

Distributed Intelligent Power Networks – A New Concept for Improving T&D System Utilization and Performance

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Abstract

This paper presents a new approach for realizing a smart, fault tolerant, controllable and asset efficient power grid through the use of massively-dispersed mass-manufactured communications-enabled sensor, power-converter and actuator networks. One example is ‘Smart Wires’, implemented using many modules of a Distributed Static Series Compensator (DSSC) device that can be clamped on to existing power lines, and can be operated so as to control the impedance of the conductor – thus controlling power flow. This approach promises important system-wide benefits including – increased line and system capacity; increased reliability; improved asset utilization; improved operation under contingencies; reduced environmental impact; incremental deployment; and rapid implementation.

Introduction

As generation and consumption of electricity has grown, investment in the transmission infrastructure has declined. The grid is aging and few new lines are being built, given high cost and permitting delays. The inability to control power flow on the grid results in poor asset utilization and is impeding the growth of the energy market. Uncertainties in transmission investment recovery and the high cost of existing power flow control solutions are further exacerbating the problem. It is generally agreed that the transmission grid is under stress, and that steps need to be taken quickly to eliminate transmission constraints and bottlenecks and to improve the utilization of existing T&D assets, to ensure the flow of reliable and affordable electricity [1].

These problems are well recognized in the industry. However, the overall factors that govern our ability to act are almost impossibly complex and multi-dimensional. Key issues include – public policy that is stalled in political wrangling; a semi-regulated Balkanized utility industry; differing state regulations; impact of transmission investments that extends beyond the investor’s territory; a centralized and aging technology architecture; substantial legacy infrastructure and potentially stranded assets; conversion of the T&D infrastructure to an ‘energy super-highway’; right of way and environmental issues; foreign oil dependence and sustainability; etc. It is clear that technology is only a small piece of the overall puzzle. It is easy in such situations to declare that no progress is possible and to maintain status-quo. However, one only has to look at the IT industry and the Internet to see a situation where a regulated and established industry, much like the utility industry, was disrupted and transformed with significant societal benefit.

It seems that one of the key driving factors in the transformation of the IT industry was the advent of massively distributed solutions. Rapid advances in microelectronics, computing and communication technologies disrupted the established technology of centralized switches and copper pipes. Less than a decade ago, conventional wisdom (including \$5 Billion of Bill Gates’ money) bet on infrastructure-intensive satellite phones to connect the world’s masses. The success and rapid adoption of cell phone technology around the world, has eliminated the

centralized satellite phone as a competitor, and clearly demonstrates the superiority of a distributed solution. Distributed solutions offer several unique advantages including –

- Use of commoditized mass-produced building blocks networked together to realize higher performance at lower cost,
- Massive redundancy, coupled with self-organizing and self-healing properties to realize high system reliability and availability,
- System can be implemented incrementally with full backward compatibility, and can be upgraded as technology or customer needs change

With the exception of a limited interest in distributed generation (driven by the need to appear 'green'), the utility industry has continued to concentrate on large 'lumped' systems as the preferred solution for its infrastructure. Perhaps, there is an unstated assumption that a massively distributed solution could not be meaningfully applied to the utility industry. This paper challenges that assumption and suggests that a truly distributed approach to power networks may realize significant operational, economic and societal benefits.

Active Power Flow Control

By way of example, one can examine the problem of controlling power flow on the grid. The underlying assumption for a vibrant energy market is that the T&D infrastructure could optimally transport energy from where it was generated to where it was needed. New generating plants were located at the cross-section of gas lines and power lines, and much hope was riding on the ability of free markets to operate and realize their full potential. The laws of physics (Ohms Law, Kirchoff's Current Law – KCL, and Kirchoff's Voltage Law – KVL) have unfortunately prevailed, preventing the vision from becoming reality.

The distribution of current in a meshed network (important for high reliability) is governed by line impedances. In such a network, the first line that becomes 'congested', i.e. becomes overloaded, limits the capacity of the network. Trying to push more power through the network can cause lines to trip and can initiate a cascading failure, even though most of the lines may be operating below their rated capacity. The situation is rendered even more complex due to a requirement for continued operation under a (N-1) contingency condition. This requires that the system continue to operate with one failure, such as a tripped line. As a consequence, the system operator has to provide sufficient safety margin so that a line can continue to operate within its nominal rating even under the worst-case single failure condition that can be anticipated. This results in a further erosion of the available transfer capacity for the system. Another unintended consequence of KCL and KVL is 'loop flows', or circulating currents that flow in unintended paths. The presence of loop flows on a given line can limit the transfer capacity for the line owner, resulting in loss of potential revenue. As demand increases, these factors can result in transmission loading relief calls, gaming, curtailed service and poor system reliability – even as the critical assets (the power lines) remain under-utilized.

