lower. In traditional transmission systems power electronics in form of HVDC and SVC are regarded as standard system components today, see below. An overview of medium voltage applications of power electronics can be found in [5]. Here a review of the development trends and system requirements are given.

The application of power electronics in distribution systems is rather new. While transmission systems the additional investments sometimes required for power electronics systems, can quite often be motivated by various reasons, this has not been the case in distribution systems. I distribution systems the requirements on costs and simplicity are higher as compared with those in high voltage grids. But the needs to control power flow and to integrate de-centralized power sources into the grid have increased the need of research and development in this field.

A critical parameter in converters in distribution systems is the losses. Not only the losses *per se* are of interest but also its implications on the converter design. It is desirable, or even quite often a requirement, to have air-cooling in these applications. Solutions with soft switching are then of course attractive. Development regarding new device technologies, such as silicon-silicon bonding and packaging, are also of great importance for reducing the LCC.

Another potential application in distribution systems, perhaps also in transmission systems, is the use of semiconductors for circuit beaker applications. Here transfer switches, but also standard switches, are regarded as potential candidates for semiconductors. Combined with short circuit current limiters this could enhance the performance of the system. Semiconductor based breakers will decrease the need for maintenance.

Power quality has during the last decade become an important aspect. Some of the problems with power quality are caused by power electronics, e.g. harmonics, but power electronics based devices can also alleviate these problems. There are a number of standard solutions available today, and new devices are developed as a response to the needs of the industry, [6].

C. Transmission Systems

The use of power electronics for bulk power transmission has a long history. The first commercial HVDC link was commissioned 50 years ago, and even if the valves were not semiconductor based but mercury arc valves, the principle is the same as in the thyristor based HVDC plants today. The HVDC technology has evolved significantly since then, and is still continuing to evolve [7]. Some of these recent developments are reviewed below. Recently, HVDC links based on Voltage Source Converters (VSC) have been introduced in transmission systems, [8]. In these HVDC systems valves with current switch-off capabilities are used, e.g. with IGBTs as active elements, and substantial system benefits can be achieved. Currently the rating of these HVDC links is limited, but they are believed to increase in the future [7]. The HVDC technology has improved the efficiency and flexibility of the power systems where they have been installed.

Another type power electronics based devices that have attracted a lot of attention during the last years are the Flexible AC Systems (FACTS) devices [9]. As will be shown below they introduce additional controllability in the system, which can be used to reduce losses or enhance the security.

1) HVDC: The HVDC technology is today regarded as well proven. Numerous HVDC links are in operation all over the world, and new links are continuously being commissioned. In the traditional HVDC technology based on thyristor technology the most recent developments have been aiming at increasing the reliability, decreasing the cost, and reducing the use of land. Firstly, some new trends in the traditional, i.e. thyristor-based, HVDC technology will be reviewed.

Reactive compensation equipment and filters have required large areas in many HVDC projects. Continuously tunable ac- filters and active dc-filters have reduced this need for land substantially. This opens up for new applications where land use can be a limiting factor. Another way of reducing the requirement on reactive compensation is provided by Capacitor Commutated Converter (CCC). In this converter, which also uses thyristors, capacitors connected in series with the ac side feeders provide a boost in the commutating voltage resulting a decreased need of reactive power, and hence of land use. Furthermore, the CCC can operate successfully when connected to very weak ac systems. The most recent type of HVDC converters is based on VSC technology. This new technology offers a number of additional features as compared with the traditional HVDC technology. These converters can be connected to systems that are very weak, in principle to systems without any generation from rotating machines. In addition the active and reactive power can be controlled independently of each other, four-quadrant operation. Presently it is estimated that this technology could be deployed for applications with a power rating below 300 MW [7], but it is foreseen that this limit will be raised in the future, and this technology will take over a large part of the HVDC market.

Very dramatic improvements in the control and protection of HVDC systems have also taken place. The most recent achievements in hardware, software, and communication technology have been implemented resulting in enhanced performance and flexibility.

2) FACTS: The HVDC link is not the only power electronics based piece of equipment that has been relatively common in power systems. Numerous Static Var Compensators (SVCs), which are shunt-connected devices, are also in service, predominantly for voltage control. The first SVCs were thyristor based, but recently VSC technology has also been used in SVC applications. Recently, series connected system components have been put into operation in power systems. There are number of such devices, such as Thyristor Controlled Series Capacitors (TCSC), Unified Power Flow Controller (UPFC), and the market is still in its infancy. These devices increase the controllability of active, and reactive, power flows dramatically. This can be used to cope with volatile load flow patterns in the system and to increase the system security. Since these devices have not only a local impact on the system, but rather global, wide area based systems with information from different parts of the system might be needed, [10].

D. Electricity Generation

The integration of many new power sources requires, as mentioned above, an interface converting the output from primary energy source to the required waveform and frequency. In the case of photovoltaic and fuel cells a direct current has to be converted into a fundamental frequency current. In other cases, e.g. in wind power and hydro power applications, a non-fundamental frequency, sometimes also of varying frequency, has to be converted to a frequency compatible with the grid. In all these cases a power electronics interface is a necessary pre-requisite for an efficient utilization of these primary power sources.

The integration of these primary energy sources is subject to extensive research currently, [11]. The interaction between voltage source inverters in a weak system, e.g. an island system, is investigated in [12], and it is shown that inverters with hysteretic control will not exhibit any adverse interactions.

Energy storage devices have also in most case to be interfaced through power electronics.

III CONCLUSIONS

This paper has suggested a definition of sustainability that besides the traditional environmental aspects also takes the possibilities for future innovations and developments. A key feature for a sustainable energy system would the flexibility to adopt and integrate new energy sources and other new system components. In this paper it has been shown that such flexibility is offered by power electronics based solutions with different functions in an electric power system.

ACKNOWLEDGMENT

The author would like to thank Dr. Ambra Sannino for her initiative to organize this panel. I believe the papers presented here will be helpful for many engineers in industry and academia in giving a useful overview of important developments and findings in a rapidly evolving topic.

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Göran Andersson (M'86, SM'91. F'97) was born in Malmö, Sweden. He obtained his M.S. and Ph.D. degree from the University of Lund in 1975 and 1980, respectively. In 1980 he joined Asia's, now ABB, HVDC division in Ludvika, Sweden, and in 1986 he was appointed full professor in electric power systems at the Royal Institute of Technology (KTH), Stockholm, Sweden. Since 2000 he is full professor in electric power systems at the Swiss Federal Institute of Technology (ETH), Zürich, where he heads the powers systems laboratory. His research interests are in power system analysis and control, in particular power systems dynamics and control involving HVDC and other power electronics based equipment. He is a member of the Royal Swedish Academy of Engineering Sciences and Royal Swedish Academy of Sciences

5. EXECUTIVE OVERVIEW: ENERGY STORAGE OPTIONS FOR A SUSTAINABLE ENERGY FUTURE

Robert B. Schainker, EPRI, USA

Abstract--Sustainability of electric power systems will involve very large use of renewable energy sources for power production. Some of these sources, e.g. wind and solar, have a characteristic stochastic behavior, which makes their output power production difficult to predict and have high power output fluctuations. Energy storage devices will be needed at different locations in the power system, to level the mismatch between renewable power generators and consumption and/or to store the surplus of power from renewable sources for later use during non-generation time periods or low power generation time periods. This presentation will give an overview of different storage technologies and how they can be used in a sustainable power system.

Index Terms— Battery storage plants, capacitive energy storage, compressed air energy storage, energy storage, flywheels, pumped storage power generation, super conducting magnetic energy storage.

Introduction

The ability to store electricity on a large scale would have a profound strategic liberating effect on the utility industry and would enable sustainable energy future. Supply and demand would not have to be balanced instantaneously. Thus, utilities would have much greater flexibility in operating their equipment and conducting power transactions. Further, stockpiling the excess electricity produced at night by base-load plants and using the stored energy during the daytime would enable utilities to use more fully their base-load generation plants and lower overall costs. This load-shifting, stockpiling approach would also be applied to transmission and distribution assets. Thus, storage technologies provide a unique opportunity for dramatic increases in asset utilization of many types of currently underutilized transmission and distribution equipment. The stockpiling of electric energy is also particularly useful for enhancing the use of renewable generation plants (e.g., wind farms and solar plants). Many wind plants produce much of their energy at night when the wind is higher. Solar plants produce electricity intermittently based on daylight variations. Thus, storing renewable energy would allow renewable plants to be dispatched during the day when the load (and price) is the highest and allow customers to get more value from such environmentally attractive power resources. Also, utilities, in general, could obtain more renewable credits from state/federal regulators by using renewable energy to displace higher priced premium fossil fueled plants currently used for daytime peaking and intermediate duty service.

The above benefits, in part, provided the motivation to build the nation's 38 pumped- hydro storage plants, one compressed air energy storage plant, and a few battery energy storage plants. Other types of energy storage technologies have been under development for decades, with each aimed at one or more applications within the electric network infrastructure. A critical insight gained from past storage plant operations (and techno-economic application studies) is that a variety of power ratings (kW to MW scale) and energy discharge ratings (millisecond to hour scale) are needed to match the wide spectrum of energy storage applications in the current and forecasted electric grid infrastructure. Some storage plants are suited (economically and performance wise) for one application and not for other applications. Also, once a plant is built with a specified discharge capability, it can be used for any time interval and power setting less than its design MW and discharge time interval capabilities. For example, a 100 MW–2-hour battery plant used for peak shaving/load management can also be used for voltage support (for any combination of real and reactive AC voltage support) over an extended time interval for any power level up to 100 MVARs. And, when a battery plant is operated at part load, it usually has the added benefits of having increased AC-AC efficiency and lower maintenance costs.

A large-scale 'classic' lead-acid battery plant was built and tested at Southern California Edison in the 1990's. And, "advanced" medium scale battery storage - potentially one of the most flexible options of all - is now being developed and field-tested at a number of utility sites. The present economic situation offers growing incentives for the industry to put such technologies to work, as utilities facing an uncertain future strive to pare operating costs and use their existing capacity more effectively.

Other important insights, related to the importance of energy storage today, respond to the following realities: a) in an uncertain future for how the electric infrastructure will evolve in the near to long term, energy storage plants in many cases provide lower cost alternatives to building new transmission, distribution, and generation equipment; b) storage plants are likely to greatly enhance the utilization of renewable plants (particularly, wind power generation) and provide an effective way to respond to likely CO_2 based regulations; c) storage plants provide an effective load management means to lower the capacity and installed cost of distributed generators since storage plants could take care of the peak demand thus allowing the distributed generator to operate, in general, as a base loaded device; d) storage plants provide a very effective means to stabilize price shocks if the reregulated electric marketplace does not work the way the market designers thought it would (e.g., unintended, and very costly consequences happened when California market designers "improved" the market rules); and e) storage plants have undergone significant techno-economic advances over the last five to ten years that have yet to be fully exploited; namely, storage plants are now less costly, more reliable, and sitable (e.g., flow battery systems have incremental energy storage costs one tenth that of previous battery systems, super-capacitor and flywheel modules have successfully undergone proof of principle and field tests at the small module size, and compressed air energy storage plants now have cost attractive designs for above ground air storage as well as underground air storage (note: 75% of the U.S. has potential for underground reservoir based compressed air plants).

Energy storage has traditionally been seen as a way to shave peaks and improve the capacity factor of base-load generation. But as competition increases, utilities are beginning to look at the advantages of operating a storage plant more strategically – as a hub of an extended and flexible energy management network. A number of utility visionaries see energy storage playing a much broader role in the future, one that is strikingly congruent with the institutional forces pressing on today's utility industry. Most utilities are aware that energy storage systems can help them meet peaks and increase the productivity of base-load power plants, but the vision of energy storage that's beginning to evolve shows that energy storage devices can offer a strategic business tool. Some utilities are now viewing storage plants in an opportunistic manner, by providing a business edge in an era of increasing competition and increased reregulation.

