Distributed FACTS—A New Concept for Realizing Grid Power Flow Control

Deepak Divan and Harjeet Johal

***Abstract*—Flexible ac Transmission Systems (FACTS) devices are used to control power flow in the transmission grid to relieve congestion and limit loop flows. High cost and reliability concerns have limited the widespread deployment of FACTS solutions. This paper introduces the concept of Distributed FACTS (D-FACTS) as an alternative approach to realizing cost-effective power flow control. By way of example, a distributed series impedance (DSI) and a distributed static series compensator (DSSC) are shown that can be clipped on to an existing power line and can, dynamically and statically, change the impedance of the line so as to control power flow. Details of implementation and system impact are presented in the paper, along with experimental results.**

***Index Terms*—Flexible ac transmission systems (FACTS).**

I. Introduction

THE power grid infrastructure in the U.S. is in urgent need of modernization. Of the challenges facing utilities, possibly the most urgent is the issue of eliminating transmission constraints and bottlenecks. Increasing congestion and loop flows on the transmission and sub-transmission system degrades system reliability, increases energy prices and prevents full utilization of existing assets [1]. As system operators are required to maintain operation under (N-1) and often (N-2) contingencies, system capacity can be dramatically decreased even as existing lines operate significantly below their thermal limits. The increase in generation connected to the grid, a sustained decrease in transmission infrastructure investments over the last two decades, and long delays in citing and approval of new transmission lines has exacerbated the problem considerably. Under such conditions, it becomes critical that existing T&D resources be fully utilized.

Possibly the most significant issue in terms of grid utilization is that of active power flow control. Utility customers purchase real power, megawatts and MW-Hrs, and not voltage or reactive power. Thus, control of how and where real power flows on the network is of critical importance, and is the underlying premise behind the realization of an electricity market. Congested networks limit system reliability and constrain the ability of low cost generators to provide interested customers with low-cost power. The situation is considerably aggravated when one sees that neighboring lines are running below capacity, but cannot be utilized, while uncontrolled "loop-flows" result in overloads on existing lines. Active power flow control requires cost-effective "series VAR" solutions, that can alter the impedance of the power lines or change the angle of the voltage applied across the line, thus controlling power flow. Series reactive compensation has rarely been used other than on long transmission lines, mainly because of high cost and complexity of achieving voltage isolation and issues related to fault management.

There is general consensus that the future power grid will need to be smart and aware, fault tolerant and self-healing, dynamically and statically controllable, and asset and energy efficient. The accepted and technically proven approach for realizing a smart grid, in particular achieving control of active power flow on the grid, has been through the use of Flexible ac Transmission Systems or FACTS [2]–[4]. FACTS devices, such as STATCON, SVC, SSSC and UPFC can be inserted in series or shunt, or a combination of the two, to achieve a myriad of control functions, including voltage regulation, system damping and power flow control. Typical FACTS devices can operate at up to 345 kV and can be rated as high as 200 MVA. Even though FACTS technology is technically proven, it has not seen widespread commercial acceptance due to a number of reasons. i) High system power ratings require the use of custom high power GTO or GCT devices with significant engineering effort - raises first cost. ii) High fault currents (60 000 Amps) and basic insulation requirements (1000 KV) stress the power electronics system, especially for series systems that are required for power flow control. iii) Utilities require higher reliability levels than what they have so far experienced with FACTS devices (primarily as a result of high MTTR). iv) Required skilled work force in the field to maintain and operate the system is not within a utility's core competency normally. v). High total cost of ownership, e.g., the Marcy Convertible Static Compensator (CSC) cost $54 million.

This paper discusses the concept of a distributed approach for realizing FACTS devices, in particular series FACTS devices. The increasing performance and decreasing price of electronics, power electronics and communications technologies have transformed entire industry sectors. It is proposed that a similar approach to the implementation of high power FACTS devices can provide a higher performance and lower cost method for enhancing T&D system reliability and controllability, improving asset utilization and end-user power quality, while minimizing system cost and environmental impact.

The concept of a Distributed Series Impedance (DSI) that can realize variable line impedance, helping to control active power flow is used to illustrate the feasibility of a Distributed FACTS

Manuscript received February 7, 2006. This work was supported in part by the Intelligent Power Infrastructure Consortium (IPIC), Georgia Tech. This paper was presented in the 36th IEEE Power Electronics Specialist Conference, Recife, Brazil, 12 June-17 June 2005. Recommended for publication by Associate Editor H. D. Mouton.

The authors are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30318 USA (e-mail: deepak.divan@ece.gatech.edu; harjeet.johal@gatech.edu).

Digital Object Identifier 10.1109/TPEL.2007.909252

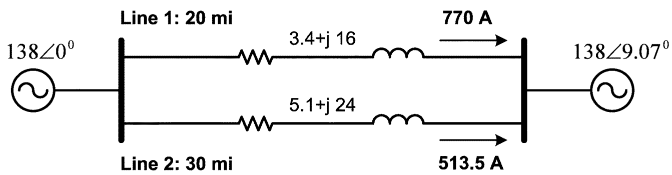

Fig. 1. Circuit schematic of a 2 bus system.

or D-FACTS approach. The concept can be further extended to realize a Distributed Static Series Compensator or DSSC, using modules of small rated (~10 kVA) single phase inverters and a single turn transformer (STT), along with associated controls, power supply circuits and built-in communications capability. These concepts are discussed in detail, along with the benefits and issues associated with such an application.

