Control of Power Flow in Transmission Lines using Distributed Series Reactors

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Abstract

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

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Chapter 1: Introduction and Literature Review

The energy demand of the world is increasing continuously with increased industrialization and modernization of cities and towns. As a result more power has to be transferred from generating sites to load sites. As the demand for power increases, the generation and transmission networks have to be augmented to meet future energy requirements [1]. As can be seen from figure 1.1(a) and figure 1.2, Transmission networks constitute a significant component in the cost of supplied electrical energy. Furthermore, figure 1.1(b) shows that new transmission capacity supports significant amounts of renewable energy sources in the grid. However, the growth in the transmission networks is much slower and acts as a bottleneck when compared to the generation growth. Transmission networks take a much longer time to plan and construct as compared to generation units [2]. This could potentially lead to a major roadblock in the supply of electricity in the future. The Recent Department of Energy (DOE) report highlights the problem of congestion in Transmission lines near major metropolitan centers [3]. Transmission networks face much more public opposition and as a result take longer to get approvals and land for the construction of new lines [4]. Acronyms such as NIMBY (Not In My Backyard) and BANANA (Build Absolutely Nothing Anywhere Near Anyone) have become popular .As the load continues to increase, it is possible that the transmission network may not be able to keep up with the increase in demand, and thus there is a need to invest in means of increasing existing transmission capacity.

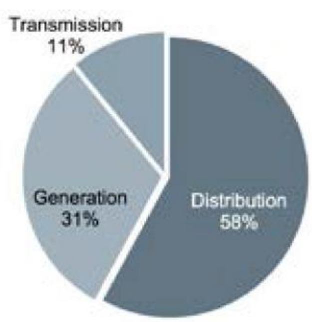

Figure 1.1 Cost of Transmission networks in Power supply. Edison Electric Institute, Transmission Projects: At a Glance, Edison Electric Institute, March 2014. Used under fair use, 2015.

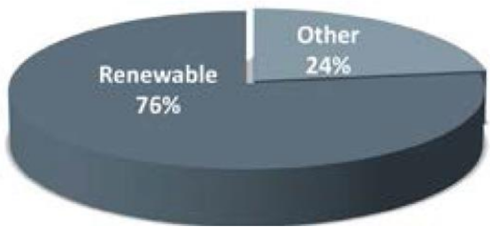

Figure 1.2 Portion of new transmission projects supporting renewable energy. Edison Electric Institute, Transmission Projects: At a Glance, Edison Electric Institute, March 2014. Used under fair use, 2015

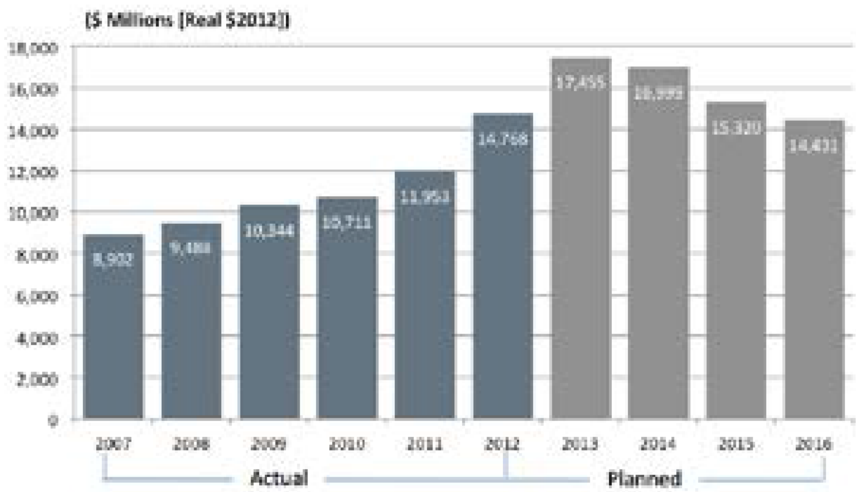

Figure 1.3 Transmission system past and future investments. Edison Electric Institute, Transmission Projects: At a Glance, Edison Electric Institute, March 2014. Used under fair use, 2015.

A good amount of literature exists on increasing transmission capacity of lines [5,6,7,8], especially advancements that have been made in the field of Flexible AC Transmission Systems (FACTS) [9,10,11,12]. FACTS devices can be used in the transmission network for a variety of purposes, like increasing power flow, improving voltage imbalance, power factor correction, protection and others. One interesting application of FACTS devices is that they can be used to change the reactance of the transmission lines [13,14]. As the real power transmitted over a balanced transmission line is approximately given by[15]:

$$P = \frac{V_s V_R}{X} \sin \delta \qquad (1.1)$$

,where P is the real power, V_s and V_R are the sending end and receiving end voltages, respectively, X is the reactance of the line, and δ is the phase angle between the sending end and the receiving end voltages.

From equation (1.1) it may be seen that it is possible to increase the real power transmitted over the line by four ways:

1) Increasing the Transmission voltage: This is the most common method of increasing the transmission capacity of the lines. In order to transmit more power over a line the voltage may be increased. However there is a limitation to this method after a certain voltage value. At higher operating voltages, the insulation costs increase dramatically [4]. Hence voltage can only be increased so far.

2) Increasing the Phase angle: Increasing the phase angle can increase the power flow to a certain extent. But the maximum power flow that can be achieved is at $\boldsymbol{\delta}$=90°. However, the stable operation of the power system usually limits this angle to a much lower value.

3) Reducing the Reactance of the line: Reducing the reactance of the line can help in transmitting more power over the line [15]. The reduction in reactance is achieved by adding capacitors to the transmission line. The addition of capacitors reduces the overall reactance of the transmission line and allows more power to be transmitted over the line. However this can lead to transmission lines operating beyond their thermal limit. Furthermore adding capacitors to the line introduces many problems [14].

4) Increasing the reactance of the line: The addition of reactance to the transmission line will reduce its transmission capacity. Even though this method might seem to be counterintuitive at first, as increasing the reactance would reduce the power flow through that line, in a meshed transmission network having many different lines at different voltages operating in parallel, this method can shift the power flow from overloaded lines to more lightly loaded lines. This technique will be discussed in more detail in the remainder of this work.

A practical transmission system consists of many lines at different voltages connected in parallel [16]. As energy requirements have grown over many decades, higher level voltage transmission systems have been built on top of and in parallel with older, lower voltage transmission systems. In this meshed network if one transmission line becomes overloaded, the operation of the entire system becomes limited. One solution to the overload is to add a line in parallel to the overloaded line in order to transmit more power over the network. However, with such a solution there is often still significant transmission capacity available on other parallel paths which remains unutilized.

With multiple transmission system voltages operating in parallel, usually the low voltage lines become overloaded first, and the high voltage lines are left with unused transmission capacity [16]. In order to increase the transmission capacity of the network, it is required to shift the power flow by some mechanism from the low voltage, overloaded lines to the high voltage, lightly loaded lines. Distributed series reactors provide a mechanism for transferring power flow from overloaded lines to lightly loaded lines.

Distributed Series Reactors (DSRs) are a new Distributed FACTS technology (d-FACTS) that consist of an inductor that can be coupled to the transmission line and which provides reactive power to the line [17,18]. A detailed discussion about the structure and mechanism of DSR operation can be found in [19,20]. Figure 1.3 shows a picture of a DSR connected to a transmission line. By activating DSRs on a particular transmission line the reactance of the transmission line is increased. As the reactance of the line increases, the power flow over the line reduces and the flow finds an alternate parallel route. This forms the basis of power flow transfer from overloaded lines to lightly loaded lines in a transmission network using DSRs. Adding DSRs to the transmission lines increases the reactance of the diagonal elements of the impedance matrix shown in equation (1.2). A circuit schematic of a simple inverter-less DSR [20] is shown in figure 1.4. The DSR is coupled to the transmission line through a transformer and depending upon the operation of the switch S_M either a negligible leakage inductance is coupled to the line or a large magnetizing inductance is coupled to the line. Each DSR adds about 50µH of magnetizing inductance or about 1.885 mΩs of reactance to the self-impedance matrix of the transmission line when the DSR is turned on by opening the switch S_M. The DSR is inbuilt with a power supply for the control circuitry and protection switches S_1 to protect the device during short-circuit and other abnormal system conditions. Depending upon the control methodology, DSRs can also include a current sensor and communications receiver for coordination with the transmission system operator. Initial field trials of DSRs have shown a lot of promise [21].

$$Z_{line} = \begin{pmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{pmatrix} \tag{1.2}$$

The rest of the thesis is organized as follows. Chapter 2 explains the mechanism of DSR operation by a two line example. Chapter 3 introduces the IEEE 39 bus system used in the study. Chapter 4 discusses the operation of DSRs in symmetrical and unsymmetrical fashion in order to increase the power flow. In Chapter 5 the economic evaluation of different DSR operation schemes is presented. Chapter 6 gives a comparison of the sequence voltages and power flows between the different DSR operation techniques. Chapter 7 analyzes the application of DSRs to reduce voltage imbalance in the transmission network. Finally Chapter 8 gives the conclusions and underlines the future scope of work.

Figure 1.4 DSR connected to a Transmission line. http://www.smartwires.com. Used under fair use, 2015.

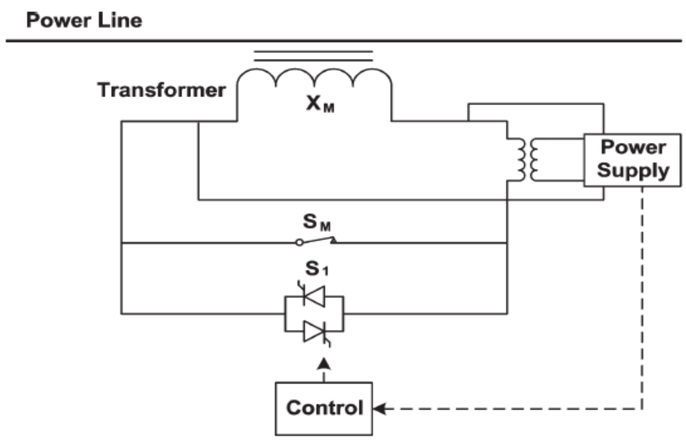

Figure 1.5 Circuit Schematic of an inverter-less DSR [20]

Chapter 2: Power Flow over Two Parallel Lines

The phenomenon of transferring power flow from overloaded lines to lightly loaded lines can be better understood by considering the two line example shown in Figure 2.1. In Figure 2.1 there are two transmission lines, operating at 230 kV and 345 kV, connected in parallel and supplying power from a generating station to a load. At any given load level, the 230 kV line will be carrying more power per its unit capacity than the 345 kV line. This results from the basic power flow relation given in equation (1.1). The parameters of the 230 kV line and 345 kV line at the full load level are shown in tables 2.2 and 2.3, respectively.

In this study 3-phase models of the transmission lines are used [16]. In [16] it has been shown that using the unbalanced 3-phase model for a transmission line gives much better results as far as DSR allocation is concerned. In practice most transmission lines are not transposed, and thus the need to use the unbalanced, 3-phase model to obtain more accurate design results. Figure 2.2 shows the phase spacing of the 500kV, 345 kV and 230 kV transmission lines used in the study here. Table 2.1 presents the impedance matrices of the 230 kV and 345 kV lines in ohms.

