Active Smart Wires: An Inverter-less Static Series Compensator

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***Abstract* -- Technologies such as dynamic line rating and FACTs have emerged to increase the utilization and the reliability of the existing T&D network without requiring new line construction. The development of the Distributed Series Reactance (DSR) technology, a distributed FACTs (D-FACTs) solution also known as Smart Wires, has been funded by the utility community, given the promise of DSR for reliable and inexpensive power flow control. The DSR is capable of increasing the line reactance, pushing power onto other lines, but it is unable to decrease line reactance and draw power flow onto the line. Utilities have noted the value of a technology capable of injecting inductance or capacitance into the line. A previous approach to push or pull power used an inverter based variable injection technique, but was expensive and was unable to meet utility expectations for MTBF and maintenance requirements. Active Smart Wires (ASW) is a new concept for a low-cost, high reliability method to increase or decrease power flow in a transmission line. Simulation results are provided.[1]**

***Index Terms*-- AC-AC Power Conversion, FACTS, Power Electronics, Power Flow Control, Power System Reliability, SSC**

I. Introduction

Reliability degradation and congestion on the existing transmission and distribution networks has led to the development of new technologies capable of improving network operation without new line construction. The Distributed Series Reactance (DSR) technology employs a fleet of 10 kVA modules mounted on the conductor at points along the transmission line to increase line impedance. Each DSR module, as seen in Fig. 1, gradually activates once a pre-defined line current is reached. If the pre-defined line current values follow an appropriate statistical distribution, the net effect of the DSR fleet is the injection of an increasing amount of impedance as line current increases beyond a threshold level. System-level simulation results have demonstrated the value of the DSR technology [1]. A proof of concept module rated for an injection of 13 V at 750 A on a 169 kV line has been constructed and tested under steady-state and system fault conditions [2]. A team of utilities has initiated a program for the pilot deployment of DSR modules with a target lifetime in excess of 20 years and requiring no maintenance. Additional system benefits are realizable if the fleet of modules can be configured to increase or decrease line reactance [2]. The DSSC and DSI, seen at the top and bottom of Fig. 2 respectively, are able to increase and decrease line reactance and thus can decrease or increase active power flow. To enable full active power flow control, each module requires non-local information, imposing a communications requirement not necessary for the DSR.

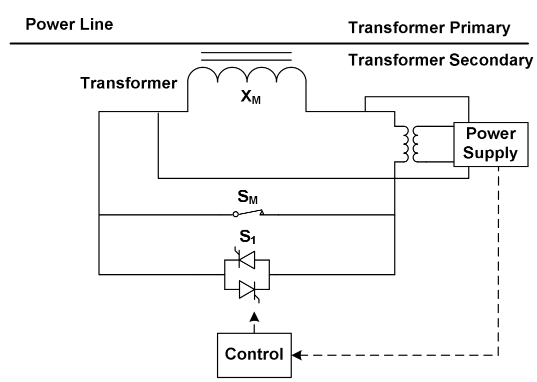

Fig. 1. Topology of the previously proposed Distributed Series Reactance (DSR) for series power flow control

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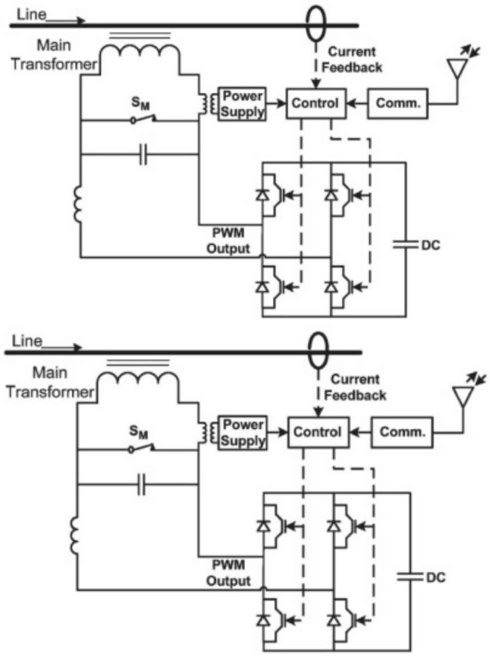

Fig. 2. Previously proposed series power flow control topologies: Distributed Static Series Compensator (DSSC) at top and Distributed Series Impedance (DSI) at bottom

II. Existing Solutions

The DSSC module at the top of Fig. 2 operates as a low-rated Static Series Compensator (SSC). A fleet of said modules operated together achieves the required capacitive or inductive injection. A 6.5 kVA laboratory prototype of the DSSC has demonstrated the ability to increase or reduce line current with extremely fine granularity [3]. Unlike a traditional SSC that requires high voltage isolation, the low mass of the DSSC allows suspension from the high voltage conductor [4]. However, the DSSC rating is limited by the lifetime of the DC capacitor and aerodynamic and mass constraints imposed by the mounting method. Given that DSSC installation cost is expected to comprise a significant fraction of the total system cost, maintenance visits for capacitor replacement are not cost justifiable. Capacitor life extension with active cooling is difficult due to extreme temperature range and the need to operate with passive cooling. Therefore, an alternative solution avoiding the use of the DC capacitor is preferred.