II. Principles of Active Power Flow

For controlling power flow on transmission lines, the series elements clearly have the highest potential and impact. The real and reactive power flow, P and Q, along a transmission line connecting two voltage buses is governed by the two voltage magnitudes V_1 and V_2 and the voltage phase angle difference, $\delta = \delta_1 - \delta_2$

$$P_{12} = \frac{V_1 V_2 \sin\delta}{X_L} \tag{1}$$

$$Q_{12} = \frac{V_1^2 - V_1 V_2 \cos\delta}{X_L} \tag{2}$$

where X_L is the impedance of the line, assumed to be purely inductive.

Control of real power flow on the line thus requires that the angle δ, or the line impedance $\mathrm{X_L}$ be changed. A phase shifting transformer can be used to control the angle δ. This is an expensive solution and does not allow dynamic control capability. Alternatively, a series compensator can be used to increase or decrease the effective reactive impedance X_L of the line, thus allowing control of real power flow between the two buses. The impedance change can be effected by series injection of a passive capacitive or inductive element in the line. Alternatively, a static inverter can be used to realize a controllable active loss-less element such as a negative or positive inductor or a synchronous fundamental voltage that is orthogonal to the line current [3], [4].

Fig. 1 shows a simple power system with two lines by way of illustration. Line 1 is 20 miles long and Line 2 is 30 miles long. Line 1 reaches thermal limit before Line 2 does. At that point no more power can be transferred without overloading Line 1, even though Line 2 has additional unutilized capacity.

Transmission and sub-transmission systems today tend to be increasingly meshed and inter-connected. The ability to switch out faulted lines without impacting service has a dramatic impact on system reliability. However, in such interconnected systems, current flow is determined by line impedances, and the system operator has very limited ability to control where the currents flow in the network. In such systems, the first line to reach thermal capacity limits the capacity of the entire network, even as other lines remain considerably under-utilized. For example, if series reactive compensation could be applied to the two line system in Fig. 1, an additional 52 MW of power could be transferred between the two busses by changing the line reactance by 20%.

Series FACTS devices can control power flow by varying the parameters in (1). Such devices typically require a break in the line and a high voltage platform, further adding to the cost and complexity. What is clearly required is a cost-effective, scalable and controllable series impedance device that can be incrementally deployed, and that features high reliability and availability. A distributed approach to implementing series FACTS devices is seen to be very attractive and is discussed next (see Table I).

III. Distributed Series Impedance

For a typical 138 kV transmission line, the impedance $\mathrm{X_L}$ is approximately 0.79 ohms/mile [5]. At the line thermal capacity of 770 A corresponding to 184 MVA of power flow, the voltage drop across the line impedance is thus 608V/mile. A 2% change in line impedance would thus require injection of 12.16 V or 0.0158 ohms/mile. This translates into an inductance of 42 μH or 9.24 kVAR (12 V at 770 A). This is a surprisingly small value of impedance to have a significant impact on the power line capacity and could be accomplished with one single 9.24 kVAR module deployed per mile of the line. Such a module could be small and light enough to be suspended from the power line, floating both electrically and mechanically, on the line itself! This also raises the possibility of implementing a Distributed Series Impedance DSI, as shown in Fig. 2, using a large number of such 'standard' modules that can be clamped around an existing power line conductor. Such a distributed solution to power flow control, essentially a distributed FACTS or D-FACTS solution, can offer significant benefits over conventional FACTS technology.

The series injection of impedance or voltage at each module can be accomplished using a single turn transformer (STT), which uses the line conductor itself as a winding of the transformer. By floating the device on the wire, all issues of voltage rating and insulation are avoided.

The redundancy provides for uninterrupted operation in the event of a unit failure, giving high reliability and availability. The STT allows handling of high levels of fault current, typically a challenging problem for series connected devices. The target power rating of ~9.2 kVA allows the use of readily-available high-volume low-cost components and manufacturing technologies to realize very low unit module cost. The devices can be incrementally deployed as needed, providing an unprecedented level of scalability. Finally, the DSI device can be clamped on to an existing power line, simplifying the installation and commissioning process. These properties demonstrate a unique level of functionality for series D-FACTS devices that is radically different from conventional FACTS devices. Implementation of a Distributed Series Impedance is discussed next.

A. Distributed Series Impedance-Principle of Operation

A simple implementation of a DSI uses three switches, a capacitor and an inductor, in conjunction with the STT as shown

TABLE I
INCREASE IN POWER TRANSFER BY CHANGE OF LINE REACTANCE

Line Reactance (Ω)	Line Currents (A)	Load Angle (deg.)	Line Power (MW)	Transferred Power (MW)
$X_1 = 16$ $X_2 = 24$	$I_1 = 770$ $I_2 = 513.5$	$\delta = 9.07^0$	$P_1 = 176.5$ $P_2 = 117.7$	294.2
$X_1 = 19.2$ $X_2 = 19.2$	$I_1 = 770$ $I_2 = 756$	$\delta = 10.81^0$	$P_1 = 177$ $P_2 = 169.4$	346.4

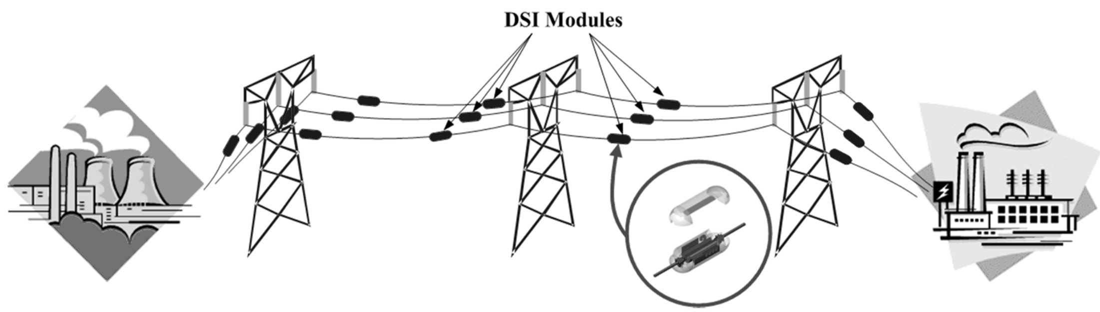

Fig. 2. DSI modules on power lines.

