Smart Wires – A Distributed, Low-Cost Solution for Controlling Power Flows and Monitoring Transmission Lines

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Abstract**-- Smart Wires is a family of three Distributed FACTS (D-FACTS) technologies able to realize low-cost transmission line monitoring and power flow control in meshed networks. Smart Wires will allow utilities to increase power transfers in meshed networks by increasing average line utilization. The technology is projected to have significantly lower cost and lead time than alternatives, namely new line construction, reconductoring, or conventional FACTS technology. This paper overviews the work done to date to demonstrate the feasibility and impact of the technology, including prototype development and system simulations.**

Index Terms**—Dynamic Thermal Rating, Flexible AC Transmission Systems (FACTS), Power Flow Control, Power Systems, Power System Condition Monitoring, Power System Control, Power System Monitoring, Power System Reliability, Power Transmission Lines, Smart Grid**

I. INTRODUCTION

THE existing transmission grid in many industrialized countries is congested after a period of low investment relative to generation and load growth. In addition, emerging requirements such as mandates for renewable energy and regulation to increase the scope of power markets, are anticipated to further stress the transmission grid.

The level of renewable penetration in many systems is already so high that existing renewable generators regularly experience curtailment [1]. Curtailment of wind generation in Texas in 2009 was typically 12% of available wind production during daily peak production periods, leading to a dramatic slowdown of new wind generation investment [1]. Some regions with high-cost renewable resources have relied on the purchase of Renewable Energy Credits (RECs) to meet renewable energy mandates, without contracts for the physical import of the renewable energy. This is possible at low levels of renewable energy penetration. At higher penetration levels, REC-based compliance schemes complicate the integration of renewables and ultimately limit the growth of renewable generation.

To illustrate how REC-based compliance schemes limit the growth of renewables, consider two regions, one called Importer and the other Exporter. Importer has poor renewable resources while Exporter has excellent renewable resources, so Importer prefers to buy RECs from Exporter. The transmission capacity between the regions is weak. In addition to the REC transactions, Exporter elects to sell power during periods of high renewable production, to facilitate system operation. As the level of renewables generation within Exporter increases, the transmission links between Exporter and Importer occasionally saturate. To reduce the impact of saturation, Exporter can invest in energy storage to transfer renewable energy to Importer during periods with low renewable production. Exporter can also add conventional generation with high ramp rates to allow renewables to serve more of Exporter's native load. Also, Exporter may chose to curtail renewable generation during peak production periods. Energy storage, adding fast response conventional generation, and curtailment will all increase the cost of energy. Even if cost increases are tolerable, consistent growth in the capacity of renewable generation within Exporter's footprint will eventually completely fulfill Exporter's native load and saturate transmission links to Importer. At this point, without additional transmission capacity, an upper bound will be imposed on the growth of renewables within Exporter's region. Further increases in renewable penetration will require new transmission capacity or the use of high-cost renewable resources within Exporter's area. This thought experiment shows that low-cost methods to increase transmission capacity are a key enabler to ensure that plentiful renewable resources, often distant from load centers, are utilized. Low-cost expansion of transmission capacity also avoids the use of costly alternatives such as a massive deployment of multi-hour energy storage and the reliance on renewable generation sited in areas with poor resources.

Transmission constrains have led to plans for massive transmission projects. The Texas Competitive Renewable Energy Zone (CREZ) is a $5B plan to move 18 GW of wind from west Texas and the panhandle to the major load centers in east Texas consisting of 2300 miles of new 345 kV transmission [2]. An analysis by dena shows that the number of miles of high voltage transmission in Germany must be

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increased by 5%, or 850 km, between 2006 and 2015 to accommodate expected increases in renewable generation during that time [3]. The dena study estimates another 1000 km of high voltage transmission will be necessary between 2015 and 2020 to reach 20% penetration of renewable in Germany.

In addition to high cost, a number of issues beset the construction of new transmission lines. It takes exorbitantly long to permit and build high voltage transmission lines, especially if lines cross state or national borders. Also, the use of a meshed grid to maximize reliability, coupled with the lack of power flow control, results in free-rider problems. This problem, described in [4], means that the entity that invests in the line's construction is unable to fully capture the benefits of the investment. The assurance that the asset owner reaps the benefits of investments made is a fundamental requirement of efficient markets. The free-rider problem limits the feasibility of a competitive transmission market, resulting in a regulated transmission industry. Finally, the long lead times for transmission construction and imperfect foresight lead to inefficient capital allocation.

Recent cases and reports by the European Commission demonstrate a commitment to expanded electricity markets [5, 6]. The European Commission has concluded that existing international transmission links are insufficient to enable increased trade [5] and has opened cases against utilities not providing access to national transmission systems [6]. The commission has concluded that transmission investments are required to meet its goals for expanded electricity markets. Technologies able to minimize the cost of transmission improvements will improve the efficiency of the market and reduce opposition to future efforts to promote market functions.

