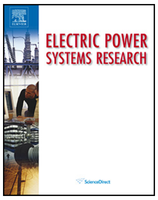
Electric Power Systems Research xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Electric Power Systems Research

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



Implementation of non-intrusive energy saving estimation for Volt/VAr control of smart distribution system

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ARTICLE INFO

Article history:
Received 1 February 2014
Received in revised form
22 September 2014
Accepted 26 September 2014
Available online xxx

Keywords:
Volt/VAr optimization
Energy savings
Real time estimation
Distribution systems
Smart grid

ABSTRACT

There has been a growing interest among power distribution utilities to explore smart grid technologies to improve the operational efficiency and reliability. As electricity distribution grid is evolving to become “smart”, energy demand reduction is one of the goals for the distribution utilities. In order to obtain this goal, utilities need to commit significant financial resources. Therefore, it became important to assess the benefit of new technologies such as Volt/VAr control (VVC). To compute the energy savings due to VVC implementation, existing algorithms are intrusive, and generally require altering the distribution system control settings and operating points, which is undesirable for system operator. On the other hand, these may require large amount of historical data. In this paper, implementation of a new non-intrusive energy saving estimation algorithm has been presented for integrated Volt/VAr control by Avista Utilities in Northwest USA. Developed algorithm utilizes measurements from smart distribution system. Develop algorithm allows studying the energy saving in long term as it requires no change in control settings of actual distribution system. Satisfactory results have been obtained and validated against field data from experiments on real feeders by Avista Utilities.

1. Introduction

With ongoing smart grid activities, improving efficiency and reducing energy consumption are essential for sustainable grids [1]. Numbers of smart grid (SG) technologies are being deployed by the electric utilities to realize the sustainability and efficiency goals. One of the SG technologies refers to distribution automation for Volt/VAr control (VVC) implementation in distribution system. Distribution systems are generally radial power system from distribution substation to the end-user below 69 kV and with higher R/X ratio. Integrated VVC using an intelligent voltage and reactive power control helps in energy savings based on connected load at any given time.

Electric Power Research Institute (EPRI) published a report about the effect of reduced voltage on the power system [2]. International organization such as American National Standard Institute (ANSI C84.1-1995) and Canadian Standard Association (CAN3-C235-83) provide broad regulations and standards about acceptable range of voltage level at distribution feeders [3,4]. These documents specify that the consumer should have voltage in the range of 114–126 V for nominal service. Before conservation voltage reduction (CVR) studies, utilities traditionally kept average voltage above 120 volts to provide a “safety margin” during peak loading hours [5].

Northwest Power and Conservation Council (NWPCC) worked on assessing the potential of loss reduction due to CVR implementation as discussed in [6]. In 1987, Pacific Northwest National Laboratory (PNNL) worked with Bonneville Power Administration (BPA) to conduct a study on the economic benefits of CVR implementation in the BPA area. A potential conservation of 2.37×10^6 MWh/year was reported by PNNL. Between 1988 and 1990, Snohomish PUD implemented CVR on all of its distribution feeders and reported positive energy savings. Hydro-Quebec conducted experiments at Pierre-Boucher substation (near Montreal) in 2005 and 2006 to evaluate the benefits of CVR for saving energy consumption, and to determine the economic feasibility of CVR implementation [7].

Abbreviations: AMI, advanced metering infrastructure; ANSI, American National Standards Association; CBC, capacitor bank control; CVR, conservation voltage reduction; DER, distributed energy resources; DMS, distribution management system; EOL, end of line; EPRI, Electric Power Research Institute; LDC, line drop compensation; LTC, load tap changer; NWPCC, Northwest Power and Conservation Council; PNNL, Pacific Northwest National Laboratory; RES, renewable energy source; SCADA, Supervisory Control and Data Acquisition; SG, smart grid; VC, voltage control; VVC, Volt/VAr control.

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http://dx.doi.org/10.1016/j.epsr.2014.09.023
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Please cite this article in press as: S. Chanda, et al., Implementation of non-intrusive energy saving estimation for Volt/VAr control of smart distribution system, Electr. Power Syst. Res. (2014), http://dx.doi.org/10.1016/j.epsr.2014.09.023

These studies demonstrated that implementation of CVR may lead to economic benefits and will definitely impact the society being a sustainable solution. According to DOE's 2008 report [8], peaking power cost was $1681 per kW, $1966 per kW for wind and $6171 per kW for solar panel. This has been a driving motivation for several power utilities to implement CVR to reduce their peak power cost. It must be noted that CVR is a concept to conserve energy (save energy) and VVC is a mechanism to enable CVR. VVC can also result in realizing other goals like voltage control, loss minimization and power factor control.

Ongoing development of the SG has many implications, opportunities and objectives. One of the key objectives is reducing energy demands, and an integrated optimization for VVC demonstrated to achieve moderate energy savings. It basically refers to the operation of a distribution system with coordinated operation of voltage regulation and reactive power resources with the objective of controlling distribution system voltage levels and reactive power within acceptable range.

