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CIGRE US National Committee
2014 Grid of the Future Symposium

Initial Field Trials of Distributed Series Reactors and Implications for Future Applications

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SUMMARY

Distributed Series Reactors (DSRs) are a low-cost alternative for flow control on an individual phase basis. The devices are clipped onto line conductors, typically at each end of multiple spans, and can be installed or relocated in a very short time. Pilot tests on utility lines have demonstrated that DSRs perform as designed. Depending on the sophistication of the communication and control system, a wide range of operating characteristics may be possible. Studies are identifying advanced applications in future grid operation.

KEYWORDS

Distributed Series Reactors, FACTS, D-FACTS, Power Flow Control, Line Rating, Line Impedance, Series Reactance

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INTRODUCTION

The US grid is frequently described as aging, and many transmission lines have been in operation beyond their 30 - 50 year design lifetimes, but in reality inspection and maintenance programs ensure that structures, foundations, insulators, conductors, and sag issues are readily detected and repaired or even uprated. However, contingencies which may be caused by widespread severe weather, a desire to expand supply capacity and meet short lead times to encourage new industries, reduced use or retirement of older coal plants, or a need for outages to allow uprating, may challenge the ability of a grid to meet criteria for delivering power during certain windows of time.

Alternatives used to respond to these challenges tend to be situation-specific, uneconomic, and a burden for system operators. Flexible alternating current transmission systems (FACTS) are potentially attractive for power flow control, but are rarely used for this purpose due to their cost, centralized nature, and station space requirements, while they represent a cost and location commitment that is better suited to a long term need where often the requirement is for a limited time.

Distributed Series Reactors (DSRs) are an alternative approach for flow control that has been developed by a vendor working initially with the Tennessee Valley Authority (TVA) and the California Energy Commission and then advanced further with the additional participation of Southern Company, National Rural Electric Cooperative Association (NRECA), Baltimore Gas and Electric, Department of Energy (DOE), the National Electric Energy Testing Research and Applications Center (NEETRAC) and the DOE Advanced Research Program Agency - Electric (ARPA-E) [1]. DSRs are devices that are clamped to phase conductors and powered by the line current. A magnetic link allows the device to inject inductive reactance to increase line impedance. In a meshed transmission grid, increased impedance in one path results in transfer of power flow to other paths.

TECHNOLOGY DEVELOPMENT

In 2009, the National Electric Energy Testing Research and Applications Center (NEETRAC) established an initiative to develop and test a prototype DSR, develop a specification for the next-generation DSR, develop and test the next-generation DSR, and review the test results. The initiative founding members were TVA, Southern Company, Baltimore Gas and Electric, and NRECA.

The DSR, shown in Figure 1, consists of a split transformer hung from the conductor. The conductor forms the primary winding of the transformer. When the secondary winding is shorted, the unit operates in monitoring mode and negligible inductance is coupled in series with the line. When the secondary winding is opened, the magnetizing inductance of the transformer is coupled in series with the line, and the unit operates in injection mode.

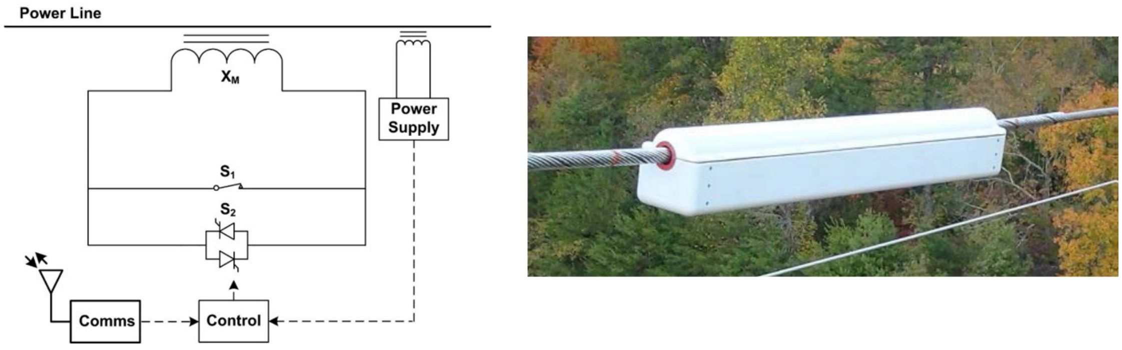


Figure 1: DSR on a Line Conductor

Over the operating range the coupled inductance is more than 50 microhenries (µH), as shown in Table 1. While an individual device has a very small effect on the impedance of a line phase, adding numbers of them can change reactive impedance by several percent. For a 161 kV line, one device per phase per mile provides approximately 2% impedance change. Thus 10 devices per phase per mile change the impedance by 20%. Since the devices are relatively inexpensive and can easily be hung at each end of each conductor span it is practical to consider adding quite large numbers of them, typically one at each end of each span.