Energy Storage Options: Current Status

Pumped-Hydroelectric Storage

In operation worldwide for more than 70 years, pumped-hydro plants are still the only energy storage technology in widespread use. Such plants use off-peak power to pump water uphill to an elevated reservoir. When electricity is needed, the water is released to flow to a lower reservoir, and its "potential" energy is used to drive turbines. There are now about 38 pumped- storage plants in the United States, but several factors may limit further deployment of this storage option. Pumped-storage plants require a significant land area with suitable topography for the upper and lower reservoirs; many of the best sites are already taken and proposed plants have encountered opposition from environmental groups. Pumped-storage plants have a capital cost of about $1000/ kW and, at this price, must be large (in the 1000-MW to 2000-MW range). These factors make for long lead times and a significant investment for each new plant. Underground pumped hydro, in which the lower reservoir would be excavated from subterranean rock, may provide more siting flexibility and EPRI and DOE R&D have shown that this approach is technically feasible. Unfortunately, at present, such a plant has significantly higher capital cost. Thus, no underground pumped hydro plants exist today. In general, pumped hydro plant round trip efficiency is 70% to 80% (nominally 75%), depending on plant size, penstock diameter, hydro turbines used, and the height between the upper and lower reservoir. Overall efficiency also depends of the level of power generation, with most systems designed to operate most effectively between 90 and 100% of maximum power output. Some new variable speed pumped hydro plants can operate with high efficiencies between 70 and 100% of maximum power output. These systems will provide easier start up and more flexibility to the system operator.

Compressed-Air Energy Storage (CAES)

CAES plants use off-peak electricity to compress air into an underground reservoir or surface vessel/piping system. When electricity is needed the air is withdrawn, heated via combustion with any one of a variety of fuels, and run through expansion turbines to drive an electric generator. Such plants burn about one-third the premium fuel of a conventional simple cycle combustion turbine and produce one-third the pollutants per kWh generated. The compressed air can be stored in several types of underground media, including caverns in salt or rock formations, porous rock formations, and depleted natural gas fields. Since this technology uses fuel and electricity in its storage cycle, it is considered as a hybrid storage and generation plant. Its AC-AC roundtrip efficiency (when properly accounting for thermal and electrical input energies) is about 85%.

A 290-MW, 4 hour CAES plant has been in operation in Huntorf, West Germany since 1978, demonstrating strong performance - 90% availability and 99% starting reliability. EPRI has sponsored numerous technical and economic studies to determine the technical feasibility and economic viability of deploying CAES in the United States. These studies found that some three-fourths of the United States has geology potentially suited for reliable underground air storage. The required turbo machinery is available off-the-shelf from a number of vendors for plant sizes ranging from 20 to 350 MW. As a direct result of this work, CAES technology is now gaining a foothold in the United States, with the first such plant built by Alabama Electric Cooperative (a 110-MW – 26 hours plant called the AEC McIntosh CAES plant) which uses a man-made solution-mined salt cavern. It should be noted that solution-mined salt caverns are based on an 80-year-old oil/gas storage technology used for natural gas, propane, and oil storage. The AEC plant was built based on a competitively awarded fixed-price, turnkey contract, costing about $400/kW. The plant was built in about 2.5 years and has been successfully operating since June 1991.

In the last 10 years or so, a number of advanced CAES cycles have been developed and evaluated by EPRI. Some require much less fuel than the ‘conventional’ designs used at the German and Alabama plants and some use above ground piping systems to store the air (for up to about 5 hours of storage, depending on economic trade-off studies). Many of the new CAES design options take advantage of new developments in simple cycle and combined cycle gas turbines plants; and some utilize the ‘waste’ heat from the compression cycle to minimize (or reduce to zero) the fuel based heat needed during the generation cycle. Thus, if one wants to evaluate the application of CAES to their needs, there is a number of very interesting options to consider.

Battery Storage

A most familiar energy storage device may also be the most flexible, responsive, and reliable. At the beginning of the 20th century, in the dawn of the electric age, Thomas Edison and the new electric companies used batteries to store and deliver energy to the grid. Batteries may again play an important role in modern/future utility systems. Battery systems are modular, quiet and nonpolluting, so they can be installed near load centers and in existing suburban substations. Factory-built modules reduce construction lead-time and allow utilities to accurately match load growth without overbuilding new capacity. Quick response is one of the battery technology's strong points: batteries can respond to load changes in about 20 milliseconds. The AC-AC round trip efficiency of battery modules is in the 60% to 80% range, depending on how often they are cycled and the type of electrochemistry used in the battery.

Southern California Edison with EPRI demonstrated the technical performance and economic feasibility of lead-acid battery storage in a 10-MW, 4-hour discharge plant built at the 12-kV Chino substation in July 1988. During a two-year test and evaluation program, the Chino facility demonstrated the cost and benefits of battery storage for load leveling; voltage, VAR, frequency control; and spinning reserve duty. A number of other battery systems have been built and used successfully on the grid since 1988.

EPRI, U.S. Department of Energy, U.S. utilities (and others, world wide) are developing advanced batteries that pack more energy into a smaller package, last longer, and cost less than lead-acid devices (e.g., sodium sulfur and various flow batteries – Regenesys®, vanadium redox, and zinc-bromide systems).

Super conducting Magnetic Energy Storage (SMES)

A prospect that holds considerable promise, due to its innate high efficiency in storing DC electric energy is SMES. Off-peak AC power, converted to direct current, is fed into a doughnut-shaped electromagnetic coil of super=conducting wire. The coil is kept at super-conductive temperature by a refrigeration system designed to meet the super-conducting properties of the special materials used to fabricate the magnetic coil. A SMES unit stores and discharges DC power at efficiencies of 98% or more and switch between charging and discharging within 17 milliseconds. The stored energy in the coil is proportional to the square of the DC current flowing in the coil. Depending on the SMES device capacity, the coil could be in the 1 meter diameter range, for 1-MW – 1 second modules and 1000 meters in diameter for 1000-MW – 5 hour plants. The refrigeration losses and the AC-DC-AC losses have to be considered as part of any techno-economic evaluation and/or any round trip efficiency evaluation of SMES. Recent advances in so-called high temperature superconductors (that operate successfully at liquid nitrogen temperatures) enhance the ultimate attractiveness of this technology. A number of 1 to 3 MW (with 1 to 3 seconds of discharge capability) SMES devices have been successfully operating since 1998, for power quality and system stability applications.

Flywheel Energy Storage

Another storage option having a successful history (in voltage support/regenerative breaking transportation, power quality and UPS applications) is flywheel energy storage, which takes advantage of the kinetic energy charge and discharge capability of a spinning wheel. Since the stored energy is proportional to the square of the wheel speed, recent developments have focused on using high tensile strength composite materials (instead of making the wheel out of homogeneous metals) to increase wheel speed, to reduce device size, weight, and cost. Advanced flywheel developments include operating the wheel in a vacuum and replacing the standard bearing with a levitated magnetic bearing (using a conventional magnets, sometimes in concert with bulk superconductors) to reduce the bearing heat losses. Also, research is underway to lower eddy current losses and/or to improve cooling systems that remove heat from the wheel inside a vacuum enclosure. In general, small flywheels (up to 1-kW for 3 hours and 100kW for 30 seconds) have had good commercial success. Larger wheels approximately 250-kW for 10 to 15 minutes are under development. An important recent flywheel application of a medium scale flywheel system is New York Power Authority's successful application of ten 100-kW, 30-second flywheels for regenerative breaking and startup of subway transit cars in New York City. The AC-AC round trip efficiency of flywheel modules is in the 80% to 85% range, depending on bearing losses, winding losses, and how often they are cycled.

Super-Capacitor Energy Storage

Over the last 10 years, super-capacitors originally developed for military applications have been used commercially (e.g., for cell phone and power quality applications). These types of capacitors occupy a very small volume that is over 1000 times smaller than metallic foil type of capacitors. Like most capacitors, super-capacitors are ideal for high power, short-discharge applications; and they have very long cyclic life. Currently, commercial applications for super-capacitors are less than 100-kW and have less than a 1 to about 10 seconds of discharge time. The storage capacity of any capacitor is proportional to the square if its voltage. Today, each super-capacitor cell operates in the 2-volt range. Thus, cells are "series" packed in a module, with adjacent modules connected in parallel. Due to reliability issues, the module voltage is currently limited to the 200 to 400 volt range. As such, high-voltage utility applications are still in the development and early testing stage.

Hydrogen Energy Storage

Over the last few years, increased funding has produced some very encouraging progress in hydrogen used as a non-CO_2 producing fuel (since its combustion product is water vapor). Its major applications are for electric vehicles and electricity production via fuel cells. The long-term vision for hydrogen production is that hydrogen would not come from reforming methane or via any other chemical process using fossil based fuel; but rather, hydrogen would be produced by electrolysis of water using off-peak electricity (e.g., from hydro, wind, photovoltaic or nuclear plants). One of the key technical challenges to accomplish this vision is the development of a safe, reliable, and low cost storage system for the off-peak generated hydrogen. At present, hydrogen is produced at a low pressure (e.g., at 30 psia to 300 psia) and is then mechanically compressed and stored in high-pressure tanks/vessels/pipelines (e.g., at about 5000 psia in tanks for application to fuel cell electric vehicles). High-pressure electrolyzers are currently in the conceptual design and lab-scale, proof-of-principle stage. When coupled with high-pressure storage vessels, economically attractive electric energy storage systems based on a hydrogen cycle could materialize as commercially viable. The AC-AC round trip efficiency for these systems is expected to be in the 60% to 85% range, depending on the operating pressure and efficiency of an electrolyzer-fuel cell combination or the operating pressure and efficiency of a reversible fuel cell device (which is a type of fuel cell that incorporates a reversible fuel cell that can accomplish both hydrolysis and electrolysis in the same cell).

Economics and the Competitive Edge

Storage certainly can reduce operating costs by allowing a utility to both maintain spinning reserve and satisfy peak demand with inexpensive off-peak power. And, for capacity-constrained utilities, storage plants can defer or eliminate the need to build new generating capacity. But storage plants cost money too, often more than combustion turbine peaking plants. Utilities are accustomed to evaluating technologies on a cost per kilowatt basis. Utility planners simplistically compare storage plants directly with generation plants (usually simple cycle combustion turbines), even though storage plants are not primary generating technologies and often provide many more benefits than generation units. These benefits need to be quantified separately.

So, why turn to storage? It is a matter of summing up the multiple benefits storage plants provide – within and beyond an individual generation mix. For example, one benefit is a matter of buying low and selling high. Utilities routinely transfer power over the interconnected transmission network, which allows a utility short on capacity to purchase power, or one with a surplus to sell power to the highest bidder. An energy storage plant (or set of plants strategically located) puts a utility in a position to buy electricity when it's cheapest (usually off-peak over a non-congested transmission corridor) instead of during on-peak time periods. This strengthens a generator/utility's bargaining position in the wholesale marketplace.

And other utilities aren't the only players in the high-stakes game of electric power brokering. As a result of the 1978 Public Utility Regulatory Policies Act (PURPA), and the 1996 FERC Order's 888 and 889, utilities are required to allow non-utilities or independent power producer's access to, and use of utility transmission systems. Prior to these government orders, electricity production decisions were made centrally by vertically integrated utilities relying on generators they owned or exchanges with neighboring utilities. In particular, FERC's orders caused fundamental shifts in the electricity infrastructure and dramatically changed the use and operation of electricity production and delivery systems. As a consequence, storage plants can not only help manage generation and load fluctuations, storage plants can help enable regional grid operators to manage the flow of energy from independent power producers internally and externally to their regions.

Energy storage allows a utility and/or energy broker to put independently produced off-peak power into inventory to meet next-day peaks. As in any other marketplace, the company who can store a product and sell it at his choosing has a competitive edge in buy-and-sell agreements.

