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RESEARCH ARTICLE

Investigation of distributed series reactors in power system applications and its economic implementation

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Summary
The transmission system expansion planning process requires lots of calculations looking many years into the future, and the results are based on assumed load growth. If the load growth assumed in the planning process is not correct and unexpected load growth occurs for some load points, the transmission system could face serious congestion and even overloading problems. In this paper, transmission line impedance adjustment techniques using distributed series reactance (DSR) is considered. The DSRs can be used to control power flow and alleviate overloading problems. A new term, DSR congestion relief factor, is introduced. The DSR congestion relief factor measures the increase of transmission line capacity with the application of DSRs. Parametric studies run on the IEEE 39-bus system are presented. These studies investigate the economic benefits of DSRs and the use of DSRs for single contingencies and compare DSRs with existing technologies for expanding the transmission system.

KEYWORDS
distributed series reactance (DSR), smart grid economy, transmission congestion

1 | INTRODUCTION

In transmission system planning projects, the cost of congestion is often a consideration. Building new transmission lines may not be the most cost-effective approach to alleviating congestion.[1] Many researchers have looked for a way to control power flow that is less costly than building new lines. For some cases, the only solution to control flow is to invest in new lines, but in some cases, there are other solutions. One new technique for controlling power flow, distributed series reactors (DSRs), shows promise.

Distributed series reactors are lightweight devices that can be installed quickly on transmission lines.[2] Distributed series reactors can be used to increase the capacity of a transmission system by moving flow from heavily loaded lines to lines that are in parallel and which have unused capacity. This is accomplished by using the DSRs to increase the reactance of the heavily loaded lines. In the study here, DSRs are used as an alternative way to alleviate overloading problems, providing economic benefits over building new transmission lines.

One of the traditional power flow control methods is transmission switching, which has been used for solving overload problems. Glavitsch[3] proposes transmission switching to alleviate congestion and shows that transmission switching reduces generation costs.[4,5]

A few studies[6–16] investigate several different methods for controlling power flow. Other authors[6,7] use series and shunt compensator devices to control power flow. Other studies[8–10] propose using flexible alternating current transmission system devices, but these devices are expensive for large-area implementations. Distributed series reactors have been developed to be used as distributed flexible alternating current transmission system (DFACTS) devices.[11–13] Kreikebaum et al[14] explain a distributed approach for realizing active power flow on existing lines by using DFACTS devices. Baby and Thilepa[15] investigate the flexibility of control that can be used with DFACTS devices. Kreikebaum et al[16] offer smart wires that can help reduce transmission investment to meet renewable portfolio standards. Omran et al[17] propose DSR module design suggestions to balance delivery voltages. Rahimi et al[18] offer a DSR solution for voltage imbalance.

The work here focuses on how DSRs can be used to control power flow and investigates optimizing the number of DSRs used to alleviate loading problems. Using DSRs to defer capital investments is also considered.

This paper is organized as follows. The DSR algorithm and a relief factor calculation are introduced in section 2. Economic evaluation and investment deferral are discussed in section 3. The case studies and discussions of the results are provided in section 4. Conclusions are given in section 5.

2 | CONGESTION RELIEF FACTOR AND DSR ALGORITHM

2.1 | Congestion relief factor

Distributed series reactor modules can be installed on meshed networks to provide a controllable reactance that may be used by operators to control power flow. Figure 1 shows the IEEE 39-bus transmission system used in this work. Line ratings, line lengths, and load flows for the system shown in Figure 1 are presented in Table 1.

The DSR congestion relief factor is defined as the rate of maximum system loading without DSRs to the maximum system loading with DSRs, as given by

$$\text{DSR congestion relief factor} = \frac{\text{Loading without DSR}}{\text{Loading with DSR}}.$$

Distributed series reactors may be used to postpone investments in new transmission lines. The deferred investment in new transmission lines can provide economic benefits. Figure 2 illustrates the algorithm used to calculate the congestion relief factor and associated economic savings.

