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Automation infrastructure and operation control strategy in a stand-alone power system based on renewable energy sources

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ABSTRACT

The design of the automation system and the implemented operation control strategy in a stand-alone power system in Greece are fully analyzed in the present study. A photovoltaic array and three wind generators serve as the system main power sources and meet a predefined load demand. A lead-acid accumulator is used to compensate the inherent power fluctuations (excess or shortage) and to regulate the overall system operation, based on a developed power management strategy. Hydrogen is produced by using system excess power in a proton exchange membrane (PEM) electrolyzer and is further stored in pressurized cylinders for subsequent use in a PEM fuel cell in cases of power shortage. A diesel generator complements the integrated system and is employed only in emergency cases, such as subsystems failure. The performance of the automatic control system is evaluated through the real-time operation of the power system where data from the various subsystems are recorded and analyzed using a supervised data acquisition unit. Various network protocols were used to integrate the system devices into one central control system managing in this way to compensate for the differences between chemical and electrical subunits. One of the main advantages is the ability of process monitoring from distance where users can perform changes to system principal variables. Furthermore, the performance of the implemented power management strategy is evaluated through simulated scenarios by including a case study analysis on system abilities to meet higher than expected electrical load demands.

1. Introduction

Greenhouse gas emissions (mainly CO_2, NO_x and CH_4) are the main contributors to global warming and are also related to the excessive usage of fossil fuels that meet the world's energy demands, from simple daily domestic needs up to heavy industrial applications. In order to prevent the aggravation of detrimental effects, environmental friendly solutions have to be proposed and applied. These solutions should focus on the elimination, or at least minimization, of carbon based fuels and should develop a both efficient and cost-effective, application that could replace conventional power production processes.

Stand-alone power systems based on renewable energy sources (RES), could offer off-grid power supply for the electrification of remote areas that are not connected to the main grid, the powering of telecommunication stations and the desalination of water; processes that require significant amounts of energy. Such integrated systems usually comprise a power production unit based on RES, complemented by short- and long-term energy storage units.

The rate of development and application of stand-alone power systems has increased significantly over the past few years. Starting from simple applications back in the 1990s with the exploitation of solar systems [1,2], the research society has moved to more complicated systems with the introduction of short-term and long-term energy storage units [3–5] that aim to the efficient and cost-effective operation accounting also for the variations in regional weather data. The analysis of such complicated and demanding systems has sparked the interest of theoretical studies that focus on the integration of the various units through overall power management strategies [6–10]. Design analysis based on the economic evaluation of the involved subsystems has also been another research area that is constantly developing [11–13] and lies on the optimal selection of system sizes and configurations. However, real-time operation of stand-alone power systems as implemented by the automation infrastructure and its mathematical modeling background, has received limited attention in literature. Most studies

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focused on the description of individual subsystems along with their electronic parts [14–18], while other studies that describe the stand-alone power system as an entity, failed to address the important details and features regarding unit integration, their auxiliaries section (converters, inverters, etc.) and their overall operation. One of the few concrete studies over this research area is found in [5], where a quite sufficient approach for the description of the converters used in stand-alone power systems was presented, along with a brief analysis on their capacity and ability to deliver the amount of energy needed. Roncero-Sánchez et al. [19] also described the use of *PWM* (pulse-width modulation) converters for the connection of wind generators to the main grid. The characteristics of the electronic parts gave rise to the design of state-feedback controllers that can be used for current control. Despite the importance of system integration under well-designed converters, one of the vital parts for a reliable system operation is the data acquisition system. Agbossou et al. [20] and Little et al. [21] presented the architecture of an automatic operation that has been applied in two similar hydrogen-based systems utilizing solar and wind energy. All necessary connections were sufficiently described in conjunction with the monitoring system, but the applied power management strategy was limited shown. Koutroulis and Kalaitzakis [22] developed an integrated computer-based data-acquisition system for RES plants and the proposed method was based on an easy-to-use graphical environment, for processing, displaying and storing the collected data. In their study, they proposed the remote-user operation that is essential in autonomous applications.

