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Stochastic analysis of solar and wind hybrid rooftop generation systems and their impact on voltage behavior in low voltage distribution systems

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ABSTRACT

In recent years, with the expansion of residential distributed generation systems, advanced measurement infrastructures and distribution management systems, hybrid photovoltaic (PV) and wind turbine (WT) rooftop generation systems (hybrid systems) are flourishing. Since the output power of these systems highly depends on weather conditions that can change during a day, their increased level of penetration may have significant effects on residential low voltage distribution networks (residential networks).

The objective of this paper is to study the effects of different penetration levels of these hybrid systems on daily voltage profile, voltage fluctuation and voltage imbalance of balanced and unbalanced residential networks during different seasons of a year. In order to model uncertainties of daily active and reactive power consumption by residential homes and also daily PV and WT system output power during different seasons with 1-min resolution, our study used the ARIMA simulator in the MATLAB R2013b software environment. The evaluations in this paper are focused on voltage behavior in a standard balanced and unbalanced three-phase four-wire low voltage residential network with the results providing valuable information and data for universities and industry working to advance the fast growth of these hybrid systems. Some key findings are as follows: (1) The increased penetration level of the hybrid system leads to decreased voltage violation of the acceptable limit. (2) Tap-changer operation prevents more voltage drop, and the system voltage drop exceeds acceptable limits for a few minutes. (3) In unbalanced conditions, the LV distribution transformer must be equipped with an automatic tap-changer. (4) Unique seasonal distribution functions of active and reactive power, solar and wind system power have been developed using 1-min system performance modeling.

1. Introduction

Because of technological advances in small-scale residential distributed generation (DG) systems and power electronics equipment, now it is possible to install and drive these systems in residential and commercial applications all over the world (Camilo et al., 2017; Campos et al., 2016; Shahnia et al., 2010).

One of the residential small-scale distributed generation systems is a combination of photovoltaic and wind systems, where in some cases a battery is employed for energy storage and stabilizing the generated power (Chen, 2013). These hybrid systems can be utilized for supporting the residential loads as a consistent and reliable resource. Because of this, application of these systems is expected to increase. Given the limited number of publications on this topic and the increased potential for their development, we designed a study of these hybrid systems in a residential network.

Since output power of these DG systems depends on weather conditions, rapid changes in wind speed and solar irradiation, cause new challenges in voltage and power regulation in low voltage (LV) distribution networks (Babacan et al., 2017; Liu et al., 2012; Nguyen et al., 2016; Yan et al., 2014). Masoum et al., 2012 by simulating an LV distribution network in Western Australia with balanced load curve and by analyzing the effects of rooftop PV in different penetration levels has shown that in case of not controlling these PV systems, some problems would occur in the voltages of residential feeders. In (Ari and Baghzouz, 2011), the effects of transient clouds on voltage flicker and tap changes of transformers in a balanced distribution system with 20% PV penetration level were studied. Assuming a balanced LV distribution network and a constant power factor in residential loads, the authors of (Tonkoski et al., 2012) have dealt with studying the effects of feeder impedance, feeder length and short-circuit impedance of transformer on voltage profile of LV distribution network in the presence of PV systems. The authors in (Pompodakis et al., 2016) have shown that in the case of not controlling reactive power in balanced LV distribution networks, and when PV penetration levels are increased, overvoltage problems will occur.

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Nomenclature

Acronyms

ARIMA	auto regressive integrated moving average
ACF	auto-correlation function
CDF	cumulative distribution function
DG	distributed generation
LV	low voltage
NREL	National Renewable Energy Laboratory
OLTC	on-load tap-changer
PACF	partial auto-correlation function
PDF	probability distribution function
PPRDR	penetration percentage of residential DG resources
pu	per-unit
PV	photovoltaic
R/X ratio	the amount of resistance of a line divided by its reactance
VIF	voltage imbalance factor
WT	wind turbine