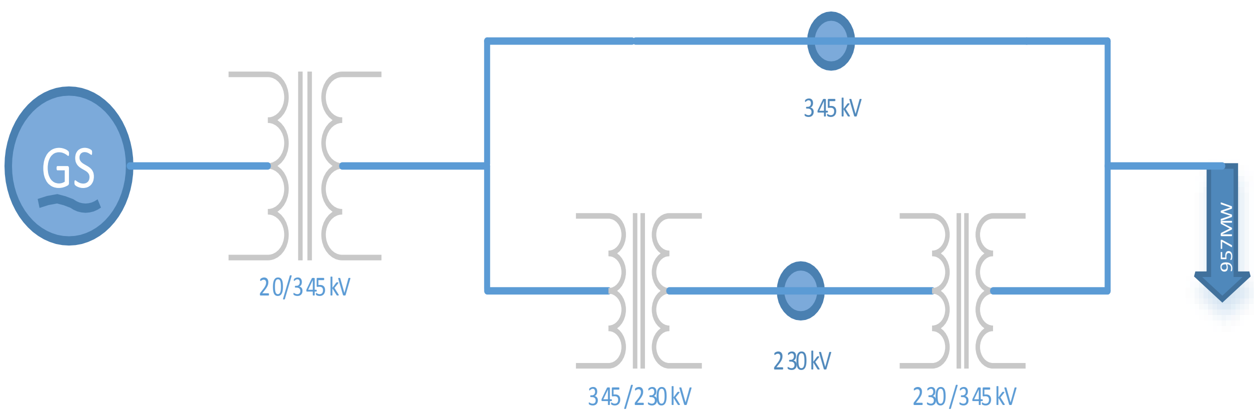

Figure 2.1 Two line system having a 230 kV line in parallel with a 345 kV line

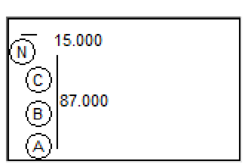

Figure 2.2 500 kV line phase spacing

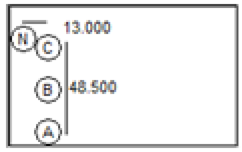

Figure 2.3 345 kV line phase spacing

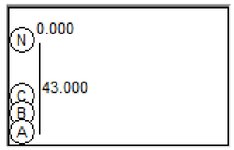

Figure 2.4 230 kV line phase spacing

230 kV line 345 kV line

Table 2.1 3-phase impedance matrices for Line1, 230 kV line, and Line 2, 345 kV line

Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
6.56+j46.4 Ω	4.93+j23.4 Ω	5.04+j20.56 Ω	6.44+j46.53 Ω	4.92+j19.52 Ω	5.22+j16.15 Ω
	6.75+j46.2 Ω	5.15+j23.8 Ω		6.87+j46.1 Ω	5.49+j18.98 Ω
		6.98+j46 Ω			7.6+j45.4 Ω

From tables 2.2 and 2.3 it can be seen that, for the given load shown in Figure 2.2, the 230 kV line has less transmission capacity left than the 345 kV line at full load. If the load is further increased, the 230 kV line will eventually overload.

The parameters of the two lines at 107% load level are shown in tables 2.4 and 2.5. From table 2.4 it can be seen that Phase A of the 230 kV line is overloaded. But from table 2.5 it can be seen that there is still significant transmission capacity available on the 345 kV line and even on phases B and C of the 230 kV line itself. This leads to a significant unutilized transmission capacity. Figure 2.3 shows the total remaining capacity on each line as the load is grown from 100% to 107%. Considering phases B and C of the 230 kV line, the unutilized capacity of the 230 kV line is given by equation (2.1)

Capacity remaining on 230kV line=(3.4%+2.7%)of 124MW=7.5MW. (2.1)

The unutilized capacity of the 345 kV line is given by

Capacity remaining on 345kV line=(13.6%+18.8%+18.5%) of 279MW=142MW (2.2)

Thus, from equations (2.1) and (2.2), the total unutilized capacity of the two lines is given by

Total Unused Capacity=142+7.5=149.5MW (2.3)

Table 2.2 Parameters of 230 kV line at 100% load (957 MW)

Phase(A,B or C)	Phase Voltage(kV)	Current(A)	Power Flow(kW)	% capacity remaining
Phase A	122.5	862.2	111265	7.6%
Phase B	128.9	840.1	109530	10%
Phase C	129.4	845.4	109510	9.4%

Table2.3 Parameters of 345 kV line at 100% load (957 MW)

Phase(A,B or C)	Phase Voltage(kV)	Current(A)	Power Flow(kW)	% capacity remaining
Phase A	183.9	1116.3	215037	20.3%
Phase B	193.4	1059.1	206016	24.4%
Phase C	194.1	1063.1	207168	24.1%

Table 2.4 Parameters of 230 kV line at 107% load

Phase(A,B or C)	Phase Voltage(kV)	Current(A)	Power Flow(kW)	% capacity remaining
Phase A	121.1	933.4	119624	0%
Phase B	128.5	901.4	116977	3.4%
Phase C	128.9	907.8	117060	2.7%

Table 2.5 Parameters of 345 kV line at 107% load

Phase(A,B or C)	Phase Voltage(kV)	Current(A)	Power Flow(kW)	% capacity remaining
Phase A	181.7	1209.1	231183	13.6%
Phase B	192.7	1136.5	219963	18.8%
Phase C	193.3	1141	221360	18.5%

If the power flow could be shifted from the overloaded phase(s) to the phase(s) with unused capacity, an overall increase in the transmission capacity of the network would ensue. This would delay, or in some cases eliminate, the construction of new transmission lines.

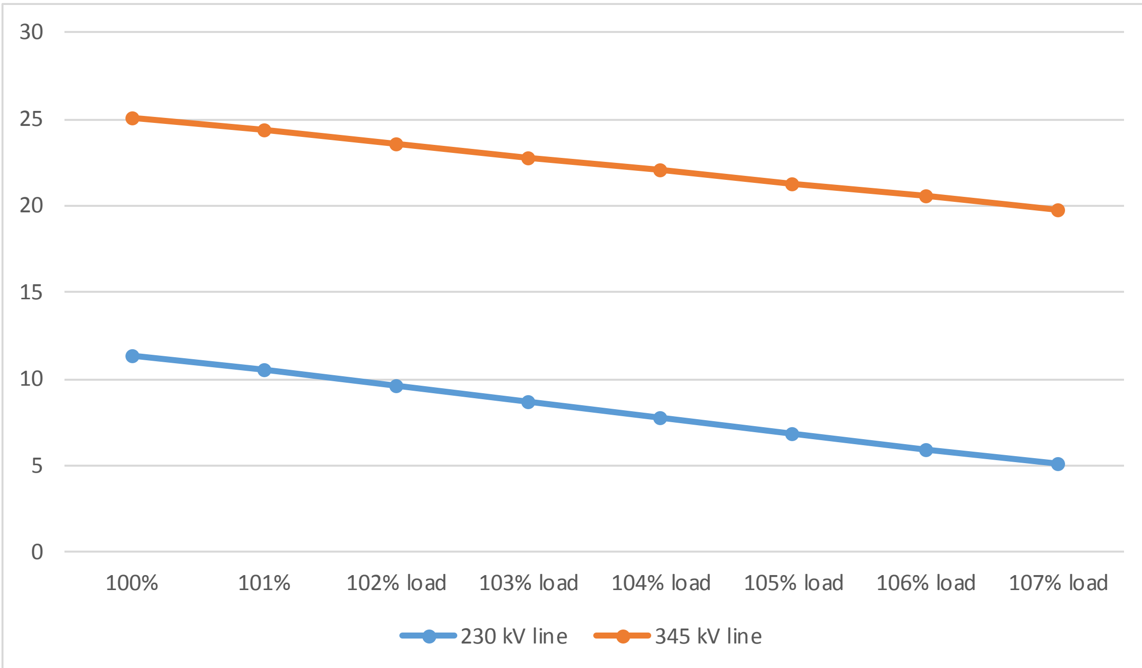

Figure 2.5 Percentage capacity remaining on two parallel line system with load increase

Chapter 3: Description of the Test System used in Study

In this study the IEEE 39 bus, 3-phase, unbalanced model which originally had only 345 kV lines, is further modified to have 230 kV, 345kV and 500kV lines running in parallel. The modified 39 bus model is shown in Figure 3.1. In the figure parallel lines that have been added to the model are illustrated by showing 230kV lines in brown, 500kV lines in red, and 345kV lines in blue.

Line 1 shown in Figure 1 is a 230 kV line. Line 1 is in parallel with Line 2, which is a 345kV line. Line 3 is again a 345 kV line and is in parallel with Line 4 which is a 500 kV line shown in red. The construction used for lines 1, 2 and 4 is shown in Figure 2.2. An ACSR conductor with a 1.737 inch diameter and stranding as 84/19 is used [22]. Each phase has a bundled conductor having two ACSR conductors. The lines are each 50 miles long. The 3-phase impedance matrices used for the lines are shown in Table 2.1.

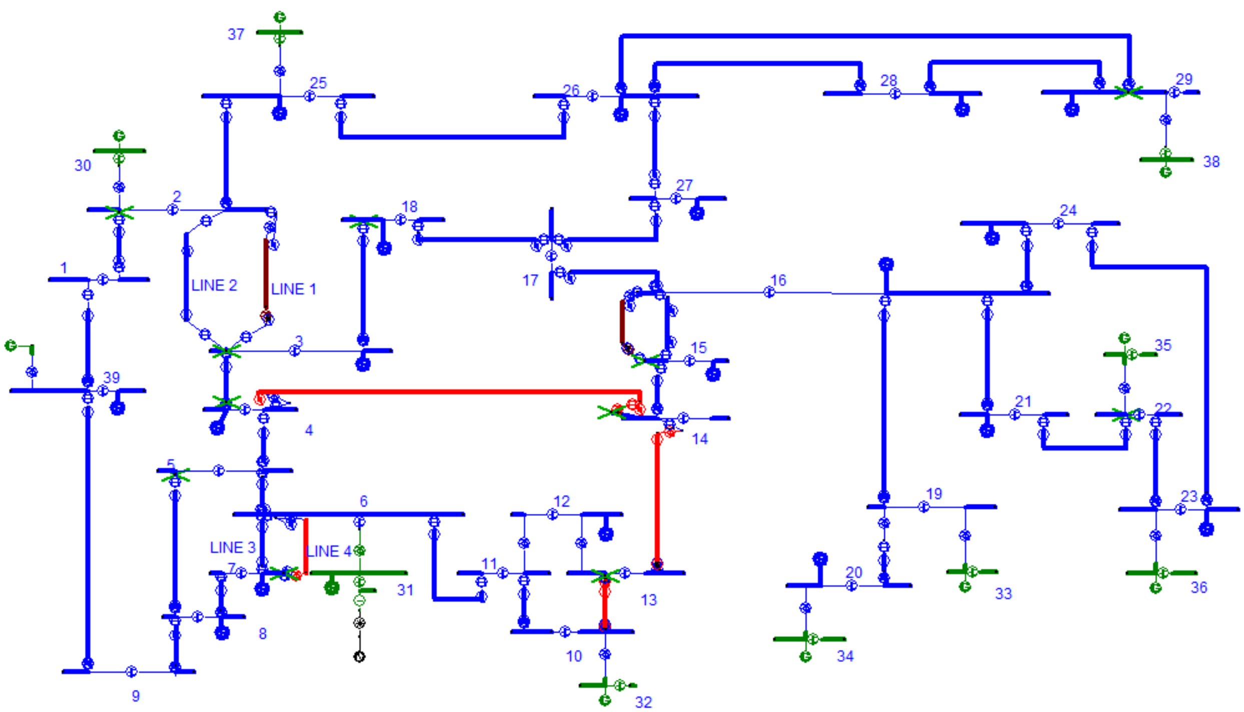

Figure 3.1 IEEE 39 bus model modified to 3-phase, unbalanced transmission model: 500kV lines shown in red, 345 kV lines shown in blue, and 230 kV lines shown in brown

Chapter 4: Case Study 1: Operation of Unbalanced, Parallel Lines to Increase Power flow.

In this case study lines 1 and 2 shown in Figure 3.1 are considered. The flow path created by lines 1 and 2 together will be referred to as flow path 1, or Path 1 for short. Three cases are evaluated for Path 1, where the maximum power that can be transferred for each case is determined. The cases are: 1) No DSRs are used; 2) DSRs are operated in a symmetrical fashion; 3) DSRs are operated in an unsymmetrical fashion in an attempt to better utilize the capacity of each phase in the 230 kV line.

As we increase the load in the system, the 230 kV line overloads first while there is still significant transmission capacity available on the 345 kV line. Normally this 345kV transmission capacity would be unused because of creating the overload on the 230 kV line if it was used, but DSRs can be operated on the 230 kV line, pushing power to the 345 kV line, and thus using more of the capacity of Path 1. The addition of DSRs to the 230 kV line increases its reactance. By increasing the reactance of the 230 kV line power is pushed from the 230 kV line to the parallel 345kV line.

4.1 CASE 1: No DSRs used:

In the first case the load is uniformly increased to 157% of the base load and the parameters of the 230 kV and 345kV lines are measured. As can be seen from tables 4.3 and 4.4, the 230 kV line is overloaded while there is still significant unused transmission capacity on the 345 kV line.

At first the load is increased to the point just before the 230 kV line is overloaded. For this the load is increased to 149% and this operating point would determine the maximum amount of power that can be transferred over the two parallel lines without the aid of DSRs. The results of increasing the load to 149% on 230 kV and 345 kV lines is shown in tables 4.1 and 4.2. From table 4.1 it can be seen that the 230 kV line is about to reach its maximum capacity on the phase A, while there is capacity still available on phases B and C. Table 4.2 on the other hand shows that all the phases of the 345 kV line have available transmission capacity which could be utilized if power flow could be diverted to these lines.

