Control Applications and Economic Evaluations of Distributed Series Reactors in Unbalanced Electrical Transmission Systems

By

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ABSTRACT

An important issue in today's power system is the need to analyse and determine the adequacy of transmission capacity. There is a need for approaches to increase transmission system capacity without construction of new transmission facilities, all while assuring secure operation of the grid. New technologies can enhance efficiency and reliability, increase capacity utilization, enable more rapid response to contingencies, and increase flexibility in controlling power flows on transmission lines. Distributed Series Reactor (DSR) control is a new smart grid technology that can be applied to control flows in the transmission system. DSRs can be used to balance phase flows in a single line as well as to control the distribution of flow in parallel flow paths.
This dissertation investigates the Design of Distributed Series Reactors (DSRs) on transmission lines and provide *guidelines and considerations* for their implementation in bulk power system transmission networks to control power flow to: increase the exisiting transmission capacity utilization, alleviate overloads due to load growth and contingencies, and mitigate the effects of unbalanced voltages, unbalanced transmission line impedances and unbalanced loads by balancing flows in the phases of an unbalanced line.

This dissertation provides several DSR System Design aspects; *for* a single line by performing an experiment for EHV and high voltage three parallel transmission lines, and *for* lines within the boundaries of a power system by deployment of DSRs over the IEEE 39 bus system that is modified and modelled as a 3-phase unbalanced transmission model with 345 kV lines that accounts for tower geometry and as a balanced, 3-phase model that is derived from the unbalanced, 3-phase model, and *finally for* lines within a control area and a set of tie lines among control areas by deployment of DSRs over a real system control area and the tie lines connecting this area to other power pool areas.

For all experiments and simulations in this dissertation lines are modelled as 3-phase lines. The DSR system design for Unbalanced vs. Balanced 3-phase systems (Unbalanced immittance, Unbalanced load) are examined. Also the Distributed vs. Lumped models for 3-phase systems are tested. Comparison between DSR system design and transposition for voltage balancing was performed. The effect of bundling the conductors for DSR system design was investiagted.

In this dissertation an economic evaluation of DSR System Design for parallel lines and for the IEEE 39 bus three-phase unbalanced line model for N-1 criterion contingency with load growth is performed. The economic evaluation performed for the DSR system design of a power system versus new transmission line construction showed that DSRs can be cost effective in managing load increases from year to a year, and thus avoid larger investments in new line construction until load expectations are proven to be true. Thus, a major value of DSRs is handling load growth in the short term, delaying larger investments.

Although many aspects of DSR control implementation have yet to be explored, this work has demonstrated the fundamental concept is sound and the economics are compelling.

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1 Introduction

1.1 Overview

Electricity is the driving force behind industry and subsequently the economy. Availability and power quality are the main concerns for the end users. Customers expect the electric power to be available continuously with no interruption. Reliability of a power system is a measure of the ability of the system to provide customers with adequate supply. Major outages can have a significant economic impact on utility providers as well as the end users.

The U.S. electric power grid faces a wide variety of threats, including natural, physical, cyber, and space weather. The U.S. power system has been affected by outage events caused by incorrect planning, operational error, equipment failures, environmental conditions, adverse weather effects, and load conditions like the 1965 and 2003 blackouts [1] [2]. Due to the complexity of modeling and computation, it is a difficult task to analyze the entire grid configuration. Electricity relies on an interconnected system that is composed of three distinct elements. Traditionally, functional zones represent these three elements. These zones are used to divide an overall power system into sub-systems under evaluation [3] [4]. The functional zones depicted in Figure 1.1 are generation, transmission, and distribution systems [3].

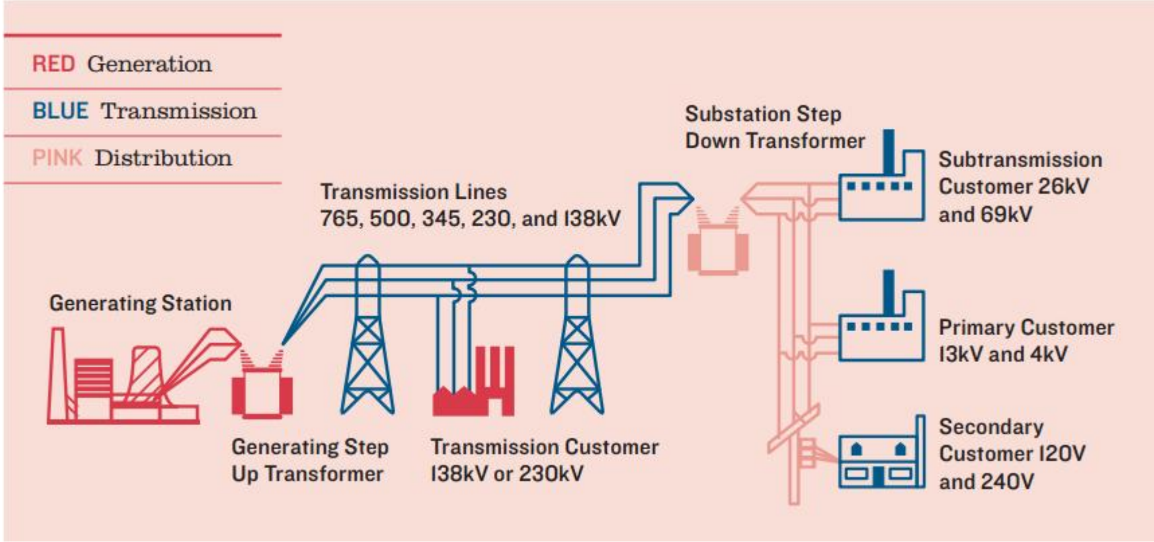


Figure 1.1 Typical Functional Zones, Generation, Transmission, and Distribution Systems

In Figure 1.1, after the generator voltage (13.8~24 kV) is boosted for long distance transmission (345~765kV), the extra-high-voltage (EHV) transmission line transmits the energy to the transmission station. Following EHV transmission, the voltage may then be reduced (138 ~ 230kV), and energy transmitted to switching stations, where the voltage is further reduced to sub-transmission levels (26~138kV). The transmission voltages commonly (but not exclusively) used in the U.S. are 138 kV, 230 kV, 345 kV, 500 kV, and 765 kV [3] [5]. At the distribution substation, the voltage is changed from sub-transmission level to primary distribution levels (4.16~34.5kV). Each primary feeder supplies its downstream network transformers, which reduce the voltage to secondary distribution levels (120~240V or 480V~4.16kV), and feed customers. Some large commercial or industrial customers are fed directly from feeder, sub-transmission (26 ~ 69kV), or transmission voltage levels (138 ~ 230kV).

The system of interest in this study is the Electrical Transmission System. The Transmission System is generally considered the portion of the electric power system between the bulk power generation sources and the distribution system and consumer [6]. The goal of a Transmission System is to carry electric power at EHV and high voltage levels over long distances from the generating units to the distribution system efficiently, reliably, and within established operating criteria. These criteria consist of voltage and frequency requirements that are designed to protect both the utility grid infrastructure as well as devices receiving their power from the grid.

Topologically, the transmission and sub-transmission line configurations are mesh networks (as opposed to radial), meaning there are multiple paths between any two points on the network. This redundancy allows the system to provide power to the loads even when a transmission line or a generating unit goes offline. Because of these multiple routes, however, the power flow path cannot be specified at will. Instead power flows along all paths from the generating unit to the load. The power flow through a particular transmission line depends on the line's impedance and the amplitude and phase of the voltages at its ends [5].

1.2 Grid Current Status

The electric power system of U.S. consists of three independently synchronized grids: the Eastern Interconnection, the Western Interconnection, and the Electric Reliability Council of

Texas (ERCOT). They are linked by only a few low-capacity direct current (dc) lines. These three grids are shown in Figure 1.2.

Physically, the U.S. electric grid consists of approximately 170,000 miles of high-voltage (above 200 kilovolts or kV) electric transmission lines and associated equipment, and almost 6 million miles of lower-voltage distribution lines. These include approximately 2,400 miles of 765 kV alternating current (ac) lines, and more than 3,000 miles of 500 kV dc lines. The U.S. grid serves about 125 million residential customers, 17.6 million commercial customers, and 775,000 industrial customers [5] [7].

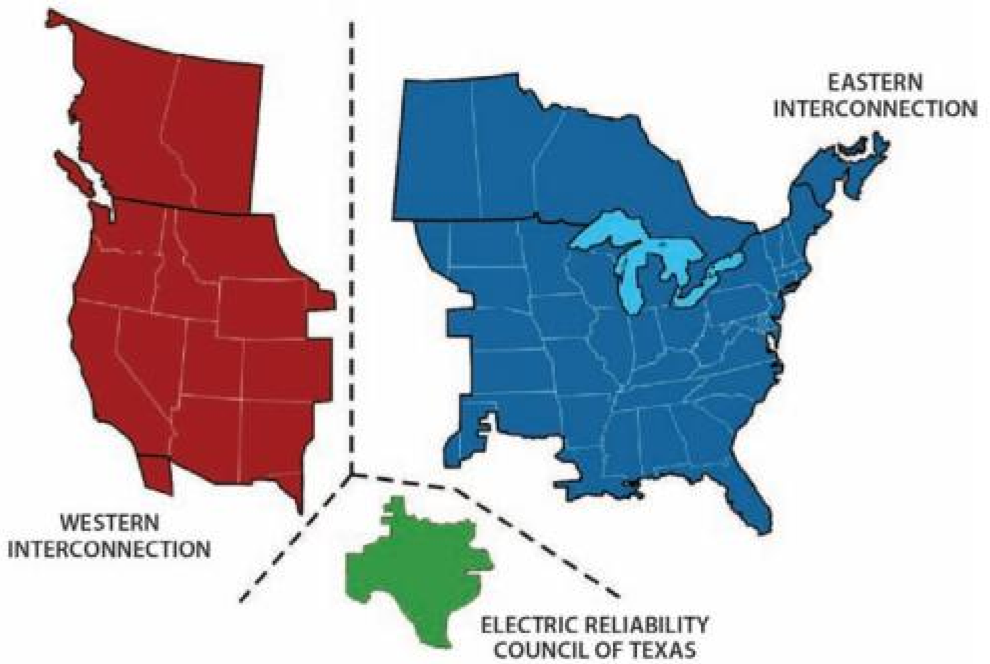


Figure 1.2 Interconnections of the North American Electric Grid

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. Reliability is the most common justification for transmission investment in the U.S. Transmission projects are developed either to meet reliability standards by the North American Electric Reliability Corporation (NERC) and regional reliability authorities or to accommodate uncertain future growth and development without violating those standards.

According to the NERC 2012 Long Term Reliability Assessment Report, the North American electricity demand growth for the next decade (2013–2022) as a 10-year compound annual growth rate for summer demand is 1.35% and for winter demand is 1.29%. To meet this demand growth, the main issue is not in providing generation but it is about providing appropriate transmission systems that would reliably meet the customer electricity requirements[5] [8]. Due to the difficulty and complexity associated with the power flow control and to help alleviate some of the control issues, utilities are investing in new, “smart” devices that have increased control and communication capabilities. Though these devices offer flexibility and opportunities for more advanced control strategies, a utility cannot simply replace its entire infrastructure overnight. There should be ways to allow advanced control devices to coexist in both planning and operating processes for the foreseeable future. Thus this dissertation presents Design procedures for a "smart" device which is the Distributed Series Reactor to primarily control the power flow over transmission lines to better utilize the existing network facilities and to improve the efficiency of the grid.

1.3 Simulation and Analysis Platform

The Distributed Engineering Workstation (DEW) software is used in this dissertation for power system analysis and system integration. It is the object oriented software based on the generic analysis approach. It is developed more than 20 years ago at Virginia Tech [9].

The Generic Analysis approach is a combination of physical network modeling and generic programming. The physical network modeling is developed for both steady-state and dynamic analysis of system models. Generic programming is one step beyond object oriented programming. It is based on the use of iterators that access and manipulate objects. In DEW, iterators are referred to as topology iterators, and are used to access and manipulate network objects in respect to physical connections. The topology iterator represents a graph-based approach that does not need to maintain or use matrices in analysis [10]. It eliminates very large system matrix updates following changes in system topology created by such things as sectionalizing device operations or equipment failures. With topology iterators, after any topological change model updates will operate only at the local component topology in constant time [10, 11]. The network solution approach used in DEW is also referred to as Graph Trace Analysis (GTA). Research on GTA has been conducted for many years at Virginia Tech [11, 12]. In DEW the analysis approach uses one model for all types of analysis. The technology is referred to as Integrated System Model (ISM). The scope of ISM includes transmission and distribution networks through customer loads. It easily displays and manipulates GIS system data [13]. Currently, commercialized power system software packages often use different models for different applications [14]. The ISM allows using a common model for different aspects of smart grid like planning, reliability, substation engineering, operation, and load forecasting. Figure 1.3 shows the major functional parts of the DEW software.

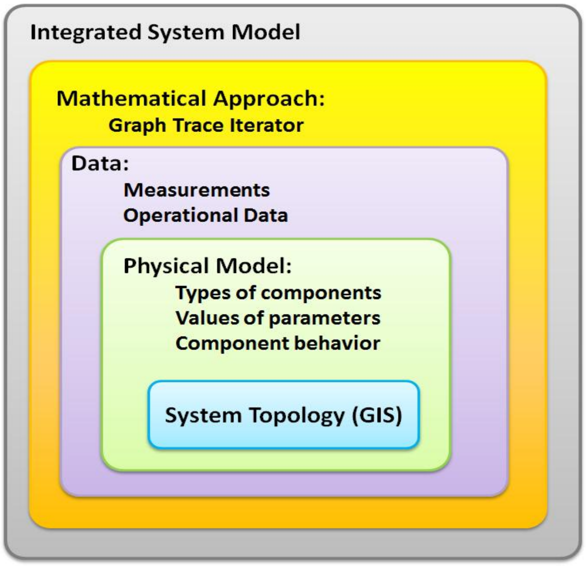


Figure 1.3 Major functional parts of DEW software

1.4 Dissertation Objectives and Research Questions

The need for modern electricity infrastructures and more capable grid components brings attention to Distributed Series Reactor (DSR) technology because of its control capabilities.

The DSR technology is investigated in this work. 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, or used to control the distribution of flow in parallel paths.

The major objective of this dissertation is to investigate the Design for deployment of Distributed Series Reactor on transmission lines. DSR was first presented as a D-FACTS device that is used to control power flow and to reduce transmission investment as a power flow controller, but its Design aspects were not addressed in the literature.

This dissertation targets determining the fundamentals of DSR system design to make optimum use of its control capabilities and to provide ***guidelines and considerations*** for their implementation in bulk power system transmission network control for:

- Increasing transmission system capacity to serve larger loads.
- Alleviating overloads that result due to increased load with N-1contingency criterion by controlling power flows in parallel transmission lines.
- Mitigating the effects of unbalanced voltages, unbalanced transmission line impedances and unbalanced loads by balancing flows in the phases of an unbalanced line.

DSR system design aspects performed in this study are for a single line, lines within the boundaries of a power system, lines within a control area and for a set of tie lines among control areas.

DSR system design for Load Growth and N-1 Contingency Analysis is performed and a study for DSR Economic Worth is evaluated.

This dissertation answers a broad question which is “How do we DESIGN with Distributed Series Reactor?” by answering a number of challenging questions related to the smart grid technology “Distributed Series Reactor.” Some of these questions are:

- How can DSRs affect the amount of power delivered to the load?
- How does the impedance model of the 3-phase transmission line (Balanced vs. Unbalanced) affect the DSR system design?
- How does the 3-phase line (Distributed vs. Lumped) model affect the DSR system design?
- How can the DSR allocation over the line impact the system performance/behavior?
- How can DSRs be used to balance the voltage at the delivery point?
- How does DSR compare to Transposition?
- How can DSR system design be applied to control the power flow and adjust the voltage for a single line, lines within the boundaries of a power system, lines within a control area and for a set of tie lines among control areas?
- How does the bundling of the conductors affect the DSR system design?
- What is the breakeven cost of DSRs when compared to new line construction for different DSR system designs?

1.5 Dissertation Outline

This dissertation consists of five chapters. This introductory chapter presents an overview of the power system functional zones and the current status of the electric grid. The software used for system analysis is then introduced. The research objectives and research questions that are answered via this study are then summarized.

Chapter 2 is the literature review. It presents the challenges that the electrical power transmission system is facing. It then shows a number of existing solutions and opportunities that are used to overcome these challenges and that can be used to improve transmission and distribution capacity and to obtain a reliable and efficient electric grid.

Chapter 3 presents an experiment performed using three parallel transmission lines to determine the fundamentals of DSR system design for a single line. This experiment studies the modeling and application of DSR as a power flow controller on the three parallel transmission lines supplying a load. Design ideas and considerations for the DSR control over parallel transmission lines are highlighted in this chapter.

Chapter 4 illustrates the DSR system design for:

1- A power system and
2- A multi-area control and tie lines design.

In the Design for a power system, the IEEE 39 bus system modeled as a 3-phase balanced and unbalanced system was adopted for the simulations. The study was implemented for load growth of a power system under N-1 line contingency criterion. A cost benefit analysis for the DSR system design of the IEEE 39 bus three-phase unbalanced line model for N-1 contingency criterion with load growth is performed.

In the Design for multi-area and tie lines design a simulation was performed 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.

Chapter 5 presents the conclusion, lists the contributions of this work, and envisions possible future work.

1.6 Publications Related to the Dissertation

[1] S. Omran, R. Broadwater, J. Hambrick and M. Dilek, "**DSR Design Fundamentals: Power Flow Control**," *2014 IEEE Power and Energy Society General Meeting*, July 2014.

[2] I. Grant, F. Kreikebaum, J. Shultz, S. Omran and R. Broadwater, "**Initial Field Trials of Distributed Series Reactors and Implications for Future Appication**," *CIGRE US National Committee 2014 Grid of the Future Symposium*, 2014.

[3] S. Omran, R. Broadwater, J. Hambrick, M. Dilek, C.Thomas, and F. Kreikebaum, "**Load Growth and Power Flow Control with DSRs in Unbalanced Transmission Networks**," *IEEE Transactions on Smart Grid*, Feb. 2015 (submitted).

[4] S. Omran, R. Broadwater, J. Hambrick, M. Dilek, C.Thomas, and F. Kreikebaum, "**Power Flow Control and N-1 Contingency Analysis with DSRs in Unbalanced Transmission Networks**," *Electric Power Systems Research - Elsevier Journal*, March 2015(submitted).

[5] S. Omran, M. Nazir, and R. Broadwater, " **Distributed Series Reactors (DSRs) for Power Flow Control in Unbalanced Transmission: Economic Evaluation**," *GSA Research Symposium , Virginia Tech,* 25 March 2015.

2 Electrical Power Transmission Challenges and Opportunities

2.1 Transmission Infrastructure Challenges

The enhancement of electrical transmission system facilities faces several challenges. This section presents some of these challenges that hinder improving the utilization of transmission capacity.

2.1.1 Siting, Permitting and Delayed Construction

Despite the issuance of U.S. Energy Policy Act of 2005 “EPAct 2005”, intended to attract investment in the transmission grid, the risks associated with planning, siting, permitting, and constructing new transmission facilities are considered a major challenge. This was also recognized by the Policy Statement that FERC released recently stating that developing transmission presents risks and challenges unlike investment in any other utility plant [15].

Appendix A introduces examples of transmission projects that were delayed through lengthy permitting processes [16]. According to analyses by the Edison Electric Institute (EEI), the U.S. power industry reversed a downward trend in transmission investment in the late 1990s. The uncertainty about the nature and extent of power industry restructuring had triggered a decline in transmission investment in the 1980s and the 1990s. During this period the electric load on the Nation’s grid more than doubled. This resulted in increasing transmission congestion in certain regions. The long-term trend of declining transmission investment between the 1970s and the 1990s recovered in the late 1990s, and transmission investments grew at a 12 percent annual rate between 1999 and 2003. Reliability and generation interconnection needs were viewed as the main reasons for increasing transmission investments in the United States during this period. Figure 2.1 represents the U.S. transmission investment forecast through 2015, based on (1) EEI’s projected capital expenditure growth rates applied to the 2009 U.S. total investment level, and (2) estimated investment requirements associated with transmission circuit-mile additions data from NERC [2].

Further, over the recent years there has been increasing public opposition towards locating power lines close to people communities. Acronyms such as NIMBY (Not In My Back Yard) and

BANANA (Build Absolutely Nothing Anywhere Near Anyone) have become more and more popular. Thus the transmission grid is now getting more congested which results in compromised reliability and higher energy cost.

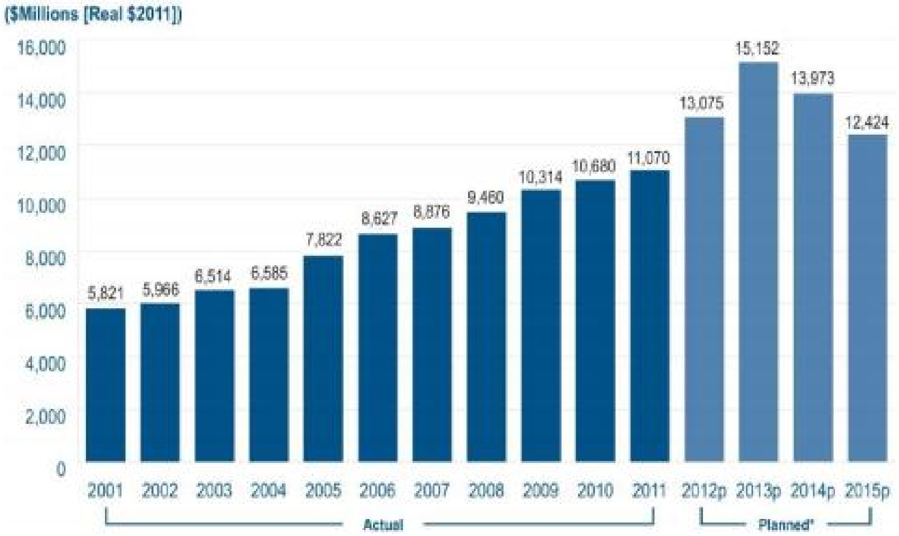


Figure 2.1 Estimated Historical and Projected Transmission Investment in the U.S. from 2001 to 2015

2.1.2 Aging Power Grid and Congestion

Congestion and transmission bottlenecks have become a regular issue for system operators. The aging power-grid is under stress, resulting in compromised reliability and higher energy costs. Transmission Congestion occurs on electric transmission facilities when actual or scheduled flows of electricity across a line or piece of equipment are restricted below desired levels.

In some cases, transmission expansion might simply move a constraint from one point on the grid to another without materially changing the overall costs of congestion. In other cases, the cost of building new facilities to remedy congestion over all affected lines may exceed the cost of the congestion itself, and, therefore, remedying the congestion would not be economic. In other cases, alternatives other than transmission, such as increased local generation (including distributed generation), energy efficiency, energy storage, and demand response may be more economic than transmission expansion in relieving congestion. Thus, finding that a transmission path or flowgate is frequently congested should lead to further study of the costs and impacts of that congestion, and to a careful regional study of a broad range of potential remedies to larger reliability and economic problems [16].

2.1.3 Underutilization of Existing Transmission Facilities

The transmission system was originally structured as a radial network because they were easier to build and operate. However, this caused the system to suffer a poor reliability as a single fault resulted in an extended outage for all downstream customers. For the sake of reliability of the existing transmission grid, it is designed nowadays as a meshed network. Failure in one section of a meshed network is compensated for by supplying power via other transmission lines, thus maintaining power to customers. This increases the system reliability but at the expense of power flow control. The electric current always flows on the path of lowest impedance; this may result in an uneven loading of the network. Power flow control over transmission lines can be quite complex in a meshed grid; one of the lines can become overloaded while other lines in the grid may still be lightly loaded. The first line to reach its thermal capacity limit will limit the power transfer capacity of the system, even though much of the system may be operating much below the thermal capacity limit. Controlling the flow on overloaded lines and re-routing it to more lightly loaded lines can improve the utilization of the existing transmission line capacity, thus delaying the investment in transmission system infrastructure. Thus, utilities in North America and all over the world are trying to incorporate new technological innovations to expand the transmission capacity and make best use of the current assets and facilities [17]. Ways and solutions to expand the transmission system capabilities with no new transmission lines construction have been presented in the literature [18, 19, 20, 21, 22, 23, 24, 25, 26, 27] [28] . Opportunities and technologies related to smart wire grid and distributed series compensator were also proposed in the literature to increase transmission capacity utilization [29, 30, 31, 32, 33]. The following section gives an overview of these solutions and opportunities and highlights their impact and limitations on power-flow control.

2.2 Existing Solutions and Opportunities to Improve Transmission and Distribution Capacity

Some existing solutions to enhance the transmission and distribution performance and improve the capacity are presented in this section [5] [16] [31] [34].

2.2.1 State Estimation

Providing the ability to control the flow of current can help the system operators to use the network resources more efficiently. State estimation is one such technique that monitors the prevailing systems conditions to extract the unused capacity from the grid. It estimates the unknown network quantities, voltage magnitudes, phase angles, etc. from measurable quantities such as the generator injected powers, line reactance, transformer tap settings. Most of the time the measured quantities are not error free and may get corrupted by digitization noise. State estimators have trouble estimating a system state during unusual or emergency conditions, unfortunately when they are most needed.

2.2.2 Optimal Power Flow

This is a similar technique of improving the utilization of lines and transfer capacity of the existing network. Optimal power flow gives the optimal dispatch of power through a network satisfying a given objective function. The objective function is formulated so as to improve the grid operation. For example it can be minimization of line losses, fuel costs or reactive power generation. The optimization is done satisfying the system constraints, which can be specified as limits on the line current flows, voltage magnitudes, and reactive power of shunt VAR compensators, etc.

Optimal power flow simulations must be carried out every time the loading or the operating conditions on the network change. A central control and communication units are required to compute the new state of the system and adjust the control variables. Computational complexity and the requirement of an extensive communication capability make this approach difficult to implement for very large power networks.

2.2.3 Extra High Voltage (EHV) Transmission Lines

This is a mature technology appropriate for long distance transmission. EHV transmission systems have voltage greater than 242 but less than 1,000 kV. The highest in commercial operation in the USA is 765 kV level, while 345 kV and 500 kV are standard voltage levels. Such lines are capable of transmitting more power over longer distances but require larger, more expensive transformers, insulators and towers as well as wider rights of way. As a result the highest voltage AC lines are most economical for large capacity, long distance electricity transmission.

2.2.4 Direct Current (DC) Transmission Lines

The transmission system consists mainly of Alternating Current (AC) lines due to their desirable characteristics, such as the ease of voltage transformation. However DC lines can be valuable additions to AC transmission network. High voltage DC lines are not limited by stability considerations and therefore theoretically they are not limited in length.

The cost of the metal which conducts electricity for DC transmission lines is lower than for AC lines of the same voltage because fewer conductors are necessary and conductor utilization is better. But the cost for DC substations is significantly higher because transformers only work for AC, so more expensive power electronic converter stations are required to convert between AC and DC. Also tapping a DC line – that is, connecting a load in the middle of the line – requires a costly and complex converter station instead of a much less expensive transformer as for an AC line. The electrical losses in an AC/DC converter station are higher than in an AC substation. However, the losses per mile of a DC line are lower than those of an AC line. Thus, DC is especially suited to long distance, point to point power transmission, where a single generating site connects to a single point on the AC grid.

2.2.5 Underground and Submarine Transmission

These cables are used in locations where overhead transmission lines are impossible or undesirable. A severe constraint when these cables are used for AC transmission is the high capacitive charging current required, generally limiting length to just tens of miles. DC cables are limited only by electrical losses. Despite innovations in insulation materials, the complexity of assembling and installing cables means that cables will remain more expensive than overhead lines. However, the difficulty of siting overhead transmission lines can make underground submarine cables an attractive option in some areas despite the greater expense.

2.2.6 Superconductors

Low temperature superconductors have emerged from the research labs within the past decade. Superconductors are materials that have extremely low electrical resistance when cooled below a certain critical temperature, which is different for each superconductor. They have a much higher power capacity compared to normal conductors of the same physical size, but are constrained by the difficulty of maintaining adequate cooling. Above some maximum current level, the material reverts from superconducting behavior to a normal conductor having high impedance.

2.2.7 Phasor Measurement Units (PMU)

PMUs are powerful devices that provide a rich stream of frequent, time stamped data on transmission system conditions that system operators can use to anticipate contingencies, reduce the risk of wide area blackouts, enhance system efficiency, and improve system models. They measure defining characteristics of voltages and currents at key substations, generators, and load centers, such as cities. System frequency and other quantities are often measured. Taken together with known line characteristics, these measurements can be used to calculate instantaneous power flows throughout the system. PMUs report data more frequently than SCADA systems, where PMUs have a reporting rate of 30 times/sec and even higher. PMUs are being widely deployed, but work is needed to network these devices into systems, convert data from these systems to actionable information, and employ this information in the control of the grid.

New algorithms, software, and communication systems are required to integrate PMUs effectively into system operations. Sometimes available valuable data are not shared as widely as would be beneficial. One recent promising initiative has been undertaken in February 2010 by the North American Electric Reliability Corporation (NERC) to enhance high value data sharing. The benefits of the PMU will be realized with the success of such an initiative, as PMUs have the potential to greatly benefit the transmission network, but mechanisms for sharing data are immature, and many tools for data analysis have yet to be developed.

2.2.8 Dynamic Line Ratings (DLR)

Dynamic line rating systems also can potentially increase the capacity of transmission lines. Historically, system operators establish the thermal limits of lines under seasonal worst case assumptions, where a hot windless day is an example of a worst case scenario in the summer. This static limit is often conservative relative to actual conditions. DLR systems measure changing environmental conditions and update system models accordingly, increasing transmission capacity limits in all but a few worst case scenarios. DLR are implemented with a variety of sensors. One design deployed uses just 2 sensors, one to measure line tension and another to measure air temperature. These 2 pieces of data allow operators to determine average conductor temperature, the main determinant of a line's thermal limit.

DLR systems are attractive in the case of transmission lines linking wind generation to the rest of the transmission network. Wind generators require more transmission capacity when wind is strongest; strong winds are precisely the conditions in which DLR systems improve transmission capacity. However, where wind resources are far from load centers the long connecting lines needed would tend to be limited by stability rather than thermal properties. DLR systems will not improve the capacity of these lines.

DLR systems installed on existing transmission lines have shown to improve the capacity by 5% to 30%. Increase in penetration of DLR systems between now and 2030 is expected due to the positive results of previous deployment of DLR.

2.2.9 Flexible AC Transmission Systems (FACTS)

FACTS are controllers that employ power electronics and that are connected to the transmission network to enable more rapid and flexible control of the system.

Main FACTS devices include: Static VAR Compensator (SVC), Static Synchronous Compensator (SSC), Thyristor Controlled Series Compensator (TCSC), and Unified Power Flow (UPF) Controller. These devices are to be deployed on transmission systems to control the voltage level at the nodes, improve system stability characteristics, and control the flow of the power. They have been deployed on real transmission networks. However, the deployment of devices, other than the SVC, has been limited because of the cost. Research and Development efforts to reduce the cost will be necessary if FACTS devices are to become a significant factor in power systems of the future.

FACTS devices change the system parameters, such as voltage magnitude, voltage angle, or the line reactance, to improve the transmission capacity and utilization of existing lines by controlling the flow of current through them.

Figure 2.2 shows a simple two bus system, with the associated parameters. The basic equation governing the flow of real and reactive power between the two buses/nodes is described by equations 1.1 and 1.2

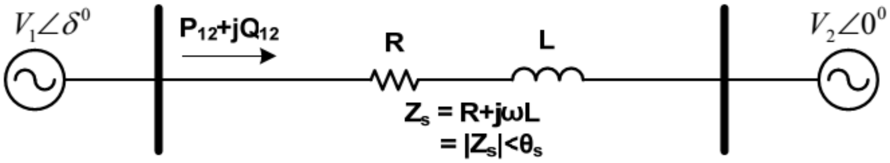


Figure 2.2 Two bus system

$$P_{12} = \frac{V_1V_2}{|Z_s|}\cos(\theta_s - \delta) - \frac{V_2^2}{|Z_s|}\cos\theta_s \quad watt/phase \quad (1.1)$$

$$Q_{12} = \frac{V_1V_2}{|Z_s|}\sin(\theta_s - \delta) - \frac{V_2^2}{|Z_s|}\sin\theta_s \quad watt/phase \quad (1.2)$$

P_{12} and Q_{12} : the flow of real and reactive power from Bus 1 to Bus 2,
V_1 and V_2: the voltage magnitudes at the two buses,
δ: the phase difference between the voltages at the two buses,
$|Z_s|$: the absolute value of line impedance, and
θ: the angle of the line impedance

The equations can be further simplified if the line resistance (R) is neglected as shown in equations (1.3) and (1.4). This assumption holds true if the reactance of the line (X_L) is much greater than the resistance (R).

$$P_{12} = \frac{V_1V_2}{X_L}\sin\delta$$

$$= \frac{V^2}{X_L}\sin\delta \ , if \ |V_1| = |V_2| = |V| \quad (1.3)$$

$$Q_{12} = \frac{V_1V_2}{X_L}\cos\delta - \frac{V_2^2}{X_s}$$

$$= \frac{V^2}{X_L}(\cos\delta - 1) \, , if \ |V_1| = |V_2| = |V| \ (1.4)$$

Here X_L is the line reactance.

