21, rue d'Artois, F-75008 PARIS
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Optimization of Fault Detection and Control with D-FACTS Sensing

F. BELL
Smart Wire Grid
United States

SUMMARY

The Distributed Series Reactance (DSR) module controls power flow in transmission lines by injecting reactance into congested lines forcing electricity to flow through less congested lines, allowing greater and more efficient utilization of the transmission assets already in place. This Distributed Flexible AC Transmission System (D-FACTS) device is distributed throughout the transmission network and senses factors in the line and communicates this data to the operator. This paper introduces the wide range of DSR capabilities that can be further utilized through smart, effective data processing to augment protection schemes and after-action diagnostics. The speed of communication and sensing tested in the DSR is proof that these capabilities are within reach.

KEYWORDS

FACTS, D-FACTS, sensing network, transmission, fault detection, power flow control, distributed monitoring, power line communication, power line data processing, after-action diagnostics

Frances.Bell@smartwiregrid.com

INTRODUCTION

Distributed Series Reactance (DSR) modules are Distributed Flexible AC Transmission System (D-FACTS) devices that alter the impedance in transmission lines to bias power flow in the desired direction and thereby reduce congestion in overloaded lines. Sensing and communication features are, by necessity, already built into the device and can be further utilized to augment security and protection schemes in transmission systems. In the simplest form, DSRs monitor line current and take autonomous action [3] by gradually increasing impedance in the line by comparing the existing line currents to the pre-determined current limit. As DSRs are implemented with power flow control and a wide range of sensing capabilities, these devices can be further utilized to augment protection schemes and aid in after-action diagnostics. These features can be implemented rapidly and at low cost by incorporating smart data processing that utilizes the sensing and communication system already set in place.

Energy demand is rapidly changing as heavy load locations move and the mix of power generation types changes to incorporate the increase in renewables, which adds stress and congestion to the grid. Because of this rapidly evolving energy climate, new transmission innovation technology is needed to meet new demands placed on the grid. In the past few decades, transmission infrastructure has developed slowly while consumption and generation have continuously developed and grown. The transition to a mesh electrical delivery system has aided in making the grid more reliable in many ways, including providing the ability to isolate faulted sections without interruption. However, the limited ability to control power flow creates a network that is congested and poorly utilized. Maintaining integrity of the system with shifting demand and rapidly changing power supply can be solved with sensors and switches that have the ability to effectively control power flow on the grid and improve reliability and security.

There are devices already on the market that aim to solve these issues, but none have been implemented widely enough to be successful. Existing technologies used for power flow control include the development of new lines, shunt VAR compensation, as well as Flexible AC Transmission System (FACTS) devices. However, these solutions have not been fully utilized due to high cost and implementation challenges. Additionally, these solutions cannot communicate occurrences at regular intervals and do not provide capability for detecting and responding to sudden contingency events on the grid.

Congestion on many paths comes as a result of limitations in only a small number of the lines that comprise the path. The result is a path that is congestion-limited even though its aggregate name plate capacity is significantly higher than the congestion rating. Transmission utilities generally have large footprints and many assets stretched out along challenging geographies; most lines span for miles with very limited monitoring and automation to predict, prevent, or diagnose contingency conditions. Incorporating sensing, communication, and power flow control to effectively monitor and maintain these assets would provide an enhanced level of security, efficiency, and reliability to the grid. Until recently, the cost of sensing and communication was too high to implement on a vast transmission system, but now, with D-FACTS devices, a grid that can be monitored and better-maintained is within reach. Tens of thousands of D-FACTS distributed across these lines for flow control purposes also create a sensing network to read power flow and line state statistics, which then can process and transmit this information to the system operator for a close-up set of data that details occurrences and contingency events on transmission lines.

D-FACTS offer flexibility, inherent "intelligence," fault tolerance, high sensing, low cost, and rapid deployment characteristics that provide an ideal platform for grid monitoring [5]. The concept of using D-FACTS modules as transmission control and sensing devices has been postulated, researched, and developed since in the early 1990s. Since that time, D-FACTS modules have been implemented and the DSR is a method of sensing and response for the grid as well as an optimized approach to power flow control. The DSR module controls power flow in transmission lines by injecting reactance into congested lines, forcing electricity to flow through less congested lines, allowing for more efficient utilization of the transmission assets already in place. Additionally, the DSR module has the capability of sensing conditions in the line and communicating this data to the operator. This paper proposes an additional use for these distributed devices to process line data and respond to contingency conditions on transmission lines by augmenting existing protection schemes for a more reliable and responsive grid. This rapid and secure protection scheme can be realized through a network of sensors in which D-FACTS offer low cost, flexible, and rapid deployment capabilities.