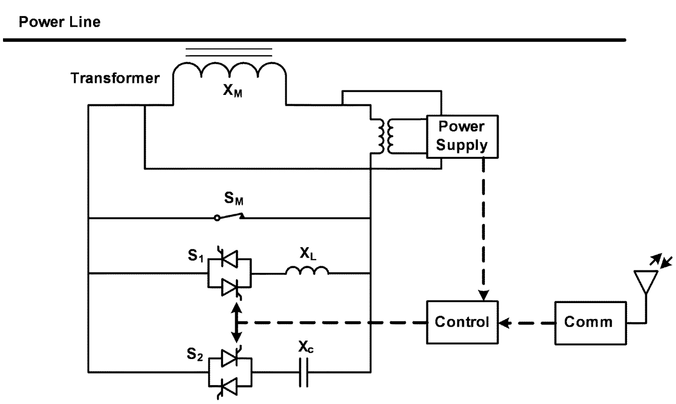

Fig. 3. Circuit schematic of DSI.

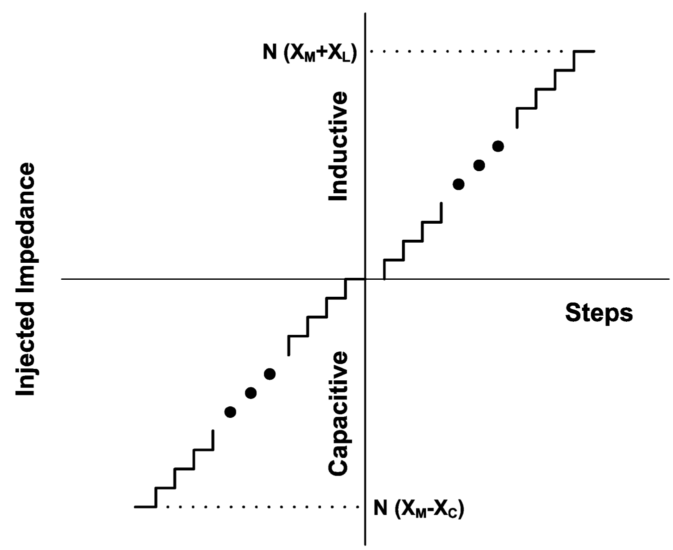

Fig. 4. Profile of line impedance as the modules are switched.

in Fig. 3. Static switches are preferred for fast response under fault conditions. The STT is designed with a large number of secondary turns, say 50:1. The STT is normally bypassed by the normally-closed electro-mechanical switch $\mathrm{S_M}$, while opening it allows injection of the desired impedance. Switch $\mathrm{S_1}$ is closed to inject an overall inductance, while $\mathrm{S_2}$ is closed to inject capacitance X_C. Control power can be derived from the line itself using a current transformer.

If N devices are used in series along the power line, one can realize 2N discrete values of line impedance as shown in Fig. 4. If N was a large number, say 100, the impedance could be changed with 0.5% resolution, approximating a linearly varying line impedance. Operation of individual modules would need to be coordinated with a communications link, and would be controlled by the system operator [8]. This would clearly require establishing a communications infrastructure that could cost-effectively connect individual modules and the SCADA/EMS systems.

B. Distributed Series Reactor-Principle of Operation

Fig. 5 shows an even simpler implementation of a Distributed Series Reactor (DSR), that can be deployed in interconnected or meshed power networks, and can be autonomously controlled at the individual module level, using a simple control strategy with no communications to dramatically increase the capacity of the overall power grid [6]. As in the case of the DSI, a normally closed electromechanical switch $(\mathrm{S_M})$ is used to bypass

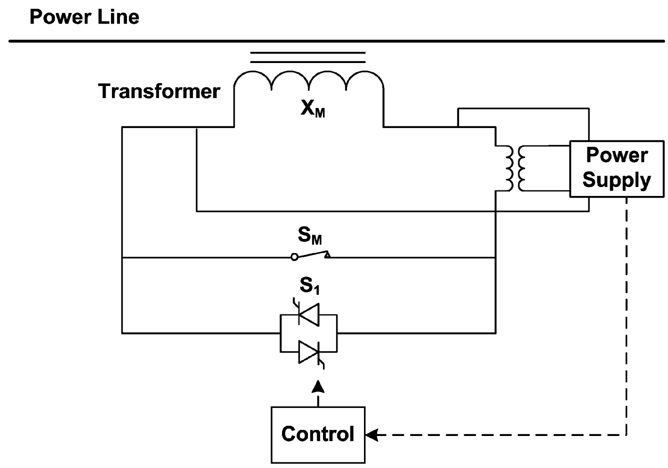

Fig. 5. Circuit schematic of DSR.

