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A novel smart meter technique for voltage and current estimation in active distribution networks

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ABSTRACT

For distribution network operators to make effective decisions about real-time applications, they should have complete knowledge of all system variables. However, measuring all variables is infeasible due to the large number of system buses and the consequently high cost of measurement devices. Network operators are thus in serious need of methods that can estimate system voltages and currents with only a few measuring devices. This paper presents a novel voltage, current, and power loss estimation technique for distribution networks characterized by a high level of distributed generation (DG) penetration. The proposed method is based on online measurements from smart meters (SMs) placed at a few selected locations in addition to the measurements from DGs production meters; the estimation is derived without any pseudo measurements. The ingenuity of the proposed technique is that the SM locations are dependent on the network topology only, which means that their locations remain unchanged regardless of penetration levels and/or DG injection points. The proposed technique also includes consideration of variations in X/R ratios and laterals. The developed algorithm was implemented and tested on three radial distribution feeders to show the capability of the proposed technique for estimation for balanced as well as unbalanced distribution networks. The results of a comparison with the actual load flow demonstrate the accuracy and effectiveness of the new technique.

1. Introduction

Distribution networks are swiftly becoming active because of the proliferating integration of distributed generators (DGs). Once connected to the network, DGs boost the system voltage profile, enhance power quality by improving supply continuity, reduce undesirable gas emissions, and decrease system upgrading costs due to the deferral of new investments [1,2]. However, excess DG integration could have an adverse effect on a distribution network. High DG penetration creates problems related to reverse power flow, fault current increments, thermal capacity limit violations in the lines, and steady state voltage rises [3].

If they are to be aware of voltage rise and thermal capacity violation problems, system operators require online measurements of all system voltages and currents. Measurements of voltages and currents enable a system operator to take corrective action to eliminate problems arising from excess DG penetration. However, the installment of intelligent measuring devices at all system buses might not be cost-effective. A need thus exists for estimation techniques that can determine system voltages and currents with only a few meter measurements.

Many researchers have developed measurement schemes that facilitate voltage assessment in distribution grids. Their studies can be classified into two main categories. The first category is concentrated on adapting the conventional state estimation methods employed in transmission grids for use in distribution grids [4–12]. The second category is focused on the placement of measuring devices for the assessment and calculation of system voltages [13–15]. Although both categories are targeted at the estimation of distribution system voltages, they differ in a number of aspects, as explained in the following sections.

1.1. Distribution system state estimation

State estimation (SE) denotes "a data processing algorithm for converting redundant meter readings and other available information into an estimate of the state of an electric power system" [4]. In a distribution system, real-time measurements are usually limited, which means that, network observability is impossible without pseudo and virtual measurements. The use of pseudo measurements is a crucial characteristic of distribution system SE. Pseudo power injection measurements at feeder buses can be determined based on customer billing data and typical load profiles or could even be defined as Gaussian

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distributions [5]. However, customer power-consumption behavior could change drastically due to power generated by customer-owned DGs. Since a customer can thus be a producer, establishing consumption behavior based on pseudo measurements is no longer valid [4]. For large distribution networks with thousands of buses and different load types, an accurate determination of load profiles for all system buses becomes extremely difficult.

A method for placing voltage measurement devices for distribution system estimation was presented in [7] and [8]. To reduce unmeasured voltage magnitude deviations, a specific number of measurement devices were placed on busbars. However, this method was performed offline and cannot estimate currents or power losses. The authors of [10] presented an SE method for low voltage distribution networks based on the placement of smart meters (SMs) in order to improve the uncertainty associated with the estimated voltage. However, this method assumed that 50% of customers and DGs are equipped with SMs that can transmit power injection measurements and voltage measurements.