TABLE 1 Information of transmission lines with load flow

From Bus	To Bus	% Loading	MW Flows	Line Rating, MVA	Length, Miles
1	2	29.320	119.182	400	34.605
2	3	42.789	361.896	850	12.853
2	25	21.447	233.381	1100	69.210
3	18	8.624	32.862	400	10.876
3	4	24.381	72.542	600	12.853
4	14	44.534	263.325	600	7.910
4	5	27.268	164.307	600	79.097
5	8	53.994	316.562	600	7.910
5	6	80.347	482.167	600	1.977
6	11	57.196	343.587	600	6.921
6	7	72.079	425.807	600	5.932
7	8	31.937	190.901	600	3.955
8	9	18.107	14.632	600	22.740
10	13	50.021	302.798	600	3.955
10	11	58.402	346.567	600	3.955
13	14	58.454	295.991	500	8.898
14	15	8.570	31.359	600	17.797
15	16	43.157	288.727	750	8.898
16	24	20.646	42.698	500	2.966
16	21	31.970	329.597	1000	7.910
16	19	44.049	451.230	1000	15.819
16	17	33.796	204.839	600	6.921
17	27	8.508	13.421	500	12.853
17	18	30.849	191.135	600	6.921
19	20	35.393	174.871	500	6.921
21	22	49.322	604.481	1200	7.910
22	23	14.389	42.797	500	5.932
23	24	28.217	351.329	1200	21.752
25	26	12.422	76.761	600	31.639
26	29	16.586	190.224	1100	56.356
26	28	12.316	140.862	1100	42.515
26	27	24.549	267.643	1100	12.474
28	29	30.215	347.693	1100	13.842