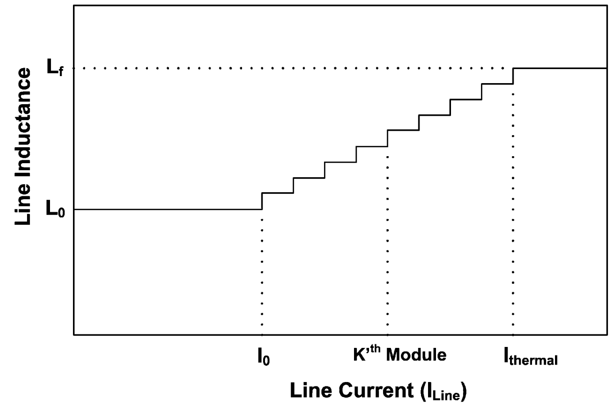

Fig. 6. Increase in line inductance with switching in of DSR modules.

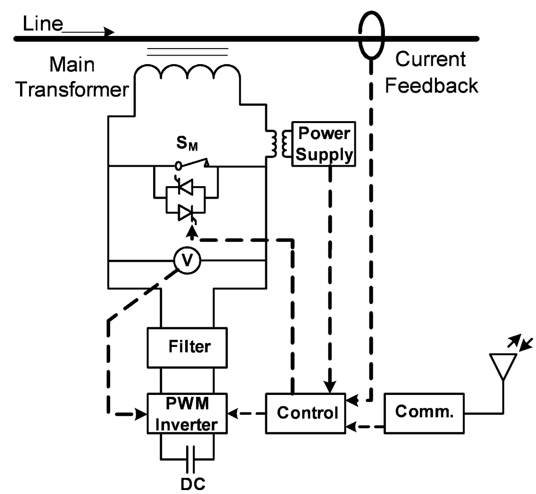

Fig. 7. Circuit schematic of DSSC.

the module when it is not energized. With $\mathrm{S_M}$ open, switch $\mathrm{S_1}$ controls insertion of the series reactance. With $\mathrm{S_1}$ closed, a minimal level of reactance, corresponding to the STT leakage reactance, is inserted in the line. With $\mathrm{S_1}$ open, the STT magnetizing inductance, tuned to the desired value by setting the air-gap, is inserted into the line.

At a system level, as the current in a particular line exceeds a predetermined value, increasing numbers of DSR modules are switched in, gradually increasing line impedance and diverting current to under-utilized lines. As the overall control objective is to keep lines from thermal overload, the control strategy is seen to be very simple. A control algorithm for DSR module operation is defined in (3).

$$L_{\mathrm{inj}} = L_f \frac{(I - I_0)}{(I_{\mathrm{thermal}} - I_0)} \tag{3}$$

where

L_{inj} is the injected line inductance;

L_f is the final value of inductance with all the DSR modules on the line active;

I_0 is the triggering value of current for a module;

I_{thermal} is the thermal limit beyond which there is no injection.

Different modules on a line have predetermined switching levels (based on line current) that collectively provide a line inductance that increases as the line current increases above a defined threshold, as seen in Fig. 6. Pre-selected lines that are likely to see overload conditions at certain times of the day or under defined contingency conditions can be modified with DSR modules to automatically handle the congestion when it occurs, and to minimally impact the system under "normal" operating conditions. Deployment of DSR modules on a power line can thus help to realize the concept of a "Current Limiting Conductor." Control of DSR modules, when implemented on multiple lines, has to ascertain that no oscillations or interactions occur. An exponentially decaying estimator, as shown in (4), is used within each module to minimize interactions between modules and lines

$$L_{\mathrm{exp}} = (L_{\mathrm{inj}} - L_{\mathrm{prev}}) \left(1 - \mathrm{e}^{-(t-t_0)}\right) + L_{\mathrm{prev}} \tag{4}$$

valid over $t_0 \leq t \leq t_0 + \Delta t$.

L_{exp} corresponds to actual injection demand at every sampling instant.

Simulations on a 4 bus system and the IEEE 39 bus system using PSCAD validate that the system operates as desired [6]. The DSR provides possibly the simplest implementation of a Distributed System Impedance.

C. Distributed Static Series Compensator

The concept of a Distributed Static Series Compensator (DSSC) is discussed next to illustrate one more of a possible family of Distributed FACTS or D-FACTS devices. DSSC modules consist of a small rated ($\sim$ 10 kVA) single phase inverter and a single turn transformer (STT), along with associated controls, power supply circuits and built-in communications capability. As in the case of the DSR, the module consists of two parts that can be physically clamped around a transmission conductor. The transformer and mechanical parts of the module form a complete magnetic circuit only after the module is clamped around the conductor. The weight and size of the DSSC module is low allowing the unit to be suspended mechanically from the power line. A circuit schematic of DSSC module is shown in Fig. 7.

Fig. 7 shows the STT with a normally closed switch $\mathrm{S_M}$ consisting of a normally closed electromechanical switch and a thyristor pair that maintains the unit in bypass mode until the inverter is activated. The dc control power supply transformer is excited by the current that flows in the STT secondary winding. A simple single-switch pre-regulator is used to control the dc voltage of the control power supply. At approximately 100 A of line current, the dc power supply can initiate a turn-on of the module. As the switch S_M is turned off, the inverter dc bus is charged up and inverter operation is initiated. The inverter can now inject a quadrature voltage into the ac line to simulate a positive or negative reactance. dc bus voltage regulation is maintained using power balance through a small "in-phase" voltage component, in a manner similar to active filter control [9]. The command of how much quadrature voltage is to be injected can be derived autonomously, or can be communicated from the system operator. The overall system control function is achieved by the use of multiple modules operating in a coordinated manner using communications and smart controls.