The DSI at the bottom of Fig. 2 is a single turn transformer (STT) augmented with an inductor (X_l), capacitor (X_c) and communications. N is the transformer turns ratio of the Single Turn Transformer with the convention that $N_1 = 1$. The injection into the line is dependent on the state of the switches (S_1 and S_2) and the relay (S_m). Combinations of the three passive elements (X_m, X_c, and X_l) allow the injection of four non-zero impedance levels in series with the line. Since AC capacitors are used, the DSI possesses a similar reliability and cost of ownership as the DSR. However, a single DSI module offers significantly less control granularity than a single DSSC. A fleet of DSI modules operated in coordination would achieve significantly more control granularity than a single module. However, for some applications, the use of a fleet of modules to provide granularity may not be feasible. An example is a small fleet of DSI modules installed on a short line. Ideally, an alternative module would provide the control of the DSSC and the reliability of the DSI.

III. Proposed Solution

Fig. 3. presents a schematic of a module that provides the benefits of both the DSI and DSSC. The module consists of an STT with a magnetizing reactance (L_m), two AC switches (S_1, S_2) realized using IGBTs, an AC capacitor (C), two filtering elements (L_f, C_f), a relay (S_m) to provide failsafe operation, and a communications and control package. The air gap of the STT is turned to produce the required magnetizing inductance, eliminating the need for the additional inductor used in the DSI. As with the DSR, the use of an STT turns ratio of at least 20 to 1 guarantees that secondary currents, even under fault conditions, are small enough to allow the use of low-cost IGBTs. With S_1 on and S_2 off, the parallel equivalent of L_m and C is injected in series with the line. With S_1 off and S_2 on, L_m is injected in series with the line. Switching S_1 and S_2 in a complementary fashion with duty ratio (D) produces the effective AC capacitance seen in (1) at B-B'.

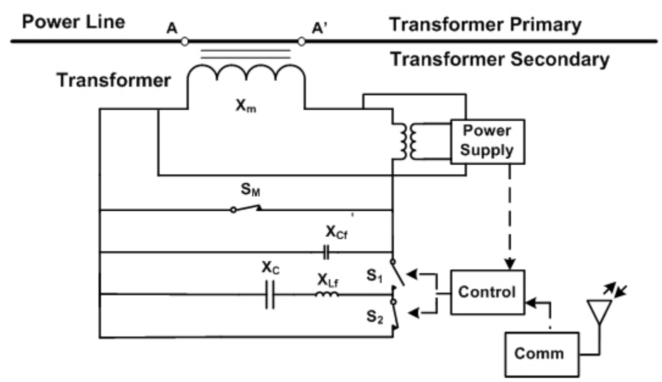

Fig. 3. Schematic of the proposed Active Smart Wires device, an Inverter-less SSC

$$X_{c,eff} = \frac{X_C}{D^2} \qquad (1)$$

The impedance change in the transmission line, seen from A-A', is the parallel equivalent of X_l and $X_{c,\ eff}$, reflected across the transformer, as seen in (2). The theoretical change in transmission line impedance as a function of D for a single module is shown by the solid line in Fig. 4, with a resonant peak at D = 0.707 given the assumed parameter values. The module shows the desired functionality, inducing an inductive impedance for duty ratios below 0.707 and capacitive impedance for values above 0.707. The resonant peak is reduced by incorporating realistic losses as shown in the dashed line of Fig. 4. The impact of the resonant peak is likely to be further mitigated by STT saturation.

$$\left(\frac{X_m * X_c}{X_m D^2 + X_c}\right) n^2 \tag{2}$$

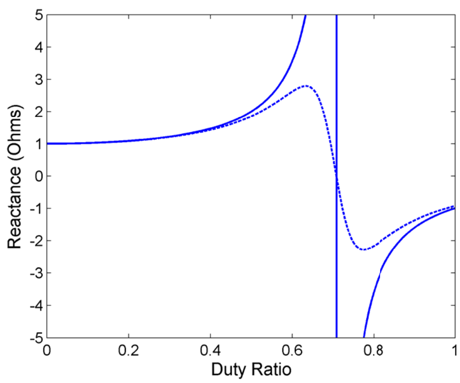

Fig. 4. Theoretical change in line reactance as a function of duty ratio for a module with $X_c = 0.5\ \Omega$, $X_l = 1\ \Omega$, and n=1. Solid line is for lossless capacitor and inductor while broken line includes losses (0.1 Ω ESR for inductor and 0.05 Ω ESR for capacitor).

