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Autonomous Fossil Fuel and Renewable Energy (RE)-based Power Systems

A.S. Neris

2.1 Introduction

Autonomous power systems (APS) comprise a solution for the electrification of applications when the access to a large transmission network is not economically viable or even impossible. Their size can range from few hundred Watts to tens or hundreds of MW.

Rural areas in developing and developed countries, without the necessary grid infrastructure, are a characteristic example of applications with a high potential for the development of autonomous power systems. Taking into account the strong correlation between the economic development in these areas and their electrification, the importance of powering them is evident. Other application fields include holiday houses, physical islands and remote telecommunication and industrial installations.

Autonomous power systems can be based on renewable energy (RE) units, such as wind turbines, photovoltaic systems or small hydro power stations and fossil-fuel generators. Due to the intermittent nature of renewable energy, storage devices and/or appropriate demand management strategies are necessary when conventional generators are not included in the system.

In the case of autonomous power systems electrified by fossil-fuel units, diesel generators are usually utilised, due to their low cost and reliability. However, the fuel used is polluting and expensive taking into account the transportation costs. A solution to these problems can be the introduction of renewable sources in the power mix, when adequate resources are available. In such a case considerable improvement can be accomplished in terms of fuel saving. However, for the achievement of a large penetration of renewable sources technical issues related to system stability and reliability of supply, due to the fluctuating and intermittent characteristics of renewable resources, must be confronted. Similarly to the previous case of renewable-based APS, this can be achieved through the introduction of controllable storage devices and/or demand-management techniques.

In the following, a description of the operational characteristics for renewable and conventional generation technologies, used in APS, will be provided. Based on this information, a technical overview of APS will be performed, with emphasis on stability and energy management issues. Finally, economic evaluation of APS design will be analysed in terms of the relevant optimisation problem configuration.

2.2 Generation Technologies in Autonomous Power Systems

2.2.1 Renewable Generators

2.2.1.1 Wind Turbines

Wind turbines convert the kinetic energy of the air mass flowing through the blades into rotational energy at the generator shaft. Generators used in wind turbines of small sizes (up to tens of kW) are permanent magnet synchronous or induction machines. For larger wind turbines (hundreds of kW up to the MW scale) some other types of generation schemes are also used, such as the doubly fed induction generator (Ackermann, 2005).

Figure 2.1 shows the most common cases for the utilisation of a wind turbine in an APS. In the first configuration, a wind turbine with a permanent magnet generator is the only power source. Battery storage is used for the compensation of the intermittent nature of the wind resource, and the wind turbine operates as a battery charger. This task is supported by a dedicated controller that serves as an interface with the storage system. The rectifier shown in the control scheme is used for the conversion of the variable AC generator voltage to DC voltage. The load control functionality is used for the energy management of the system according to the available wind power and the batteries’ state of charge. When the system must serve AC loads, a DC/AC converter is also included. In the second case, the same wind turbine is connected to an APS grid including other power sources with the capability to control voltage and frequency. The grid interface comprises a rectifier and an inverter.

Comparing the configuration and the operation logic of the two schemes, some major differences can be highlighted. First, in the second configuration, storage is not included since it is assumed that the APS grid is capable of absorbing all the power produced by the wind turbine. A difference also exists regarding the control strategy of the power electronic inverters. In the first case, the inverter is controlled in order to produce an AC voltage waveform of constant frequency and magnitude. In the second case the inverter behaves as a controllable AC current source. The amplitude of the current waveform is defined by the desired power production level of the wind turbine, while synchronization of this waveform with the voltage waveform at the point of connection is achieved through the utilisation of dedicated control circuits. Finally, in the second case, the existence of the power electronic interface between the wind turbine generator and the APS grid allows maximum power extraction from the wind, for wind speeds below nominal. This objective can be achieved through the appropriate regulation of the wind turbine rotor speed in order to operate with optimum aerodynamic efficiency factor (Leithead, 1991).

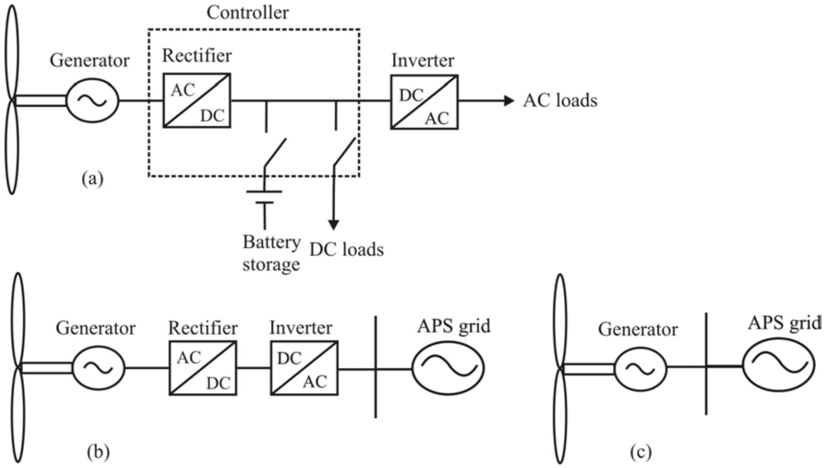

Figure 2.1. Utilisation schemes for wind turbines driving a permanent magnet synchronous generator (a) and (b), or an induction generator (c)