Also, a system operator needs spinning reserve and load-following capability, but generators may not want to be assigned those functions. Storage is an ideal way to do that, because storage units can start up quickly (with time constants measured in seconds to 5 minutes) and respond much more rapidly to load fluctuations than fossil-fired units whose ramp rate time constants are measured in 10 to 30 minutes. Also, energy-storage systems can buffer customers from lack of reliability or availability in third-party generation, which greatly reduces the price volatility and grid operator angst associated with the capability to meet the required maximum load occurring during peak demand time periods.

Storage can also buffer the other great concern that has shown up with the growth of independent generators - power quality. The electric grid operates on a very pure diet of 60-cycle alternating current, and computers and other high-tech end-use equipment are becoming increasingly finicky about what is fed them. By means of sophisticated control equipment and precise operating procedures, grid operators and distribution companies are to ensure the quality of power as it is being supplied. Independent/third party generators, however, are generally not paid for, or are not equipped to fine-tune voltage and control frequencies to expected levels. Storage systems can buffer utilities and their customers from such glitches. You don't have to worry about how the independents supply the power or even, within reason, about their reliability and power quality.

With a storage system separating generators and customers, independent generators become a more useful part of the power equation. The emphasis on the generation side can shift to providing electricity at low cost, rather than meeting goals of low cost plus reliability plus power quality. Adding storage to the generation mix allows the grid operator and/or the distribution company to handle these concerns in a cost-effective way.

These ideas dovetail neatly with utility efforts to expand into new markets through energy service options. Some utilities are developing a menu of end-use technologies to facilitate this expansion. Other efforts are focusing on differentiating the basic electrical service itself. Utility service is traditionally measured in terms of kilowatt-hours. But from a business-planning standpoint that service is a bundle of characteristics or attributes. Reliability, power quality, price, and convenience - these and other attributes are part of the service that a utility offers its customers. And different customers value different attributes. Some utilities are exploring ways to unbundle service options to make electricity more competitive and to increase the value of their utility service.

Reliability is perhaps the most frequently cited attribute, but reliability can mean different things to different customers. Some customers, such as semiconductor manufacturing firms may want advance warning of an outage so they can reschedule production. Others, such as poultry processors, are more concerned with the duration of an outage because they deal in a perishable product whose value depends on refrigeration. There are also customers willing to endure occasional interruptions in exchange for lower rates. So, there is a spectrum of customers out there. Offering them a spectrum of services is one of the key strategies utilities can use to be more competitive. Storage is one of the key technologies that can provide the flexibility to enable utilities to do that. The example here would be installing a battery system at or near the customer's facility to provide a buffer against unexpected outages.

It is important to note that energy can be stored on both sides of the meter. For example, installing thermal energy storage systems in homes and businesses makes it possible for off-peak energy to be used for heating and cooling during peak periods, reducing customers' electric bills and helping utilities smooth their load curves. Batteries too can be used to store energy on the customer side, with electric vehicles providing a good example. In addition, innovative time-of-day rates can influence customers to change their production to effect changes in load shape.

Another novel application for storage lies in the area of transmission planning. The forces that are reshaping the structure of the industry – non-utility generation, power wheeling and re-regulation - have increased the burden on the transmission lines that carry bulk power between generators and load centers. The power system is a machine that was designed to perform certain functions. If we want it to perform other functions - such as allowing large blocks of electricity to go looking for competitive markets - we have to augment the electric infrastructure with the appropriate hardware and software components.

While pressures on the transmission system increase, the costs of building a new transmission line has also increased - to as much as $750,000 per mile. Obtaining rights-of-way and the necessary approvals to install new lines can take five to seven years or more. In many cases it is not possible to install new lines to large metropolitan load centers, even though the demand from those centers has the existing lines loaded to capacity during peak time periods. Batteries and other fast-response storage technologies can help in the operation of transmission and distribution systems. Installing a storage plant near a load center - a battery system at a substation, for example - may be an attractive alternative to adding a new transmission line or upgrading an existing one. One can charge the battery at night when transmission/distribution lines are not fully loaded, then feed that stored energy into the transmission/distribution system to serve the peak load the following afternoon. Placing storage units close to metropolitan load centers could also bring environmental benefits. Heightened concern over air quality may result in legislation to further reduce emissions from fossil-fired plants and perhaps restrict their deployment in some areas. Environmentally benign storage technologies could be used to park base-load power from remote generators without adversely affecting air quality in urban load centers.

Conclusions

Thus, energy storage plants can and will ultimately play an important role in a sustained energy future. Storage plants will significantly alter the penetration and use of renewable plants and will improve the economic use of the existing generation, transmission and distribution infrastructure. The benefits of such plants cover a wide spectrum of economic dimensions, each of which is currently being understood and quantified. The ultimate success and penetration of storage plants will be determined, in part, on grid planners, operations and independent power producers understanding and taking advantage of these economic benefits.

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Robert B. Schainker is a Technology Fellow in the Power Delivery & Markets Division of the Electric Power Research Institute (EPRI) in Palo Alto, California. Dr. Schainker joined EPRI in 1978 as a Project Manager in the Advanced Power System Division, moving to his present position in 2001.

Before joining the Institute, Dr. Schainker was with Systems Control, Inc., Palo Alto, for nine years. Starting as a Project Engineer, he was promoted to Senior Engineer and Program Manager for the Energy and Environmental

Program. Dr. Schainker is a member of the Institute of Electric and Electronic Engineers. He is the author of over fifty publications on the subjects of Flexible AC Transmission System (FACTS) technologies, energy storage technologies (including compressed air energy storage, super-conducting magnetic energy storage, battery storage, and pumped hydro storage), economic benefits analyses for electric utilities, optimal control theory, unit commitment and dispatch, dynamic benefits analysis applied to utility operations and planning, adaptive control, estimation and information theory, statistical sensitivity analysis and two-phase flow.

Dr. Schainker received a B.S. degree in Mechanical Engineering in 1965, and M.S. degree in Electrical Engineering in 1966, and a Ph.D. degree in Applied Mathematics in 1969, all from Washington University, St. Louis, Missouri.

6. EFFICIENCY ANALYSIS OF LOW AND MEDIUM-VOLTAGE DC DISTRIBUTION SYSTEMS

Daniel Nilsson, and Ambra Sannino, Chalmers University of Technology, Gothenburg, Sweden.

Abstract-- In this paper, sustainability aspects connected to the use of dc for power delivery in low- and medium-voltage distribution systems are treated. The efficiency of an example ac system, a dc system and a mixed ac-dc system are calculated and compared. It is shown that, under the assumption of a substantial reduction in semiconductor losses, the total system losses decrease using dc. This means that for the same energy delivered, less energy must be produced from the available sources, thereby indirectly reducing the environmental impact of energy production. Moreover, the dc system seems to lead to better utilization of the HV/MV transformer, so that the same system can be expanded to supply a higher load without changing the transformer.

Index Terms—environment, power distribution system, direct current (dc), power electronics, efficiency, losses.

Introduction

Environmental concerns pose strong requirements on electricity production, which is responsible for a major portion of carbon dioxide (CO_2) emissions linked to global warming and the greenhouse effect. By increasing the use of renewable energy sources to produce electricity, CO_2 emissions can be reduced. However, fossil fuels will still stand for a consistent portion of the total energy production in future scenarios [1].

Inefficient use of electricity, i.e., power losses, also contributes to CO_2 emissions: for one kWh utilized, more than one kWh has to be produced, with consequent release of CO_2 if the energy comes from fossil fuels. Losses cannot be avoided in the transport and utilization of electricity. However, measures that reduce the losses in the transmission and distribution of electrical power will have a beneficial effect on the environmental impact of power systems.

Since many years now, direct current (dc) has been used for transmitting power over long distances in high-voltage dc (HVDC) transmission using voltage between tens and hundreds of kV [2]. With HVDC, the power transmitted over a given distance is largely increased as compared to an ac line. Despite the additional losses in the two converter stations at the ends, losses are also greatly reduced [3]. This is mostly due to the absence of the reactive current component, which increases the current magnitude, thus the losses, in the ac line.

DC systems at lower voltage levels are today used only in very specific applications, among which telecommunication equipment using 48 V dc [4], shipboard systems [5], and traction systems [6]. However, most equipment in use today in offices and households is consumer electronics that uses low-voltage (LV) dc. Some loads contain an input transformer and a rectifier to obtain the proper dc voltage for the electronic equipment. When the equipment is in stand-by mode, the transformer absorbs a small open-circuit current that creates stand-by losses. As an example, the total domestic power consumption of consumer electronic equipment in stand-by mode in the EU has been estimated to around 36 TWh/year and it is predicted to increase to 62 TWh/year in 2010 [7]. Using dc for powering the equipment would eliminate these losses. Moreover, losses during normal operation would also decrease, because both the input transformer and rectifier can be removed without major design changes, provided that a proper voltage level is used. Newer electronic equipment, where the single-phase rectifier is supplied directly by the ac system and followed by a dc-dc regulator, does not cause stand-by losses. However, losses in the first conversion stage can be avoided by supplying with dc. Moreover, the reactive current component taken by the loads is eliminated, and losses in the cables are reduced.

Alternative power distribution systems including dc have been proposed, for example in [8] and [9], where, however, the aspect of possible loss reduction and higher effectiveness is not mentioned. In a feasibility study for a dc system for offices carried out in [10], some simplified loss calculations are included, but only a LV dc system is considered and a diode rectifier is used as power electronic interface to the LV ac system, which is unlikely to be the case. Still, these calculations show positive results.

In this paper, the concept of using direct current for power distribution is extended to include both low- and medium-voltage (MV) distribution. First, the proposed dc distribution concept is presented and loss calculations for ac and dc system are explained. An example system is then presented and its efficiency analyzed when using only ac, mixed ac-dc and only dc. Results are used to compare the three solutions. Losses in the converters are taken into account, both at the interface with the ac grid and between different voltage levels within the dc grid.

DC Distribution System

A scheme of the existing ac system compared to the proposed dc system for LV distribution is presented in Figure 1. As mentioned, in newer electronic equipment the single-phase rectifier is supplied directly by the ac system and followed by a dc-dc regulator, as shown in Figure 1(a). By supplying with dc, the first conversion stage can be removed. Easier integration of distributed generation units is possible since photovoltaic systems [11] and fuel cells [12] generate energy at dc and therefore could be directly connected to an LV dc network. Connection to today's ac network requires one dc-ac conversion. A two-stage conversion (ac-dc and back, similarly as in ac drives) is necessary for connecting to the ac grid variable-speed wind turbines and micro turbines using natural gas. Using dc would save one conversion also in this case.

In offices and facilities with high reliability requirements, a big battery block for back-up energy storage can be used to provide uninterruptible power to low-consumption sensitive loads like computers, instead of using a number of Uninterruptible Power Systems (UPS), constituted by a rectifier, a battery block and an inverter, as in Figure 1(a). This allows removing a number of small converters.

The dc system is simpler, as many conversion steps are avoided, and each step causes losses and reduces the reliability of the system. Due to the absence of a reactive current component, the same active power drawn by the load results in lower current magnitude, thus in lower losses, in the dc system as compared to the ac system.

In the proposed system, many small rectifiers are replaced by one bigger converter needed to interface the LV dc grid with the upstream ac grid. To achieve high power quality in the LV dc grid, a Voltage Source Converter (VSC) based on IGBTs can be used as interface (Figure 2). The VSC can be controlled with Pulse Width Modulation (PWM) techniques with high switching frequency to achieve high controllability and power quality. Active and reactive power drawn from the ac grid can be controlled independently with a high bandwidth. The ac currents can be controlled to be sinusoidal and at the same time the dc voltage can be regulated to the desired value in spite of load variations. The VSC can allow bi-directional power flow, which can be desirable if generation is present in the dc grid: the flow of power can thus be reversed to the ac grid during light-load situations. Finally, with proper control, the VSC can keep the dc voltage constant in spite of disturbances on the ac supply, thereby effectively decoupling the two grids [13]. Note, however, that this will normally require an overrating of the converter, but it reduces on the other hand the need for stored energy in the dc network if high reliability is required.

