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Neural network-based active power curtailment for overvoltage prevention in low voltage feeders

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ABSTRACT

As non-controllable and intermittent power sources, grid-connected photovoltaic (PV) systems can contribute to overvoltage in low voltage (LV) distribution feeders during periods of high solar generation and low load where there exists a possibility of reverse power flow. Overvoltage is usually prevented by conservatively limiting the penetration level of PV, even if these critical periods rarely occur. This is the current policy implemented in the Northern Territory, Australia, where a modest system limit of 4.5 kW/house was imposed. This paper presents an active power curtailment (APC) strategy utilizing artificial neural networks techniques. The inverter active power is optimized to prevent any overvoltage conditions on the LV feeder. A residential street located in Alice Springs was identified as a case study for this paper. Simulation results demonstrated that overvoltage conditions can be eliminated and made to comply with the Australian Standards AS60038 and AS4777 by incorporating the proposed predictive APC control. In addition, the inverter downtime due to overvoltage trips was eliminated to further reduce the total power losses in the system.

1. Introduction

Photovoltaic (PV) technology adoption is growing rapidly, in particular for grid-connected applications, around the world. Currently, PV systems are widely installed in countries such as Japan, Spain, and US (Trends in Photovoltaic Applications, 1992). In addition to their environmental benefits, PV systems have a number of technical and economical benefits in distribution systems.

Historically, distribution systems were designed and operated under the premise that power flows only in one direction; from distribution substations to end users. Local utility operators are responsible for ensuring power quality and reliability according to the relevant standards, regulations and utility requirements. The feasibility of grid-connected PV systems had been successfully demonstrated in Wittkopf, Vallapan, Liu, Ang, and Cheng (2012), Rahim, Saidur, Solangi, Othman, and Amin (2012), Diez-Mediavilla, Alonso-Tristan, Rodriguez-Amigo, Garcia-Calderon, and Dieste-Velasco (2012), Munoz, Nofuentes, Aguilera, Fuentes, and Vidal (2011). By generating electricity closer to the residential consumers, it is possible to reduce distribution and transmission system congestions and power losses.

However, the use of distributed generation (DG) at the distribution level does not come without technical challenges. Now, with the addition of intermittent, consumer-owned and non-dispatchable units, current standard procedures for managing such power requirements might not be as effective as before. This has led to many electricity utilities adopting conservative system limits regarding the size of DG units that can be installed in distribution networks without requiring any impact assessment studies.

Overvoltage (or voltage-rise) is one of the main reasons for adopting such conservative system limits such as on rooftop PV systems (Tonkoski & Lopes, 2011; Ueda, Kurokawa, Tanabe, Kitamura, & Sugihara, 2008). This is because during high PV generation and low load periods, there is a possibility of reverse power flow in the low voltage (LV) feeder (Brabandere, Woyte, Belmans, & Nijs, 2004; Katiraei, Mauch, & Dignard-Bailey, 2007; McNutt, Hambrick, Keesee, & Brown, 2009; Tonkoski & Lopes, 2011; Ueda et al., 2008; Ueda et al., 2008). This reverse power flow in the feeder contributes to overvoltage. If significant overvoltage occurs, the inverters will disconnect (or trip) itself from the grid and this will result in lost electricity production for the PV owner.

A number of different approaches (Kulmala, Maki, Repo, & Jarventausta, 2009; Masters, 2002; Pruggler, Kupzog, Bletterie, & Helfried, 2008) had been presented in the literature. In general, the proposed solutions to address the overvoltage issue can be broadly classified into six methodologies.

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Nomenclature

a_x	experimental value
I_{pv}	PV system current
N	total number of datasets
P_c	curtailed power
P_{mppt}	PV inverter power
P_{opt}	optimized inverter power
p_x	predicted value
V_b	system bus voltage
V_{max}	maximum allowable system voltage
V_{min}	minimum allowable system voltage
V_{pole}	pole voltage
V_{pv}	PV system voltage

Abbreviations

ANN	artificial neural network
APC	active power curtailment
BP	back propagation algorithm
DG	distributed generation
LV	low voltage
MRE	mean relative error
NT	Northern Territory
NTG	Northern Territory Government
PV	photovoltaic
PWC	Power and Water Corporation
R^2	correlation coefficient
RMSE	root mean square error