The equation highlights that both the real and reactive power flows between any two buses can be controlled by changing the voltage magnitudes, voltage phase difference, or the reactive impedance of the line. All FACTS devices alter one or more of these system parameters to control the flow of power. Controlling the power flow by changing the different parameters is presented in the following sections.

Controlling Power-flow through Voltage Magnitude:

Voltage magnitude of a bus, or in general of a particular node, can be increased by generating shunt Vars and can be decreased by absorbing shunt Vars. For example, if the bus voltage needs to be increased, a shunt capacitor is used to generate Vars so as to reduce the reactive power flowing through the line. On the other hand if the node voltage needs to be decreased, a shunt inductor can be connected to absorb more Vars from the system, and consequently increase reactive current flowing through the line.

One of the biggest concern with the use of Static Var Generators SVGs is that they pollute the power system with harmonics [35]. In a three phase system the shunt banks are normally connected in a delta configuration to cancel the triplen harmonics. Another associated problem with employing a shunt capacitor is the possibility of resonance with the line inductances. The biggest disadvantage of using SVGs, besides their slower response, is the fact that their ability to provide Var support is voltage dependent.

For this reason, voltage-source based Var generators, also known as Static Compensators (STATCOMs), were introduced in 1988 [36]. Their operation is similar to that of a synchronous condenser, which exchanges reactive power at its terminals by varying the field excitation. They employ a four quadrant inverter to generate a voltage in phase with system voltage so that only reactive power can be exchanged with the system.

STATCOMs are seen to be more robust in providing reactive support to the network as their level of injection is independent of the variations in system voltage.

Controlling Power-flow through Series Impedance Control:

Power-flow through a line can also be altered by changing the series line reactance. The flow of current is dictated by the lowest impedance path, and hence the power-flow through a line can be decreased by inserting a series inductor, or can be increased through insertion of a series capacitor. Most of the research effort in the past has been devoted to series capacitive compensation. Series capacitive compensation can also help to improve the voltage stability of the system by cancelling a portion of the series line reactance.

There are several issues associated with the use of a series capacitor on a power line. Series installation of the capacitor has to be done at a substation and requires additional infrastructure such as isolation platforms, cooling systems, and other protection devices. Another issue of concern is sub-synchronous resonance with the turbine-generator unit. The series capacitor can form a resonant circuit with the line reactance under fault or nominal conditions. These design requirements increase the cost and complexity of the solution. As a result, the penetration of this technology has been limited to a few project demonstrations sponsored by utilities.

A voltage lagging the line current would translate into a series capacitor while a voltage leading the line current would imply a series inductor.

Practical implementation of the technology is limited by the cost of coupling transformers, inverter circuits, and DC energy storage.

Controlling Power-flow through Phase Angle Control:

In meshed networks, phase shifting technology can be used to control unscheduled power flows and increase transfer capacity of the network.

Phase shifting transformers, or phase angle regulators, can provide a continuous phase control range. The injected series voltage increases the loading of the lines, as both real and reactive currents flow through the shunt-connected primary winding. To compensate for these loading effects, a separate shunt-connected reactance compensator may be required. This further increases the complexity and cost of the technology. Moreover, the control problem is seen to be very complex and has not been validated on a large scale power system.

Unified power flow controllers (**UPFC**) can control all three line parameters, voltage, angle, and impedance, to affect the power-flow. Although UPFC is the most versatile power-flow controller, its penetration into the utility market has been limited by the high installation and operation costs. It requires skilled professionals for its control and maintenance, and also suffers from low reliability of the electronics.

2.2.10 Distributed FACTS (D-FACTS)

The difficulties in convincing utilities to invest in FACTS technology are:

1. High Cost: Converter complexity and semiconductor ratings make FACTS devices an expensive solution. Moreover, the maintenance and repair calls for skilled labor, which further increases the cost.
2. Low Reliability: A single component failure can prove to be fatal in the overall performance of the module. Further, currently available power electronic components are not suitable for operation in the hostile utility environment.

3. Custom Engineering: Most FACTS devices are custom-designed and have long build times. They further require additional infrastructure, such as mounting platforms and isolation transformers.

These limitations can be attributed to the lumped nature of FACTS devices. The reliability of the technology can be increased and the cost can be decreased, if the same control objective is served by replicating a lumped controller into smaller controllers and distributing them over the grid. Thus, the concept of Distributed FACTS (D-FACTS) was proposed in [31] [32]. It consists of single phase devices that can clamp onto existing conductors, providing easy installation and the possibility for on-site repairs. The cost of the technology is lower, as off-the-shelf components can be used to meet the ratings of the individual controllers/devices and can be further scaled down with volume production. The reliability of the solution is also improved as the failure of a single component or even a complete device is seen to have limited impact on the overall functionality of the solution.

The Distributed Static Series Compensator (DSSC) and the Distributed Series Impedance (DSI) were introduced as D-FACTS devices to be used as a solution for power flow control. As these devices are inverter based technology, issues of reliable operation will arise and thus the Distributed Series Reactor (DSR) was proposed as an advance to the concept of D-FACTS [30] [33] [37] .

2.2.11 Distributed Series Reactor (DSR)

As adjusting the impedance and admittance of the transmission line is one method to control the power flow, Distributed Series Reactor controller was first proposed as a D-FACTS device to fulfill this objective. Lines that are likely to see overloads at certain times of the day or under defined contingency conditions can be modified with DSR modules to automatically control the line reactance and thus current flow.

The DSR technology is based on modifying the series line reactance. DSR modules are mounted on the transmission line and they are activated when the line current reaches a certain threshold value. When a transmission line reaches its capacity, DSRs can be switched on to increase its series reactance. When an alternate path is available, this increase in series reactance will cause flow to shift to parallel lines [38].

A DSR system cannot only restore a secure system operation under contingency conditions by diverting the excess current to other lines, but can also improve the transmission capacity under such conditions. Thus, a self-healing network with *controllable valves* can be realized. However the benefits from the DSR modules can only be realized if a stable system operation is guaranteed without any interaction between the modules and the network [34].

The DSR adds reactance to the self-impedance (diagonal elements of the impedance matrix) of the line model. 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 [38]. In this study the DSR modules implemented values are 50µH/module (0.01885 ohms).

Technology development:

Distributed Series Reactors has been developed by a vendor working initially with the Tennessee Valley Authority (TVA) and the Department of Energy Advanced Research Program Agency - Electric (ARPA-E) [31]. DSRs, are clamped to phase conductors and powered by induction from the line current. A magnetic link allows the device to inject inductive reactance to increase line impedance. In a meshed transmission grid, increased impedance in one path results in transfer of power flow to other paths.

The distributed series reactor, shown in Figure 2.3, consists of a split transformer hung from the conductor. The conductor forms the primary winding of the transformer. When the secondary winding is shorted, the unit operates in monitoring mode and negligible inductance is coupled in series with the line. When the secondary winding is opened, the magnetizing inductance of the transformer is coupled in series with the line, and the unit operates in injection mode.

Over the operating range the coupled inductance is more than 50 microhenries (µH). While an individual device has a very small effect on the impedance of a line phase, adding numbers of them can change reactive impedance by several percent. For a 161 kV line, one device per phase per mile provides approximately 2% impedance change. Thus 10 devices per phase per mile change the impedance by 20%. Since the devices are relatively inexpensive and can easily be hung at each end of each conductor span, it is practical to consider adding quite large numbers to a line.

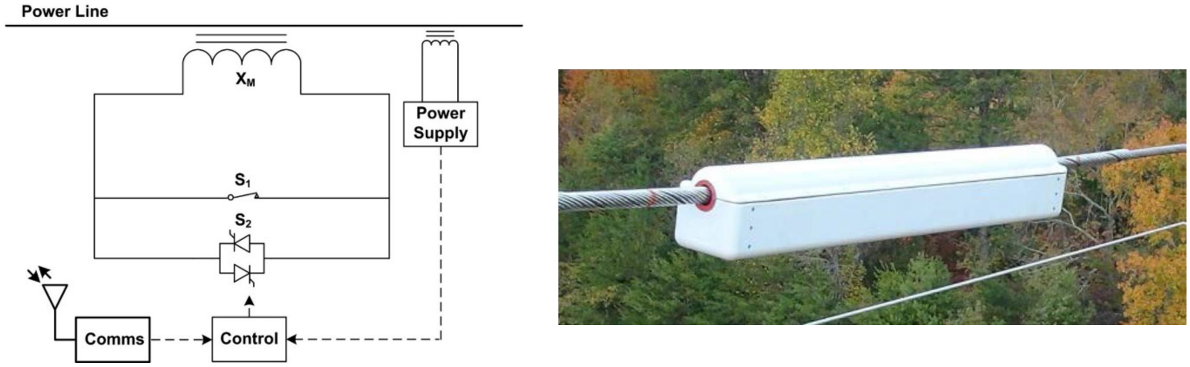


Figure 2.3 DSR on a Line Conductor

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 in response to system conditions, or controlled automatically for more complex applications. Communications may be simply through one way power line carrier, or two way through cell phone circuits. Manual or automatic control is achieved as shown in Figure 2.4 through real-time communications. A Super DSR manages a set of proximate distributed series reactors and communicates with a DSR System Manager, which interfaces the entire fleet of DSRs with the energy management system (EMS). The central system manager allows configuring, monitoring and operating the DSRs as well as data archival. A DSR can provide line current, conductor temperature, fault location indication, fault current, ambient temperature, conductor vibration, conductor sag angle, and conductor blowout angle.

When the DSR controller detects a fault it returns the units to monitoring mode in less than 100 microseconds to ensure that the DSRs do not interfere with existing protection schemes. To date, none of the DSR pilot deployments have required any changes to protection settings [39].

Applications:

Applications include reliability improvement, delaying new line construction, reduction of congestion/redispatch, simplification or removal of operating procedures, maintenance and construction outage support, phase balancing, and improved situational awareness.

Figure 2.4 DSR Communications

DSRs can be deployed to simplify or eliminate a remedial action scheme (RAS) or special protection scheme (SPS). In a study for a utility, a specific n-2 asset outage resulted in tripping generation and load with a RAS. Deploying DSRs on a number of transmission lines simplified the RAS and eliminated 1200 megawatts (MW) of generation and load shedding. In another study, DSRs in tandem with conventional system upgrade methods were able to eliminate 1800 MW of generation and load shedding. In another study DSRs added to six congested lines significantly reduced average electricity cost within an Interconnection. DSRs can dynamically adapt to mitigate congestion over a range of operating conditions.

Deployments to date:

The first pilot test included 100 units installed over 17 spans of a 21 mile 161 kV line owned by the Tennessee Valley Authority. Installations averaged approximately 10 minutes per unit, including wire brushing the conductor, installation of protector rods, and installation of an associated vibration damper. Figure 2.5 shows an installation in progress.

Test results:

The pilot test at TVA demonstrated DSR operations for the first time on an energized line. Due to grid limitations, the DSRs could not be exercised through their full range, but all operating functions were successfully demonstrated. Operations tested performance of the units at four stepped setpoints.

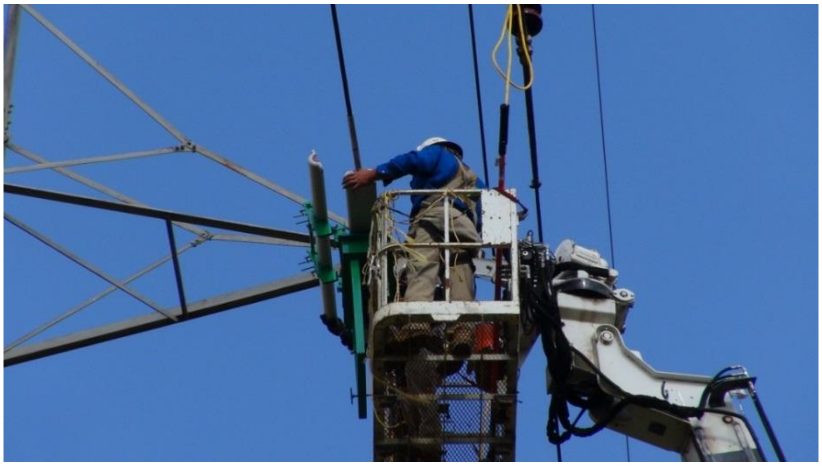


Figure 2.5   DSR Installation on TVA 161 kV Line

TVA also explored phase balancing with the DSRs. One of the phases of the test line tends to run 20-30 A higher than the other two phases, so all DSRs on this particular phase were placed in injection mode, while the other two phases were set to monitor mode. The DSRs caused a 20 A drop on the higher phase, increasing current on the other two phases, almost equally balancing the three phases of the line.

While it may seem that DSRs are best suited to shorter lines since a smaller number of devices can achieve a desired percentage impedance change, in fact they are equally suited to lines of any length with an essentially fixed relationship between the percentage of line cost (or cost per mile) to fully equip it with DSRs and the percentage impedance change achieved. The value of a given installation is determined from system studies and will be dependent on the individual relationship of the line and existing power flows in the grid [39].

Impact on Power System Protection

Relays sense faults on the system and send trigger signals to the circuit breakers. Circuit breakers interrupt the fault and disconnect the faulted transmission line or equipment. The particular relay of interest is the distance protection relay. The relay calculates the impedance of the line to the fault by sensing the voltage and the current at the point of installation. If the impedance of the line or the equivalent length of the line to the fault is smaller than the zone of protection, a trigger signal is initiated. Figure 2.6 shows protection zones and tripping times of a typical distance relay installed at Bus A.

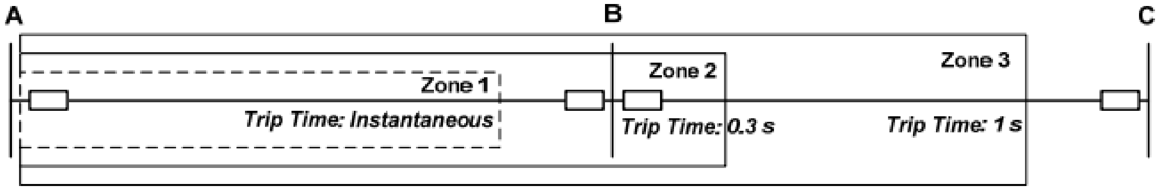


Figure 2.6 Zones of protection and tripping times for a distance relay installed at Bus A

The DSR modules increase the impedance of the line and as a result, the distance protection relay can mal-operate and predict the distance of the fault to be outside the zone of protection. To rectify this problem, two possible solutions were proposed in[34].

1. The operating logic of the relay can be changed to dynamically incorporate the additional impedance of the modules in the zone of protection. The operating logic would then calculate the number of active modules on the line from the measurement of the operating line current value. The relay would adjust for the compensated line impedance and modify the zone of protection dynamically. Though the solution is viable, it introduces additional complexity in the network.
2. DSR modules are by-passed in a time much faster than the operating time of the fault detection algorithm of the distance relay. This will ensure that the relay only sees the uncompensated impedance of the line under a fault. This seems to be a more plausible approach for deploying DSR modules on a system wide basis.

From the practical implementation of DSRs and as mentioned and highlighted earlier under the “Technology development” subsection, the second solution proposed here is the one utilized to ensure that DSRs do not interfere with the protection schemes of the system, and none of the DSR pilot deployments have required any changes to protection settings.

2.3 Conclusion of Chapter 2

The U.S. grid is frequently described as aging, and many transmission lines have been in operation beyond their 30 - 50 year design lifetimes, but in reality inspection and maintenance programs ensure that structures, foundations, insulators, conductors, and sag issues are readily detected and repaired or even uprated. However, contingencies that may be caused by widespread severe weather, a desire to expand supply capacity and meet short lead times to encourage new industries, reduced use or retirement of older coal plants, or a need for outages to allow uprating, may challenge the ability of a grid to meet criteria for delivering power during certain windows of time. Moreover, transmission infrastructure projects are facing several challenges. Some of these challenges are; the delayed construction due to siting and permitting issues, the congestion, and the under-utilization of already existing transmission facilities.

Existing solutions and opportunities to improve transmission and distribution capacity is the deployment of technologies and techniques that better utilize the existing network facilities and improves the efficiency of the grid. Some of these technologies and techniques presented in this chapter are; state estimation, optimal power flow, extra high voltage (EHV) transmission lines, direct current (DC) transmission lines, underground and submarine transmission, superconductors, phasor measurement units (PMU), dynamic line ratings (DLR), Flexible AC Transmission Systems (FACTS), distributed FACTS (D-FACTS), and Distributed Series Reactor (DSR) which was first proposed as a D-FACTS device to control the power flow over transmission lines by adjusting the impedance and admittance of the line.

Distributed Series Reactors has been developed by a vendor working initially with the Tennessee Valley Authority (TVA) and the Department of Energy Advanced Research Program Agency - Electric (ARPA-E). The DSR model adds reactance to the self-impedance (diagonal elements of the impedance matrix) 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. In this study the DSR modules implemented values are 50µH/module (0.01885 ohms).

DSRs can be controlled in several ways. They can be used in injection mode to change the reactive impedance of the line for controlling the power flow and phase balancing or can be used in monitoring mode to provide line current, conductor temperature, fault location indication, fault current, ambient temperature, conductor vibration, conductor sag angle, and conductor blowout angle. When the DSR controller detects a fault it returns the units to monitoring mode in less than 100 microseconds to ensure that the DSRs do not interfere with existing protection schemes. To date, none of the DSR pilot deployments have required any changes to protection settings.

The pilot test at TVA demonstrated DSR operations for the first time on an energized 161 kV line and all operating functions were successfully demonstrated. TVA also explored phase balancing with the DSRs and they provided almost equally balancing of the three phases of the line.

3 Fundamentals of DSR System Design - Three Parallel Lines Experiment

3.1 Introduction: DSR System Design Investigation Aspects

The aim of the study in this chapter is to determine the fundamentals of DSR system design by performing an experiment using three parallel transmission lines. This chapter describes the results of simulations involving Distributed Series Reactor (DSR) on a three, parallel, transmission lines system to enhance the network capacity, increase line utilization, alleviate overloads, and balance the voltage at load delivery points. Several DSR system design aspects are investigated in this chapter including

- Implementation of DSRs over lines with different lengths.
- Deployment of DSRs over transmission lines having different voltage levels.
- Calculation of the value of DSRs as a function of voltage level and line length.
- Implementation of DSRs for balancing the voltage at the load delivery point for unbalanced line Z and unbalanced loads.
- Deployment of DSRs over transmission lines versus transposition of the lines for voltage balancing.
- Deployment of DSRs over single conductor transmission lines versus bundled conductor lines for load growth.

3.2 Case Study Characteristics

In this experiment DSRs are deployed over long, medium and short transmission lines. Three parallel transmission lines are used to simulate the DSR placement impact on alleviating the overloads. The DSR effect on the maximum amount of power that can be supplied to the load via these three lines is also investigated. The first line is a 230 kV line referred to in the rest of the research as (Line230), the second is a 345 kV line (Line345) and the third is a 500 kV line (Line500). Simulation results are presented for long lines (200 mile), then for medium length lines (100 mile), and finally for short lines (20 miles). A comparison between the three systems is also elaborated. DSR deployment on lines of different voltage levels is examined and the cost benefit per DSR as a function of voltage level and line length is investigated.

Moreover, the impact of DSR deployment is compared to transposition of the lines for voltage balancing. Afterwards, the behavior of the system of the three parallel lines with bundled conductors is compared to lines with single conductors.

To investigate the line model and impedance model, different cases were adopted for simulation. These cases are tabulated in Table 3.1.

Table 3.1 Simulation Case Studies Description

Case number	Line Model	Impedance Model
1	Distributed	Balanced, positive sequence
2	Lumped	Balanced, positive sequence
3	Distributed	Unbalanced
4	Lumped	Unbalanced

The line model "distributed" means that each transmission line is presented in sections (200 sections for the long lines and 100 sections for the medium lines and 20 sections for the short line), each section is one mile long represented as a π- model. Figure 3.1 (a) depicts the distributed model for the 200 mile lines system. For presentation convenience, only some sections from the beginning and the end of the lines are illustrated. The lumped model, in which the 200 miles are presented as one π- model segment is shown in Figure 3.1 (b).

The balanced line model is derived from the unbalanced line model. It is the positive sequence representation of the system obtained using the symmetrical components transformation [17] [40]. This positive sequence model is typically used in transmission systems studies, where the system is presented as single phase equivalent.

In a balanced impedance model, the self-impedances of the line are equal. For an unbalanced system, the self-impedances are not equal. For the unbalanced case, the impedance matrix and shunt admittance matrix for the three lines are symbolically represented as follows

$$Z_{line} = \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} \\ z_{ab} & z_{bb} & z_{bc} \\ z_{ac} & z_{bc} & z_{cc} \end{bmatrix} \Omega$$

$$Y_{line} = \begin{bmatrix} y_{aa} & y_{ab} & y_{ac} \\ y_{ab} & y_{bb} & y_{bc} \\ y_{ac} & y_{bc} & y_{cc} \end{bmatrix} \mu\text{S}$$

For the balanced impedance system, the impedance matrix for the line model is as follows

$$Z_{line} = \begin{bmatrix} z_{aa} & 0 & 0 \\ 0 & z_{bb} & 0 \\ 0 & 0 & z_{cc} \end{bmatrix} \Omega$$

where $Z_{aa} = Z_{bb} = Z_{cc}$, and the shunt admittance matrix is as follows

$$Y_{line} = \begin{bmatrix} y_{aa} & 0 & 0 \\ 0 & y_{bb} & 0 \\ 0 & 0 & y_{cc} \end{bmatrix} \mu\text{S}$$

where $y_{aa} = y_{bb} = y_{cc}$.

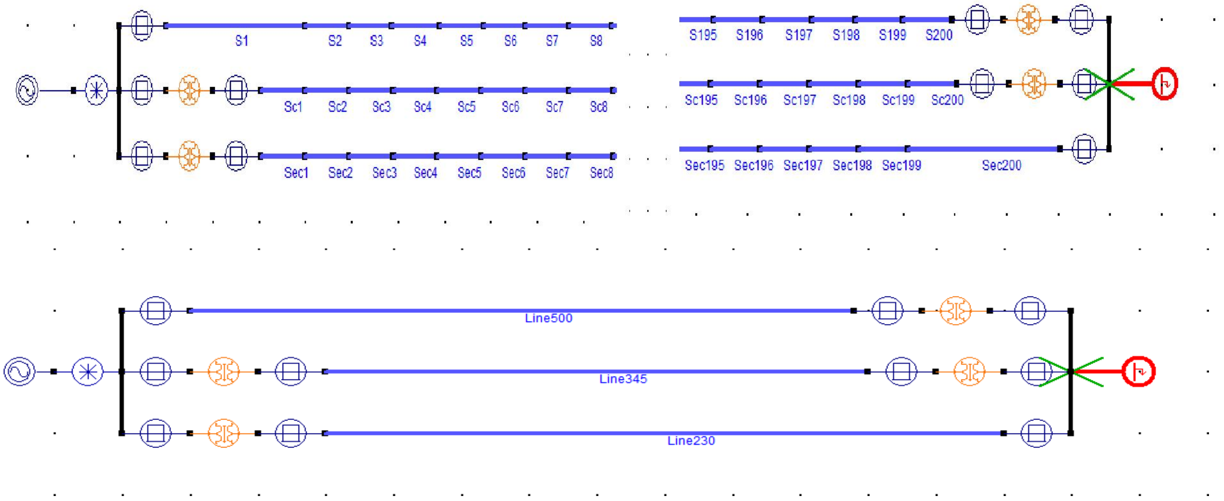


Figure 3.1 (a) Distributed Line Model (b) Lumped Line Model – two types, balanced and unbalanced

3.3 DSR System Design Algorithm for the three lines experiment

The maximum amount of power that can be delivered to the load over the three transmission lines with no DSRs deployed is determined. Afterwards when load power is gradually increased, an overload is observed over Line230. DSRs are deployed on this line to alleviate the overloading, and then once more the load is increased. This process is repeated until no more DSR addition is effective or until the line capacities are fully utilized. The flowchart in Figure 3.2 illustrates the algorithm implemented in the experiment.

3.4 Simulation Results

Different case studies described in Table 3.1 are simulated and results are presented in the following sub-sections. For the distributed line model cases, DSRs are first deployed on the first sections of the overloaded line (FRONT), then they are evenly distributed along the line

(EQUAL), and finally they are placed at the last sections of the line (END). These 3 scenarios are used to test if there is a difference between different allocations and if there is preference of one allocation over the others.

3.4.1 Deployment of DSRs over lines of different lengths to improve line utilization and capacity

3.4.1.1 Long Transmission Lines - 200 Mile

Results for the three parallel 200 mile lines are represented in this section. The simulation results are presented first for the distributed model, then for the lumped model. The line loading ratings were set to their surge impedance loading SIL value, as in case of long lines the capacity is limited by its surge impedance loading which is below the thermal capacity [41] [42] [43] [44].

Distributed Model (Line230|| Line345|| Line500):

In this case the system is a distributed line model with both balanced (positive sequence) and unbalanced systems being tested. With no DSRs deployed a maximum of 950.9 MVA were supplied to the load through the three parallel lines. When the load was further increased an overload was observed on Line230. DSRs were implemented to alleviate this overload via the three placement configurations. DSRs are first deployed on the first 25 sections of the overloaded line (FRONT), then they are evenly distributed along the line (EQUAL), and finally they are placed at the last 25 sections of the line (END). For all allocations of DSRs the overload over Line230 was alleviated and the flow was shifted to the other 2 lines, thus increasing the power flow over them. The END allocation is the one that provided maximum load power with minimum number of DSR modules deployed. For the unbalanced system the load maximum power was increased from 950.9 MVA to 1,192.4 MVA; an increase of about 25% when Line230 was END loaded with a total of 7,875 DSRs. Table 3.2 presents simulation results for both balanced and unbalanced distributed systems. Table 3.3 shows the comparison and the relative error between the preferred allocations for both systems. The % error calculated and presented in this table and through the entire chapter **is relative to the distributed unbalanced case** which is assumed to be the more accurate representation of the system.

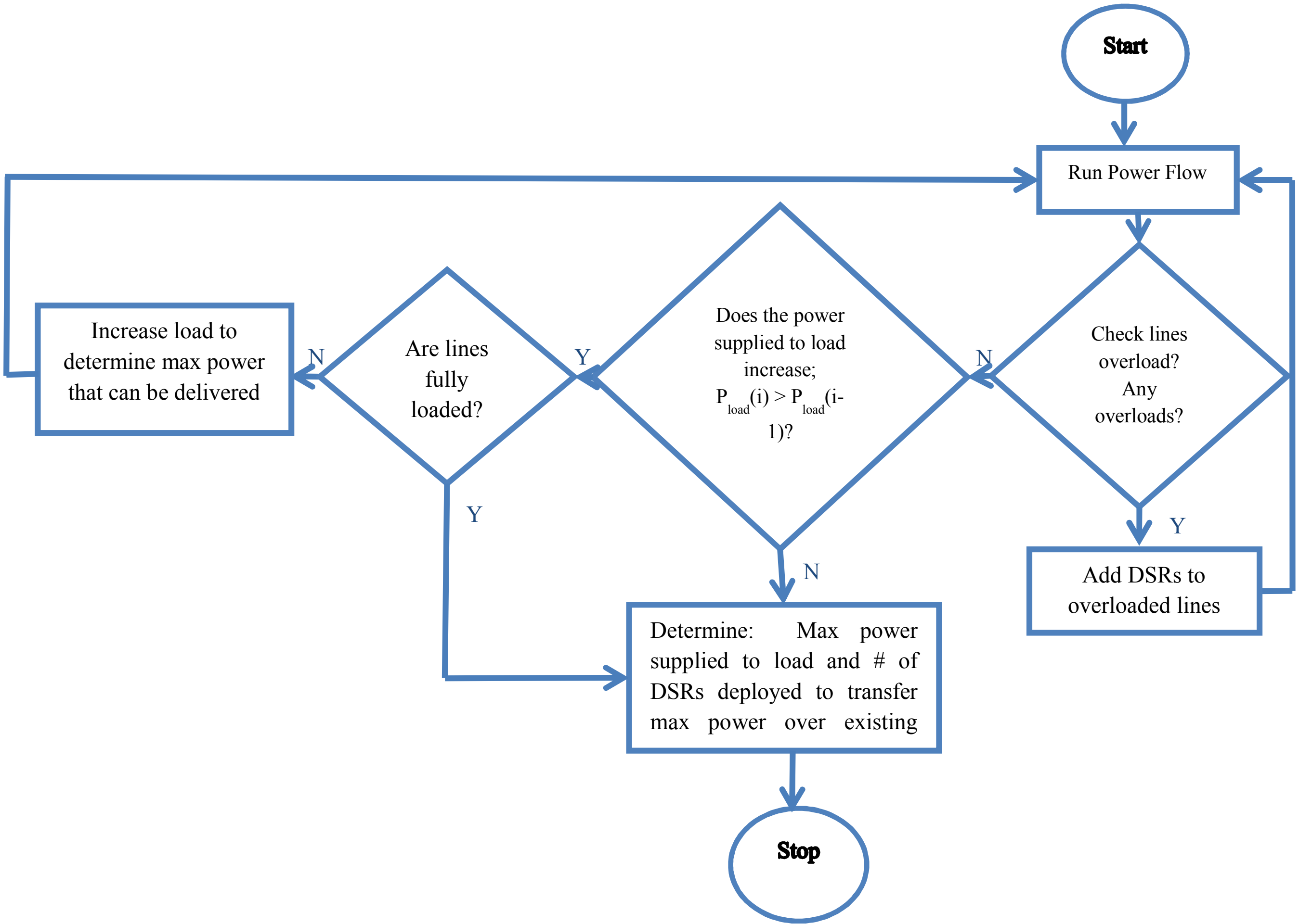


Figure 3.2 DSR deployment algorithm for the three line experiment

Table 3.2 Long Line Distributed Model Results for DSR deployment over Line230

	FRONT		END		EQUAL	
	# DSR	**MVA**	**# DSR**	**MVA**	**# DSR**	**MVA**
Dist. Unbalanced	8625	1201.1	7875	1192.4	7950	1197.2
Dist. Balanced	8250	1204.4	7650	1197.1	7800	1200.4

Table 3.3 Distributed model preferred allocation results for DSR deployment over Line230

	# DSR - preferred allocation	**% relative error**	**MVA**
No DSR - Dist. Unbalanced	__	__	950.9
Dist. Unbalanced	7875 - END	__	1192.4
Dist. Balanced	7650 - END	2.94117647	1197.1

The results in Table 3.2 and Table 3.3 shows that the balanced distributed system underestimates the number of DSR modules deployed over Line230 when compared to the unbalanced system with a % relative error of about 3% . Table 3.4 and

Table 3.5 summarize the findings and results for the % line loading and % voltage drop (%VD). The impact of the unbalance in impedance and admittance values of the lines and consideration of the mutual impedance arose when investigating the phase voltage imbalance. Table 3.6 shows the results for the % voltage imbalance and % power imbalance of the three lines with and without DSRs. With no DSRs an imbalance exists for the three lines, and this imbalance percentage increases when DSRs are deployed. The significance of this imbalance is that some phases of the lines are lightly loaded and others are fully loaded. The % voltage imbalance and % power imbalance are defined and calculated using the following

$$\%\, Voltage\ Imbalance = \frac{maximum\ deviation\ from\ average\ voltage}{average\ voltage} * 100\%$$

$$\%\, Voltage\ Imbalance = \frac{max\{\, |Vav - VA|,\ \ |Vav - VB|,\ \ |Vav - VC|\}}{Vav} * 100\%$$

$$\%\, Power\ Flow\ Imbalance = \frac{maximum\ deviation\ from\ average\ power}{average\ power} * 100\%$$

$$\%\, Power\ Flow\ Imbalance = \frac{max\{\, |Pav - PA|,\ \ |Pav - PB|,\ \ |Pav - PC|\}}{Pav} * 100\%$$

Table 3.4 Line loading percentage for DSR deployment over Line230

	% Line Loading								
	Line 230			Line 345			Line 500		
	A	B	C	A	B	C	A	B	C
No DSR - Dist. Unbalanced	89.05	96.23	99.85	70.08	70.19	69.98	65.49	65.28	65.16
Dist. Unbalanced	99.05	97.57	99.95	99.24	99.81	99.46	92.65	92.67	92.47
Dist. Balanced	99.99	99.99	99.99	99.87	99.87	99.87	92.93	92.93	92.93

Table 3.5 Voltage drop percentage for DSR deployment over Line230

	% VD								
	Line 230			Line 345			Line 500		
	A	B	C	A	B	C	A	B	C
No DSR - Dist. Unbalanced	7.71	2.51	1	7.71	2.51	1	7.73	2.52	1.01
Dist. Unbalanced	18.41	9.79	7.84	18.37	9.76	7.81	18.38	9.77	7.82

Table 3.6 Voltage imbalance and power imbalance for DSR deployment over Line230

	% V Imbalance	% Power Imbalance		
		230	345	500
No DSR - Dist. Unbalanced	4.14	0.07	0.07	0.07
Dist. Unbalanced	7.3	0.07	0.08	0.07

The loading on Line345 and Line500 is greatly increased; however, the addition of DSRs in conjunction with increasing load also increases the % voltage drop and % volt imbalance. Thus, when DSRs are deployed to increase the transfer capability of the lines, reactive power compensation may be needed.