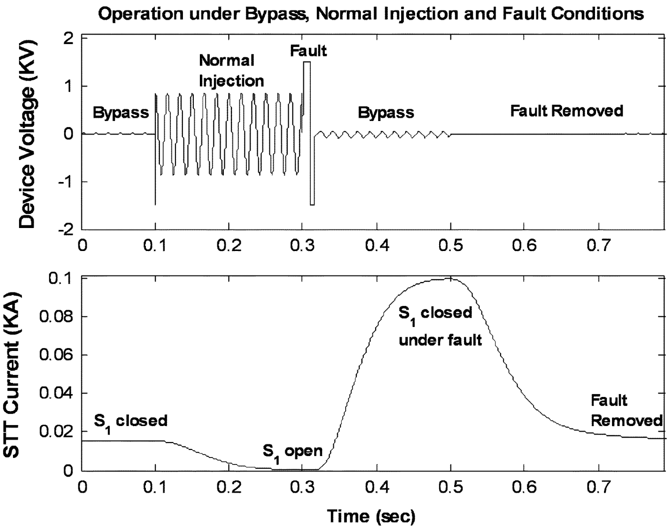

Fig. 8. Operation under bypass, normal Injection and fault conditions.

D. Design Consideration for DSIs

Some important design considerations of DSI modules, including DSSCs, need to be mentioned. As the module is to be clamped on to the line, it does not see the line voltage and does not need to meet the BIL (Basic Impulse Level) limits. The unit can thus be applied at any line voltage, ranging from 13 KV to 500 KV. The line current typically is in the range of 500 to 1500 A per conductor. The STT, with a turns-ratio of say 50:1, thus only impresses 10 to 30 A on the secondary side of the STT. At this current rating, it is possible to use mass-produced thyristors and IGBTs to realize low cost. Further, under line fault conditions, even for fault currents as high as 60 000 A, the STT reduces the maximum 3–6 cycle current stress to under 1200 A, well within the capability of widely available small thyristor power devices.

The critical issue with the DSI module is its weight. Based on detailed discussions with utility engineers, a module weight of 50–65 kg is deemed acceptable. Utilities already use 50 kg zinc dampers on power lines to prevent oscillations. The heaviest component in the DSI is the single turn transformer (STT). If a break in the wire is to be avoided, the only mechanism for series injection is through induction. As the line frequency is 60 hertz, the core material of choice is silicon steel, with a saturation flux density of 1.6 Tesla. For such STT designs, the core weight would be much more than the copper winding weight. Design guidelines for such STTs have been developed in the literature [7].

While DSI operation at the target design point of $\sim$10 kVAR is important, its behavior under light and no-load conditions must also be understood. In order to provide safe operation under start-up and failure modes, the DSIs are designed with a normally closed switch (S_M) that bypasses the STT coil. In the bypass mode, the injected impedance in the line is less than 0.8 μH per module, and losses per module are estimated at under 100 W per module, when the module is active and bypassed. If thyristors are used in the bypass mode, the device losses at 1000 A of line current (assuming a 50 : 1 STT turns ratio) are estimated at 25 W. Using 100 A, thyristors would provide adequate surge rating to handle a 50 000 A fault current in the line.

The DSR module in Fig. 5 could accommodate the largest STT rating consistent with the weight restriction. This is because additional components are minimal and very light. For the DSSC circuit in Fig. 7, additional components, i.e., the inverter, heat sinks, filter elements, a bypass switch, are all required. The hostile environment and long projected service life ($\sim$30 years) makes moving parts such as fans undesirable, making thermal management a major challenge as well.

Other important issues include operation in high E-fields and minimization of corona discharge, sealing of the unit against rain and moisture, and ability to operate while clamped on the power line without damaging the conductor. Finally, for the application to have commercial viability, the module must be extremely low-cost, be mass-manufactured, and should be easy to clamp-on to the line, including possibly on a live line. It should be noted that the DSI units will be clamped around single conductors. Transmission lines frequently use up to four conductors in a bundle to increase line capacity, with a line spacing of 18 in. It is anticipated that the DSI units will fit in the space between conductors, and may be deployed in a staggered manner, one per conductor.

E. Simulation Results

Various implementations of the DSI have been simulated. The DSR model assumes a 9.24 kVAR series inductance injection at a current of 770 A. Based on experimental STT units built and tested, the leakage inductance is 0.8 μH, while the inserted inductance is 0.042 mH. Fig. 8 shows the simulation results of DSR operation, including turn-off of Switch S_1 under normal conditions and turn-on of S_1 under fault current conditions. Saturation of the transformer limits the secondary voltage to $+/-1.5$ KV. When a fault condition is detected, the system automatically switches over into bypass mode.