Table 4.3 shows power flow in each of the phases of the 230 kV line and the remaining transmission capacity of each phase at 157% load. From Table 4.3 it can be seen that the power flow over the line has exceeded the transmission capacity and all the three phases are overloaded, with Phase A having the highest overload. Table 4.4 shows the Power flow in the 345 kV line and the remaining transmission capacity of that line at 157% load. As can be seen from Table 4.4, there is still transmission capacity available on the 345 kV line, especially on phases B and C. Comparing Tables 4.3 and 4.4 it can be seen that the 230 kV line is overloaded while there is still unused transmission capacity on the 345 kV line. Figure 4.1 shows the total capacity remaining on each of the lines as the load is increased in this case.

Table 4.1 230 kV line parameters just before overload starts at 149% load

Phase(A, B or C)	Phase-to-neutral voltage(kV)	Current (A)	Power Flow(kW)	% capacity remaining
Phase A	127	946	125495	0.2%
Phase B	136	890	121287	6.1%
Phase C	135	906	122961	4.4%

Table 4.2 345 kV line parameters just before overload starts at 149% load

Phase(A, B or C)	Phase-to-neutral voltage(kV)	Current (A)	Power Flow(kW)	% capacity remaining
Phase A	191	1227	243061	13.7%
Phase B	204	1121	228233	21.1%
Phase C	203	1138	232135	20.0%

Table 4.3 Case 1: 230 kV line parameters at 157% load

Phase(A, B or C)	Phase-to-neutral voltage(kV)	Current (A)	Power Flow(kW)	% capacity remaining
Phase A	123	1050	135924	-10.8%
Phase B	134	963	129430	-1.7%
Phase C	134	984	131839	-3.9%

Table 4.4 Case 1: 345 kV line parameters at 157% load

Phase(A, B or C)	Phase voltage(kV)	Current (A)	Power Flow(kW)	% capacity remaining
Phase A	185	1365	263354	4%
Phase B	201	1215	243593	14.5%
Phase C	201	1233	248425	13.2%

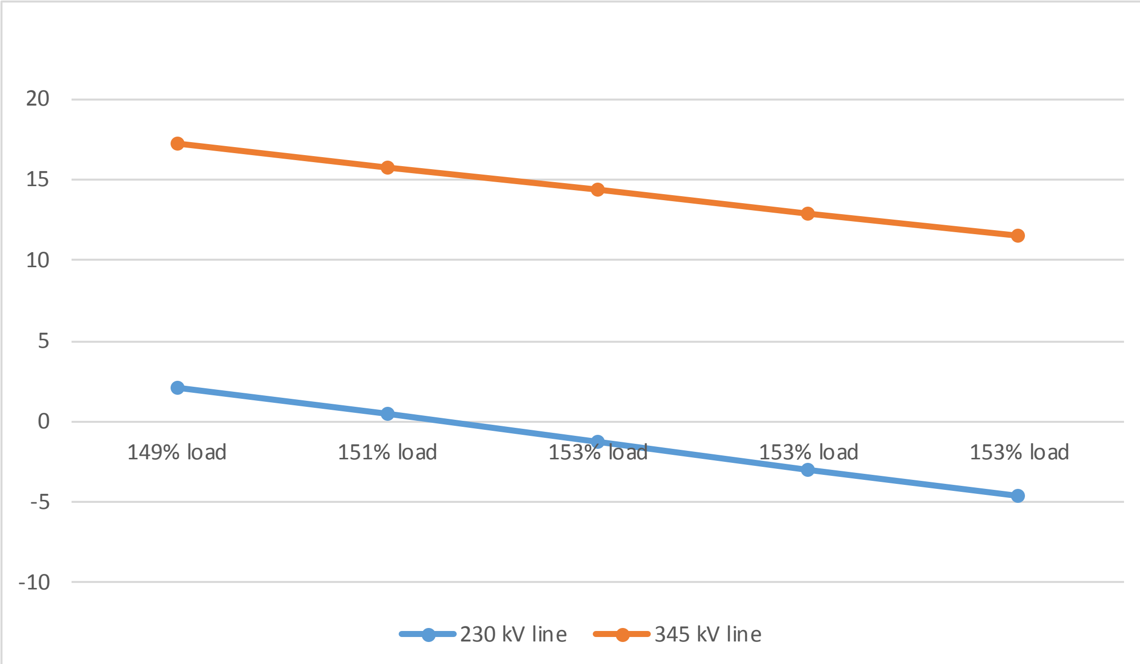

Figure 4.1 Percentage capacity remaining on lines with no DSRs

4.2 CASE 2: DSRs are operated in a symmetrical fashion:

In this case an equal number of DSRs are operated on the three phases of the 230 kV line. This is the procedure that would normally be followed using single line equivalent models. As can be seen from tables 4.5 and 4.6, by increasing the load to 157% and adding 600 DSRs uniformly across the three phases (200 DSRs are operated on each phase), the overload on the 230 kV line can be removed and power flow is transferred to the parallel 345kV line. Figure 4.2 shows the algorithm used for the operation of DSRs, whereas figure 4.3 shows the percentage capacity remaining on the lines with the load increase.

Even though the above method is able to alleviate the overload on the 230 kV line it has obvious drawbacks. As can be seen from tables 4.5 and 4.6, the DSRs are also added to phases which do not require them. Phase A had a significant overload and requires 200 DSRs to remove the overload and transfer the excess power to the 345 kV line. However, phases B and C had a very small amount of overload to begin with. By adding the same number of DSRs to phases B and C more power was transferred from them than was required to remove the overload condition. As a result the network is left with unused transmission capacity on phases B and C of the 230kV line.

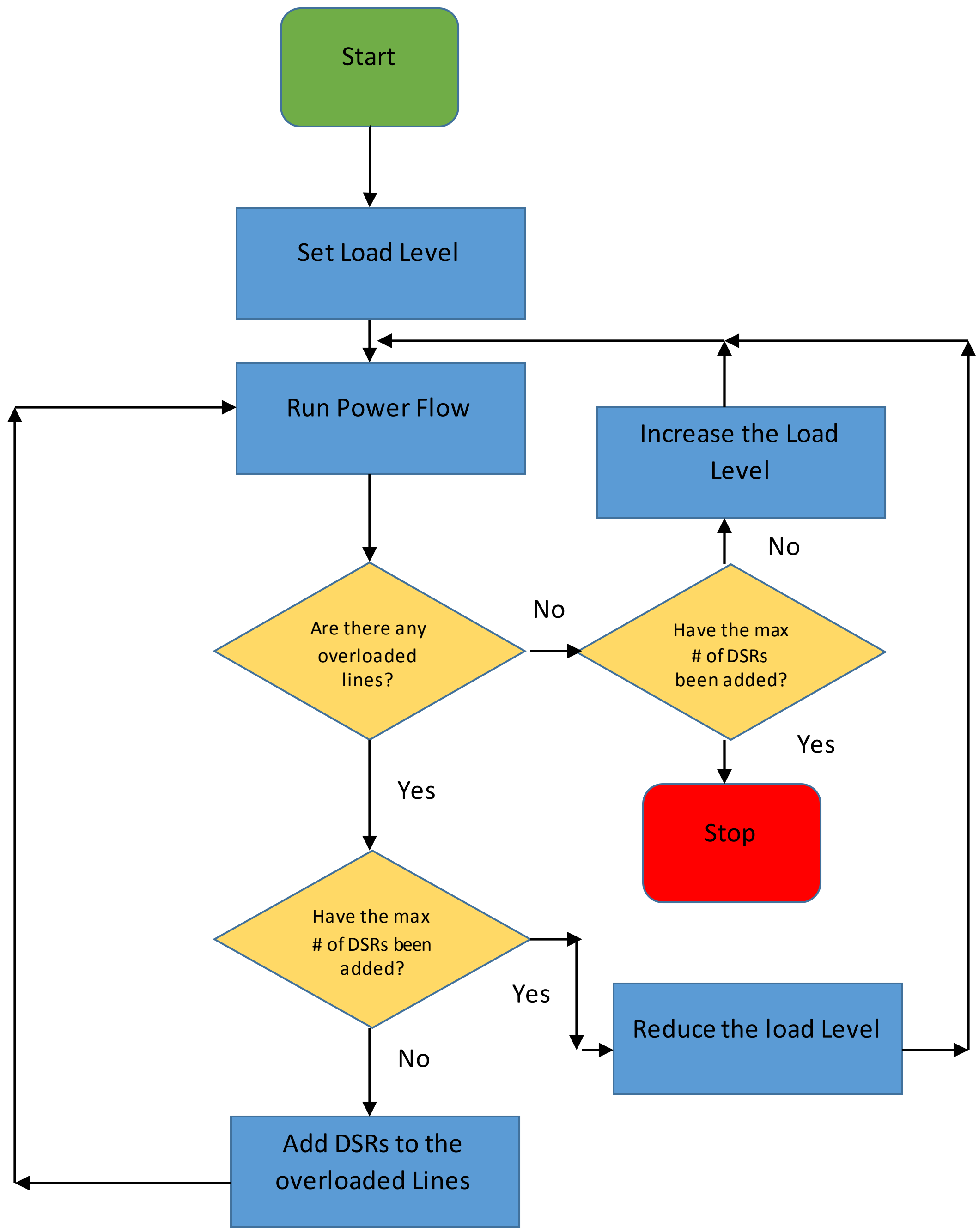

Figure 4.2 Flowchart showing the process of Symmetrical DSR operation for increasing power flow

Table 4.5 Case 2: 230 kV line parameters

Phase(A, B or C)	Phase voltage(kV)	Current (A)	Power Flow(kW)	% capacity remaining	No. of DSRs added
Phase A	123	948	121829	0%	200
Phase B	134	854	114452	9.9%	200
Phase C	134	879	117700	7.2%	200

Table 4.6 Case 2: 345 kV line parameters

Phase(A, B or C)	Phase voltage(kV)	Current (A)	Power Flow(kW)	% capacity remaining
Phase A	185	1413	272410	.6%
Phase B	201	1263	253027	11.1%
Phase C	201	1280	257435	10%

By adding equal numbers of DSRs to all the phases, a large number of DSRs have been used unnecessarily and this has further created unused transmission capacity on the B and C phases of the 230 kV line. The comparison of Power flows between cases 1 and 2 is given in tables 4.7 and 4.8. From the tables it can be seen that there is an increase in the power which is transmitted over the 345 kV line and a reduction in the power that is transferred over the 230 kV line.

