Enhanced Utilization of Voltage Control Resources With Distributed Generation

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Abstract—Distributed generation (DG) is increasing in penetration on power systems across the world. In rural areas, voltage rise limits the permissible penetration levels of DG. Another increasingly important issue is the impact on transmission system voltages of DG reactive power demand. Here, a passive solution is proposed to reduce the impact on the transmission system voltages and overcome the distribution voltage rise barrier such that more DG can connect. The fixed power factors of the generators and the tap setting of the transmission transformer are determined by a linear programming formulation. The method is tested on a sample section of radial distribution network and on a model of the all island Irish transmission system illustrating that enhanced passive utilization of voltage control resources can deliver many of the benefits of active management without any of the expense or perceived risk, while also satisfying the conflicting objectives of the transmission system operator.

Index Terms—Energy resources, linear programming, losses, power distribution planning and operation, power transmission planning, wind power generation.

I. Introduction

THE penetration of distributed generation (DG) is rapidly increasing on power systems across the world. Ambitious government targets for renewable generation and generally increasing oil and gas prices have served to maintain and indeed accelerate this demand for DG connections. These factors combined have presented a considerable challenge to distribution network operators (DNOs) and increasingly to transmission system operators (TSOs). In particular, DG poses well established technical challenges for the existing network infrastructure.

DNOs must now facilitate the connection of DG onto networks which were not designed for generation, while maintaining the DNO's primary role of delivering a secure and reliable supply of electricity to consumers. The main technical barrier to DG on distribution networks has been found to be voltage rise due to significant active power injections from DG [1]. It is mainly an issue on rural networks due to their high impedance and low X/R ratio. A range of planning and operational methods have been proposed to alleviate the voltage rise barrier. In [2] and [3], methods for network capacity assessment and the optimal allocation of DG subject to the network constraints were proposed using ac optimal power flow (OPF) and linear programming models, respectively. A number of active voltage control schemes have also been proposed utilizing power factor control and tap changers in both a centralized and distributed manner [4]–[7]. The transition from a passive network to an active one has been widely mooted but, despite the range of voltage control methods developed, there has yet to be a migration to active network management. In [8], a novel approach to (decentralized) active management was proposed where rather than utilizing DG to control the bus voltage, power factor control was designed to counteract the impact of that generator's active power output. This then allows the DNO to connect more DG, but in the traditional fit and forget manner.

The vast majority of work in this area has ignored the growing impact of DG on the transmission system. However, increasing penetrations of DG are presenting a challenge to TSOs as they plan and operate the transmission system. The utilization of wind farms as reactive power ancillary service providers was examined in [9], where it was highlighted that modern wind farms have the capability to contribute reactive power and other ancillary services. Conventional large scale generation which is dispatchable and used for voltage control is being displaced by DG which in many cases is non-dispatchable and does not have voltage control enabled. A consequence of this is increasing demand for reactive power at distribution network interfaces, below which DG is connected. This new additional reactive power demand is placing a strain on transmission system voltage resources and resulting in lower voltages at times of high DG output [10]. The issues of voltage rise on the distribution network and reactive power demands on the transmission system are conflicting. The selection of a fixed inductive power factor by the DNO serves to alleviate the distribution voltage rise issue, however the result is a large reactive power demand being made on the transmission system.

In this paper a method is proposed to determine the enhanced utilization of voltage control resources for DG, such that the requirements and objectives of both the TSO and DNO are met. It

is proposed here to determine an individual power factor setting for each generator that will facilitate more DG capacity than the current fixed power factors and reduce the negative impact on the transmission system. The settings of the on load tap changer of the transmission transformer are included as a variable in this formulation, as it will have an impact on the voltage levels on the network. The optimization method takes account of the capacity of the generation, its reactive power capability, the total DG reactive power, the normal and standby configuration of the network, and the sensitivity of the voltage at each network bus to reactive power injections at all buses. In so doing the method can achieve many of the benefits of proposed active management methods but through a passive method which will satisfy both the DNO and TSO in an easily implementable manner and ensure that the DNO's primary duty towards load customers is not compromised in any way. DG output can be highly variable. In particular, wind power is a highly variable energy resource and its variability is captured through a time series simulation for both the distribution and transmission system which serves to validate the determined enhanced settings.