II. Existing solutions to Increase network Capacity

The solutions that exist to increase transmission capacity can be divided into two classes. The first class adds capacity through the construction of new transmission lines or the upgrade of existing lines. Neither of these solutions increase the utilization of the parallel paths not upgraded. The second class of solutions, power flow control, seeks to increase the capacity of a meshed system by routing more power onto lightly loaded parallel paths, thereby increasing average system utilization. Power flow control can increase system capacity without requiring new line build, but can also increase the possibility of cascading failures in the absence of fast control. Solutions exhibiting low-cost, high reliability, short lead time to installation, and ease of scaling are most likely to be adopted. It should be noted that an underlying assumption for increasing system capacity via power flow control is enhanced visibility of the state of the system relative to the level typical today. This requires improved sensing at a local level, ideally at a per-span level, and a communication infrastructure that can aggregate and present this information to system operators for action.

A number of power flow control solutions exist, such as the series reactor, the phase shifting transformer, the Static Series Synchronous Compensator (SSSC), and the Unified Power Flow Controller (UPFC). The price of FACTS solutions offering dynamic response, such as the SSSC and UPFC, are in the range of $150-300/kVA. Phase shifting transformers without dynamic control capability, are in the range of $30-50/kVA. Technologies with dynamic response are preferred to avoid cascading blackouts following the outage of a grid asset. However, the technologies capable of dynamic response are often plagued by poor reliability and high cost, which have severely limited the penetration of FACTS devices. As a result, new line construction and reconducting have been the dominant methods used to increase network capacity.

III. Overview of Smart Wires

Georgia Tech has developed the Smart Wires technology to convert an existing transmission line to a smart asset, able to monitor and regulate its power flow, thereby shifting excess power to underutilized lines in the network. The technology is a distributed solution, with a fleet of modules fixed directly to the conductor. Each module acts autonomously, resulting in high reliability without the costly hardening required to make centralized FACTS devices reliable. As such, the modules can be incrementally deployed on existing transmission lines in a very specific and targeted manner, providing sensing of transmission line status along the length of the line, as well as providing the mechanism to achieve actual control of line currents.

A. *Smart Wires (SW)*

The simplest version of the technology, Smart Wires (SW), monitors line current and takes autonomous action. As current builds up on Smart Wires (SW), the modules autonomously take action, gradually increasing the impedance of the line by sensing line current and comparing it against a reference current based on the line capacity. The heart of each module is a 'single-turn transformer' coupling the line current with control circuitry, along with a fast acting switch that inserts the leakage impedance of the STT in series with the transmission line when the switch is closed. When the switch is open, the leakage and magnetizing impedances of the STT are inserted in series. Fig. 1 shows a circuit schematic.

The Smart Wires modules are self-powered using the line current and do not require communications among the devices or to a central control center. The module operates at line potential and does not connect to the ground, eliminating isolation issues. A 3D rendering is shown in Fig. 2. The target retail price for Smart Wires is $1000 per 10 kVA module.

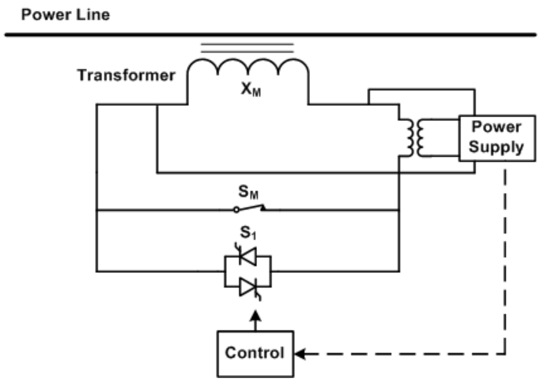

Fig. 1. Circuit schematic of a Smart Wires module showing the magnetizing inductance (X_m) of the single turn transformer, thyristor pair to toggle between operating modes during faults (S_1), relay (S_m) for toggling between operating mode outside of fault conditions, power supply, and control modules

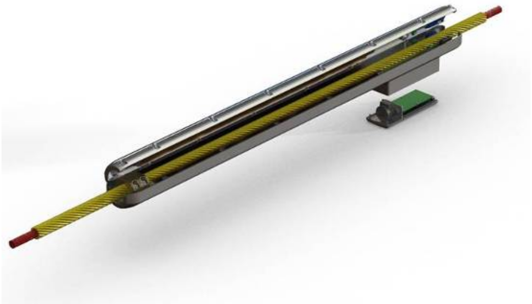

Fig. 2. 3D rendering of a single Smart Wires module

B. *Reporting Smart Wires (RSW)*

Georgia Tech has also developed two more advanced versions of Smart Wires. The first, called Reporting Smart Wires (RSW), augments SW with additional sensors and a wireless sensor network. Each RSW module still makes autonomous decisions. However, each RSW relays its state as well as the Real-time Dynamic Thermal Rating (RDTR) of the local section of transmission line to the utility, Transmission Service Provider (TSP), or Independent System Operator (ISO) through a unidirectional communication channel.

