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Feasibility of DSR applications in transmission grid operation—Control of power flow and imbalanced voltage

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ABSTRACT

Distributed Series Reactors (DSRs) can be used to control power flow to more fully utilize the capacity of a transmission network, delaying investment in new transmission lines. In this paper the IEEE 39 bus standard test system is modified to a 3-phase, unbalanced model consisting of 230 kV, 345 kV and 500 kV lines, where lines of different voltage run in parallel. This model is used to study load growth and the effect of adding DSRs to alleviate resulting overloads, and in particular to alleviate overloads on lines of different voltage running in parallel. The economic benefit of adding DSRs to the network is compared to the addition of new transmission lines in the network. In the second part of the paper the effect of unsymmetrical operation of DSRs on a single transmission line is studied and compared to the symmetrical operation of DSRs. It is found that unsymmetrical operation of DSRs is more economical. Finally the unsymmetrical operation of DSRs to reduce voltage imbalance in the network is considered.

1. Introduction

The energy demand of the world is increasing continuously with increased industrialization and modernization of cities and towns. As a result more power has to be transferred from generating sites to load sites. As the demand for power increases, the generation and transmission networks have to be augmented to meet the energy requirements [1]. Transmission networks constitute a significant component in the cost of supplied electrical energy. Furthermore, new transmission capacity supports significant amounts of renewable energy sources in the grid. However, the growth in the transmission networks is much slower and can be a bottleneck when compared to generation growth. Transmission networks take a much longer time to plan and construct as compared to generation units [2]. This could potentially lead to a major roadblock in the supply of electricity in the future. A recent Department of Energy (DOE) report highlights the problem of congestion in transmission lines near major metropolitan centers [3]. Transmission network infrastructures face much more public opposition and as a result take longer to get approvals and land for the construction of new lines [4]. As the load continues to increase it is possible that the transmission network may not be able to keep up with the increase in demand, and thus there is a need to invest in means of increasing transmission capacity.

A good amount of literature exists on increasing transmission capacity of lines [5–8], especially advancements that have been made in the field of Flexible AC Transmission Systems (FACTS) [9–12]. FACTS devices can be used in the transmission network for a variety of purposes, like increasing power flow, improving voltage imbalance, power factor correction, protection and others. One interesting application of FACTS devices is that they can be used to change the reactance of transmission lines [13,14].

Distributed Series Reactor (DSR) is a new smart grid Distributed FACTS technology (D-FACTS) that is primarily being applied to control flows in the transmission system to better utilize the existing transmission capacity. A DSR consists of an inductor that can be coupled to the transmission line and which provides reactive power to the line [15–17]. In order to increase the transmission capacity of networks with low voltage lines in parallel with high voltage lines it is required to shift power flow by some mechanism from the low voltage, overloaded lines, to the high voltage, lightly loaded lines. Distributed Series Reactors provide a mechanism for transferring power flow from overloaded, lower voltage lines to lightly loaded, higher voltage lines.

Recent publications relevant to DSR technology include: [15] which investigated Distributed Series Reactors (DSRs) for controlling the flows over transmission lines, alleviating overloads and increasing the maximum power delivered to the load. The authors

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investigated the DSR system design over parallel lines by performing a series of experiments using three long parallel transmission lines. Several case studies were evaluated in which the three long lines were variously modeled to investigate the impact of different line models (lumped vs. distributed), and impedance models (balanced vs. unbalanced). Ref. [16] proposed the use of an Active Smart Wire, which is a DSR module with an AC capacitor, two AC switches and a communications package. It was proposed to control power flows on a strained grid. In [17] the authors studied the impact of Smart Wires in reduction of transmission investment required to implement policies like Renewable Portfolio Standards (RPS). The authors here defined the Smart Wires as standard transmission lines that are augmented with large numbers of DSRs. Refs. [18,19] introduced the concept of Distributed, Flexible, AC Transmission Systems (D-FACTS) as an alternative approach to realizing cost-effective power flow control. A detailed discussion about the structure and mechanism of DSR operation can be found in [18,19]. In [18] the distributed static series compensator (DSSC) device, a distributed FACTS device, was introduced as a means to control power flow in the transmission system by changing line reactance. [19] discussed the concept of a distributed approach for realizing FACTS devices, in particular distributed series impedance (DSI) and distributed static series compensator (DSSC) were presented. In [20] initial field trials and pilot tests of DSR deployment by electric utilities were presented and implications for future applications were suggested.

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 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.

The value of the reactance added depends on the number of DSR modules activated and the selected reactance for each DSR module [15,20]. In this study the DSR modules inject 50 μH/module (0.01885 Ω).

DSRs can be controlled in several ways. They can be pre-programmed to operate at a given current threshold, managed manually from an operating center, or controlled automatically for more complex applications. Manual or automatic control is achieved through real-time communications [20].