- Reducing the voltage of the secondary LV transformer by adjusting the tap setting (Masters, 2002). Assuming the tap cannot be changed frequently, the main challenge is to be able to find an optimal setting that can be used during rated and no generation of PVs (during the night) without violating the upper and lower voltage limits.
- Allowing the DG to absorb reactive power (Bollen & Sannino, 2005; Carvalho, Correia, & Ferreira, 2008; Gaonkar, Rao, & Patel, 2006; Rafa, Anaya-Lara, & McDonald, 2008; Vasquez, Mastromauro, Guerrero, & Liserre, 2009). Reactive power control will result in higher currents, and subsequently losses, in the LV feeder. In addition, lower power factors are observed at the input of the feeder, especially in LV systems where voltages are less sensitive to reactive power. This is due to the resistive nature of the feeder. In addition, the apparent power of the inverters has to be increased.
- Installing auto-transformers or voltage regulators (Masters, 2002; Salem, Talat, & Soliman, 1997; Toma et al., 2008). The addition of voltage regulators will address the overvoltage issue, but introduces another unreliability factor into the current system and also added costs.
- Increasing the conductors' size in order to reduce the line impedances (Masters, 2002). Upgrading the conductors' size is the most effective way to eliminate the overvoltage issue. However, this is a very expensive approach especially for underground feeders.
- Introduce storage for storing generated surplus power (Ananth, 2012; Su, Huang, & Lin, 2001; Ueda et al., 2008). Energy storage units such as batteries, flywheels and ultracapacitors are, again, an added cost. In addition, the cost-benefit ratio can be low if the storage units have to be sized according to the PV systems.
- Power curtailment of the DG units (Conti, Greco, & Raiti, 2009; Li & Kao, 2009; Lin, Hsieh, Chen, Hsu, & Ku, 2012; Omran, Kazerani, & Salama, 2011; Tonkoski & Lopes, 2011; Tonkoski, Lopes, & El-Fouly, 2010; Tonkoski, Lopes, & El-Fouly, 2011; Tonkoski, Lopes, & Turcotte, 2009; Ueda et al., 2008). This option of active power curtailment is the most attractive option here because it requires minor modifications to the inverter control logic. Also, it is only activated when needed thus minimizing the amount of curtailed active power and hence minimizing unnecessary losses.

Power curtailment strategies can be classified into two categories; reactive power control and active power control. Both usually have two defined constants. One is the starting voltage of the control, and the other is the recovery voltage. Existing systems normally operate at such that the control will start when the output terminal voltage becomes higher than the starting voltage and the control will stop when the voltage becomes lower than the set value of the recovery voltage. The starting voltage is normally higher than the recovery voltage in order to prevent unexpected fluctuations of the output. Phase advance reactive power control will shift the current phase until the power factor reaches 0.85. The active power regulation will reduce the output power until the output terminal voltage becomes lower than the recovery voltage. Since reactive power control is not sufficiently effective in lowering the voltage in power distribution lines due to the small reactance (Tonkoski & Lopes, 2011). For this study, the focus will be on active power control.

As previously mentioned, there are numerous studies in the development of power curtailment strategies for grid-connected PV systems. Tonkoski and Lopes did a study on 12 net-zero energy houses equipped with rooftop PV systems in a 240 V/75 kVa Canadian distribution feeder. Using the experimental solar irradiance and load profiles, overvoltage conditions were eliminated by investigating several power curtailment strategies (Tonkoski & Lopes, 2011). Besides, other published articles from Tonkoski et al. also presented several different active power curtailment (APC) strategies for overvoltage prevention (Tonkoski et al., 2009, 2010, 2011). Similarly, Brabandere et al. proposed a scheme to prevent overvoltage conditions through PV power curtailment at voltages close to the maximum limit. In addition, it was shown that their approach enables even more PV systems to be installed whilst improving voltage quality (Brabandere et al., 2004). Ueda et al. published a paper proposing and analyzing an advanced method to minimize the output energy losses due to overvoltage for PV systems with battery storage. It was concluded that overvoltage is one of the major factors contributing to low performance ratios and results showed that energy losses can be reduced (Ueda et al., 2008). Lin et al. proposed the use of APC strategies to reduce the PV power injection during peak periods to prevent overvoltage. Simulation results showed that not only overvoltage can be eliminated, but had also improved the cost effectiveness of system which led to better utilization of the solar energy resources (Lin et al., 2012). Also, Omran et al. present a comparative economic analysis of three different methods to reduce power fluctuations. The power curtailment method was found to be the most economical solution compared to adding battery storage and dumping excessive loads (Omran et al., 2011). Lastly, Conti et al. presented a novel power curtailment logic (where operation modes can be switched depending on the network operating conditions) which adjusts the active power produced by the generators to eliminate