A transmission line's safe maximum thermal capacity is affected by the line's ambient weather conditions which may vary widely over the course of a day, or even an hour, and also along the length of the line. At present utilities do not have accurate real time information of line thermal conditions and are unable to produce an accurate RDTR, leading to conservative operation. According to [7], if an accurate RDTR could be produced, a utility could increase power flow through the line by 10-30% for 90-98% of the time, compared to current techniques. Coupled with power flow control, RDTR would allow the utility to re-route power through uncongested lines and further increase system transfer capability. Also, more accurate RDTR estimates would allow a utility to overload a line less conservatively during an emergency event. The RDTR of a transmission line is not a single value, but a series of short term overload currents associated with a series of short term durations. The loci of RDTR points can be represented in the form of an I-T Thermal Limit Curve (ITLC). The prediction of ITLC is not a trivial task due to the uncertain and time variant ambient weather conditions, as well as the inherent nonlinearity of the conductor thermal dynamics. The authors have used advanced artificial intelligence (AI) based algorithms to accurately, quickly and simplistically predict the ITLC. The sensing and reporting aspect of RSW has been developed under an ongoing NSF funded project.

The RSW relays its status and the estimated ITLC continuously through wireless communication back to the substation, thus averting the cost of delivering wired communication to each RSW module. To develop the sensing and communications technology, a standalone Power Line Sensor (PLS) was developed, as seen in Fig. 3. Each sensor module can operate as a communication node, and communications would occur between adjacent working sensor nodes. Self-organizing techniques ensure that failure of single or multiple nodes do not affect the ability of the network to continue operating. The PLS functionality is being integrated with SW to produce RSW.

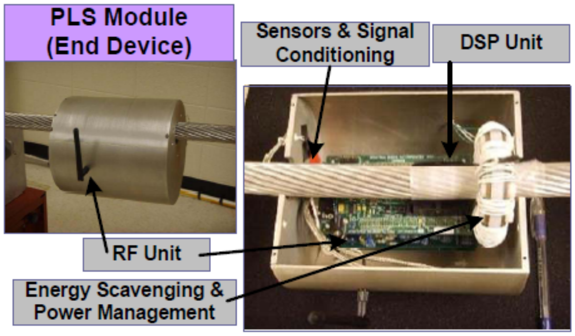

Fig. 3. Prototype of the power line sensor network (PLSN) integrated into the RSW to provide ITLC estimates to the transmission operator at low-cost

C. *Active Smart Wires (ASW)*

The third, and final version of Smart Wires, called Active Smart Wires (ASW), has the ability to increase or reduce line impedance. When operated with centralized control, ASW can be used to channel power flows away from one path and onto a specific alternative path. A laboratory prototype, has been built and tested for verification of the ASW concept.

D. *Hardware Testing*

A proof of concept SW device seen in Fig. 4 has been fabricated and tested. The module was tested under high voltage (166 kV) and high current (1 kA normal and 25 kA fault) conditions to examine corona inception, effects of operation on conductor temperature, and the efficacy of the fault protection system. Fast dynamic response of the Smart Wires modules has been demonstrated. The SW, RSW and ASW modules are currently being redesigned to meet utility specifications.

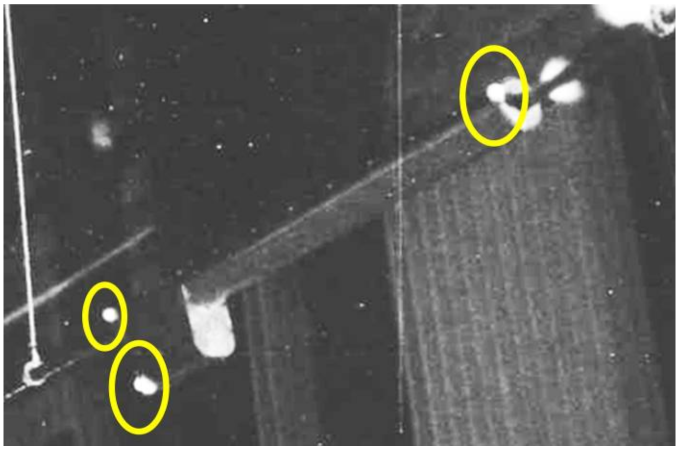

Fig. 4. Corona testing of proof of concept device. Corona effects outlined in yellow

IV. SYSTEM LEVEL IMPACTS

Smart Wires (SW) can be used as a cost-effective solution to a number of problems that plague most modern AC transmission systems. In this section the system level benefits of SW are quantified through case studies.