One can also think about extending the dc system up to higher voltage levels, as shown in Figure 3. Conversion between different dc voltage levels requires dc-dc converters, which substitute today's distribution transformers. Again, the current magnitude is lower for the same active power, so the losses in the cables are lower. Existing cables can thus be used more efficiently. However, there will be losses in the dc-dc converters. The voltage drop, now only due to the resistive term, is also lower and this effect is much more noticeable at MV than at LV, where the reactance of the cables is small. By using advanced control techniques for the converter interface, rejection of disturbances coming from the transmission or sub transmission system can be achieved, thus decoupling the dc grid from the upstream ac system. However, disturbances can now occur within the dc grid, which may be transferred from one voltage level to the other by the dc-dc converters. These will have to be taken care of by proper control of the dc-dc converters and of the energy storage, if present.

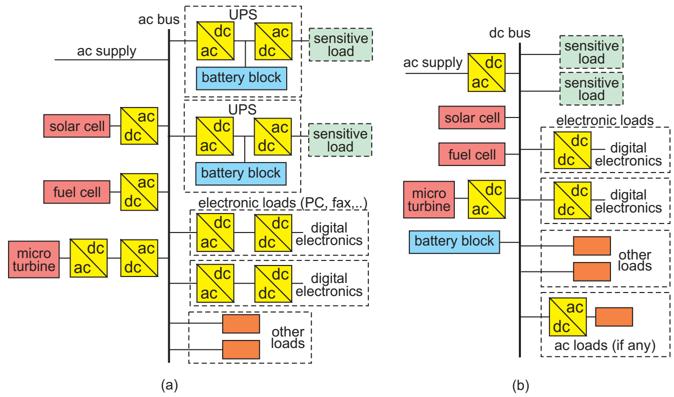

Figure 6 - Scheme of the existing ac LV distribution system (a), and of the proposed dc LV distribution system (b).

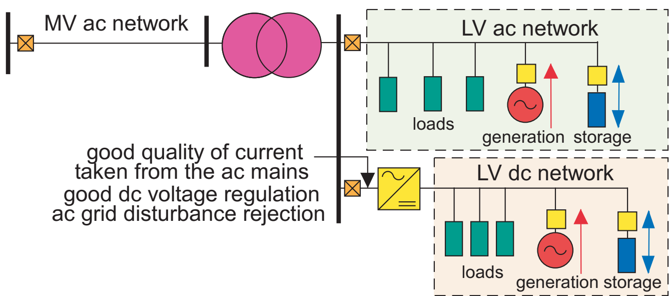

Figure 7 – Interaction between ac and the dc LV grid with converter interface.

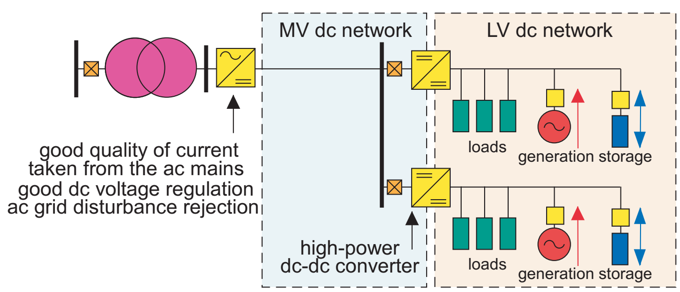

Figure. 8 – MV dc grid.

Loss Calculation in AC and DC System

Cable losses

From the load power consumption P and the power factor cos φ, the current I_{ac} taken by the load and the power losses DP_{ac} can be calculated. For single-phase feeders

$$I_{ac} = \frac{P}{E \cdot \cos\varphi} \qquad (1)$$

$$\Delta P_{ac} = 2 \cdot rL \cdot I_{ac}^2 = 2 \cdot \frac{rL}{\cos^2\varphi} \cdot \frac{P^2}{E^2} \qquad (2)$$

where E is the rms phase voltage, r the cable resistance per unit length and L the cable length. In a dc system only active power is present. For the same load power consumption and the same cable, current and power losses for the dc system are

$$I_{\mathrm{dc}} = \frac{P}{U_{\mathrm{dc}}} \qquad (3)$$

$$\Delta P_{\mathrm{dc}} = 2 \cdot rL \cdot I_{\mathrm{dc}}^2 = 2 \cdot rL \cdot \frac{P^2}{U_{\mathrm{dc}}^2} \qquad (4)$$

where U_{dc} is the dc voltage, which can be taken equal to $\sqrt{2} \cdot E$ without risk of damage to the cable insulation. The dc-ac current ratio I_{dc}/I_{ac} and dc-ac loss ratio DP_{dc}/DP_{ac} result as

$$\frac{I_{\mathrm{dc}}}{I_{\mathrm{ac}}} = \frac{E}{U_{\mathrm{dc}}} \cdot \cos\varphi = \frac{\cos\varphi}{\sqrt{2}} \qquad (5)$$

$$\frac{\Delta P_{\mathrm{dc}}}{\Delta P_{\mathrm{ac}}} = \frac{I_{\mathrm{dc}}^2}{I_{\mathrm{ac}}^2} = \frac{E^2}{U_{\mathrm{dc}}^2} \cdot \cos^2\varphi = \frac{\cos^2\varphi}{2} \qquad (6)$$

For a three-phase ac load, with analogous symbols,

$$I_{\mathrm{ac,3}} = \frac{P}{\sqrt{3} \cdot U_{\mathrm{ac,3}} \cdot \cos\varphi} \qquad (7)$$

$$\Delta P_{\mathrm{ac,3}} = 3 \cdot rL \cdot I_{\mathrm{ac,3}}^2 = \frac{rL}{\cos^2\varphi} \cdot \frac{P^2}{U_{\mathrm{ac}}^2} \qquad (8)$$

where U_{ac} is the rated ac voltage (line-to-line). The dc voltage U_{dc} can be taken equal to $\sqrt{2/3} \cdot U_{\mathrm{ac}}$, resulting into

$$\frac{I_{\mathrm{dc}}}{I_{\mathrm{ac,3}}} = \frac{\sqrt{3} \cdot U_{\mathrm{ac}}}{U_{\mathrm{dc}}} \cdot \cos\varphi = \frac{3}{\sqrt{2}} \cdot \cos\varphi \qquad (9)$$

$$\frac{\Delta P_{\mathrm{dc}}}{\Delta P_{\mathrm{ac,3}}} = \frac{2}{3} \frac{I_{\mathrm{dc}}^2}{I_{\mathrm{ac,3}}^2} = 2 \frac{U_{\mathrm{ac}}^2}{U_{\mathrm{dc}}^2} \cdot \cos^2\varphi = 3 \cdot \cos^2\varphi \qquad (10)$$

From Eqs. (5) and (6), it is clear that the current in the dc system is always lower than in the single-phase ac feeder delivering the same active power. Consequently, losses are also lower regardless of the load power factor. In the three-phase case, instead, the load current is higher in the dc case for load power factor higher than about 0.57. This is understandable because two conductors instead of three carry the same power. Consequently, losses are also higher. The plot in Figure 4 shows the variation with the load angle of the dc-ac current ratio and dc-ac loss ratio in the single-phase and three-phase cases.

The situation can change if a higher voltage can be used for the same cable. Moreover, if an existing three-phase cable is used with dc, there will be one conductor that is not used. There is the possibility to use two conductors in parallel and the third as a return path. The cable cannot be loaded to its maximum, but the resistance will be lower. In many existing ac systems, as a result of upgrading, there are two three-phase cables of the same cross-section in parallel. If dc is applied in this case, each cable can be used as one pole, thereby reducing the resistance to only one third.

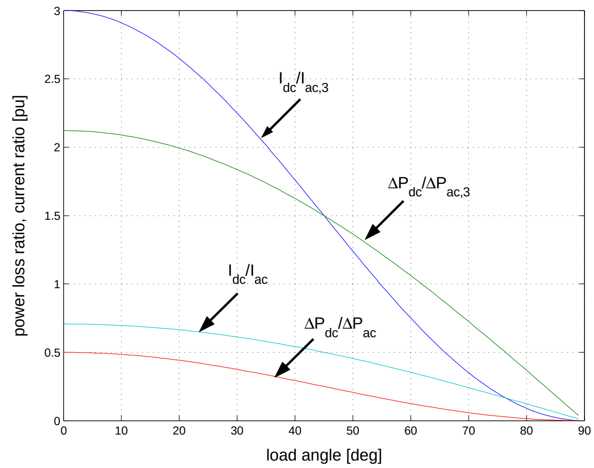

Figure 9 – Dc-ac current ratio I_{dc}/I_{ac} and dc-ac loss ratio DP_{dc}/DP_{ac} in single-phase and three-phase cases.

Transformation and conversion losses

In the ac system, there are losses due to the transformation between two different voltage levels. These are straightforward to calculate, known the short-circuit resistance of the transformer and the output current. In the dc system, there are losses in the ac-dc conversion by the VSC and in the dc-dc conversion between different voltage levels of a multilevel dc system. The losses in the VSC are conduction losses and switching losses. Accurate calculation of the conduction losses is complicated because the current is carried partly by the IGBT and partly by the anti-parallel diode. Both can be modeled as a constant voltage drop with a resistance in series. However, in [14] it is observed that, for a series of IGBT modules from a well-known manufacturer, the on-state resistance of the diode is very close to that of the IGBT and therefore the following simplified expression for calculating the conduction losses per phase leg can be derived

$$\Delta P_{\mathrm{cond}} = \frac{2\sqrt{2}\cdot V_{\mathrm{on}}\cdot I_{\mathrm{rms}}}{\pi} + r_{\mathrm{on}}\cdot I_{\mathrm{rms}}^{2} \qquad (11)$$

where I_{rms} is the rms value of the actual current through the module, r_{on} the on-state resistance of the IGBT (equivalently, of the diode) and V_{on} the on-state voltage drop. To calculate the switching losses, the energy losses during turn-on E_{on} and during turn-off E_{off}, for the IGBT, and the reverse recovery energy E_{RR}, for the diode, must be known. They are obtained from the data sheets of the components. The switching losses are proportional to the switching frequency [14] as

$$\Delta P_{\mathrm{sw}} = \frac{2\cdot\sqrt{2}}{\pi}\cdot\frac{I_{\mathrm{rms}}}{I_{\mathrm{nom}}}\cdot\left(E_{\mathrm{on}}+E_{\mathrm{off}}\right)\cdot f_{\mathrm{sw}} + E_{\mathrm{RR}}\cdot f_{\mathrm{sw}} \qquad (12)$$

where I_{nom} is the rated current of the IGBT module.

Case Study

In this Section, a case study will be presented to analyze the effect on power losses of replacing ac with dc in LV and MV distribution. Power losses and transformer utilization are studied for a case with only ac, for a mixed ac-dc system, and finally for a system with only dc. The three systems are equivalent in that they supply the same total load.

A AC System

The system, shown in Figure 5, is composed of a 150/20 kV transformer (T2), rated 10 MVA, which supplies a number n_{MV} of MV feeders at nominal voltage 20 kV. Each MV feeder supplies a number n_{s} of substations, placed at a distance L_{s} from each other. Each substation transformer (T1) is rated 800 kVA and supplies a number n_{LV} of three-phase LV feeders per substation, which are rated 70 mm^2 and have length L_{LV}. Each of these feeders in turn supplies a number n_g of single-phase cables, rated 1.5 mm^2, feeding a group of loads. The number of loads in each group is n_l. The loads consume P = 300 W each at cos$j$ = 0.8 and are placed at a distance L_l from each other. Transformer parameters are reported in Table I. Cable parameters are reported in Table II. For all three cases, $n_l = 5$, $n_g = 45$, $n_{LV} = 6$, $n_s = 4$, $n_{MV} = 4$, $L_l = 10$ m. The total active power supplied by the ac system is thus $P_{tot} = P \cdot n_l \cdot n_g \cdot n_{LV} \cdot n_s \cdot n_{MV}$ = 6.48 MW.

