Power Flow Control and N-1 Contingency Analysis with DSRs in Unbalanced Transmission Networks

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

Keywords: Distributed Series Reactor(DSR) Design, Electric Power Transfer, Load Growth, N-1 Contingency Analysis, Power Flow Control, Unbalanced Transmission Systems.

1 Introduction

The US grid is frequently described as aging. Today's grid meets today's requirements, but new and different demands are driving the expansion and adaptation of the transmission grid and the evolution of its supporting institutions. Utilities in North America and all over the world are trying to incorporate new technological innovations to expand the transmission capacity using current assets and facilities [1]. Ways to expand transmission system capacity with no new transmission

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construction have been presented in the literature [2], [3]. Controlling power flow over lines to enhance system capacity has been also addressed in the literature [4],[5],[6].

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

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

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

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

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

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

2 DSR Technology And Design Strategy For Handling N-1 Contingencies With Load Growth

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

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

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

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

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

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

The following describes how lines are selected for DSR additions.

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

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

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

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

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

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

In the work here the load is uniformly grown in discrete increments, where the N-1 contingency criterion is considered for each load growth increment. When an overload is observed the DSR placement algorithm presented in Fig.1 is used to try and find a DSR design that can be used to

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

alleviate the overload. If DSRs are not able to handle overloads when a certain line is failed, a 345 kV line will be added in parallel with the failed line that has identical characteristics to the original 345 kV lines [27]. A line whose failure results in the DSR 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 design is applied.

3 IEEE 39 bus Three-phase System 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 with N-1 line contingency. 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[25]. The voltage magnitude and angle of the sources are maintained constant as the load is grown. 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.

The unbalanced impedance model of the lines is used, where the line impedance matrix has self-impedances that are unequal and symmetrical but unequal off diagonal elements. The same is true for the shunt admittance matrix of the unbalanced model.

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

$$Z_{\text{line}} = \begin{bmatrix} 0.18 + j 1.27 & 0.13 + j 0.53 & 0.14 + j 0.44 \\ 0.13 + j 0.53 & 0.19 + j 1.26 & 0.14 + j 0.52 \\ 0.14 + j 0.44 & 0.14 + j 0.52 & 0.21 + j 1.24 \end{bmatrix} \Omega/\text{mile} \quad (3)$$

and the shunt admittance matrix is

$$Y_{\text{line}} = \begin{bmatrix} j 4.938 & -j 0.930 & -j 0.405 \\ -j 0.930 & j 4.977 & -j 0.941 \\ -j 0.405 & -j 0.941 & j 4.934 \end{bmatrix} \mu\text{S}/\text{mile} \quad (4)$$

4 Simulation Results of DSR Design for N-1 Contingency with 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 design is initiated. We are assuming that the projected load growth for the next 40 years is 1% per year. We want to evaluate DSRs that will be needed for the projected load growth to handle overloads during contingencies. Results and findings for the critical lines, and the total number of DSRs deployed for each design are presented in Table 1. The DSR modules deployed over each line for each load level is presented in Table 2. 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 DSRs deployed over them. These are recorded in Table 3. The results and findings obtained for each load level is explained in the following subsections.

4.1 100% (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 2 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%.

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 design application was successful in alleviating these overloads. Results of the simulation of the unbalanced, 3-phase model for the 110% load are illustrated in Fig. 2-a. 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 [25].

For an increase in load to 111%, overloads were observed for the failure of 4 lines out of the 35 lines. The DSR 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 1.

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 Fig. 2-b.

TABLE 1
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 2
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 3
MAXIMUM % CHANGE IN IMPEDANCE FOR LINES WITH DSRs DEPLOYED

	Maximum % 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

Fig. 2-a 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.

Fig. 2-a DSR design #2 for 110% system load

Fig. 2-b DSR design #3 for 111% system load

Fig. 2-b 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.

4.2 111% - 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.

Tables 1 and 2 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.

The results of Design #6 show how overloads at the 122% load level are alleviated when constructing a new line parallel to Line 15-16 and deploying 300 DSR modules over Line 5-6.

4.3 122% - 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 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 Tables 1 and 2, a new line was constructed parallel to Line 2-3. 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.

4.4 136% - 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 Tables 1 and 2.

Some observations obtained from the results shown in Tables 1, 2 and 3 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 1.
- Adding DSRs for flow control can sometimes result in a high percentage change in impedance as shown in Table 3. 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. The goal in this study was to keep the voltage drop within $\pm 10\%$ of the nominal voltage.

The percentage of voltage imbalance is calculated using

$$\frac{\text{maximum deviation from average voltage}}{\text{average voltage}} * 100\% \quad (5)$$

$$\frac{\max \{ |V_{av} - V_A|, |V_{av} - V_B|, |V_{av} - V_C| \}}{V_{av}} * 100\% \quad (6)$$

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
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 Fig.

3. Fig. 3 also shows where new lines were built. The total load supplied and the numbers of DSRs deployed to remove the overload are presented in Fig. 4.

Fig. 3 Highest % of overload removed at different system load levels

It may be observed from Fig. 3 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.

4.5 New Line Construction: Alternate Design

As discussed in the previous section, the DSR 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 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.

Fig. 4 DSRs deployed, increase in load, the total load supplied, and % system loading at which line reinforcement occurred

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 Design #10 for the 140% load level, 2 more lines, which are Line 7-8 and Line 6-11, were strengthened, resulting in 50.15 miles of new transmission lines[27]. Table 5 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 5
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

4.6 Multi-Area Control Design

This section presents the simulation results of using DSRs to control the power flow of a real power system over tie lines connecting different power pool areas and control the power flow over the transmission lines within an area itself. An area (Area1) with 525 buses (52 load buses, 64 generator buses) and 302 transmission lines is simulated. This area connects to its neighbouring area (Area2) through 8 tie lines. The maximum load power that can be supplied to the loads in Area1 with the existing transmission facilities is 11.35 GW. A further increase in load results in overloading the lines within Area 1 and overloads on the 8 tie lines. The DSR modules are used to alleviate the overload and control the power flow over the transmission lines and tie lines. Case studies for increases in load are investigated, where the load increases range from 5% - 24% load growth. Table 6 depicts the total number of DSRs deployed in Area1 and the power delivered over the tie lines for the different load growth percentages.

