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Optimal integration of DER and SST in active distribution networks

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ABSTRACT

The power distribution system is evolving towards a smart grid paradigm facilitated by infrastructure improvement, innovative technologies, and electronically-interfaced devices. The solid state transformer (SST) promises to be one of the most significant power electronically-interfaced devices to be integrated in the next generation distribution network due to its extensive energy management capability to handle interconnected AC and DC source(s) and load(s). In this paper, a three-phase unbalanced Optimal Power Flow (OPF) algorithm is extended for integrating distributed energy resources (DER) and SSTs in the future distribution networks. The purpose of the OPF is to optimize the economic operations of DERs in conjunction with the SST to improve system efficiency and voltage profiles, while controlling DER penetration. The topology and functionalities of the SST are introduced and modeled in the OPF algorithm. Comprehensive models of loads, conductors, voltage regulators, transformers, and pricing schemes are considered for accuracy. Based on the theoretical foundations, simulations are conducted on the IEEE 123 bus test system. The entire algorithm is also visualized in a quasi-static time-series (QSTS) manner to capture the variability of the system and response of the SSTs in different control modes. This can be adopted by distribution automation enterprises for active distribution networks.

1. Introduction

The electric power industry is undergoing profound changes as it moves toward a smart grid (SG) paradigm to achieve higher levels of energy efficiency, renewable energy resource integration, economic benefits, system reliability, and security [1]. Most restructuring, thus far, has taken place at the transmission or sub-transmission levels, while a majority of distribution systems continue to operate as monopolies with aging infrastructures. Traditional distribution system operators (DSOs) have limited options to purchase power from customers. In most cases, they procure power at wholesale prices from generation companies in the forward and/or futures market, and sometimes in the spot market, and supply their customers directly through distribution feeders at fixed electricity rates set by regulatory bodies [2]. However, distribution systems are evolving as a result of an infusion of smart grid technology and an increasing penetration of DERs. DERs are variable sized power generation units located at or close to customers. Various types of DERs are currently available which include conventional or micro-turbine generators (fueled by natural gas, diesel, etc.) and renewables (wind, solar photovoltaic or solar thermal, biomass, etc.). High penetration of DERs can create bi-directional power-flow complexity for many applications. However, in the envisioned smart distribution system, high penetration of DERs can create a new window for DER owners to participate in economic operations as independent entities or market players [3]. Therefore, DSOs of today are beginning to feel the urgency to adopt a vastly different operational paradigm. In the new environment, DSOs can take more active role in command and control in the presence of increasing DER penetrations, leading to potentially better economic benefits and quality of energy service to customers [4]. A similar type of operation of DSOs has been observed in France to increase the reliability of distribution system [5].

The SST has drawn significant attention from the research community due to its extensive energy management capability with real and reactive power control. Besides, it has a reduced size and weight compared to the conventional iron-core type transformers with plug and play capability. Moreover, it can handle different types of AC and DC sources, and loads together [6,7]. For instance, the SST can deal with a combination of DERs, energy storage systems (ESS), and loads. Recent advancements in the power semiconductor technology have accelerated the utilization and commercialization of the SST with in-built parallel inverters, which has raised its potential to replace or supplement the conventional distributed transformers [8–11]. SSTs are also able to control voltage and power balance for higher energy efficiency [12,13]. Over the past few years, research efforts have targeted

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MVA level substations for SST installation [7,14,15].

As discussed earlier, since the SST can be considered as the future energy management device to integrate various types of DERs and loads in distribution systems, an OPF is needed for the operational scheme. The OPF needs to consider the conventional unbalanced distribution feeder with mixed phases (single, double, and three phase), non-linear loads, and other voltage regulating devices. These considerations can create more realistic scenarios for dispatching high DER penetration and economic operation by maintaining the security constraints such as, voltage and reactive power support. The OPF should also be generalized so that the modifications for SSTs can be included. Several OPF methodologies are suggested in the literature considering different objectives with different techniques for accurate and faster convergence. A second-order convex relaxation is proposed for fast-scale smart inverter response to control the reactive power and voltage profile in distribution systems with high PV penetration [16,17]. An optimal solution for real and reactive power inverter set point is proposed in [18] to bridge the temporal gap between long-term optimization and real-time inverter control. This method improves the system efficiency and stability with the participation of PV owners in the network. The authors utilized ∊-subgradient method with semidefinite programming relaxations to bypass the non-convexity of AC OPF formulation. A locational marginal price (LMP) based policy constraint is presented in [19] with high DER penetration to incentivize DER participation for reducing energy losses in distribution systems. They proposed a mathematical model using co-operative game theory by specifying the share of each DER unit in the reduced loss. An optimization routine is created in [20] for dispatching power from DERs and other sources using least-cost dispatch. A cost-causality-based tariff, which uses nodal pricing to recover the cost of losses, is employed in [21] over a tariff that averages the cost of losses and the Amp-mile method is used to recover the fixed network costs. The authors compared the tariff change with and without a DER integrated network from Uruguay. In [22], a genetic algorithm (GA) is used for optimal placement and sizing of DER to maximize the profit of DSOs. The authors evaluated the profit based on reduced losses in the presence of DER, and the electricity cost with and without incorporating DER. Voltage profile improvement is also considered in their methodology. Moreover, it is now widely accepted that system performance can be enhanced by integrating energy storage. Therefore, a second order cone programming (SOCP) OPF formulation is used in [23] to allocate dispersed storage systems (DSSs) while minimizing line current flows and load curtailment and maximizing DSS round-trip efficiency.