DSRs represent a new technology providing greater control over flow and voltages, where the control can be exercised for lines in parallel and even for the individual phases of a single line. Many transmission lines are unbalanced (i.e., long lines that have not been transposed) and not all loads are balanced, resulting in unbalanced flows in the phases of a line and unbalanced delivery point phase voltages. This paper considers the operation of DSRs in unbalanced situations, and the contribution of this work is that it shows that DSRs operated in an unsymmetrical fashion can result in more fully utilizing the capacity of parallel lines as well as balancing delivery point voltages.

The rest of the paper is organized as follows. Section 2 introduces the IEEE 39 bus system used in the study. Section 3 discusses the operation of DSRs in symmetrical and unsymmetrical fashion in order to increase the power flow and gives a comparison of the sequence voltages and power flows among the different DSR cases considered. In Section 4 an economic evaluation is presented. Section 5 analyzes the application of DSRs to reduce voltage imbalance. Finally Section 6 provides conclusions and underlines the future scope of work.

2. Description of the IEEE system used in study

In this study the IEEE 39 bus standard transmission model is modified to be a 3-phase, unbalanced model, as many of the transmission lines in the US are unbalanced. The authors introduced this

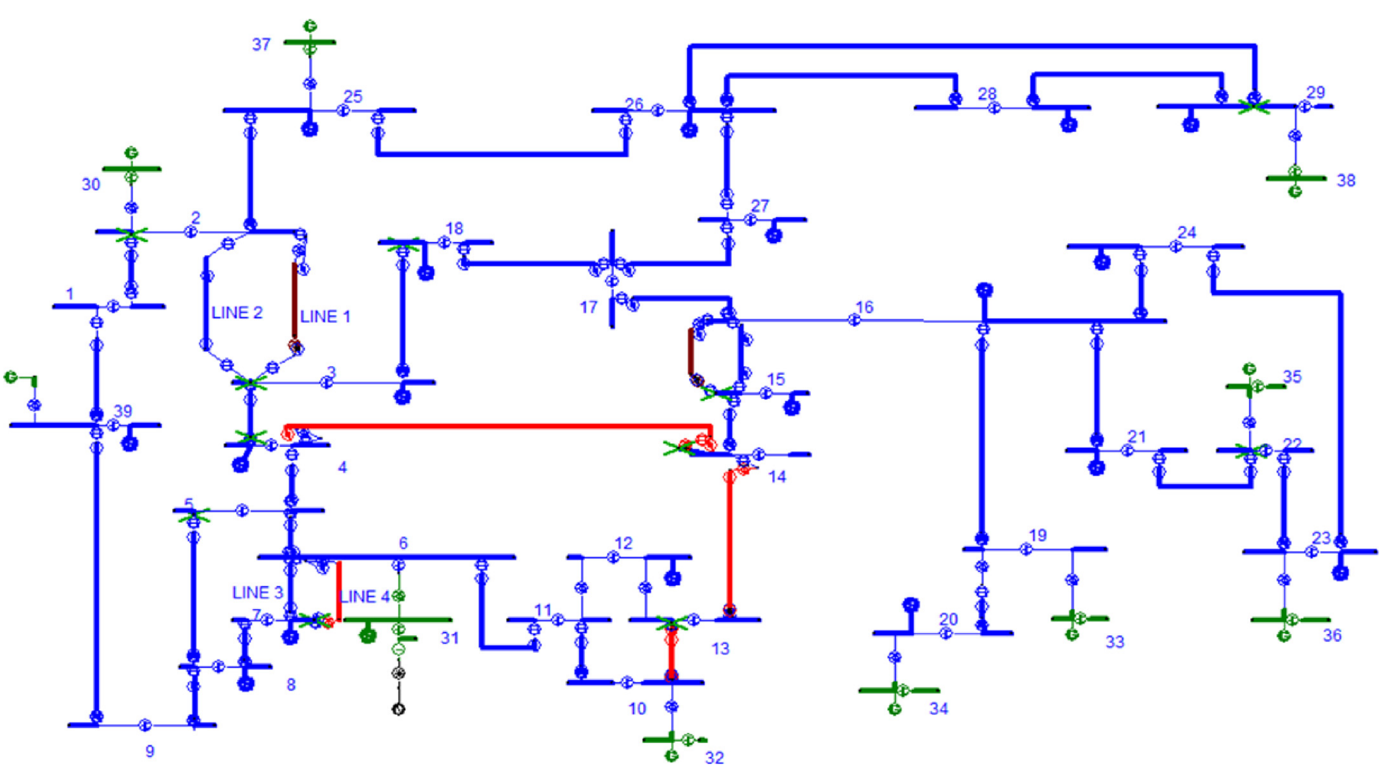

Fig. 1. IEEE 39 bus model modified to 3-phase, unbalanced transmission model: 500 kV lines shown in red, 345 kV lines shown in blue, and 230 kV lines shown in brown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)