Wind turbines driving induction generators (third case), are mostly used in APS applications where voltage is produced by other controllable power sources such as diesel generators. They are directly connected to the grid, and their rotational speed is defined by the grid frequency and their power production level.

The power that can be produced by a wind turbine is defined by the following equation:

$$P = \frac{1}{2}\rho A C_{\mathrm{P}} v_{\mathrm{w}}^{3} \tag{2.1}$$

where:
ρ is the air density (kg/m^3)
A is the rotor swept area (m^2)
C_p is the aerodynamic efficiency factor. It is a function of the rotor blades design and angle as well as the relative speed of the rotor and wind (known as the tip speed ratio)
v_w is the effective wind speed (m/s)

The form of a wind turbine power curve is shown in Figure 2.2. The wind turbine starts producing electricity when wind speed exceeds the cut-in threshold. From that point up to the nominal wind speed, power increases proportionally to the cube of wind speed. For higher wind speeds, power is kept close to the nominal value due to the blades aerodynamic design (passive stall control). Alternatively, a control system regulating the pitch angle of the blades can be used for the same purpose (Freris, 1990).

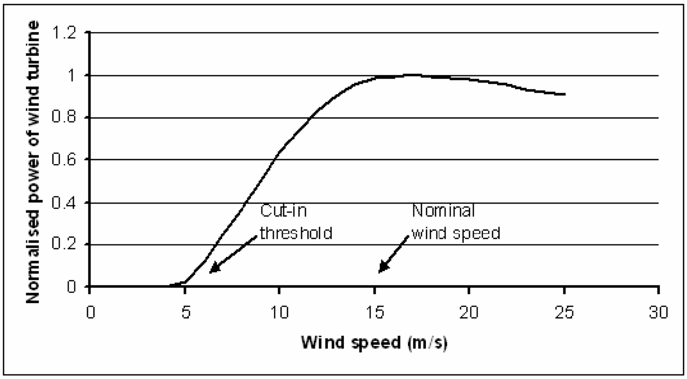

Figure 2.2. Wind turbine power curve

Wind speed varies over a wide range of time scales. Turbulent fluctuations in the time range of seconds to minutes are important for the assessment of the power quality and the stability of frequency and voltage in an APS. Hourly and daily variations on the other hand, are decisive for the evaluation of the wind potential in a considered site. For the characterisation of wind potential the primary input consists of time series of wind speed measurements. These measurements are usually average values in time steps of 10 min or 1 h. If the height of the meteorological mast used for the acquisition of measurements is lower than the height of the wind turbine tower then a mathematical formula must be used for the transformation of measurements, due to the wind shear effect (Manwell, 1998).

Finally, air density is a critical parameter for the evaluation of available wind power and as such it should be estimated from measurements of air pressure and temperature which are both dependent on the altitude above sea level.

2.2.1.2 Small Hydro Plants

Hydro power systems utilise the energy of flowing water for the production of electricity. A general consensus for the definition of small hydro power plants does not exist. The upper power limit varies from 2.5 to 25 MW, depending on the country, but 10 MW is the most acceptable one and has been proposed by the European Small Hydro Association (Thematic Network on Small Hydro Power, 2005).

Small hydro power plants are usually of the run of river type. In such schemes electricity is generated when the water is available and provided by the natural flow of the river. When the river dries up and the flow falls below some predetermined amount, the plant generation ceases.

The main components comprising a small hydro power plant are the civil works for the water diversion and the necessary mechanical and electrical equipment. Water is diverted from the river at the intake position, where a weir is built at an elevation higher than the power house. From that point, water is driven through a channel or a penstock to the turbine-generator set. Depending on the size of the plant and the considered application, synchronous or induction generators may be used.

The control system of the plant provides a number of functionalities including start-up and shut-down, synchronisation to the grid, monitoring of the upstream water level, operation of the flow valve control of the turbine to match the availability of water, detection of faults and activation of necessary alarms.