By using resistance and reactance of transformers and cables, the power losses in the system have been calculated and used to obtain the efficiency h of the distribution system

$$\eta = \frac{P_{tot}}{P_{in}} \cdot 100 \qquad (13)$$

where P_{in} is the total active power input to the system at the primary of T2. The transformer utilization, indicated as u_{T1} and u_{T2}, respectively, for T1 and T2, has also been calculated as the ratio of the apparent power at the primary of the transformer and it's rating

$$\upsilon_T = \frac{3 \cdot U_1 \cdot I_1}{S} \cdot 100 \qquad (14)$$

where I_1 is the actual primary current of the transformer and the other symbols have the meaning indicated in Table I. The current supplied by the secondary winding of the transformers takes into account the losses in the downstream feeders. For the base case studied, the lengths L_{LV} and L_s have been set at 20 m and 2 km, respectively. To analyze which system parameters impact the losses most, the calculations have been repeated for different cases by varying the lengths L_{LV} and L_s. Also the short-circuit impedance of the transformer has been changed by a factor, indicated as k_{T1} and k_{T2}, respectively, for T1 and T2, to see how this impacts efficiency and transformer utilization. Results obtained are reported in Table III.

In the base case, the efficiency of the system is 97.3%. In all cases considered, the losses do not change by more than 1%, even in Case 4, where the short-circuit impedance of the MV/LV transformers is doubled and the efficiency becomes lowest and equal to h = 96.4%. The losses vary significantly also when the short-circuit impedance of T2 is doubled (Case 5) and when the length L_{LV} is changed to 50 m (Case 2). On the other hand, h decreases only by 0.3% when L_s is doubled to 4 km (Case 3). The utilization of T1, u_{T1}, is slightly higher than 65%, except for Case 4, in which the short-circuit impedance of T1 is doubled. The utilization of T2, u_{T2}, is about 91%, except for the two cases in which the short-circuit impedance of the transformers is changed.

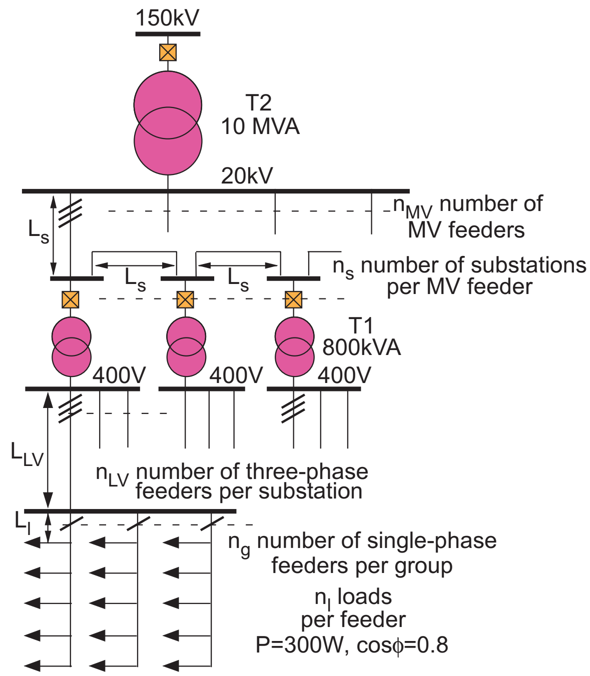

Figure 10 – Case study: ac grid.

TABLE I – RATED PARAMETERS OF TRANSFORMERS

Transformer	Rating S [MVA]	Primary voltage U_1 [kV]	Secondary voltage U_2 [kV]	Winding resistance R_T [W]	Leakage reactance X_T [W]
T1	0.8	20	0.4	$2.46\cdot10^{-3}$	$9.81\cdot10^{-3}$
T2	10	150	21	0.303	6.06

TABLE II – PARAMETERS OF CABLES

Rated voltage U [kV]	Cross section s [mm^2]	Resistance r [W/km]	Reactance x [W/km]
20	240	0.125	0.132
1	70	0.443	0.076
1	1.5	0.14	0.1

TABLE III – RESULTS OF AC SYSTEM CALCULATIONS

Case number	L_{LV} [m]	L_s [km]	k_{T1} [pu]	k_{T2} [pu]	h [%]	u_{T1} [%]	u_{T2} [%]
1	20	2	1	1	97.3	65.2	91.0
2	50	2	1	1	96.5	65.6	91.6
3	20	4	1	1	97.0	65.2	91.4
4	20	2	2	1	96.4	66.8	93.6
5	20	2	1	2	96.6	65.2	98.9

B Mixed AC-DC System

In this system, the load at LV level is supplied with dc instead of ac. The loads consume P = 300 W each, as in the previous case, but they do not absorb reactive power. It is assumed that they are all single-phase loads that can function properly with 325 V dc, which is equal to the peak value of the ac phase voltage of 230 V rms and is the most appropriate dc voltage level for supplying electronic equipment [10]. Note that this does not require replacement of the cables because the insulation should be able to withstand this voltage. For the three-phase cables, only two conductors are used and there is the possibility that the rated current is exceeded (see Eq. (9)). However, in order to be able to compare the three systems, the loading has been chosen such that this does not occur and the same configuration can be used for the three systems.

This voltage is obtained by using an IGBT-based VSC placed at the output of each 800-kVA-distribution transformer, as shown in Figure 6. Losses in the dc cables are calculated according to Esq. (4) and losses in the VSC according to Eqs. (11) and (12). Here, the same values as in [14], reported in Table IV, are used for the IGBT modules. Note that r_{on}, E_{on}, E_{off}, and E_{RR} vary in proportion to the rating of the module. For intermediate ratings, the values can be interpolated.

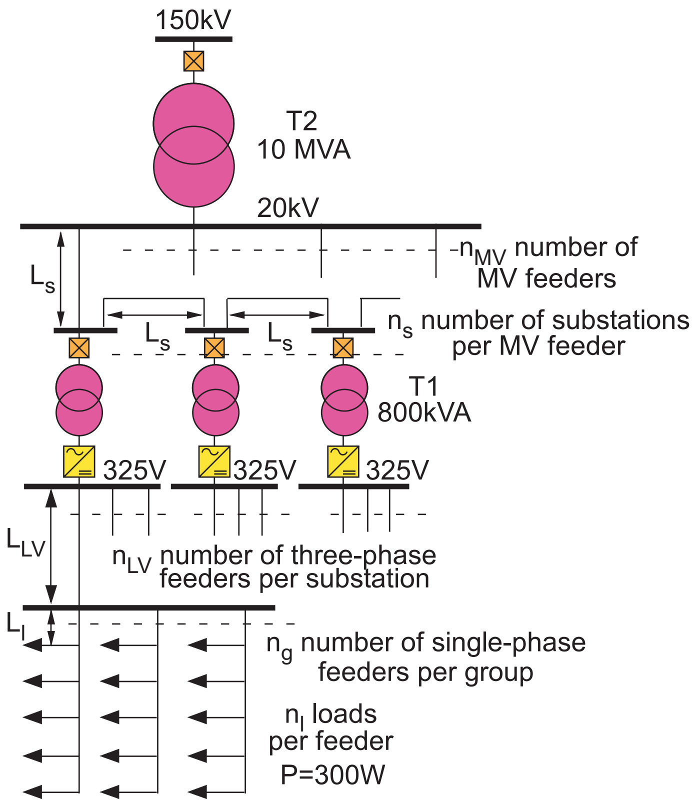

Figure 11 – Case study: mixed ac-dc grid.

TABLE IV – PARAMETERS OF IGBT MODULES (FROM [14])

IGBT module	Rated current I_{nom} [A]	Turn-on and turn-off energy $E_{on} + E_{off}$ [mJ]	Recovery energy E_{RR} [mJ]	On-state resistance r_{on} [mW]	On-state voltage drop V_{on} [V]
1	300	183	40	3.1	1.2
2	600	367	81.3	1.6	1.2
3	1200	733	163	0.8	1.2

For the system analyzed here, the nominal current of the IGBTs is 1200 A in all cases. The switching frequency has been set to 1500 Hz, which is a reasonable value for medium- and high-power applications. In order to study the effect of changes in the semiconductor losses on the total efficiency of the system, the total losses in the converter can be adjusted by a factor K_{IGBT} (no changes are made in the value of the losses calculated based on Table IV when this factor is set to one).

Results of the calculations are reported in Table 5. It can be seen clearly by comparing cases number 1 through 5 in Table III and Table V that for this mixed system there is in fact no gain in efficiency. This because the losses of the VSC are added to the losses of the transformers, already present in the ac solution. The losses in Case 1 are 0.9% higher than in the ac system. The biggest difference (1.6%) occurs in Case 2, when the length L_{LV} of the three-phase LV cables is increased. This is obvious because more current is flowing in these cables compared to the ac case; see Eq. (9), so they contribute more to the total losses in this case. In Cases 3 through 5, the difference with the corresponding cases for the ac system is lower (0.5-0.7%). It can also be noticed from Table V that the utilization of T2 drops drastically as compared to the ac case, due to the absence of the reactive power of the loads.

By increasing the switching frequency to 2500 Hz in Case 6, the losses increase by only 0.3% as compared with Case 1. Even if a reduction of the semiconductor losses by half is assumed ($K_{IGBT} = 0.5$), the total losses only decrease by about 0.6%, and they still remain slightly higher than the corresponding ac cases.

TABLE V – RESULTS OF MIXED AC-DC SYSTEM CALCULATIONS

Case number	L_{LV} [m]	L_s [Km]	k_{T1} [pu]	k_{T2} [pu]	f_{sw} [Hz]	K_{IGBT} [pu]	h [%]	u_{T1} [%]	u_{T2} [%]
1	20	2	1	1	1500	1	96.4	52.1	67.7
2	50	2	1	1	1500	1	94.9	53.0	68.9
3	20	4	1	1	1500	1	96.3	52.1	67.9
4	20	2	2	1	1500	1	95.9	52.5	68.4
5	20	2	1	2	1500	1	96.0	52.1	69.2
6	20	2	1	1	2500	1	96.1	52.3	68.0
7	20	2	1	1	1500	0.5	97.0	51.8	67.3
8	20	2	1	1	2500	0.5	96.8	51.9	67.5

C DC System

In the system using dc for both MV and LV levels, which is shown in Figure 7, the VSC is placed right after T2. The same cables can be used with a dc voltage equal to the peak value of the rated ac voltage of 20 kV, i.e. about 16 kV, with no risk of damage to the insulation. However, if the poles of the dc-link of the VSC have a potential to ground of ± 16 kV, the rated system voltage can be increased to 32 kV dc by still using the same cables. Converter stations of this size, in terms of power and voltage ratings, already exist in a number of VSC-based HVDC projects [15]. In one specific project, the ac voltage is 132 kV, which is transformed down to 17.9 kV by a transformer and then to ± 16 kV dc by the VSC [16,17.

The rest of the system has the same configuration as in the previous examples, with the exception of the MV/LV transformers that are now replaced by dc-dc converters. Since the power flow is assumed unidirectional, as there are only loads at the LV level, and galvanic insulation between the two voltage levels is desired, the dc-dc converter used will most likely be a full-bridge isolated boost converter [18], where two phase legs use IGBT modules and two-phase legs use diodes. Note that in this application the IGBT modules will be placed on the high voltage (HV) side of the converter. Losses are again divided into conduction losses and switching losses, and both terms are calculated with Eqs. (11) and (12) given above. For the HV/MV converter station, the losses are now considered a fixed percentage of the input power, equal to 1.7%, of which 1.2% is due to the semiconductors.