IV. Simulation Setup

Fig. 5 shows a 10 kVA Active Smart Wires unit embedded in the high-current test-rig located on the Georgia Tech campus. The system in Fig. 5 was simulated in Saber using the parameters seen in Table 1. Ideal switches with non-zero turn-on and turn-off times were used. Duty cycle control was employed. Specifications for the STT were taken from laboratory measurements of the STT fabricated for the DSR proof of concept module [2]. STT saturation was neglected. The high current test-rig is rated for 1200 A. It should be noted that the 10 kVA rating is for duty ratios of 0 and 1 respectively. Intermediate ratios provide higher ratings.

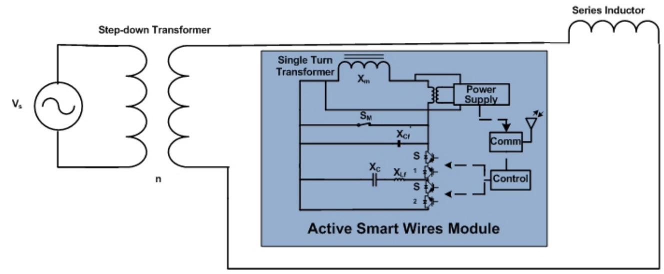

Fig. 5. Active Smart Wires module shown in blue, embedded in the Georgia Tech high current test-rig.

Table 1: Module parameters used in simulation

Item	Value
Source voltage (Vs)	377 V
Step down transformer duty ratio (n)	10:1
Inductance of transmission line series inductor	90 µH
Switching frequency	10 kHz
L_m (line side)	41.6 µH
C	450 µF
C_f	30 µF
L_f	20 µH
ESR of L_f	50 mΩ
Turns ratio of STT	1:25
Winding resistance of high side of STT	164 Ω
R_{on}	1 mΩ
t_{on}, t_{off}	1 µs

V. Simulation Results

The current and voltage characteristics at the secondary terminals of the STT are shown in Fig. 6 over the full duty ratio range. The red line indicates the line current of 400 A which flows when the Active Smart Wires module is bypassed by closing switch S_m. The module exhibits capacitive impedance for high duty ratios and inductive impedance for a low duty ratios.

Fig. 7 shows the phase angle between the voltage across the Active Smart Wires module and the line current for a duty ratio of 0.1. Fig. 8 shows the same for a duty ratio of 0.9. A comparison of Fig. 7 and Fig. *8* shows the transition from inductive impedance to capacitive impedance. Fig. 9 and Fig. 10 show the steady-state voltage ripple across the terminals of the Active Smart Wires module for the duty ratios of 0.1 and 0.9 respectively.

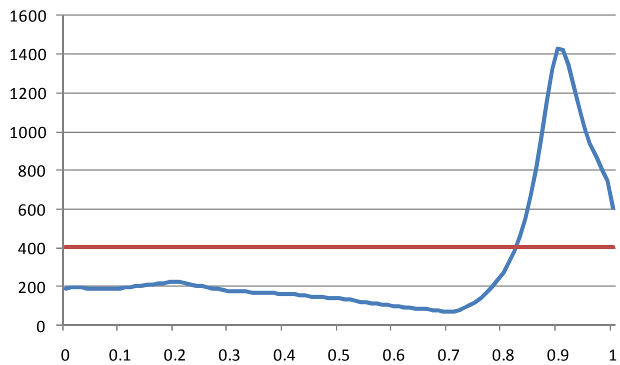

Fig. 6. Line Current (A RMS) vs. duty ratio for a single Active Smart Wires module during simulated operation in the Georgia Tech high-current test-rig