In addition, if the hydro plant is the only controllable source in the APS, voltage and frequency control of the grid should be included. In such a case, a synchronous generator must be used, in order to control voltage through the automatic voltage regulator of the machine. Frequency regulation can be achieved through the control of the water flowing to the turbine. For this task, speed governors are used that detect speed deviation and convert it into a change in the position of servomotors used for the control of valves and gates (Penche, 1998).

For smaller hydro power systems, such a solution is considered to be complex and additionally a danger exists of rapid control valve movement introducing damaging surge pressure waves in the pipelines or instability in the overall control system (Roberts, 2002). A preferable solution to maintain frequency close to its nominal value is the utilisation of load control. For the implementation of this scheme, secondary or even dump controllable loads are switched on and off, according to frequency-deviation measurements.

For the exploitation of available hydro power in a considered site, two physical quantities must exist, the flow rate of water and a head. Flow rate is the volume of water passing per second and it is measured in m^3/s. Head is the water pressure, which is created by the altitude difference between the water intake and the turbine. It can be expressed by the relevant vertical distance. A classification of sites exists, depending on the head values (British Hydropower Association, 2005). Sites with heads less than 10 m are considered "low-head", from 10-50 m are "medium-head" and above 50 m are classified as "high-head" sites. The power that can be produced by a hydro plant is expressed by the following equation:

$$P = n\rho g Q H \tag{2.2}$$

Where:
P is electrical power output (kW).
n is the overall efficiency of generation
ρ is the water density (1000 kg/m^3)
g is specific weight of water (9.81 kN/m^3).
Q is the flow rate (m^3/s)
H is the head (m)

Overall efficiency is calculated by the partial efficiencies of the plant components, including the pipelines, the turbine, the transmission system and the generator. Taking them into account, overall efficiency can range from 66% to 77%. While head can be considered almost constant, water flow varies over time and measurement records for at least a year are necessary for the determination of the hydro potential in a considered site.

2.2.1.3 Photovoltaic Systems

Photovoltaic systems convert sunlight energy into electricity. This procedure is based on the photovoltaic effect, a process in which the incidence of sunlight in a semiconductor arrangement of two layers causes the development of a voltage difference between them (Rai, 1999).

Figure 2.3 depicts the main configurations for the utilisation of a photovoltaic system in an APS. The photovoltaic array is assembled from a number of photovoltaic modules (the smallest commercially available unit) connected in parallel and/or in series in order to match the power needs of the project and the voltage thresholds of the other equipment. In the first case, the photovoltaic system is the only power source. A battery bank is used to cover demand needs when photovoltaic power is not adequate. This configuration is similar to that presented in the wind turbine section, with one exception. Due to the fact that the photovoltaic arrays are DC power sources there is no need to use a rectifier. In the second case the photovoltaic system is connected to a larger APS with power sources capable to control voltage and frequency. A DC/AC converter, equipped with a control functionality that allows maximum power-point tracking, is used as a grid interface.

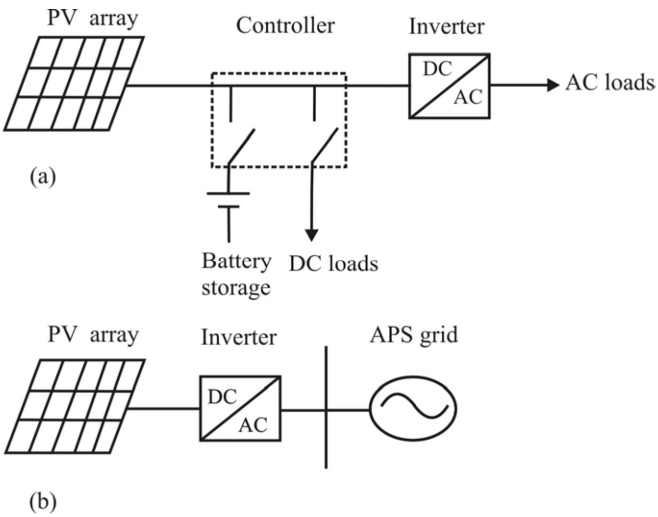

Figure 2.3. Utilisation schemes for photovoltaic systems

The operation of a photovoltaic system is governed by the current-voltage characteristic curves of the photovoltaic module. Such a set of curves, for different values of the incident solar irradiance and constant photovoltaic module temperature, is shown in Figure 2.4. The curves consist of two parts. In the first part the photovoltaic module behaves as a constant-current source, with amplitude proportional to the solar irradiance level. In the rest of the curve, current decays rapidly with the increase of voltage. Maximum power extraction is obtained at the knee point of the curves. For the tracking of this point, under varying environmental conditions, a number of algorithms have been developed (Esram, 2007).