A. *Increased Available Transfer Capacity*

The total power throughput of a transmission network, also called the Available Transfer Capacity (ATC), is limited by the first line that reaches the thermal limit, even though the rest of the lines in the system are substantially underutilized. As discussed in [8], the ability of the Smart Wires to increase transmission network ATC is demonstrated using the IEEE 39 bus system shown in Fig. 5. The system consists of 10 generators, 19 load buses and 45 transmission lines. The generators are modeled as constant voltage sources while the loads are modeled as constant impedances with unity power factor. Each line is assumed to have a thermal rating of 750 A. The entire system is simulated in PSCAD.

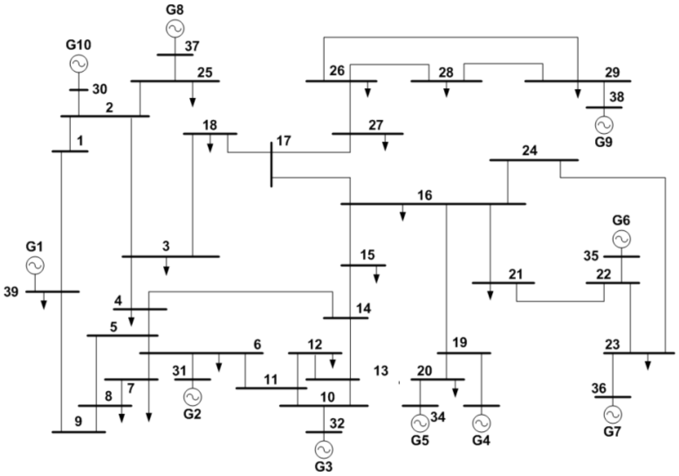

Fig. 5. IEEE 39 Bus system used to evaluate impact of SW on ATC

The loading of the system is increased until one of the lines (Line 21-22) reaches its thermal limit. At this operating point the total system loading is 1904 MW, while the average line loading is seen to be only 59%. The lower blue curve in Fig. 6 shows the line utilization of selected lines at this operating point. The real situation is even worse as it is driven by the need to have spare system capacity and to ensure system integrity and reliability under (N-1) or (N-2) contingency conditions. This reduces the allowed line current levels under normal operating conditions drastically below nominal thermal limits, and further degrades system utilization. A contingency study on the IEEE 39 bus system showed that the outage of Line 19-16 was the worst case (N-1) contingency. Under this line outage, the transfer capacity of the system is limited to only 1469 MW.

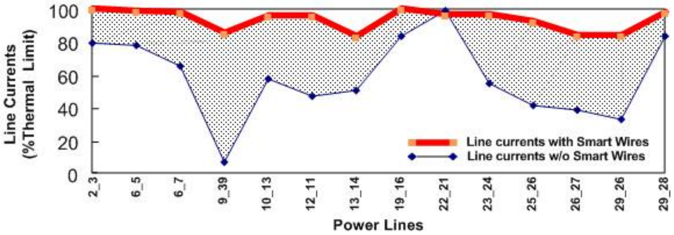

Fig. 6. Line utilization of IEEE 39 Bus system with (red) and without (blue) Smart Wires, as a percentage of thermal rating

To increase the transfer capacity of the system, SW modules were added to the lines of the network which get overloaded as the system load is increased. The SW are modeled as fixed inductors, with each module being 50 µH, rated for 10 KVA at 750 A. This is an ideal model, which does not incorporate losses and nonlinearities. However, it captures the impact of DSR technology on improving system capacity and reliability and provides an estimate on the number of modules required to realize the required gains.

The upper red curve of Fig. 6 illustrates an increase in line usage that can be realized from a redistribution of the current through the network, as the system load is increased. System utilization increases by a factor 1.58, from 59% to 93.3% This increase in utilization was obtained without addition of new lines and with all lines operating within their thermal limits. The system capacity was seen to improve from 1904 MWs to 2542 MWs, an increase of 33.5%. The lines outfitted with SW and the total MVA injection of SW required per line are shown in Fig. 7.

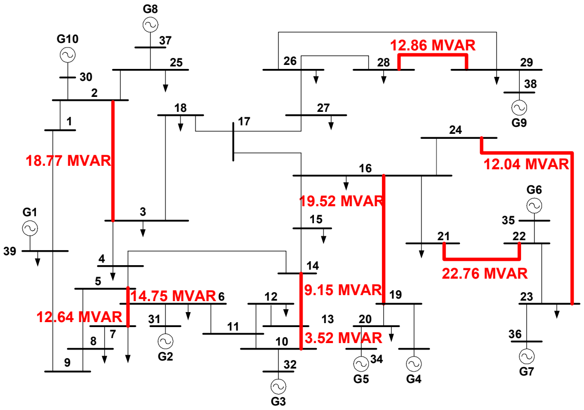

Fig. 7. IEEE 39 bus system with red lines indicating those equipped with Smart Wires. Values next to the red lines indicate the aggregate rating of Smart Wires modules installed on the line to increase system ATC from 1904 MW to 2542 MW.