D-FACTS AND THE DSR

The functions of a D-FACTS module are managing power flow, sensing line status continuously, and communicating line status and contingency events. In particular, the DSR monitors line current so when the current passes a set threshold, the DSR injects impedance into the line to redirect power and thereby reduces congestion in the over loaded line. Additionally, the DSR's sensing capabilities are extensive and include line current, line temperature, line frequency, line voltage phase, sag, fault count, fault current peak and fault current profile. As illustrated in *Figure 1*, the DSR is coupled to the line through a single-turn transformer allowing for reactance injection on command. The module is self-powered using the line current from the single-turn transformer. The module is in bypass mode when the electromagnetic switch, S_M, is closed. When S_M is open, S_1 closes and series reactance is then inserted into the line. The DSR contains an internal fault protection scheme allowing the module to revert to bypass mode under fault current conditions or lightning strikes, then resume normal function after these high current conditions have passed. Since the DSR is not connected to ground, it operates at line potential thus eliminating isolation issues.

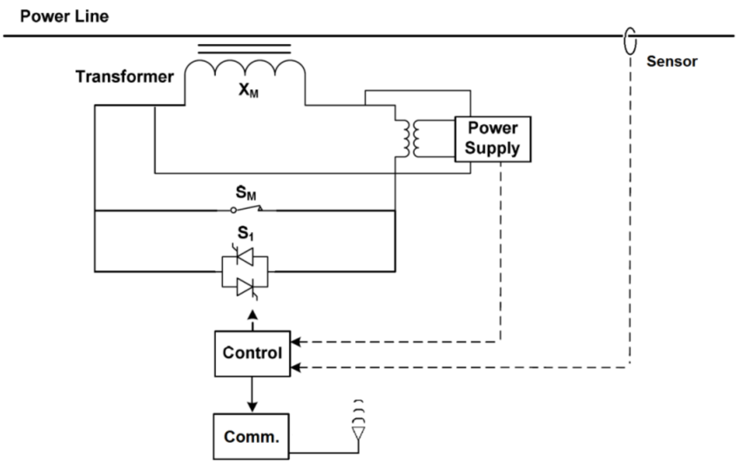


Figure 1: Schematic of the DSR

To determine when injection mode begins, DSR modules can either be pre-set to run independently or the operator can choose to remotely control the devices to increase or decrease the current set-point at which reactance begins to be injected. As the current increases in the line, more DSR modules are activated thus linearly increasing the impedance to reduce loading in the line as shown in *Figure 2*. The more modules distributed along a line, the larger the impact the devices will have on the power flow.

