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A design methodology of stand-alone photovoltaic power systems for rural electrification

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ABSTRACT

A promising way to electrify regions lacked to reliable access to electricity is the employment of stand-alone photovoltaic power systems (SPPSs). Recently, the cost of electricity from such systems has fallen, and it is expected that this tendency will continue in the future. Within this paper, a new design methodology of highly reliable and sustainable SPPSs is presented. The approach consists of the following processes: prediction of the load demand, characterization of the PV performance on site, sizing the SPPS considering different storage technologies, and forming the most effective design. On the other hand, a new dimensionless number will be introduced to characterize the PV performance at a particular location. In order to demonstrate the methodology, an intention to electrify 93 households in a rural community is given as an example. The results show that a SPPS configuration including compressed air energy storage and supercapacitor may be the most effective SPPS design.

1. Introduction

Extending the national power grid for rural electrification is in some cases not possible hampering progress in local living conditions and economic development. For this reason, it is necessary to provide access to electricity through other means.

Diesel generators are an option for rural electrification. They have the advantage that they can provide low-cost electricity [1]. However, there are some serious drawbacks; fuel can be extremely expensive due to the transportation difficulty, or completely inaccessible among other issues such as obstacles by natural forces [2]. Moreover, the generators produce electricity with high carbon intensity [3].

Renewable energy sources represent inexhaustible sources that exist in almost all regions of the world in contrast to fossil fuels, which are concentrated in some regions. In this context, stand-alone renewable power systems are attractive and climate-friendly solutions for rural electrification. The interest in such systems also for other applications such as water pumping stations [4] and desalination systems [5] has actually grown steadily in last decades [6].

Globally, solar energy is the most available renewable source [7]. Apart from that, the production costs of photovoltaic (PV) modules have fallen in the last years, while their efficiencies increased steadily. It is expected that these tendencies will continue in the future [8], making the PV technologies more attractive for rural electrification. Fig. 1 shows the price development for crystalline modules on different markets. The conversion efficiency rate of the PV technology was in the range of 12–15% in 1990s [9]; today, it can reach a value of up to 25% [10].

There is a considerable amount of articles [12–30] that investigated stand-alone photovoltaic power systems (SPPSs), e.g. in terms of system configuration, energy management and power controlling. To our present state of knowledge, no article that treated the different designing aspects completely and systematically has been published. In this paper, a methodology including the relevant designing points, starting with the prediction of load demand up to the assembly of best optimal system configuration, is introduced.

A SPPS mainly consists of a PV unit, an energy buffer and units for power conditioning and system controlling. The energy buffer absorbs/delivers fast fluctuating power and stores energy for long time (seasonally) [31,32]. To meet these tasks, the PV unit and a high-power storage (HPS) subsystem, which is characterized with fast response time, are oversized sometimes [33]. However, this option is costly. It is rather beneficial to combine two different storage technologies that complete each other (a high-energy storage (HES) technology, which is characterized with high specific energy, and a HPS technology), forming a hybrid energy storage

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Nomenclature

C_1	constant (h)
C_2	constant (h)
$DA_{a,i}$	daily activity of an appliance (–)
FOU	frequency of use (1/day)
m	natural number (–)
n	natural number (–)
P	power (kW)
$P_{a,i}$	power consumption of an appliance (kW)
Ph	photovoltaic number (–)
P_{HES}	energy flow (to be stored/stored) into/from high-energy storage (kW)
$P_{HES,C}$	power led to the high-energy storage (kW)
$P_{HES,D}$	power provided from the high-energy storage (kW)
P_{HPS}	energy flow (to be stored/stored) into/from high-power storage (kW)
$P_{L,i}$	power loss by a device (kW)
P_{Load}	load power (kW)
P_N	nominal power of a photovoltaic unit (kW)
$PR_{a,i}$	penetration rate of an appliance (–)
P_{PV}	photovoltaic power (kW)
P_{STC}	photovoltaic power at Standard Test Conditions (kW)
S	constant (–)
$SBC_{a,i}$	standby power consumption of an appliance (kW)
SOC	state-of-charge (kW h)
$SOC_{C,min}$	minimal state-of-charge during charging (kW h)
$SOC_{D,max}$	maximal state-of-charge during discharging (kW h)
SV	seasonal variation (–)
t	time (h)
t_d	time of day (mm:hh)
t_y	time of year (mm:hh:dd)
UCT	use-cycle duration (min)