B. Reducing Transmission Investment required to Meet Renewable Penetration Mandates

In order to facilitate the adoption of renewable energy, many regions have introduced mandates requiring that a given fraction of annual demand be sourced from renewable generation by a certain year. In many areas, it might be preferred to import renewable energy rather than build generation facilities in resource poor areas to meet renewable mandates. Relying on distant, low-cost renewable generation will lead to increased inter-area power transactions. In order to sustain such high levels of inter-area transactions, considerable transmission investment has to be directed towards inter-area links. Smart Wires can be used to reduce the transmission investment required to meet renewable mandates.

To examine the transmission investment benefits achieved by the use of Smart Wires for meeting renewable mandates, a study was conducted on the IEEE 39 bus system. It is assumed that the entire system is divided into 4 regions – the North East (NE) region, the North West (NW) region, the South West (SW) region and the South East (SE) region. Fig. 8 shows the demarcations of the four different regions in the IEEE 39 bus system. It is assumed that the system at present (*Year 0*) sources 1% of its energy from renewable generation and the renewable mandate requires 20% of demand be served by renewable generation in 19 years, increasing in increments of 1% each year.

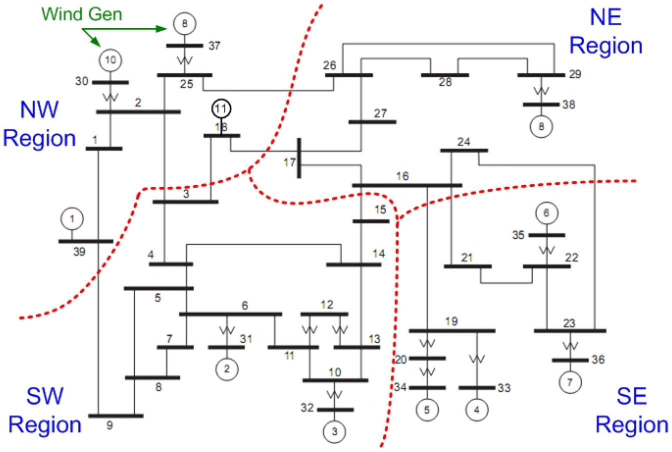

Fig. 8. IEEE 39 bus system used to examine impact of Smart Wires on the cost of meeting renewable energy mandates for a multi-area system. Low-cost wind resources confined to the NW region. Red lines demarcate the region boundaries.

For the purpose of the study, a number of simplifying assumptions are made. It is assumed that buses 30 and 37 are wind generators and are the sole sources of renewable energy for the entire system. Thus the entire amount of renewable energy required by the 4 regions must be supplied from the NW region. Also inter-area tie-lines are considered to be much longer than the intra-area tie-lines. It is thus assumed that upgrading inter-area tie-lines would be much more expensive than upgrading the intra-area ones. As a result, this study *only* accounts for the cost to upgrade the inter-area tie-lines.

The wind generators as well as the loads are assigned an intra-day variation characteristic as shown in Fig. 9. The total initial peak load of the system is assumed to be 4880 MW. It is assumed that the peak loads at each of the buses increase at an annual rate of 2%. It is assumed that wind generation capacity at any particular time-step is sufficient to meet the renewable mandate.

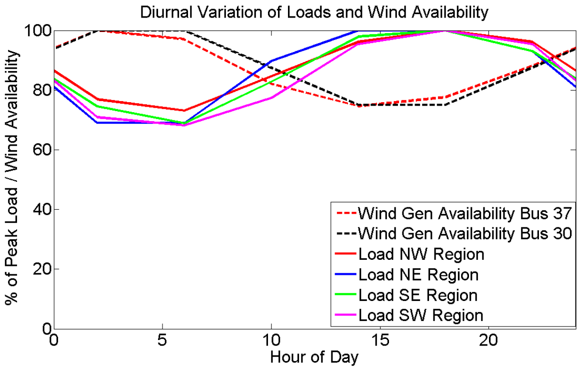

Fig. 9. Diurnal variation of loads and wind availability

The transmission investments are studied for the 2 cases –

1. **Business As Usual (BAU) Case:** In case if a transmission line is constrained, the utility simply upgrades the line by building a line of same rating parallel to the existing line. Hence after the upgrade the rating of the line doubles while its impedance gets halved.
2. **Smart Wire Case:** Apart from the regular line upgrade, the utility also has the option of inserting Smart Wires module to mitigate congestion. The transmission investment takes into account both the tie-line upgrade as well as the insertion of Smart Wires modules.