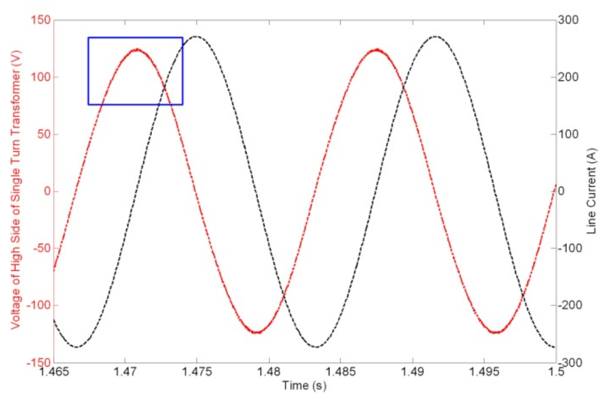

Fig. 7. Voltage (red) across high side of ASW STT and Current (black) through transmission line when ASW operated with duty ratio of 0.1 (inductive impedance mode). Region demarcated by the blue rectangle is shown in more detail in Fig. 9

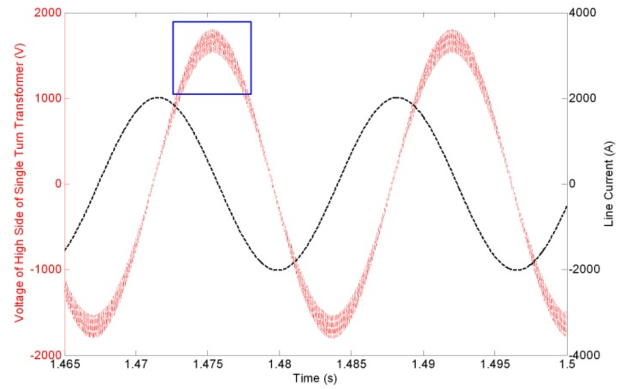

Fig. 8. Voltage (red) across high *s*ide of ASW STT and Current (black) through transmission line when ASW operated with duty ratio of 0.9 (capacitive impedance mode). Region demarcated by the blue square shown in more detail in Fig. 10

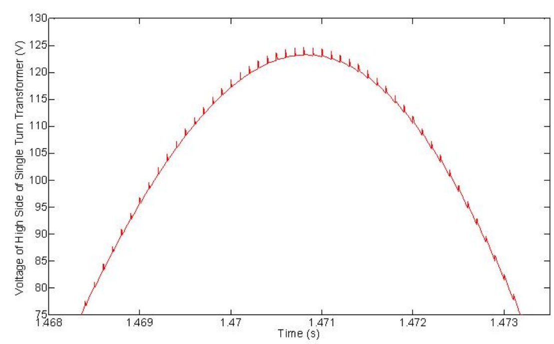

Fig. 9. Close-up view of voltage across high side of ASW STT with duty ratio of 0.1 (inductive impedance mode)

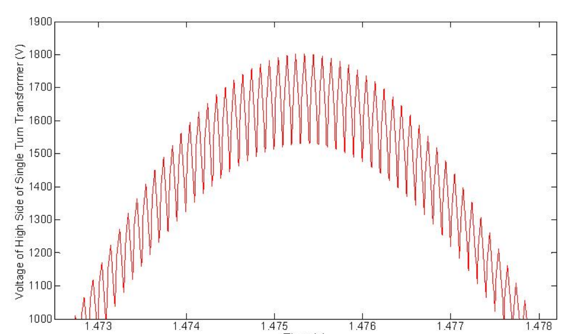

Fig. 10. Close-up view of voltage across high side of ASW STT with duty ratio of 0.9 (capacitive impedance mode)

VI. CONTROL

As specified in Section IV, the current rating of the high-current test -rig is 1200 A RMS . However, for a portion of the capacitive range of operation, the Active Smart Wires module causes more than 1400 A to flow in the line compared to a baseline flow of 400 A. This is attributable to the low line impedance. If the Active Smart Wire modules are deployed on a transmission line as envisioned, the fleet of Active Smart Wires modules will be sized so the line impedance is reduced by no more than 20% from its nominal value during operation. At this level of impedance change, line flows will not treble as seen when used with the Georgia Tech high-current test-rig.

While extreme variation in current will be limited by properly sizing the fleet of Active Smart Wires modules, care must still be taken for control. The extreme sensitivity of line current to duty ratio near the resonant peak of Fig. 6 suggests that operation in this region should be avoided.

VII. CONCLUSIONS

The need to control power flows on the grid is rapidly increasing as additional renewable resources are added to an already strained grid. It is critical that cost effective solutions be available to maximize grid asset utilization. This paper proposes the Active Smart Wires module, a new method for realizing Static Series Compensator functionality, without requiring the use of reliability limiting inverters and DC capacitors. The Active Smart Wires module is fabricated by augmenting a Distributed Series Reactance (DSR) module with an AC capacitor, two AC switches and a communications package. This yields a reliable system. This also suggests that the proposed Active Smart Wires module, like its predecessor the DSR, will be cost effective. Simulation results validate the ability to inject desired and controllable impedance into the line.

REFERENCES

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