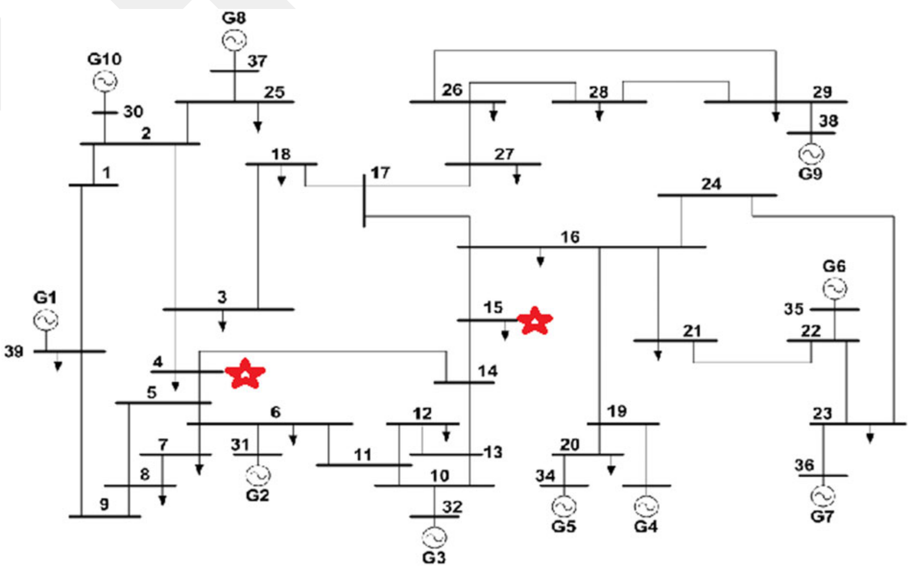

FIGURE 1 IEEE 39-bus transmission systems used in this study

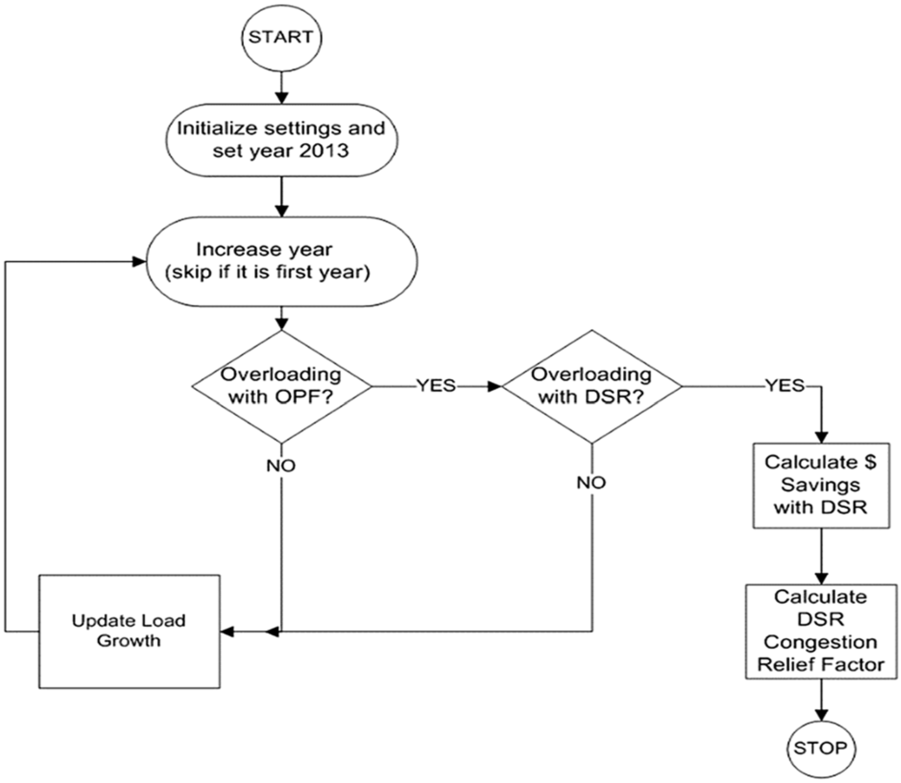

FIGURE 2 Algorithm for calculating the congestion relief factor and its associated economic savings. DSR, distributed series reactor; OPF, optimal power flow

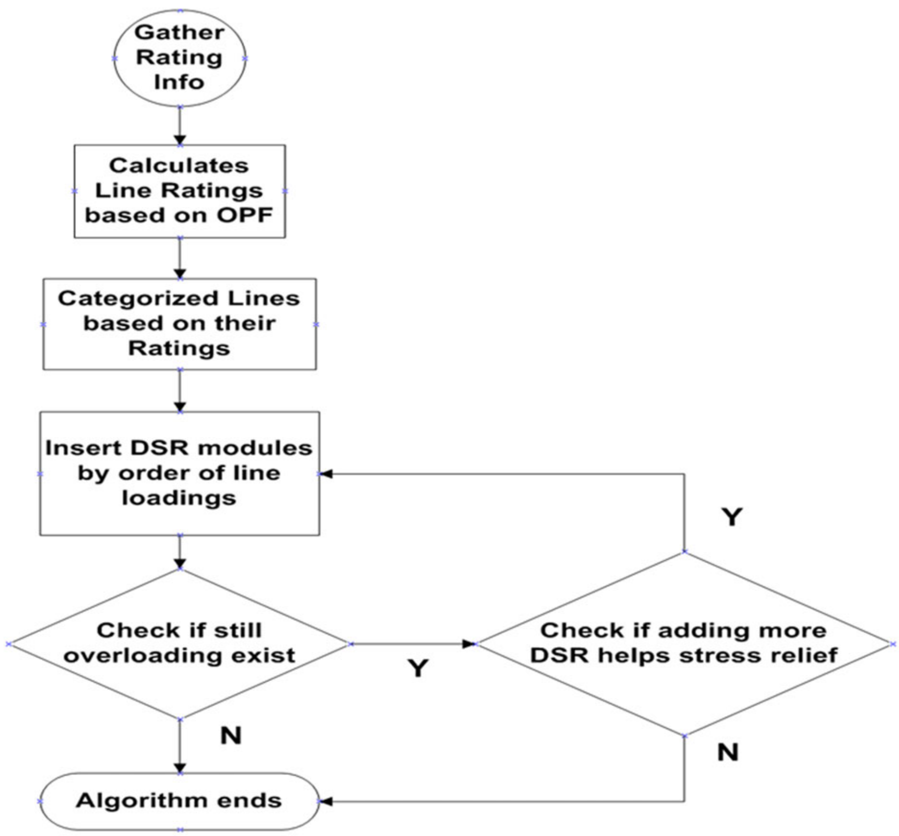

FIGURE 3 Algorithm for placing and operating DSRs. DSR, distributed series reactor; OPF, optimal power flow

2.2 | DSR methodology and algorithm

The DSR technology is based on increasing the impedance of a line, thereby pushing power flow from the line to other parallel paths. When a transmission line approaches its thermal rating, DSR modules may be activated to increase line impedance. This increases the power flow through parallel lines that may still have remaining capacity, more fully utilizing the capacity of the transmission system.

The DSR modules used for this study have an inductance of 0.05 mH/module (0.01885 Ω). The DSR algorithm used here to place and operate DSRs is shown in Figure 3.