Lumped Model (Line230 || Line345 || Line500):

With the lines represented as a lumped model, deployment of DSRs alleviated the overload over Line230 and increased the loading over the other parallel lines, Line345 and Line500, as shown in Tables 3.7- 3.11. Deployment of 7,488 DSR modules increased the maximum power supplied over the three lines from 949.7 MVA to 1,186.1 MVA; an increase of about 24% for the unbalanced lumped system. The Lumped model underestimates the number of DSRs deployed when compared to the distributed model, resulting in an error of about 5% relative to the distributed, unbalanced case.

The line loading is greatly increased for Line345 and Line500, but again this comes at the expense of the voltage drop and voltage imbalance as elaborated in Tables 3.9 -3.11.

Table 3.7 Three long lines Lumped model results for DSR deployment over Line230

	# DSR	MVA
Lumped Unbalanced	7488	1186.1
Lumped Balanced	7497	1227

Table 3.8 Lumped model preferred allocation results for DSR deployment over Line230

	# DSR - preferred allocation	% relative error	MVA
No DSR - Lumped Unbalanced	—	—	949.7
Lumped Unbalanced	7488	5.16826923	1186.1
Lumped Balanced	7497	5.04201681	1227

Table 3.9 Line Loading percentage for DSR deployment over Line230

	% Line Loading								
	Line 230			Line 345			Line 500		
	A	B	C	A	B	C	A	B	C
No DSR - Lumped Unbalanced	89.06	96.14	99.87	65.87	69.44	71.52	61.08	63.87	66.04
Lumped Unbalanced	90.63	93.96	100	91.22	94.83	97.19	84.77	87.4	89.88
Lumped Balanced	100	100	100	99.96	99.96	99.96	92.51	92.51	92.51

Table 3.10 Voltage drop percentage for DSR deployment over Line230

	% VD								
	Line 230			Line 345			Line 500		
	A	B	C	A	B	C	A	B	C
No DSR – Lumped Unbalanced	8.7	3.08	1.58	8.7	3.08	1.58	8.71	3.09	1.6
Lumped Unbalanced	20.17	10.83	8.84	20.17	10.83	8.84	20.19	10.84	8.86

Table 3.11 Voltage imbalance and power imbalance for DSR deployment over Line230

	% V Imbalance	% Power Imbalance		
		230	345	500
No DSR – Lumped Unbalanced	4.44	0.06	0.06	0.04
Lumped Unbalanced	7.9	0.05	0.03	0.03

This exercise shows how the application of DSR on different allocations over the long transmission line improved the utilization of the parallel long lines and increased the maximum power delivered to the load; still some allocations are preferred over others as they provide maximum power using fewer numbers of DSRs. The approximate model of the long transmission lines as one lumped π- model underestimates the number of DSRs needed for power flow control, which emphasizes the importance of the distributed modeling of long transmission lines. DSR deployment over long transmission lines introduces increases in voltage drop which may require capacitive compensation. For unbalanced long lines phase voltage imbalances increase with the increase in the number of DSRs deployed.

3.4.1.2 Medium Transmission Lines - 100 Mile (Line230 || Line345 || Line500)

In this case the system consists of three parallel 100 mile long lines; Line230, Line345 and Line500. With no DSRs deployed, a maximum of 992.3 MVA were supplied to the load through the three parallel lines. When the load was further increased an overload was observed on Line230. DSRs were implemented to alleviate this overload via the three placement configurations. DSRs are deployed over the first 12 sections of the overloaded line (FRONT), then they are evenly distributed along the line (EQUAL) and finally they are placed at the last 12 sections of the line (END). For all allocations of DSRs the overload over Line230 was alleviated and the flow was shifted to the other 2 lines. Table 3.12 presents simulation results for both balanced and unbalanced models for distributed and lumped parameter systems. Table 3.13 shows the comparison and the relative error between the preferred allocations for the different systems.

Table 3.12 Medium Line results for DSR deployment over Line230

	FRONT		END		EQUAL	
	# DSR	**MVA**	**# DSR**	**MVA**	**# DSR**	**MVA**
Dist. Unbalanced	4140	1297.2	4068	1292.5	4068	1293.6
Dist. Balanced	3924	1302.6	3816	1300.8	3852	1301.7

	# DSR	**MVA**
Lumped Unbalanced	4110	1300
Lumped Balanced	3873	1320.9

Table 3.13 Medium line preferred allocation results for DSR deployment over Line230

	# DSR - preferred allocation	% relative error	MVA
Dist. Unbalanced	4068 - END	___	1292.5
Dist. Balanced	3816 - END	6.603773585	1300.8
Lumped Unbalanced	4110	1.032448378	1300
Lumped Balanced	3873	5.0348567	1320.9

The results in Table 3.12 and Table 3.13 show that the END allocation is the one that provided maximum load power with the minimum number of DSR modules deployed. For the distributed unbalanced system, the load maximum power was increased from 992.3 MVA to 1,292.5 MVA; an increase of about 30% when Line230 was END loaded with a total of 4,068 DSRs.

It is also shown that the balanced distributed system is conservative in estimating the number of DSR modules deployed over Line230 when compared to the unbalanced system with a % relative error of about 6.6%. And the lumped models overestimate the number of modules to be deployed.

3.4.1.3 Short Transmission Lines - 20 Mile (Line230 || Line345 || Line500)

In this case the system consists of three short parallel 20 mile lines; Line230, Line345 and Line500. With no DSRs deployed, a maximum of 1,024 MVA were supplied to the load through the three parallel lines. When the load was further increased, an overload was observed on Line230. DSRs were implemented to alleviate this overload via the three placement configurations. DSRs are first deployed on the first 3 sections of the overloaded line (FRONT), and then they are evenly distributed along the line (EQUAL) and finally they are placed at the last 3 sections of the line (END). For all allocations of DSRs, the overload over Line230 was alleviated and the flow was shifted to the other 2 lines. Table 3.14 presents simulation results for both balanced and unbalanced models for distributed and lumped systems. Table 3.15 shows the comparison and the relative error between the preferred allocations for different systems.

Table 3.14 Short line results for DSR deployment over Line230

	FRONT		END		EQUAL	
	# DSR	**MVA**	**# DSR**	**MVA**	**# DSR**	**MVA**
Dist. Unbalanced	810	1346.4	810	1346.4	810	1346.4
Dist. Balanced	783	1352.3	774	1352.3	774	1352.3

	# DSR	**MVA**
Lumped Unbalanced	819	1349.3
Lumped Balanced	780	1355.2

Table 3.15 Short line preferred allocation results for DSR deployment over Line230

	# DSR - preferred allocation	% relative error	MVA
Dist. Unbalanced	810 - None	___	1346.4
Dist. Balanced	774 - END	4.651163	1352.3
Lumped Unbalanced	819	1.111111	1349.3
Lumped Balanced	780	3.846154	1355.2

Table 3.14 and Table 3.15 show that there is no allocation preference for the distributed unbalanced system whereas for the distributed balanced the END allocation is the one that provided maximum load power with minimum number of DSR modules deployed. For the

distributed unbalanced system, the load maximum power was increased from 1,024 MVA to 1,346.4 MVA, an increase of about 31% when Line230 was loaded with a total of 810 DSRs.

It is also shown that the balanced distributed system underestimates the number of DSR modules deployed over Line230 when compared to the unbalanced system with a % relative error of about 4.6%. And the lumped models overestimate the number of modules to be deployed.

To summarize the findings of the experiment of deploying DSRs over lines of different lengths to improve the transfer capability and increase the utilization of parallel lines Table 3.16 presents comparisons between DSR deployment over Line230 for long, medium and short lines with Line230, Line345, and Line500 operating in parallel.

Table 3.16 Comparisons between DSR deployments over Line230 for long, medium and short lines

	200 Mile Line		**100 Mile Line**		**20 Mile Line**	
	# DSR - preferred allocation	**% relative error***	**# DSR - preferred allocation**	**% relative error***	**# DSR - preferred allocation**	**% relative error***
Dist. Unbalanced	7875 - END	___	4068 - END	___	810 - None	___
Dist. Balanced	7650 - END	2.94	3816 - END	6.60	774 - END	4.65
Lumped Unbalanced	7488	5.16	4110	1.03	819	1.11
Lumped Balanced	7497	5.04	3873	5.03	780	3.84

*** The error % is relative to the distributed unbalanced case which is the more accurate representation of the system**

3.4.2 Deployment of DSRs on lines of different voltage levels

In this section the effect of the line voltage level on the DSR deployment is investigated. As shown in the results reported in the previous section, the three lines become more fully utilized (Line230& Line345 ~99% loaded, Line500 ~93% loaded) when DSRs are deployed on Line230, and thus there is no need to add DSRs to Line345. Therefore, two scenarios are adopted to deploy DSRs over lines of different voltages; where two lines of the three are to be used to supply the load at a time.

Scenario1: Line230 will be disconnected, Line345 & Line500 will supply the load and DSRs are deployed on Line345,

Scenario2: Line345 will be disconnected; Line230 & Line500 will serve the load and DSRs are deployed on Line230.

Simulation results for the long line system and the medium line system are presented in the following subsections consecutively.

3.4.2.1 Long Transmission Lines - 200 Mile

Scenario1: Line230 disconnected and Line345 || Line500

Line230 is disconnected and Line345 in parallel with Line500 are serving the load. Load is increased till Line345 is overloaded and DSR modules are deployed over Line345 to alleviate the overload. The EQUAL allocation utilized less number of DSRs to reach the maximum MVA to be delivered to the load for both the balanced and the unbalanced distributed system in Scenario 1, where results are shown in Table 3.17. The balanced system model is under-estimating the number of modules to be deployed, also the lumped system results are under-estimating the number of DSR modules. These observations are similar to what was obtained in the experiments in section 3.4.1 where the three lines were operating in parallel.

Table 3.17 Results for Scenario 1 – DSRs deployed over Line345

	FRONT		END		EQUAL	
	#DSR	MVA	#DSR	MVA	#DSR	MVA
Dist. Balanced	1950	1093	1875	1088.9	1875	1090.7
Dist. Unbalanced	2025	1091.3	1950	1087	1950	1088.9
	#DSR	MVA				
Lumped Balanced	1740	1110.1				
Lumped Unbalanced	1839	1106.6				

Scenario2: Line345 disconnected and Line230 || Line500

In this scenario Line345 is disconnected and Line230 in parallel with Line500 are supplying the load. The load is gradually increased until an overload is observed over Line230. When the overload occurs DSRs are deployed over Line230 to alleviate the overload, increasing the power flow through Line500. The END allocation provided the least number of DSR modules to be deployed to supply the maximum power to the load. The results for scenario 2 are presented in Table 3.18

The main concern of this section is to determine the effect of the voltage level of the line on the number of DSRs and the amount of power it provides to the load, thus the number of DSRs versus the MVA and Amperes were recorded for all allocations for the 2 scenarios, and the slopes ΔMVA/DSR and ΔAmp/DSR were calculated for all allocations. Table 3.19 presents the results of the two parallel lines in both balanced and unbalanced systems.

Table 3.18 Results for Scenario 2 – DSRs deployed over Line230

	FRONT		END		EQUAL	
	#DSR	**MVA**	**#DSR**	**MVA**	**# DSR**	**MVA**
Balanced distributed	10875	869.3	9975	859.3	10200	863.2
Unbalanced distributed	11325	865.1	10275	856.4	10425	860.6

The slope ΔAmp/DSR for Line230 is smaller for all allocations in both scenarios than that for Line345, which indicates that deploying DSRs over Line345 is more effective than deploying them over Line230, in the sense that changes in Amperes is more when DSRs are deployed over Line345. In other words, deploying 1 DSR over Line345 gives a greater increase in Amperes than deploying 1 DSR over Line230. This was not as apparent in the calculation of ΔMVA/DSR slope.

Table 3.19 Comparison of parallel line performance using distributed models – 200 mile lines for different voltage levels

Impedance Model	Line Combination	# DSR - allocation using fewest DSR	MVA before - after	Slope ΔMVA/DSR	Slope ΔAmp/ DSR
Dist. Balanced	Line345 Line500	1875 - EQUAL	1069.3 - 1090.7	0.01	0.24
Dist. Balanced	Line230 Line500	9975 - END	715.5 - 859.3	0.01	0.19
Dist. Unbalanced	Line345 Line500	1950 - EQUAL	1066.4 - 1088.9	0.01	0.24
Dist. Unbalanced	Line230 Line500	10275 - END	683.5 - 856.4	0.01	0.21

3.4.2.2 Medium Transmission Lines - 100 Mile

In this experiment a medium length line (100 mile) is used to simulate the deployment of DSRs over lines of different voltages. Scenarios 1 and 2 tested for the long lines are repeated here with Line230, Line345 and Line500 being 100 miles in length. Results for both scenarios are presented in Table 3.20 and Table 3.21.

Table 3.20 Scenario 1 Results – DSRs deployed over Line345 (Line230 disconnected and Line345 || Line500)

	FRONT		END		EQUAL	
	# DSR	**MVA**	**# DSR**	**MVA**	**# DSR**	**MVA**
Balanced	936	1213.4	936	1212.2	936	1212.8
Unbalanced	936	1213.1	936	1212.1	936	1212.5
	# DSR	**MVA**				
Lumped Balanced	900	1234.3				
Lumped Unbalanced	915	1218.9				

Table 3.21 Scenario 2 Results – DSRs deployed over Line230 (Line345 disconnected and Line230 || Line500)

	FRONT		END		EQUAL	
	# DSR	**MVA**	**# DSR**	**MVA**	**# DSR**	**MVA**
Dist. Unbalanced	5256	964.8	5076	959.8	5148	963.5
Dist. Balanced	5148	967.6	4968	965.1	5040	966.3
	# DSR	**MVA**				
Lumped Unbalanced	4986	957.4				
Lumped Balanced	4995	985.3				

For the 100 mile lines, in scenario 1 the different allocations yielded the same number of DSRs to be deployed over Line345, whereas for scenario 2 the 100 mile lines required fewer numbers of DSR modules when Line230 was END loaded with DSRs.

Table 3.22 presents the slopes ΔMVA/DSR and Δ Amp/DSR calculated for allocations that yielded the minimum number of DSRs to be deployed for the balanced and unbalanced distributed model of the 100 mile lines system.

Table 3.22 Comparison of parallel line performance using distributed models – 100 mile lines for different voltage levels

Impedance Model	Line Combination	# DSR - allocation using fewest DSR	MVA before - after	Slope ΔMVA/DSR	Slope ΔAmp/ DSR
Dist. Balanced	Line345 Line500	936 - None	1163.2 - 1213.4	0.053	0.48
Dist. Balanced	Line230 Line500	4968 - END	733.1 - 965.1	0.046	0.4
Dist. Unbalanced	Line345 Line500	936 - None	1160.3 - 1213.1	0.056	0.5
Dist. Unbalanced	Line230 Line500	5076 - END	711 - 959.8	0.049	0.42

For the medium length lines (100 mile) it can be observed that deployment of DSRs on higher voltage lines (345 kV in our case study) provide more power and current per unit DSR. From Table 3.22 it is shown that the slopes ΔMVA/DSR and Δ Amp/DSR have larger values for DSRs deployed over Line345 than for DSRs deployed over Line230 for both balanced and unbalanced systems.

Table 3.23 and Table 3.24 introduce a comparison between the cases studied and present the error between each case relative to the distributed unbalanced case study.

Table 3.23 compares the DSRs deployed over the medium length (100 mile) lines for 230 kV versus 345 kV and presents the error in the number of DSRs deployed for different models; distributed balanced, lumped unbalanced and lumped balanced relative to the distributed unbalanced model.

For the 345 kV level, relative errors of the approximated lumped parameter models are larger than for the 230kV voltage level.

Table 3.24 introduces comparisons between deployment of DSRs over different 345kV line lengths. Relative errors are larger for long lines than for medium length lines. Also it is shown that there is a preference for the EQUAL allocation for the long 200 mile line, whereas for the medium 100 mile line there is no discrepancy between allocations.

Table 3.23 DSR deployment over medium length (100 mile) lines of different voltages

	100 Mile Line - 230||500		100 Mile Line - 345||500	
	# DSR - preferred allocation	% relative error*	# DSR - preferred allocation	% relative error*
Dist. Unbalanced	5076 - END	___	936 - None	___
Dist. Balanced	4968 - END	2.173913	936 - None	___
Lumped Unbalanced	4986	1.805054	915	2.295082
Lumped Balanced	4995	1.621622	900	4

Table 3.24 DSR deployment over Line345 for different lines lengths

	200 Mile Line 345 || 500		100 Mile Line 345 || 500	
	# DSR - preferred allocation	% relative error*	# DSR - preferred allocation	% relative error*
Dist. Unbalanced	1950 - EQUAL	___	936 - None	___
Dist. Balanced	1875 - EQUAL	4	936 - None	___
Lumped Unbalanced	1839	6.03588907	915	2.295081967
Lumped Balanced	1740	12.06896552	900	4

3.4.3 Cost benefit per DSR as a function of voltage level and line length

In this section the dollar benefit per DSR as a function of voltage level and line length is calculated for the case studies presented in the previous sections. That is to say, the cost per DSR is calculated for DSRs deployed over lines of different voltage levels and different lengths. The cost benefit is calculated for the distributed unbalanced case assuming that it is the most accurate representation of the system. The cost of the DSR is calculated based on the amount of the MVA flow increased over the lines due to the DSR addition. The MVA flow increased over a line has a cost that depends on the voltage and the length of this line; this cost is divided by the number of

DSRs deployed to evaluate the economic value of the DSRs. The costs used for 345 kV line and 500 kV line are 2.5 M$/mile and 3.5 M$/mile respectively [43]. Calculations for different line lengths and different voltage levels are shown in the following subsections. Then a comparison between the different cases is presented in the last subsection.

3.4.3.1 DSR Cost Calculations for Long Transmission Lines - 200 Mile

Line230 || Line345 || Line500

Table 3.25 presents the results of the experiment introduced in section 3.4.1.1 for the distributed unbalanced three parallel lines, showing the MVA flow over each line with and without DSR addition.

Table 3.25 Results for distributed unbalanced 200 mile line with Line230, Line345 and Line500 in parallel

	# DSR - preferred allocation	MVA Flow			Total MVA Flow	Total Load MVA
		Line 230	Line 345	Line 500		
Dist. Unbalanced No DSR	___	128.4	270.1	553.2	951.7	950.9
Dist. Unbalanced	7875 - END	125.8	350.5	716.6	1192.9	1192.4

The cost of the MVA flow increase over Line345 and Line500 is calculated as follows:

Cost of increased MVA flow =

(350.5 MVA - 270.1 MVA)/400 MVA * (200 mile * 2.5M$/mile) + (716.6 MVA - 553.2 MVA)/880 MVA * (200 mile * 3.5 M$/mile) = 230.47 M$

where 400 MVA is the SIL of Line345 and 880 MVA is the SIL of Line500.

The addition of 7875 DSRs to Line230 caused this increase in the MVA flow over Line345 and Line500. Thus to calculate the investment cost per DSR the cost value of the MVA increase is divided by the number of DSRs added as follows

Cost/DSR = 230.47 / 7875 = 0.029267 M$/DSR = **29,267 $/DSR**.

Thus for the distributed unbalanced three parallel long lines, the investment in 7875 DSRs to be deployed over Line230 with a cost of 29,267 $/DSR will provide an increase in MVA flow to better utilize the capacity of the parallel lines Line345 and Line500.

Line230 disconnected and Line345 || Line500

Table 3.26 presents the results of the experiment introduced in section 3.4.2.1 in scenario 1 for the distributed unbalanced three parallel lines, where Line230 is disconnected. Line345 and Line500 operate in parallel to serve the load. Table 3.26 also shows the MVA flow over each line with and without DSR addition.

Table 3.26 Results for distributed unbalanced 200 mile line with Line345 and Line500 in parallel

	# DSR - preferred allocation	**MVA Flow**		**Total MVA Flow**	**Total Load MVA**
		Line 345	**Line 500**		
Dist. Unbalanced No DSR	___	350.4	716.4	1066.8	1066.4
Dist. Unbalanced	1950 - EQUAL	340.3	749	1089.3	1088.9

The benefit cost per DSR for this experiment is calculated as follows:

Cost of increased MVA flow = (749 MVA – 716.4 MVA)/ 880 MVA * (200 mile * 3.5M$/mile)

= 25, 9318 M$.

Cost/DSR = 25, 9318 / 1950 = 0.013298 M$/DSR = **13,298 $/DSR**.

Thus for the long lines; Line345 and Line500 operating in parallel, the investment in 1950 DSRs to be deployed over Line345 with a cost of 13,298 k$/DSR will provide an increase in MVA flow to better utilize the capacity of the higher voltage parallel line Line500.

Line345 disconnected and Line230 || Line500

Table 3.27 presents the results of the experiment introduced in section 3.4.2.1 in scenario 2 for the distributed unbalanced three parallel lines, where Line345 is disconnected. Line230 and Line500 operate in parallel to serve the load. Table 3.27 shows the MVA flow over each line with and without DSRs addition.

Table 3.27 Results for distributed unbalanced 200 mile line with Line230 and Line500 in parallel

	# DSR - preferred allocation	**MVA Flow**		**Total MVA Flow**	**Total Load MVA**
		Line 230	**Line 500**		
Dist. Unbalanced No DSR	___	129	555.2	684.2	683.5
Dist. Unbalanced	10275-END	120.3	736.5	856.8	856.4

The benefit cost per DSR for this experiment is calculated as follows:

Cost of increased MVA flow = (736.5MVA – 555.2MVA)/ 880MVA * (200 mile * 3.5M$/mile)

= 144,215 M$.

Cost/DSR = 144,215 / 10275 = 0.014035 M$/DSR = **14,035 $/DSR**.

Thus for the long lines; Line230 and Line500 operating in parallel, the investment in 10275 DSRs to be deployed over Line230 with a cost of 14,035 $/DSR will provide an increase in MVA flow to better utilize the capacity of the higher voltage parallel line Line500.

3.4.3.2 DSR Cost Calculations for Medium Transmission Lines - 100 Mile

Line230 || Line345 || Line500

Table 3.28 presents the results of the experiment introduced in section 3.4.1.2 for the distributed unbalanced three parallel medium 100 mile lines, showing the MVA flow over each line with and without DSRs addition.

Table 3.28 Results for distributed unbalanced 100 mile line with Line230, Line345 and Line500 in parallel

	# DSR - preferred allocation	**MVA Flow**			**Total MVA Flow**	**Total Load MVA**
		Line 230	**Line 345**	**Line 500**		
Dist. Unbalanced No DSR	___	139.9	281.7	576	997.6	992.3
Dist. Unbalanced	4068 - END	139.3	380.6	777.7	1297.6	1292.5

The benefit cost per DSR for this experiment is calculated as follows:

Cost of increased MVA flow = (380.6MVA – 281.7MVA)/400 MVA * (100 mile * 2.5M$/mile) + (777.7 MVA – 577.6 MVA)/880 MVA * (100 mile * 3.5 M$/mile) = 141,397 M$

Cost/DSR = 141,397 / 4068 = 0.034758 M$/DSR = **34,758 $/DSR**.

Thus for the distributed unbalanced three parallel medium lines, the investment in 4068 DSRs to be deployed over Line230 with a cost of 34,758 $/DSR will provide an increase in MVA flow to better utilize the capacity of the parallel lines Line345 and Line500.

Line230 disconnected and Line345 || Line500

Table 3.29 presents the results of the experiment introduced in section 3.4.2.2 in scenario 1 for the distributed unbalanced three parallel lines, where Line345 is disconnected. Line230 and Line500 operate in parallel to serve the load. Table 3.29 shows the MVA flow over each line with and without DSR addition.

Table 3.29 Results for distributed unbalanced 100 mile line with Line345 and Line500 in parallel

	# DSR - preferred allocation	**MVA Flow**		**Total MVA Flow**	**Total Load MVA**
		Line 230	**Line 500**		
Dist. Unbalanced No DSR	___	381.4	779.3	1160.7	1160.3
Dist. Unbalanced	936	379.7	833.8	1213.5	1213.1

The benefit cost per DSR for this experiment is calculated as follows:

Cost of increased MVA flow = (833.8MVA – 779.3MVA)/ 880MVA * (100 mile * 3.5M$/mile)

= 21,676 M$.

Cost/DSR = 21,676 / 936 = 0.023158 M$/DSR = **23,158 $/DSR**.

Thus for the medium lines; Line345 and Line500 operating in parallel, the investment in 936 DSRs to be deployed over Line345 with a cost of 23,158 $/DSR will provide an increase in MVA flow to better utilize the capacity of the higher voltage parallel line Line500.

Line345 disconnected and Line230 || Line500

Table 3.30 presents the results of the experiment introduced in section 3.4.2.1 in scenario 2 for the distributed unbalanced three parallel lines, where Line345 is disconnected. Line230 and Line500 operate in parallel to serve the load. Table 3.30 shows the MVA flow over each line with and without DSR addition.

Table 3.30 Results for distributed unbalanced 100 mile line with Line230 and Line500 in parallel

	# DSR - preferred allocation	**MVA Flow**		**Total MVA Flow**	**Total Load MVA**
		Line 345	**Line 500**		
Dist. Unbalanced No DSR	___	139.8	576.2	716	711
Dist. Unbalanced	5076 - END	134.7	825.7	964.8	960.4

The benefit cost per DSR for this experiment is calculated as follows:

Cost of increased MVA flow = (825.7MVA – 576.2MVA)/ 880MVA * (100 mile * 3.5M$/mile)
= 99,232 M$.

Cost/DSR = 99,232 / 5076 = 0.019549 M$/DSR = **19,549 $/DSR**.

Thus for the meduim lines; Line230 and Line500 operating in parallel, the investment in 10275 DSRs to be deployed over Line230 with a cost of 19,549 $/DSR will provide an increase in MVA flow to better utilize the capacity of the higher voltage parallel line Line500.

3.4.3.3 DSR Cost Calculations for Short Transmission Lines - 20 Mile

Line230 || Line345 || Line500

Table 3.31 presents the results of the experiment introduced in section 3.4.1.3 for the distributed unbalanced three short 20 mile parallel lines, showing the MVA flow over each line with and without DSR addition.

Table 3.31 Results for distributed unbalanced 20 mile line with Line230, Line345 and Line500 in parallel

	# DSR - preferred allocation	MVA Flow			Total MVA Flow	Total Load MVA
		Line 230	Line 345	Line 500		
Dist. Unbalanced No DSR	___	142	289.9	593.8	1025.7	1024
Dist. Unbalanced	810	142.3	395.8	809.8	1347.9	1346.4

The benefit cost per DSR for this experiment is calculated as follows:

Cost of increased MVA flow = (355.8MVA – 289.9MVA)/400 MVA * (20 mile * 2.5M$/mile) + (809.8 MVA – 593.8 MVA)/880 MVA * (20 mile * 3.5 M$/mile) = 25,419 M$

Cost/DSR = 25,419 / 810 = 0.031381 M$/DSR = **31,381 $/DSR**.

Thus for the distributed unbalanced three parallel short lines, the investment in 810 DSRs to be deployed over Line230 with a cost of 31,381 $/DSR will provide an increase in MVA flow to better utilize the capacity of the parallel lines Line345 and Line500.

3.4.3.4 Comparison of Cost Benefit per DSR for Different Voltage Levels and Line Lengths

This section presents a comparison of dollar benefit per DSR for the cases studied in the three previous subsections.

Line230 || Line345 || Line500

Table 3.32 and Figure 3.3 depict the results for the three lines; Line230, Line345 and Line500 operating in parallel to supply the load for the three line lengths studied; long, medium, and short.

Table 3.32 Results for long, medium, and short lines; Line230, Line345, and Line500 in parallel

Line Length (miles)	**20**	**100**	**200**
#DSR	810	4068	7875
MVA delivered w/o DSR	1024	992.3	950.9
MVA delivered with DSR	1346.4	1292.5	1192.4
MVA increased	322.4	300.2	241.5
Dollar benefit per DSR (k$)	31.381	34.758	29.267

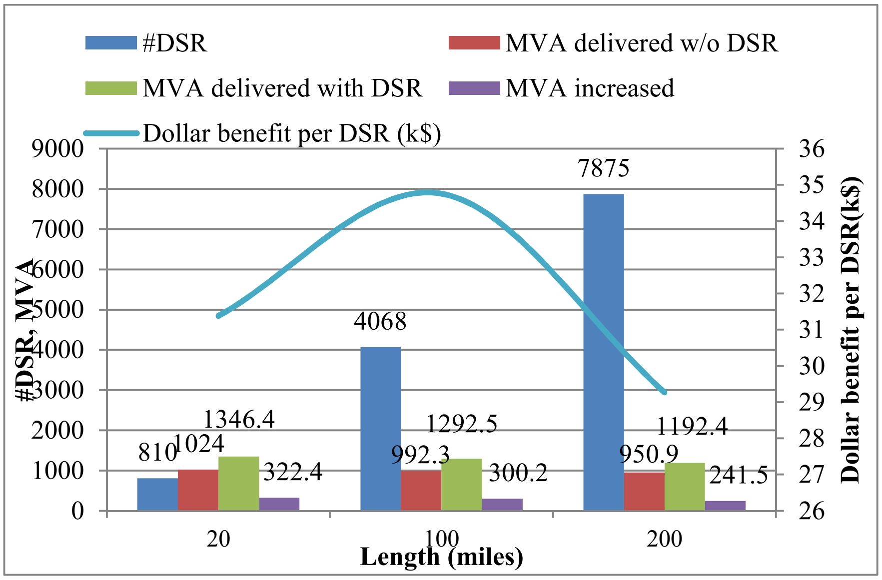


Figure 3.3 Results for long, medium, and short lines; Line230, Line345, and Line500 in parallel

Line230 disconnected and Line345 || Line500

Table 3.33 and Figure 3.4 depict the results for the 200 mile versus 100 mile lines for Line345 and Line500 operating in parallel to supply the demand.

Table 3.33 Results for long, and medium lines; Line345 and Line500 in parallel

Line Length (miles)	**100**	**200**
#DSR	936	1950
MVA delivered w/o DSR	1160.3	1066.4
MVA delivered with DSR	1213.1	1088.9

MVA increased	52.8	22.5
Dollar benefit per DSR (k$)	23.158	13.298

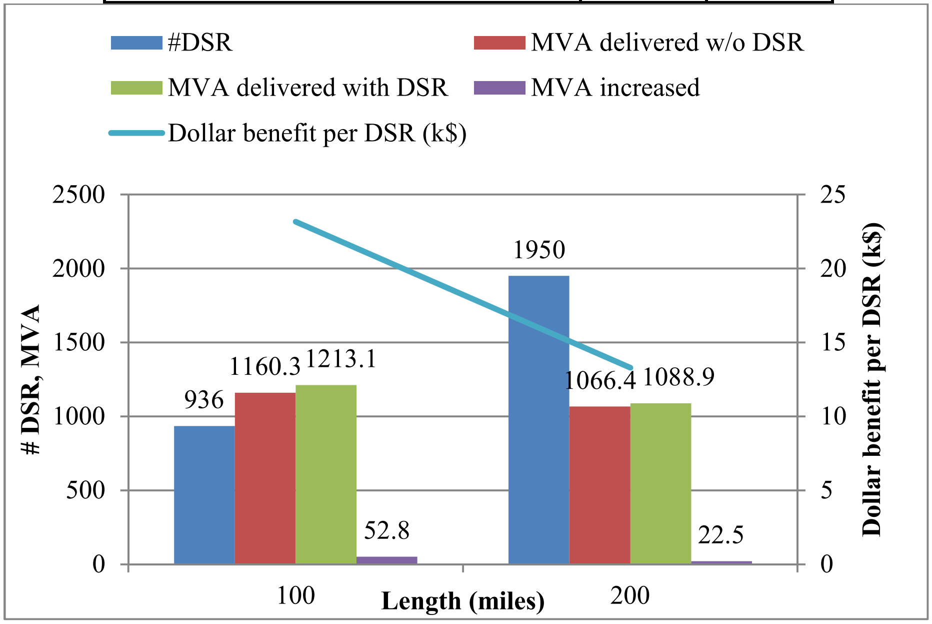


Figure 3.4 Results for long, and medium lines; Line345 and Line500 in parallel

Line345 disconnected and Line230 || Line500

Table 3.34 and Figure 3.5 depict the results for the 200 mile versus 100 mile lines for Line230 and Line500 operating in parallel to supply the demand.