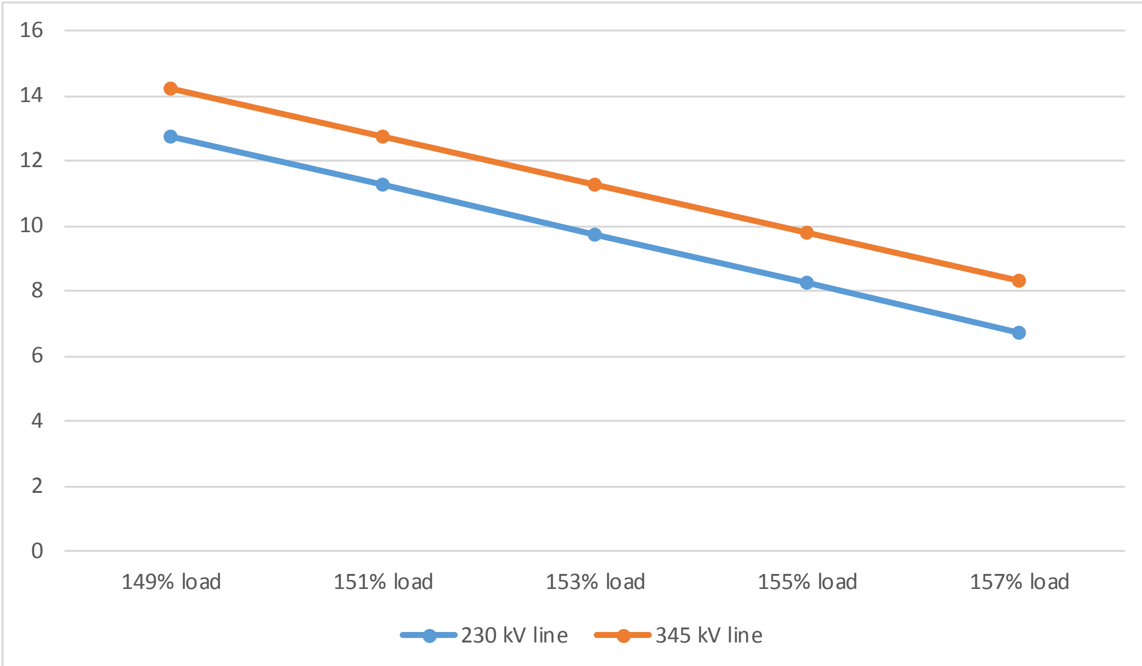

Figure 4.3 Case 2: Percentage capacity remaining on lines with symmetrical DSR operation

Table 4.7 Comparison of the phase power flows between case 1 and case 2

Phase(A , B or C)	230 kV before adding DSRs(kW)	230 kV after adding DSRs(kW)	Change in Power flow(kW)(%)	345 kV before adding DSRs(kW)	345 kV after adding DSRs(kW)	Change in Power flow(kW)(%)
Phase A	125495	121829	-3666(-2.9%)	243061	272410	29349(10.5%)
Phase B	121287	114452	-6835(-5.4%)	228233	253027	24794(8.88%)
Phase C	122961	117700	-5261(-4.2%)	232135	257435	25300(9.06%)
Total	369743	353981	-15762(-4.2%)	703429	782872	79443(9.48%)

Table 4.8 Comparison of total line flows between case 1 and case 2

Line	Power Transmission before adding DSRs(kW)	Power Transmission after adding DSRs(kW)	Increase in Power Transmission(kW)(%)
230 kV	369743	353981	-15762(-4.17%)
345 kV	703429	782872	79443(9.48%)
Total	1073172	1136853	63681(5.24%)

4.3 CASE 3: DSRs are operated in an unsymmetrical fashion:

In this case, a different number of DSRs are operated on each phase of the 230 kV line. The 3-phase model of the transmission line allows operation of different number of DSRs on each phase. As can be seen from Table 4.9, with the system load increased to 157%, adding a total of 300 DSRs amongst the three phases alleviates the overload completely from the 230 kV line and furthermore almost fully utilizes the capacity of the 230 kV line. Table 4.10 shows the results for the 345 kV line, where it can be seen that the capacity of Phase A is almost fully utilized, while phases B and C still have remaining transmission capacity. Figure 4.4 shows the control mechanism of DSR operation in this case, whereas figure 4.5 shows the percentage capacity remaining on the lines with the load increase.

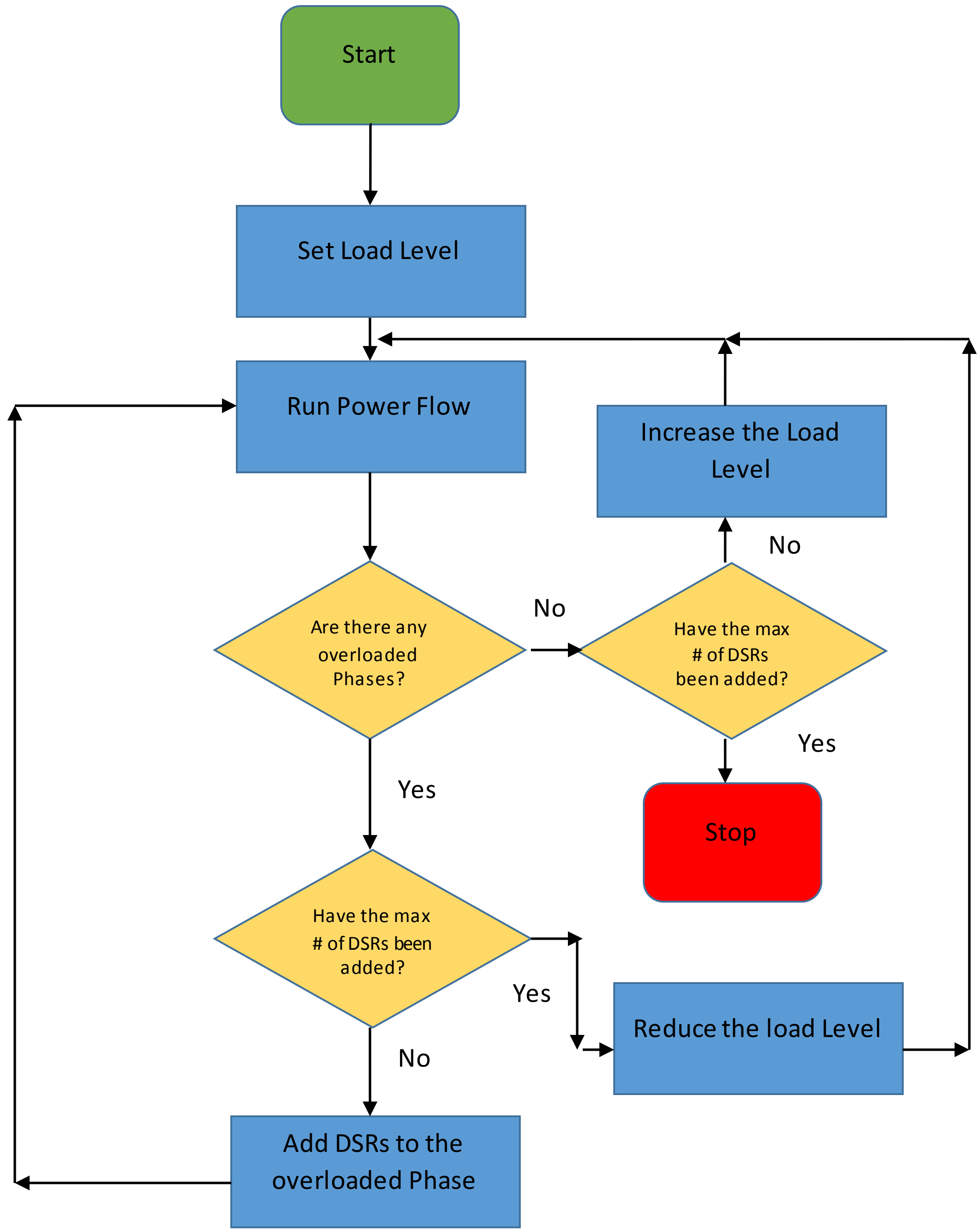

Figure 4.4 Flowchart showing the process of unsymmetrical DSR operation for increasing power flow

Table 4.9 Case 3: 230 kV line parameters

Phase(A, B or C)	Phase voltage(kV)	Current (A)	Power Flow(kW)	% capacity remaining	No. of DSRs added
Phase A	123	947	122123	0.1%	251
Phase B	134	942	127301	0.6%	0
Phase C	134	984	126238	0.0%	49

Table 4.10 Case 3: 345 kV line parameters

Phase(A, B or C)	Phase voltage(kV)	Current (A)	Power Flow(kW)	% capacity remaining
Phase A	184	1417	272542	0.3%
Phase B	202	1225	244868	13.9%
Phase C	201	1248	251698	12.2%

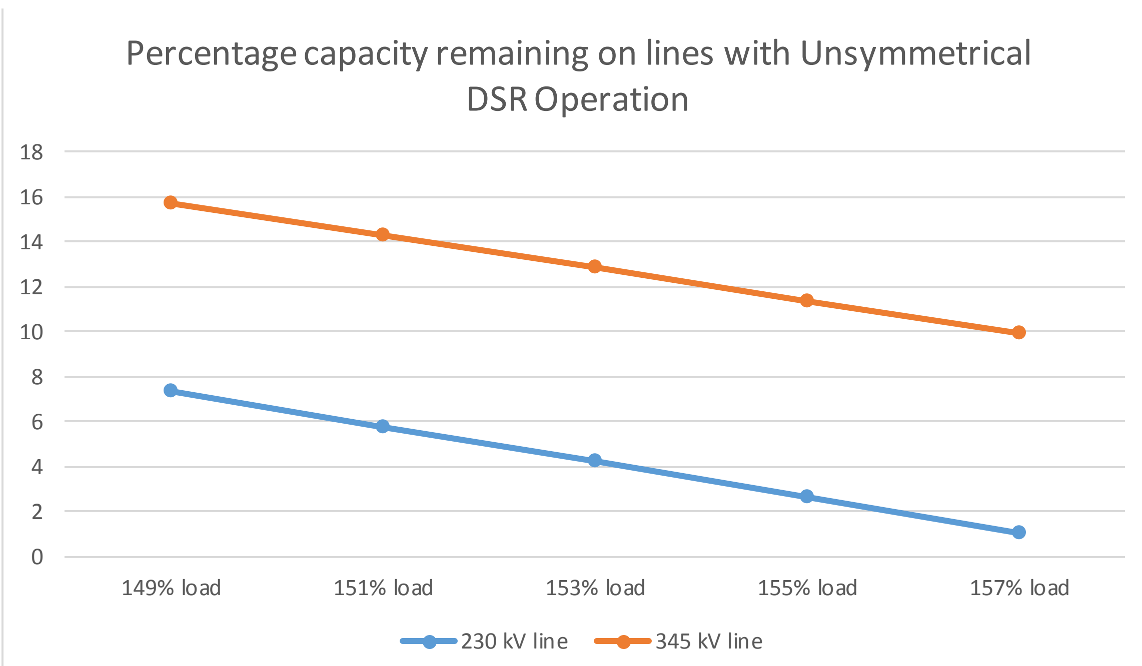

Figure 4.5 Case 3: Percentage capacity remaining on lines with unsymmetrical DSR operation

Tables 4.11, table 4.12 and figure 4.6 provide a comparison among the power flows for the three cases. As can be seen from table 4.11, which gives a comparison between cases 2 and 3, there is an increase in the utilization of transmission capacity of phases B and C of the 230 kV line when fewer numbers of DSRs are added to these phases. This leads to a reduction in the power flow over the B and C phases of the 345 kV lines. Table 4.12 shows the comparison between total power flows in the three cases. As can be seen from the table, in unsymmetrical DSR operation, there is a net increase in the transmission capacity of both the lines and the overall highest increase in total transmission capacity, this while using only half the number of DSRs as in case 2 where the DSRs are operated symmetrically.

Table 4.11 Comparison of the phase power flows between case 2 and case 3

Phase(A, B or C)	230 kV Symmetrical DSRs(kW)	230 kV Unsymmetrical DSRs(kW)	Change in Power flow(kW)(%)	345 kV Symmetrical DSRs(kW)	345 kV Unsymmetrical DSRs(kW)	Change in Power flow(kW)(%)
Phase A	121829	122123	294(.23%)	272410	272542	132(.05%)
Phase B	114452	127301	12849(10.2%)	253027	244868	-8159(-2.9%)
Phase C	117700	126238	8538(6.78%)	257435	251698	-5737(-2.05%)
Total	353981	375662	21681(5.74%)	782872	769108	-13764(1.64%)

Table4.12 Comparison of total line flows between case 1, case 2 and case 3

Line	Power Transmission before DSRs (kW)	Power Transmission Symmetrical DSR operation (kW)	Increase in Power Transmission with Symmetrical DSR operation (kW)(%)	Power Transmission Unsymmetrical DSR operation (kW)	Increase in Power Transmission with Unsymmetrical DSR Operation (kW)(%)
230 kV	369743	353981	-15762(-4.17%)	375662	5919(1.56%)
345 kV	703429	782872	79443(9.48%)	769108	65679(7.84%)
Total	1073172	1136853	63681(5.24%)	1144770	71598(5.89%)