The conventional approach has been to balance the network to the extent possible through generator dispatch and the use of appropriately positioned reactive or VAR compensation. Unfortunately, both control approaches have a weak influence on how real power flows in a network. Achieving full control of the power flow on the power grid requires that the impedance of the power lines, or the phase angle of the voltage across individual power lines be made variable and controllable. Most existing techniques for grid control have focused on 'shunt' connected devices that operate in parallel with the grid and are not very effective for achieving power flow control. In some instances, series capacitors are used to increase the capacity of long

lines. However, this can cause instability and sub-synchronous resonance and complicates the issue of system protection under fault conditions.

FACTS Technology

A new technology that holds the promise of realizing a smart grid and achieving power flow control is Flexible AC Transmission Systems or FACTS [2-4]. FACTS devices, such as STATCOM, SVC, SSSC and UPFC can be inserted in series with a line, connected in parallel, 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 –

- High total cost of ownership. The Marcy Convertible Static Compensator (CSC), recently commissioned in New York for a cost of \$54 million, shows that deploying a large number of similar systems across the entire grid could be prohibitively expensive.
- Difficulty in establishing dollar value for decreasing congestion, or for increasing system capacity or reliability, makes computation of ROI difficult.
- High fault currents (60,000 Amps) and basic insulation requirements (1000 kV) stress the power electronics system, making implementation of FACTS systems, in particular series connected devices required for power flow control, very difficult and expensive.
- Single point of failure yields reliability of 94%, significantly lower than the 99.99% reliability that is typical for the utility system itself.
- Highly customized design of FACTS devices requires skilled work force in the field to maintain and operate the system, not within a utility's core competency normally. This leads to high total cost of ownership.

As a result, even though FACTS technology has been commercially available for over 10 years, few installations have been purchased by utilities. Shunt connected devices, such as SVCs and STATCOMs that are used for voltage regulation and VAR support, have been more effective and are seeing broader deployment. Series connected devices, such as SSSCs that are required to achieve power flow control, are significantly more difficult and expensive to implement and have rarely been deployed. Active power flow control, important from a grid utilization and control perspective, thus remains very difficult to implement and continues to be a challenge.

Distributed FACTS – A New Concept

This paper discusses the concept of a distributed approach for realizing the functionality of FACTS devices [5]. 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 Static Series Compensator (DSSC) is used to illustrate the feasibility of a Distributed FACTS or D-FACTS approach.

DSSC modules consist of a small rated (~10 kVA) single phase inverter and a single turn transformer (STT), along with associated controls, power supply circuits and built-in communications capability. 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. Figure 1 shows a schematic of how such a module could be realized.