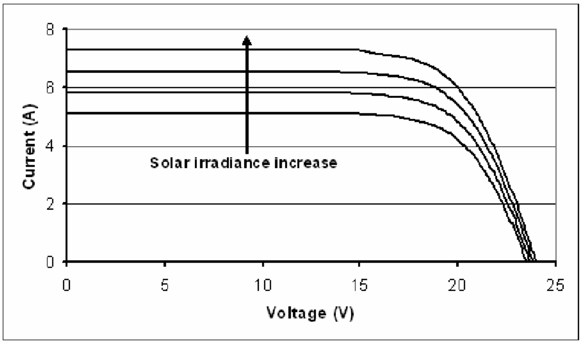

Figure 2.4. Photovoltaic module characteristics

Manufacturers provide operating characteristics of photovoltaic modules in standard conditions, which are defined by a solar irradiance value equal to 1000 W/m^2 and a photovoltaic module temperature equal to 25°C. The most important of them is the maximum power that can be obtained at these conditions and is used for the determination of the photovoltaic module nominal power. However, in a considered site, solar irradiance changes during the day. In addition, depending on the environmental conditions, due to the internal thermal losses of the photovoltaic module, its temperature also varies. As a result, the maximum extracted power is usually lower than that provided by the manufacturers.

Overall efficiency of photovoltaic systems is defined by the maximum efficiency of photovoltaic modules, the maximum power point tracking efficiency and the efficiency of the power converter used for the connection to the grid. Maximum efficiency of a photovoltaic module expresses the maximum exploitable percentage of solar energy for a certain irradiance level. It depends on the materials and manufacturing process used. For standard conditions, values obtained are in the range 5–15%. Maximum power-point tracking efficiency expresses the effectiveness of the implemented maximum power-point control algorithm. The value of this efficiency depends on the algorithm used and the environmental conditions. Finally, the DC/AC conversion efficiency depends mostly on the utilisation of a galvanic insulation transformer or not. It is a function of the inverter output power. Typical values at nominal power are in the range 90–95% (Abella, 2004).

For the characterization of solar resource, measured irradiance data as well as site-specific parameters are needed. These include geographic information (site latitude and longitude) for the calculation of the solar angle that also varies during the day, as well as ambient temperature for the estimation of the photovoltaic module temperature (Manwell, 1998).

2.2.2 Diesel Generators

Diesel engines belong to the category of reciprocating engines. They are used for power generation in applications with isolated power-source requirements or in situations where sudden demands for back-up power are expected. The inherent advantage of these prime movers is that they are low inertia structures that can be started and shutdown quickly, so that immediate requirements for additional power can be met without significant delay (Putgen, 2003).

Figure 2.5 presents in a block diagram form, the main components of a diesel generator. These include the speed governor, the diesel engine, the synchronous generator and the exciter of the generator with the automatic voltage regulator (AVR).

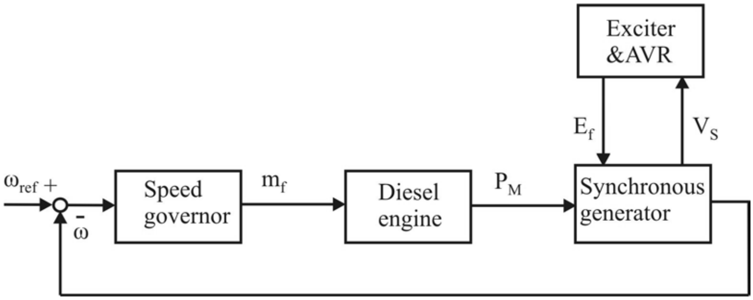

Figure 2.5. Diesel generator functional diagram

Diesel engines used for power generation are usually four-stroke and operate in four cycles (intake, compression, combustion and exaust) (Resource Dynamics Corporation, 2001). Initially, air is introduced in the combustion cylinder and compressed as the piston moves upwards. After that, fuel is injected. As the piston approaches the top of its movement, the air-fuel mixture is ignited due to the compression. The pressure of the generated gases forces the piston to move downwards. The energy of the moving piston is converted to rotational energy via a crankshaft. As the piston reaches the bottom of the stroke an exaust valve opens and the exaust gases are expelled from the cylinder by the rising piston.

Mechanical power produced by the engine (P_M) is proportional to the fuel consumption rate (m_f). This quantity is regulated by the speed governor that senses the difference of diesel-generator rotational speed (ω) from its reference value (ω_{ref}), and acts accordingly. A simple proportional (droop) controller is basically used allowing the shear of load between diesel generators according to their capacity. The addition of an integral term allows the minimisation of the speed error and as a result frequency can be restored to its nominal value after a disturbance (Stavrakakis, 1995). The exciter and the AVR of the synchronous generator allow terminal-voltage (V_s) regulation through the appropriate change of generator field voltage E_f.