From Table 6 it can be seen that at the early load increase percentages, till about 15% load growth, fewer numbers of DSRs are required. For the 120% load level and above, large numbers of DSR modules are needed.

TABLE6 DSRs DEPLOYED AND POWER DELIVERED FOR DIFFERENT LOAD GROWTH PERCENTAGES IN AREA1

% System Loading	105%	110%	115%	120%	121%	122%	123%	124%
#DSR Deployed	300	1200	3600	12000	15000	16500	19200	24600
Power 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

For an increase of 1.5 GW (15% load growth) in load, 3600 DSR modules are required. For an increase of 2 GW (20% load growth) in load, 12000 modules are required. Thus, for a 0.5 GW increase in load from 15% load growth to 20% load growth, more than 3 times the number of DSRs are required than for the previous 1.5 GW increase. This implies that DSRs may be more effective during early stages of load increase. Detailed results for the 15% load growth case are presented here.

For a load growth of 15%, two transmission lines and three tie-lines are overloaded. Applying the DSR control algorithm, a total of 3600 DSRs are deployed over the six lines to alleviate the overload and to shift the power flow to other more lightly loaded lines in the system. The power supplied after this deployment is 12.86 GW, resulting in an increase of 1.5 GW in load being achieved using 3600 DSR modules. Table 7 shows the results for the six lines before and after DSR deployment.

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

TABLE 7 DSR DEPLOYMENT RESULTS FOR THE LOAD GROWTH OF 15% IN AREA1

Line type	No. of DSRs deployed	Max Load % w/o DSR	Max Load % with DSR	Total MVA w/o 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

5 Economic Worth of DSR Design vs. New Line Construction

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

5.1 DSR Design

Table 8 shows the number of DSRs to be added and deployed over each line for each year to support a load growth to 140% in 40 years while handling N-1 contingency. To reach a load growth of 40% it is shown in Table 8 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 [27]. Table 2 presents the DSRs for each line for each load level design, and Table 8 presents the cumulative DSR design for 40% load growth while handling the N-1 contingency requirement. Fig. 5 depicts the number of DSRs added and the new lines constructed each year for the targeted 40% load growth.

TABLE 8
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

Fig. 5 DSRs and new lines added per year for 140% system load

5.2 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 Design #10, Line 7-8 and Line 6-11 were constructed, resulting in the addition of about 51 miles of new transmission lines.

Table 9 shows the 5 lines added and their lengths, highlighting the 2 additional lines added for the new line construction alternate design study. Fig. 6 depicts the lines in miles built each year to support the 40% load growth in 40 years.

Fig. 6 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 5.

From Fig. 5 and 6 it may be seen that the DSR design is delaying the construction of new lines for over 10 years.

TABLE 9
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	
		144.72

Fig. 6 New lines constructed per year for a 140% system load with the New Line Construction Alternate Design

5.3 DSR Worth Evaluation

The cost of the new line construction design will be used to evaluate the economic value of the DSRs. The evaluation uses the present worth value, shown in (7), for each design presented in the previous 2 subsections. This calculation sets an upper limit on the worth of a DSR. The present worth value for the two designs are shown in (8) and (9).

$$Present\ Value\ (P) = \frac{Future\ Value\ (F)}{(1+i)^n} \quad (7)$$

Present worth value for the DSR design =

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

$$= [2025 * C_{DSR} + 7500 * C_{DSR} / (1+0.1)^{10} + 2850 * C_{DSR} / (1+0.1)^{20} + 975 * C_{DSR} / (1+0.1)^{21}] + [(28.79 * C_{Line}) / (1+0.1)^{11} + (29.09 * C_{Line}) / (1+0.1)^{22} + (36.69 * C_{Line}) / (1+0.1)^{36}] \quad (8)$$

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 the new line construction design =

$$(28.79 * C_{Line}) + (58.18 * C_{Line}) / (1+0.1)^{20} + (36.69 * C_{Line}) / (1+0.1)^{30} + (27.48 * C_{Line}) / (1+0.1)^{40} \quad (9)$$

By equating (5.2) with (5.3) that has the cost of a DSR as an unknown, an upper limit on the cost of a DSR that will make it a better investment can be estimated, as shown in (10).

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

Using a construction cost of a 345 kV line C_{Line} as 2.5M\$/ mile [28]-[30], 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 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.

6 Conclusions

This paper studied controlling power flow on unbalanced transmission lines using DSRs under N-1 line contingencies. An unbalanced, 3-phase model of the physically modelled 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. The authors assumed a projected load growth for the next 40 years of 1% per year.

The DSR placement algorithm was used to try and find a DSR 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.

DSR design to control the power flow of a real power system over tie lines connecting different power pool areas and to control the power flow over transmission lines within an area itself is investigated for different load growth values under N-1 tie line contingencies. DSRs were more effective at early stages of load increase, as during the early load growth stages fewer numbers of DSRs were required to alleviate all overloads under N-1 contingencies.

An economic evaluation of DSRs for N-1 contingencies with load growth was presented. 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 to new line construction came to 11,557 \$ per DSR.

DSRs can be cost effective in managing load increases from year to a year, and can delay making 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 is 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 can offer other value streams not considered in this paper, such as control for balancing unbalanced transmission system voltages.

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