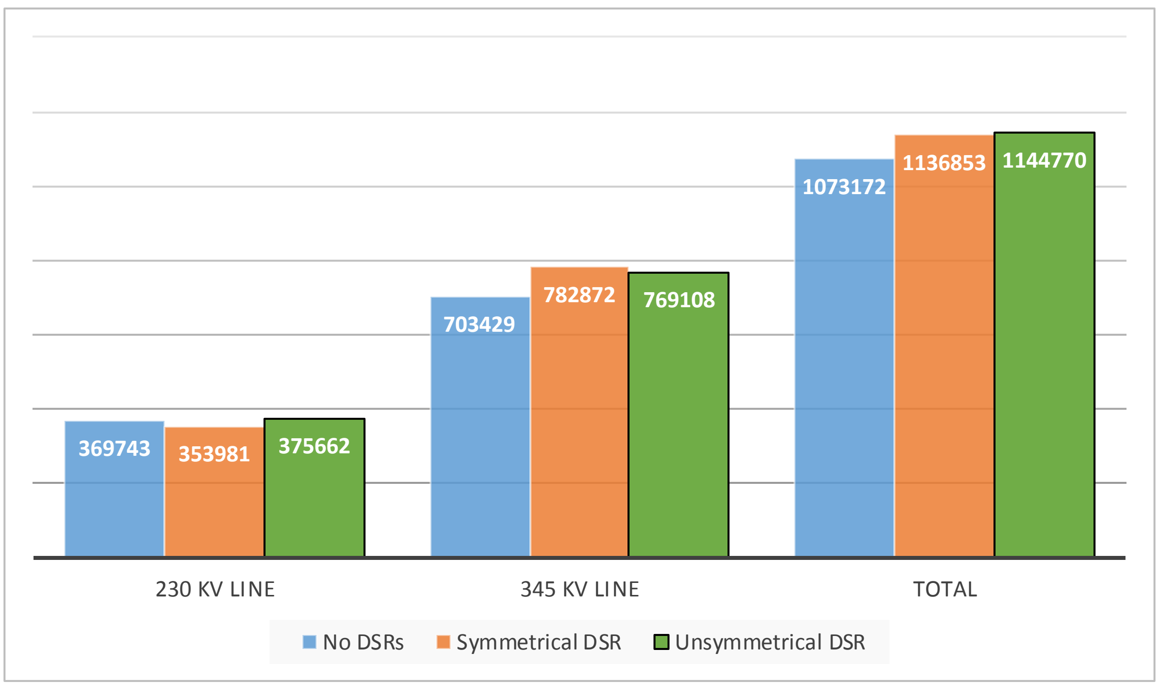

Figure 4.6 Power transmission for different DSR operation techniques

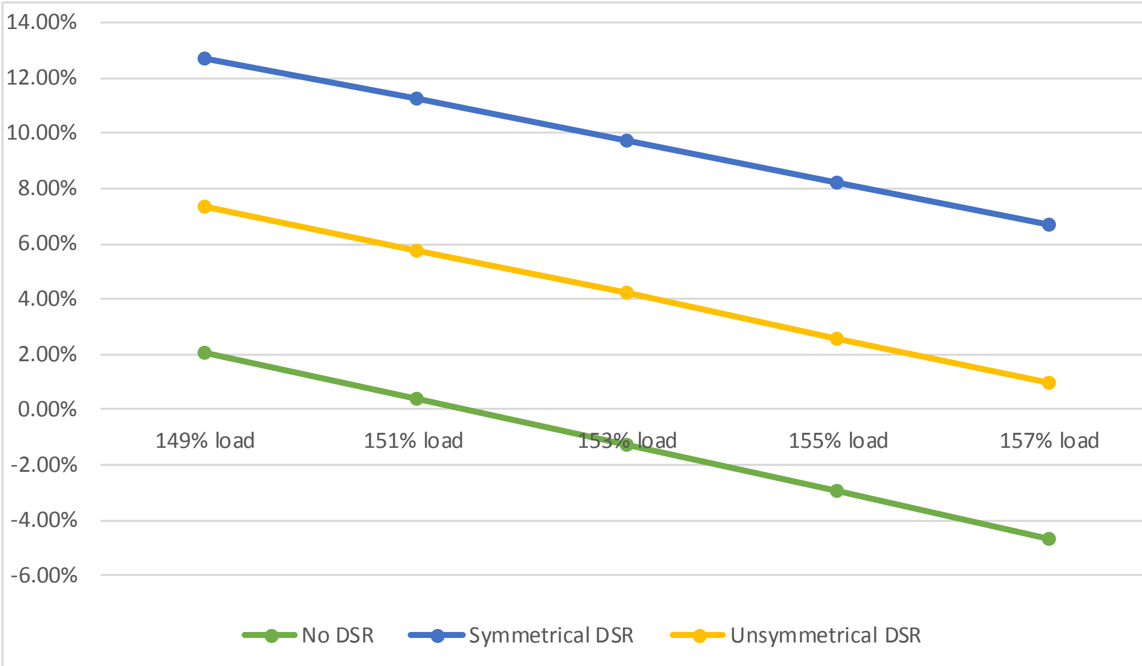

Figure 4.7 Percentage capacity remaining on 230 kV line with different DSR operation cases

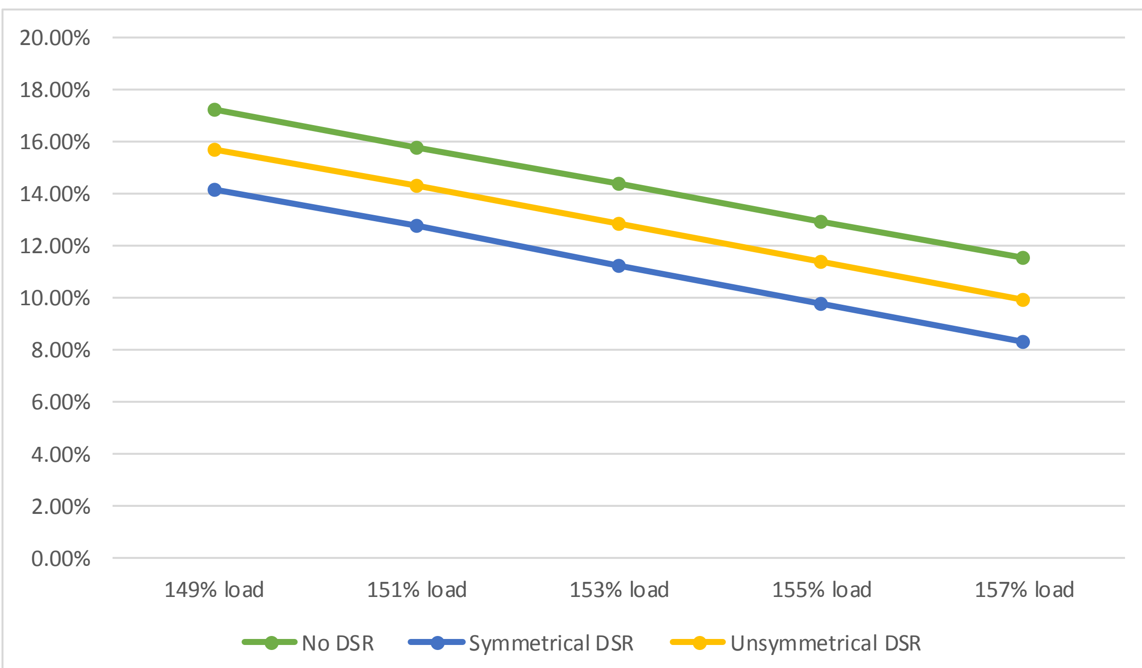

Figure 4.8 Percentage capacity remaining on 345 kV line with different DSR operation cases

Chapter 5: Economic Evaluation of different DSR Operation techniques

In this chapter the economic benefit of using different DSR operation techniques is compared to the cost of new transmission line construction. Based on the cost of construction of 230 kV and 345 kV lines, the dollar worth of DSRs is calculated for two cases, case 1 with symmetrical DSR operation and case 2 with unsymmetrical DSR operation. Since case 2 uses unsymmetrical DSR operation, it utilizes half the number of DSRs as case 1, using symmetrical DSR operation, and thus the cost margin per DSR addition is much higher for unsymmetrical DSR operation.

5.1 Cost Calculations for DSRs Operated in a Symmetrical Fashion (Case 2)

The DSR cost calculations for symmetrical addition of DSRs are performed in this section. Table 5.1 presents the results of the DSR symmetrical operation for Path 1 showing the total MW flow over each line with and without DSRs.

Table 5.1 Economic results for symmetrical addition of DSRs over 230 kV line of Path 1

	# DSR	Total MW flow		Total flow
		Line 1	Line 2	
No DSR	__	369.743	703.429	1073.172
With DSR	600	353.981	782.872	1136.853

Construction costs of 2.5M$/ mile, and 1.7 M$/mile for the 345 kV line and the 230 kV line, respectively, are used to calculate the economic worth of the DSRs [23], [24].

The cost of the MW flow increase over Line 2 is calculated as follows:

Cost of increased MW flow=

$$\frac{782.87\ \text{MW} - 703.43\ \text{MW}}{850\ \text{MW}} * (50\text{mile} * 2.5\ \text{M\$/mile}) = 11.68\ \text{M\$} \qquad (5.1)$$

where 850 MW is the loading capacity of Line 2.

The symmetrical addition of 600 DSRs to Line 1; 200 DSRs over each phase caused this increase in the MW flow over Line 2, so to calculate the investment cost per DSR the cost value of the MW increase is divided by the number of DSRs added as

$$Cost\ per\ DSR = \frac{11.68M\$}{600} = 19{,}470\frac{\$}{DSR} \qquad (5.2)$$

Thus, for DSR operation in a symmetrical fashion the investment in 600 DSRs to be deployed over Line 1 with a cost of 19,470 $/DSR will provide an increase in MW flow that is the same as the construction of a new transmission line to supply the same amount of power.

5.2 Cost Calculations for DSRs Operated in an Unsymmetrical Fashion (Case 3)

Table 5.2 presents the results of the DSR unsymmetrical operation over the 230 kV line of Path 1 showing the total MW flow over each line with and without DSRs, making it obvious how deployment of DSRs increased the flow significantly over Line 2 and also an increase over Line 1 is observed.

Table 5.2 Economic results for unsymmetrical addition of DSRs over 230 kV line of Path 1

	# DSR	Total MW Flow		Total flow
		Line 1	Line 2	
No DSR	__	369.743	703.429	1073.172
With DSR	300	375.662	769.108	1144.77

The cost of the MW flow increase over Line 1 and Line 2 is calculated as follows:

Cost of increased MW flow

$$= \frac{375.66\ MW - 369.74\ MW}{378\ MW} * \left(50\ mile * 1.7\frac{M\$}{mile}\right) + \frac{769.11\ MW - 703.43\ MW}{850\ MW} * \left(50\ mile * 2.5\frac{M\$}{mile}\right) \qquad = 10.99\ M\$ \tag{5.3}$$

,where 850 MW, and 378 MW are the loading capacities of Line 2 and Line 1, respectively.

The addition of 300 DSRs to Line 1 caused this increase in the MW flow, so to calculate the investment cost per DSR the cost value of the MW increase is divided by the number of DSRs added as follows:

$$Cost\ per\ DSR = \frac{10.99 M\$}{300} = 36{,}633\frac{\$}{DSR} \tag{5.4}$$

Thus for the unsymmetrical operation of DSRs, the investment in 300 DSRs to be deployed over Line 1 with a cost of 36,633 $/DSR will provide an increase in MW flow that is the same as the construction of a new transmission line to supply the same amount of power. Table 5.3 shows the comparison of the results of symmetrical and unsymmetrical operation of DSRs on the 230 kV line, whereas figure 5.1 shows the total transmission capacity of Path 1 under the three DSR operation cases.

