Electric Power Systems Research 146 (2017) 124–131

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Potential of solid-state transformers for grid optimization in existing low-voltage grid environments

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ARTICLE INFO

Article history:
Received 23 March 2016
Received in revised form
19 December 2016
Accepted 15 January 2017

Keywords:
DIgSilent
Distribution grid
Fluctuating energy sources
Power quality
PV
Solid-state transformer

ABSTRACT

The transformation of the electrical energy system in Switzerland leads to a significant increase of decentralized, fluctuating generation sites connected to low-voltage (LV) grids. Voltage level restrictions have been identified as the main factor limiting the amount of photovoltaic generation systems which can be integrated in typical distribution grids. This work analyzes the future potential of solid-state transformers replacing conventional low-frequency transformers on level 6 of the electrical grid. Distribution grids are capital intensive and typically feature lifetimes of several decades. The analysis presented here, therefore, is based on the precondition of a persistent grid core. Two existing suburban grids in Switzerland have been investigated using DIgSilent Power Factory for grid simulations. The grid topologies are real and the load characteristics are based on long-term measurements. The focus of this work lies on the LV grid. SST capability to guarantee the required voltage quality is compared to alternative strategies or technologies, such as reactive power contribution by PV systems and distributed battery storage plants.

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1. Introduction

The electrical energy system in Switzerland is in the process of transformation from a system dominated by centralized power plants to a system with a significant amount of decentralized, and small generation sites. The *Energy Strategy 2050* developed by the Swiss government foresees an increase in distributed energy resources, especially photovoltaic (PV) generation sites, which are connected to the low-voltage distribution grid [1]. Based on the envisioned energy production scenarios *C&E* (fossil central and renewable energies) and *E* (renewable energies and imports), PV sites with a peak power of 12.4 GW are planned to be installed by the year 2050 throughout the country. As comparison, average electricity demand is forecast to remain on a similar level as today, varying between 6 and 8 GW depending on the considered scenario. Thus, PV generation needs to be handled intelligently.

In recent years, power electronics based distribution transformers, also known as solid-state transformers (SST) have been proposed as a replacement for standard low-frequency transformer (LFT) in future smart distribution grids [2–4]. SST's are multifunctional tools acting on stability and power quality on medium (MV) and low-voltage (LV) level in parallel. Considerable work has been done developing this new technology, regarding the overload of SST's [5,6], the management of LV grids [6], and voltage and current control on MV side [7]. Proposed SST multiport structures allow flexible integration of e.g. distributed generation or battery storage both in AC or DC [3]. The management of attached DC microgrids has been studied in [8,9]. The future renewable electric energy delivery and management system (FREEDM) is a new power grid based on power electronics, high bandwidth digital communication, and distributed control [10]. It constitutes an ideal grid design including SST's as key technology. A considerable fraction of loads and energy sources are linked directly to DC-ports, since SST's are known to be more efficient and economic when the inverter stage on LV side can be omitted [11].

However, grid architecture is often historically grown and is being continuously updated and extended step by step as new components such as distributed energy resources (DER) or storage (DES) are being added to the AC system. Additionally, distribution grids are capital intensive and their components are typically durable with lifetimes of several decades. These reasons hinder changes to power grids with significant architectural impact in a short time.

This study analyzes the potential of SST's in existing grid environments. The evolution of the grid is considered a step by step process following the scenarios for Switzerland mentioned previously under the precondition of a stable grid topology. The advantages of SST's are elaborated and compared with presently available technologies in LV grids.

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http://dx.doi.org/10.1016/j.epsr.2017.01.024
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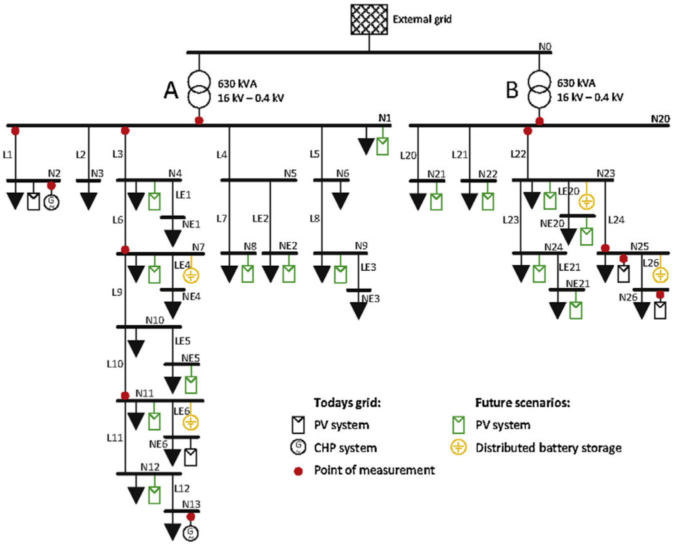

Fig. 1. Grid models A and B used for this work are based on existing LV distribution grids. The parameterization of trafos, lines and generation sites corresponds to the real components. The dots designate measurement points for phase voltages, phase currents, active and reactive power. Additional PV sites have been introduced in accordance with future scenarios.