The results of the calculations are shown in Table VI. The first three cases can be readily compared with the corresponding cases in Table III and Table V. In Case 1 and 3, losses are slightly higher than in the ac system (0.5% and 0.3%, respectively). However, when the length of the three-phase LV cables is changed in Case 2, the efficiency is 1.3% lower than in the corresponding ac case. It also drops by 1.6% as compared to Case 1 with dc. This is again because the three-phase LV cables are more loaded in the dc case, so their length impacts the losses greatly. This is also the only change that affects the utilization of the dc-dc converter, which increases by 0.9%, whereas in the other cases it is almost constant (51.3-51.4%). However, there is a big difference in the utilization of T2, as compared to the ac case, due to the fact that there is now no reactive power circulating in the system downstream of the transformer. However, the utilization of T2 is almost the same as in the mixed ac-dc case, which indicates that the reactive power is mostly due to the load consumption and not to the MV grid. It could therefore be of interest to study further how the results change with the load power factor.

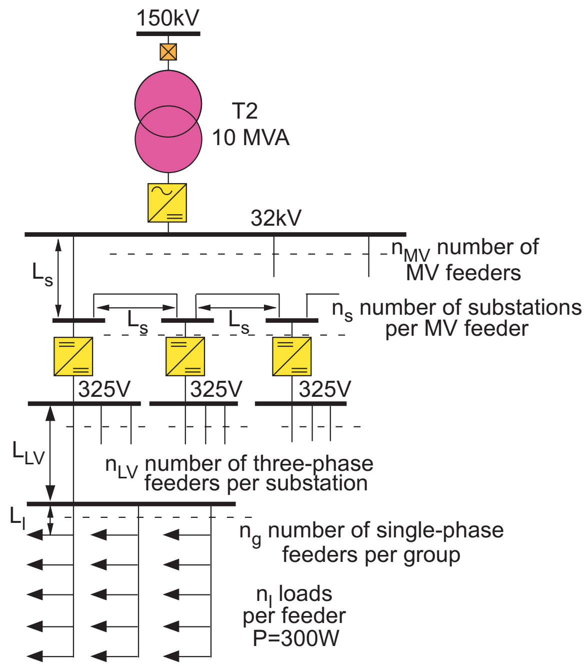

Figure 12 – Case study: multilevel dc grid.

TABLE VI – RESULTS OF DC SYSTEM CALCULATIONS

Case number	L_{LV} [m]	L_s [Km]	U_{dc} [kV]	f_{sw} [Hz]	I_{IGBT} [A]	K_{IGBT} [pu]	h [%]	$u_{dc\text{-}dc}$ [%]	u_{T2} [%]
1	20	2	32	1500	25	1	96.8	51.3	67.1
2	50	2	32	1500	25	1	95.2	52.2	68.2
3	20	4	32	1500	25	1	96.7	51.3	67.2
4	20	2	32	2500	25	1	96.7	51.4	67.1
5	20	2	32	1500	25	0.5	97.5	51.3	66.6
6	20	2	32	2500	25	0.5	97.5	51.3	66.6
7	20	2	16	1500	25	1	96.4	51.4	67.4
8	20	2	32	1500	75	1	96.8	51.4	67.1

The efficiency of the system depends only marginally on the switching losses in the converters, as it can be seen from Case 4, where an increase in the switching frequency to 2500 Hz causes the losses to increase by only 0.1% (note, however, that the switching frequency is changed only for the dc-dc converters, not for the ac-dc converter station). If a decrease in semiconductor losses by half is assumed, the efficiency of the system becomes higher than that of the ac system, with the total losses going down to 2.5% (see Case 5 and 6 in Table VI). The efficiency of the dc system is maximized by using a rated voltage of 32 kV for the MV level. By using 16 kV (Case 7), the losses go up by 0.4%. Still, there is a consistent reduction in the loading of T2. Finally, the effect of choosing different IGBTs with higher nominal current has been considered in Case 8 (75 A instead of 25 A), but no consistent changes have been noticed in the loss calculations. This probably because when the rated current increases, the resistance, thus the conduction losses, decrease (see Table IV), whereas the energy, and thus the switching losses, increases, so the two effects even out in this case.

The most important conclusion is that the low utilization of the transformer allows expanding the system, if the load increases, without changing the transformer. The number of MV feeder's n_{MV} (240-mm^2 cables at 32 kV dc) can be increased from 4 to 6, before the utilization of T2 reaches 100%. This means that the total system power is increased by 50%, thus becoming 9.72 MW. The efficiency of the system is still $h = 96.8\%$, which is obvious because the losses in the converter station have been expressed as a fixed percentage of the input power. However, the utilization of the dc-dc converter is also very low, as seen from Table VI. The load supplied at LV level can be increased by increasing the number of modules served by one dc-dc converter n_{LV} from 6 to 9, while keeping the number of MV feeders unchanged ($n_{MV} = 4$), thus obtaining a system serving a total load power of 9.72 MW with $h = 96.7\%$, $u_{dc\text{-}dc} = 77.0\%$ and $u_{T2} = 101\%$.

Conclusions

In this paper, the efficiency of dc systems is studied. Losses for an example ac system, a dc system and a mixed ac-dc system are calculated and compared. Losses for the mixed ac-dc system are about 1% higher than for the ac system. The efficiency increases if dc is applied at both MV and LV levels, but losses are still about 0.5% higher than for the ac system. The efficiency of the pure dc system becomes higher than for the ac system under the assumption that semiconductor losses decrease by half. Moreover, internal losses due to ac-dc conversions in the loads have not been considered here.

For both solutions involving dc, the loading of the HV/MV transformer is much lower than for the ac system. This means that the system can easily withstand a load increase without changing the transformer. Note, however, that no capacitive compensation has been considered in the ac case. A more thorough analysis should be done including power factor correction and different load power factors.

It can concluded that, although today reduction of cable losses may not be the decisive factor for adopting dc, this may change in the future, depending on the developments in semiconductor technology. It still deserves, however, to be considered among the advantages with using a dc system.

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Biographies

Daniel Nilsson (S'02) received the M. Sc. degree from Chalmers University of Technology, Gothenburg, Sweden in 2002. Since December 2002 he is working towards his Ph.D. at the Department of Electric Power Engineering of Chalmers University of Technology, Gothenburg, Sweden. His research project is about dc distribution systems.

Ambra Sannino (S'99, M'01) received the M. Sc. degree and the Ph.D. degree from the University of Palermo, Italy in 1997 and 2001, respectively. During 1998 she was a trainee at ABB Corporate Research Center at Heidelberg, Germany. From August 1999 to September 2000 she was a guest researcher at the Department of Electric Power Engineering of Chalmers University of Technology, Gothenburg, Sweden, where she is currently working as Assistant Professor. Her interests include applications of power electronics in power systems and power quality.

7. GENERATION RELIABILITY FOR SMALL ISOLATED POWER SYSTEMS ENTIRELY BASED ON RENEWABLE SOURCES

Math Bollen, STRI AB, Ludvika, Sweden
Stephen R. Connors, Massachusetts Institute of Technology, Cambridge, MA, USA
Jimmy Ehnberg, Chalmers University of Technology, Gothenburg, Sweden.

Abstract

This paper investigates generation reliability for power systems entirely based on renewable energy sources. Stochastic models for solar and wind power is used together with simpler models of small-scale hydropower and storage. The load model is deterministic and based on industrial activities with a maximum load of 28 kW. 38 different cases with different supply configurations are simulated using Monte-Carlo simulation. It can be concluded that a system with only wind power has a higher availability than a system with only solar power. However solar power is more regular which allows for a more efficient use of storage. To obtain a high availability large storage capability is needed or a combination of sources.

Introduction

If the developing countries will have the same development regarding energy as have been in the industrial part of the world the resource will not be enough. Therefore a different energy behavior is needed. Not only more efficient use of energy (energy saving) but also more widespread use of renewable energy sources.

For rural or remote areas, where an extension of the existing grid is not economically or technically possible, electrified has to be carried out in the form of small isolated power systems. Traditional energy supply for remote rural areas is wood for cooking, candles for lights and batteries and diesel generators for TV and other leisure activities. The traditional sources contribute not only to the deforestation and green house effect but also lead to further waste of our limited natural resources.

Electrification does not only save the environment and the resources but will also have a positive effect on the conditions of the social system. The way of living will change through possibilities for small-scale industrial activities, use of refrigerators for vaccine and education during the evening. Education during dark hours is important as adults and older children typically have to do agriculture work during daytime. Another reason for electrifying is avoiding migration, which could lead to poverty belts around nearby cities [1].

Using wind or solar power in combination with diesel generators supplying isolated power systems (alone or in combinations with wind power) is a well-studied area [2] but the next challenge is to build a power system based entirely on renewable energy sources. Ideas of how to use renewables in the power supply are many and some are presented in [3]. The main sources that are currently available as mature technology are solar, wind and hydropower, but others may become available in the future.

The purpose of this paper is to study the possibilities for small isolated power systems based entirely on renewable sources. The focus is on solar and wind power, for which stochastic models have been developed, but also hydropower and storage are considered. In this investigation no economical aspects have been considered, but the study results can be used as a basis for an economic optimization.

Models of Renewables and Load

To be able to investigate the generation reliability of a power system based entirely on renewable energy sources, models of sources, storage and load are needed. In this section a general overview of the models is presented.

Solar power

The model used for solar power has been presented in detail in [4]. The model is based on geographical location, time and meteorological conditions. The geographical location part is deterministic while the meteorological conditions are considered stochastic. The meteorological part is introduced through the cloud coverage. A Markov theory based model is used for simulating cloud coverage [4].

Wind power

For obtaining wind power time series data a model based on Markov theory has been used. The model is divided into two parts: one for low wind (hourly mean value below yearly mean) and one for high wind (hourly mean value above yearly mean). The transition probabilities in the Markov model are calculated from yearly mean-value-normalized wind speed data that are discretised into 9 plus 14 levels, for the low-wind and high-wind parts, respectively. The output from the model should be adapted to the site-specific yearly mean wind speed value. To obtain the power from a wind turbine at the specific site a wind-power curve is used, obtained for a commercially-availability wind turbine. The model is presented in more detail in [5].

Hydro micro-turbines

A model has been based on a weak flow-of-river in combination with a small reservoir. The flow-of-river is considered constant. The required flow to cover 10 % of the maximum load is 0.4 m^3/s with a mean water drop of 1 m and an overall efficiency of 70~\%, which is achievable in systems with weak flows [6].

Storage

There are currently several different storage technologies with different advantages and disadvantages. The main types of technologies are [7]:

- Mechanical: for example pumped hydro, compressed air energy storage and flywheels.
- Electrical: for example super conducting magnetic storage and capacitors/ultra capacitors.
- Electrochemical: for example batteries and flow batteries.

Which one to use is hard to decide at this stage because the usefulness of the technologies is often dependent on the location. Some of the technologies are not currently suitable for this application but might be in the future. Therefore no specific storage technology has been chosen and an efficiency of 80 % is assumed. In all other aspects the storage has been considered ideal.

Load

The behavior of the load is one of the main factors in reliability calculations since that sets the demand on the power supply. Since the load is so important all conclusions should be related to the behavior of load. For this calculation a simple industrial-load-based model has been used. The model can be seen in Figure 1: the load is at 100 % between 07.00 and 19.00 (considered daytime). The mean load is assumed to be 15 kW, which gives a total energy consumption of 360 kWh/day.

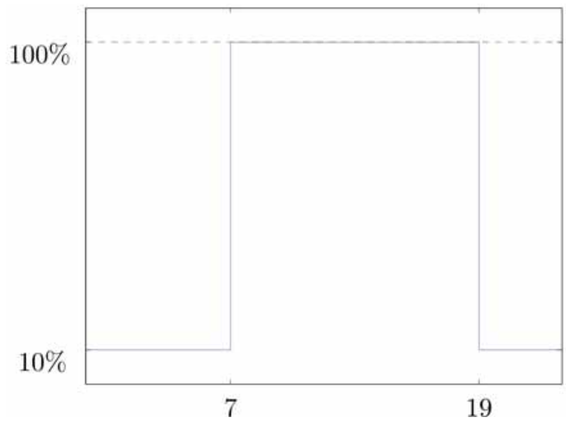


Figure1. The load curve used for the reliability calculations.