Table 5.3 Economic comparison of symmetrical and unsymmetrical operation of DSRs on 230 kV line

DSR Operation Case	# DSRs	230 kV line MW Flow	345 kV line MW Flow	Total MW Flow
No DSRs	-	369.743	703.429	1073.172
Symmetrical DSR Operation	600	353.981	782.872	1136.853
Unsymmetrical DSR Operation	300	375.662	769.108	1144.77

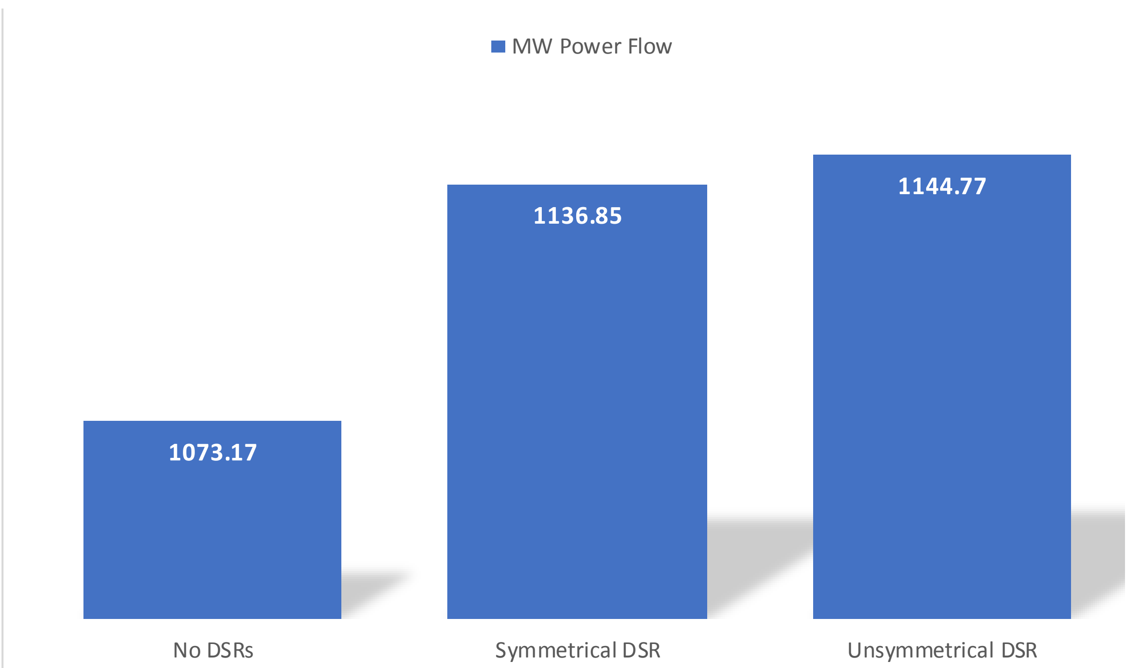

Figure 5.1 MW Power flow for different DSR operations

Chapter 6: Comparison of Sequence Voltages and Power Flows for different DSR Operations

6.1 Comparison of Sequence Voltages under DSR Operation

Tables 6.1 and 6.2 show voltage imbalances for the three DSR operational cases. When DSRs are added to a transmission line the impedance of the diagonal elements of the impedance matrix of the line are increased. If a line is unbalanced to begin with, this increase in impedance leads to an increase in the imbalance of the phase voltages. An unsymmetrical operation of DSRs can increases the voltage imbalance further as illustrated in tables 6.1 and 6.2, but the unsymmetrical operation allows the full utilization of the capacity of the lines. While altering the power flow of the network, the goal here is to keep the voltage imbalance within 4%.

Tables 6.3 and 6.4 show the comparison of voltage imbalance at the sending end and receiving end of the lines, respectively. From table 6.3 it can be seen that as DSRs are added to the 230 kV line, the voltage imbalance at the sending end of the line increases, and the increase is more for the unsymmetrical DSR addition case. However, the increase in imbalance at the sending end is very minimal. Table 6.4 shows the imbalance in the voltage at the receiving end of the lines. From the table it can be seen that the imbalance again increases with the addition of DSRs and is more prominent for the unsymmetrical addition of DSRs. Figure 6.1 shows a comparison of the voltage imbalance at receiving end under different DSR operation cases. The increase in voltage imbalance is much more significant in this case as compared to the increase in voltage imbalance at the sending end of the line. However, the increase in voltage imbalance is still within 4%. Figure 6.2 shows the comparison of the percentage voltage imbalance at the receiving end of the lines for different DSR operation cases.

Table 6.1 Comparison of voltage imbalance for 230 kV line

Sequence Voltage(V)	230kV (No DSR)	230kV (Symmetrical DSR Operation)	230kV (Unsymmetrical DSR Operation)
Zero Sequence(V)	4439	4537	4836
Positive Sequence(V)	130846	130606	130688
Negative Sequence(V)	4115	4185	4458
Percentage Voltage Imbalance	3.39%	3.47%	3.7%

Table 6.2 Comparison of voltage imbalance for 345 kV line

Sequence Voltage(V)	345kV (No DSR)	345kV (Symmetrical DSR Operation)	345kV (Unsymmetrical DSR Operation)
Zero Sequence(V)	6658	6806	7254
Positive Sequence(V)	196270	195909	196032
Negative Sequence(V)	6173	6277	6688
Percentage Voltage Imbalance	3.39%	3.47%	3.7%

Table6.3 Comparison of voltage imbalance at sending end of lines

Sequence Voltage(V)	Sending end(No DSR)	Sending end (Symmetrical DSR Operation)(change)	Sending end (Unsymmetrical DSR Operation)(change)
Zero Sequence(V)	1420	1439(+19)	1481(+61)
Positive Sequence(V)	205205	205163(-42)	205176(-29)
Negative Sequence(V)	1773	1801(+28)	1766(-7)
Percentage Voltage Imbalance	.69%	.7%(+.01%)	.72%(+.03%)

Table 6.4 Comparison of voltage imbalance at receiving end of lines

Sequence Voltage(V)	Receiving end (No DSR)	Receiving end (Symmetrical DSR Operation)	Receiving end (Unsymmetrical DSR Operation)
Zero Sequence(V)	6658	6806(+148)	7254(+596)
Positive Sequence(V)	196270	195909(-361)	196032(-238)
Negative Sequence(V)	6173	6277(+104)	6688(+515)
Percentage Voltage Imbalance	3.39%	3.47%(+.08%)	3.7%(+.31%)

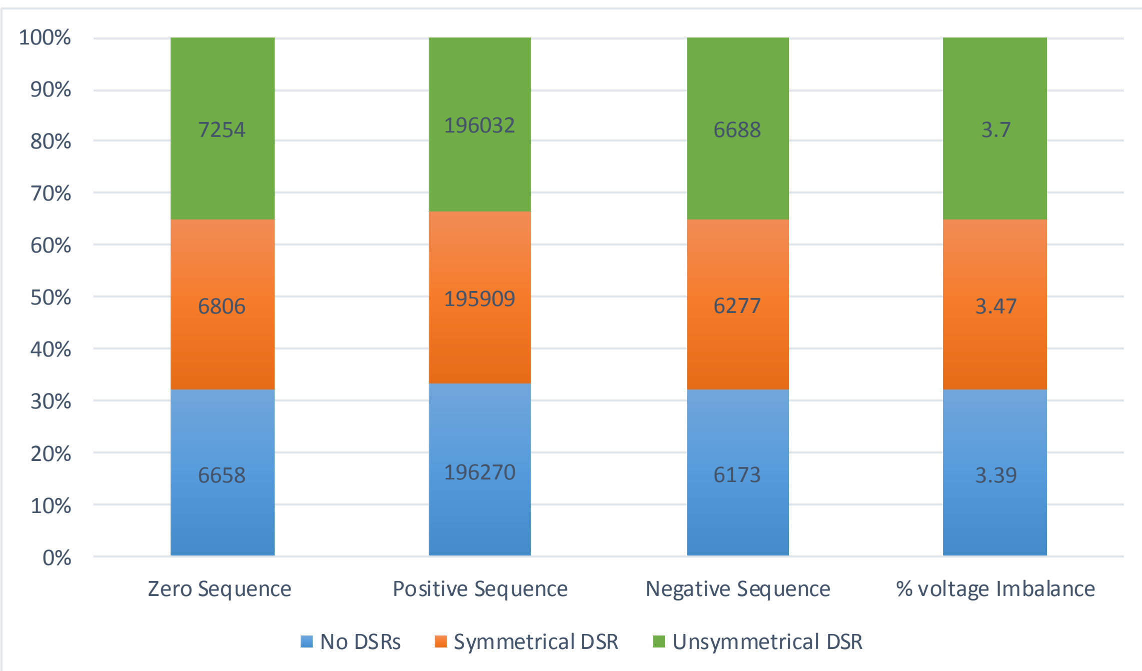

Figure 6.1 Comparison of voltage imbalance at receiving end of lines

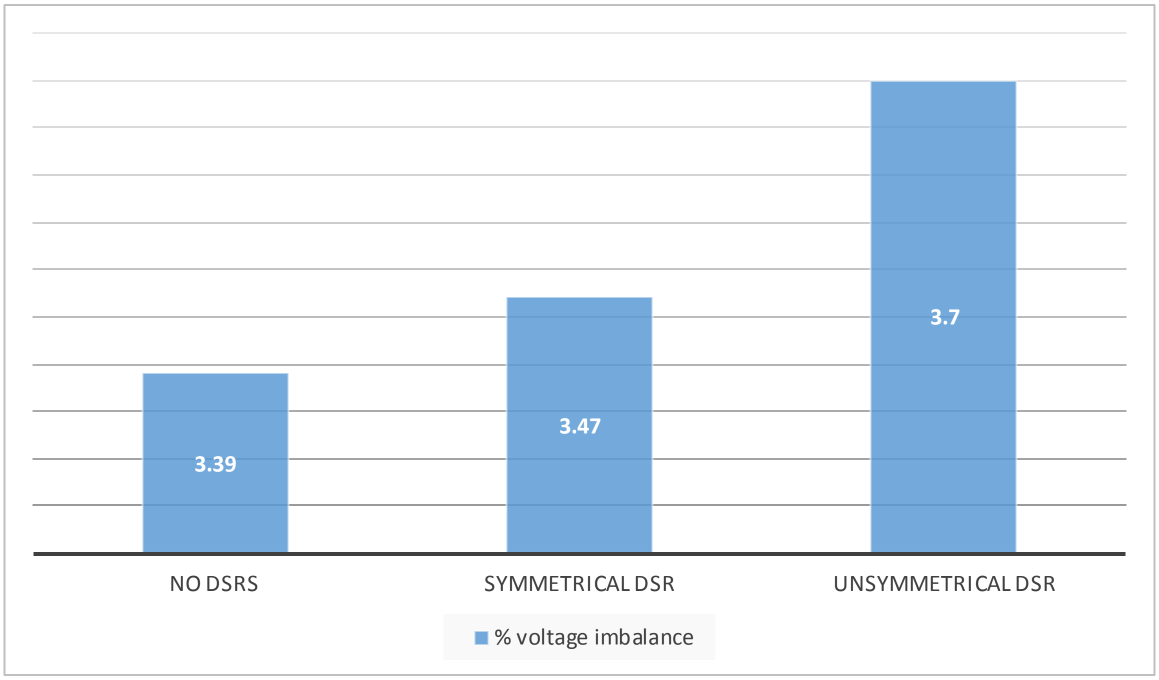

Figure 6.2 Percentage voltage imbalance at receiving end of lines

6.2 Comparison of Power Flow under DSR Operation

Tables 6.5 and 6.6 show the comparison of power flows for the 230 kV and 345 kV lines, while figure 6.3 and 6.4 also shows a graphical comparison of the power flow for the 230 kV and 345 kV lines under different DSR operation cases. From the figures it can be seen that when no DSRs are added, the 230 kV line is overloaded at 149% load while there is still transmission capacity available on 345kV line. By adding DSRs symmetrically to the 230 kV line and increasing the load to 157%, the power flow is shifted to the 345 kV line. However, this method shifts power flow from all phases of the 230 kV line, even the ones which were minimally overloaded. As a result excess power is transferred to the 345 kV line creating unused transmission capacity on phases B and C of the 230 kV line. Furthermore, this method utilizes more DSRs than are necessary for shifting the power flow. With unsymmetrical DSR operation, power flow is mainly shifted from just the overloaded phase of 230 kV line, i.e, Phase A. This way the full capacity of the 230 kV line is utilized at 157% load before the power flow is shifted to the 345 kV line by the addition of DSRs. This way overloads are removed from the system effectively with minimal utilization of DSRs.