The DSR was further used in a four bus system, shown in Fig. 9. The values of line inductance and resistance are numerically displayed in the figure. With the DSR units bypassed, the maximum power that can be transferred through the network is limited by Line 2 and Line 5, as shown in Fig. 10. An increase

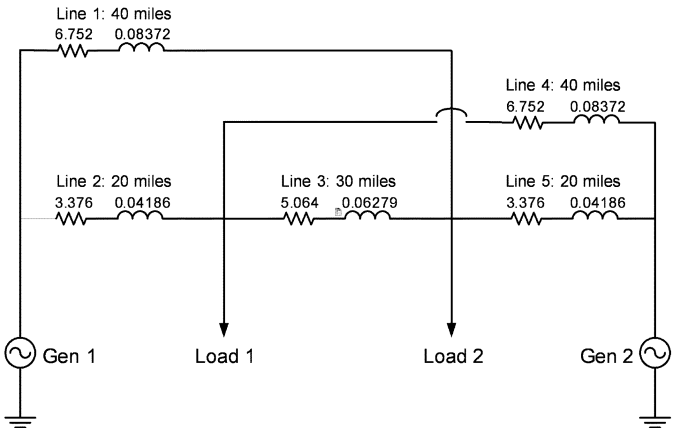

Fig. 9. Detailed schematic of the 4 bus system.

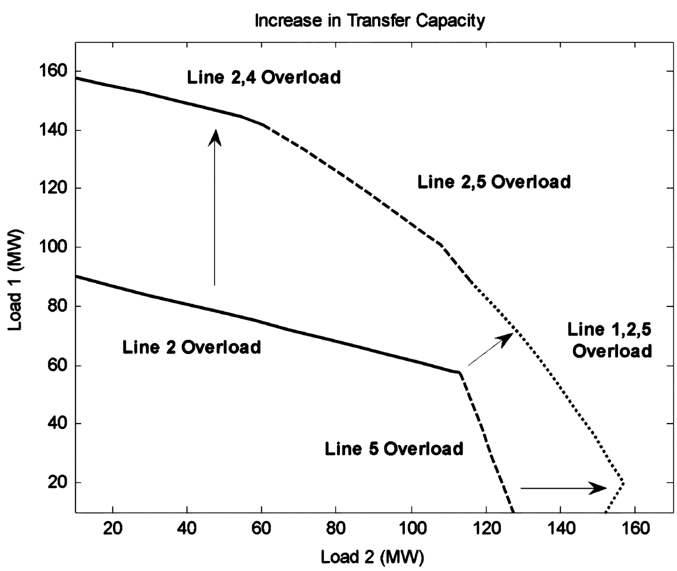

Fig. 10. Increase in ATC with DSR modules.

in the load throughput by as much as 45% can be realized with 9 MVAR injection when the load is concentrated at Load 1. This shows the ability of the DSR devices to automatically control the level of current in the grid, automatically operating so as to keep power lines out of thermal overload.

Fig. 11 shows system operation under contingency condition when Line 2 is tripped due to a fault. This causes a thermal overload on Line 5. It is seen that the current in Line 5 is rapidly reduced, keeping the line within its thermal limit, preventing a possible cascading blackout or load shedding. It should be noted that these gains are realized with no communication between modules. Further, the system showed dynamic self-organization properties, automatically redistributing the current under contingency conditions. It is clear that significant gains in system operation can be obtained through the deployment of DSI modules.

F. Experimental Results

By way of example, details are presented for a DSSC module that was designed, built and tested in the laboratory under a

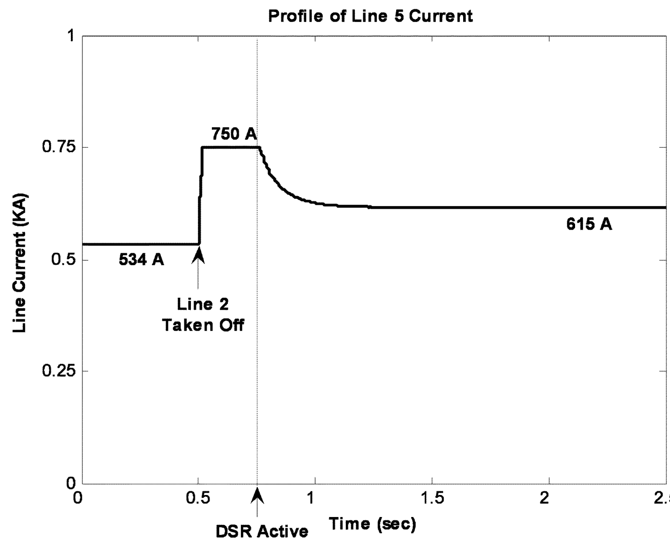

Fig. 11. Performance under contingency condition.

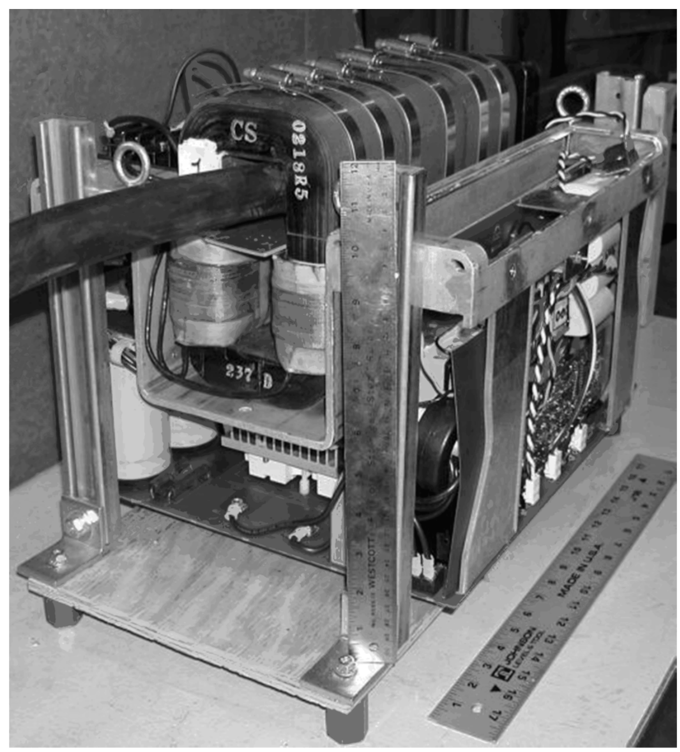

Fig. 12. Concept model of DSSC.