Table 1: DSR Characteristics

Model	**Rated Current (A)**	**Injection Mode Inductance at Rated Current (µH)**	**Reactance added per DSR* (p.u.)**			
			115 kV	138 kV	161 kV	230 kV
750	750	47	1.34e-4	9.30e-5	6.84e-5	3.35e-5
1000	1000	42	1.20e-4	8.31e-5	6.11e-5	2.99e-5
1500	1500	37	1.05e-4	7.32e-5	5.38e-5	2.64e-5

DSRs can be controlled in several ways. They can be pre-programmed to operate at a given current threshold, managed manually from an operating center in response to system conditions, or controlled automatically for more complex applications. Communications may be simply through one-way power line carrier, or two-way through cell phone circuits. Manual or automatic control is achieved as shown in Figure 2 through real-time communications. A Super DSR manages a set of proximate DSRs and communicates with a DSR System Manager, which interfaces the entire fleet of DSRs with the energy management system (EMS).

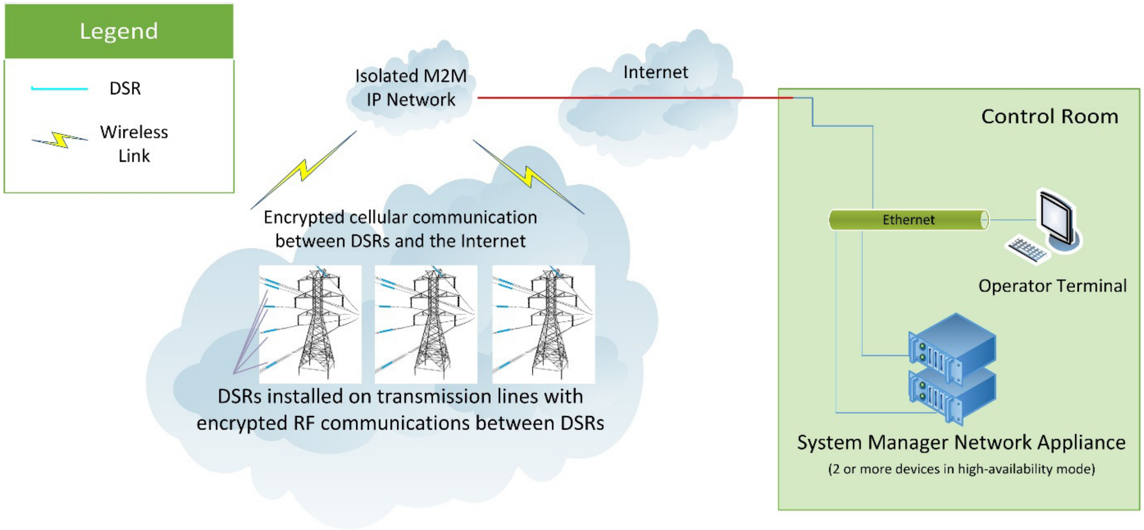


Figure 2: DSR Communications

The central System Manager allows configuring, monitoring and operating the DSRs as well as data archival. A DSR can provide line current, conductor temperature, fault location indication, fault current, , conductor vibration, conductor sag angle, and conductor blowout angle.

When the DSR controller detects a fault, it returns the units to monitoring mode in less than 4 milliseconds to ensure that the DSRs do not interfere with existing protection schemes. To date, none of the DSR pilot deployments have required any changes to protection settings.

APPLICATIONS

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

DSRs can be deployed to simplify or eliminate a remedial action scheme (RAS) or special protection scheme (SPS). In a study for a utility, a specific N-2 asset outage resulted in tripping generation and load with a RAS. Deploying DSRs on a number of transmission lines simplified the RAS and eliminated 1200 megawatts (MW) of generation and load shedding. In another study, DSRs in tandem with conventional system upgrade methods were able to eliminate 1800 MW of generation and load shedding.

In a further study DSRs added to six congested lines significantly reduced average electricity cost within an Interconnection. DSRs can dynamically adapt to mitigate congestion over a range of operating conditions.

DEPLOYMENTS TO DATE

The first pilot test included 100 units installed over 17 spans of a 21 mile 161 kV line owned by the Tennessee Valley Authority. Installations averaged approximately 10 minutes per unit including wire brushing the conductor, installation of protector rods and installation of an associated vibration damper. Figure 3 shows an installation in progress.