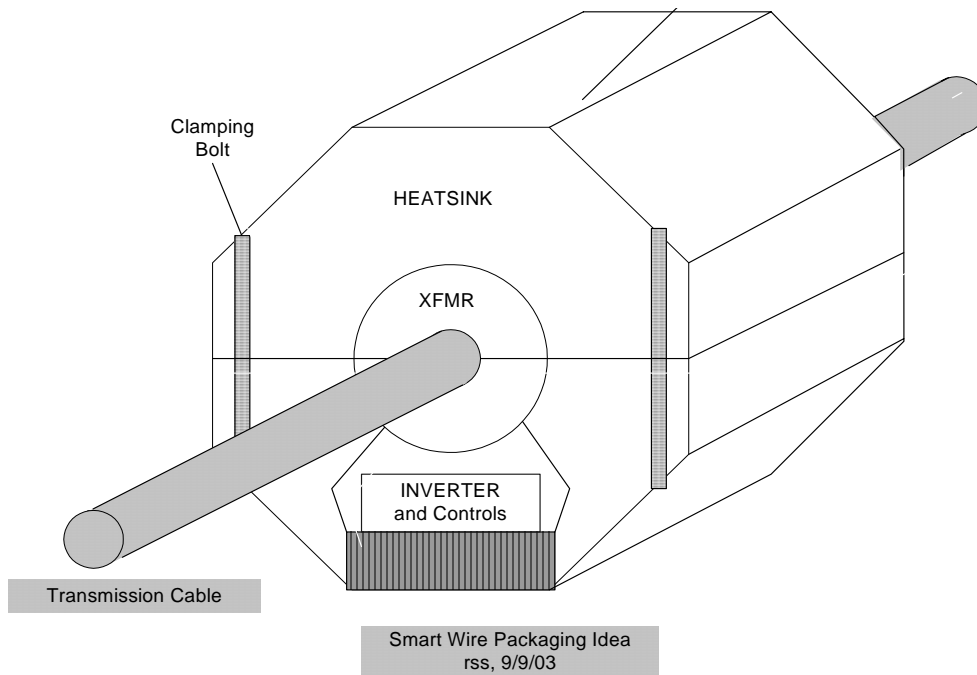


Figure 1: Concept drawing of a Distributed Static Series Compensator module

The module is self-excited from the power line itself. The unit normally sits in bypass mode until the inverter is activated. Once the inverter is turned on, the DSSC module can inject a quadrature voltage or reactive impedance in series with the line. This allows the module to inject positive inductance, so as to increase line impedance and ‘push’ current into other parts of the network. Alternatively, it can inject a ‘negative inductance’, thus reducing line impedance so as to ‘pull’ current in from other parts of the network. The overall system control function is achieved by using a large number of modules coordinated through communications and smart controls. It should be noted that any module deployed along a power line would, in addition to the power converter, also contain appropriate sensors to monitor the condition of the line on a distributed basis so that it can be fully utilized. It is seen that a massively distributed deployment of DSSC modules (and sensors) on existing transmission and sub-transmission lines would allow system operators to specify and achieve desired levels of loading on individual lines, and would substantially improve the utilization of the existing power grid.

Figure 2 shows a schematic of a DSSC module. Some important attributes of the DSSC module need to be mentioned. As the module is clamped on to the line itself, it does not see the line voltage and does not need to meet high insulation levels. The unit can thus be applied at any line voltage, ranging from 13 kV to 500 kV without significant redesign. The line current typically is in the range of 500 to 1500 Amperes per conductor. The STT, with a 100:1 turns ratio, thus only impresses 5 to 15 Amperes on the inverter. At this current rating, it is possible to use mass produced IGBTs to realize low cost. Further, under line fault conditions, the line current can exceed 60,000 Amperes for stiff systems. As has been seen, this poses the highest stress for conventional FACTS devices. The STT reduces the fault current level to 600 Amperes, allowing widely available power devices to handle the fault current level.