For simulation, the MATLAB-based open source software MATPOWER is used. Starting from *Year 0*, for each of the years, the loadings of the load buses as well as the available wind generation for the wind buses are generated, for each of the 6 time steps. It is assumed that all the wind generation that is available at a particular time-step must not be curtailed due to congestion, in order for the wind plants to meet revenue requirements. An optimal power flow is run for each of the time steps to check for any tie-line congestion. In case congestion is encountered it is mitigated by one of the following strategies:

1. Line upgrade in BAU case
2. Line upgrade and/or Smart Wire installation in Smart Wire case.

For the BAU case, the upgrades involve only tie-line upgrades and thus can be easily expressed in terms of MW-miles. Fig. 10 shows the various line upgrades that are required by the system to meet the renewable mandate for BAU. For the Smart Wires case, the upgrades may involve not only tie-line upgrades but also insertion of Smart Wire modules. It is estimated that the cost of 1 MVA of Smart Wires modules is equivalent to that of 100 MW-miles of new line, based on a MW-miles cost of $1000 and an estimated SW cost of $100/kVA [9]. Fig. 11 shows the tie-line upgrades required by the 39 bus system in order to meet the renewable mandate with Smart Wires.

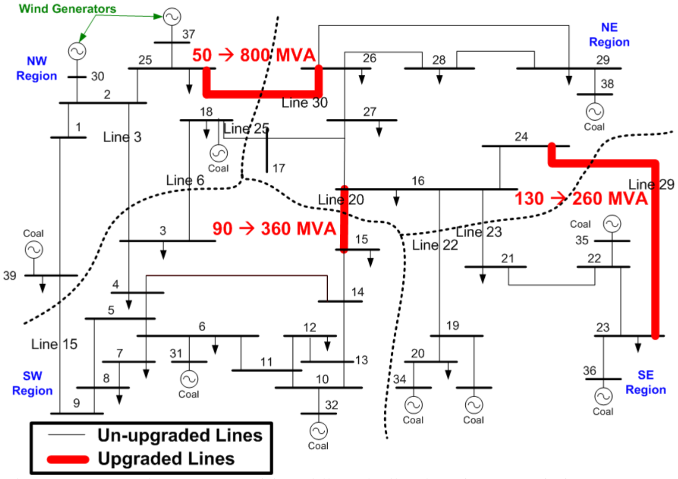

Fig. 10. Four region system with red lines indicating the upgraded transmission lines to meet renewable mandates. Red text indicates the pre- and post-upgrade line ratings.

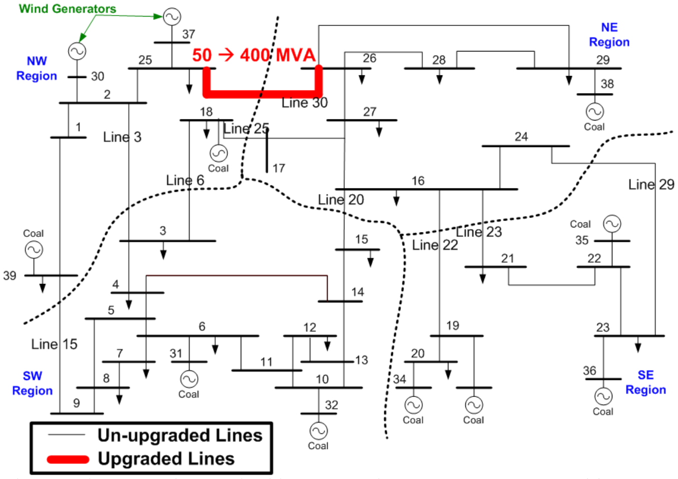

Fig. 11. Line upgrades required in Smart Wires case to meet renewable mandates. Lines on which Smart Wires modules are installed are not shown.

Fig. 12 compares the transmission investments incurred in the BAU case with that of the Smart Wires case. It is seen that in the Smart Wires case it is possible to postpone transmission line upgrades by installing SW. It is seen that at the end of Year 19, the transmission investment required in the Smart Wires case is approximately 48.9% of that in the BAU case, indicating a potential savings of about 51.1%. In this analysis the discount rate is taken as zero, i.e. a MW-mile upgrade of transmission line at Year 0 is equivalent that at Year 19. Taking a discount rate of about 4% further widens the gap between the BAU and the DSR case, for a savings of 54%. The load growth, fuel price and regulatory projections that drive the planning process are more likely to deviate from actuality for longer range estimates. Thus, the appreciable cost difference between SW and BAU in the short-term, during which utilities can be most assured of the result, is notable.

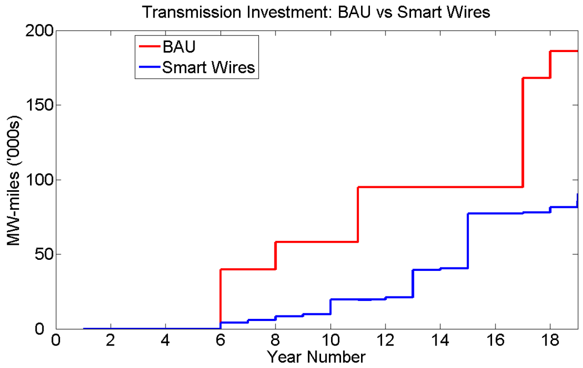

Fig. 12. Comparison of transmission investment required to meet renewable energy mandates for BAU vs. Smart Wires

V. Design of Communications and Sensing Capability

RSW augments SW with ILTC estimation and communications with the transmission operator. Together, these functions allow the operator to reliably schedule higher power transfers through the transmission network.