Figure 3: DSR Installation on TVA 161 kV Line

TEST RESULTS

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

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

While it may seem that DSRs are best suited to shorter lines since a small number of devices can achieve a desired percentage impedance change, in fact they are equally suited to lines of any length since the ratio of cost to add DSRs versus original line cost is approximately constant for a given percentage impedance change. The value of a given installation is determined from system studies and will be dependent on the individual relationship of the target line and existing power flows in the grid. Some examples are provided below.

ADVANCED DESIGN: CASE FOR UNBALANCED, THREE-PHASE MODELS

DSR design involves determining the number and location of DSRs needed to prevent an overload. As part of the ARPA-E project, EDD developed a DSR Design Tool. The tool uses Discrete Ascent Optimal Programming [2], and at each step of the optimization algorithm places DSRs on lines that have the most effect on power flow per DSR. Studies have shown that fewer DSRs placed on a line with no overload can be more effective than DSRs placed on the overloaded lines.

DSR design results are very dependent upon the model used to perform the study. That is, a three-phase model of a system with non-transposed lines and unbalanced impedances can give very different results than the single-phase, positive sequence equivalent of a non-transposed line.

The IEEE 39-bus standard model was modified to a three-phase model, and then all transmission lines in the standard model were replaced with 345 kV line models that use the unbalanced construction illustrated in Figure 4 [3]. The length of the 345 kV lines used in the Unbalanced, 3-phase model were made proportional to the positive sequence impedances of the lines in the IEEE 39-bus standard model, where a 20 mile line corresponded to the smallest positive sequence impedance in the standard model, and a 100 mile line was used for the largest positive sequence impedance.

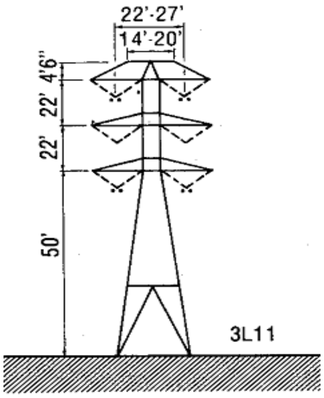
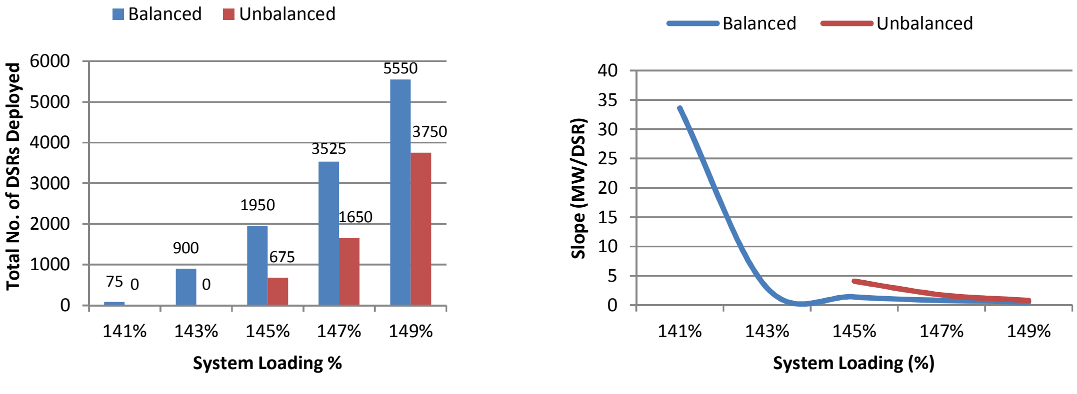


Figure 4: 345kV line construction used in the Unbalanced, 39-bus, 3-Phase Model

A second model used in DSR design studies was then derived from the Unbalanced, 39-bus, 3-phase model by applying symmetrical component transformations to the admittance matrices of the lines. The ratings of corresponding lines in the Unbalanced and Balanced 3-phase models were made the same.

Studies to evaluate DSRs for handling load growth were then performed for both models. In the design studies the load from the IEEE 39-bus standard transmission model provided the initial starting load, or 100% loading, and the load was then increased uniformly. Design results for the two 3-phase models are compared in Figure 5. Figure 5 (a) compares the total number of DSRs deployed versus percent loading level. It should be noted that the Balanced model has line overloads starting at 141% loading, and thus DSRs being added to eliminate overloads starting at 141% loading, whereas the Unbalanced model does not see overloads until the 145% loading level is reached.

From Figure 5(a), the Balanced, 3-phase model has more DSRs added to correct overload problems. These extra DSRs in the Balanced model design are explained by the comparison in Figure 5 (b), which shows the rate of change of MWs per DSR at each loading level. Starting at the 145% loading level the rate of change of MWs per DSR is larger for the Unbalanced model than the Balanced model.