Abbreviations

CAES	compressed air energy storage
HES	high-energy storage
HPS	high-power storage
HyES	hydrogen energy storage
MPPT	maximum power point tracking
NOO	number of occupants
O&M	operational and maintenance
PHES	pumped hydroelectric energy storage
PMS	power management strategy
PV	photovoltaic
SMES	superconducting magnetic energy storage
SPPS	stand-alone photovoltaic power system
TES	thermal energy storage
VRB	vanadium redox battery
ZEBRA	zero emission battery research activities

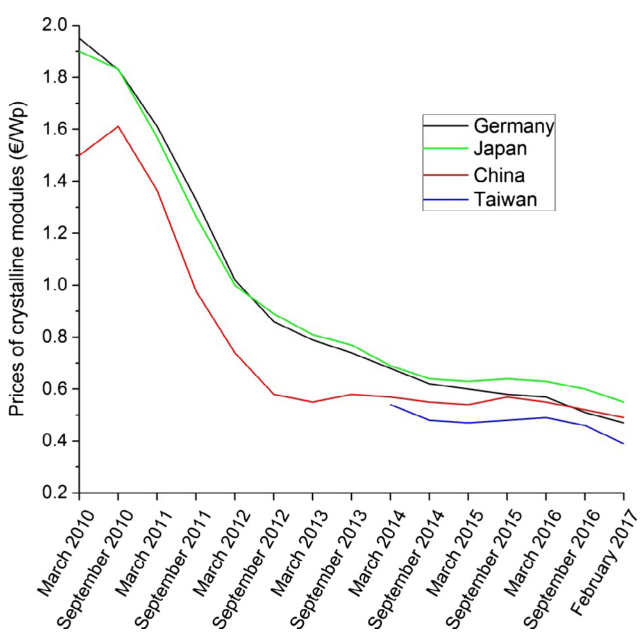

Fig. 1. Price development for crystalline modules on different markets [11].

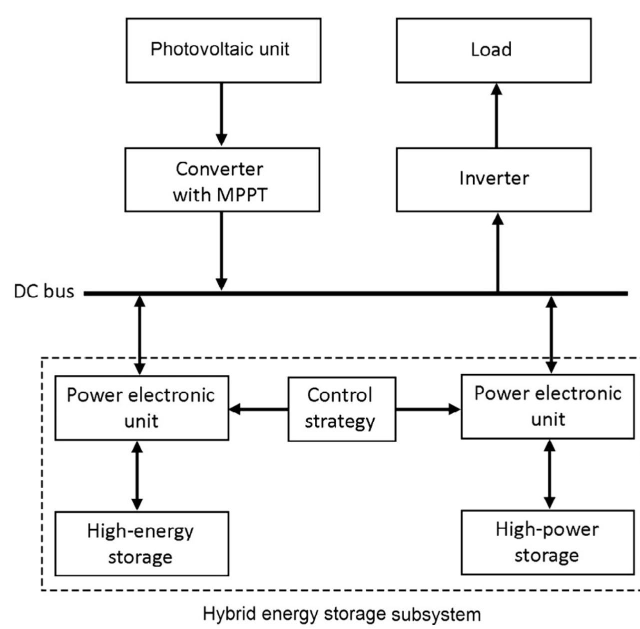

Fig. 2. Typical scheme of SPPSs.

subsystem that can satisfy the requirements for optimal shifting of PV and load fluctuations [17,34–36]. Fig. 2 displays the typical architecture of SPPSs based on hybrid energy storage [12,15,16,19–21,37–43]. At times of high solar radiation, the PV unit supplies the load, while the surplus energy is led to the hybrid energy storage subsystem. At times of low or no solar radiation, the storage subsystem delivers the power supply deficit. The HES (primary storage) receives and supplies slightly fluctuating power. The HPS (secondary storage) supports the HES and treats the energy not managed by HES [44,45]. The power conditioning and system controlling units serve to harvest the maximum energy amount from solar energy and to ensure an optimal operation with high level of reliability and sustainability.

A flow diagram that illustrates the steps of the design methodology introduced in this paper is shown in Fig. 3. Firstly, the load profile is forecasted and the PV performance on site is characterized. Taking these as boundary conditions, a sensitivity analysis is carried out under the variation of the relevant technical param-