project jointly funded by TVA and Soft Switching Technologies (Fig. 12). Details of the results have been presented in a previous paper, and are summarized here [8]. The unit was designed for line currents of up to 1500 A and fault currents of over 12 000 A. The IGBT inverter was rated at 6.7 kVA and was used to provide the fault current ride-through capability. Based on an STT turns ratio of 90 : 1, the nominal current in the IGBT inverter at 1500 A was less than 20 A. The inverter devices were controlled using sine-triangle PWM at 12 kHz using a PIC microcontroller. dc bus control was realized using a signal in-phase with the line current, while a command reference signal provided the desired quadrature voltage injection. The power supply was designed

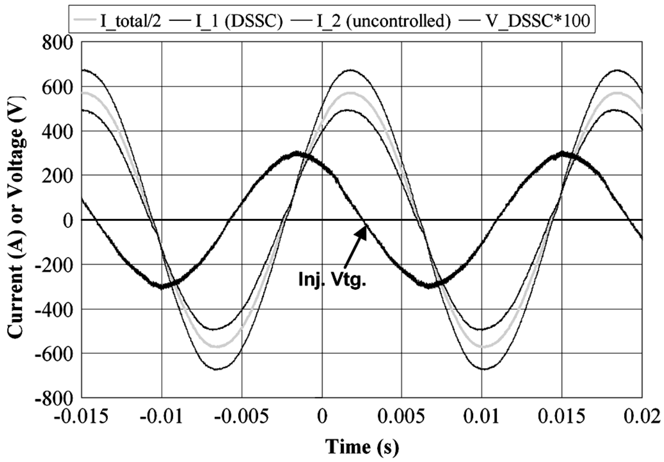

Fig. 13. DSSC operation under leading voltage injection.

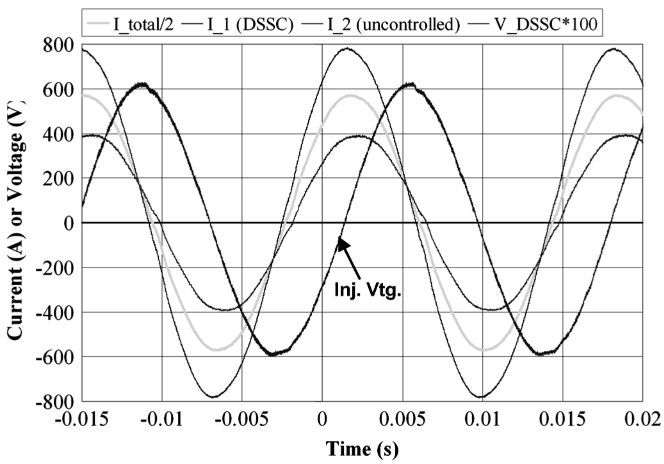

Fig. 14. DSSC operation under lagging voltage injection.

to operate over a range of 300–1500 A in steady state, with ride-through for current surges up to 12 000 A.

The module demonstrated injection of positive and negative inductance, quadrature voltage of $+/-4.6$ V, and the ability to steer power flow through a desired path in a parallel connection. Figs. 13 and 14 show DSSC operation under leading and lagging voltage injection conditions.

With zero injection, the voltage impressed across the STT is seen to be in-phase with the current, corresponding to losses in the circuit. The DSSC module was tested under normal and fault currents of up to 12 000 A, and behaved as anticipated. Finally, the DSSC module was used to demonstrate the ability to steer current between two parallel lines as commanded (Fig. 15).

The DSSC module validated the possibility that self-excited D-FACTS devices can be implemented, and that the STT structure allows injection of reasonable voltage levels into the line without exceeding the weight targets that would allow the modules to be clamped on to existing power lines. It also validated that the STT reduces current levels on the “high-voltage” side to levels that can be cost-effectively managed with ‘commodity’ power devices. This opens up the possibility that D-FACTS devices can provide series reactive compensation in a much more cost-effective manner than with other existing solutions.

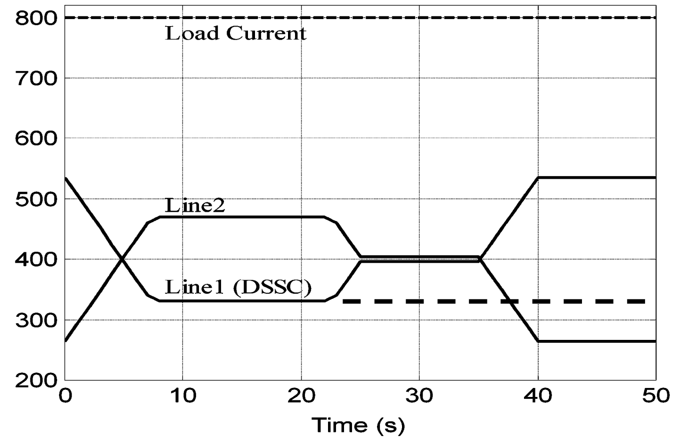

Fig. 15. Line flow control with DSSC.