In order to avoid increased wear and maintenance requirements of diesel engines, these units are not allowed to operate below a percentage of their nominal power that is called the technical minimum. Typical values of this limit are 20–

35%, depending also on the age and the overall condition of the engine. Figure 2.6 depicts the fuel consumption as a function of the power produced by a 120 kW diesel generator. As can be seen from this diagram, diesel generators are inefficient when operating at low loads. Since the operating cost of a diesel generator is defined by its fuel consumption, optimum economic operation is achieved when the diesel generator operates close to its nominal value.

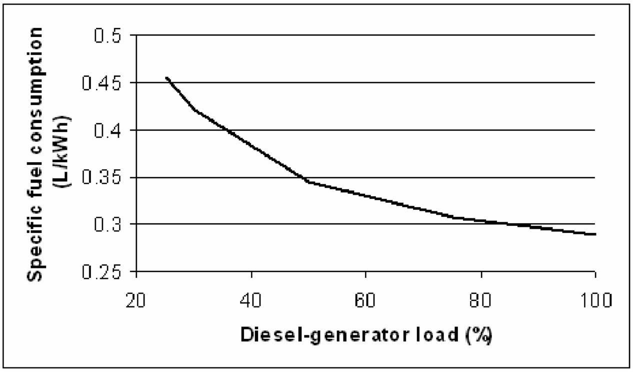

Figure 2.6. Diesel-generator fuel consumption characteristic

2.3 Technical Overview of Fossil-fuel and RE-based Autonomous Power Systems

2.3.1 Autonomous Power System Configurations

Depending on the system size and configuration, autonomous power systems can be classified in two large categories. The first one includes smaller power systems (with wind turbines and/or photovoltaic generators) build around a central storage device. Their power range can be up to few kW. These can be characterised as DC-based systems since the generating and storage devices are connected in a DC bus. A generic layout diagram describing their structure has been presented in the previous chapter. The second category includes larger power systems, such as those used for the electrification of small villages and physical islands. The power portfolio of these systems includes renewable and diesel generators connected through an AC distribution network. Their power range can be from a few kW up to several MW. A diagram showing such a configuration is presented in Figure 2.7 where some control devices necessary in order to manage considerable degrees of renewable penetration (*i.e.* the ratio of instantaneous power produced by renewable generators to the instantaneous consumed power) are also included (San Martin *et al.*, 2005).

In DC-based systems, the battery bank acts like a power damper, smoothing any short-term or long-term fluctuations, resulting from the renewable power units or the demand side. Regulation is mainly based on a few battery parameters such as the state of charge and the voltage. On the contrary, in AC-based systems the key issues are balancing of power and voltage regulation on very short time scales. This is done by the controllers of conventional generators, the use of synchronous compensators, dispatchable loads, storage and advanced hierarchical control systems. A more detailed analysis of this case follows in the next sections.

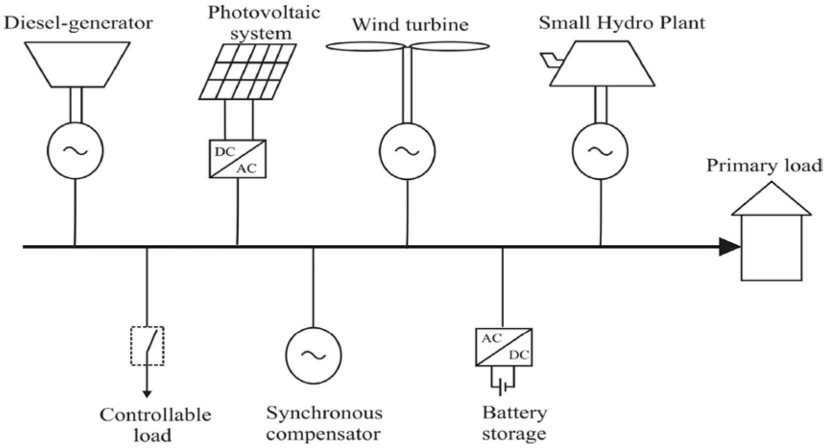

Figure 2.7. AC-based autonomous power system

2.3.2 Stability Isssues and Solutions

Preservation of acceptable levels of power quality is an essential requirement for the operation of power systems, APS included. Frequency stability and voltage control are the most important aspects of this issue. The European Standard EN–50160 (European Standard EN–50160, 1994) requires that for a non-interconnected (*i.e.* autonomous) power system, frequency and voltage should be within a range of:

- 50 Hz ± 2% (*i.e.* 49–51 Hz) during 95% of a week; 50 Hz ± 15% (*i.e.* 42.5–57.5 Hz) during 100% of a week
- 230 V ± 10% (*i.e.* 207–253 V) during 95% of a week; 230 V–15% +10% (*i.e.* 195.5–207 V) during 100% of a week

In an AC-based APS, frequency is defined from the rotational speed of one or more synchronous generators. Any disturbance of the production-consumtpion balance will result in a variation of the kinetic energy stored in the rotating masses of the generator sets according to the following equation:

$$\sum P_{\mathrm{G}} - \sum P_{\mathrm{L}} = \sum_{i} \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2} J_{\mathrm{i}} \omega_{\mathrm{i}}^{2}\right) \tag{2.3}$$

where:
P_G, P_L denote produced and consumed active power
J_i, ω_i are the moment of inertia and the rotational speed of the i_{th} machine.

As an example, we will consider an APS with a configuration similar to the one presented in Figure 2.7. According to the above equation, fluctuations of power in RE-based generators, for example due to passing clouds in the photovoltaic system or due to wind-speed variations in the wind turbine will result in deviations of the diesel-generator speed and the electrical frequency of the system. When the penetration level of RE-based generators is small, compared to the electrical load of the APS, these fluctuations can be compensated by the speed governor of the diesel generator. However, if the penetration increases, then frequency variations may exceed the limits imposed by the EN–50150 and depending on their amplitude an unstable situation may occur. This situation will lead to a power interruption due to the operation of frequency-protection devices.

Another dangerous condition concerns a potential case of a sudden disconnection of a large number of RE-based generators. Such an incident might take place due to a fault occurrence in the network that will depress voltages to levels lower than the under-voltage protection settings of these generators or due to the occurrence of high wind speeds that will cause a forced disconnection of the wind turbine for safety reasons. In such a case, if appropriate spinning reserve from the diesel-generator is not available, the power imbalance will cause a frequency depression that, depending on the renewable energy penetration, might lead in a power interruption also.

A solution to avoid these situations is the implementation of limitations on the power produced from renewable generators, depending on the operating condition of the system. Such a measure can improve the power quality and stability of the APS. On the other hand, bearing in mind that the introduction of renewable sources in an APS fed by diesel generators aims at the improvement of the operational efficiency and the minimisation of the fuel utilisation, this solution is far from being optimal.

A more promising alternative is the inclusion of energy storage in the autonomous power system. Different storage technologies such as batteries, flywheels or pumped storage may be used, depending on the needs and the size of the system (Barton, 2004). This solution can offer a number of valuable functions for the safety and quality of the power system operation. These functions, among others include:

- Spinning reserve: A small energy storage system can act as a fast reserve source for the time needed to start conventional generators, in cases where power production from renewable sources is interrupted due to some internal protection trip. It can also smooth the power step due to a sudden change in the generation from renewable sources thus giving time to the conventional generators to adapt their output.
- Energy transfer: Power from renewable sources cannot be controlled and often has a daily power profile different from the load demand. Through a

storage system the energy surplus in high-generation periods can be stored and released in low-generation periods.

- Frequency regulation: The response of diesel governors to changes in generator output is dynamically limited and large frequency fluctuations can be expected. Inverter-interfaced storage can change its power output from +100% to –100% and *vice versa*, within a single cycle of the system voltage. Therefore, with a small storage, stabilisation of system frequency can be achieved by instantaneously supplying the power imbalance.

In addition to these functions, when production of renewable generators is capable of meeting consumption, a possibility exists to switch off the diesel generator and utilise the storage device for frequency control. Such a mode of operation has been realised in practice in the autonomous grid of Kythnos island (Belhomme, 2006). In the implemented configuration, a synchronous compensator, that is a synchronous motor equipped with an AVR is used for voltage control. The battery inverter provides the necessary current in order to regulate frequency.

An alternative or complementary solution to the introduction of storage is the utilisation of secondary controllable loads in the system that will be activated when the production of renewable generators exceeds the current demand. Such loads might be desalination units, water heating, house or district heating, *etc.*

So far, issues related to the frequency stability of an APS have been presented. Maintaining voltage levels in the AC buses of an autonomous power system close to their nominal value is a similar problem. Such an objective can be obtained if equilibrium can be achieved between produced and consumed reactive power in the system. The influence of renewable generators on voltage control depends on the type of the interface used for the connection to the grid. Induction generators in wind turbines or small hydro plants, consume reactive power. A partial compensation can be achieved using local capacitors. Power electronic inverters used for the connection of photovoltaic systems and wind turbines are reactive power neutral.