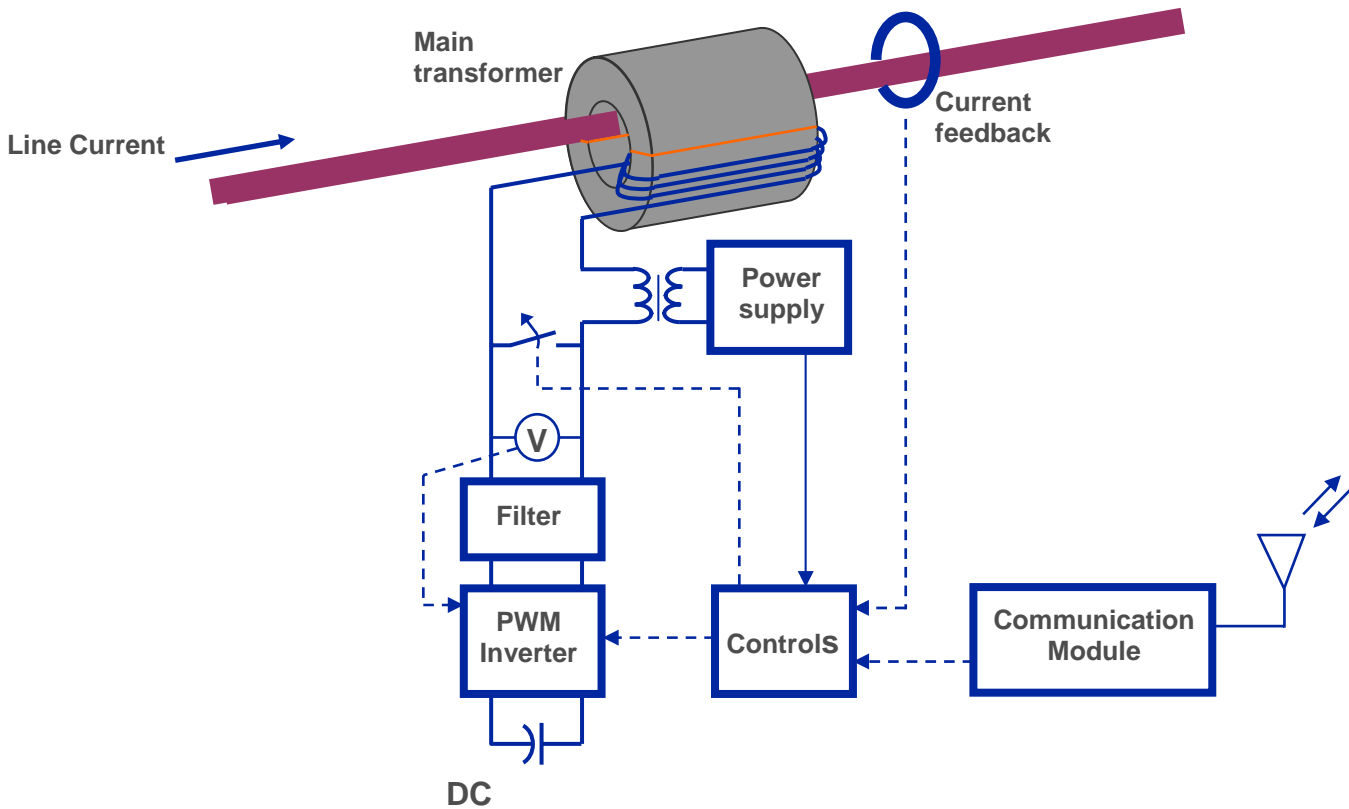
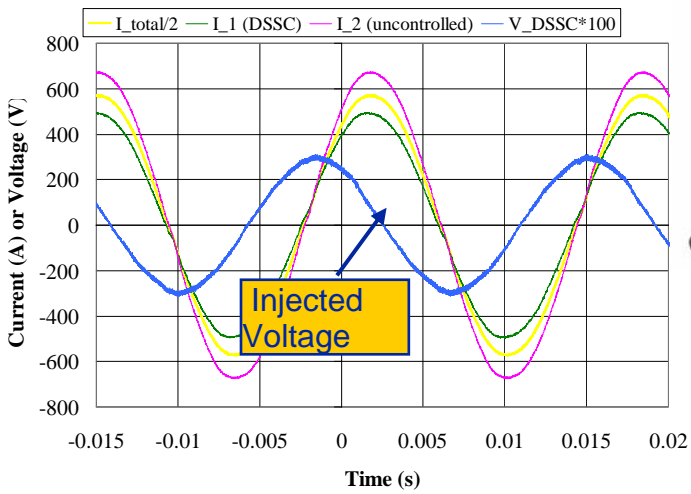
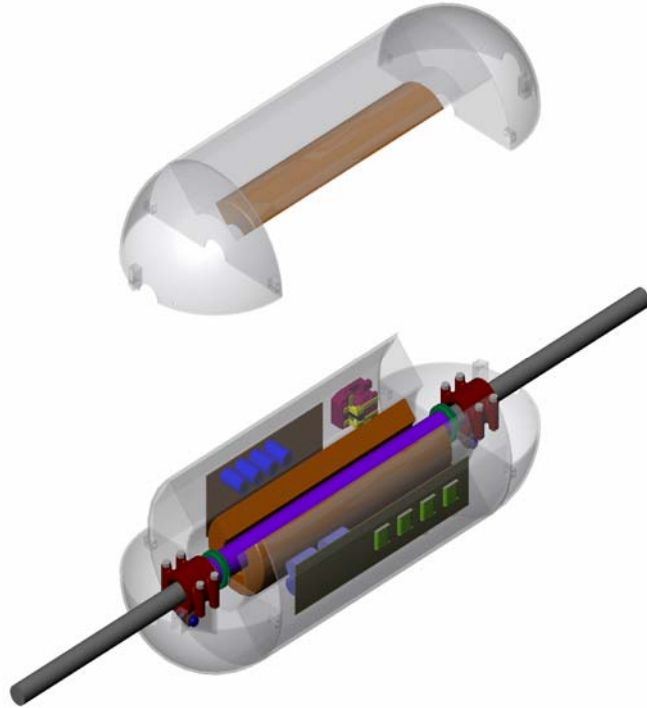
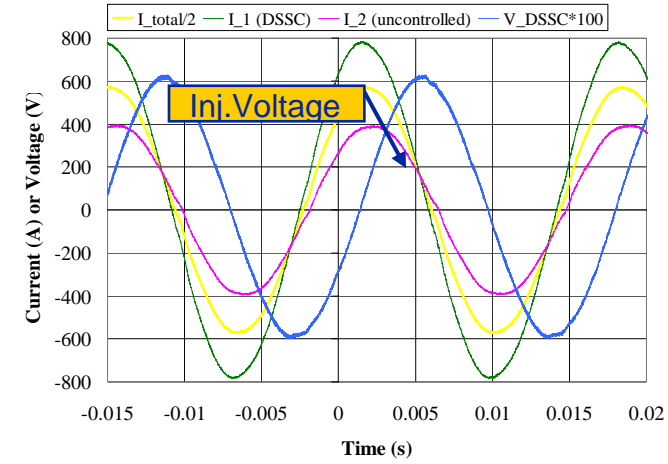