Table 3.34 Results for long, and medium parallel lines; Line230 and Line500 in parallel

Line Length (miles)	**100**	**200**
#DSR	5076	10275
MVA delivered w/o DSR	711	683.5
MVA delivered with DSR	960.4	856.4
MVA increased	249.4	172.9
Dollar benefit per DSR (k$)	19.549	14.035

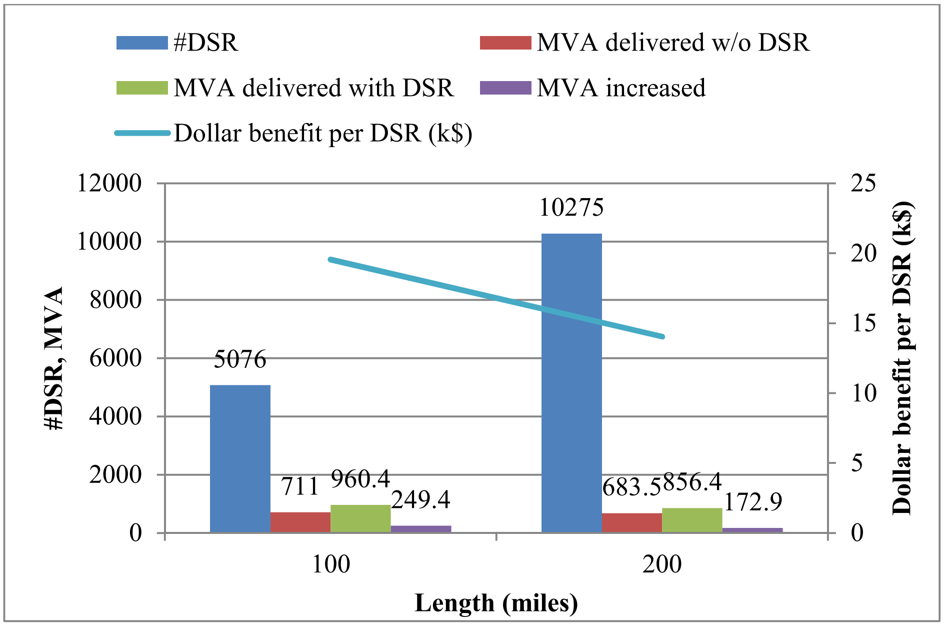


Figure 3.5 Results for long, and medium lines; Line345 and Line500 in parallel

From results presented in Figure 3.4 and Figure 3.5 it can be concluded that:

- The shorter the parallel path, the larger the cost per DSR added.
- The smaller the voltages difference between parallel paths, the larger the cost value of the DSRs.

3.4.4 Voltage Balancing using DSR System Design and Transposition

Voltage unbalance is one of the important voltage problems that power quality studies are concerned with. It represents the voltage magnitude and phase deviation from nominal values. Also voltage unbalance caused by the asymmetry in the system may have destructive effects on power system equipment. These effects are greater on some specific equipment, such as induction motors and power transformers. Little unbalance in voltages can cause excessive unbalance in currents, where the power system has more losses in the unbalanced condition. The cost of operation of the system would increase significantly due to the increase in the losses of power transformers, induction motors and transmission lines in the presence of voltage unbalance caused by the asymmetry in the system [45] [46].

The voltage balance in a power system is affected by several parameters which are: 1- The generator bus voltages, 2- Load and transformers currents, and 3- Geometry of the transmission lines, as it affects the impedance of the lines. Analyzing these parameters we can say that the first parameter is not much effective as the output voltage of generators is mostly balanced because of the operation and structure of synchronous machines. However, the transformers and their connection to the grid can affect the distribution of the loads and hence the voltage balance. The third parameter is considered influential, as the geometry of the overhead lines on the towers may cause voltage unbalance in the system [46] [47].

However, balance can be restored by exchanging the conductor positions along the line, a technique called *transposition*. Figure 3.6 shows a completely transposed three-phase line. The line is transposed at two locations such that each phase occupies each position for one-third of the line length. High-voltage transmission lines are usually assumed to be transposed (each phase occupies the same physical position on the structure for one-third of the length of the line). In addition to the assumption of transposition, it is assumed that the phases are equally loaded (balanced loading) [17] [40].

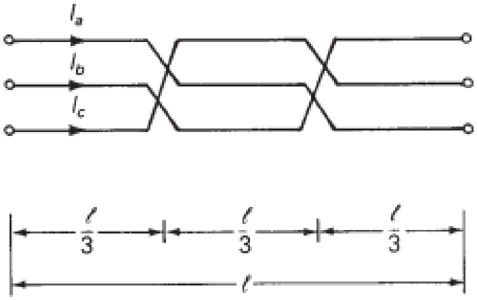


Figure 3.6 Transposed three phase line

In real practical transmission networks many long transmission lines have not been transposed, resulting in unbalanced impedances. Such unbalanced impedances can lead to unbalanced current flows and also unbalanced voltages at delivery points. If the delivery points with unbalanced voltages do not have sufficient controls to correct the voltage imbalance, then significant investments may be required. This compromises the reliability of the system and increases the energy cost.

Three standards for voltage unbalance are presented by, the International Electrotechnical Commission (IEC), the National Electrical Manufacturers Association (NEMA), and the American National Standard for Electric Power Systems and Equipment (ANSI) standards. Voltage Unbalance factor in percentage is defined by the IEC as the ratio of the negative sequence voltage to that of the positive sequence, and the zero sequence component may be used instead of the negative, but is less practical since the zero sequence cannot be present in some three phase systems. The NEMA defines the Voltage Unbalance factor as the maximum deviation from the average to the average of the phase voltage. The ANSI C84.1-2011, also defines voltage unbalance as follows: Percent voltage unbalance = 100 x (maximum deviation from average V) / (average V) [46] [47] [48] [49].

This section studies the control of the line impedance to eliminate and overcome the voltage unbalance problem in long transmission lines using Distributed Series Reactor. Distributed Series Reactor control is primarily being applied to control flows in the transmission system. However, DSRs can also be used to help balance line impedances. The DSR is to be clipped on to individual phases of the line. The DSR can be used change the impedance of the individual phases of the line in such a way as to help balance the phase flows, and thus balance the phase voltages.

An experiment to illustrate the challenges of balancing the voltage using DSR system design is presented here. Several scenarios were adopted to investigate the impact of DSR controllers on balancing the voltage at the load delivery point. The DSR system design obtained is then compared to line transposition. Three scenarios examined for the lumped model of the 200 mile parallel lines, Line230, Line345, and Line500 are

- **Scenario 1:** Balancing the voltage at the load delivery point for the unbalanced Z three line system; Line230, Line345 and line500 at various load levels.
- **Scenario 2:** Balancing the voltage for the unbalanced Z three line system with a 5% load unbalance.
- **Scenario 3:** Balancing the voltage for the unbalanced Z three line system with a 10% load unbalance.

For each scenario the power flow was run and the receiving end voltage recorded. The % voltage imbalance is calculated as:

$$\%\,Voltage\ Imbalance = \frac{maximum\ deviation\ from\ average\ voltage}{average\ voltage} * 100\%$$

where line to neutral voltage values are used.

The simulation results of the three scenarios are presented in the following subsections.

3.4.4.1 Scenario 1 Simulation Results: Voltage balancing for the unbalanced Z three line system (Line230 || Line345 || Line500)

To balance the voltage at the load delivery point, voltages of the three phases at the load delivery point at various load levels are recorded. Detailed recordings of the voltage values for each load level is presented in Table B.1 in **Appendix B**. DSR system design is implemented for the various load levels and DSRs are added on phases B and C of Line500. The numeric results are given in Table 3.35. Figure 3.7 depicts these simulation results for:

1- Deploying a total of 2500 DSRs; 2000 modules on phase B and 500 modules on phase C of Line500,

2- Deploying a total of 3400 DSRs; 2500 modules on phase B and 900 modules on phase C of Line500,

3- Transposing Line500 with Transposition I technique, which is the regular transposition shown in Figure 3.6, it is changing the phase every 1/3 the length of the line, so that the sequence of the phases are abc-cab-bca, and

4- Transposing Line500 with Transposition II technique, which is a utility solution that maintains phase rotation at substations, and the sequence of the phases are abc-cab-abc.

Observations for voltage balancing for the unbalanced Z of the three long lines can be concluded in points as follows:

1. Voltage imbalance increase with increase in load value for all design investigation aspects; no DSR, DSR addition, and transposition.
2. DSR deployment improves the voltage imbalance, where the higher the number of DSR modules deployed the lower the voltage imbalance obtained.

Table 3.35 Voltage balancing for the unbalanced Z three line system (Line230 || Line345 || Line500)

	% V Imbalance at various loads						
	900 MW	**825 MW**	**750 MW**	**675 MW**	**600 MW**	**525 MW**	**450 MW**
No DSR	3.8	3.3	2.8	2.4	2	1.6	1.2
2500 DSR on line500	2.38	2.18	1.99	1.8	1.6	1.4	1.19
3400 DSR on line500	2.03	1.91	1.78	1.65	1.5	1.34	1.18
66.7ml Transposition I	1.84	1.62	1.42	1.21	1.03	0.85	0.68
66.7ml Transposition II	2.71	2.36	2.04	1.74	1.45	1.18	0.92

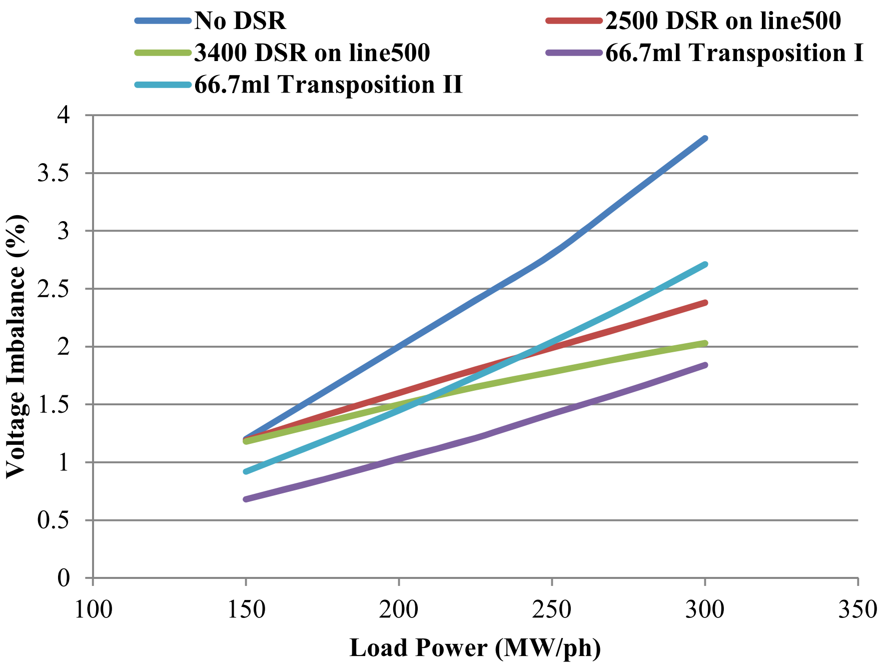


Figure 3.7 Voltage balancing for the unbalanced Z three line system (Line230 || Line345 || Line500)

3. Transposition I technique, which is the regular line transposition, provides better voltage imbalance than Transposition technique II , which is a utility solution to maintain phase rotation.
4. DSR system design for voltage balancing is comparable to line transposition. For a load of 900 MW a voltage imbalance of 3.8% was reduced to 2.03% with DSR system design and reduced to 1.84% using transposition. The choice between both depends on the accepted % voltage imbalance and the economic value of each technique.

3.4.4.2 Scenario 2 Simulation Results: Balancing the voltage for the unbalanced Z three line system with a 5% load unbalance

In this scenario the deployment of DSRs and the transposition are applied to the unbalanced impedance system, but this time the effect of load imbalance is taken into consideration, where a load unbalance of 5% is applied. Detailed recordings of the voltage values for each load level is presented in Table B.2 **Appendix B**. DSR system design is implemented for the various load levels and DSRs are added on phases B and C of Line500. Simulation results are presented numerically in Table 3.36 and depicted linearly in Figure 3.8.

Table 3.36 Voltage balancing for the unbalanced Z three line system with a load unbalance of 5%

	% V Imbalance at various loads						
	900 MW	**825 MW**	**750 MW**	**675 MW**	**600 MW**	**525 MW**	**450 MW**
No DSR	3.67	3.34	2.96	2.63	2.29	1.96	1.64
2500 DSR	3.44	3.14	2.82	2.52	2.2	1.88	1.57
3400 DSR	3.23	2.98	2.71	2.43	2.15	1.87	1.57
66.7ml Transposition I	2.58	2.35	2.13	1.91	1.69	1.47	1.25
66.7ml Transposition II	2.44	2.24	2.02	1.82	1.61	1.4	1.19

Observations for voltage balancing for the unbalanced Z of the three lines with a 5% load unbalance:

1. The load unbalance introduced to the system increased the voltage imbalance at the load delivery point, and thus various techniques were not able to reduce the imbalance to the same values as those obtained in Scenario 1 that did not consider load unbalance.
2. In this scenario Transposition II was the one that provided more reduction in the voltage imbalance than Transposition I.
3. Still DSR deployment improves the voltage imbalance, the higher the number of DSR modules deployed the lower the voltage imbalance obtained. DSR system design is comparable to Transposition techniques.

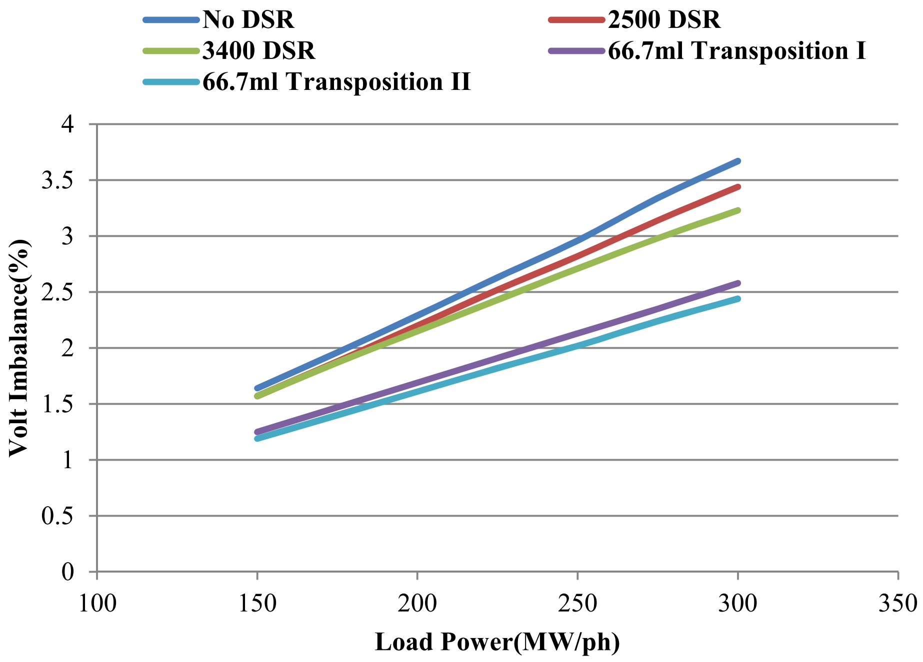


Figure 3.8 Voltage balancing for the unbalanced Z three line system with a 5% load unbalance

3.4.4.3 Scenario 3 Simulation Results: Balancing the voltage for the unbalanced Z three line system with a 10% load unbalance

This scenario is similar to Scenario 2 except that the load unbalance considered is increased to 10%. Detailed recordings of the voltage values for each load level is presented in Table B.3 **Appendix B**. DSR system design is implemented for the various load levels and DSRs are added on phases B and C of Line500. Simulation results are presented numerically in Table 3.37 and depicted linearly in Figure 3.9.

Table 3.37 Voltage balancing for the unbalanced Z three line system with a load unbalance of 10%

	% V Imbalance at various loads						
	900 MW	825 MW	750 MW	675 MW	600 MW	525 MW	450 MW
No DSR	4.76	4.34	3.92	3.49	3.08	2.66	2.25
2500 DSR	4.6	4.22	3.82	3.43	3.02	2.6	2.18
3400 DSR	4.44	4.1	3.75	3.38	2.99	2.59	2.2
66.7ml Transposition I	3.69	3.4	3.09	2.79	2.48	2.17	1.85
66.7ml Transposition II	3.57	3.28	3	2.69	2.4	2.1	1.79

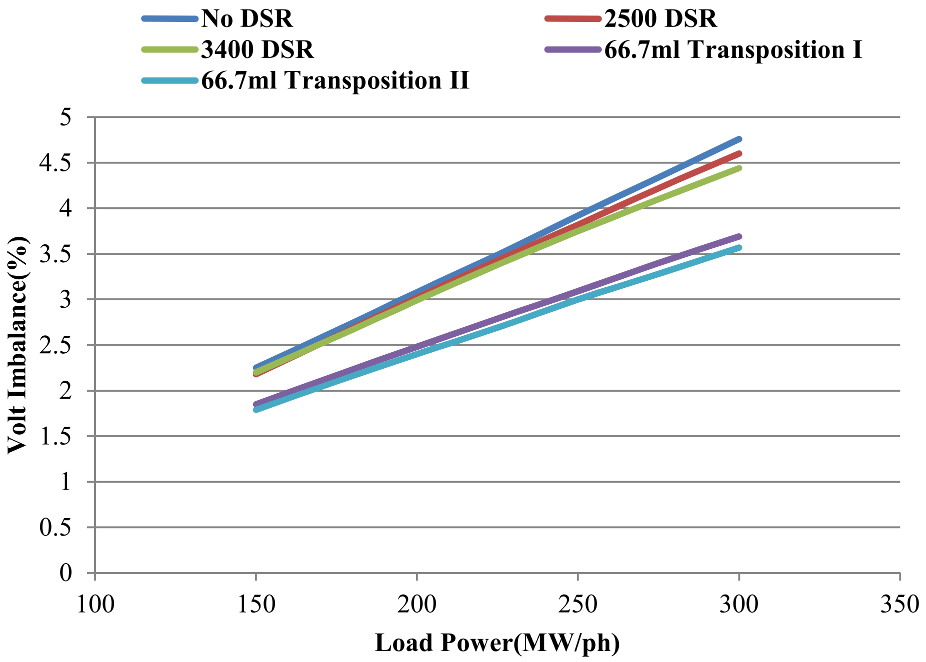


Figure 3.9 Voltage balancing for the unbalanced Z three line system with a 10% load unbalance

Observations are similar to those of Scenario 2, the only difference is that voltage imbalance values increased with the increase in load unbalance to 10% rather than 5%.

3.4.5 Bundling Conductors

Implementing Extra High Voltage has advantage of reduction in the copper losses improving efficiency. However transmission of voltage beyond 300kV will poses some problems, such as Corona effect, which causes significant power loss and interference with communication circuits if single conductor per phase is used. In order to reduce corona effect, hollow round conductors are used. Due to economic constraints, instead of using hallow round conductor it is preferable to use more than one conductor per phase, which is called Bundled Conductors. The conductors are separated from each other by means of spacers at regular intervals so they do not touch each other [50] [51]. In practical transmission lines, stranded conductors are used, and most EHV lines where the voltage exceeds 230 kV are constructed with bundled conductors. Bundle conductors have lower electric field strength at the conductor surfaces, thereby controlling corona. They also have a smaller series reactance [17] [51] [52].

Bundled conductors are primarily employed to reduce the corona loss and radio interference. However they have other advantages:

- Bundled conductors per phase reduces the voltage gradient in the vicinity of the line. Thus reduces the possibility of the corona discharge. (Corona effect will be observed when the air medium present between the phases charges up and starts to ionize and acts as a conducting medium.)
- Improvement in the transmission efficiency as loss due to corona effect is reduced.
- Bundled conductor lines will have higher capacitance to neutral in comparison with single lines. Thus they will have higher charging currents which helps in improving the power factor.
- Bundled conductor lines have higher capacitance and lower inductance than ordinary lines and have a higher Surge Impedance Loading $(Z=(L/C)^{1/2})$. The higher Surge Impedance Loading (SIL) results in a higher maximum power transfer ability.
- With increased self GMD or GMR, the inductance per phase will be reduced compared to the single conductor line. This results in less reactance per phase compared to the single conductor line.
- Bundled conductors have higher ampacity (current carrying capacity) as compared to ordinary conductors for a given weight. This is due to the reduced influence of the skin effect.

However, bundled conductors experience greater wind loading than single conductors [50] [51].

In this section an experiment is performed to examine the deployment of DSRs over bundled conductors. The three 100 mile line positive sequence balanced model is used to investigate bundling of the transmission conductors and how it affects DSR deployment. The 345kV line is bundled with two conductors and used in parallel with the unbundled 500kV line to supply the load. The 2 bundled 345 kV conductors together have an impedance equivalent to that of the unbundled 345kV line. The 345 kV two lines is equivalent to the original 345kV line in the unbundled system. Thus each of the 2 lines will have double the impedance of the single conductor. And each has a rating half that of the 345kV unbundled line. The load power in MW is increased until an overload is observed over Line345. DSRs are deployed over Line345 to alleviate the overloads for both cases, when Line345 is a single conductor and also when it is bundled. By increasing the MW supplied to the load through the parallel lines and deploying DSRs to control the flow over the lines to handle this increase in load the results presented in Table 3.38 were obtained:

Table 3.38 DSR deployed over single and bundled conductor of Line345

	Total # DSR deployed		**MVA supplied to load**		**Line Loading(%)**	
	Bundled 345	**Unbundled 345**	**Bundled 345**	**Unbundled 345**	**Bundled 345kV / 500kV**	**Unbundled 345 / 500kV**
No DSR	__	__	1191.4	1176.4	99.9 / 92.6	99.9 / 92.7
With DSR	846	873	1206.4	1227.3	100 / **94.52**	100 / **99.54**
Error (%)	3.19		1.25	4.32		

It is shown from Table 3.38 that deployment of DSRs over both bundled and unbundled Line345 models causes an increase in line loading for both Line345 and Line500. The bundled conductor utilized fewer numbers of DSRs to increase flow over the 2 parallel lines, where a % error for the number of DSR modules deployed is 3.19%.

3.5 Conclusion of Chapter 3

DSR is an emerging technology that can be used to control power flows and balance voltages in transmission networks. This chapter studied the modeling and application of DSR as a power flow controller on three parallel transmission lines supplying a load. The first line is a 230 kV line (Line230), the second is a 345 kV line (Line345) and the third is a 500 kV line (Line500). Some conclusions from the experiments include the following:

- Deployment of DSRs on different allocations over the transmission line improved the utilization of the parallel lines and increased the maximum power delivered to the load. In some cases for the long and medium length lines some allocations are preferred over others as they provide maximum power using less number of DSRs. For short lines DSR placement over different allocations gave similar results.
- For unidirectional power flow control, DSR placement at the END of the line is preferable if the line impedance is balanced.
- DSR deployment over long transmission lines introduces increases in voltage drop which may require capacitive compensation.

- The lumped π- models provide equivalent results to distributed line models when the line lengths are less than 100 miles. However, as lines become very long, 200 miles, the lumped π-model underestimates the number of DSRs needed for power flow control.
- For unbalanced long lines, phase voltage imbalances increase with the increase in the number of DSRs equally deployed over the three phases.
- The relative error between the lumped and distributed unbalanced line model in the number of DSRs deployed increases for long lines rather than medium and short lines.
- Deployment of DSRs on higher voltage long lines provides the load with more MVA and current per unit DSR.
- The shorter the parallel path the larger the cost value per DSR added.
- The smaller the voltages difference between parallel paths, the larger the cost value of the DSRs.
- Deployment of different numbers of DSRs per phase can improve the voltage imbalance over long transmission lines; the higher the number of DSR modules deployed the lower the voltage imbalance obtained.
- DSR system design for voltage balancing is comparable to long line transposition. For a load of 900 MW a voltage imbalance of 3.8% was reduced to 2.03% with DSR system design and reduced to 1.84% using transposition. The choice between both depends on the accepted % voltage imbalance and the economic value of each technique.
- Introducing unbalance to the load increased the voltage imbalance at the load delivery point. DSR deployment improves the voltage imbalance but to lower imbalance values than those reached with balanced load
- Voltage imbalance values increased with the increase in load unbalance to 10% rather than 5%. Voltage imbalance was reduced more with transposition rather than DSR deployment. For a load of 900 MW a voltage imbalance of 3.67% was reduced to 3.23% with DSR system design and reduced to 2.44% with line transposition for a load unbalance of 5%. Whereas for a load unbalance of 10% for the same 900 MW load a voltage imbalance of 4.76% was reduced to 4.44% with DSR system design and reduced to 3.57 with transposition.
- Deployment of DSRs over bundled and unbundled single conductors causes an increase in loading of lines operating in parallel. The bundled conductor utilized fewer numbers of DSRs to control the flow.

4 DSR System Design to Control Power Flow for N-1 Contingency Analysis and Load Growth - IEEE 39 Bus System Experiment

4.1 Introduction

DSRs can be used to balance flows in the phases of an unbalanced line, or used to control the distribution of flow in parallel paths. In this chapter DSRs will be used to alleviate overloads that result due to increased load in a transmission network. The design is performed for an unbalanced, 3-phase system, and then for a balanced, 3-phase model derived from the unbalanced model, where the symmetrical components transformation is used to create the balanced model.

The design of the Distributed Series Reactor (DSR) to control the power flow over transmission lines to alleviate overloads due to load growth under N-1 line contingencies is investigated. The contingency analysis is performed to assure secure operation of the grid while controlling the active power flow over transmission lines.

The work in this chapter is devoted to investigating the application of DSRs in unbalanced transmission system for load growth and also for contingency mitigation.

4.1.1 Case Study Characteristics and Description

The IEEE 39 bus test system is modified to a 3-phase model and is used to study the deployment of DSRs for controlling power flow to alleviate overloads due to load growth and contingencies. To address the consideration of generation in the design study, the ten generators in the IEEE standard model are replaced with three-phase equivalent voltage sources, where the solution of the model with the equivalent voltage sources is the same as the solution with the original power generators of the standard IEEE 39 bus model. In load growth studies that will be described shortly, the voltage magnitude and angle of the sources are maintained constant as the load is grown. The generators share in picking up the load based upon their voltage source representation. The sharing of the increased load among the generators will be presented.

Thus, the system under study has ten voltage sources, 19 loads, and 35 lines. The transmission lines in the IEEE 39 bus standard transmission system are converted to 345 kV lines modeled with the configuration and wiring shown in Figure C.1 in Appendix C. Line ratings and lengths are assumed as the IEEE 39 bus system does not provide them. Table C.1 shows the assumed ratings and lengths used for the three phase lines of the system.

To investigate the effect on DSR system design of the line impedance model, two cases are considered, an unbalanced, 3-phase impedance model, and a balanced, 3-phase impedance model. The balanced model is derived by assuming that the lines in the unbalanced model are transposed. In the unbalanced model, the self-impedances are unequal with symmetrical but unequal off diagonal elements. The same is true for the shunt admittance matrix of the unbalanced model. In the balanced model, the impedance matrix has diagonal elements that are equal in value and off diagonal elements that are zero [40] [52].

For the unbalanced impedance model, the impedance matrix for the transmission lines is given by

$$Z_{\text{line}} = \begin{bmatrix} 0.18 + j\,1.27 & 0.13 + j\,0.53 & 0.14 + j\,0.44 \\ 0.13 + j\,0.53 & 0.19 + j\,1.26 & 0.14 + j\,0.52 \\ 0.14 + j\,0.44 & 0.14 + j\,0.52 & 0.21 + j\,1.24 \end{bmatrix} \Omega/\text{mile} \qquad (4.1)$$

and the shunt admittance matrix is

$$Y_{\text{line}} = \begin{bmatrix} j\,4.938 & -j\,0.930 & -j\,0.405 \\ -j\,0.930 & j\,4.977 & -j\,0.941 \\ -j\,0.405 & -j\,0.941 & j\,4.934 \end{bmatrix} \mu\text{S/mile} \qquad (4.2)$$

For the balanced model the impedance matrix and shunt admittance matrix for the transmission lines are represented in (3) and (4) respectively:

$$Z_{+\text{ve}} = \begin{bmatrix} 0.054 + j\,0.75 & 0 & 0 \\ 0 & 0.054 + j\,0.75 & 0 \\ 0 & 0 & 0.054 + j\,0.75 \end{bmatrix} \Omega/\text{mile} \qquad (4.3)$$

$$Y_{+\text{ve}} = \begin{bmatrix} j\,0.0058 & 0 & 0 \\ 0 & j\,0.0058 & 0 \\ 0 & 0 & j\,0.0058 \end{bmatrix} \mu\text{S/mile} \qquad (4.4)$$

The steps for the calculation of the sequence matrix are explained here under in details [17]:

Z_{abc}=

$$\begin{bmatrix} 0.1816700 + j\,1.2745125 & 0.1337554 + j\,0.5391529 & 0.1413869 + j\,0.4482198 \\ 0.1337554 + j\,0.5391529 & 0.1930865 + j\,1.2645420 & 0.1486344 + j\,0.5264283 \\ 0.1413869 + j\,0.4482198 & 0.1486344 + j\,0.5264283 & 0.2122740 + j\,1.2485600 \end{bmatrix}$$

Ω/mile (4.5)

The phase impedance matrix Z_{abc} can be transformed into the sequence impedance matrix with the application of the following equation (4.6)

$$Z_{012} = [A]^{-1} \cdot [\, Z_{abc}] \cdot [A] \tag{4.6}$$

Where: $A = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$ & $a = 1\,\underline{/120^{o}}$

$$Z_{012} = \begin{bmatrix} 0.4782 + j\,2.2717 & -0.0416 - j\,0.0127 & 0.0202 + j\,0.0028 \\ 0.0202 + j\,0.0028 & 0.0544 + j\,0.7579 & 0.0483 + j\,0.0267 \\ -0.0416 - j\,0.0127 & -0.0475 + j\,0.0289 & 0.0544 + j\,0.7579 \end{bmatrix} \Omega/\text{mile} \tag{4.7}$$

Note that the off-diagonal terms are not zero. This implies that there is mutual coupling between sequences. This is a result of the nonsymmetrical spacing between phases. With the off-diagonal terms nonzero, the three sequence networks representing the line will not be independent. However, it is noted that the off-diagonal terms are small relative to the diagonal terms.

In high-voltage transmission lines, it is usually assumed that the lines are transposed and that the phase currents represent a balanced three-phase set. The transposition can be simulated by replacing the diagonal terms of the phase impedance matrix with the average value of the diagonal terms (0.1956768 + j 1.2625382), and replacing each off-diagonal term with the average of the off-diagonal terms (0.1412589 + j 0.5046003). This modified phase impedance matrix becomes:

Z_{abc}=

$$\begin{bmatrix} 0.1956768 + j\,1.2625382 & 0.1412589 + j\,0.5046003 & 0.1412589 + j\,0.5046003 \\ 0.1412589 + j\,0.5046003 & 0.1956768 + j\,1.2625382 & 0.1412589 + j\,0.5046003 \\ 0.1412589 + j\,0.5046003 & 0.1412589 + j\,0.5046003 & 0.1956768 + j\,1.2625382 \end{bmatrix}$$

Ω/mile (4.8)

Using this modified phase impedance matrix in the symmetrical component transformation equation results in the modified sequence impedance matrix

$$Z_{012} = \begin{bmatrix} 0.4781946 + j\,2.2717388 & 0 & 0 \\ 0 & 0.0544179 + j\,0.7579378 & 0 \\ 0 & 0 & 0.0544179 + j\,0.7579378 \end{bmatrix} \Omega/\text{mile} \qquad (4.9)$$

Note that now the off-diagonal terms are all equal to zero, meaning there is no mutual coupling between sequence networks. It should also be noted that the modified zero, positive, and negative sequence impedances are exactly equal to the exact sequence impedances that were first computed.

Concerning the practical deployment of DSRs, deploying 24 DSRs on the 3 phases per tower is considered. As the tower span for a 345kV line can have 10 towers per mile [53] [54], 240 DSRs (24 DSRs x 10 towers) can be placed per mile on the 3 phases.

The motivation to study the behavior of the DSR controller with different impedance models is that the transmission lines in many power systems are not transposed and as a result have unbalanced immittances. One aim of this study is to investigate the differences in DSR system design results that occur between using the balanced immittance model and using the unbalanced immittance model.

4.1.2 DSR System Design Algorithm

The DSR system design and placement algorithm is presented in this section. DSR system design involves determining the number and location of DSRs needed to prevent an overload. The DSR system design tool uses Discrete Ascent Optimal Programming [55], and at each step of the optimization algorithm places DSRs on lines that have the most effect on power flow per DSR. DSRs are deployed 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. This sensitivity is dependent on 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 either as number of modules per phase or as a reactance value in ohms. They are deployed iteratively with this chosen step size until the stopping criteria is fulfilled. The stopping criteria adopted is either to have no overloads in the system, or to obtain a certain maximum line loading, and/or to deploy a certain maximum number of DSR modules. Figure 4.1 is a flowchart that depicts the design algorithm for DSR deployment. Figure 4.2 presents the DSR control analysis setup interface.