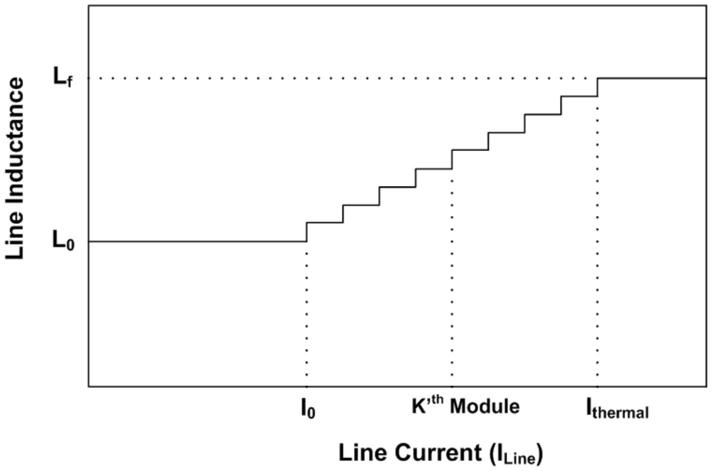
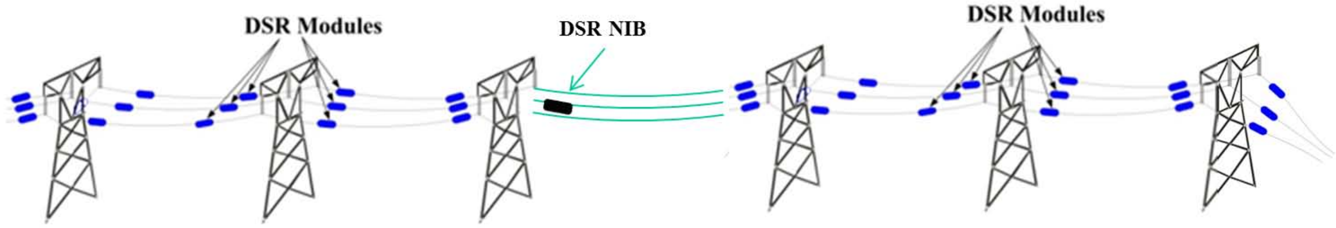
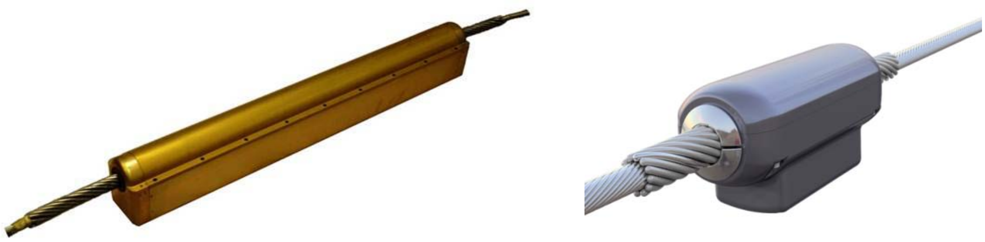


Figure 2: Correlation of line current to DSR inductance injection in the line

Additionally, DSRs transmit the information to a centralized data collection processor called the Network Interface Bridge (NIB). As illustrated in *Figure 3*, DSR modules are distributed along transmission lines mounted on each phase, requiring these devices to be installed in sets of three for balanced control and monitoring. NIBs are distributed at less frequent intervals behaving as a receiver and transmitter for large packets of DSR data.



(a)



(b)

Figure 3: a) Diagram depicting DSRs and NIB deployed on transmission lines b) image of DSR (left) and NIB (right) mounted on a line

The communication features of the DSR report the state of the device as well as the dynamic parameters of the line, but still make autonomous decisions if connection with the operator is lost. As depicted in *Figure 4*, each module contains a communication device that communicates sequentially, sending a packet of information to the next DSR device on the line until it reaches the NIB where the information of all DSR data packets is collected and processed, then transmitted to servers through a secure Internet Protocol (IP) network. NIBs are lighter weight and serve the purpose of processing DSR data quickly and rapidly sending as much of this information to the operator as desired. Self-organizing techniques ensure that the failure of a single DSR or NIB does not affect the ability and function of the D-FACTS network. Additionally, since there are tens of thousands of modules in a transmission system, the failure of one or more modules would not affect the operation of the data network. This distribution of D-FACTS devices provides continuous monitoring to detect unexpected events.