The load model is not the load in a traditional way but more like the power that should be available. The traditional load is hard to determine due to strong dependencies to different categories of industrial activity. When managing industrial activities the basic conditions are very important, it is not the actually condition but rather the consistently of the conditions that is of major importance.

Case Study

A way to study the reliability of combinations of power sources is to study different cases. A total of 38 cases with solar and/or wind power in combination with storage capability and/or hydropower have been investigated.

The solar power model is based on geographical location and therefore a location for the case study was chosen. Since the main goal was to study systems for developing countries such a location was chosen, Timbuktu (16.75º N, 3.07º W) in Mali because its sub-Saharan climate.

Meteorological data for the models is needed for Timbuktu but since that is hard to achieve, data from Sweden has been used. Wind data was obtained from Näsudden, Gotland while solar data was measured at Säve airport, close to Göteborg.

To relate the generation and storage capacity used in the simulation to the load and to compare the different power sources and storages, two ratios are introduced: Maximum Generation Capacity (MGC) and Maximum Storage Capacity (MSC). MGC and MSC are calculated according to Table I, for different power sources and storage methods.

Table I. Explanation of MGC and MSC for different sources and storages.

MGC_{wind}	The ratio between the rated power of the wind turbine and maximum load.
MGC_{solar}	The ratio between the maximum generation of the solar power (clear sky and the sun in zenith) and the maximum load.
MGC_{water}	The ratio between the power generated by flow-of-river and maximum load.
$MSC_{storage}$	The ratio between storage capacity and maximum load, in hours.
$MSC_{reservior}$	The ratio between maximum energy to be stored in the reservoir and maximum load, in hours.

In Figure 2 a schematic figure of the power flow in the system is shown. The arrows indicate the direction of flow. The power system is modeled as a single node and shown in the figure as a circle. The power system is considered ideal in all other aspects: outages in the (distribution) network are not considered in this study.

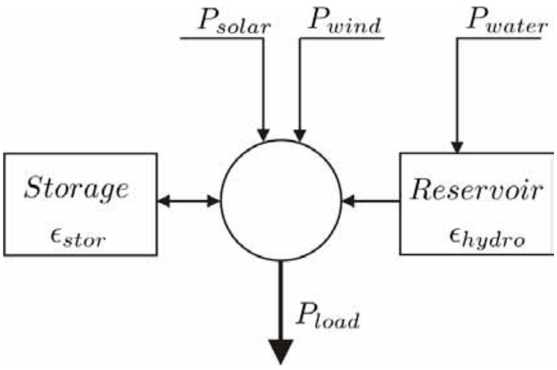


Figure.2. A schematic sketch of the system. The arrows indicate the direction of the power flow.

where

P_{wind}	Power from wind
P_{solar}	Power from sun
P_{water}	Power of the water supplying the reservoir
P_{load}	Total load of the system
$\varepsilon_{storage}$	Energy in the storage
ε_{hydro}	Energy in the reservoir

The reliability is estimated through use of Monte-Carlo simulations. The availability is the probability that the load is supplied at an arbitrary chosen time and is calculated as the mean value of ten independent simulations. A simulation time period is one year to include seasonal variations and a time step of one hour is used. The load is considered supplied if the condition in (1) is fulfilled.

$$P_{wind} + P_{solar} + \epsilon_{storage} + \epsilon_{hydro} \geq P_{load} \qquad (1)$$

For the next step the storage levels are updated according to (2) and (3).

if $P_{load} > P_{wind} + P_{solar} + \epsilon_{stor}(i)$

$$\epsilon_{stor}(i+1) = 0 \qquad (2a)$$

if $P_{load} < P_{wind} + P_{solar}$

$$\epsilon_{stor}(i+1) = \epsilon_{stor}(i) + 0.8P_{change} \qquad (2b)$$

otherwise

$$\epsilon_{stor}(i+1) = \epsilon_{stor}(i) + P_{change} \qquad (2c)$$

if $P_{load} < P_{wind} + P_{solar} + \epsilon_{stor}(i)$

$$\epsilon_{hydro}(i+1) = \epsilon_{hydro}(i) + P_{water} \qquad (3a)$$

if $P_{load} > P_{wind} + P_{solar} + \epsilon_{stor}(i) + \epsilon_{hydro}(i)$

$$\epsilon_{hydro}(i+1) = P_{water} \qquad (3b)$$

otherwise

$$\epsilon_{hydro}(i+1) = \epsilon_{hydro}(i) + P_{water} + P_{change} + \epsilon_{stor}(i) \qquad (3c)$$

where

$$P_{change} = P_{wind} + P_{solar} - P_{load} \qquad (4)$$

In (2)-(4) it can be seen that the energy in the storage is primary used, because the storage can be refilled with the over-production of the solar and wind power while the reservoir is only refilled by the flow-of-river which is small compared to the amount of energy produced by solar or wind.

Not all sources and storages are used in all simulations, to be able to investigate the individual behavior of the sources. The results are summarized in Table II.

Table II. The availability for different configurations and amount of installed power for the system shown in Figure 2.

Case No.	MGC_{solar}	MGC_{wind}	MGC_{water}	$MSC_{storage}$	$MSC_{reservior}$	Total MGC	Total MSC	Availability
1	5	0	0	0	0	5	0	0.30
2	10	0	0	0	0	10	0	0.40
3	0	5	0	0	0	5	0	0.49
4	0	10	0	0	0	10	0	0.61
5	5	0	0	1	0	5	1	0.39
6	10	0	0	1	0	10	1	0.52
7	5	0	0	3	0	5	3	0.75
8	10	0	0	3	0	10	3	0.93
9	0	5	0	1	0	5	1	0.60
10	0	10	0	1	0	10	1	0.69
11	0	5	0	3	0	5	3	0.67
12	0	10	0	3	0	10	3	0.75
13	5	0	0.05	0	1	5.05	1	0.34
14	10	0	0.05	0	1	10.05	1	0.48
15	5	0	0.1	0	1	5.1	1	0.88
16	10	0	0.1	0	1	10.1	1	0.95
17	5	0	0.2	0	1	5.2	0	0.93
18	10	0	0.2	0	1	10.2	1	0.98
19	0	5	0.05	0	1	5.05	1	0.62
20	0	10	0.05	0	1	10.05	1	0.70
21	0	5	0.1	0	1	5.1	1	0.73
22	0	10	0.1	0	1	10.1	1	0.78
23	0	5	0.2	0	1	5.2	1	0.76
24	0	10	0.2	0	1	10.2	1	0.80
25	5	0	0.1	1	1	5.1	2	0.91
26	10	0	0.1	1	1	10.1	2	0.98
27	0	5	0.1	1	1	5.1	2	0.76
28	0	10	0.1	1	1	10.1	2	0.81
29	2.5	2.5	0	0	0	5	0	0.59
30	5	5	0	0	0	10	0	0.71
31	2.5	2.5	0	1	0	5	1	0.71
32	5	5	0	1	0	10	1	0.85
33	2.5	2.5	0.1	0	1	5.1	1	0.88
34	5	5	0.1	0	1	10.1	1	0.96
35	2.5	2.5	0.1	1	1	5.1	2	0.92
36	5	5	0.1	1	1	10.1	2	0.98
37	2.5	2.5	0.1	3	1	5.1	4	0.95
38	5	5	0.1	3	1	10.1	4	0.99

Discussion

In this section all case numbers refer to the cases presented in Table II. All the odd numbers are the same case as the next even numbered case except that the generation capacity, which is only half for wind and solar power. The effect of the level of over-capacity in generation can easily be studied in this way.

Cases 2 and 4 show that wind power has a higher overall availability then solar power. However the picture is more complicated because all the availability of solar power is during daytime while the wind is spread over the whole day, as seen in Figure 3, which shows the number of times per year that there is a shortages for every hour if the day. The slightly higher numbers of shortages during daytime for wind power are due to the higher load. There might be situations where higher availability daytime is more important then during nighttime.

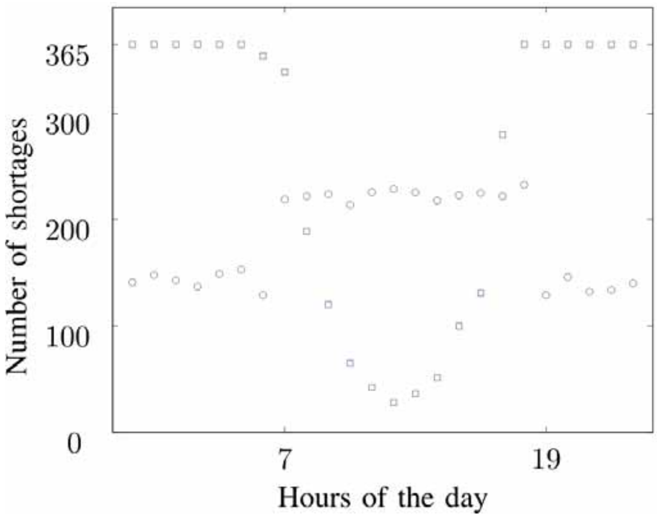


Figure 3. The number of shortages per year for each hour of the day. The squares refer to solar power (case 2) while the circles refer to wind power (case 4).

When only a single power source is used wind gives a higher availability then solar power but when storage capability is added the difference will decrease and for large storage capabilities it is the opposite way, see cases 1 to 12. This may depend on the more efficient use of storage by the solar power since it is more regular, it will fill the storage during daytime and empty it during nighttime. In Figure 4 the energy level in the storage for case 3 can be seen for a few consecutive days.

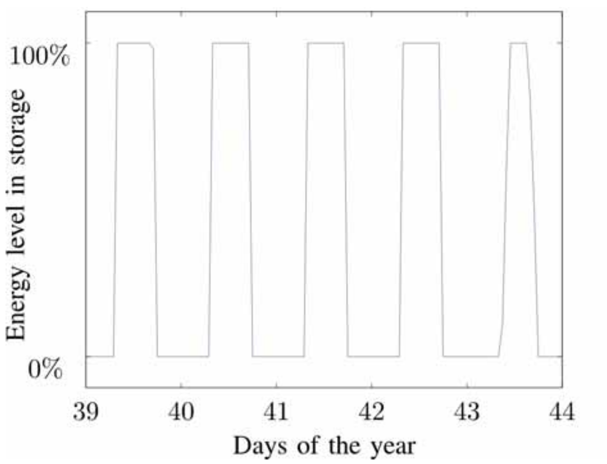


Figure 4. The energy level in the storage with solar as single power source.

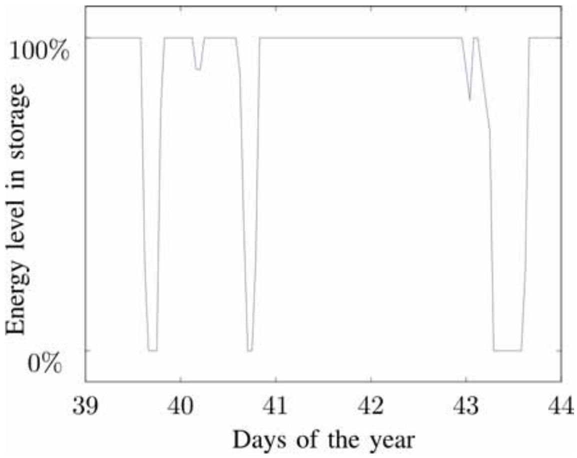


Figure 5. The energy level in the storage with wind as single power source.

The regular behavior can easily be seen if it is compared with Figure 5, which is the energy level for a few consecutive days with wind power, case 12.

A great generation over-capacity is necessary since the maximum generation rarely occurs, which can be seen in Table III, where the availability is calculated for different MGC_{solar}.

Table III. The availability for different MGC_{solar} with $MSC_{storage}$=1.0.