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

$$\Delta OL_j = \Sigma\, O_{Bij} - O_{Aij} \qquad (4.10)$$

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

$$\Delta OL_s = \text{max over j } \{\ \Delta OL_j\ \} \qquad (4.11)$$

Thus, the line is selected where ΔOL_j / Dsr is the greatest, where Dsr is the number of DSRs added at each step.

4.2 DSR System Design Results for Load Growth

DSRs can be controlled to more fully use the power transfer capacity of a set of parallel paths. In this section this control is investigated using a series of load growth values for the two 3-phase models described in section 4.1, the balanced model and the unbalanced model. DSR control for handling of single line contingencies with load growth will be considered in section 4.3.

The load is uniformly grown in 2% increments in both three-phase models until overloads are observed. When an overload is observed the DSR placement algorithm is used to try and find a DSR system design that can be used to alleviate the overload. Table 4.1 shows the number of DSRs needed on selected lines to eliminate overloads as the system load is uniformly grown.

Table 4.2 shows how the flows from the generators increase as the load is grown from 100% to 149%. It also presents the % change in generation for each generator. It is shown how all generators share in picking up the load. For the load growth study all generators are modelled as 3-phase voltage sources. The voltages used for each source are obtained from the base case and are also shown in Table 4.2. The study here stopped at 149% load growth. As will be shown shortly, at this load level the change in MW flow per DSR added becomes very small for both models.

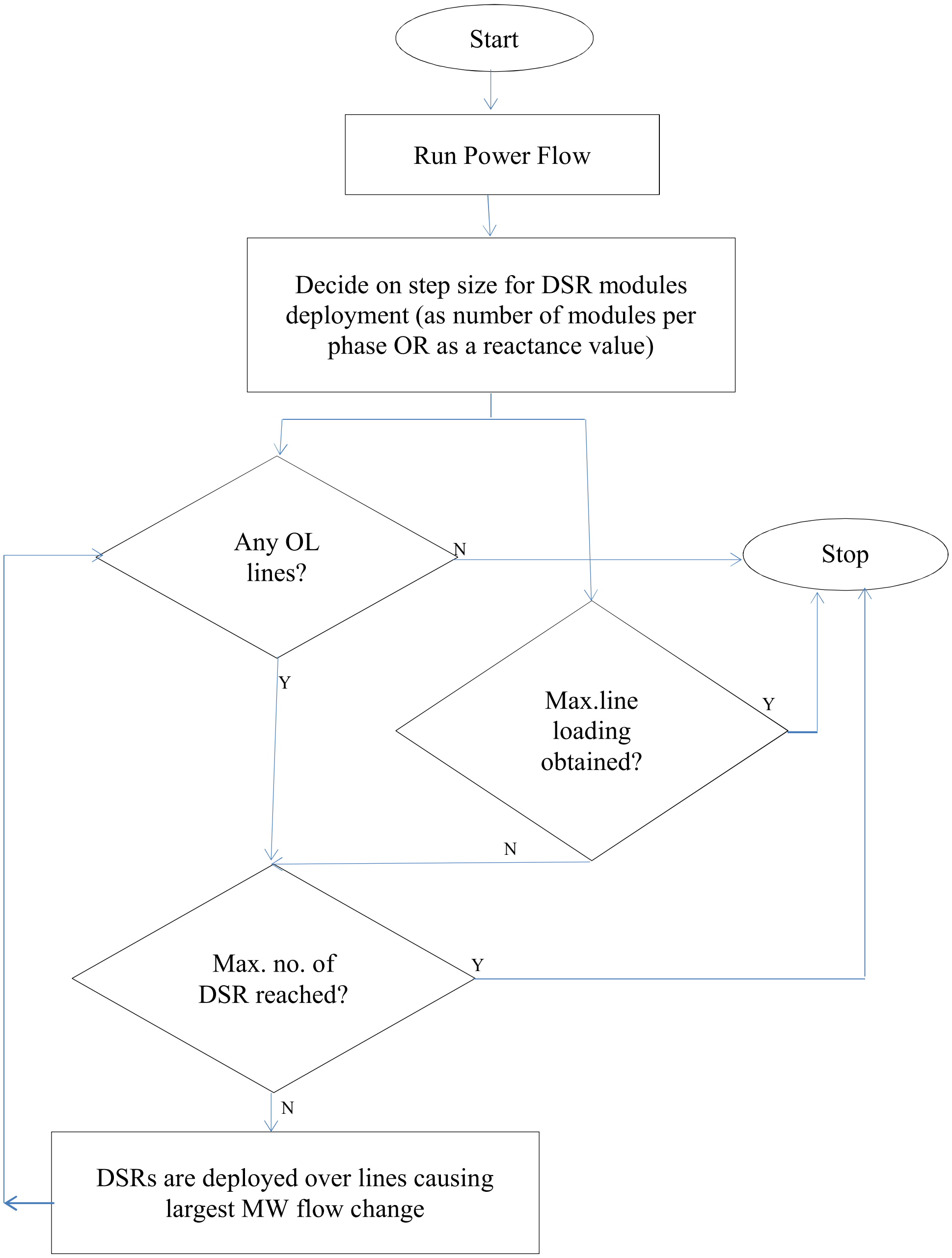
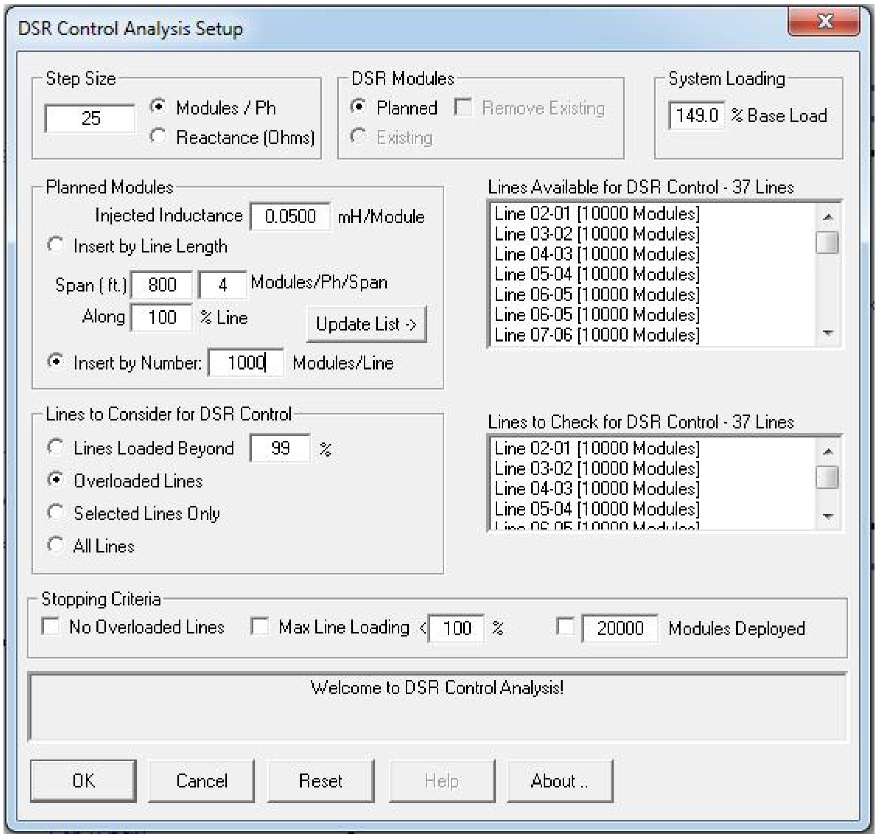


Figure 4.1 DSR deployments Flow Chart



Step Size
25 ● Modules / Ph
○ Reactance (Ohms)

DSR Modules
● Planned ☐ Remove Existing
○ Existing

System Loading
149.0 % Base Load

Planned Modules
Injected Inductance 0.0500 mH/Module
○ Insert by Line Length
Span (ft.) 800 4 Modules/Ph/Span
Along 100 % Line Update List ->
● Insert by Number: 1000 Modules/Line

Lines Available for DSR Control - 37 Lines
Line 02-01 [10000 Modules]
Line 03-02 [10000 Modules]
Line 04-03 [10000 Modules]
Line 05-04 [10000 Modules]
Line 06-05 [10000 Modules]
Line 06-05 [10000 Modules]
Line 07-06 [10000 Modules]

Lines to Consider for DSR Control
○ Lines Loaded Beyond 99 %
● Overloaded Lines
○ Selected Lines Only
○ All Lines

Lines to Check for DSR Control - 37 Lines
Line 02-01 [10000 Modules]
Line 03-02 [10000 Modules]
Line 04-03 [10000 Modules]
Line 05-04 [10000 Modules]

Stopping Criteria
☐ No Overloaded Lines ☐ Max Line Loading < 100 % ☐ 20000 Modules Deployed

Welcome to DSR Control Analysis!

Figure 4.2 DSR System Design Interface

Table 4.1 DSRs deployed on the three lines of the balanced and unbalanced models for different system loads

	% Load increase	**#DSR turned on**			
		Line 5-6	**Line 6-7**	**Line 13-14**	**Total**
Balanced	**141%**	---	75	---	75
	143%	375	525	---	900
	145%	750	1050	150	1950
	147%	1275	1650	600	3525
	149%	1950	2400	1200	5550
Unbalanced	**141%**	---	---	---	---
	143%	---	---	---	---
	145%	225	450	---	675
	147%	675	975	---	1650
	149%	1350	1800	600	3750

From Table 4.1 it may be noted that overloads start to occur in the balanced model at 141% load growth, whereas overloads do not occur in the unbalanced model until 145% load growth is reached. At the 141% and 143% load levels the unbalanced model has no overloads and no DSRs are needed. However, the balanced model experiences overloads at the 141% and 143% load levels, where 75 DSRs and 900 DSRs are required, respectively. This is quite a significant difference between the 2 models.

The overload difference between the balanced and unbalanced model is due to the approximate impedances used in the balanced model. The assumed balanced model is conservative in predicting the overload before it actually would occur. Shortly it will also be shown that the balanced model is also conservative in predicting the number of DSRs that are required to eliminate overloads, and again this is due to the approximate impedances used in the assumed balanced model.

Table 4.2 Source Voltage and Generation for 100% Load and 149% Load for the three phases

Voltage Source Bus		Voltage		Power Generated at 100% (MW)	Power Generated at 149% (MW)	% Change in MW
		kV	Deg.			
30	**A**	13.3	-4.58	102.4	196.9	92.2
	B	13.3	-124.5	98.96	184.9	86.8
	C	13.3	115.42	102.5	189.5	84.8
32	**A**	12.4	1.6	182.5	246.7	35.1
	B	12.4	-118.4	185.8	242.9	30.7
	C	12.4	121.6	186.3	246.2	32.1
33	**A**	12.6	2.07	199.8	300.8	50.5
	B	12.6	-117.9	202.1	297.4	47.1
	C	12.6	122.07	202.0	297.0	47.0
34	**A**	12.8	0.63	177.5	278.3	56.7
	B	12.8	-119.3	175.7	272.7	55.2
	C	12.8	120.6	178.5	277.0	55.1
35	**A**	13.3	4.04	193.7	292.3	50.9
	B	13.3	-115.9	198.2	290.0	46.3
	C	13.3	124.04	196.5	288.8	46.9
36	**A**	13.5	6.73	184.4	252.2	36.7
	B	13.5	-113.2	186.6	249.6	33.7
	C	13.5	126.73	186.8	250.9	34.3
37	**A**	13.0	1.15	174.6	247.6	41.8
	B	13.0	-118.8	175.8	243.5	38.5
	C	13.0	121.15	177.5	246.5	38.8
38	**A**	13.0	6.44	272.9	384.3	40.8
	B	13.0	-113.5	279.6	385.6	37.9
	C	13.0	126.44	279.5	386.5	38.2
39	**A**	13.0	-11.11	364.5	646.0	77.2

	B	13.0	-131.1	359.6	633.1	76.0
	C	13.0	108.89	371.2	643.0	73.2
Slack	**A**	12.7	0	199.9	270.2	35.1
	B	12.7	-120	198.1	262.3	32.4
	C	12.7	120	202.9	267.5	31.8

In both models when overloads occur DSRs are placed on the same three lines, which are indicated in Table 4.1 and which are also depicted in Figure 4.3. It should be noted that for the same loading condition the number of DSRs deployed using the balanced model is much higher than the number of DSRs deployed using the unbalanced model. Figure 4.4 compares the total number of DSRs deployed for different system loads for the two models.

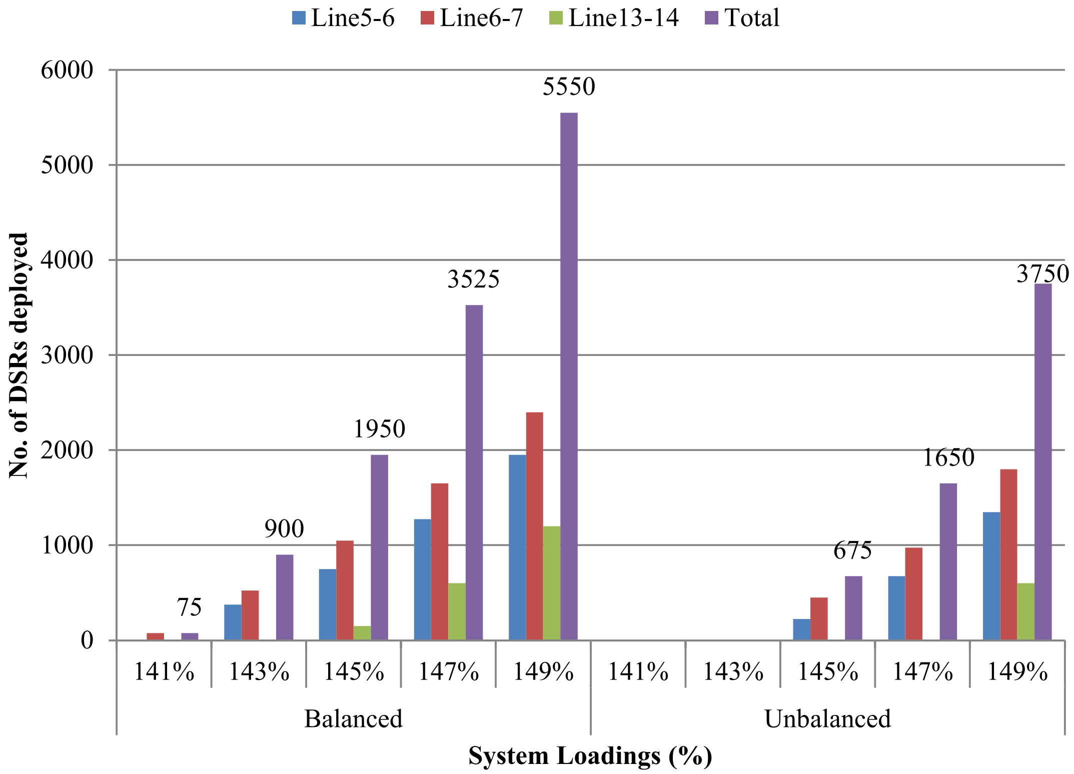


Figure 4.3 Number of DSRs deployed on each line for balanced and unbalanced models as a function of system load

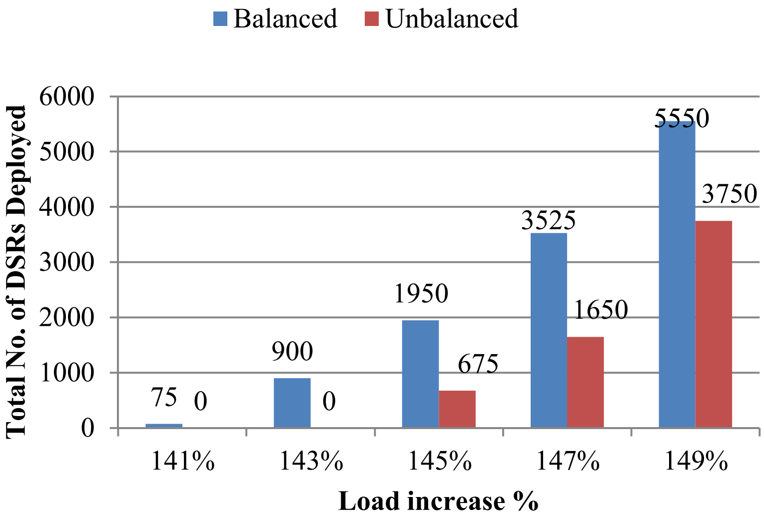


Figure 4.4 Total number of DSRs deployed for balanced and unbalanced models as a function of system load

At the 149% load level 3,750 DSRs are deployed in the unbalanced model to alleviate overloads whereas in the balanced model 5,550 DSRs are deployed. Using the balanced model thus results in an extremely conservative design. At the 149% load level the number of DSRs deployed on each line in the unbalanced model is shown in Figure 4.5. Note that the crosses (X) that appear on some of the lines in Figure 4.5 indicate independent loop markers and are used by the power flow algorithm [56] .

Table 4.3 compares the designs for the two different models, and assuming that the unbalanced model provides the more accurate design,

Table 4.3 shows the percentage error in the balanced model predictions.

Figure 4.6 plots ΔMW/DSR as a function of system loading for both models, where ΔMW represents the incremental load served when 1 DSR module is deployed at each load level. Above the 145% load level the ΔMW/DSR slope has a smaller value for the assumed balanced model, which indicates that more DSRs will be required in the balanced model to affect a given change in flow.

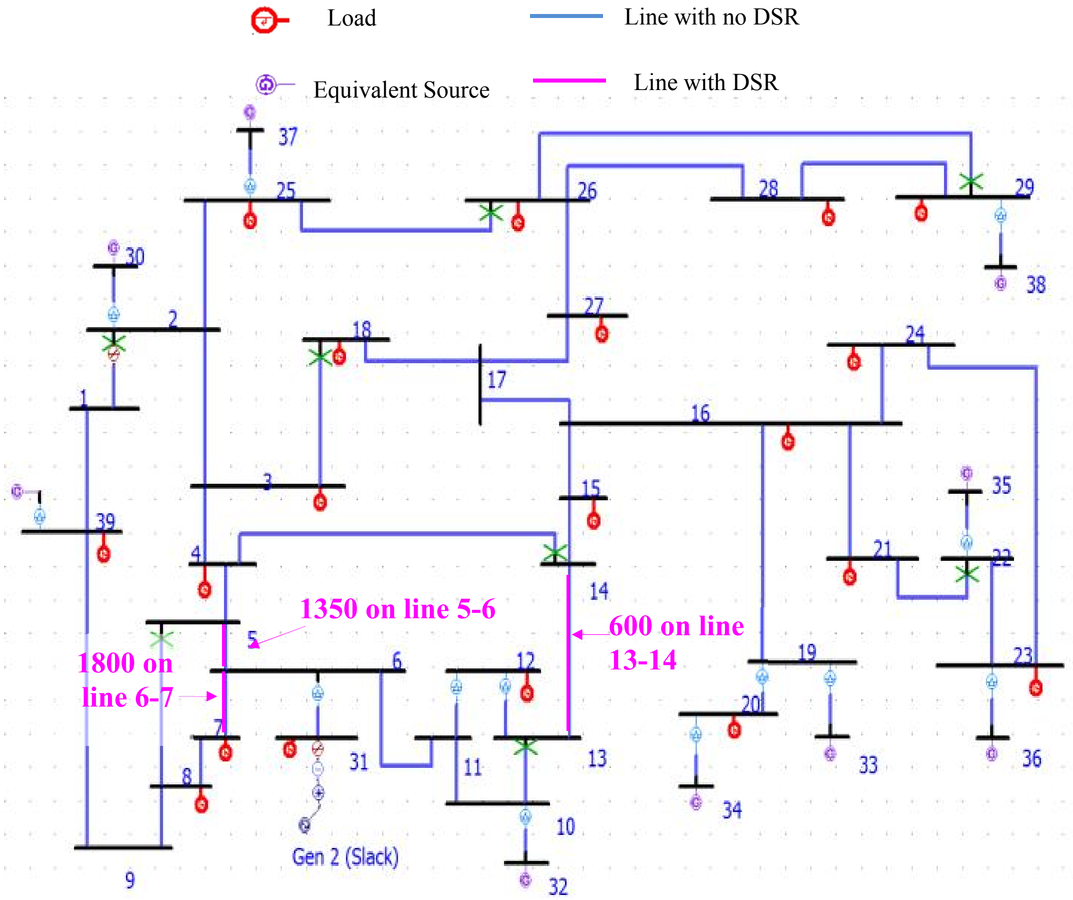


Figure 4.5 DSRs deployed on the unbalanced model for a load growth of 149%

Table 4.3 Comparison of DSR system design results for balanced and unbalanced models

	Different System Loadings									
	141 %		143 %		145 %		147 %		149 %	
	# DSR	Slope MW/DSR	# DSR	Slope MW/DSR	# DSR	Slope MW/DSR	# DSR	Slope MW/DSR	# DSR	Slope MW/DSR
Balanced	75	33.6	900	2.93	1950	1.41	3525	0.81	5550	0.54
Unbalanced	–	–	–	–	675	4.09	1650	1.75	3750	0.80
Error %	100	100	100	100	65.38	65.38	53.19	53.19	48	32.43

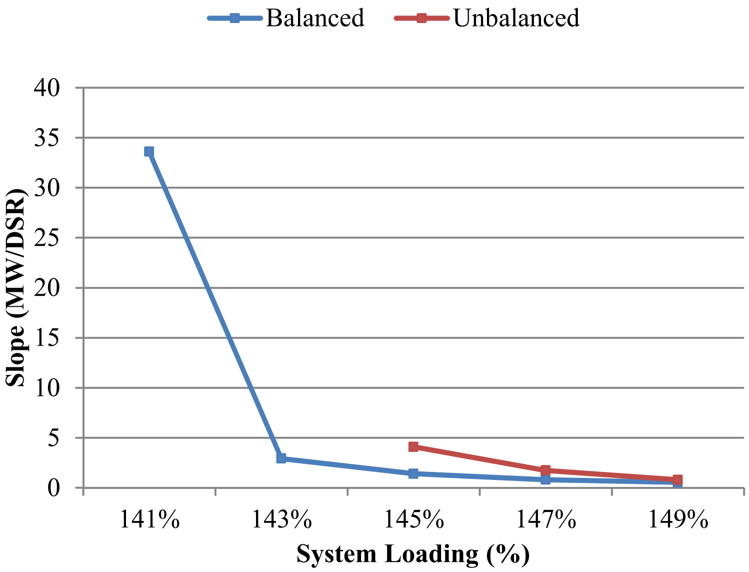


Figure 4.6 **MW change per DSR deployed for different system loadings for balanced and unbalanced models**

4.3 N-1 Contingency Analysis and Load Growth

As security and reliability of the grid are vital and main concerns, the system operators perform contingency analysis and commonly design the system to meet the N-1 contingency criterion for grid operation. Also disturbances like line outages if not healed appropriately in a timely manner can cause cascading outages leading to blackouts. Thus in this section the DSR controller is designed under N-1 contingency conditions. Lot of work has been done in the contingency analysis area [57] [58] [59] [60] [61] [62]. Recent researches were mainly concerned about how different FACTS devices operate under contingency conditions to enhance the transmission system voltage stability, steady state security limit and to alleviate overloads [63] [64] [65] [66] [67] [68] [69].

In this section, the DSRs are designed to handle all N-1 line contingencies that may occur in the system with load growth. This means that the DSRs deployed are supposed to handle the load growth with any single line failure of the 35 lines, assuring serving the required load with no overloads.

4.3.1 DSR System Design Strategy for Handling N-1 Contingency with Load Growth

In section 4.2, the load is uniformly grown in small increments and DSRs are deployed to alleviate any overloads that are observed for this load growth. Here the load is grown but this time with N-1 line contingency and again when an overload is observed the DSR placement algorithm is used to try and find a DSR system design that can be used to alleviate the overload. The DSR system design is done assuming the deployment of the same number of DSRs per phase. If DSRs are not able to handle overloads when a certain line is failed, an alternative path will be provided by adding a 345 kV line in parallel with the failed line that has identical characteristics to the original 345 kV lines [70]. A line whose failure results in the DSR system design being ineffective in handling the overloads is defined as a *Critical Line*. That is to say, when a line is failed and overloads that result cannot be alleviated by DSR placement, then the failed line is called a *Critical Line*. To handle the overload created by the failure of a *Critical Line*, a new identical line is constructed in parallel with the *Critical Line*. Once the new line is constructed, it remains in the system and is used in all future designs. The *Critical Lines* identify weak points in the system.

Each time the load is grown or the system is strengthened, a new design is initiated. In other words, after each load increment or new line construction, a total new DSR system design is applied.

In the load growth study in the previous section, the DSR system design deployed 3750 DSRs for the unbalanced 3-phase model at 149% load and N-0 conditions. The number of DSRs deployed on each line in the unbalanced model were presented in Table 4.1 and depicted in Figure 4.3 as well.

4.3.2 Simulation results of DSR system design for N-1 contingency and load growth

The N-1 contingency analysis is first performed for the base case at 100% load, then the load is increased and the N-1 contingency analysis is performed for each increased load level. For each load level, a totally new DSR system design is initiated. We are assuming that the projected load growth for the next 40 years is 1% per year. In the previous section, we studied the DSR system design for load growth. Now we want to evaluate additional DSRs that will be needed beyond the projected load growth to handle overloads during contingencies. DSRs can be separated into two types, DSRs that are needed to handle load growth, say load-DSRs, and DSRs that are needed to handle contingencies, referred to here as contingency-DSRs. In the previous section, for load growth only, it was shown that for the unbalanced model DSRs were not needed to handle load growth until 45% load growth. In the work here, all DSRs that are added are contingency-DSRs. Results and findings for the critical lines, and the total number of DSRs deployed for each design is presented in Table 4.4. The DSR modules deployed over each line for each load level is presented in Table 4.5. As the addition of DSRs affects the series line impedance value, the percentage change in impedance was tracked and the maximum percentage change in impedance was calculated for lines that have DSR deployed over them. These are recorded in Table 4.6.

The impedance values for all phases for different load levels and the % of change in impedance calculations for all phases are presented in details in Appendix D. The results obtained for each load percentage is presented in the following subsections.

4.3.2.1 100% (Base Case) - 111% Load Growth

DSRs are used for flow control with N-1 contingency. Thus for the 100% load level, all possible 35 single line contingencies are analysed. The 35 lines in the system were failed one at a time. Only 2 failed lines out of the 35 failed lines caused overloads. These overloads were all alleviated by the deployment of DSRs. Table 4.5 summarizes the findings of the 2 failed lines with overloads in the contingency analysis for the base case (Design #1). It shows the number of DSRs deployed over each line, and the % of the total overload eliminated. The failure of Line 6-7 requires deployment of 1650 DSRs on Line 5-6 to eliminate an overload of 13.76%, and the failure of Line 5-8 requires deployment of 375 DSRs on Line 6-7 to eliminate an overload of 1.21%.

Table 4.4 Load growth and N-1 contingency results for all load levels

Design #	% System Load	Failed Lines Causing Overload	Critical Lines	Total DSRs Turned On
1	100%	6-7, 5-8		2025
2	110%	5-6, 6-7, 5-8		9525

3	**111%**	__	**6-7**	0
4	120%	7-8, 15-16		3075
5	121%	5-8, 15-16		4200
6	**122%**	7-8	**15-16**	300
7	130%	2-3, 7-8		1800
8	135%	2-3, 4-5 7-8, 6-11 4-14, 16-19		4500
9	**136%**	7-8	**2-3**	1050
10	140%	7-8, 6-11		1575

Table 4.5 DSR deployment results of the N-1 contingency analysis for all load levels

Design #	% System Load	Failed Lines Causing Overload	Lines with DSRs Turned On	No. of DSRs Turned On	% Total Overload Removed
1	100%	6-7	5-6	1650	13.76
		5-8	6-7	375	1.21
2	110%	5-6	6-7	1800	10.1
		6-7	5-6 5-8	2775 3150	26.55 9.4
		5-8	6-7	3600	10.73
4	120%	7-8	5-6	225	1.83
		15-16	13-14	2850	12.9
5	121%	5-8	5-6	375	2.72
		15-16	13-14	3825	14.68
6	122%	7-8	5-6	300	2.37
7	130%	2-3	5-6 13-14	300 600	1.71 2.68
		7-8	5-6	1200	9.58
8	135%	2-3	5-6 13-14	1575 2700	9.77 10.67
		4-5	13-14	150	0.86
		7-8	5-6	1800	14.39
		6-11	13-14	375	2.05
		4-14	5-6	225	2.46
		16-19	13-14	375	2.5
9	136%	7-8	5-6	1050	8.74
10	140%	7-8	5-6	1500	12.32
		6-11	13-14	75	0.36

Table 4.6 Maximum % change in impedance for lines with DSR deployed

	Maximum % of ΔZ occurred at phase C for all lines				
	Line 5-6	**Line 6-7**	**Line 13-14**	**Line 5-8**	**Line 7-8**
110%	68.25	61.48	0	48.94	0
121%	9.18	0	62.66	0	0
135%	44.21	0	44.18	0	0
140%	36.82	0	1.22	0	0

Increasing the load to 110% and considering N-1 contingencies, overloads were observed for failure of 3 lines out of the 35 failed lines. The DSR system design application was successful in alleviating these overloads. Results of the simulation of the unbalanced, 3-phase model for the 110% load is illustrated in Figure 4.7. Note that the crosses (x) that appear on some of the lines in the following figures indicate independent loop markers and are used by the power flow algorithm [56].

For an increase in load to 111%, overloads were observed for the failure of 4 lines out of the 35 lines. The DSR system design application was not successful in alleviating all overloads caused by these contingencies. One Critical line was observed, Line 6-7. It caused overloads that could not be alleviated by DSRs. The findings of the Critical line with the new parallel construction for the 111% load level are presented in Design #3 in Table 4.4.

As DSR deployment could not handle overloads caused by the failure of the Critical Line 6-7, a new similar 345 kV parallel line was built. Results for the 111% load with the new line construction parallel to Line 6-7 is depicted in Figure 4.8.

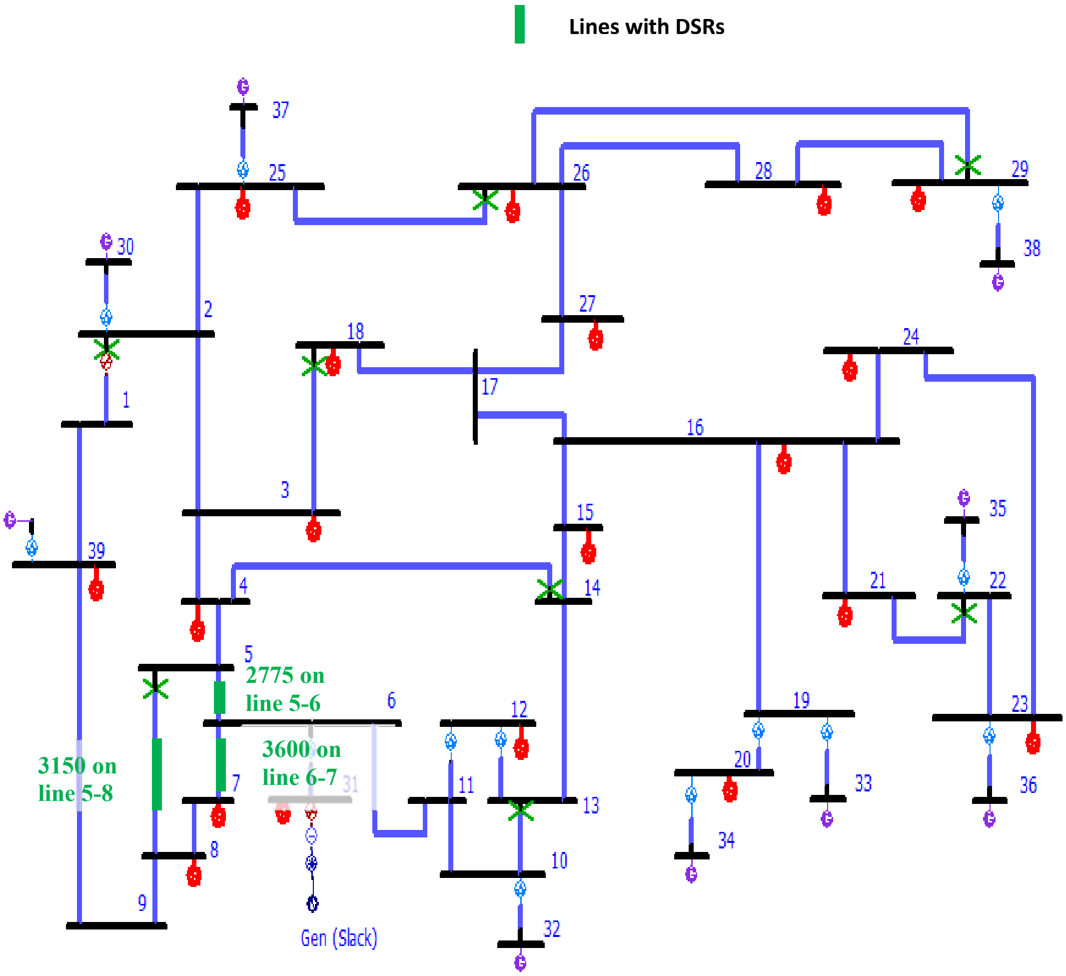


Figure 4.7 DSR system design #2 for 110% system load

Figure 4.7 shows how the deployment of DSRs over Line 5-6, Line 5-8, and Line 6-7 was capable of handling all overloads at the 110% load level. When load was further increased to 111%, DSR deployment was not able to handle all overloads and Line 6-7 was observed as a critical line.