Section II contains a description of the enhanced power factor method. The methodology is implemented and tested on a sample section of distribution network with a description of the network data and optimization parameters in Section III. Results and discussion are given in Sections IV and V with conclusions given in Section VI.

II. METHODOLOGY

A. Objective Function

The calculation of the enhanced voltage control settings requires a range of factors to be included in the formulation of the objective function and constraints. The decision variables are Q_i, the generation reactive power and ΔV_{Tap}, the target voltage setting at the on load tap changer at the substation's transformer which minimizes the reactive power from DG. The enhanced settings are determined using a linear programming (LP) formulation. The objective of the optimization is to maximize the reactive power injections across all buses with a reactive power resource. This objective is chosen as it optimizes the system from both the distribution and transmission perspectives, i.e. it will find a solution that satisfies the distribution voltage constraints (to satisfy the DNO), with the maximum possible reactive power injection (to satisfy the TSO).

1) Transmission System Impact: The maximization of reactive power injections on the distribution network is chosen as the objective because it is equivalent to minimizing reactive power import from the transmission system and will lead to the minimization of the impact on the transmission system voltages. Increasing penetrations of DG on distribution networks are beginning to cause concerns for TSOs. In particular, the reactive power demanded by DG is presenting a drain on the transmission systems reactive power resources, leading to lower voltages on the system and increased risk of voltage instability [11]. As more DG is brought online in rural regions of the system; there is often a deficit of dynamic reactive generation and voltage performance suffers as a result. From a transmission system perspective, operating points where DG output is at its maximum

and demand is low are of increasing concern. At these operating points DG is displacing large amounts of conventional generation which traditionally would have been utilized for voltage control. As a result, the minimization of reactive power import from the transmission system reduces the demand on the transmission system voltage control resources.

2) DG Capacity: On voltage constrained distribution networks, generators at voltage sensitive buses require inductive power factors, i.e., act as reactive power sinks. The maximization of reactive power injections will determine the reactive power resources that satisfy the constraints with the least amount of reactive power demand. The permissible capacity of DG that may be connected without network upgrade or the implementation of an active control scheme will thus be increased, as will be shown later in Section IV.

The objective function (J (MVAr)) is given as

$$\text{Max}: J = \sum_{i=1}^{N}[LF]_i Q_i \qquad (1)$$

where Q_i and $[LF]_i$ give the generation reactive power and load factor of the resource at the ith bus and N is the number of buses. The optimization is calculated at the maximum generation, minimum load and zero generation, maximum load operating points. Maximum generation, minimum load is the worst case scenario for voltage rise on distribution networks, hence if the voltage rise constraint is obeyed at this point, it will be obeyed for all possible operating points. A low X/R ratio results in a greater coupling between active power and voltage, which makes voltage rise a particular problem on such networks. The load factors (LF) give the average output of each resource and are employed here to calculate the average reactive power of the reactive resources. They weight each resource according to its average output and thus those resources with higher average output will, where possible, be allocated higher reactive power output (less inductive).

The diversity of energy resources and the correlation of their outputs will hence have an impact when the temporal variation of output is considered. An important factor is that the reactive power capability of the generators decreases with active power output, according to the typical P-Q relationship for generators when operated at a fixed power factor. This has the effect that as the active power output (which is the cause of voltage rise) reduces, the reactive power which is used to counteract this effect also decreases. This formulation can also take account of any existing or proposed reactive power resources on the networks, allowing the calculation of their enhanced setting.

B. Reactive Power Capability

The reactive power limits of the generation are added to the formulation as a constraint, given by

$$Q_{\min i} \le Q_i \le Q_{\max i} \quad i \forall N \qquad (2)$$

where $Q_{\min\ i}$ and $Q_{\max\ i}$ are the minimum and maximum reactive power of the generator at the ith bus. Negative values for Q_i indicate inductive reactive power (Ind.) and positive values