A method to minimize the transmission line losses to improve voltage profile through transformer tap position control and reactive power injection control has been proposed in [9]. By limiting the number of capacitor operations per day, an integrated Volt/VAr control algorithm has been proposed in [10]. Implementation of utility control center based VVC in DMS has been discussed in [11]. In [12], the focus has been mainly on using an intelligent control algorithm for VVC while maximizing the distribution system's energy savings.

All the above reported works have led to several active implementations of CVR and VVC in utilities for energy savings and peak demand reduction. One of the first automated CVR projects were carried out by PCSUtiliData for Inland Power and Light Company [13]. This project demonstrated decrease in energy demand and considerable reduction in kVAr values. Morristown Utility Systems (in east Tennessee) has been leveraging benefits of peak energy demand reduction by implementing CVR technology across its distribution systems, allowing it to conserve voltage in a load-responsive manner while keeping within the ANSI C84.1. It was deployed by Efacec ACS's PRISM SCADA System and Tantalus AMI [14]. Time-series model of load using voltage and current has been developed to evaluate CVR effect on Australian residential sector, and study shows that 1.0% voltage reduction leads to 0.4% energy saving [15].

Customer voltage based VVC studies have been carried out in Virginia by Dominion Power, one of the power utilities in North East US. Dominion power reported that $267,000 in energy savings was yielded for 8760 h for Midlothian, VA. This demonstration showed an average of 2.8% annual energy reduction [16].

Another approach that has been fairly common to estimate energy savings is the comparative study of field data obtained from 'distribution system with implementation of VVC' with the historic 'distribution system without VVC implementation'. Researchers and utilities have been using this approach mostly since CVR implementation was adopted by utilities [17]. In this kind of study, several factors, such as temperature and normal load growth are generally not considered with CVR effect. Another established procedure to find energy saving is called "Day On/Off Experiment" – where VVC algorithm runs every alternative day for certain period of time (e.g. two months) and results of ON and OFF controller are compared to find energy saving. A protocol, viz. "Standard Protocol #1 for Automated CVR" for implementing "Day On/Off Experiment" was proposed by PCS UtiliData, and was approved by NWPCC [18].

Day On/Off Experiment is the most adopted approach by utilities for VVC benefit analysis. It requires historical data by alternating On–Off day experiment, as suggested in "Standard Protocol #1 for Automated CVR". In these traditional benefit computation methods, VVC settings are switched off for a certain period of time, and then switched on for another period of time. Energy consumption patterns for both periods of time are studied, and benefits are computed. Such an approach is deemed to be "intrusive" by the authors. As more and more utilities start using CVR and VVC to improve energy savings, there is a need to establish a tool, which can compute energy saving benefits in real time, without the need of historical data, or by changing control settings.

The contributions of the paper are following: (1) development of a novel non-intrusive energy savings algorithm that can estimate the energy saving in real-time for Volt–VAr control (VVC) implementation, (2) real time field implementation and validation of this developed algorithm by an electric utility in Northwest USA. By "non-intrusive", it is implied that the control settings that is used to implement VVC need not to be altered to compute the benefits of the implementation. Developed algorithm is not dependent on weather conditions. Another distinctive feature of developed algorithm is utilizing a ZIP load model in benefit computation. Studies have been based on real field data for residential distribution feeders in Pullman, WA operated by Avista Utilities. A field experiment of actual industrial implementation of integrated VVC has been used to test the energy savings estimation algorithm.

In the following sections a non-intrusive algorithm for computing energy savings in real-time is described and the results of its implementation by a Utility have been presented.

2. Volt/VAr control approach and energy savings estimation algorithm

In this section, the non-intrusive energy savings estimation algorithm is described. It is impractical to deploy VVC in the smart grid, and then switch off for a certain period of time to compute the benefits of using this technology. It is imperative to develop a novel algorithm, which can compute the demand reductions due to implementation of VVC.

Fig. 1 shows schematic of integrated VVC for smart distribution system with the example feeder components. As shown in Fig. 1, the implemented VVC is a closed-loop scheme that collects measurements and generates appropriate control signals.

Fundamental objective of VVC is to maintain steady state voltage level within acceptable range for all loading conditions along the feeder. The impedance of the distribution lines and the magnitude of load demand affect the voltage drop between the feeder source and the end-users. Load tap changer (LTC) transformer, voltage regulators and switched capacitor banks have been traditionally used for the voltage and reactive power control [19]. Utilities usually implement VVC on selected distribution feeders, to compute profits, energy saved and other technical issues. However, a real-time algorithm, developed from a careful integration of information gathered from control settings of estimated non-smart grid data and the real field data from the smart grid, will be beneficial for the utilities to realize the benefits of VVC implementations.

The control algorithm used by utilities for switched capacitor banks is diverse and one addressed here is called 60-40 rule. Based on 60-40 rule, controller turns on the capacitor, if it will not result in more than 40% imbalance of reactive power in the distribution feeder, but will provide more than 60% of what is needed. Based on this logic, capacitors are switched on if measured reactive power of feeder is lagging and larger than 60% of capacitor size. Also, capacitors are switched off, if measured reactive power of feeder is leading and larger than 60% of capacitor size.

The developed algorithm for estimating system state without smart grid implementation using the field data from smart grid is an iterative approach. This requires adjusting the system controls till voltages and loads converges following power flow equations. Energy demands, switched capacitor states and voltage regulator

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