Symbols

FPower	daily power fluctuation
G	solar irradiation on surface of the PV system array in the current time step
G_{STC}	solar irradiation in standard test conditions
I_{MPP}	current at MPP of PV panel
I_{SC}	short circuit current of PV panel
K	efficiency temperature coefficient
Max_F_DG	maximum fluctuation of residential DG power
Max_F_P	maximum fluctuation of residential active power
Max_F_Q	maximum fluctuation of residential reactive power
Max_M_DG	maximum average residential DG power
Max_M_P	maximum average residential active power
Max_M_Q	maximum fluctuation of residential reactive power
Min_M_DG	minimum average residential DG power
Min_M_P	minimum average residential active power
Min_M_Q	minimum average residential reactive power
P_{MPP}	power at MPP of PV panel
P_{nBAT}	rated power of the battery
$P_{n_{pv}}$	rated power of PV system
P_{nWT}	rated power of wind turbine
$Power_i$	powers at i-th time step
P_{pv}	power of PV system
P_{wind}	electrical power of wind turbine
SCF_i	status of the feeder's capacitor at times (i)
TAP_i	tap positions of the transformer at times (i)
T_{cell}	temperature of PV cell in the current time step
T_{STC}	temperature in standard test conditions
V_{2i}	voltage of the secondary side of transformer at times (i)
V_{CF_i}	voltage of feeder's capacitor at times (i)
V_{DC}	DC bus voltage
VF_k	daily voltage fluctuation index of pole k
$V_{k,i}$	voltages of pole k in time step of (i)
V_{LB}	lower boundary' voltage
V_{OC}	open circuit voltage of PV panel
V_{off}	switch off voltage of feeder's capacitor
V_{on}	switch on voltage of feeder's capacitor
V_{MPP}	voltage at MPP of PV panel
V_{UB}	upper boundary' voltage
W	wind speed
$W_{cut\ in}$	wind speed when turbine starts to work
$W_{cut\ out}$	the wind speed when turbine is stopped to prevent damages
W_n	rated speed of wind turbine

Because LV distribution networks are unbalanced, another group of researchers have employed an unbalanced LV distribution network in their studies to scrutinize the effects of residential DGs on network voltage. The authors of (Shahnia et al., 2010) by considering 60, 120 and 180 kW loads on respectively A, B and C phases, created an unbalanced network. Then, by analyzing voltage imbalance sensitivity according to the power and place of single-phase residential rooftop PV systems have shown that the presence of PV at the end of feeder it may pose high imbalances in the network. Sensitivity analysis of voltage imbalance and random assessment based on a Monte-Carlo method for the uncertainties of size and location of single-phase residential PV were carried out in (Shahnia et al., 2011). In (Yan and Saha, 2012) sensitivity of phase voltage variations to power fluctuations of PV in an unbalanced distribution network was studied. The authors of that paper have shown that voltage variations due to power fluctuations of PV in unbalanced networks may lead to voltage problems. Using load data and output power in 10-min time steps, and neglecting fluctuations of PV output power it is shown in (Hu et al., 2016) that increased single-phase PV penetration may deteriorate voltage imbalance and voltage swell problems.

Surveying the works carried out in this realm illustrates that the effects of residential DG resources in PV forms have been evaluated. Nonetheless, in recent years PV-wind hybrid systems have increased and the performance of these hybrid systems can be different compared to those with only PV. Additionally, in the preceding research, residential load profile and residential DG power with 10-min to one hour time steps were used. However, due to large variations of residential loads and residential DG outputs, it is necessary to scrutinize these variations with higher temporal resolution. One of the primary objectives of this paper is to study the effect of high resolution changes of residential loads and residential DG on the voltage fluctuation index and voltage imbalance factor. In most of the published literature, a constant load curve and output power are used, and/or the worst case scenarios (e.g. low load or high load) are separately analyzed. Yet, because residential loads and residential DG outputs are random, using data collected in a year cannot adequately describe their uncertainties. Hence, to obtain the behavior of load, PV and wind system output power in other years, it would be better to utilize stochastic methods such as Monte-Carlo (Mahdavi et al., 2016), Artificial Neural Networks (Sexauer and Mohagheghi, 2015), ARIMA, and etc. The ARIMA (Auto Regressive Integrated Moving Average) model was first introduced by Box and Jenkins in the early 1970′s to predict and analyze time series (Box and Jenkins, n.d.). Since the ARIMA model is robust and easy to be understood and implemented, it is used to explain the behavior of stochastic processes like energy demand profiles, wind speed and solar radiation in high resolutions that have a strong relationship with their previous instantaneous values (Cadenas et al., 2016; Patidar et al., 2016; Reikard, 2009). For this aim, more studies on the effects of residential DG resources on LV distribution networks are essential. Moreover, this paper introduces an index for measuring voltage fluctuations (VF_k) which is simpler than flicker indices (i.e. P_{st} and P_{lt}) that have the heavy computational burden, and is easy to employ in the studies.

In this paper, in order to study simultaneous effects of PV and WT output power variations, the residential DG system is considered as a PV-wind hybrid system. Also, a scenario generation method with the help of ARIMA is presented to simulate uncertainties of residential active and reactive loads and PV and WT output powers with 1-min time steps for four seasons of a year. The main objective of this paper is to study the effects of different penetration levels of these hybrid

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