Case No.	MGC_{solar}	$MSC_{storage}$	Availability
a	1	1	0.00
b	2	1	0.17
c	5	1	0.39
d	8	1	0.49
e	10	1	0.52

The main problem with renewable sources of energy is the random behavior of its capacity. A small constant power source with storage capability can be used to compensate for this. Flow-of-river in combination with a small reservoir is such a source. The reservoir generates additional storage capabilities. The availability increases significantly if the flow-of-river MGC_{water} exceeds a level of 0.1 because it covers then the load during nighttime when the availability of the sun is zero. Increasing MGC_{water} further gives only a small increase in the availability until MGC_{water} reaches a value around 1.0 because then hydro generation will cover the total load.

By using both hydro generation and storage capabilities the benefits from both sources may be used: hydro generation covers the nighttime and the storage even outs the daytime production. For this combination solar power is more beneficial then wind in an availability point of view, compare case 25/26 and 27/28: half the amount of solar power still gives a higher availability than wind power.

Combining solar and wind is not as effective as solar and hydropower because of the good interaction between solar and hydro generation. Combining all three sources (solar, wind and hydro) gives a favorable combination as can be seen in case 33/34. It also lowers the vulnerability of the system since several different sources are used.

Despite all the generation the availability does not reach 100 %: the main problems occur in mornings and evenings as can be seen in Figure 6, case 34. Shortages occur when the load is at daytime level but it is before dawn or after dusk or the solar angle to the horizon is too small. Although the overall availability is 96 %, around six in the evening, there is insufficient energy once every four days. This problem can be decreased by adding storage capabilities to the system as done in case 36, and the result of the case can be seen in Figure 7. The risk of insufficient energy at the end of the day has dropped to once in 10 days.

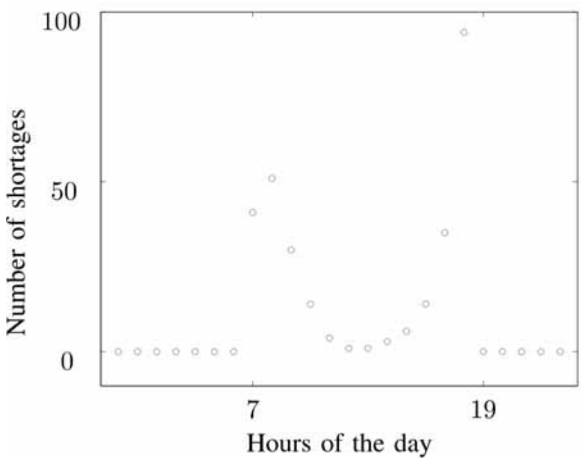


Figure6. The number of shortages per year for each hour of the day for case 34.

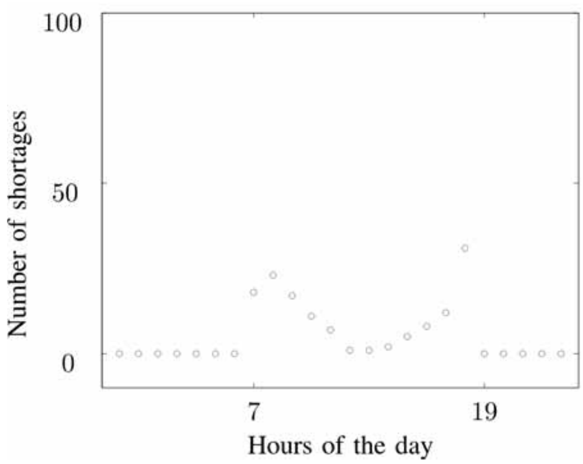


Figure 7. The number of shortages for each hour of the day for case 36.

When the load is not fully supplied some power remains available. Figure 8, for case 34, and 9, for case 36, shows the amount of available power when the load is not fully supplied. To be able to use this power some kind of load reduction schedule is needed. Such a schedule should be controlled locally to allow for a good understanding of the most essential power needs. A temporary decrease of the load by 10 % will give 17 %, for case 34, and 22 %, for case 36, less outages per year. Rescheduling industrial activities to the following day or stop water pumps or other long time running activities could do the load reduction.

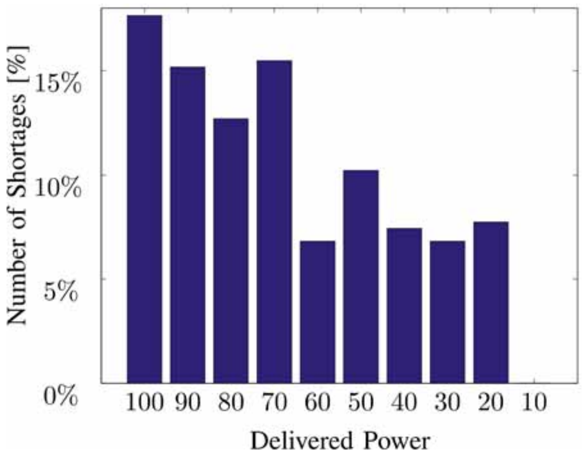
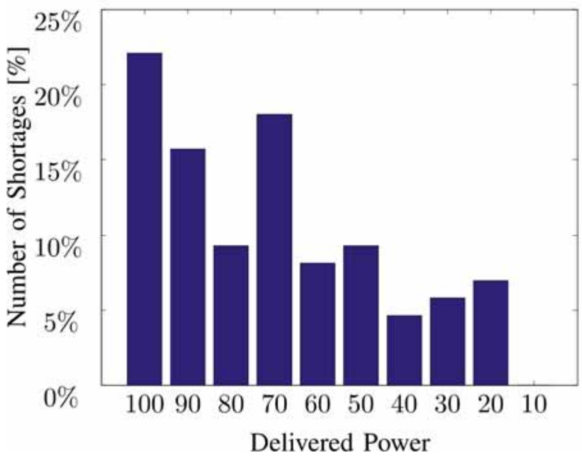


Figure 8. The available power when the load is not fully supplied, for case 34. Each bar has a width of 10 % and the highest value of the interval is shown below each bar. The 100 % values are not included.



Figore 9. The available power when the load is not fully supplied, for case 36. Each bar has a width of 10 % and the highest value of the interval is shown below each bar. The 100 % values are not included.

Conclusion

In a system based on a single power source, a wind-based system has a higher availability then a solar-based one. However the solar based system shows a much more regular behavior. A large over-capacity in generation is needed for both solar and wind due to its stochastic behavior.

Adding storage capability increases the availability more for solar-based than for wind-based systems. For large storage capabilities the solar-based system has a higher availability due to more efficient use of the storage. Combining solar and wind and a small constant hydropower source give a good availability. By active load shedding of 10 % the number of shortages per year could be reduced with up to 20 %.

When building power systems entirely based on renewables either large storage capabilities are needed or combinations of sources to secure the reliability of the system.

The studies presented in this paper combined a location in Africa with cloud-cover and wind-speed data obtained in Sweden. The aim of this stage of the work was the develop the stochastic models needed for the kind of reliability studies presented here. The authors are aware that this limits the value of the conclusions. The results should be interpreted in a qualitative way, not in a quantitative way. Before the actual building of such a system is initiated more representative local data is needed. It is also needed to decide on what is an acceptable level of reliability for such a system.

More future work includes the development of schemes for load reduction or rescheduling during periods of low available capacity.

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Biographies

Jimmy S.G. Ehnberg (S'01) received the M.Sc. degree from Lund University of Technology in 2000. Since then he has been working for his Ph.D. degree in electric power system at Chalmers University of Technology. His research interests include power system reliability and renewable energy sources.

Math H.J. Bollen (M'94-SM'96) received the M.Sc. and Ph.D. degrees from Eindhoven University of Technology, Eindhoven, The Netherlands, in 1985 and 1989, respectively. He is currently manager EMC and power quality at STRI AB, Ludvika, Sweden. Before joining STRI in December 2003, he was Research Associate at Eindhoven University of Technology, Lecturer at the University of Manchester Institute of Science and Technology, Manchester, U.K. and Professor in electric power systems at Chalmers University of Technology, Gothenburg, Sweden.

PANELISTS

1. Ambra Sannino
Power System Group
Chalmers University of Technology
Department of Electric Power Engineering
S-412 96 Göteborg
Sweden
Tel: +46 31 772 3832
Fax: +46 31 772 1633
E-mail: ambra.sannino@elteknik.chalmers.se
Title: Global Power Systems for Sustainable Development--An Introduction

2. Prabha Kundur, Ph.D., FIEEE, FCAE
President & CEO
Powertech Labs Inc.
12388, 88th Avenue
Surrey, B.C.
V3W 7R7 - Canada
Tel: +1 604-590-7469
Fax: +1 604-599-8269
E-mail: prabha.kundur@powertechlabs.com
Title: Sustainable Electric Power Systems in the 21st Century: Requirements, Challenges and the Role of New Technologies

3. Gunnar Asplund
Technical Director
ABB Power Technologies
Power Systems, HVDC
SE-771 80 Ludvika
Sweden
Tel: +46-(0) 240-782 146, +46-(0) 70- 550 1080 (cell)
Fax: +46-(0) 240-61 11 59
E-mail: gunnar.asplund@se.abb.com
Title: Sustainable Energy Systems with HVDC Transmission

4. Göran Andersson
Professor, Power Systems
EEH - Power Systems Laboratory
ETH Zentrum / ETL G 26
Physikstrasse 3
CH-8092 Zurich
Switzerland
Tel: +41 1 632 08 16
Fax: +41 1 632 12 52
E-mail: andersson@eeh.ee.ethz.ch
Title: Power Electronics Solutions for Sustainability

5. Robert B. Schainker
EPRI, Power Delivery & Markets
3412 Hillview Ave.
Palo Alto, CA 94304
USA
Tel: +1 650 855-2549 office, +1 650) 996-6186 cell
Fax: +1 650 855-8997
E-mail: rschaink@epri.com
Title: Executive Overview: Energy Storage Options for a Sustainable Energy Future

6. Daniel Nilsson,
Power System Group
Chalmers University of Technology
Department of Electric Power Engineering
S-412 96 Göteborg
Sweden
E-mail: daniel.nilsson@elteknik.chalmers.se
Tel: +46 (0)31 772 1638
Fax: +46 (0)31 772 1633

Co-author:
Ambra Sannino
Power System Group
Chalmers University of Technology
Department of Electric Power Engineering
S-412 96 Göteborg
Sweden
E-mail: ambra.sannino@elteknik.chalmers.se
Tel: +46 31 772 3832
Fax: +46 31 772 1633
Title: Efficiency Analysis of Low and Medium-Voltage DC Distribution Systems

7. Author 1:
Math Bollen (probable presenter)
STRI AB
Box 707
SE-771 80 Ludvika
Sweden
E-mail: math.bollen@stri.se
Tel: +46-240 795 00
Fax: +46-240 150 29

Author 2:
Stephen R. Connors
Director, Analysis Group for Regional Electricity Alternatives
Laboratory for Energy and the Environment
Massachusetts Institute of Technology
Room E40-465
Cambridge

MA 02139-4307
USA
E-mail: connorsr@mit.edu
Tel: +1 617-253-7985
Fax: +1 617-253-8013

Author 3:
Jimmy Ehnberg,
Power System Group
Chalmers University of Technology
Department of Electric Power Engineering
S-412 96 Göteborg
Sweden
E-mail: jimmy.ehnberg@elteknik.chalmers.se
Tel: +46 (0)31 772 1624
Fax: +46 (0)31 772 1633
Title: Generation Reliability for Small Isolated Power Systems Entirely Based on Renewable Sources

Session Chairs:

Ambra Sannino
Power System Group
Chalmers University of Technology
Department of Electric Power Engineering
S-412 96 Göteborg
Sweden
Tel: +46 31 772 3832
Fax: +46 31 772 1633
E-mail: ambra.sannino@elteknik.chalmers.se

Tom Hammons
Chair International Practices for Energy Development and Power Generation
Glasgow University
11C Winton Drive
Glasgow G12 0PZ
UK
Tel: +44 141 339 7770
E-mail: T.Hammons@ieee.org

E N D