Figure 4.8 illustrates that with the new construction of Line 6-7 at the 111% load level, all N-1 contingencies could be handled and no DSR deployment was necessary.

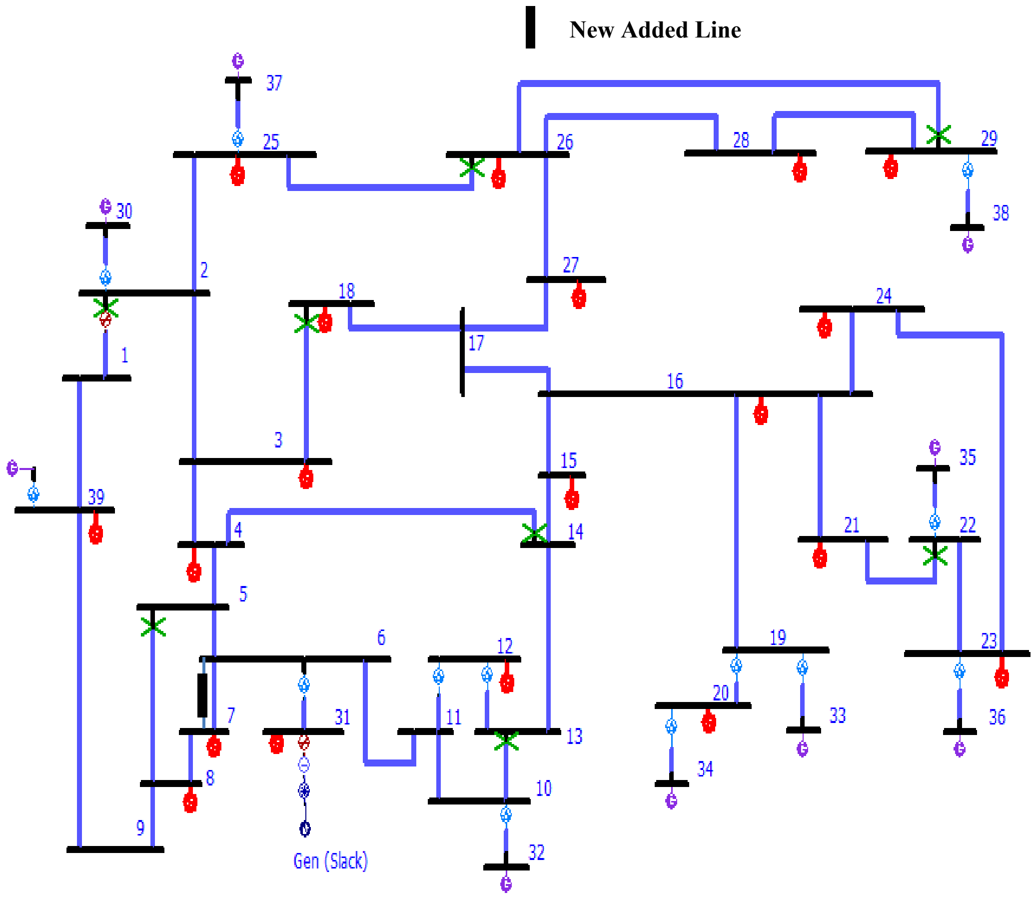


Figure 4.8 DSR system design #3 for 111% system load

4.3.2.2 111% - 122% Load Growth

With the construction of a new 345 kV line in parallel with Line 6-7 in Design #3 at the 111% load level, the load was further increased and DSR deployment succeeded in alleviating all overloads for N-1 contingencies till a critical line, Line 15-16, was observed at the 122% load level.

Table 4.4 and Table 4.5 present the simulation results for the different system load levels up to the load growth of 122%, where new line construction of a line parallel to a critical line, Line 15-16, was implemented in Design #6.

Results of the simulation of the unbalanced, 3-phase system at the 122% load level with the new parallel line construction to Line 15-16 are depicted in Figure 4.9.

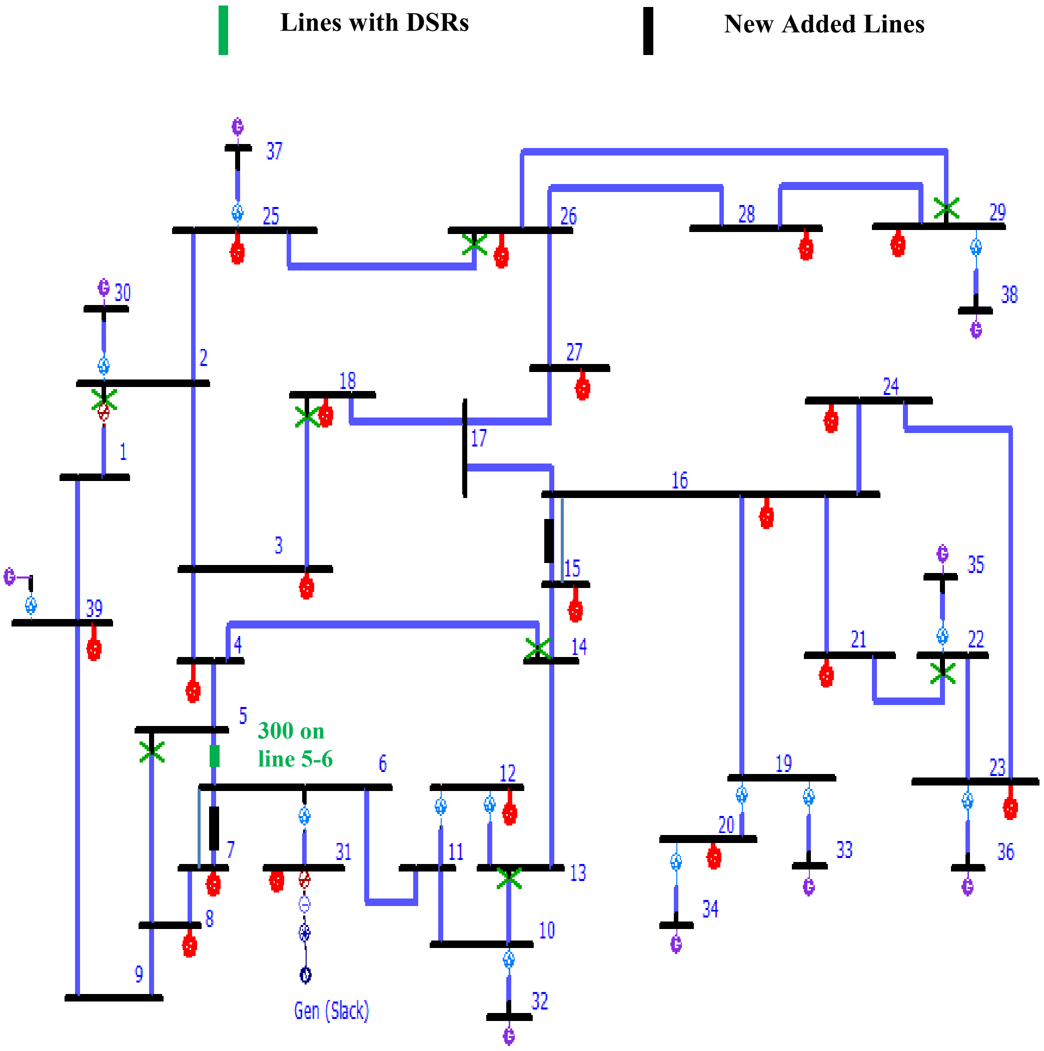


Figure 4.9 DSR system design #6 for 122% system load

Figure 4.9 shows how overloads at the 122% load level are alleviated when constructing a new line parallel to Line15-16 and deploying 300 DSR modules over Line 5-6.

4.3.2.3 122% - 136% Load Growth

At 122% load, the system has 2 new built lines that are in parallel with Line 6-7 and Line 15-16. Load was further increased with the DSR system design managing to alleviate overloads caused by line outages until 135%. At the 136% load level, Line 2-3 was observed as a critical line. Thus, in Design #9, shown in Table 4.4 and Table 4.5, a new line was constructed parallel to Line 2-3. The findings for the critical lines as well as the DSRs deployed for the136% load are presented in Figure 4.10.

As elaborated in Figure 4.10 in Design #9, while constructing a new line parallel to Line 2-3, 1050 DSRs were also deployed over Line 5-6 to ensure security under all N-1 contingencies at the 136% load level.

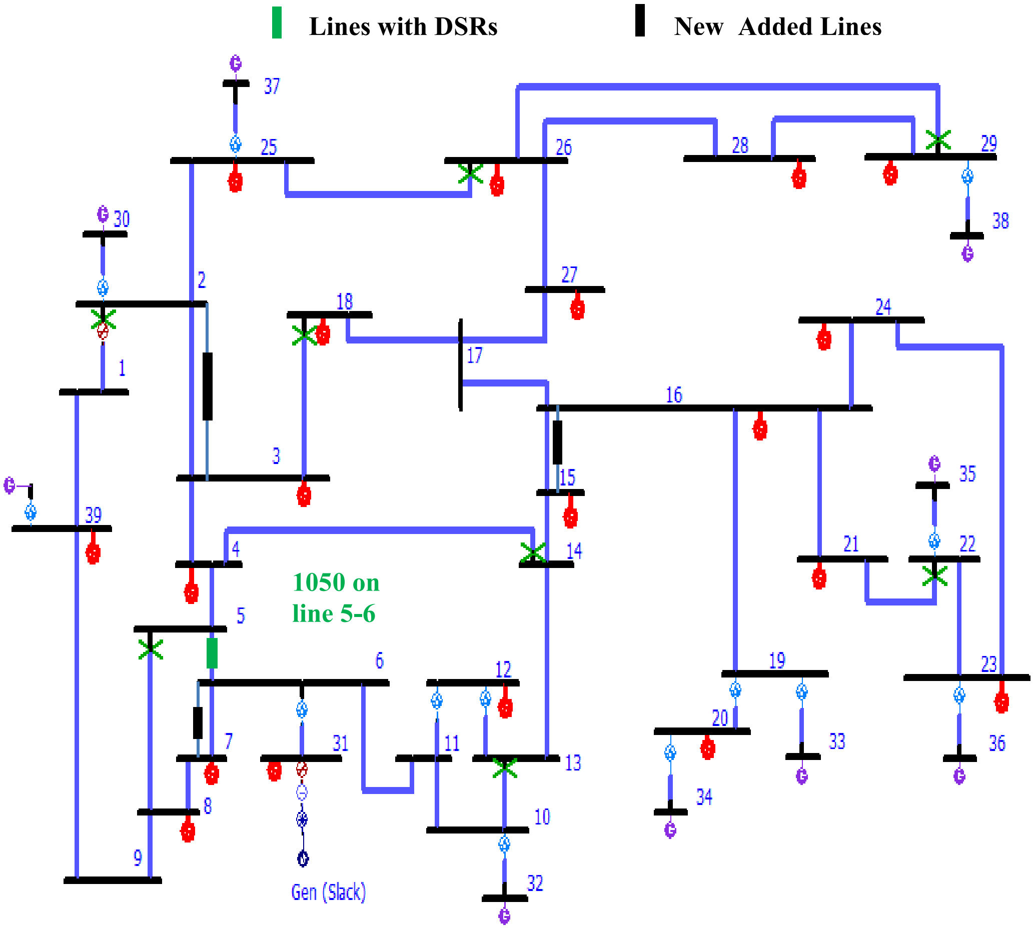


Figure 4.10 DSR system design #9 for 136% system load

4.3.2.4 136% - 140% Load Growth

After a new line was constructed in parallel with Line 2-3 in Design #9 at 136% load, the system had 3 new lines. Load was further increased and all N-1 contingencies were handled by deployment of DSRs until a load level of 140% was reached. No more new line construction was required. Results for the 140% load level are presented in Table 4.4 and Table 4.5.

Some observations obtained from the results shown in Table 4.4, Table 4.5 and Table 4.6 are:

The three critical lines identified at the 111%, 122%, and 136% load levels represent weak points in the original system.

Lines whose outage cause overloads for several consecutive loading levels tend to turn into critical lines as the load increases. This is observed for the three critical lines of this study in Table 4.4.

Adding DSRs for flow control can sometimes result in a high percentage change in impedance as shown in Table 4.6. This may cause voltage drops which require addition of more reactive controls.

For Design #10, the voltages for lines with DSRs (Line 5-6 and Line 13-14), are reported in Table 4.7. The goal in this study was to keep the voltage drop within ±10% of the nominal voltage.

The percentage of voltage imbalance is calculated using

$$\frac{\text{maximum deviation from average voltage}}{\text{average voltage}} * 100\% \qquad (4.12)$$

$$\frac{\max\{\,|Vav-VA|,\ |Vav-VB|,\ |Vav-VC|\}}{Vav} * 100\% \qquad (4.13)$$

where: V_{av} is the average voltage, and V_A, V_B, and V_C are the phase voltages.

The voltage imbalance observed with DSRs deployed at the 140% load level is higher than that for the base case with no DSRs. The voltage imbalance obtained could be corrected by placing different numbers of DSRs on different phases.

Table 4.7 Voltage of lines with & without DSRs for 100% and 140% load

Load Level %	Lines with DSRs	# DSRs Deployed	Voltage (p.u.)			Imbalance %
			Phase A	Phase B	Phase C	
100%	Line5-6	___	1.0127	1.031	1.0304	1.17
	Line13-14	___	1.0255	1.0449	1.0451	1.25
140%	Line5-6	1500	0.9252	0.9743	0.9692	3.31
	Line13-14	75	0.9391	0.9892	0.9849	3.33

The highest % of overload removed is calculated at different % load levels and is depicted in Table 4.8 and Figure 4.11. Figure 4.11 also shows where new lines were built. The total load supplied and the numbers of DSRs deployed to remove the overload are presented in Figure 4.12.

Table 4.8 DSR deployed to remove the highest % of overload and the total capacity supplied at different system load levels

% System Loading	Highest % of OL removed at the shown failed line	Total # DSR deployed	Failed Line	Total Capacity (MW)	Increase in load (MW)	Lines Reinforced
100%	13.76	1650	line6-7	6149.8		
110%	35.95	5925	line6-7	6764.9	615.1	
111%	—	—	—			Line6-7
120%	12.9	2850	line15-16	7379.5	1229.7	Line6-7
121%	14.68	3825	line15-16	7441	1291.2	Line6-7
122%	2.37	300	line7-8	7502.9	1353.1	Line15-16
130%	9.58	1200	line7-8	7994.7	1844.9	Line15-16
135%	20.44	4275	line2-3	8300.7	2150.9	Line15-16
136%	8.74	1050	line7-8	8363.7	2213.9	Line2-3
140%	12.32	1500	line7-8	8609.6	2459.8	Line2-3

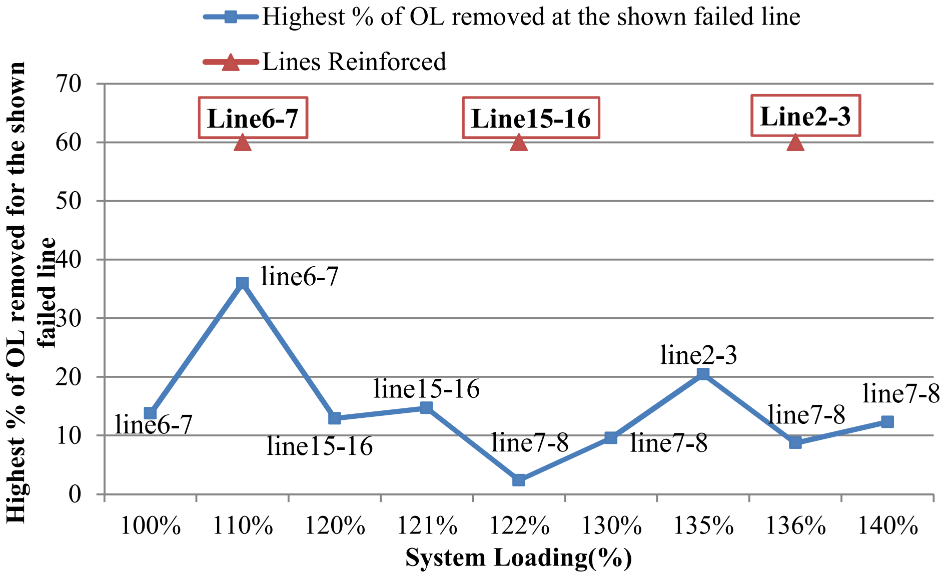


Figure 4.11 Highest % of overload removed at different system load levels

It may be observed from Figure 4.11 that for the same failed line, the highest % of overload removed increases with the increase in system load level. Whenever the failed line was strengthened with a parallel one, the highest % of overload removed drops. It is also noted that the line whose outage has the highest % of overload removed tends to turn into a critical line as load level increases and is subsequently chosen to be strengthened with a similar parallel line.

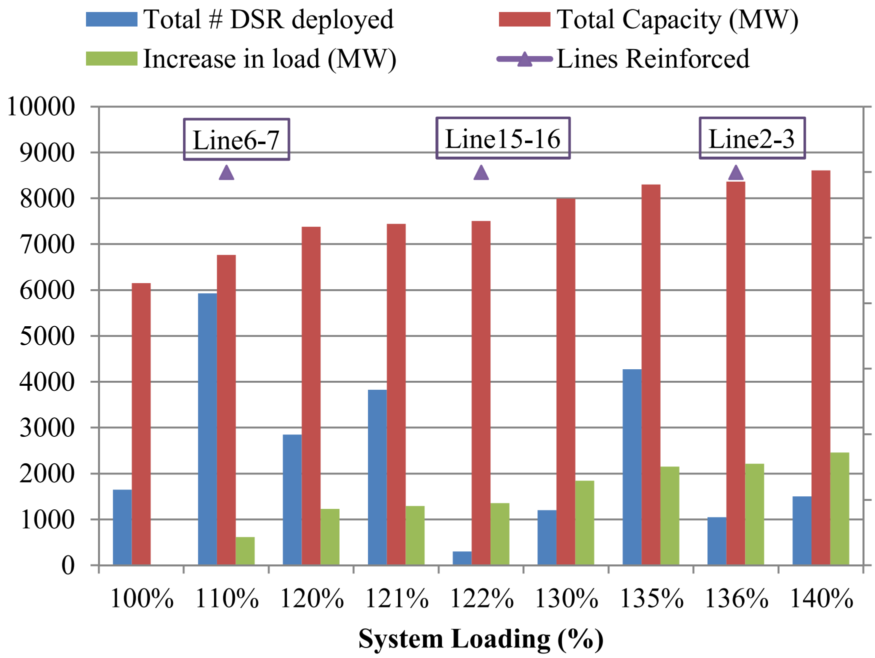


Figure 4.12 DSRs deployed, increase in load, the total load supplied, and % system loading at which line reinforcement occurred

4.3.2.5 New Line Construction: Alternate Design

As discussed in the previous section, the DSR system design for the 140% load level provides for a significant load increase with a small number of DSRs where voltage drops at peak conditions are within the design criteria. This DSR system design will shortly be compared with the conventional method of new line construction to reach the 140% load level. The study of using just new line construction to reach the 140% load level will be considered in this section.

The load is uniformly grown and if a line outage causes overloads, this line will be strengthened by constructing a new similar line parallel to it to alleviate the observed overloads. At the 100% base case load, Line 6-7 and Line 5-8 outages caused overloads. By building a new line parallel to Line 6-7 the overloads were alleviated. At the 120% load level, Line 7-8 and Line 15-16 were strengthened with similar parallel lines to alleviate overloads. For further load increases, Line 2-3 was strengthened at the 130% load level and Line 6-11 was strengthened at the 140% load level. Thus 5 lines were added to the system to reach the targeted 40% load increase.

In addition to the same 3 lines strengthened in the DSR system design #10 for the 140% load level, 2 more lines, which are Line 7-8 and Line 6-11, were strengthened, resulting in the addition of 50.15 more miles of new transmission lines [70]. Table 4.9 shows the 5 lines added and their length, highlighting the 2 additional lines for the alternate design of just adding new lines with no DSR addition.

Table 4.9 New line construction for N-1 contingency for 140% load growth highlighting new lines added

% System Load	Line Outages Causing Overload	New Lines Added to Remove Overloads	Length in Miles
100%	Line6-7, Line5-8	Line6-7	28.79
110%	___	___	___
120%	Line15-16, Line7-8	Line15-16, Line7-8	29.09 22.67
130%	Line2-3	Line2-3	36.69
140%	Line6-11	Line 6-11	27.48

Figure 4.13 depicts the DSR system design results for the 140% load level obtained in Design #10 presented in Table 4.4 and Table 4.5. Figure 4.14 shows the five new lines added to the system in the alternate design to reach the targeted load level 140%.

4.4 Economic Worth of DSR System Design vs. New Line Construction

In this section, the economic worth of the DSR system design, evaluated in terms of conventional new line construction, is performed. This economic evaluation will be performed for the 140% load level. For economic evaluation, 2 cases are adopted:

- Case1- DSR system design following the strategy explained and presented in sections 4.3.1 and 4.3.2.
- Case2- New Lines Construction with no DSR deployment to handle load growth with N-1 contingency presented in section 4.3.2.5.

Economic assessment of both cases is then performed.

4.4.1 Case 1: DSR System Design

To reach a load growth of 40% it is shown in Table 4.10 that along with the 3 new constructed lines (Line 6-7, Line 15-16 and Line 2-3), a total of 13350 DSRs were added to the system through the first 21 years. The 3 new 345 kV lines added in parallel to critical lines resulted in approximately 95 miles of new transmission lines [70]. Table 4.10 shows the number of DSRs to be added and deployed over each line for each year to support a load growth of 140% in 40 years while handling N-1 contingency. Table 4.5 presents the DSRs for each line for each load level design, and Table 4.10 presents the cumulative DSR system design for 40% load growth while handling the N-1 contingency requirement. Figure 4.15 depicts the number of DSRs added and the new lines constructed each year for the targeted 140% load growth.

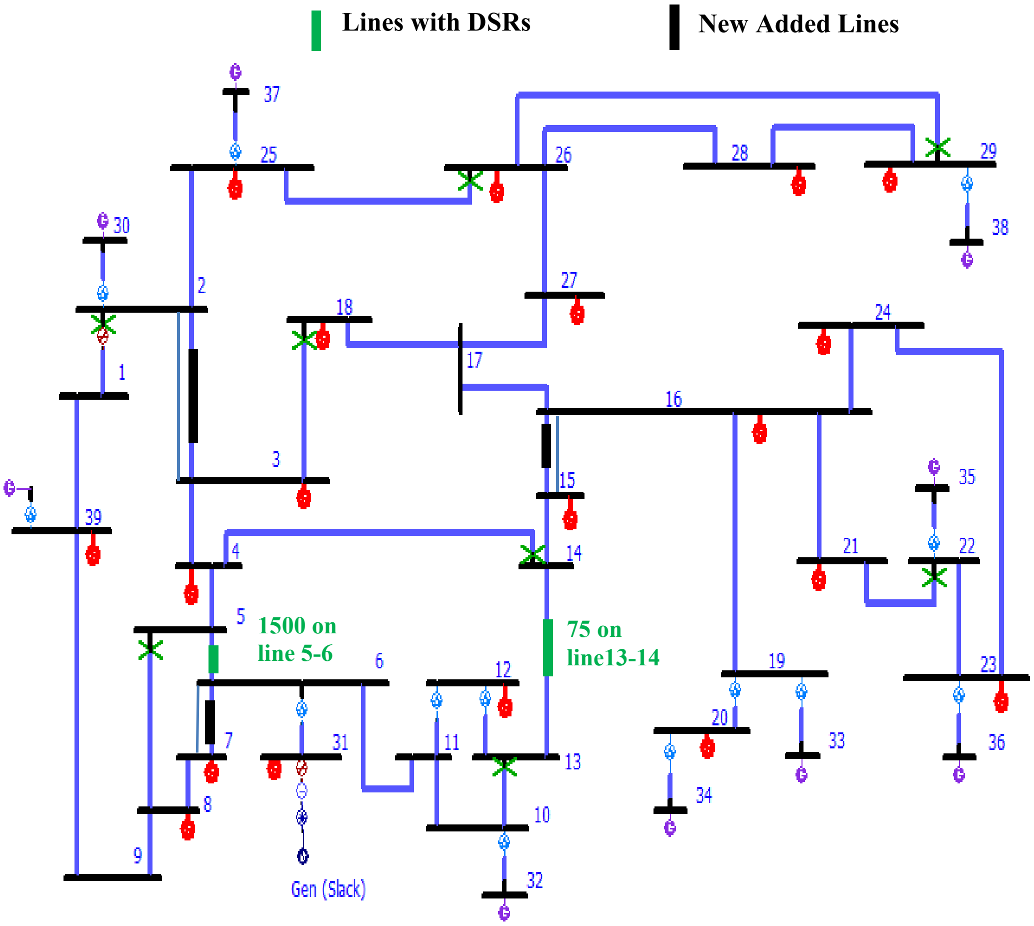


Figure 4.13 DSR system design #10 for the 140% system load

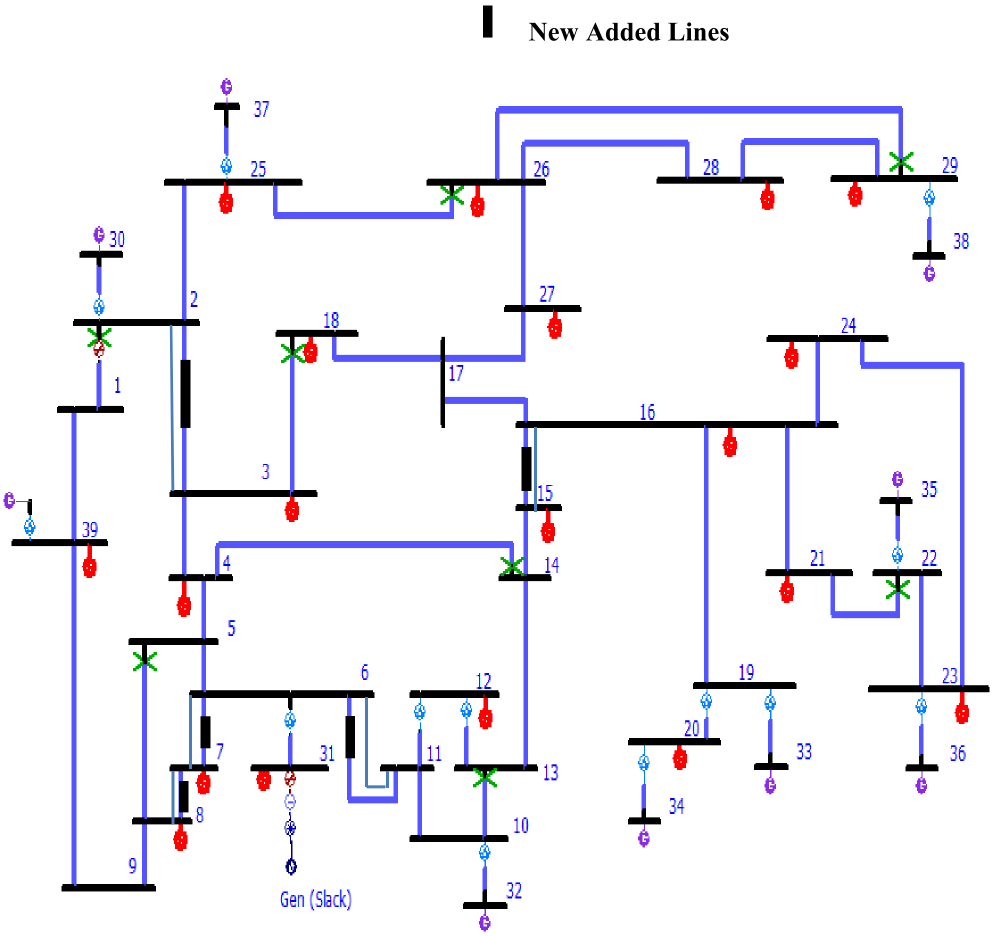


Figure 4.14 The 140% system load using only new lines construction

Table 4.10 DSR modules deployed over each line per year

Lines with DSRs	**Year 0 (100%)**	**Year 10 (110%)**	**Year 20 (120%)**	**Year 21 (121%)**	
Line 5-6	1650	1125			
Line 6-7	375	3225			
Line 13-14			2850	975	
Line 5-8		3150			
Total DSRs	2025	7500	2850	975	**13350**

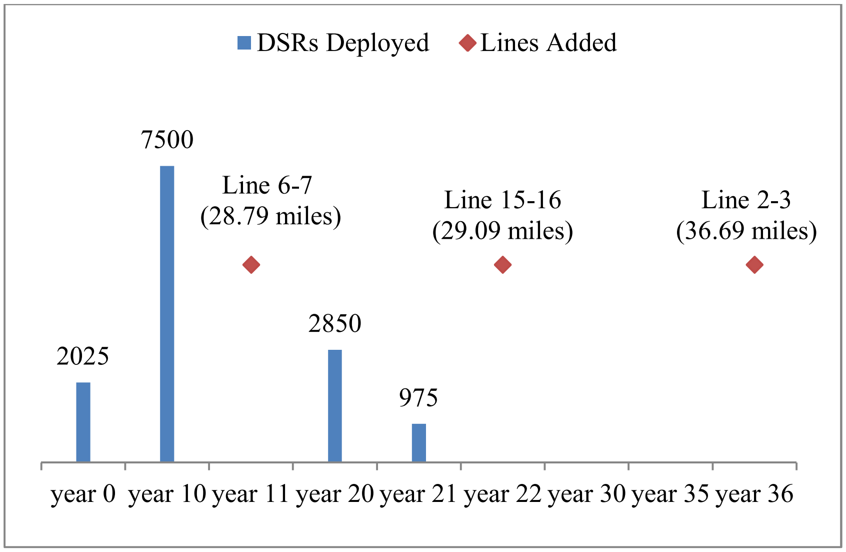


Figure 4.15 DSRs and new lines added per year for a 140% system load

4.4.2 Case 2: Alternative Design: New Line Construction

In the new line construction design presented in section III-E, 5 new lines are added to reach the 140% load level. In addition to the same 3 lines added in DSR system design #10, Line 7-8 and Line 6-11 were constructed, resulting in the addition of about 51 more miles of new transmission lines.

Table 4.11 shows the 5 lines added and their lengths, highlighting the 2 additional lines added for the new line construction alternate design study. Figure 4.16 depicts the lines in miles built each year to support the 140% load growth in 40 years.

Table 4.11 Total length in miles for new lines constructed

5 Lines added	Length (mile)	Total length(mile)
Line2-3	36.69	
Line6-7	28.79	
Line15-16	29.09	94.57
Line7-8	22.67	
Line6-11	27.48	50.15
		144.72

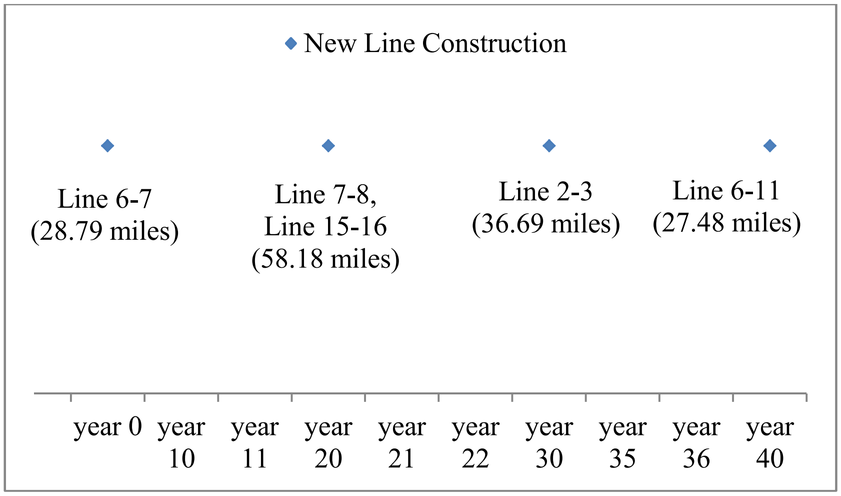


Figure 4.16 New lines constructed per year for a 140% system load with the New Line Construction Alternate Design

Table 4.11 shows the 5 lines added at years 0, 20, 30 and 40 corresponding to the load levels 100%, 120%, 130% and 140% as presented in Table 4.9.

From Figure 4.15 and Figure 4.16 it is shown that the DSR system design is delaying the construction of new lines for over 10 years.

4.4.3 DSR Worth Calculations

The cost of the new line construction design will be used to evaluate the economic value of the DSRs. The evaluation is done using the present worth value, shown in equation (4.14), of each design presented in the previous 2 subsections and equating these values. This would set an upper limit on the worth of the DSRs. The present worth value for the two designs are shown in equations (4.15) and (4.16).

$$\text{Present Value (P)} = \frac{\text{Future Value (F)}}{(1+i)^n} \qquad (4.14)$$

Where i is the interest rate and n is the number of years.