Table 6.5 Comparison of phase power flow for 230 kV line

Phase (A, B or C)	230kV (No DSR)(kW/%capacity)	230kV (Symmetrical DSR Operation)(kW)	230kV (Unsymmetrical DSR Operation)(kW)
Phase A	125495(0.2%))	121829(0%)	122123(0.1%)
Phase B	121287(6.1%)	114452(9.9%)	127301(0.6%)
Phase C	122961(4.4%)	117700(7.2%)	126238(0.0%)
Total Power Flow	369743(2.1%)	353981(6.26%)	375662(.52%)
Power flow imbalance =100[{max(Pa,Pb,Pc)-min(Pa,Pb,Pc)}/Pavg]	3.4%	6.2%	4.1%

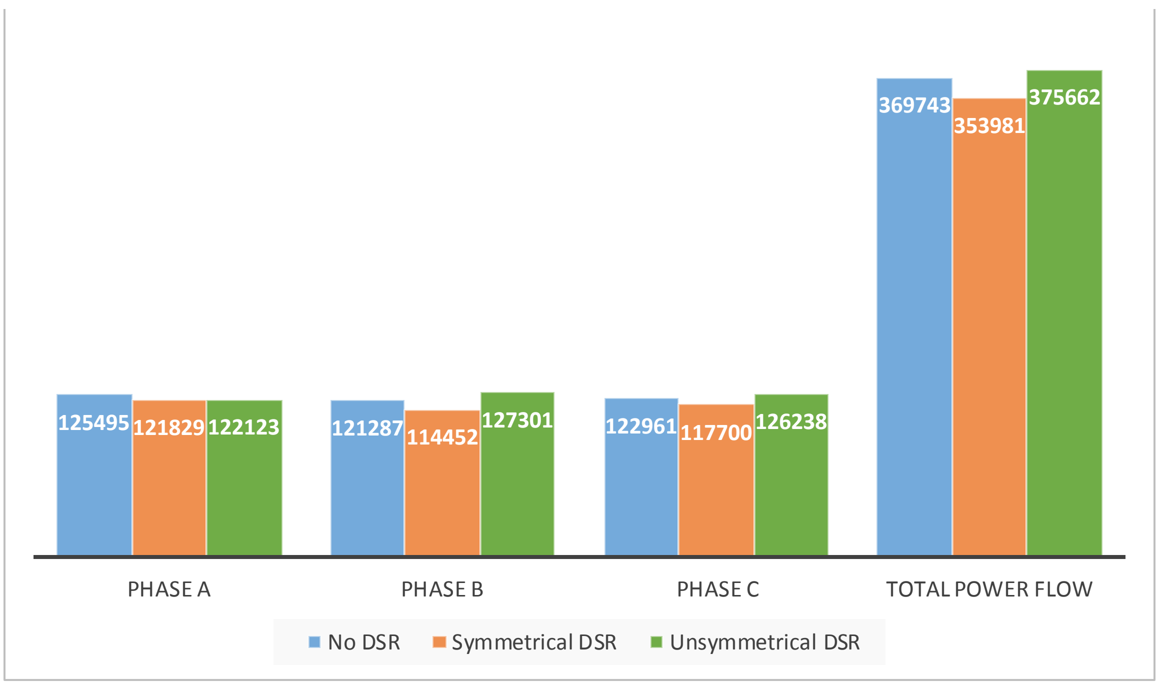

Figure 6.3 Comparison of phase power flow for 230 kV line

Table 6.6 Comparison of phase power flow for 345 kV line

Phase (A, B or C)	345kV (No DSR)(kW)	345kV (Symmetrical DSR Operation)(kW)	345kV (Unsymmetrical DSR Operation)(kW)
Phase A	243061(13.7%)	272410(.6%)	272542(.3%)
Phase B	228233(21.1%)	253027(11.1%)	244868(13.9%)
Phase C	232135(20%)	257435(10%)	251698(12.2%)
Total Power Flow	703429(17.2%)	782872(7.86%)	769108(9.48%)
Power flow imbalance =100[{max(Pa,Pb,Pc)-min(Pa,Pb,Pc)}/Pavg]	6.3%	7.4%	10.7%

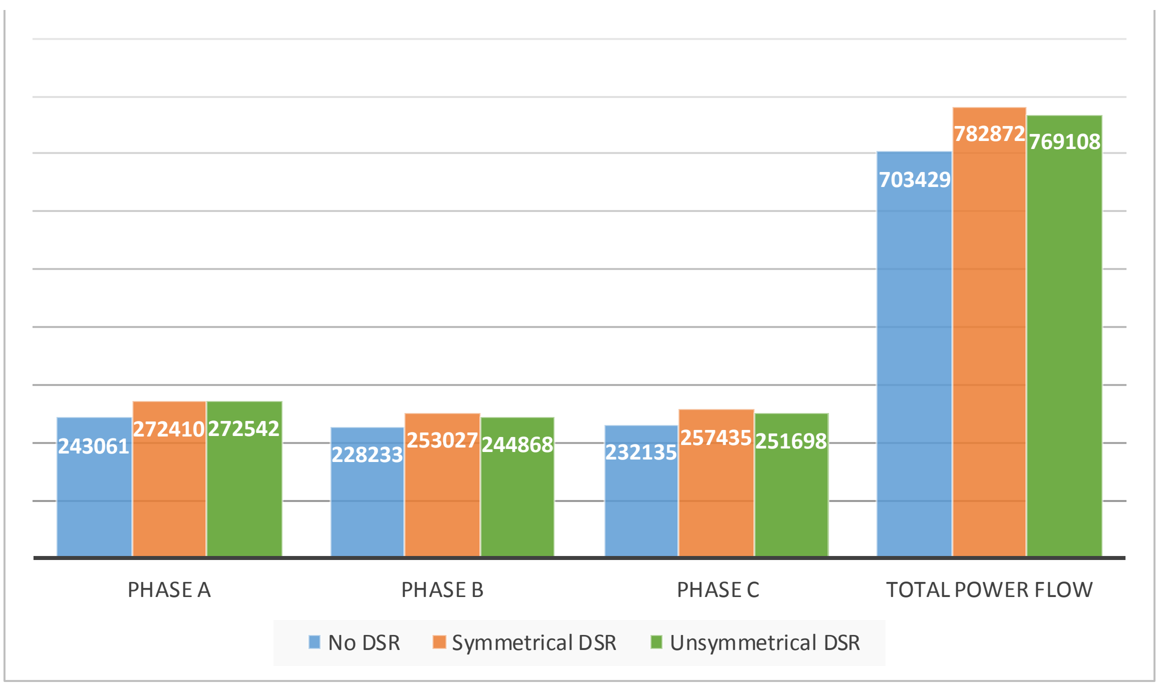

Figure 6.4 Comparison of phase power flow for 345 kV line

Table 6.7 and figure 6.5 show the changes in unbalance that result from the operation of DSRs in different cases. As can be seen from the figure there a reduction by 2.1% in the unbalance of power flow in the 230 kV line when unsymmetrical operation of DSRs is used as compared to symmetrical operation of DSRs. At the same time there is an increase of 3.3% unbalance in the 345 kV line under unsymmetrical DSR operation as compared to symmetrical DSR operation. This is due to the fact that in the unsymmetrical case DSRs are added predominantly to Phase A. Hence more power is transferred over Phase A as compared to Phases B and C. This leads to the increase in unbalance for the 345 kV line.

Table 6.7 Comparison of power flow imbalance between the three DSR operation cases

Line	%unbalance(No DSRs)	%unbalance(Symmetrical DSRs)	Change in unbalance	%unbalance(unsymmetrical DSRs)	Change in unbalance
230 kV	3.4%	6.2%	2.8%	4.1%	0.7%
345kV	6.3%	7.4%	1.1%	10.7%	4.4%

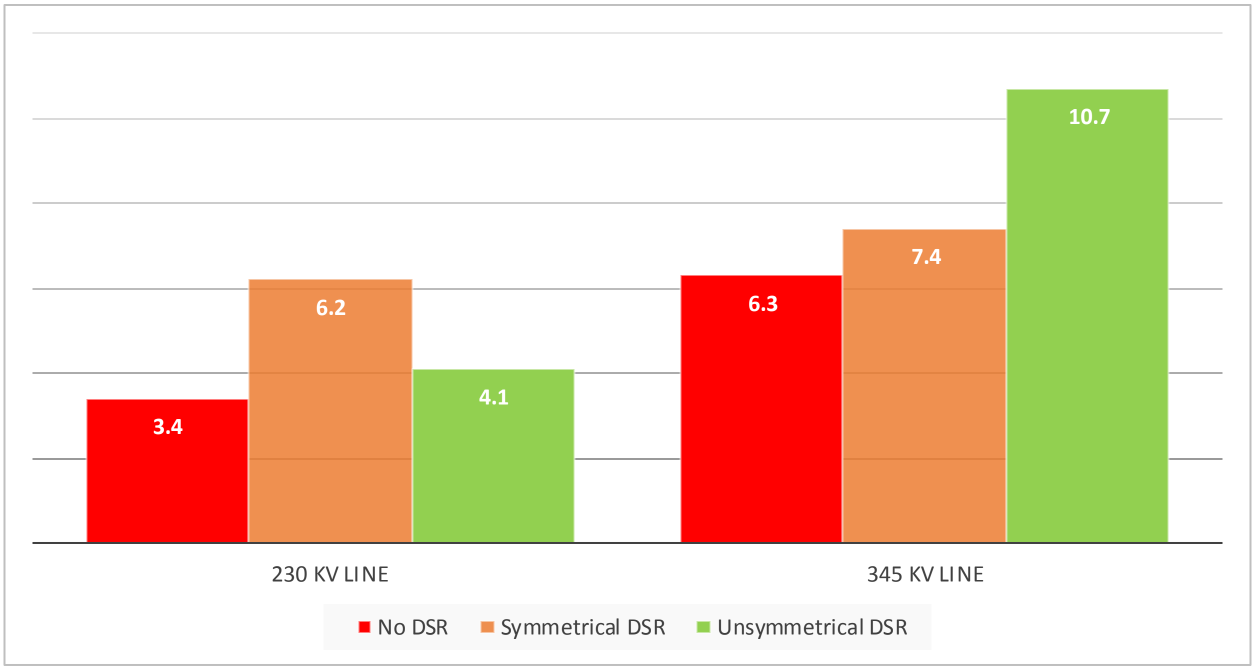

Figure 6.5 Comparison of Power flow imbalance between the three DSR operation cases

Chapter 7: Case Study 2: Operation of DSRs to reduce voltage Imbalance

In Case study 1 DSRs were added to the low voltage 230 kV line in order to increase the power flow by shifting the flow from the low voltage 230 kV line to the high voltage 345 kV line. The unsymmetrical operation of DSRs on the 230 kV line leads to an increase of the total power flow, however, it also leads to an increase in the voltage imbalance, especially at the receiving end. In situations where increasing the transmission capacity of the lines is not a concern, the operation of the DSRs can be used to reduce the voltage imbalance at the receiving end of the lines. The two operations are however contradictory to each other, if the transmission capacity is increased, the voltage imbalance increases and if the voltage imbalance is reduced, the transmission capacity also reduces. So the operation of the DSRs would depend upon the particular application, whether it is to increase transmission capacity or reduce voltage imbalance.

To showcase the application of DSRs in reducing voltage imbalance, let us again consider the IEEE 39 bus system shown in figure 3.1. For this study lines 3 and 4 that run in parallel are considered. Line 3 shown in blue is a 345 kV line and Line 4 shown in red which is a 500 kV line. The load is kept at a fixed value which is well below the maximum limit of the lines, in order to avoid overloads during the analysis. A comparison is made of the voltage imbalance at the sending end and receiving end of lines 3 and 4 with no DSRs and with unsymmetrical operation of DSRs on the 500 kV line.

7.1 Case 1: No DSRs added

This is the base case where we find the voltage imbalance at the sending end and receiving end of lines 3 and 4. The load is fixed at the base value. Table 7.1 shows the results of the sending end and receiving end sequence voltages when no DSRs are added to the 500 kV line.

Table 7.1 Voltage imbalance at the sending and receiving end of lines 3 and 4 with no DSRs

Sequence Voltage	Sending End(V)	Receiving End(V)
Zero Sequence	325.8	566.1
Positive Sequence	207105.7	206026.8
Negative Sequence	889.2	1323.3
Voltage Imbalance (%)	0.157%	0.275%

7.2 Case 2: Unsymmetrical Operation of DSRs

In this case DSRs are operated unsymmetrically over the phases of the 500 kV line and the best configuration that results in the least voltage imbalance at the receiving end is selected. It is found that when DSRs are operated in as (0, 165, 835) over the phases A, B and C, respectively, the voltage imbalance is minimum at the receiving end. Hence, by careful operation of DSRs over the high voltage line the voltage imbalance at receiving end of the line can be reduced. Table 7.2 shows the results of the voltage imbalance at the sending end and receiving ends of the line with the unsymmetrical operation of DSRs. From Table 7.2 it can be seen that there is a slight increase in the voltage imbalance at the sending end of the line, however, the receiving end voltage imbalance is almost completely reduced to zero. Figure 7.1 shows the control process for the unsymmetrical operation of DSRs to reduce voltage imbalance. Table 7.3 shows the comparison of the receiving end voltage imbalance under the two cases when the DSRs are not operated and under the case where the DSRs are operated unsymmetrically. Figure 7.1 shows the comparison of the receiving end voltage between the two DSR operation cases, whereas figure 7.2 shows the comparison of the percentage voltage imbalance between the two cases. From the figures it is seen that the unsymmetrical operation of DSRs can potentially remove the voltage imbalance at the receiving end of the lines.

