Electric Power Systems Research 136 (2016) 223–231

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Power flow control and N-1 contingency analysis with DSRs in unbalanced transmission networks

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ARTICLE INFO

Article history:
Received 26 March 2015
Received in revised form 16 February 2016
Accepted 18 February 2016
Available online 11 March 2016

Keywords:
Distributed series reactor(DSR) design
Electric power transfer
Load growth
N-1 contingency analysis
Power flow control
Unbalanced transmission systems

ABSTRACT

The need for modern electricity infrastructures and more capable grid components brings attention to Distributed Series Reactor (DSR) technology because of its control capabilities. DSRs are a new smart grid technology that can be applied to control flows in transmission or distribution systems. Design of DSRs to control power flow over transmission lines to alleviate overloads due to load growth under single line contingencies is investigated in this paper. N-1 contingency analysis is performed to assure secure operation of the grid while controlling the active power flow. The IEEE 39 bus standard model is modified to a 3-phase, unbalanced transmission model with 345 kV lines that accounts for tower geometry. The design of DSRs to control power flow under N-1 line contingency is performed using this modified 3-phase, unbalanced model. DSR design to control the power flow of a real power system over tie lines connecting different power pool areas and to control the power flow over transmission lines within the area itself is investigated. The economics of DSRs are then evaluated by comparing the DSR design with a design that uses new line construction.

1. Introduction

The US grid is frequently described as aging. Today's grid meets today's requirements, but new and different demands are driving the expansion and adaptation of the transmission grid and the evolution of its supporting institutions. Utilities in North America and all over the world are trying to incorporate new technological innovations to expand the transmission capacity using current assets and facilities [1]. Ways to expand transmission system capacity with no new transmission construction have been presented in the literature [2,3]. Controlling power flow over lines to enhance system capacity has been also addressed in the literature [4–6].

In this paper we continue the line of research initiated in [7–11], devoted to the investigation of Distributed Series Reactor (DSR) deployment for controlling flows over transmission lines. DSRs can be used to control power flow over lines to enhance system capacity, alleviate overloads, and improve the reliability. DSRs are used to balance flows in the phases of an unbalanced line, and to control the distribution of flow in parallel paths.

Adjusting the impedance and admittance of transmission lines is one method of power flow control. A number of FACTS devices, such as STATCOM, SVC, SSSC and UPFC, have emerged. These technologies are based on power electronics. They can be inserted in series or shunt, or a combination of the two, to perform control functions, including voltage regulation, system damping and power flow control. Historically, challenges that have impeded the wide scale deployment of FACTS devices are high cost and maintenance complexity [7]. DSRs are relatively simple devices and hold the promise of high reliability and low maintenance.

Contingencies may be caused by widespread severe weather, a desire to expand supply capacity and meet short lead times to encourage new industries, retirement of coal plants, or a need for line uprating due to outages, may challenge the ability of a grid to meet criteria for delivering power during certain windows of time [8]. Much work has been done in the contingency analysis area [12–17]. Recent research addressed how different FACTS devices operate under contingency conditions to enhance the transmission system voltage stability, steady state security limit and to alleviate thermal overloads [18–24].

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http://dx.doi.org/10.1016/j.epsr.2016.02.024

As the security and reliability of the grid are vital concerns, system operators commonly perform N-1 contingency analyses. Disturbances, like line outages, if not healed in a timely manner, can result in cascading outages leading to wide-spread blackouts. In this paper DSR design for N-1 contingencies with load growth in an unbalanced 3-phase transmission model is addressed.

The IEEE 39 bus test system is modified to a 3-phase, 345 kV, unbalanced model, and is used to study the deployment of DSRs for controlling power flow to alleviate overloads due to load growth under single contingencies.

The contribution of this work is the design of the DSR controller for an unbalanced, 3-phase transmission system and the investigation of the operation of the controller under N-1 contingency conditions. No previous papers in the literature studied the application of DSRs in unbalanced 3-phase transmission systems, and many of the transmission lines in the US are unbalanced. This paper will also present an economic case study to evaluate the value of DSRs in comparison to construction of new transmission lines.

2. DSR technology and design strategy for handling N-1 contingencies with load growth

DSR technology is based on modifying the series reactance of a transmission line. DSR modules are mounted on the transmission conductor and may be activated to increase the series reactance of the line. When alternate flow paths exist in the transmission system the increase in series reactance of the line will cause flow to shift to the alternate paths.

The DSR addition affects the self-impedance of the line impedance matrix Z where

Z_{ii} = self-impedance of phase i, and i = A, B, C.

Z_{ij} = mutual impedance between phases i and j, and i, j = A, B,C.