Present worth value for the DSR system design=

[Present value of DSRs deployed] + [Present value of lines added]

$$= [2025 * C_{DSR} + 7500 * C_{DSR}/(1+0.1)^{10} + 2850 * C_{DSR}/(1+0.1)^{20} + 975 * C_{DSR}/(1+0.1)^{21}]$$
$$+ [(28.79 * C_{Line})/ (1+0.1)^{11} + (29.09 * C_{Line})/ (1+0.1)^{22} + (36.69 * C_{Line})/ (1+0.1)^{36}] \qquad (4.15)$$

where C_{DSR} is the cost of one DSR module, and C_{Line} is the construction cost of the 345 kV line per mile. An interest rate of 10% is assumed.

Present worth value of new line construction design=

$$(28.79*C_{Line}) + (58.18*C_{Line})/ (1+0.1)^{20} + (36.69*C_{Line})/ (1+0.1)^{30} + (27.48*C_{Line})/ (1+0.1)^{40} \tag{4.16}$$

By equating (4.15) with (4.16) that has the cost of a DSR as an unknown, we will be able to estimate the upper limit for the cost of a DSR that will make it a better investment, as shown in (4.17).

$$\begin{aligned}&[2025*C_{DSR} + 7500*C_{DSR}/(1+0.1)^{10} + 2850*C_{DSR}/(1+0.1)^{20} + 975*C_{DSR}/(1+0.1)^{21}]+[(28.79*C_{Line})/ (1+0.1)^{11} + (29.09*C_{Line})/ (1+0.1)^{22} + (36.69*C_{Line})/ (1+0.1)^{36}]\\ &= \\ &(28.79*C_{Line}) + (58.18*C_{Line})/ (1+0.1)^{20} + (36.69*C_{Line})/ (1+0.1)^{30} + (27.48*C_{Line})/ (1+0.1)^{40}\end{aligned} \tag{4.17}$$

Using a construction cost of a 345 kV line C_{Line} as 2.5M$/ mile [43] [71] [72] [73] , the breakeven cost of a DSR is C_{DSR} = $11,557 /DSR module. Thus, if the cost of the DSR is less than $11,557 per DSR it may be a better investment to deploy DSRs, especially since the DSRs provide control flexibility not available with the fixed construction. Additionally, the DSR system design delays construction of lines, and thus, if load growth estimates are incorrect, it gives planners and operators some time to make better decisions about investments in new transmission lines. Moreover, DSRs can be moved around in the network if deployment decisions are not accurate.

4.5 Multi-Area Control Design

This section presents the simulation results of using Distributed Series Reactor (DSR) to control the power flow of a real power system over tie lines connecting different power pool areas and control the power flow over transmission lines within the area itself. An area (Area1) with 525 buses (52 load buses, 64 generator buses) and 302 transmission lines is simulated. This area is connected to its neighboring area by 8 tie lines.

Figure 4.17 illustrates the area under study (Area1) with its tie lines connections to Area2 and its peak load value for the existing system.

4.5.1 Case Study Simulation Results

The maximum load power that can be supplied to the loads in Area1 with the already existing transmission facilities is 11.35 GW. A further increase in load power results in overloading in the lines within the area and overloads over tie lines. The Distributed Series Reactor modules of 50 μH (0.01885 Ω) are used to alleviate the overload and control the power flow over the transmission lines and tie lines. Several case studies for the increase in load are investigated, these increase values range is 5% - 24% load growth. The following subsections present the results for two load growth percentage from the middle of this range to elaborate and discuss the findings. The details of the results of the all load growth percentage are presented in Appendix F.

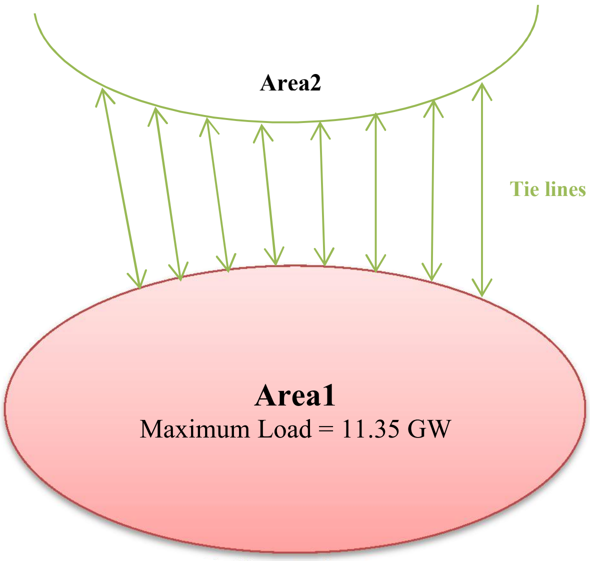


Figure 4.17 Power Areas under study

4.5.1.1 Area1 load power growth of 15%

For a load growth of 15%, two transmission lines and three tie-lines are overloaded. Appling the DSR control algorithm, a total of 3600 DSRs are deployed over six lines to alleviate the overload and shift the power flow over other lightly loaded lines in the system. The power supplied to this after this deployment is 12.86 GW, thus an increase of 1.5 GW is achieved using 3600 DSR modules. Table 4.12 shows the results for the six lines before and after DSRs implementation.

It is worth noting that Transmission line3 was not overloaded but the DSRs deployed over it caused the shift of power flow over other lightly loaded lines to help in alleviating overloads over loaded lines and to achieve better utilization of the system transmission lines.

Table 4.12 DSR deployment results for the load growth of 15% in Area1

Line type	No. of DSR modules deployed	Max Load % without DSR	Max Load % with DSR	Total MVA without DSR	Total MVA with DSR
Tie line1	300	115.6	86.7	426.5	319.8
Tie line2	300	105.5	95.6	236.3	214
Tie line3	300	103.5	99.6	146.9	141.3
Trans line1	1200	110.6	99.6	204.3	184.07
Trans line2	900	104.69	99.2	225.2	213.02
Trans line3	600	98.5	98.09	161.9	160.7

4.5.1.2 Area1 load power growth of 20%

When load power in Area1 was increased by 20%, this required the deployment of 12000 DSRs to alleviate the overload over nine lines (four tie lines and five transmission lines). The system could serve the load with 13.33 GW, which means an increase of 2GW. Table 4.13 presents the results of the lines for a load growth of 20%.

Table 4.13 DSR deployment results for the load growth of 20% in Area1

Line type	No. of DSR modules deployed	Max Load % without DSR	Max Load % with DSR	Total MVA without DSR	Total MVA with DSR
Tie line1	300	127.8	95.5	471.5	352.6
Tie line2	1200	119.1	95.07	266.6	212.7
Tie line3	1800	113.3	95.6	160.7	135.7
Tie line4	900	98.6	98.4	192.3	191.9

Trans line1	2700	116.4	96.5	213.2	176.9
Trans line2	2100	110.2	98.6	235.09	208.9
Trans line3	0	103.5	89.9	187.6	161.9
Trans line4	1800	102.8	98.3	167.2	159.03
Trans line5	300	101.1	84.3	170.4	141.8
Trans line6	0	101.04	94.2	310.9	290.1
Trans line7	900	95.9	98.5	163.1	167.5

It is shown in Table 4.13 how DSRs can be deployed over non-overloaded lines to alleviate overloads over other loaded ones. This can be shown when 900 DSRs are deployed over tie line4 and also 900 DSRs are deployed over transmission line7 while they are not overloaded, whereas the overloads over transmission lines 3 and 6 are alleviated without placing DSRs explicitly over these overloaded lines. This elaborates how the algorithm works on choosing transmission lines for deploying minimum number of DSRs to alleviate overloads, improve utilization of lightly loaded lines and improve the performance of the network.

Figure 4.18 and

Table 4.14 depicts the total number of DSRs deployed in Area1 for the different load growth percentage.

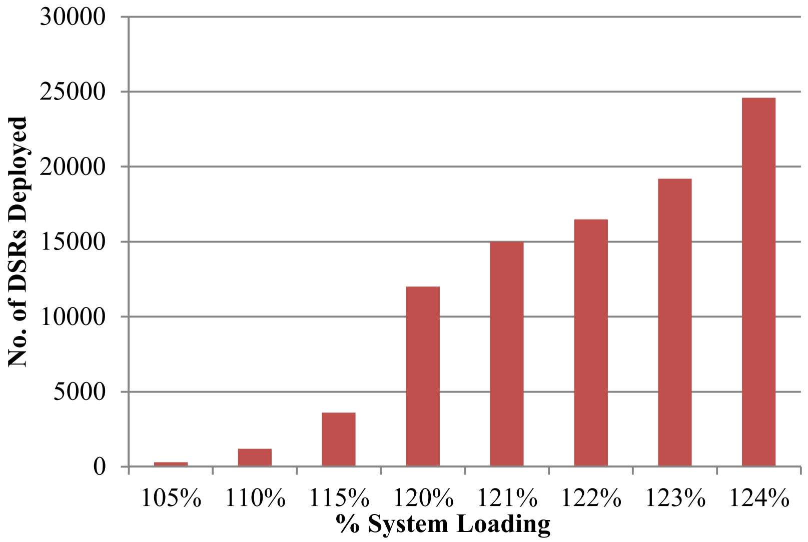


Figure 4.18 Total Number of DSR Deployed in Area1 for Different System Loadings

Table 4.14 DSR deployed and load delivered for different load growth percentage in Area1

% System Loading	105%	110%	115%	120%	121%	122%	123%	124%
#DSR Deployed	300	1200	3600	12000	15000	16500	19200	24600
Load delivered [GW]	11.88	12.37	12.86	13.34	13.43	13.53	13.62	13.71
Load increase [GW]	0.53	1.02	1.51	1.99	2.08	2.18	2.27	2.36

From Figure 4.18 and

Table 4.14 it is shown that at the early load increase percentages, till 15% load growth, fewer number of DSRs was required to supply these load percentages. For 120% load level and above, large number of modules are deployed.

For an increase of 1.5 GW (15% load growth) 3600 DSR modules are required, for an increase of 2 GW (20% load growth) 12000 modules are required. So for 0.5 more GW increase more than 3 times the number of DSRs is required.

The increase in load and the load delivered for different system load levels is presented in Figure 4.19 and Figure 4.20.

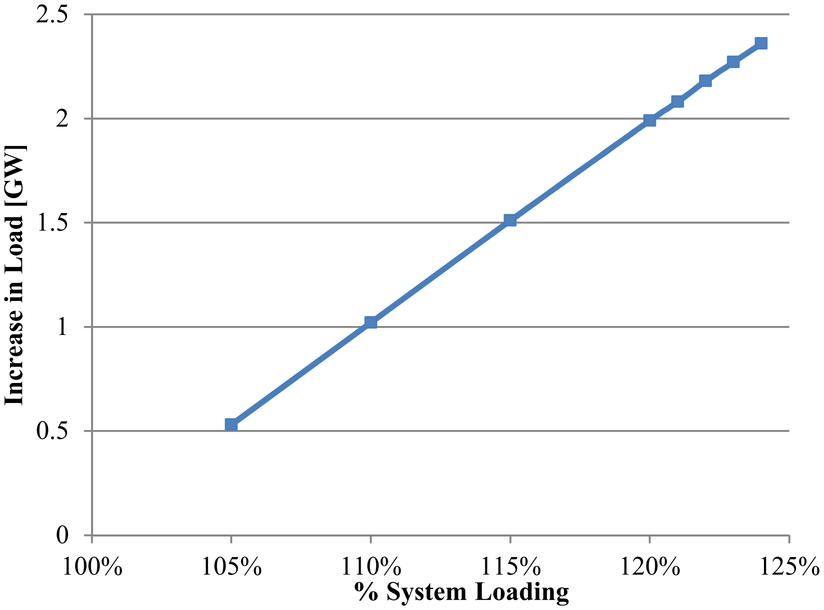


Figure 4.19 Load Increase in Area1 for Different System Loadings

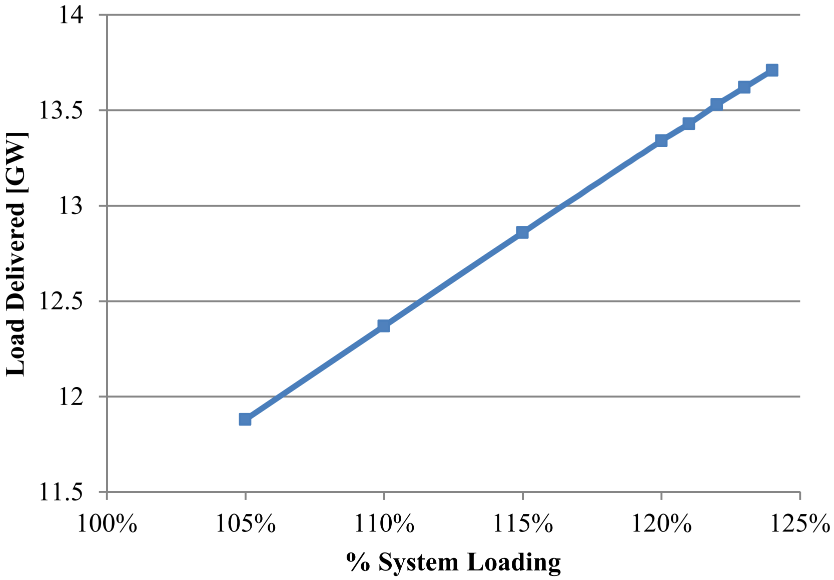


Figure 4.20 Load Power Delivered for Different System Loadings

4.6 Conclusion of Chapter 4

This chapter studied controlling power flow using Distributed Series Reactors (DSRs) and the effect that line models can have on the design. The IEEE 39 bus standard transmission system model was converted to a three-phase model using 345 kV unbalanced line models and the generators were converted to three-phase equivalent voltage sources. A second model of the system was created by assuming that the lines in the unbalanced model are transposed. This model was referred to as the balanced model. The balanced model is the positive sequence representation of the system obtained using the symmetrical components transformation.

For a given loading, use of the balanced model in the design results in many more DSRs needed for control than the unbalanced model. The application of DSRs can increase the utilization of the line capacity in a system. This increased utilization can delay or eliminate the need for building new transmission lines. Whether DSRs should be used to increase the capacity or new lines should be built is partly an economic question. This question was addressed after N-1 contingencies were considered. The value of DSRs in contingencies was investigated using just the unbalanced model.

This chapter also studied controlling power flow on unbalanced transmission lines using DSRs under N-1 line contingencies. An unbalanced, 3-phase model of the physically modeled IEEE 39 bus system was used to simulate the placement of DSRs under load growth and N-1 contingency analysis while maintaining all system voltages within +/- 10% of nominal voltage. A projected load growth for the next 40 years of 1% per year is assumed in this study.

The DSR placement algorithm was used to try and find a DSR system design that can be used to alleviate observed overloads. When DSRs were not able to handle all overloads, new line construction was implemented. Critical Lines were introduced and defined in this study as lines which when failed cause overloads that cannot be alleviated by DSR placement, and here construction of new lines is used to alleviate such overloads. At the 100% and 110% load levels DSRs were able to alleviate all overloads under N-1 contingencies. For the 111%, 122%, and 136% load levels, the system had weak points where DSRs could not relieve all the overloads observed under N-1 contingencies. These overloads were eliminated by constructing three new lines. However, this illustrates that DSRs can provide a solution to delaying the investment in infrastructure until a specific load growth percentage is reached.

The importance of analyzing the test system as a 3-phase model when designing for DSRs was revealed. It was also demonstrated that approximating an unbalanced system with a balanced model can result in many more DSRs needed to control the power flow. We could attain a high percentage of load growth with power flow control using DSRs. In the load growth study DSRs were not needed till the load level reached 145%, whereas DSRs were needed starting at the 100% load level to handle N-1 contingencies. This illustrates that what may drive the addition of DSRs in early stages is managing contingencies rather than handling load growth.

An economic evaluation of DSRs for N-1 contingencies with load growth was performed. In the economic evaluation, the study of the system with just new lines construction versus deploying DSRs to supply a load level of 140% was investigated. The value of the DSRs when compared with new line construction came to 11,557 $ per DSR.

DSRs can be cost effective in managing load increases from year to a year, and thus avoid making big investments in new line construction until load expectations are proven to be true. Thus, a major value of DSRs is handling load growth in the short term, delaying larger investments. Furthermore, as illustrated in the example studies performed here, even when new line construction is performed, the past investments in DSRs continue to provide value. Moreover, DSRs offer other value streams, such as control for balancing unbalanced transmission system voltages.

Distributed Series Reactors control was also implemented to control the power flow over transmission lines and tie lines between areas. Several scenarios for different % of load growth within the area under study (Area1) were investigated. It was shown in this area control study that DSRs can be deployed over non-overloaded lines to alleviate overloads over other loaded ones. It was also shown that in some cases overloads were alleviated without placing DSRs explicitly over the overloaded lines. This elaborated how the algorithm works on choosing transmission lines for deploying minimum number of DSRs to alleviate overloads over transmission lines within an area and tie lines connecting power pool areas and to improve utilization of lightly loaded lines to enhance the performance of the network.

5 Conclusions and Future work

5.1 Conclusions and Contributions

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. Meanwhile, transmission infrastructure projects are facing several challenges. Some of these challenges include delayed construction due to siting and permitting issues, congestion, and the under-utilization of already existing transmission facilities.

Existing solutions and opportunities to improve transmission and distribution capacity is the deployment of technologies and techniques that better utilize the existing network facilities and improves the efficiency of the grid. Some of these technologies and techniques were presented in the literature, and the pros and cons of each were reviewed.

This work presents a study concerned with the Distributed Series Reactor technology that is capable of improving transmission capacity and restoring secure power system operation under contingency conditions. This technology is based on modifying series line reactance to control power flow and thereby increase transmission system capacity without construction of new transmission facilities.

This dissertation presents an answer to a broad question which is "How do we DESIGN with Distributed Series Reactors?" DSR was first presented as a D-FACTS device that is used to control power flow and to reduce transmission investment as a power flow controller, but system Design aspects have not been addressed in the literature.

The major contribution in this dissertation is the design for the DSR controller and the novelty in this work is the analysis of the DSR system design for 3-phase transmission models. This work is significant because balanced and unbalanced, three-phase transmission system modeling is employed. Using the symmetrical components transformaton (the positive sequence model), a balanced, 3-phase model is derived from the unbalanced, 3-phase model. DSR system designs based on the unbalanced, 3-phase model and the balanced, 3-phase model are compared and used to demonstrate the effectiveness of DSR control in handling load growth and contingency analysis. In the U.S. much of the transmission system has been constructed with unbalanced impedances, and incorporating this into the analysis results in very different designs than those obtained with the commonly used balanced transmission system assumption. Significant difference is noted in the simulation results obtained for the line impedance models, i.e. balanced versus unbalanced 3-phase models.

The contribution of the DSR system design can be organized in 3 areas as follows:

1- DSR system design principles.
2- Balanced and unbalanced 3-phase analysis.
3- Economic evaluations.

The results included in each area are elaborated below.

1- DSR system design principles:

- Deployment of DSRs improves the utilization of parallel lines and increases the maximum power that can be delivered.
- For long and medium lines some DSR allocations are preferred over others as they provide maximum power using fewer numbers of DSRs. For short lines DSR placement over different allocations gave similar results.
- DSR deployment over long transmission lines introduces significant increases in voltage drops which may require capacitive compensation.
- The lumped π- models provide equivalent results to distributed line models when the line lengths are less than 100 miles. However, as lines become very long, say 200 miles, the lumped π- model underestimates the number of DSRs needed for power flow control, which emphasizes the importance of distributed modeling of long transmission lines.
- For unbalanced long lines, phase voltage imbalances increase with the increase in the number of DSRs when the DSRs are equally deployed over the three phases.
- For parallel lines representing three or more voltage levels, deployment of DSRs on higher voltage lines can provide more MVA and electric current transfer per unit DSR.
- Deployment of different numbers of DSRs per phase can improve transmission line voltage imbalance.
- DSR system design for voltage balancing is comparable to long line transposition. For a load of 900 MW a voltage imbalance of 3.8% was reduced to 2.03% with DSR system design and reduced to 1.84% using transposition. The choice of using either DSRs or transposition to achieve the improved voltage balance depends on the acceptable % voltage imbalance and the economic value of each technique.

- Bundled conductors utilize fewer numbers of DSRs to control flow than unbundled conductors.
- The DSR modules were implemented under *N-1 Line Contingency* conditions to alleviate overloads for several load growth scenarios. For some load levels, the system was considered robust as DSRs were able to alleviate all overloads under single line contingencies. For other load levels system weak points were discovered, where DSRs could not be used to relieve all overloads under N-1 line contingency. In the study here the weak points were eliminated by reinforcing some of the lines, defined in this dissertation as *Critical Lines*. Thus, DSR system design can be used to identify weak points in the transmission system.
- The driver for the addition of DSRs in early stages of load growth is managing contingencies rather than handling the load growth itself.
- DSR system design for power pool areas and the tie lines connecting them is capable of alleviating overloads within the control areas and also capable of relieving congestion over tie lines connecting the areas. In some cases DSRs may be deployed to non-overloaded lines to alleviate overloads on other lines. That is, overloads may be alleviated without placing DSRs explicitly on overloaded lines.

2- Balanced and unbalanced 3-phase analysis:

The IEEE 39 bus test system was modified to a 3-phase, 345 kV, unbalanced model, and was used to study the deployment of DSRs for controlling power flow to alleviate overloads due to load growth under single contingencies. A second model of the system was created and was referred to as the balanced model. Using the symmetrical components transformation, the balanced, 3-phase model was derived from the unbalanced, 3-phase model. The line lengths in this modified IEEE 39 bus system ranged from 20 to 100 mile long. The major outcomes from these designs are summarized as follows:

- It is noted that overloads start to occur in the balanced model at 141% load growth, whereas overloads do not occur in the unbalanced model until 145% load growth is reached. At the 141% and 143% load levels, the unbalanced model has no overloads and no DSRs are needed. However, the balanced model experiences overloads at the

141% and 143% load levels, where 75 DSRs and 900 DSRs are required, respectively. This is quite a significant difference between the 2 models.

- The overload difference between the balanced and unbalanced model is due to the approximate impedances used in the balanced model. The assumed balanced model is conservative in predicting the overload before it actually would occur.
- At the 149% load level, 3,750 DSRs are deployed in the unbalanced model to alleviate overloads whereas in the balanced model 5,550 DSRs are deployed. Using the balanced model thus results in an extremely conservative design.

3- Economic evaluations:

- The system design experiments showed that the application of DSRs can be a good solution to delay the investment in infrastructure until a specific load growth percentage is reached. It is also an indicator of when and how much generation and transmission facilities will be required to support the system.
- The shorter the parallel path, the larger the cost per DSR added.
- Larger voltage differences between parallel paths provide larger returns from DSR investment.
- In all of the economic evaluations performed the worth of DSRs ranged from $11,557 per DSR to $34,758 per DSR.
- In the studies here, DSRs were determined to be most valuable for the distributed, unbalanced, three parallel 100 mile long lines, when the investment in 4,068 DSRs provided a value of 34,758 $/DSR.
- DSRs had the least value when an economic evaluation of DSR system design of the IEEE 39 bus, three-phase, unbalanced line model for N-1 contingency with load growth was performed. The value of the DSRs when compared with new line construction came to $11,557 per DSR. It should be noted that in this study all lines had the same voltage level.
- DSRs can be cost effective in managing load increases from year to year, and thus large investments in new line construction can be avoided until load expectations are proven to be true. Thus, a major value of DSRs is handling load growth in the short term, delaying

larger investments. Furthermore, as illustrated in studies presented, even when new line construction is performed, past investments in DSRs continue to provide value.

5.2 Future Work

A number of research directions may stem out of this work:

- Investigate the ability of Distributed Series Reactors to support large scale renewable energy resource integration into the power system. Integration of large amounts of variable renewable generation can pose challenges for the electricity grid. In general, high penetrations of renewable generation are technically feasible with operational changes and increased access to transmission. With the current challenges facing transmission expansion, DSR technology can be a good alternative to the construction of new transmission facilities.
- Examine the ability of the DSR system design to simplify or eliminate a remedial action scheme (RAS) or special protection scheme (SPS). Though none of the DSR pilot deployments to date have required any changes to protection settings, more detailed studies to ensure that the DSR controller does not interfere with the protection scheme of any system under study is necessary.
- Focus on investigating the results obtained to achieve phase current balancing by DSR system design. Voltage balancing was presented in this dissertation; an extension to this balancing study can be analyzing the capability of the DSR for phase current balancing.

Appendix A: Examples of delayed transmission projects due to permitting issues

There are examples where transmission projects have been delayed through lengthy permitting processes—such as:

- American Electric Power's (AEP) 765 kV line through West Virginia and Virginia, which was delayed for over ten years by factors that included environmental challenges to land use agency approval processes.
- More recently, proponents of the Trans-Allegheny Interstate Line (TrAIL) 500kV line project through Pennsylvania had to deal with lawsuits from property owners challenging the use of old right-of-way agreements.
- There are also examples where regulatory processes led to permit denials for proposed transmission projects, as with the Arizona Public Utility Commission's denial of Southern California Edison's (SCE) proposed Devers-Palo Verde 2 transmission line.

All of these projects, were designed primarily to deliver generation from non-renewable sources.

- The New York Regional Interconnect (NYRI) is an example of a project that could serve renewable energy sources that was delayed (and possibly terminated) due to legal challenges. The NYRI project was a merchant direct current (DC) line proposed for construction from upstate New York, where it could pick up hydro generation and new wind projects planned in northern New York, off-shore in Lake Ontario, or elsewhere in Canada, and deliver it to load centers in down-state New York, tying to the electric distribution system serving Manhattan and northern New Jersey. NYRI has ceased its participation in the New York Public Service Commission's siting process because it concluded that the New York Independent System Operator's (NYISO) transmission tariffs, approved by FERC, would compromise its ability to recover the full costs of the transmission line. However, it is not clear that this result is due to legal challenges so much as to a failure by the project's planners to identify an adequate, low-risk cost recovery mechanism [16].

Appendix B: Voltage values for each phase for voltage balancing scenarios

Table B.1 Scenario 1:Voltage balancing for the unbalanced Z three line system (Line230 || Line345 || Line500)

		Various Loadings						
		900 MW	**825 MW**	**750 MW**	**675 MW**	**600 MW**	**525 MW**	**450 MW**
No DSR	**V_A p.u.**	0.934	0.9505	0.9658	0.9801	0.9933	1.0056	1.0168
	V_B p.u.	0.9827	0.9931	1.0026	1.0112	1.019	1.026	1.0322
	V_C p.u.	0.9964	1.0058	1.0143	1.0221	1.0291	1.0353	1.0407
	% Vimbl	3.813807	3.319319	2.859825	2.425831	2.022095	1.633571	1.271968
2500 DSR on line500	**V_A p.u.**	0.9434	0.9583	0.9722	0.9852	0.9973	1.0085	1.0188
	V_B p.u.	0.9673	0.981	0.9936	1.0052	1.0157	1.0252	1.0337
	V_C p.u.	0.9886	1	1.0102	1.0194	1.0276	1.0348	1.041
	% Vimbl	2.383334	2.190998	1.995968	1.800784	1.601658	1.401336	1.199289
3400 DSR on line500	**V_A p.u.**	0.9451	0.9597	0.9735	0.9862	0.9981	1.0092	1.0193
	V_B p.u.	0.9647	0.979	0.9921	1.0042	1.0152	1.0252	1.0341
	V_C p.u.	0.9844	0.9967	1.0079	1.0179	1.0267	1.0345	1.0413
	% Vimbl	2.03856	1.917967	1.782411	1.652096	1.503289	1.345759	1.18913
66.7ml Transposition I	**V_A p.u.**	0.9561	0.9697	0.9823	0.9941	1.0049	1.0148	1.0239
	V_B p.u.	0.9776	0.9887	0.9989	1.0082	1.0167	1.0244	1.0313
	V_C p.u.	0.9886	0.9988	1.0083	1.0168	1.0246	1.0316	1.0378
	% Vimbl	1.84786	1.626539	1.424987	1.218906	1.034075	0.859711	0.688652
66.7ml Transposition II	**V_A p.u.**	0.9474	0.9622	0.9759	0.9886	1.0004	1.0113	1.0212
	V_B p.u.	0.987	0.9969	1.0059	1.0142	1.0216	1.0283	1.0342
	V_C p.u.	0.987	0.9973	1.0069	1.0156	1.0235	1.0306	1.0369
	% Vimbl	2.711029	2.36098	2.041021	1.742645	1.454605	1.182333	0.928112

Table B.2 Scenario 2: Balancing the voltage for the unbalanced Z three line system with a 5% load unbalance

		Various Loadings						
		900 MW	**825 MW**	**750 MW**	**675 MW**	**600 MW**	**525 MW**	**450 MW**
No DSR	**V_A p.u.**	0.946	0.96	0.9731	0.9854	0.997	1.0079	1.018
	V_B p.u.	0.9705	0.9822	0.993	1.0029	1.012	1.0203	1.0277
	V_C p.u.	1.012	1.0202	1.0274	1.0339	1.0395	1.0443	1.0483
	% Vimbl	3.670821	3.31488	2.963087	2.630534	2.296211	1.965826	1.64512
2500 DSR on line500	**V_A p.u.**	0.9557	0.968	0.9797	0.9907	1.0011	1.0109	1.0201
	V_B p.u.	0.9542	0.9694	0.9836	0.9966	1.0085	1.0193	1.029
	V_C p.u.	1.0051	1.0151	1.0239	1.0317	1.0384	1.0441	1.0489
	% Vimbl	3.440823	3.143099	2.828736	2.520702	2.204724	1.886608	1.571982
3400 DSR on line500	**V_A p.u.**	0.9575	0.9695	0.981	0.9918	1.0019	1.0115	1.0206
	V_B p.u.	0.9512	0.9671	0.9818	0.9954	1.0079	1.0192	1.0293
	V_C p.u.	1.0014	1.0123	1.0219	1.0304	1.0378	1.0441	1.0493
	% Vimbl	3.233566	2.984164	2.713841	2.439024	2.159076	1.87004	1.571373
66.7ml Transposition I	**V_A p.u.**	0.9662	0.9776	0.9883	0.9983	1.0077	1.0165	1.0246
	V_B p.u.	0.9663	0.9786	0.9901	1.0007	1.0104	1.0192	1.0272
	V_C p.u.	1.0042	1.0131	1.0212	1.0285	1.0349	1.0405	1.0454
	% Vimbl	2.584534	2.357458	2.133618	1.915772	1.693416	1.472596	1.259202
66.7ml Transposition II	**V_A p.u.**	0.9582	0.9706	0.9823	0.9932	1.0035	1.0131	1.022
	V_B p.u.	0.9751	0.9863	0.9967	1.0062	1.0149	1.0228	1.0299
	V_C p.u.	1.0026	1.0117	1.0199	1.0273	1.0338	1.0395	1.0445
	% Vimbl	2.448993	2.240113	2.02741	1.823768	1.611952	1.401444	1.198166

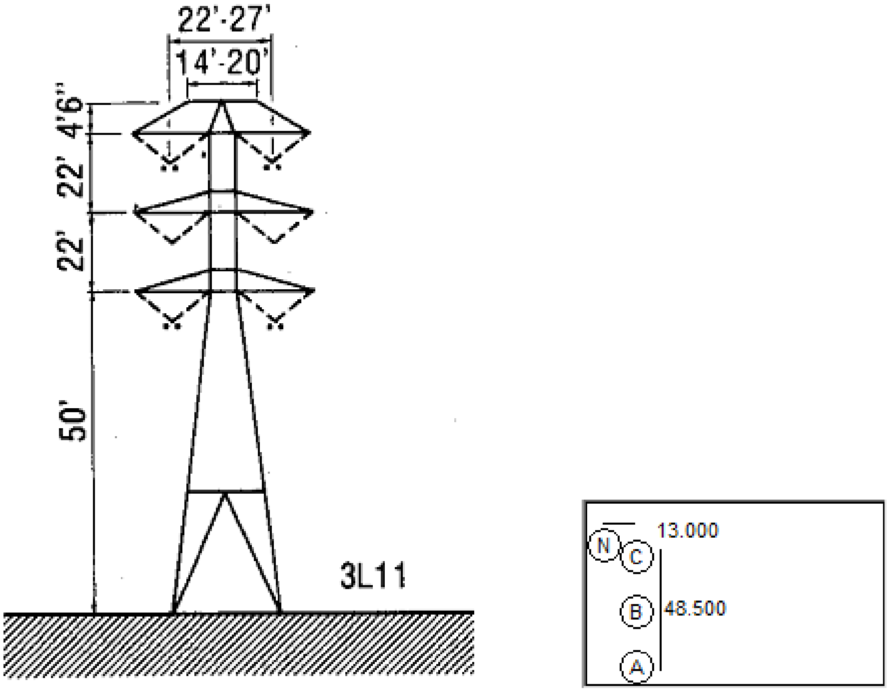
Table B.2 Scenario 3: Balancing the voltage for the unbalanced Z three line system with a 10% load unbalance

		Various Loadings						
		900 MW	**825 MW**	**750 MW**	**675 MW**	**600 MW**	**525 MW**	**450 MW**
No DSR	**V_A p.u.**	0.9573	0.9689	0.9799	0.9904	1.0004	1.0099	1.019
	V_B p.u.	0.9581	0.9713	0.9835	0.9948	1.0052	1.0147	1.0232
	V_C p.u.	1.0278	1.0346	1.0406	1.0456	1.0499	1.0533	1.056
	% Vimbl	4.763523	4.336426	3.921438	3.497426	3.082965	2.664154	2.252921
2500 DSR on line500	**V_A p.u.**	0.9673	0.9771	0.9866	0.9957	1.0045	1.013	1.0211
	V_B p.u.	0.941	0.9579	0.9736	0.9881	1.0014	1.0135	1.0245
	V_C p.u.	1.0216	1.0301	1.0375	1.0439	1.0491	1.0534	1.0567
	% Vimbl	4.604253	4.222455	3.829603	3.434951	3.021277	2.607228	2.185475
3400 DSR on line500	**V_A p.u.**	0.9691	0.9787	0.988	0.9968	1.0054	1.0137	1.0216
	V_B p.u.	0.9377	0.9553	0.9716	0.9867	1.0006	1.0133	1.0247
	V_C p.u.	1.0184	1.0278	1.036	1.0429	1.0488	1.0535	1.0573
	% Vimbl	4.444141	4.105611	3.75217	3.380254	2.99856	2.596981	2.20067
66.7ml Transposition I	**V_A p.u.**	0.9757	0.9849	0.9938	1.0022	1.0102	1.0178	1.0251
	V_B p.u.	0.9549	0.9686	0.9814	0.9933	1.0042	1.0141	1.0231
	V_C p.u.	1.0198	1.0275	1.0342	1.0401	1.0452	1.0494	1.0529
	% Vimbl	3.694414	3.404898	3.096963	2.790223	2.483985	2.171162	1.857405
66.7ml Transposition II	**V_A p.u.**	0.9682	0.9784	0.9882	0.9975	1.0063	1.0147	1.0227
	V_B p.u.	0.9631	0.9758	0.9875	0.9984	1.0083	1.0174	1.0256
	V_C p.u.	1.0184	1.0261	1.033	1.0389	1.0441	1.0484	1.052
	% Vimbl	3.576635	3.28826	3.001296	2.698695	2.406251	2.100308	1.7966

Appendix C: 345 kV Line Configuration

Houston Lighting & Power Company 3L11 Structure

The lattice tower structure for the 345 kV line used to convert the IEEE 39 bus standard test system to a physical system is shown in Figure C.1(a). An ACSR conductor with a 1.737 inches diameter and the stranding as 84/19 is used with this tower structure [54]. The spacing of the 3-phase line is shown in Figure C.1(b). Table C.1 shows the ratings and lengths assigned for the three phase lines of the system.