In this paper, a three-phase unbalanced OPF algorithm, presented in [24], is extended to solve the optimal integration of DERs and SSTs. It uses the primal-dual interior point method (PDIPM), which is widely recognized for its ability to solve non-linear optimization problems [25]. In [26], PDIPM is used to balance the phase voltages by injecting reactive power from the PV based DERs. The algorithm is also used in [27] to reduce the generation cost. The Hessian inverse matrix was used to check the convergence of the algorithm. In our work, we have used the Karush–Kuhn–Tucker (KKT) optimality conditions with three other criteria to check the convergence [25]. This paper uses additional variables for generation cost from DERs and substation using piecewise and quadratic representations, respectively. The algorithm features the rectangular coordinate format as used in current injection method (CIM) power flow analysis [28], and is adaptive to handle comprehensive and non-linear models of constant impedance, current, or power (ZIP) loads and different branch elements. It may be customized to adopt new devices or new constraints. The modifications to the OPF formulation for SST implementation is categorized and included in the algorithm. The SST has different control modes, two of which are – unity power factor (UPF) and var control modes. The latter enables the SST to operate as a controllable reactive power source that can be optimally operated by the DSOs using OPF analysis [12]. Both control methodologies are demonstrated in simulation results and compared with traditional transformers. Compared to the OPF in the literature, the features of this OPF can be summarized below:

- A three-phase unbalanced OPF is extended for the integration of DER and SST. The objective of the OPF is to minimize the generation cost in the presence of SST.
- Marginal generation and shadow price are demonstrated for different control modes of SST and compared with the conventional case.
- Convergence of the OPF is tested using four different criteria to assure the optimal solution within the security limits.

The entire simulation is done in MATLAB on the IEEE 123 bus test system. To strengthen the analysis, a quasi-static time-series (QSTS) simulation is also conducted using the proposed OPF for voltage profile analysis.

2. Distribution feeder modeling

Precise modeling of distribution feeders leads to more accurate results for OPF problems. All the components of a typical feeder are described below.

2.1. Component modeling

A pi-model for branch elements in a distribution network is shown in Fig. 1. The general equations relating the nodal voltages at both ends of the branch (V_i and V_j) and the branch currents at the two ends (I_i and I_j) are given in (1) and (2).

$$\begin{bmatrix} I_i^{abc} \\ I_j^{abc} \end{bmatrix} = \begin{bmatrix} Y_{ii} & Y_{ij} \\ Y_{ji} & Y_{jj} \end{bmatrix} \begin{bmatrix} V_i^{abc} \\ V_j^{abc} \end{bmatrix} \tag{1}$$

where

$$Y_{ii} = C_{ii}\frac{Y_A}{a_T a_T^*} + Y_B,\ Y_{ij} = C_{ij}\frac{Y_A}{a_T^*},\ Y_{ji} = C_{ji}\frac{Y_A}{a_T},\ Y_{jj} = C_{jj}Y_A + Y_B. \tag{2}$$

$i, j \in \mathbb{Z}$ denotes the sending and receiving nodes, respectively where $i \neq j$. Y_A and Y_B represent the three-phase series and shunt admittance matrices of branch element,respectively; a_T refers to three-phase voltage ratio matrix; and C corresponds to the transforming matrices defined in Table 1. where

$$C_I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},\ C_{II} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix},\ C_{II} = \begin{bmatrix} -1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix}.$$

The detailed models of each type of conductor is explained in the following parts.

2.1.1. Conductor

The impedance matrix of the untransposed 3-wire or 4-wire conductors can be calculated using Carson's equations [29]. Since all conductor segments are connected in Y or Y-G with no off-nominal turns ratio change, the voltage ratio matrix a_T and all the transforming matrices, C are considered as diagonal identity matrix (C_I).

2.1.2. Transformer

Three phase transformers in distribution systems may have many

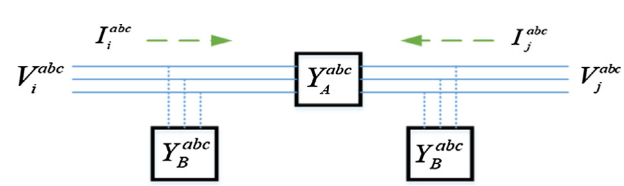

Fig. 1. π-model diagram for branch elements.