The aim of this paper is to present a complete study that focuses on the automation system design and its implementation in a stand-alone power system located at Neo-Olvio, Xanthi, Greece [6]. The main challenge in such complicated systems is the successful integration of the involved units. All different devices are integrated into one central control unit and based on their communication protocols an overall Supervisory Control and Data Acquisition System is developed. A user friendly-environment is also proposed in order to allow for remote operation and system monitoring. Along with the analysis of the control architecture and the integrated infrastructure an algorithm (power management strategy) has been developed for the efficient operation of the system. The algorithm performance is assessed through a simulated scenario at three different load demand levels. The objective of the theoretical simulation analysis is (i) to calculate the contribution of the subsystems towards a reliable system operation, (ii) to identify design modifications needed for the protection of the subsystems from excessive utilization that can limit their operating lifetime and (iii) to maintain the eco-friendly character of the application through the implementation of the control strategy. Such an analysis is considered as a necessary step prior to scale-up attempts and consistent with the operation planning of stand-alone power systems.

2. Description of the main units in the stand-alone power system

The stand-alone power system under consideration consists of several subsystems that contribute with different levels towards meeting a load demand. A photovoltaic system (*PV*) consisted of 144 photovoltaic panels, each one rated at 69.4 W_p results in a total installed capacity of 10 kW_p with an overall average efficiency of 10%. Three wind generators rated at 1 kW_p each, are also installed and contribute to the wind energy exploitation. The energy storage system comprises short-term and long-term storage units. The short-term power needs (in a time scale of minutes up to a few seconds) are satisfied through parallel strings of lead/acid cells of similar capacity, contributing to an overall accumulator of 3000 Ah (4×750 Ah). Each accumulator bank consists of 24 cells connected in series, with a nominal voltage of 2 V each, thus providing a nominal DC-bus voltage of 48 V. The accumulator is a critical element for the efficient operation of the autonomous energy supply system as it regulates the power flow in the system. The long-term power needs are met by a hydrogen-based system that is consisted of a PEM electrolyzer, a hydrogen storage unit and a PEM fuel cell. The PEM electrolyzer is supplied with pure water at the anode and through the utilization of electrical power, hydrogen is produced at the cathode. The minimum and maximum power levels that the electrolyzer is allowed to operate as set by the manufacturer are 1.05 kW ($P_{min,elec}$) and 4.2 kW ($P_{max,elec}$), corresponding to 25% and 100% of the nominal power, respectively. The produced hydrogen is initially stored in buffer tanks until the pressure inside these tanks reaches a preset limit of 7 barg. At that point, a hydrogen compressor raises the gas pressure to the final storage pressure levels ranging between 15 and 30 barg. In this way, the buffer tank serves as a regulatory unit to compensate for fluctuations in the hydrogen production rate and also allows for significant energy savings [6,7]. The capacity of the final hydrogen storage system is 1 m^3/at 30 bar which is equivalent to around 35 kWh. The stored hydrogen is utilized during periods of power deficit in the autonomous system in a PEM fuel cell, rated at 4 kW_p. Hydrogen is supplied at the anode whereas air is supplied at the cathode. The produced water is collected and stored in a tank to be subsequently utilized in the electrolyzer so that a self-sustain closed loop system in water is maintained. Strict water quality specifications apply and therefore a water monitoring and conditioning unit is installed. In case the stored hydrogen is not sufficient to meet the system power deficit, an installed diesel generator provides the necessary power to the system, but is mainly considered as a back-up emergency unit. The system components are connected through multiple relevant converters of each kind, DC/DC (PV array, fuel cell), AC/DC (wind generators, electrolyzer, diesel generator), to the accumulator which forms the DC bus. There the energy is either stored by the charging sources (fuel cell, diesel generator, PV array, wind generators) or consumed by supplying the internal (electrolyzer, auxiliary units) and external load. A schematic of the installed componets and their interconnections is shown in Fig. 1. Information on the flow of energy (both chemical and electrical) via the subsystems is also provided. At this point it is highlighted that the sizing of each subsystem was based on the approach of Zhou et al. [13] and for the short-term energy storage system (accumulator) a prerequisite that was applied referred to an overall autonomy of 1–1.5 days during the worst case scenario.

3. Integrated infrastructure and implementation of the control system

Designing flexible control architecture is one of the key factors to enable interoperability, extensibility and automated operation of an autonomous power system. Furthermore, there is a need to integrate different devices into one central control system. The choice of the communication protocol is dictated by each device manufacturer and as a result, various network protocols are implemented in the stand-alone power system at Neo Olvio. These devices use common or industrial communication protocols such as RS-232C, Ethernet or Controlled Area Network (CAN). Also in order to transmit data from the site to a central master control unit, which is a Supervisory Control And Data Acquisition (SCADA) system, a distributed Profibus network is used. The fuel cell, the electrolyzer and the DC/DC converter use CAN protocol to communicate with the SCADA system, whereas the DC/AC inverters use common serial protocols which are converted through a serial bridge server into TCP/IP (Transmission Control Program/Internet