1.2. Real-Time voltage estimation

Unlike traditional SE, real-time methods rely on only a few real-time voltage measurements and then employ different procedures to assess the distribution system voltage profile. The lack of redundant meter measurements prevents these methods from being able to detect bad data or to identify network configuration errors. Since they are unable to estimate the voltage at all system buses, such methods estimate the voltage profile based on a determination of the global maximum and minimum system voltages. The authors of [13] and [14] introduced a strategy for voltage estimation and control via the placement of remote terminal units (RTUs) at DG and terminal buses. Their strategy was aimed at estimating global maximum and minimum system voltages and at controlling the steady state voltage rise problem through the substation voltage regulator. This approach is applicable only on feeders without laterals and with fixed X/R ratios for all line segments. As well, the RTUs in the control scheme must measure the voltage at a neighboring bus, which might be physically difficult. A further drawback is that the study reported in [13] was unable to estimate feeder currents in order to judge whether they exceed feeder capacity with increased DG penetration. A subsequent study [15] suggested an amended version of this scheme, which needed fewer measurements for the estimation of the global extreme voltage. This approach reduces the communication and calculation burdens on the RTUs, but the other disadvantages mentioned still apply.

To summarize, distribution system SE methods are adequate when redundant meter measurements are obtainable. Enough billing and load profile historical data must also be available so that sufficient pseudo measurements can be generated to overcome the lack of observability and to allow the detection and identification of bad data. For large distribution systems, in which only very few real-time measurements are available and insufficient billing records or load profile data exist, real-time methods are candidate alternatives to traditional SE methods. Real-time methods could be used for obtaining voltage profile estimations based on the measurements available. However, these methods provide only an approximate voltage profile and are unable to estimate branch currents and system power losses.

This paper presents a novel technique of voltage, current, and power loss estimation in active distribution networks. The new method eliminates the disadvantages of real-time estimation techniques and also overcomes the lack of observability that occurs due to limited measurements. The proposed method is dependent on real-time measurements from SMs placed at a few locations that remain fixed regardless of the number and placement of DGs. Moreover, the proposed method utilizes the active and reactive power measurements from production meters located at DGs buses. In the proposed approach, the meters communicate the variables they have measured to a central control unit (CCU) that can estimate the complete voltage profile of the feeder as well as all line currents and system losses. The proposed method offers an effective alternative to SE in the case of insufficient pseudo measurements and a lack of observability. The main contributions of the scheme presented here are as follows:

1) The method is suitable for any radial distribution feeder configuration with an unlimited number of laterals, and it can execute the estimation for a variety of X/R ratios.
2) The SM locations are selected based only on the network topology. These locations are unaffected by new DG installation.
3) The limited number of SMs used in the proposed method significantly reduces communication congestion and delays.
4) With the proposed method, the number of SMs required for a large number of DGs is much lower than with other real-time voltage assessment methods.

The proposed estimation method was implemented and tested on the 33-bus and 69-bus test feeders. For validation purposes, the results were compared with actual load flow results. The findings and accompanying discussion confirm the effectiveness of the proposed scheme.

2. Structure of the proposed system

In order to gain more benefits of the existing smart meters, SMs should be employed in multiple functions in addition to the conventional energy consumption management. Although nowadays SMs are mainly employed for billing purposes with communication intervals around 10 min, they could provide the flexibility needed for new functionalities. Several meter manufacturers allow real-time readout of SMs internal instrumentation values with fast reporting rates less than one minute [16]. These internal measurements prolong the SMs functionalities to a new horizon. Thus, the new generation of SMs is capable of measuring the voltage, active power and reactive powers and communicates them with high reporting rates. Moreover, continuous developments are carried out to enhance SMs reporting rates and to increase their functionalities for cost-benefit ratio improvement. These enhancements make SMs suitable for the proposed technique.

2.1. Meters placement strategy

The general strategy for meters placements includes the placement of SMs at every branching bus of the system (each branching bus is the start bus of a lateral) and at all end buses of all system laterals. Moreover, SMs (work as production meters) are placed at DGs buses and reports the DGs power generation to the CCU. As can be seen in the sample system shown in Fig. 1, structure of the proposed system consists of an SM at every branching bus and at each terminal bus of the feeder laterals.

2.2. SMS and CCU responsibilities

Fig. 2 depicts the function of each SM, which is responsible for the following:

1) Measuring the voltage magnitude at its bus;
2) Measuring the active and reactive powers in the upstream and downstream lines connected directly to its bus;
3) Communicating its measurements to the CCU.

The CCU located at the substation bus is responsible for the following:

1) Knowing the distribution network topology and the impedance of each line section;