Each iteration of the algorithm of Figure 3 includes the following steps:

Step 1. Using power flow, calculate the percentage loading for each line.

Step 2. Order lines from high to low on the basis of percentage line loading and flag lines loaded beyond 90%.

Step 3. Insert DSRs on lines loaded 90% and more than 90%.

The iteration is continued until there is no more stress relief with the addition of DSRs or there are no overloaded lines in the system.

TABLE 2 Cost of traditional equipment for congestion relief

Line Description	New Cost, $/mile
230-kV single circuit	927 000
230-kV double circuit	1 484 000
345-kV single circuit	1 298 000
345-kV double circuit	2 077 000
500-kV single circuit	1 854 000
500-kV double circuit	2 967 000

TABLE 3 Location of inserted DRS modules and costs of insertions for cases 1 and 2

From Bus	To Bus	No. of DSR Installed	Cost of DSR, k$	Length, miles	Cost of TL, k$
5	6	750	3750	1.977	2566
13	14	300	1500	NA	NA

Abbreviations: DSR, distributed series reactor; NA, there is no need to build extra transmission lines; TL, transmission line.

3 | ECONOMIC EVALUATIONS

As mentioned previously, economic benefits arise from using DSRs. This is because DSRs can be controlled so that the capacity of parallel paths is fully used. And DSR implementations can be less expensive than building new lines.

In section 4, the economics of 8 cases are compared. In the cases, the building of extra capacity with traditional methods is compared with investments in DSRs. Table 2 presents the construction cost for new transmission lines used in this study.[19–22] In this work, it is assumed that DSRs cost $5000/module.

In the comparisons, economic savings accrue because of the deferral of large capital investments in building new lines. The building of new lines needed for meeting load growth criteria can be delayed by using DSRs to more fully utilize the capacity of the existing system.

4 | CASE STUDIES AND DISCUSSIONS

Relative to the transmission system of Figure 1, 8 cases are considered as follows:

Case 1. Ten percent annual load growth applied to load points 4 and 15. These load points are shown as stars in Figure 1.

Case 2. The same as case 1, but this time, DSR modules are injected into the system, and the results are compared with case 1. The purpose of this case is to show how the DSR algorithm of Figure 3 can be used to control power flowing to the new load growth.

Case 3. Five percent annual load growth applied to all load points.

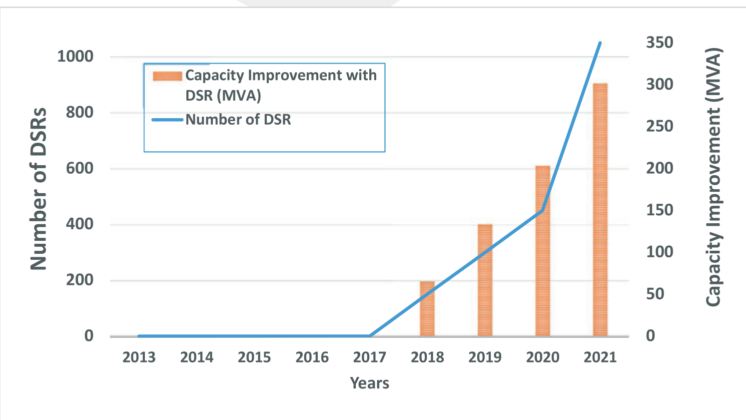

FIGURE 4 Capacity improvement associated with the distributed series reactor (DSR) number for cases 1 and 2

Case 4. The same as case 3, but this time, DSR modules are injected into the system, and the results are compared with case 3.

Case 5. One of the largest generation units, the unit at bus 35 in Figure 1, is taken out of service.

Case 6. The same as case 5, but this time, DSRs are used to control flows during the single generation contingency.

Case 7. In this case, a single line outage contingency is investigated on transmission lines 4 to 14.

Case 8. The same as case 8, but this time, DSRs are used to control flows during the single line contingency.

The 2 stars shown in Figure 1 mark the load points, busses 15 and 4, where the load growth occurs for cases 1 and 2. In cases 1 and 2, only the loads at busses 15 and 4 are increased by 10% annually. The other loads remain the same. In these 2 cases, we wish to show advantages of DSR usage for specific load growth. For the rest of the cases, cases 3 to 8, 5% of load growth is applied annually to each bus in the system, starting from 2013 until a system overload occurs without DSRs and then again with DSRs.