A. Estimation of I-T Thermal Limit Curve (ITLC)

The ITLC of a line is dependent on a number of factors including irradiance, ambient temperature, humidity, amount of precipitation on the line, and wind speed. These parameters vary significantly over the lengths of typical transmission lines. Typically, at least one Smart Wires module will be installed on each span of the transmission line. By integrating sensing capabilities in SW to yield RSW, the variation in environmental parameters which drive RDTR, and ultimately ITLC, can be accurately assessed.

While a multitude of environmental parameters could be measured by each RSW, doing so would be prohibitively expensive. As an alternative, Georgia Tech has developed a method using neural networks to estimate ITLC solely through the measurement of ambient temperature and line current. Given that line current is a control variable for SW, the additional hardware requirements for RSW sensing are minimal, simply an ambient temperature measurement and sufficient computational capability to run the neural network.

As discussed in [10], a three–layer multilayer perceptron neural network (MLPN) is used to estimate the ITLC. To validate the MLPN approach, a simulation is used to compare the ITLC estimates of the MLPN to that of the prevailing standard, IEEE 738, over a 6 day period. The time-series of measurable environmental and conductor quantities are shown in Fig. 13. The ITLC estimated using the MLPN and IEEE 738 methods are shown in Fig. 14 for two different wind speeds. The MLPN estimates closely track the IEEE 738 estimates for both wind speed scenarios.

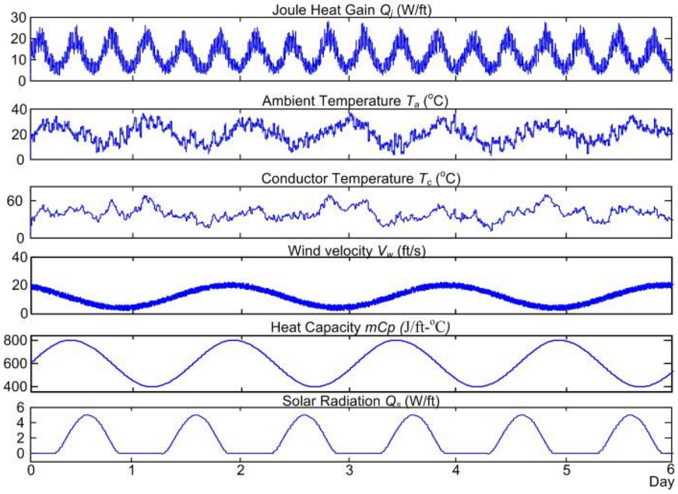

Fig. 13. Variation of conductor heat gain, ambient temperature, conductor temperature, wind velocity, conductor heat capacity, and solar radiation over the 6 days used for to compare the efficacy of RSW ITLC to IEEE 738 ITLC

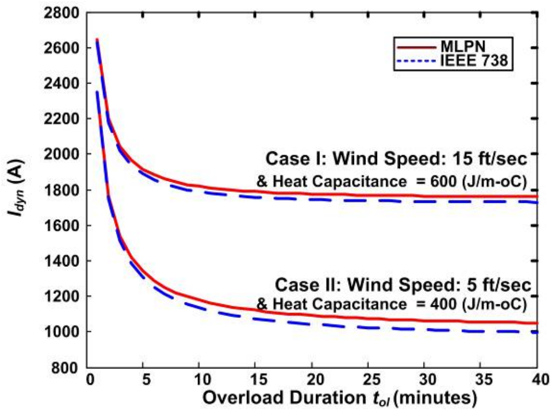

Fig. 14. I-T Thermal Limit Curve (ITLC) comparing the accuracy of RSW (using MLPN) and IEEE 738 estimates of ITLC

B. Communications

The expanse of the power transmission network and minimal penetration of dedicated communication infrastructure outside of substations challenge the feasibility of implementing technologies which require communications. In most parts of the industrialized world, it may be possible to utilize the cellular system for processes that require a reporting frequency in the range of seconds to minutes. To avoid reliance on cellular communications, a wireless peer-to-peer communication system was developed to enable the RSW and ASW modules to communicate back to a master node at the substation. The master node would be connected to the utility SCADA system. Given the presence of intense electrical and magnetic fields in the vicinity of transmission lines and substations, field tests have been conducted to demonstrate the robustness of the communication system.

As discussed in [11], an off-the-shelf Digi XBee-Pro RF module, compliant with the IEEE 802.15.4 standard, was used at each communication node. The module includes ZigBee features which allow point-to-point, point to multipoint, and peer-to-peer communication. ZigBee also supports 128 bit encryption.