(a) (b)

Figure 5: Comparison of design results for Balanced and Unbalanced 3-phase models

APPLICATIONS TO THE GRID OF THE FUTURE

When alternative paths exist in the power system, DSRs can often be controlled to access existing transmission line capacity that cannot be used today due to overloads on other lines, analogous to what automatic control often does in other areas. Automatic control allows us to take an existing plant and increase production at a lower cost than building a bigger plant.

Table 2 presents results of a study of the Unbalanced, 39-bus, 3-phase model described above. The study required satisfying a 40% load growth while handling all first contingencies. For certain contingencies DSRs were not effective. In such cases new 345 kV lines were added to the model so that the contingency could be handled. Altogether three new 345kV lines were added in parallel to existing lines, resulting in 95 miles of new transmission lines. Along with the three new lines, 1575 DSRs were also added to the system using the EDD Design Tool to achieve the 40% load growth. The 3 new lines added to the system only allowed for a 25% load growth without contingency problems, and so the DSRs were needed to achieve the 40% load growth where all first contingencies were handled.

Table 2: Results for Unbalanced, 3-Phase Model Design to Achieve 40% Load Growth While Handling all First Contingencies

Case	Max % Loading	Max Load MWs	MW Increase from Base
Base	100%	6309	
With 3 Lines Reinforced with Parallel Lines	125%	7886	1577
With 3 Lines Reinforced and 1575 DSRs	140%	8833	2524

Assuming a construction cost for 345kV lines of 1.3M$/mile [4,5,6], the cost per MW increase for the three new lines can be calculated as 78k$/MW, where the three new lines provided for 1577 MW of load growth as shown in Table 2. Using this cost per MW increase as a reference, the worth of each DSR per MW increase is 47k$/MW, i.e. if a DSR costs 47k$, then the per unit MW increase obtained by adding the 3 new lines is the same as that of adding the 1575 DSRs. In applications thus far, DSRs cost significantly less than 47k$.

Since lines in the transmission system are often not transposed, DSRs can be used in place of transposition to help balance receiving end voltages. If the sending end voltage of a line is unbalanced then line transposition does not help, but DSRs can still help balance the receiving end voltage. Unbalanced transmission leads to unbalanced voltages delivered to distribution systems. Such unbalanced voltages affect distribution system operations, and can prevent conservation voltage reduction programs from realizing their full potential.

Model-based control facilitates maximization of DSR benefits. Under a distributed version of model-base control, each transmission line with DSRs will have a local controller. The local controller will use a model of the three-phase line to make decisions about imbalanced operation of DSRs between phases to balance the line operation. Also a model-based, hierarchical system control can calculate where and how many DSRs to operate to control system flows. During normal system conditions DSRs will be operated to achieve the best economic operation. Lower generation cost that today cannot be accessed by some load areas due to transmission system limits, will be more fully utilized. With contingencies, real-time

DSR control can affect flows so overloads are eliminated, even in lines that do not have DSRs.

Fully integrating DSRs with EMS allows for coordinated optimization of the power system. For example, the capabilities of the DSRs post-contingency can be used to realize a generation dispatch that would be infeasible if DSRs were responding to local control. The optimality of the dispatch can be further extended by combining DSRs with dynamic line rating. The improved dispatch can be used to achieve lower production costs, higher reliability, or a combination of multiple objectives.

An advanced concept yet to be fully modeled is a grid with all lines equipped with DSRs, dynamically optimized in real time through a State Estimator or similar controller.

CONCLUSIONS

DSRs have been successfully demonstrated as a low-cost method of controlling power flow in a meshed transmission grid. Pilot tests have confirmed ease of application and relocation, hardware reliability, and controllability. Studies of potential applications continue and show that wider scale installations can achieve more sophisticated goals.

BIBLIOGRAPHY

[1] Deepak Divan et al, "A Distributed Static Series Compensator System for Realizing Active Power Flow Control on Existing Power Lines", *IEEE Transactions on Power Delivery*, 2007

[2] R. Broadwater, et al, "Minimum Loss Optimization in Distribution Systems: Discrete Ascent Optimal Programming," *Electric Power Systems Research Journal,* vol. 36, no. 2, pp. 113-121, 1996.

[3] EPRI, Transmission Line Reference Book - 345kV and above, Electric Power Research Institute, Third Edition, 1982.

[4] "Transmission and Substation Capital Costs," Western Electricity Coordinating Council, Aug.2012.

[5] A. Silverstein, "TRANSMISSION101 - Transmission Capital Cost by Voltage," in *NCEP Transmission Technologies Workshop*, April, 2011.

[6] "Generation & Transmission Model, Version2," Western Renewable Energy Zones, June 2009.