In case 1, the power flow was run from 2013 by increasing the load to 10% on load busses 15 and 4, and in 2018, an overload occurred on the lines between busses 5 and 6. The system loading for 2018 was 9047 MW.

In case 2, the power flow with DSR modules was run from 2013 by increasing the load to 10% on load busses 15 and 4, and in 2021, an overload occurred on the lines between busses 5 and 6. The system loading for 2021 for case 2 was 9782 MW.

From the information given in Tables 1 and 2, the cost of building extra transmission lines is calculated and represented in Table 3. Table 3 also shows the location of inserted DSR modules, number of inserted DSR modules, and cost of DSRs for case 2. In the Table, NA means that there is no need to build extra transmission lines for those lines.

The total capacity improvement with installation of 1050 DSR modules is 301 MVA (based on 2018 loading). The congestion relief factor is calculated as follows:

$$\text{DSR congestion relief factor} = 9047/9782 = 0.924$$

Figure 4 shows the number of DSR modules inserted in the system and capacity improvement with DSRs. The results are represented until 2021, as adding extra DSR modules

TABLE 4 Capital deferral savings for cases 1 and 2

From Bus	To Bus	Cost of DSR, k$	Capital Cost, k$	Deferral Savings (3 y) Present Value, k$
5	6	3750	2566	466

Abbreviation: DSR, distributed series reactor.

TABLE 5 Location of inserted DRS modules and cost of insertions for cases 3 and 4

From Bus	To Bus	No. of DSR Installed	Cost of DSR, k$	Length, miles	Cost of TL, k$
6	7	1000	5000	5.932	7699
13	14	900	4500	8.898	11 549
2	3	150	750	NA	NA

Abbreviation: DSR, distributed series reactor; NA, there is no need to build extra transmission lines; TL, transmission line.

TABLE 6 Capital deferral savings for cases 3 and 4

From Bus	To Bus	Cost of DSR, k$	Capital Cost, k$	Deferral Savings (3 y) Present Value, k$
5	6	5000	7 699	1400
13	14	4500	11 549	2100

Abbreviation: DSR, distributed series reactor.

TABLE 7 Location of inserted DRS modules and cost of insertions for cases 5 and 6

From Bus	To Bus	No. of DSR Installed	Cost of DSR, k$	Length, miles	Cost of TL, k$
13	14	900	4500	8.898	11 549
6	7	150	750	5.932	7 699

Abbreviation: DSR, distributed series reactor; TL, transmission line.

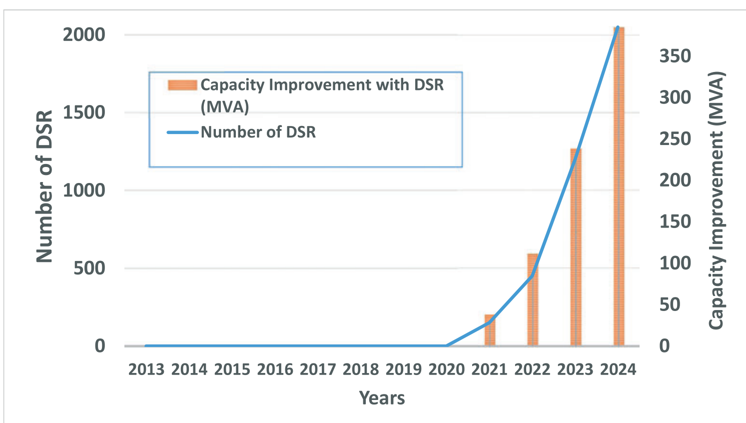

FIGURE 5 Capacity improvement associated the distributed series reactor (DSR) number for cases 3 and 4

does not help alleviate system overloading and capacity improvement after 2021, so the algorithm stops there. Economic savings are evaluated on the basis of the building of extra capacity with traditional methods versus investments in DSRs.

Another economic benefit with DSR is to defer large capital investments in building new lines. In cases 1 and 2, DSR investment would postpone extra capacity requirement for 3 years (from 2018 to 2021), so financial benefit comes from deferral of large capital investment, as shown in Table 4. Yearly interest rate is assumed to be 7.65% for present value calculation for all cases. The results from Table 4 show that by just delaying the capital investment for 3 years, utilities will save up to $466 000.