In the work here, the DSR adds reactance to the self-impedance of the line model. The value of the reactance added depends on the number of DSR modules activated and the selected reactance for each DSR module [7,8]. In this study the DSR modules inject 50 μH/module (0.01885 Ω). The objective of the DSR design here is to handle all N-1 contingencies that may occur in the system with load growth. This means that the DSRs are deployed to ensure that all lines operate within thermal ratings with the increased load, even with any single line failure of the 35 lines in the model.

The DSR design and placement algorithm deploys DSRs on the transmission lines that provide the largest MW flow decrease in the overloaded lines. This is accomplished by calculating for a given line the change in MW in the overloaded lines for DSR addition to the given line. Thus, a line receiving DSRs may not be overloaded. This sensitivity is dependent on the utilization factor of the line. Accordingly, a set of lines are selected for DSR placement. DSR modules are placed iteratively with a certain step size that is chosen as the number of modules per phase. The step size (i.e., the number of DSRs added per iteration, is an input to the program). In the work here 25 DSRs per step are used. Using the chosen step size and sensitivity results derived from a three-phase, unbalanced power flow, the DSRs are deployed iteratively until the stopping criterion is fulfilled [25]. The stopping criterion adopted is to have no overloads in the system. Fig. 1 is a flowchart that depicts the design algorithm for DSR deployment for load growth with N-1 contingencies.

The following describes how lines are selected for DSR additions.

Let O_{Bij} = overload of line i before DSRs are added to line j, in MW

O_{Aij} = overload of line i after DSRs are added to line j, in MW

Define $$\Delta OL_j = \sum O_{Bij} - O_{Aij} \quad (1)$$

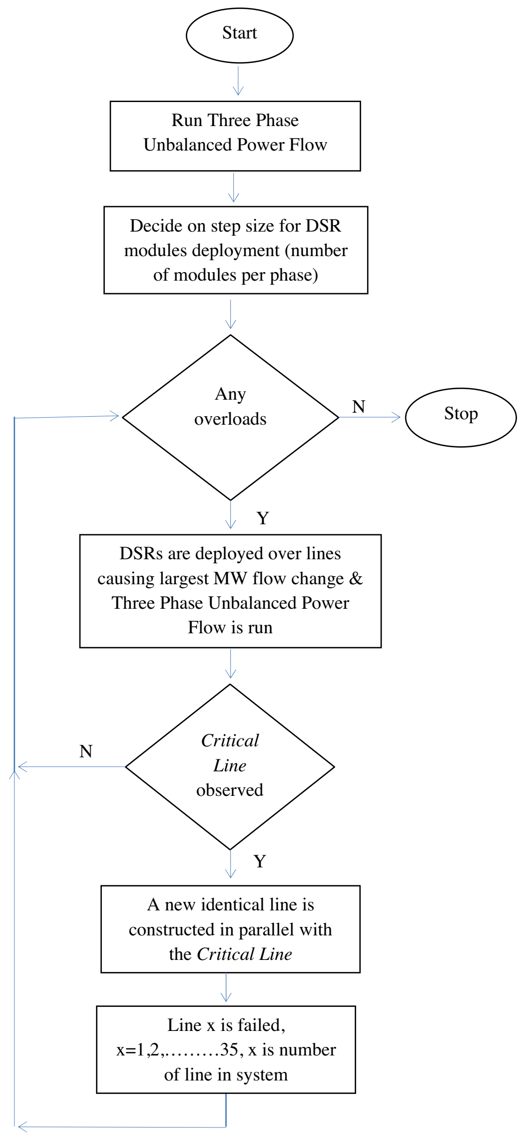

Fig. 1. Flowchart of DSR placement algorithm for load growth and N-1 contingencies.

thus ΔOL_j represents the total decrease in overloads considering all overloaded lines in the system where DSRs are added to line j. The line 's' to add DSRs to is then selected by

$$\Delta OL_s = \max \text{ over } j \, \{\Delta OL_j\} \quad (2)$$

thus, the line is selected where ΔOL_j/Dsr is the greatest, where Dsr is the number of DSRs added at each step. The algorithm used is based upon Discrete Ascent Optimal Programming, which is a greedy algorithm [26]. The Discrete Ascent Optimal Programming algorithm uses the sensitivity of flow in one line due to the impedance change in another line. Since the sensitivities are calculated for each phase, the unbalanced effects are included. However, a symmetrical placement of DSRs is used in this work. The DSR design is done assuming the deployment of the same number of DSRs per phase.

In the work here the load is uniformly grown in discrete increments, where the N-1 contingency criterion is considered for each load growth increment. When an overload is observed the DSR placement algorithm presented in Fig. 1 is used to try and find a DSR design that can be used to alleviate the overload. If DSRs are not able to handle overloads when a certain line is failed, a 345 kV line will be added in parallel with the failed line that has identical