Figure 2: Circuit schematic of a DSSC module

Based on the simple analysis above, the DSSC module can inject 10 kVAR of effective positive or negative inductance, or quadrature voltage. At a current of say 750 Amperes of line current, this represents 13 volts of series reactive injection. It seems inconceivable that a small rated DSSC module could appreciably affect power flow on a transmission line. Table 1 shows the potential of the DSSC for achieving power flow control. Assuming a 138 kV transmission line with a thermal current limit of 770 Amperes gives a line capacity of 184 MVA. The reactive voltage drop across the line inductance is 608 volts/mile. This suggests that an injection of 60 volts (5 modules) per mile per phase can change the impedance of the line, and potentially its power flow by 10%. For the 138 kV transmission line under consideration, this represents as much as 18 MW of additional power flow capability.

A DSSC module was designed, built and tested in the laboratory (Figure 3). The unit was tested at line currents of up to 1500 Amperes, and under fault currents of over 12,000 Amperes. The module demonstrated injection of positive and negative inductance, quadrature voltage injection of +/-4.6 volts, fast dynamic response capability, and the ability to steer power flow in a mesh.

Figure 3: DSSC module concept and experimental waveforms showing leading and lagging voltage injection



	138 kV	345 kV	765 kV
Thermal Line Capacity	184 MVA	1195 MVA	6625 MVA
Current carrying capacity	770 A	2000 A	5000 A
# of conductors/ diameter (inches)	1/1.0	2/1.2	4/1.45
Reactance ohms/mile	0.79	0.60	0.54
Reactive voltage drop/mile	608 V	1200 V	2700 V
1% Compensation/mile	6.1 V	12 V	27 V
Smart Wire kVA- 1% Comp/mile	14 kVA	72 kVA	400 kVA
Total 10 kVA modules/mile/1%	1.4	7.2	40

The module was built out of components that are routinely used in high volume products such as motor drives and UPS systems, typically available at price points as low as \$50/kVA in volume.

Configuring the DSSC module as part of a communications enabled sensor network, but one based on power line communications techniques, will allow the system to operate in a coordinated manner. Wireless sensor networks are becoming available at price points approaching \$10 per node, and it is expected that DSSC communication costs, in commercial volume, could be comparable. Overall, it is estimated that commercial DSSC modules will cost less than \$100/kVA, including installation and commissioning costs. Currently, series FACTS controllers can cost over \$300 per kVA, with limited opportunity for cost reduction.

Conclusions

The DSSC module demonstrates the concept of a new type of power system controller – one based on the use of mass-manufactured communications-enabled power converter networks that provide cost-effective control of the impedance of existing power lines, allowing control of current and thus power flow in the conductor. Such a distributed approach can realize significant benefits including –

- Higher system capacity and reduced congestion giving improved asset utilization
- High reliability through redundancy and insensitivity to single module failure
- Staged and incremental deployment provides budgetary flexibility and scalability
- Zero footprint and deferment of new lines provides positive environmental impact
- Standard modules for lower cost, easy maintenance and rapid implementation
- Augmentation of existing legacy infrastructure as needed

It is proposed that a distributed approach to power flow control can simultaneously solve some of the most daunting issues that have held back widespread commercialization of FACTS technology. The new paradigm mimics developments in other networked applications, and builds on technology developments that are commoditized and widely available, and have disrupted established technology infrastructures. It can achieve a modernization of the power grid, allowing enhanced asset utilization and increasing system efficacy. By providing control of active power flow on the grid, it can also enable a smoother functioning of the energy market, reducing societal energy costs by allowing end-users to access lower cost energy producers.

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