In cases 3 and 4, the benefit of DSR algorithm is tested for overall system load growth. For case 3, power flow was run from 2013 by increasing the load to 5% on all the busses, and in 2021, an overload occurred on the lines between busses 13 and 14. System loading on 2021 for case 3 is 9604 MW.

In case 4, the power flow with DSR modules was run from 2013 by increasing the load to 5% on all the busses, and in 2024, an overload occurred on the lines between busses 13 and 14. System loading on 2024 for case 4 is 10 820 MW.

Similar to cases 1 and 2, the cost of building extra transmission lines is calculated on the basis of the data in Tables 1 and 2 and presented in Table 5.

Table 5 also shows the location of inserted DSR modules, number of inserted DSR modules, and cost of DSRs for case 4.

Total capacity improvement with installation of 2050 DSR modules is 384 MVA based on 2021. The congestion relief factor is calculated as follows:

$$\text{DSR congestion relief factor} = 9604/10\,820 = 0.887$$

Figure 5 shows the number of DSR modules inserted in the system and capacity improvement with DSRs. The results are represented until 2024, as adding extra DSR modules does not help to alleviate system overloading and capacity improvement after 2024, so the algorithm stops there. Economic savings are evaluated on the basis of the building of extra capacity with traditional methods versus investments in DSRs. In cases 3 and 4, another economic study with DSR is whether large capital investment in building new lines can be deferred up to 3 years (from 2021 to 2024), and the results are presented in Table 6. The same yearly interest rate is assumed to be 7.65% for present value calculation.

There are generation outage case results represented in cases 5 and 6. In case 5, power flow without DSR modules was run from 2013 by increasing the load to 5% on all the busses, but in this case, one of the biggest sources was taken out in bus 35, and in 2020, an overload occurred on the lines between busses 13 and 14 and between busses 5 and 6. System loading on 2020 for case 5 is 9300 MW.

In case 6, the power flow with DSR modules was run from 2013 by increasing the load to 5% on all the busses, but in this case, one of the biggest sources was taken out in bus 35, and in 2021, an overload occurred on the lines between busses 13 and 14 and between 5 and 6. System loading on 2021 for case 6 is 9678 MW.

TABLE 8 Capital deferral savings for cases 5 and 6

From Bus	To Bus	Cost of DSR, k$	Capital Cost, k$	Deferral Savings (1 y) Present Value, k$
6	7	4500	7699	4362
13	14	750	11 549	6543

Abbreviation: DSR, distributed series reactor.

TABLE 9 Location of inserted DRS modules and cost of insertions for cases 7 and 8

From Bus	To Bus	No. of DSR Installed	Cost of DSR, k$	Length, miles	Cost of TL, k$
11	10	1000	5000	3.955	5 133
11	6	600	3000	6.921	8 983
7	6	750	3750	5.932	7 699
3	2	450	2250	12.853	16 683
5	4	150	750	NA	NA

Abbreviation: DSR, distributed series reactor; TL, transmission line.

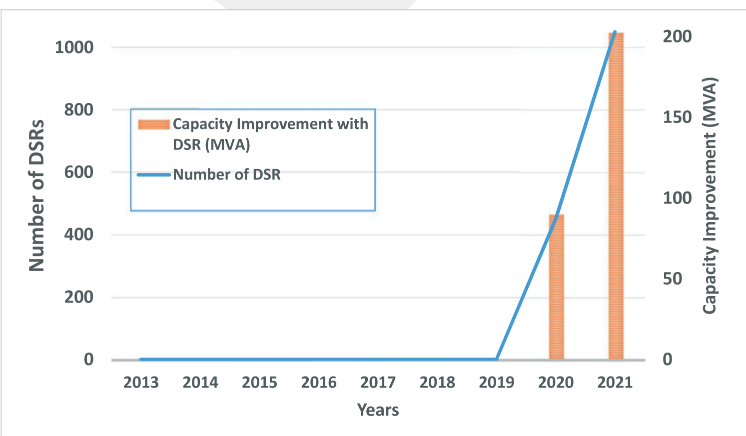

FIGURE 6 Capacity improvement associated with the distributed series reactor (DSR) number for cases 5 and 6