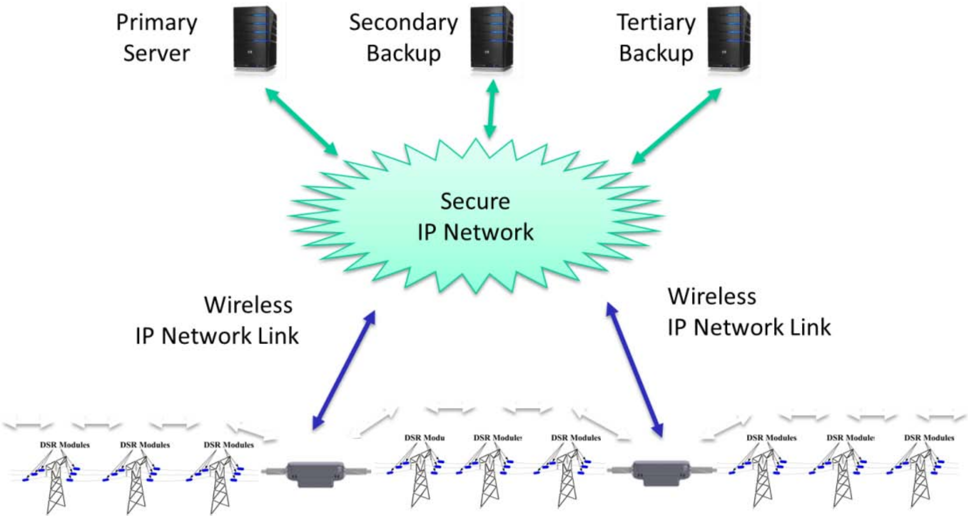


Figure 4: Sensing network communication diagram

The DSR has been realized through the ability to produce a multi-functioning device that can be distributed with enough regularity that accurate line sensing calculations can be obtained. This method of distributed DSRs is successful due to a low cost, rapid method of communicating and responding to power flow management. The next section will discuss new features that have been tested and can be implemented in the DSR to further augment security and protection schemes in the transmission system.

FUTURE OF D-FACTS SENSING

The existing capabilities of the DSR, power management, line sensing, and communications, can be optimized by adding a fourth feature: data processing. Data processing would give continuous estimation of line status to aid in detecting incipient faults and other contingency conditions. Processing line information from the D-FACTS sensors can play an important role in a faster and more reliable protection scheme as well as after-action diagnostics. Additionally, with fast data processing and analytics, operators can be provided with continuous and distributed updates on main transmission lines. Two components of data processing that will be discussed in the rest of this section are a response system that reacts to detected contingency conditions and an operator control interface. A key aspect in analyzing this data is the ability to process the information rapidly while it is still actionable. With these analytics, the addition of an operator control interface will allow for optimization planning and continuous line status updates.

A. *Response to Contingency Conditions*

Through information processing, D-FACTS's existing sensing capability can be useful for augmenting system reliability and protection as well as after-action diagnostics. This augmented protection scheme could not only add speed to fault detection and other contingency events, but it could also be used to accurately and rapidly determine fault type through calculating the fault current rate of rise. Location of fault can be determined through power directionality sensing and current magnitude. During fault, DSRs store a total profile of a fault and can be downloaded to include a total fault image and information before and after the occurrence. NIBs have faster communication capabilities than a network of DSRs, which can be utilized to rapidly detect a contingency event. Once action has been taken, a detailed analysis from DSRs can be delivered for after-action diagnostics. *Figure 5* timelines illustrate the speed at which a NIB can detect, process, and communicate a fault to the protection scheme.

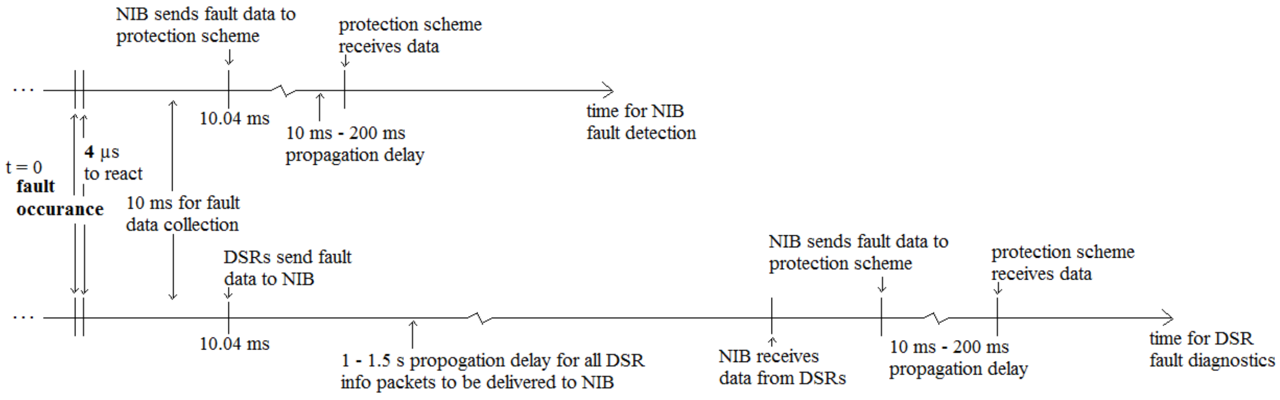


Figure 5: Top time line illustrates the speed of the NIB reaction to fault detection and communication; the bottom timeline shows the speed of the fault detection in the DSR's sensing and communication