(a) (b)

Fig. C.1 The 3-phase 345kV line (a) Lattice Tower Structure (b) Phases spacing

Table C.1 IEEE 39 Bus Three Phase Lines Ratings And Length

From Bus	To Bus	Line Rating (MVA)	Length (miles)
1	2	400	71.39
2	3	850	36.69
2	25	1100	31.28
3	18	400	34.28

3	4	600	47.3
4	14	600	33.72
4	5	600	33.59
5	8	600	31.47
5	6	600	20
6	11	600	27.48
6	7	600	28.79
7	8	600	22.67
8	9	600	64.91
10	13	600	22.28
10	11	600	22.28
13	14	500	30.02
14	15	600	45.49
15	16	750	29.09
16	24	500	24.39
16	21	1000	34.52
16	19	1000	42.55
16	17	600	28.41
17	27	500	39.61
17	18	600	27.48
19	20	500	34.91
21	22	1200	35.18
22	23	500	29.32
23	24	1200	63.17
25	26	600	59.7
26	29	1100	100
26	28	1100	79.83
26	27	1100	36.17
28	29	1100	36.7
39	1	500	49.81
39	9	600	49.81

Appendix D: Percentage Change in Impedance

	Modulus/ Absolute of the Impedance for each phase:														
	line5-6			**line6-7**			**line13-14**			**line5-8**			**line7-8**		
	Zaa	**Zbb**	**Zcc**	**Zaa**	**Zbb**	**Zcc**	**Zaa**	**Zbb**	**Zcc**	**Zaa**	**Zbb**	**Zcc**	**Zaa**	**Zbb**	**Zcc**
No DSR	25.7	25.6	25.3	37.1	36.8	36.5	38.6	38.4	38	40.5	40.3	39.9	29.2	29	28.7
110%	43.1	42.9	42.6	59.5	59.3	58.9	38.6	38.4	38	60.2	59.9	59.4	29.2	29	28.7
121%	28.1	27.9	27.7	37.1	36.8	36.5	62.5	62.3	61.8	40.5	40.3	39.9	29.2	29	28.7
135%	37	36.8	36.5	37.1	36.8	36.5	55.5	55.2	54.8	40.5	40.3	39.9	29.2	29	28.7
140%	35.1	34.9	34.7	37.1	36.8	36.5	39.1	38.9	38.5	40.5	40.3	39.9	29.2	29	28.7
145%	38.9	38.7	38.4	37.1	36.8	36.5	43.3	43.1	42.7	40.5	40.3	39.9	29.2	29	28.7
149%	42.1	42	41.7	39.4	39.2	38.8	46.6	46.3	45.9	40.5	40.3	39.9	30.6	30.4	30.1

	Maximum % of change of Impedance:														
	line5-6			**line6-7**			**line13-14**			**line5-8**			**line7-8**		
	Zaa	**Zbb**	**Zcc**	**Zaa**	**Zbb**	**Zcc**	**Zaa**	**Zbb**	**Zcc**	**Zaa**	**Zbb**	**Zcc**	**Zaa**	**Zbb**	**Zcc**
110%	67.3	67.7	68.3	60.6	61	61.5	0	0	0	48.5	48.7	48.9	0	0	0
121%	9.07	9.11	9.18	0	0	0	61.8	62.1	62.7	0	0	0	0	0	0
135%	43.6	43.9	44.2	0	0	0	43.6	43.8	44.2	0	0	0	0	0	0
140%	36.3	36.5	36.8	0	0	0	1.21	1.21	1.22	0	0	0	0	0	0
145%	50.9	51.2	51.6	0	0	0	12.1	12.1	12.2	0	0	0	0	0	0
149%	63.7	64	64.6	6.3	6.33	6.38	20.6	20.7	20.8	0	0	0	4.8	4.82	4.86
Phase C is the one that has the max % change for all lines															

	Average % of change of Impedance:				
	Line 5-6	**Line 6-7**	**Line 13-14**	**Line 5-8**	**Line 7-8**
110%	67.75	61	0	48.7	0
121%	9.121	0	62.21	0	0
135%	43.9	0	43.87	0	0
140%	36.56	0	1.214	0	0
145%	51.23	0	12.16	0	0
149%	64.08	6.33	20.68	0	4.83

Appendix E: Number of DSRs deployed on each line for each load percentage for N-1 Contingency and Load Growth

100% Base Load:

Line(s) Failed	**No. of DSR turned on lines**			**Overloads removed**			
	Line 5-6	**Line 6-7**	**Line 13-14**	**Line**	**%Before**	**%After**	**% Total OL removed**
Line 07-06	1650			Line 06-05	113.76	99.89	13.76
Line 08-05		375		Line 07-06	101.21	99.87	1.21

110% Load Growth:

Line(s) Failed	**No. of DSR turned on lines**				**Overloads removed**			
	Line 5-6	**Line 6-7**	**Line 13-14**	**Total**	**Line**	**%Before**	**%After**	**% Total OL removed**
Line 06-05		1800			Line 07-06	110.1	99.66	10.1
Line 07-06	2775			5925	Line 06-05	126.55	109.86	35.95
		3150 on line5-8			Line 08-05	109.4	99.05	
Line 08-05		3600			Line 07-06	110.73	99.93	10.73

120% Line6-7 Reinforced:

Line(s) Failed	**No. of DSR turned on lines**			**Overloads removed**			
	Line 5-6	**Line 6-7**	**Line 13-14**	**Line**	**%Before**	**%After**	**% Total OL removed**
Line 08-07	225			Line 06-05	101.83	99.93	1.83
Line 16-15			2850	Line 14-13	112.9	99.99	12.9

121% Line6-7 Reinforced:

Line(s) Failed	No. of DSR turned on lines			Overloads removed			
	Line 5-6	Line 6-7	Line 13-14	Line	%Before	%After	% Total OL removed
Line 08-05	375			Line 06-05	102.72	99.55	2.72

122% Line6-7 and Line15-16 Reinforced:

Line(s) Failed	No. of DSR turned on lines			Overloads removed			
	Line 5-6	Line 6-7	Line 13-14	Line	%Before	%After	% Total OL removed
Line 08-07	300			Line 06-05	102.37	99.82	2.37

130% Line6-7 and Line15-16 Reinforced:

Line(s) Failed	No. of DSR turned on lines			Overloads removed			
	Line 5-6	Line 6-7	Line 13-14	Line	%Before	%After	% Total OL removed
Line 03-02	300		600	Line 14-13	102.68	99.59	4.39
				Line 06-05	101.71	99.5	
Line 08-07	1200			Line 06-05	109.58	99.6	9.58

135% Line6-7 and Line15-16 Reinforced:

Line(s) Failed	No. of DSR turned on lines				Overloads removed			
	Line 5-6	Line 6-7	Line 13-14	Total	Line	%Before	%After	% Total OL removed
Line 03-02	1575		2700	4275	Line 14-13	110.67	99.69	20.44
					Line 06-05	109.77	99.52	
Line 05-04			150		Line 14-13	100.86	99.98	0.86
Line 08-07	1800				Line 06-05	114.39	99.65	14.39
Line 11-06			375		Line 14-13	102.05	99.71	2.05

Line 14-04	225				Line 06-05	102.46	99.82	2.46
Line 19-16			375		Line 14-13	102.5	99.82	2.5

136% Line6-7 and Line15-16 and Line2-3

Line(s) Failed	**No. of DSR turned on lines**			**Overloads removed**			
	Line 5-6	**Line 6-7**	**Line 13-14**	**Line**	**%Before**	**%After**	**% Total OL removed**
Line 08-07	1050			Line 06-05	108.74	99.87	8.74

140% Line6-7 and Line15-16 and Line2-3

Line(s) Failed	**No. of DSR turned on lines**				**Overloads removed**			
	Line 5-6	**Line 6-7**	**Line 13-14**	**Total**	**Line**	**%Before**	**%After**	**% Total OL removed**
Line 08-07	1500				Line 06-05	112.32	99.8	12.32
Line 11-06			75		Line 14-13	100.36	99.88	0.36

145% Line6-7 and Line15-16 and Line2-3

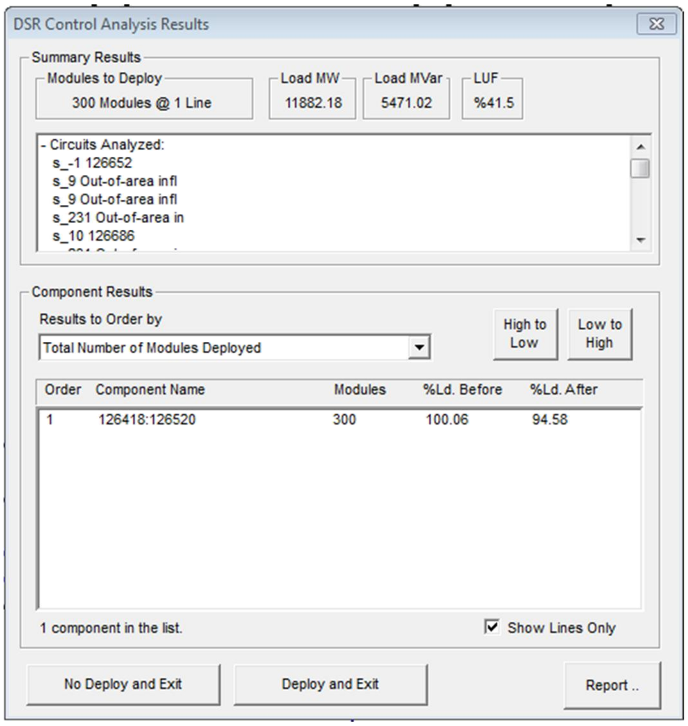
Line(s) Failed	**No. of DSR turned on lines**			**Overloads removed**			
	Line 5-6	**Line 6-7**	**Line 13-14**	**Line**	**%Before**	**%After**	**% Total OL removed**
Line 08-07	2100			Line 06-05	117.01	99.81	17.01
Line 11-06			750	Line 14-13	104.47	99.71	4.47
Line 14-04	75			Line 06-05	100.78	99.89	0.78
Line 19-16			600	Line 14-13	104.27	99.94	4.27
Line 22-21			300	Line 14-13	102.03	99.85	2.03

149% Line6-7 and Line15-16 and Line2-3

Line(s) Failed	**No. of DSR turned on lines**			**Overloads removed**			
	Line 5-6	**Line 6-7**	**Line 13-14**	**Line**	**%Before**	**%After**	**% Total OL removed**
Line 04-03	225			Line 06-05	102.34	99.72	2.34
Line 05-04			525	Line 14-13	102.83	99.56	2.83
Line 06-05			375	Line 14-13	101.71	99.52	2.6
		225 on line7-8		Line 08-07	100.89	99.95	
Line 07-06 (1&2)		375		Line 6-7(2)	102.79	99.71	2.79
		375		Line 6-7(1)	102.79	99.71	2.79
Line 08-07	2625			Line 06-05	120.98	99.89	20.98
Line 11-06			1275	Line 14-13	107.88	99.77	7.88
Line 14-04	375			Line 06-05	104.35	99.91	4.35
Line 14-13	225			Line 06-05	102.44	99.62	2.44
Line 19-16			1275	Line 14-13	108.76	99.68	8.76
Line 22-21			975	Line 14-13	106.63	99.65	6.63

Appendix F: Area Control Design Results Snapshots

5 % Load Growth:



Modules to Deploy: 300 Modules @ 1 Line

Load MW: 11882.18

Load MVar: 5471.02

LUF: %41.5

- Circuits Analyzed:
  s_-1 126652
  s_9 Out-of-area infl
  s_9 Out-of-area infl
  s_231 Out-of-area in
  s_10 126686

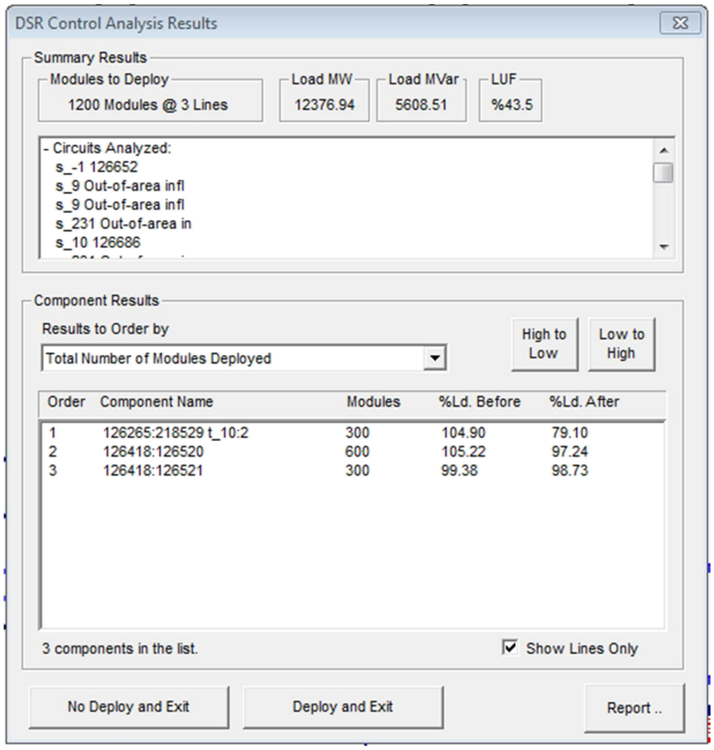
Results to Order by: Total Number of Modules Deployed

Order	Component Name	Modules	%Ld. Before	%Ld. After
1	126418:126520	300	100.06	94.58

1 component in the list.

☑ Show Lines Only

10% Load Growth:



Modules to Deploy: 1200 Modules @ 3 Lines

Load MW: 12376.94

Load MVar: 5608.51

LUF: %43.5

- Circuits Analyzed:
  s_-1 126652
  s_9 Out-of-area infl
  s_9 Out-of-area infl
  s_231 Out-of-area in
  s_10 126686

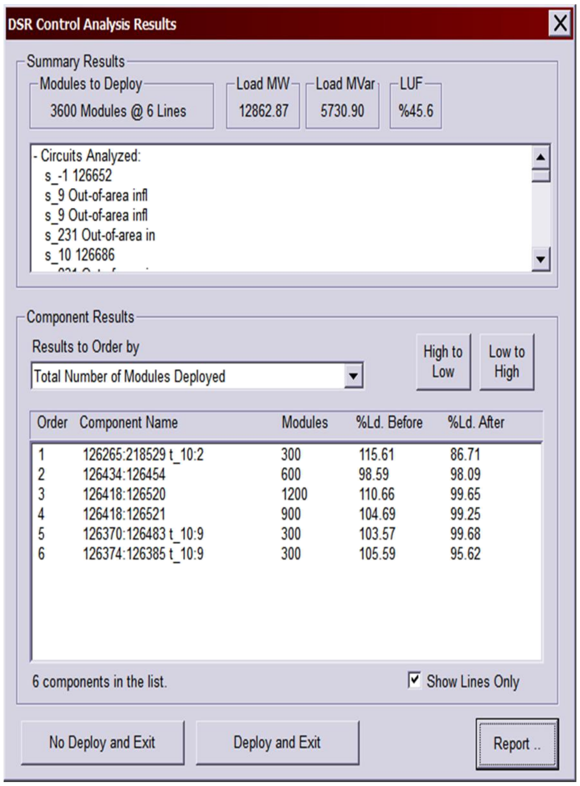
Results to Order by: Total Number of Modules Deployed

Order	Component Name	Modules	%Ld. Before	%Ld. After
1	126265:218529 t_10:2	300	104.90	79.10
2	126418:126520	600	105.22	97.24
3	126418:126521	300	99.38	98.73

3 components in the list.

☑ Show Lines Only

15 % Load Growth:



Modules to Deploy	Load MW	Load MVar	LUF
3600 Modules @ 6 Lines	12862.87	5730.90	%45.6

- Circuits Analyzed:
  s_-1 126652
  s_9 Out-of-area infl
  s_9 Out-of-area infl
  s_231 Out-of-area in
  s_10 126686

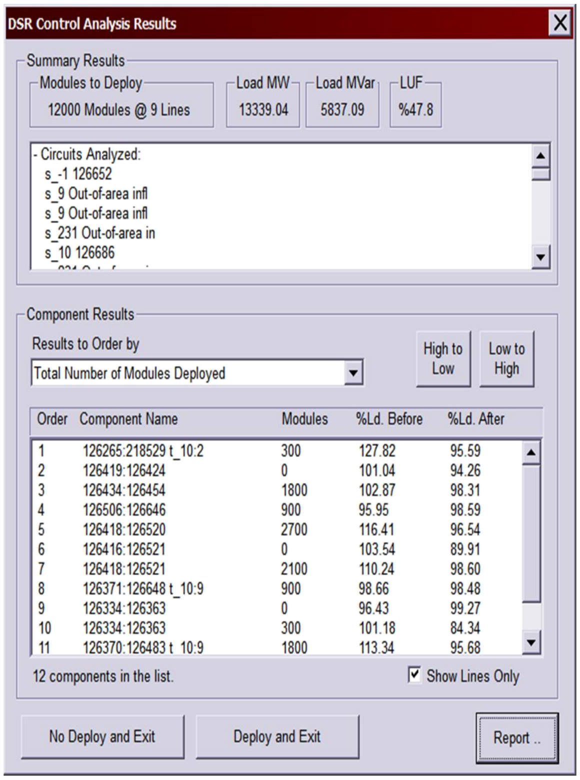
Results to Order by: Total Number of Modules Deployed

Order	Component Name	Modules	%Ld. Before	%Ld. After
1	126265:218529 t_10:2	300	115.61	86.71
2	126434:126454	600	98.59	98.09
3	126418:126520	1200	110.66	99.65
4	126418:126521	900	104.69	99.25
5	126370:126483 t_10:9	300	103.57	99.68
6	126374:126385 t_10:9	300	105.59	95.62

6 components in the list.

☑ Show Lines Only

20 % Load Growth:



Modules to Deploy	Load MW	Load MVar	LUF
12000 Modules @ 9 Lines	13339.04	5837.09	%47.8

- Circuits Analyzed:
  s_-1 126652
  s_9 Out-of-area infl
  s_9 Out-of-area infl
  s_231 Out-of-area in
  s_10 126686

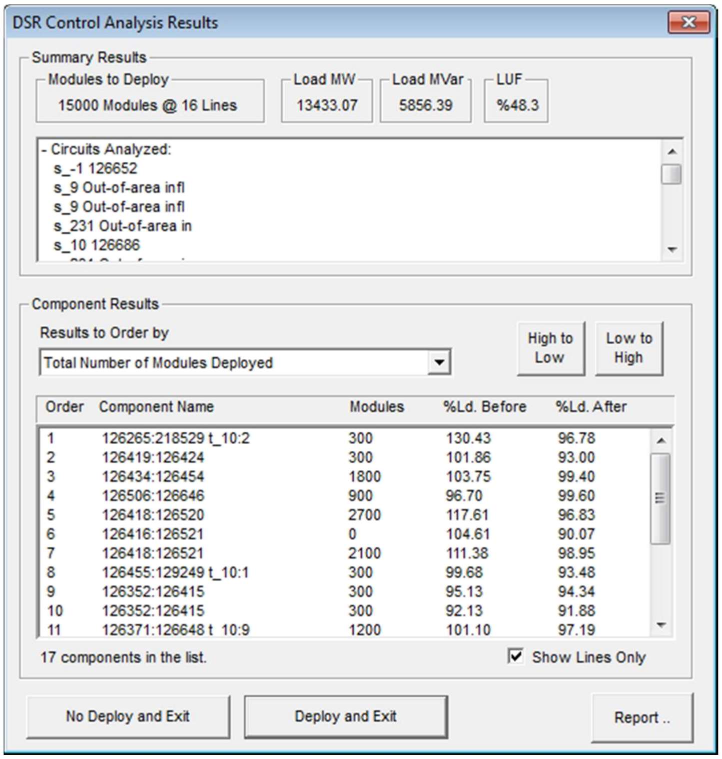
Results to Order by: Total Number of Modules Deployed

Order	Component Name	Modules	%Ld. Before	%Ld. After
1	126265:218529 t_10:2	300	127.82	95.59
2	126419:126424	0	101.04	94.26
3	126434:126454	1800	102.87	98.31
4	126506:126646	900	95.95	98.59
5	126418:126520	2700	116.41	96.54
6	126416:126521	0	103.54	89.91
7	126418:126521	2100	110.24	98.60
8	126371:126648 t_10:9	900	98.66	98.48
9	126334:126363	0	96.43	99.27
10	126334:126363	300	101.18	84.34
11	126370:126483 t 10:9	1800	113.34	95.68

12 components in the list.

☑ Show Lines Only

21 % Load Growth:



Summary Results

Modules to Deploy	Load MW	Load MVar	LUF
15000 Modules @ 16 Lines	13433.07	5856.39	%48.3

- Circuits Analyzed:
  - s_-1 126652
  - s_9 Out-of-area infl
  - s_9 Out-of-area infl
  - s_231 Out-of-area in
  - s_10 126686

Component Results

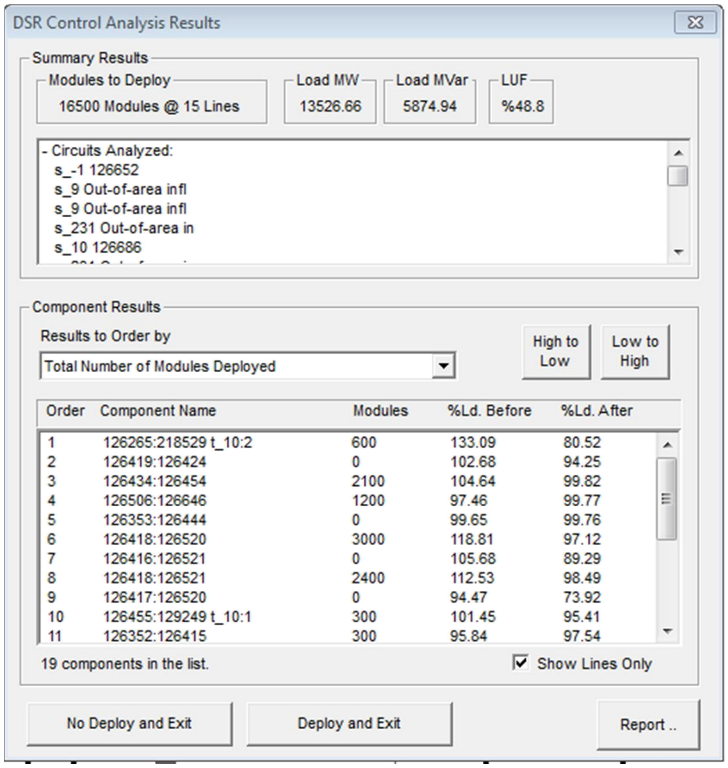
Results to Order by: Total Number of Modules Deployed

Order	Component Name	Modules	%Ld. Before	%Ld. After
1	126265:218529 t_10:2	300	130.43	96.78
2	126419:126424	300	101.86	93.00
3	126434:126454	1800	103.75	99.40
4	126506:126646	900	96.70	99.60
5	126418:126520	2700	117.61	96.83
6	126416:126521	0	104.61	90.07
7	126418:126521	2100	111.38	98.95
8	126455:129249 t_10:1	300	99.68	93.48
9	126352:126415	300	95.13	94.34
10	126352:126415	300	92.13	91.88
11	126371:126648 t_10:9	1200	101.10	97.19

17 components in the list.

☑ Show Lines Only

22 % Load Growth:



Summary Results

Modules to Deploy	Load MW	Load MVar	LUF
16500 Modules @ 15 Lines	13526.66	5874.94	%48.8

- Circuits Analyzed:
  - s_-1 126652
  - s_9 Out-of-area infl
  - s_9 Out-of-area infl
  - s_231 Out-of-area in
  - s_10 126686

Component Results

Results to Order by: Total Number of Modules Deployed

Order	Component Name	Modules	%Ld. Before	%Ld. After
1	126265:218529 t_10:2	600	133.09	80.52
2	126419:126424	0	102.68	94.25
3	126434:126454	2100	104.64	99.82
4	126506:126646	1200	97.46	99.77
5	126353:126444	0	99.65	99.76
6	126418:126520	3000	118.81	97.12
7	126416:126521	0	105.68	89.29
8	126418:126521	2400	112.53	98.49
9	126417:126520	0	94.47	73.92
10	126455:129249 t_10:1	300	101.45	95.41
11	126352:126415	300	95.84	97.54

19 components in the list.

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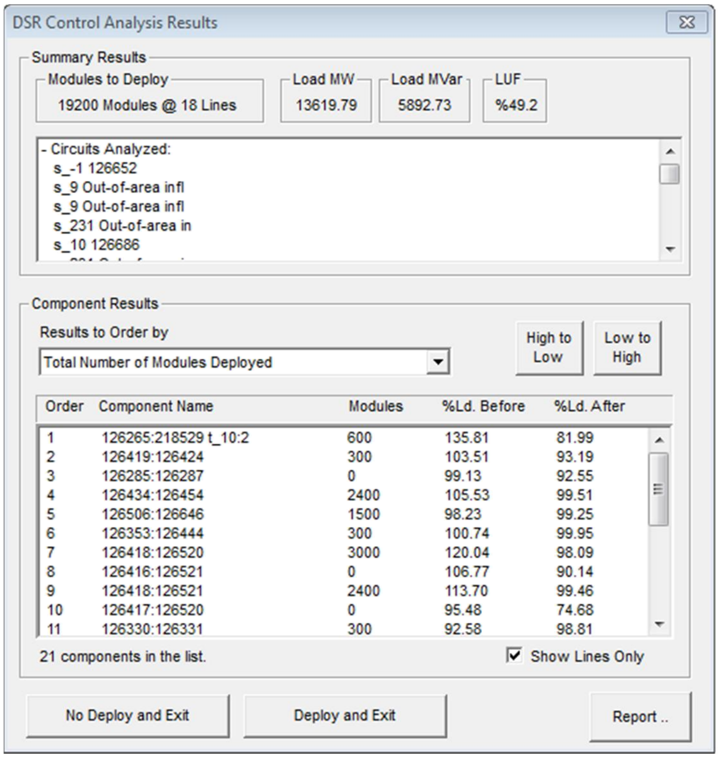
23 % Load Growth:



Modules to Deploy: 19200 Modules @ 18 Lines
Load MW: 13619.79
Load MVar: 5892.73
LUF: %49.2

- Circuits Analyzed:
  s_-1 126652
  s_9 Out-of-area infl
  s_9 Out-of-area infl
  s_231 Out-of-area in
  s_10 126686

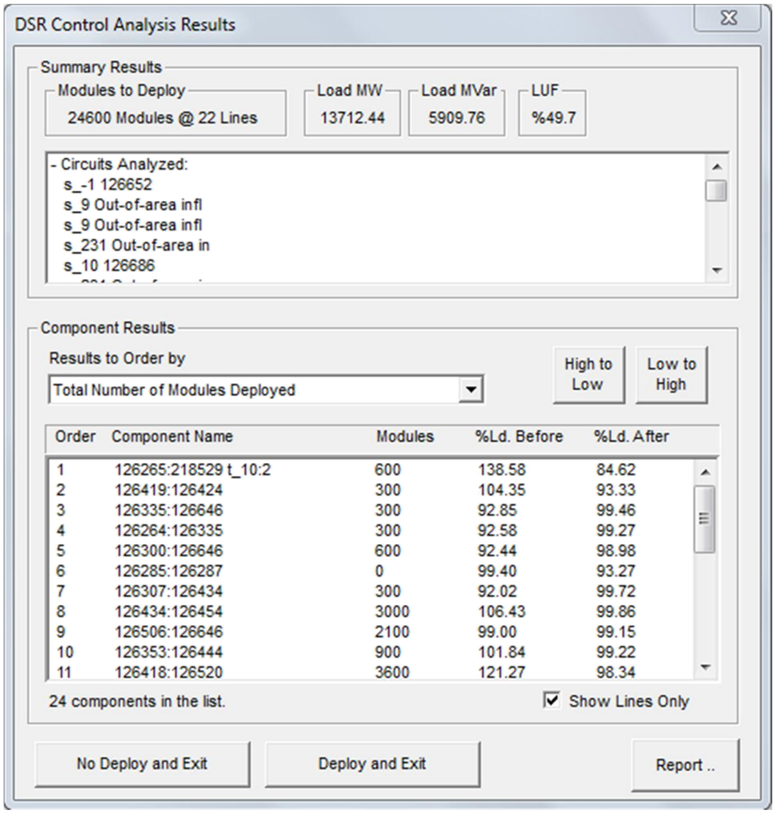
Results to Order by: Total Number of Modules Deployed

Order	Component Name	Modules	%Ld. Before	%Ld. After
1	126265:218529 t_10:2	600	135.81	81.99
2	126419:126424	300	103.51	93.19
3	126285:126287	0	99.13	92.55
4	126434:126454	2400	105.53	99.51
5	126506:126646	1500	98.23	99.25
6	126353:126444	300	100.74	99.95
7	126418:126520	3000	120.04	98.09
8	126416:126521	0	106.77	90.14
9	126418:126521	2400	113.70	99.46
10	126417:126520	0	95.48	74.68
11	126330:126331	300	92.58	98.81

21 components in the list.

☑ Show Lines Only

24 % Load Growth:



Modules to Deploy: 24600 Modules @ 22 Lines
Load MW: 13712.44
Load MVar: 5909.76
LUF: %49.7

- Circuits Analyzed:
  s_-1 126652
  s_9 Out-of-area infl
  s_9 Out-of-area infl
  s_231 Out-of-area in
  s_10 126686

Results to Order by: Total Number of Modules Deployed

Order	Component Name	Modules	%Ld. Before	%Ld. After
1	126265:218529 t_10:2	600	138.58	84.62
2	126419:126424	300	104.35	93.33
3	126335:126646	300	92.85	99.46
4	126264:126335	300	92.58	99.27
5	126300:126646	600	92.44	98.98
6	126285:126287	0	99.40	93.27
7	126307:126434	300	92.02	99.72
8	126434:126454	3000	106.43	99.86
9	126506:126646	2100	99.00	99.15
10	126353:126444	900	101.84	99.22
11	126418:126520	3600	121.27	98.34

24 components in the list.

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