When a distribution grid exists, active power flow also influences voltages profiles. This happens because in such systems, the resistive part of the lines or cables is higher than the inductive part. As a result, when active power produced by the renewable generator is not consumed locally, it flows to the upstream network causing a voltage rise. This situation is not desirable when limits imposed by the EN–50160 regulation are exceeded. A solution could be the introduction of a local storage device that will act as a sink for the active power excess (Barton, 2004).

2.3.3 Energy Management in Autonomous Power Systems

Energy management is a functionality that aims at the achievement of a reliable and efficient operation of an autonomous power system. The first objective is related to the capability of the system to serve the loads with minimum interruptions caused by insufficient power supply. The second objective is related to the minimisation of fossil-fuel generator costs and thus the cost of produced energy. An increased renewable penetration level, makes the fulfilment of these tasks more complex. This is because, although it is beneficial since it displaces conventional generation and as a result allows for fuel saving, its intermittent character may endanger reliability of supply.

The implementation of energy management necessitates the utilisation of appropriate algorithms for decision making, according to the operating state of the system, and the existence of hardware for the interface with the power devices in order to acquire information and transmit command signals. The complexity of energy management infrastructure depends on the system size and structure.

In smaller autonomous power systems, energy management is usually integrated in the controller of the main power device. For example in a DC-based APS, energy management is implemented by the controller of the battery storage system. Input signals include power production from renewable generators and current consumption level. Depending on their values and on the batteries' condition, determined mainly by their state of charge, appropriate decisions are made. These may include the disconnection of loads or the initiation of a fossil-fuel generation operation in order to start battery charging.

In larger autonomous power systems, energy management functionality, usually resides in a central control system. For the exchange of information with the power devices (fossil-fuel and renewable generators, controllable loads and storage) a SCADA (supervisory control and data acquisition) application is used. This application acquires measurements and other information signals from local control devices and issues commands to them through a communication link. A software database forms the link between the energy management application and the SCADA. Additionally a human/machine interface for monitoring purposes as well as a number of functionalities such as alarm monitoring and handling are present in most of the commercially available SCADA configurations.

Tasks performed within an energy management system of a large APS, include consumption and renewable generation forecast, unit commitment and economic dispatch of conventional generation and finally issue of set points to the power units (Hatziargyriou, 2002). The time horizon covered by the forecasts is 24 h ahead. The minimum consumer estimated load and the allowed technical minimum of the conventional generators determines the amount of renewable energy that can be absorbed by the system. The maximum consumer load determines the necessary power capacity that must be available. The variability of load and renewable power determine the necessary spinning reserve in order to ensure adequate power quality and reliability. This information is used in order to schedule the necessary conventional generation units in the unit commitment process. The calculation of set-points for the generators production is based on an optimisation procedure that uses their fuel consumption versus production characteristics. If storage devices and secondary controllable loads are included in the APS configuration, they are also considered in the unit commitment and dispatching processes. The final outcome of this procedure consists of set-points and ON/OFF commands that are transmitted to the power units via the SCADA application. In order to take into account renewable power variability, unit commitment and economic dispatch cycles are executed several times per day.

2.4 Economic Evaluation

2.4.1 Optimisation Problem Definition

Selection and sizing of the power components comprising an autonomous power system are the core issues that should be examined during the design process. In fossil-fuel-based APS, the criterion for the generators sizing is the expected peak load. The choice of the appropriate RES technologies is based on the available potential in the examined area. As a next step, an optimisation procedure is followed in order to determine the size of the RES-based generators and the storage devices. The task of this procedure is the minimisation of an objective function, describing economic parameters of the APS. The optimum solution must also fulfil a number of system operation constraints.

Objective functions usually utilised include the net present cost of the APS investment and the expected average cost of produced energy (NREL, 2004). The net present cost of the system is the cost of installing and operating the system over the lifetime of the project. It can be calculated by the ratio of the total annualised cost (Euro/year) and the capital recovery factor. The total annualised cost is the sum of the annual operating and maintenance costs, the annualised capital costs and the annualised replacement costs of each component. Operating costs are mostly related to the fossil-fuel generators and more specifically to their fuel consumption characteristics. Maintenance costs depend on the number of operating hours of each power device. Capital costs include equipment and installation costs. The capital recovery factor is calculated by the following equation:

$$\mathrm{CRF}\ (i, N) = \frac{i(i+1)^N}{(i+1)^N - 1} \tag{2.4}$$

where:
i is the interest rate and N is the number of years defined by the project lifetime.