2. Simulation model

Two existing suburban grids located in Rheinfelden (AG) have been investigated. The grid topologies are shown in Fig. 1. The grid is simulated in DIgSILENT PowerFactory [12]. Nodes and lines correspond to real bus bars and cables with the exception of the nodes and lines denoted with *NE* and *LE*. These feeders represent simplified main feeders imposing the same voltage drop along the equivalent cable length [13]. With this simplification, the influence of a group of buildings can be approximated by one load or generation site, still reproducing the maximum voltage drop or voltage rise present in the real grid.

The grid models representing today's state contain each a 630 kVA LFT, four PV generation sites with a total of 134 kW peak power and two combined heat and power (CHP) plants with 90 and 48 kW peak power, respectively. Grid A represents 83 and grid B 23 building connections. Grid B feeds a shopping center which is the dominating load in this grid, whereas in grid A variations among the loads (mainly households) are smaller.

At 12 measurement points distributed in the grids electrical data has been collected with a resolution of 1 min for more than one year. The measured quantities include phase-to-phase voltages, phase currents, reactive and active power. The measured power flows have been used to scale the weighted loads connected to the corresponding feeder. This approach yielded realistic load characteristics based on the measurement data.

Future scenarios have been implemented by introducing additional photovoltaic sites according to the energy perspectives for Switzerland in the year 2050 [1]. A total of 400 kW peak power per grid has been derived by evenly distributing the projected 12.4 GW of installed PV power to the total of installed trafo power in the whole country. This amount of PV power has been distributed to the generation sites in the grid in two ways (see also Fig. 1):

Statistical distribution: The total amount of PV peak power has been distributed with some statistical variations to all nodes of the grid.

Worst case distribution: The total amount of PV peak power has been distributed dominantly at the end of the longest feeder in each grid. The generation sites already present today have not been changed.

Table 1
Standard deviations $\sigma_{avg-sim}$ between averaged and simulated phase-to-phase voltage. For comparison, the standard deviations σ_{avg-xy} between the three measured phase-to-phase voltages ab, bc, and ca and their average is given as well.

	Node N13 [V]	Node N26 [V]
Summer	$\sigma_{avg-sim} = 0.85$ $\sigma_{avg-xy} = 0.76, 0.74, 0.82$	$\sigma_{avg-sim} = 0.57$ $\sigma_{avg-xy} = 0.47, 0.53, 0.66$
Winter	$\sigma_{avg-sim} = 1.03$ $\sigma_{avg-xy} = 0.53, 0.86, 0.76$	$\sigma_{avg-sim} = 0.61$ $\sigma_{avg-xy} = 0.45, 0.58, 0.54$

Since the amount of projected peak PV power (400 kWp per grid) is subject to substantial variations from grid to grid due to statistical and environmental effects, four coarse graduations have been used for simulation: −50% (→ 200 kWp), nominal (→ 400 kWp), +50% (→ 600 kWp), and +100% (→ 800 kWp).

In order to be able to compare the performance of a traditional LFT with an SST, a user defined SST model has been implemented. A three-stage SST topology has been assumed which decouples the LV and MV grids and allows separate control of voltage and current [3,14]. Since the grid simulations reported here focus on the LV grid, only the output stage of the SST needs to be considered. An ideal sinusoidal and balanced three-phase network has been assumed which allows to model the output stage of the SST as an AC voltage source controllable in a range of ±10%.

3. Model validation

The measurement data collected in the grid was used to validate the model and the given parametrization of cables, loads and generation sites. The following three steps have been taken for this purpose:

(1) Measured power flow data for active and reactive power was imprinted at the points of measurement in the grid model (see also Fig. 1).
(2) During load flow simulation all loads on the feeders below the measurement points were scaled according to the measured load flow. At the same time, voltages and currents for nodes and branches were calculated, respectively.
(3) The calculated node voltages were compared with measurement data.

The furthermost node in each grid was chosen for comparison, since the largest deviation resulted at these points. Standard deviations between the calculated, symmetric phase-to-phase voltage and the average of measured phase-to-phase voltages for a week in summer and winter have been calculated. The results are given in Table 1. The standard deviation is less than 0.26% during the time periods which proves the model to be highly accurate.

4. Results

Load flow simulations have been conducted for a week in summer with highest generation as described in Section 2. The simulations are based on measurement data acquired in the year 2012 in the grids analyzed in this work. Calculated and scaled loads were kept equal for all generation scenarios, whereas the amount of PV generation has been adjusted according to prospected future developments [1]. The simulation was carried out with a resolution of 3 min.

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