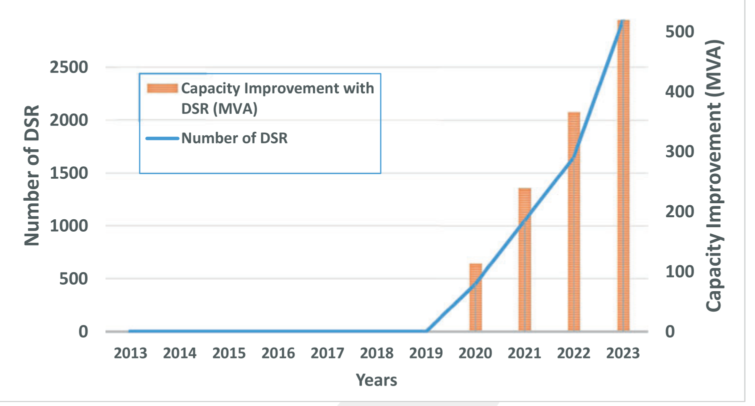

FIGURE 7 Capacity improvement associated with the distributed series reactor (DSR) number for cases 7 and 8

Table 7 shows the cost of building extra transmission lines with the inserted DSR module locations, inserted numbers of DSRs, and cost of DSRs for cases 5 and 6. Total capacity improvement with installation of 1050 DSR modules is 202 MVA based on 2020. The congestion relief factor is calculated as follows:

$$\text{DSR congestion relief factor} = 9300/9678 = 0.96$$

Figure 6 shows the number of DSR modules and capacity improvement with DSRs when there are generation outages. Capital deferral study for cases 5 and 6 showed that DSR would postpone extra capacity requirement for 1 year (from 2020 to 2021), so financial benefit with 7.65% yearly interest rate is shown in Table 8. The final case study is the outage of one of the largest transmission lines.

In case 7, the power flow without DSR modules was run from 2013 by increasing the load to 5% on all the busses, but in this case, one of the lines was taken out (lines 4-14), and in 2020, an overload occurred on the lines between busses 2 and 3, 6 and 7, 6 and 11, and 10 and 11. System loading on 2020 for case 7 is 9402 MW. In case 8, the power flow with DSR modules was run from 2013 by increasing the load to 5% on all the busses, but in this case, one of the lines was taken out (lines 4-14), and in 2023, an overload occurred on the lines between busses 2 and 3, 6 and 7, 6 and 11, and 10 and 11. System loading on 2023 for case 8 is 10181 MW.

Table 9 shows the cost of building extra transmission lines with the inserted DSR module locations, inserted numbers of DSRs, and cost of DSRs for cases 7 and 8. Total capacity improvement with installation of 2950 DSR modules is 510 MVA. The congestion relief factor is calculated as follows:

$$\text{DSR congestion relief factor} = 9402/10\ 181 = 0.923$$

Figure 7 shows the number of DSR modules and capacity improvement with DSRs when there are line outages. Capital deferral study for cases 7 and 8 shows that DSR would postpone extra capacity requirement for 3 years (from 2020 to 2023), so financial benefit with a 7.65% yearly interest rate is shown in Table 10.

TABLE 10 Capital deferral savings for cases 7 and 8

From Bus	To Bus	Cost of DSR, k$	Capital Cost, k$	Deferral Savings (3 y) Present Value, k$
11	10	5000	5 133	933
11	6	3000	8 983	1633
7	6	3750	7 699	1400
3	2	2250	16 683	3034

Abbreviation: DSR, distributed series reactor.

5 | CONCLUSIONS

The DSR is a smart grid technology that can be used to manage power flow and capacity expansion, reduce overloads during contingencies, and increase line utilization. This study represents a new control method of power flow by using DSR modules. Algorithm is tested on the IEEE New England (39-bus) test system. The results and observations with the DSR algorithm are stated here:

- The proposed algorithm with DSR modules can be used to manage power flow and capacity expansion and reduce overloads when some areas require special load growth.
- The proposed algorithm with DSRs is tested for constant load growth applied to each bus, and the results show that the proposed algorithm is also useful for entire-system expansion planning.
- Single contingency of generation outage is tested with the proposed algorithm. The results show that the proposed algorithm fully utilizes the capacity of the existing system by using DSRs when generation outages occurred.
- Line outages are also tested with the proposed algorithm, and one of the largest lines was taken out by considering the worst case; the results show that the DSR algorithm can utilize capacity effectively, when there are line outages and also overloading problems when there is a line contingency as well.
- Simulation results show the practicability and success of the DSR technique as a control for power flow in providing a cheaper alternative to the construction of new transmission lines.

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