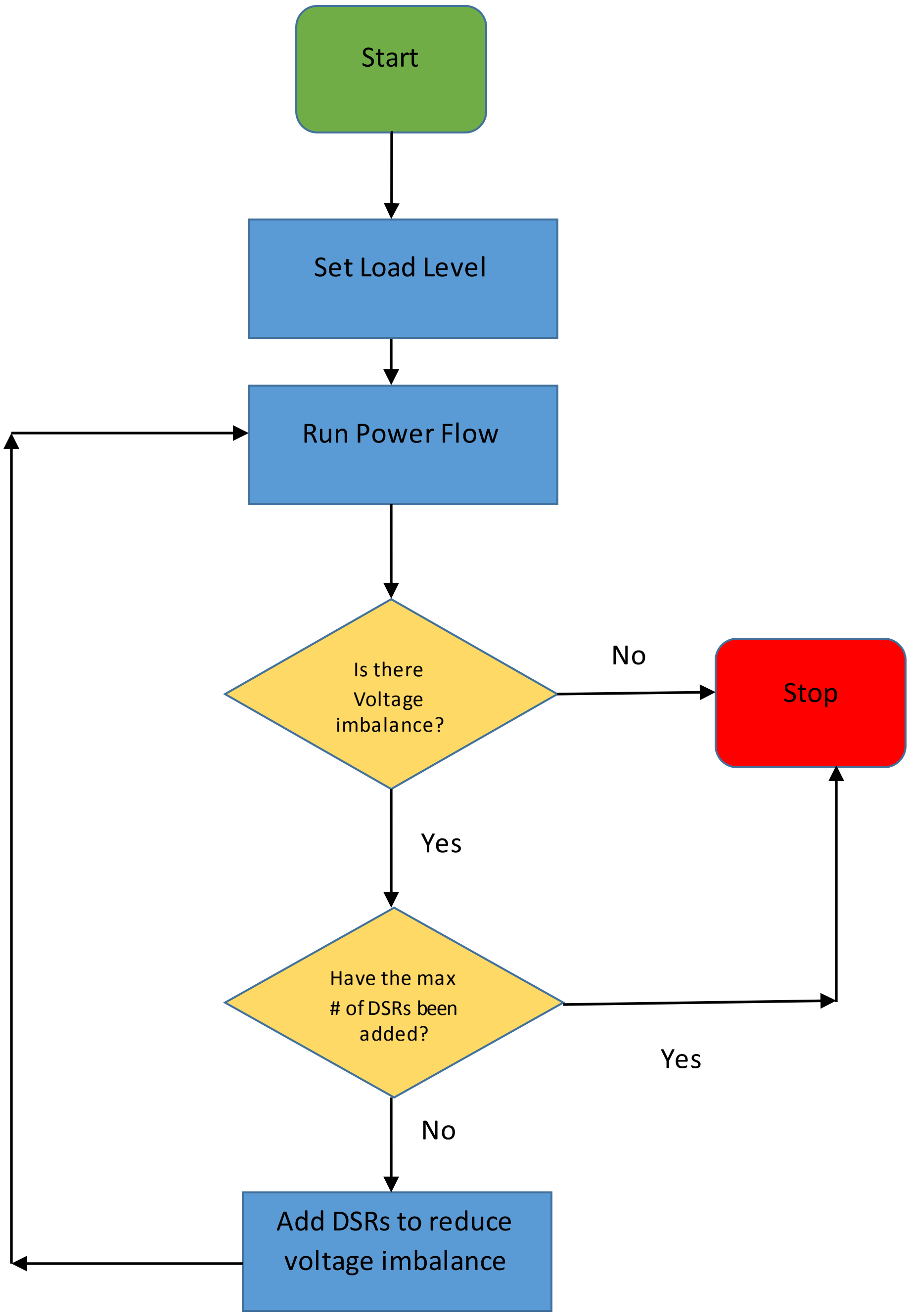

Figure 7.1 Flowchart showing the process of unsymmetrical DSR operation for reducing voltage imbalance

Table 7.2 Voltage imbalance at the sending and receiving end of lines 3 and 4 with unsymmetrical operation of DSRs

Sequence Voltage	Sending End(V)	Receiving End(V)
Zero Sequence	372.35	18.3
Positive Sequence	207072.28	205879.96
Negative Sequence	810.38	1653.17
Voltage Imbalance (%)	0.179%	0.008%

Table 7.3 Comparison of voltage imbalance at receiving end between case 1 and case 2

Sequence Voltage	No DSR Operation	Unsymmetrical DSR Operation	% Change
Zero Sequence(V)	566.1	18.3	-547.8(-96.7%)
Positive Sequence(V)	206026.8	205879.96	-146.8(-.07%)
Negative Sequence(V)	1323.3	1653.17	329.8(+24.9%)
Voltage Imbalance (%)	0.275%	0.008%	-.267%

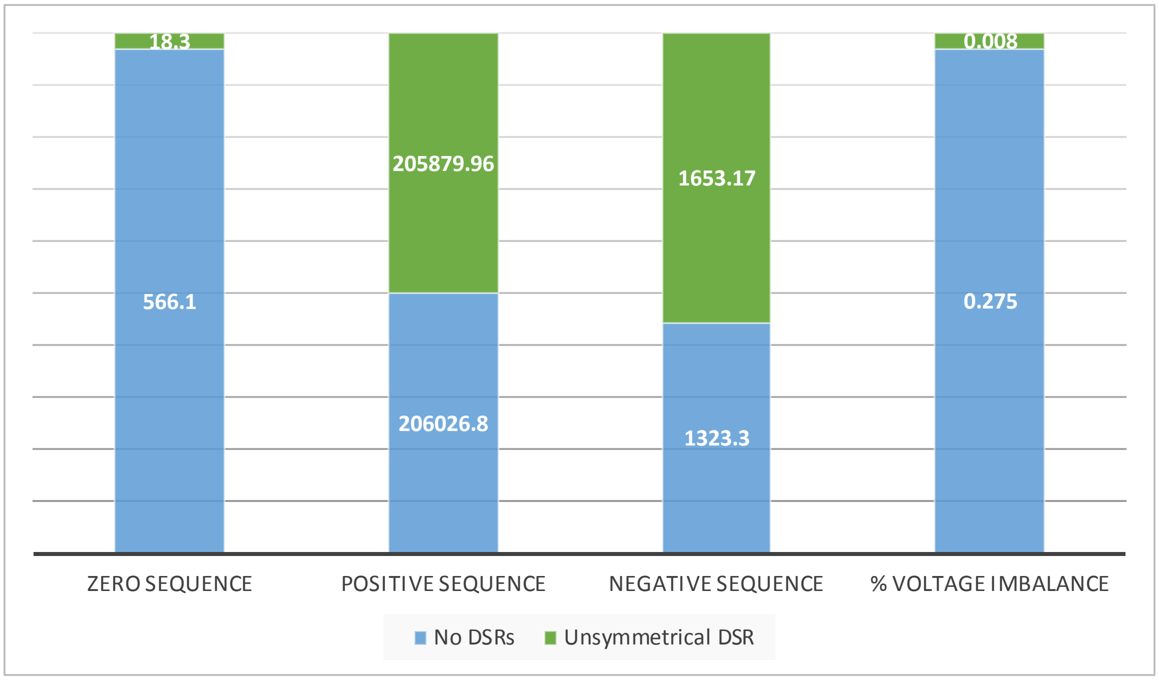

Figure 7.2 Comparison of voltage imbalance at the receiving end of lines

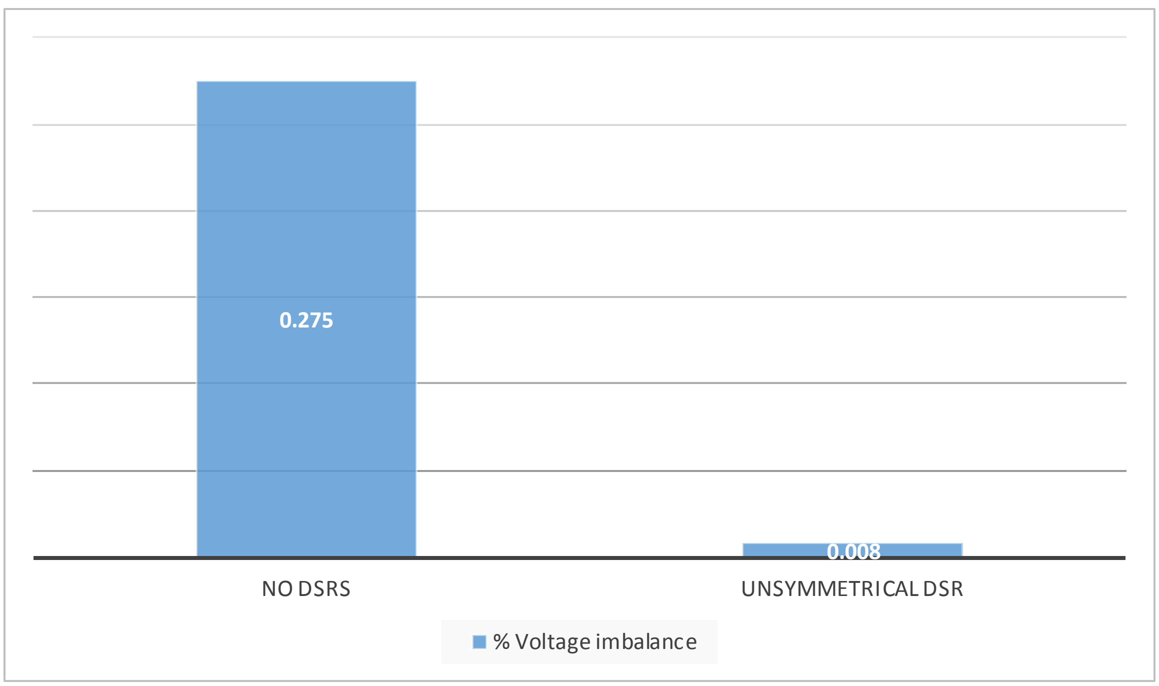

Figure 7.3 Percentage voltage imbalance for different DSR operation cases

Chapter 8: Conclusion and Scope for future study

This work studied the application of Distributed Series Reactors (DSRs) in increasing transmission capacity and reducing voltage imbalance in unbalanced transmission networks. The IEEE 39 bus standard transmission system model was modified to a 3-phase, unbalanced, transmission system model consisting of lines at 230 kV, 345 kV and 500 kV. This modified model was then used to test the operation of DSRs in flow control of parallel lines operating at different voltage levels. The modified model was also used to test using DSRs to balance delivery point voltages on the transmission system.

It was shown that as the network load is increased and without employing DSRs, the full capacity of the transmission network remains underutilized as the low voltage line, the 230 kV line, overloads first and the high voltage line, the 345 kV line, is left with significant unused transmission capacity. In order to increase the utilization of the capacity on the high voltage line, DSRs are added to low voltage line, and this has the effect of pushing more power towards the alternate high voltage path.

The 3-phase equivalent model allows changes to be made to the individual phases of the transmission lines. This ability is exploited to study the unsymmetrical operation of DSRs to increase transmission capacity. With the unbalanced transmission lines evaluated, it is found that unsymmetrical operation of DSRs is more beneficial than symmetrical operation. With the unsymmetrical operation only half the number of DSRs are utilized to achieve the same transmission capacity increase. Hence, unbalanced operation of DSRs over the phases of the low voltage line can result in substantial transmission capacity increase while using substantially fewer DSRs. The economic analysis of different DSR operation cases reveals that the cost margin per DSR for symmetrical operation is \$19,470 and for unsymmetrical operation is \$36,644. The downside is that the unsymmetrical operation increases the voltage imbalance at the receiving end of the lines, but this increase is not large.

The second part of the work studied the application of DSRs to reduce voltage imbalance. In applications where reducing the voltage imbalance rather than increasing the transmission capacity is the main concern, DSRs can be useful. The modified 3-phase, IEEE 39 bus system is again used to study the voltage imbalance. In this case a 345 kV line in parallel with a 500 kV line is considered. It is found that under certain unsymmetrical DSR operation on the 500 kV line, the voltage imbalance at the receiving end of the line can be reduced from 0.275% to about 0.008%. Hence, depending upon the application, DSRs can perform either of the two functions, i.e. increasing transmission capacity or reducing voltage imbalance.

In conclusion DSRs can be used to increase power flow and, in situations where the lines involved are not operated at their limits, reduce voltage imbalance. Future work will investigate the usefulness of DSRs to achieve both goals.

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