Clearly, important engineering issues need to be resolved. These include the ability of the DSI modules to operate in a high electric and magnetic field environment; to operate in a hostile environment including wide temperature range; ability to operate without active cooling; and ability to operate without damage for long periods of time; ability to install and commission the system at low cost; etc. These issues will be addressed in future papers.

IV. Conclusion

This paper presents a distributed approach for realizing active power flow control on existing power lines through the use of a new class of distributed FACTS or D-FACTS devices. The distributed implementation seems to overcome some of the most significant issues that have limited a wider deployment of series FACTS devices. D-FACTS can realize significant change in power line impedance to improve the power transfer capacity of an interconnected power system by using light-weight self-excited modules that float on the power line. Such devices can operate with or without communications and use small-rated low-cost power devices. D-FACTS sustain the operation of the system even during contingency conditions, improving the reliability of the overall network. Under fault conditions, the units can instantly revert back to their bypassed mode, allowing protective relaying to operate without change if so desired.

The ability to control line impedance using series VAR injection represents a critical need for the power industry. Distributed FACTS devices may offer a new approach to meeting this critical need.

References

[1] S. Abraham, National Transmission Grid Study May 2002 [Online]. Available: http://www.eh.doe.gov/ntgs/, U.S. Dept. of Energy

[2] N. Hingorani, “Flexible ac transmission,” *IEEE Spectrum*, vol. 30, no. 4, pp. 40–45, Apr. 1993.

[3] L. Gyugyi, C. D. Schauder, and K. K. Sen, “Static series compensator: A solid-state approach to the series compensation of transmission lines,” *IEEE Trans. Power Del.*, vol. 12, no. 1, pp. 406–407, Jan. 1997.

[4] S. Bhattacharya, B. Fardanesh, B. Shperling, and S. Zelingher, “Convertible static compensator: Voltage source converter based facts application in the new york 345 KV transmission system,” *Int. Power Electron. Conf. Records*, pp. 2286–2294, Apr. 2005.

[5] A. Bergen, *Power System Analysis*. Englewood Cliffs, NJ: Prentice-Hall, 1986.

[6] H. Johal and D. M. Divan, "Current limiting conductors: A distributed approach for increasing system capacity and reliability," in *Proc. Transmission Distribution Conf. Exposition 2005 IEEE PES*, New Orleans, LA.

[7] M. Rauls, D. Novotny, and D. Divan, "Design considerations for high-frequency coaxial winding power transformers," *IEEE Trans. Ind. Appl.*, vol. 29, no. 2, pp. 375–381, Mar. 1993.

[8] D. Divan, W. Brumsickle, R. Schneider, B. Kranz, R. Gascoigne, D. Bradshaw, M. Ingram, and I. Grant, "A distributed static series compensator system for realizing active power flow control on existing power lines," in *IEEE PSCE Conf. Records*, Oct. 2004.

[9] P.-T. Cheng, S. Bhattacharya, and D. Divan, "Operations of the dominant harmonic active filter (DHAF) under realistic utility conditions," *IEEE Trans. Ind. Appl.*, vol. 37, no. 4, pp. 1037–1044, Jul. 2001.

Deepak Divan received the Bachelors of Technology degree from the Indian Institute of Technology, Kanpur, in 1975, and thr master's and Ph.D. degrees from the University of Calgary, Calgary,AB, Canada in 1979 and 1983, respectively.

From 1985 to 1995, he was a Professor with the Department of Electrical and Computer Engineering, University of Wisconsin, Madison. He was also Associate Director of the Wisconsin Electric Machines and Power Electronics Consortium, the first university–industry consortium on campus that he helped to grow to include over 60 industrial sponsors. In 1995, he started Soft Switching Technologies and as President, CEO, and Chairman of the Board, he was responsible for raising venture capital funding from leading investors including GE Capital and JP Morgan Partners, for developing a line of power line disturbance monitoring and mitigation products to help factories avoid costly unscheduled downtime, and for positioning the company as a leader in this emerging market. In 2003–2004, he served as Chairman and Chief Technology Officer for the company, successfully transitioning company operations to an experienced management team. He joined Georgia Tech in 2004 to create a strong program in the application of power electronics and related technologies to power systems and demanding defense and industrial applications. He holds 32 patents, has published approximately 200 technical papers, including over 12 prize papers, and has given many invited presentations at technical and business oriented meetings. He is currently the director of Intelligent Power Infrastructure Consortium (IPIC), a university-industry-utility consortium that has been formed to provide a focal point for the academic teaching and research program in advanced power technologies at Georgia Tech.

Harjeet Johal received the B.S. degree in electrical power engineering from the Indian Institute of Technology, Delhi, in 2003. He started his graduate studies at Georgia Institute of Technology in 2003 and is currently pursuing the Ph.D. degree under the supervision of Dr. Deepak Divan.

His research focuses on increasing T&D system capacity and enhancing reliability. He is working on modeling distributed series impedances, which can be used to alter the line flow in a meshed power network to maximize the transfer capacity and network utilization. His research aims at developing passive clip-on modules that automatically increase the impedance of the line once a current threshold is reached, diverting current to other unloaded parts of the network. He has been a teaching assistant for five semesters and a research assistant for four semesters at Georgia Tech.

Mr. Johal is a co-recipient of the 2005 IEEE Power Electronics Specialist Conference (PESC) Best Paper Award. He was also awarded with the Best Undergraduate Project Award in 2003.