Both the NIB and the DSR have a threshold point of 1800 A at which point the module is instantaneously tripped and a fault is detected. The computer processor within the NIB reacts in 4 µs to record fault data for 10 ms then sends the fault information to the protection scheme. As can be seen from the timeline, propagation time can vary depending on the speed of the IP network that the data is being transmitted through. Since the NIB communicates directly with the protection scheme, it sends the fault detection information much faster. The protection scheme can receive contingency event data within 20 ms with a rapid communication network. This speed is useful for augmenting system reliability and quickly reacting to prevent cascading in the system. Once the contingency event has been responded to, enough time will have passed for the DSRs to propagate up the line to reach the NIB at which point the NIB delivers all the gathered DSR information to the data processor. Data analysis including fault location, fault type, and which phases are effected is delivered in about three seconds.

In short, the speed of the NIB communication can be utilized by first using NIBs to detect a fault in as quickly as 20 ms then shortly following with the networked DSR information for detailed analysis in about 3 seconds that includes fault location and type. Other sensor data such as temperature, sag, vibration, motion, leakage, etc. can be incorporated into this analysis to better predict contingency events and continuously monitor the state of the transmission line. With the speed of the NIB to transmit and process data to the protection scheme, D-FACTS can be used to enhance the reliability and security of the protection scheme. Additionally, the distributed feature of these DSR modules gives detailed analysis of the contingency event on the lines.

B. *Operator Control Interface*

As part of the contribution to an augmented protection scheme, it is imperative to have an operator control interface through which the operator can easily and accurately read the system analysis from the DSR sensors and quickly determine solutions after contingency events have occurred. In order to have an integrated operator control interface, it is important to have visual status updates of the transmission system, rapid data processing during contingency events, and planning tools to determine optimized DSR location for power flow control and line sensing. With these devices, operators can have enhanced tools for responding to unplanned events including faults.

Currently, the DSR outputs large arrays of tables full of data at frequent intervals that cannot be quickly interpreted by an operator. In order to make use of this large amount of information, the data must be processed and reduced to the appropriate level for an operator to digest. This can be achieved by processing the data and outputting the analysis into graphical or schematic form for a system overview. Then, if the operator is interested in a particular line of portion or the system, tables and lists of requested data can be retrieved. Transmission operators already interact with and use a graphical interface to plan, maintain, and read the grid. The distributed sensing information could be incorporated into this interface and would enhance this analysis of the computing system already in place by giving localized line status updates, next step processing after contingency events, and more detailed information for planning transmission development.

Visual status updates would provide an overview of measured line parameters. A map of transmission lines and power flow information would be displayed with detailed sensing data when requested by the user. User-defined flags would appear when there is an issue and notices would flash for lines with increased congestion and incipient contingency events. Lists and data sheets would not be displayed at this top level of information processing, but translated into a constantly changing schematic that can be analyzed quickly and accurately by the user. Necessary tables of data would display only at the operator's request when investigating particular lines after a contingency event. Next step processing can be used after an event such as a fault has occurred. At this point, the system can determine which breakers have been tripped, describe the event by calculating where the fault is located between DSRs, and propose problem resolution options. Additionally, this system analysis can be utilized for system planning at optimized locations for D-FACTS or added transmission lines.

These three features improve the real-time situational awareness of the transmission system that will allow improvement of grid operations and planning against measured metrics on the lines. Accurate real-time information allows for higher line capacity and safer operation with faster corrective action. In order to build these analytical tools, system integration and data analysis interfaces must be developed so that the operator only receives the necessary information to read lines and make effective decisions.

CONCLUSION

D-FACTS have been realized now that DSRs have been implemented for power flow control on congested lines. The wide range of DSR sensing capabilities can be further utilized through smart, effective data processing to augment protection schemes and after-action diagnostics. The speed of communication and sensing tested in the DSR is proof that these capabilities are well within reach. Work is underway to demonstrate data processing and DSR optimization planning.

ACKNOWLEDGEMENTS

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