Two loop-back tests were performed. In the first, one of the communication modules was attached to a conductor carrying up to 1000 A of current in an indoor environment. In the second, the connection quality was tested in an outdoor environment for a range of distances and line-of-sight conditions. The results are seen in Table 1 and Table 2. In both tables, PSR is the percent of Packets Successfully Received. Given that at least one RSW or ASW module is expected to be installed on each span of a transmission line, the tested ranges should be more than sufficient to provide reliable communications, even if one or more modules fail. For more redundancy or on lines that are lightly populated with modules, small repeaters may be installed, attached directly to the conductor in a similar manner as the Smart Wires modules.

Table 1
INDOOR LOOP-BACK TEST RESULTS IN HIGH CURRENT ENVIRONMENT

Current (A)	Range (m)	RSSI (dBm)	PSR
1000	50	-70~-75	100%
1000	100	~-92	~45%
500	10	-45~-50	100%
500	50	~-73	100%
500	100	~-93	~45%

Table 2
OUTDOOR LOOP-BACK TEST RESULTS

Range (m)	RSSI (dBm)	PSR	Conditions
200	~-76	~95%	Nearly line of sight
400	~-83	~80%	Trees along transmission path
500	-92	~35%	Trees and buildings along transmission path

VI. NEXT STEPS

The Smart Wires modules are currently under development with the support of the NEETRAC Smart Wire Focused Initiative, funded by three electric utilities (Georgia Power, the Tennessee Valley Authority (TVA), and Baltimore Gas and Electric (BG&E)), the National Rural Electric Cooperative Association (NRECA) representing 900 member cooperatives, the Department of Energy and Zenergy Power. A fleet of Smart Wires modules are expected to be installed on the Georgia Power or TVA systems in late 2011 or early 2012 to demonstrate the impact of the technology in an operating system.

VII. CONCLUSIONS

The family of Smart Wires modules provides varying degrees of transmission network visibility and power flow control at a projected price point and reliability level not feasible with current solutions. A system simulation shows that Smart Wires modules installed on a few heavily load transmission lines within a system can increase ATC significantly. Another simulation shows the transmission investment necessary to meet renewable energy mandates costs half as much using Smart Wires than with conventional approaches, based solely on new line construction. Simulation and field testing shows the viability of more advanced versions of Smart Wires, with integrated sensing, communications, and enhanced power flow control capabilities. These more advanced versions offer even larger increases in ATC. Work is underway to demonstrate Smart Wires impacts on actual system operation.

VIII. REFERENCES

[1] NREL, "Wind Energy Curtailment Case Studies: May 2008 – May 2009," NREL/SR-550-46716, October 2009, downloaded December 15, 2009 from http://www.nrel.gov/docs/fy10osti/46716.pdf

[2] B. Smitherman, "Building the Electric Grid of the Future in Texas; aka the CREZ Projects," Public Utility Commission of Texas, Jan. 2010.

[3] DENA, "Planning of the Grid Integration of Wind Energy in Germany Onshore and Offshore up to the Year 2020: Summary of the Essential Results of the Study," March 15, 2005. Available as of June 30, 2010 at http://www.wind-energie.de/fileadmin/dokumente/Themen_A-Z/Netzausbau/stud_summary-dena_grid.pdf

[4] P. Joskow, J. Tirole, "Merchant Transmission Investment," mimeo, Center for Energy and Environmental Policy Research, MIT 2003, accessible as of 30June2010 at http://web.mit.edu/ceepr/www/publications/workingpapers/2003-004.pdf

[5] Decision No 1364/2006/EC of the European Parliament and of the Council, *Official Journal of the European Union*, September 22, 2006, L 262/1-23. Available as of June 30, 2010 at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:262:0001:0023:EN:PDF

[6] G. Cervigni, The Swedish Interconnectors Case: Electricity market design through competition policy?, April 2010, available as of June 30, 2010 at http://www.lecg.com/about/publications/PublicationDetail.aspx?pub=3486

[7] J.L. Lilien, Ampacimon as a tool for transmission line assets management. University of Liège, June 2008. Available at www.ampacimon.com

[8] H. Johal, "Distributed Series Reactance: A new approach to realize grid power flow control," Ph.D. dissertation, School of. Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, 2008.

[9] 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," *IEEE Transactions on Power Delivery*, Vol. 22, Issue 1, pp. 642-649, Jan. 2007.

[10] Y. Yang, R. G. Harley, D. Divan, T. Habetler, "MLPN based Parameter Estimation to Evaluate Overhead Power Line Dynamic Thermal Rating," in *Proc. 15th Annual Conference on Intelligent System Applications to Power Systems*, pp. 1 – 7.

[11] Y. Yang, D. Divan, R. Harley, T Habetler, "Design and Implementation of Power Line Sensornet for Overhead Transmission Lines," in *Proc. 2009 IEEE PES Power & Energy Society General Meeting*, pp. 1 – 8.

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