The average cost of energy can be calculated by the ratio of the total annualised cost and the energy produced by the power system during a year. Constraints that should be respected during the optimisation process concern the preservation of the production-consumption balance, the technical minimum of fossil-fuel generators, the necessary reserves for the operation of the APS and the minimum reliability of the supply level of the APS. The last parameter can be expressed as the permissible amount of unserved energy or the allowable percentage of time during which the load will not be served over the examined period. The fulfilment of these constraints is necessary in order to obtain a solution that is compatible with the physics of the concerned application. At the same time a compromise is necessary between the cost and the reliability of the APS operation in order to arrive at an optimum solution.

Due to the complexity of the optimisation problem, a solution in a closed form is not feasible and for this reason simulation methodologies are usually used. The respective tools utilise logistic models of the power components and are based on an energy-balance approach. Their use allows the examination of the impact of different configurations and operating strategies on the economics of an APS. In the following section the basic principles lying behind the operation of such tools are presented and analysed.

2.4.2 Simulation Methodology

The main characteristics of the simulation tools used for the sizing and performance evaluation of autonomous power systems in the design stage, include the way of representing the system, the definition of the APS control strategy, the simulation time step and methodology and finally the output of the simulation process.

For the system representation, usually a single-bus approach is used for the AC part of an autonomous power system. This means that the influence of the distribution grid that possibly exists is not taken into account. If DC components such as photovoltaic units or batteries are part of the system, these are connected to a separate DC bus and a power electronic converter is used as an interface. Renewable generators are represented by the static relations describing the energy-conversion process. Such relations for wind turbines and small hydro power plants have been presented in previous sections. Photovoltaic generators can be modelled using the linear relation between the produced power and the solar irradiance level or a detailed circuit representation of the photovoltaic modules. The last approach is more complex but provides more accurate result. Fossil-fuel generators are modelled using their fuel consumption characteristic curves and their technical minimum. Storage devices are described by the algebraic relations governing the dependence between storage capacity and operational parameters of these devices. Such a model for lead acid battery storage systems is provided in Manwell, 1993. In each of these cases, conversion efficiency is also taken into account also incorporating the dependence from the device operating point. It should be mentioned that power electronic converters are modelled basically using only their conversion efficiency.

The implemented control strategy for the operation of an APS refers to the definition of system reserves and the dispatching policy for the fossil-fuel generators and storage devices. System reserves are expressed as a percentage of the load consumption and renewable power-generation levels. If these percentages are set to a high value, a more reliable operation can be achieved but at a higher cost. Therefore these design parameters should be selected carefully in order to achieve an optimum setting, while preserving an appropriate reliability level. Dispatching policy concerns the set of rules governing the operation of fossil-fuel generators and storage devices. Two possible dispatch strategies are load following and cycle-charging (NREL, 2004). In the first one, whenever a fossil-fuel generator operates, produced power is only used to cover the primary load needs. Charging of storage devices or serving of secondary loads is left to renewable sources. In the second strategy, when a fossil-fuel generator operates, its power level is set at nominal value in order to serve secondary loads and charge the storage devices.

The time step implemented in the simulation tools is of the order of a few minutes up to one hour. It is also assumed that the time series of primary load and renewable resources, sampled at multiples of this time step over the examined period, are available. As was mentioned earlier, preservation of energy balance during the entire simulation is the main issue. In this sense, at every time step the power produced by the renewable generators is calculated. This quantity is subtracted from the primary load value and the remaining load should be served by the fossil-fuel generators and the storage devices. Load sharing among them is performed according to the selected dispatch strategy, and the least-cost principle while satisfying the operating reserve requirements.

Simulated time period is usually one year. In this way a more complete view of the expected power system operation can be created, since seasonal variation of load and renewable resources can be taken into account (Bechrakis, 2006). The output of the simulation process includes calculated economic results, an overview of the energy balance, performance characteristics of the power devices and time series of the input and output quantities. The analysis of economic results allows identification of the optimum system configuration as well as the parameters that mostly influence the various costs. Examination of the energy balance shows the percentage of renewable penetration achieved as well as the degree of energy utilisation. During the simulation process, any excess energy generated by renewable sources or conventional generators, because their technical minimum exceeds the load, is supposed to be dissipated in a dump load if it cannot be stored. The amount of this energy is a crucial parameter for the economic evaluation of an autonomous power system. Performance characteristics of power devices reveal important information related to their expected utilisation. As an example, statistics about the expected evolution of the state of charge of a battery storage system can provide insight in the possible stressing of this device and as a consequence in its expected life-time. Finally, time series produced by the simulation, can provide useful detailed information regarding the expected system behaviour during the entire simulation period. Such information can be the coincidence of renewable generation and load-consumption pattern, which can be used for the tuning of the system design parameters.

Simulation principles presented in this section will be used in Chapter 5 for the analysis of 5 existing autonomous power systems and their optimum redesign as hydrogen-based systems.

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