Introduction to the Smarter Grid – Part 1

Maike Luiken, Associate Editor

The Canadian Electricity System is expected to deliver power reliably, efficiently, and at low cost with increasingly higher performance expectations, while operating conditions are changing greatly. To meet these demands, the electrical power system is evolving. One key trend is the deployment of more communications, control, and information technology — giving rise to the "Smart Grid" or "Smarter Grid" or a 'new more flexible energy network' called the "enernet" (a term coined by Bob Metcalfe, the inventor of Ethernet).

> "Electricity has become all pervasive in the world today. This has been accomplished by continued developments in power systems over the past 130 years. Although power systems engineers have always kept pace by embracing new enabling technologies as they developed, recently there has been a trend to classify the new developments under the umbrella of 'smart grid'. Smart grid embraces the entire power system and is another step in the continuing effort to make the grid more versatile, resilient and reliable."
>
> **Om Malik**, Distinguished power researcher.

SOME TRENDS AND CHALLENGES:

Electricity consumption patterns are changing
- Increasing number of DC devices
- Time of use rates and smart metering change demand patterns
- Expected addition of electrical vehicles drawing power and potentially storing power
- 50% population increase over the past 30 years in Canada – growth expected to continue through immigration

Addition of - potentially - a vast number of 'generators' from renewable energy sources into the electrical grid
- Widely distributed generation
- Stranded generation due to mismatch of generation to load
- Intermittent generation – Solar PV, Wind

DC versus AC: Interest in DC power is rising
- DC's efficiencies – potentially 5 -15% savings
- DC data centres
- Hybrid AC-DC power systems
- Building DC microgrids

High Capacity TransCanada Interconnect proposed
- HVDC transmission

New Generation opportunities
- Hydroelectric generation to potentially grow to 236 TW provided transmission capacity is in place (*)
- Tidal power

Energy Conservation is becoming policy
- Zero-Net-Energy Buildings (ZEBs) in the USA for all new commercial construction by 2030
- Mandatory Perform Achieve Trade (PAT), a trading scheme aimed at reducing energy consumption in industries across India.

Aging electrical infrastructure requires costly replacement
- Replace with "the same" or invest in new "smarter" technology – at what cost?

Increasing Interest in the development and deployment of microgrids
- Increase system resiliency
- Increase local resiliency
- Decentralization
- Open new market opportunities
- Challenges include expense, complexity, islanding and the impact of islanding microgrids on the grid

Technology developments
- Storage, including integrated storage between the electricity and gas grids, and demand side storage
- Demand side management
- Pervasiveness of power electronics
- Data analytics for predictive maintenance and dynamic assessment
- Modeling and simulation
- Integration of modern communications, control, and automation

Security risks are increasing
- Severe weather
- Physical attacks - including theft of copper
- Cyber attacks

Environmental/Sustainability/ Health concerns are mounting
- Communications/education to share factual information
- Economic concerns, such as property values

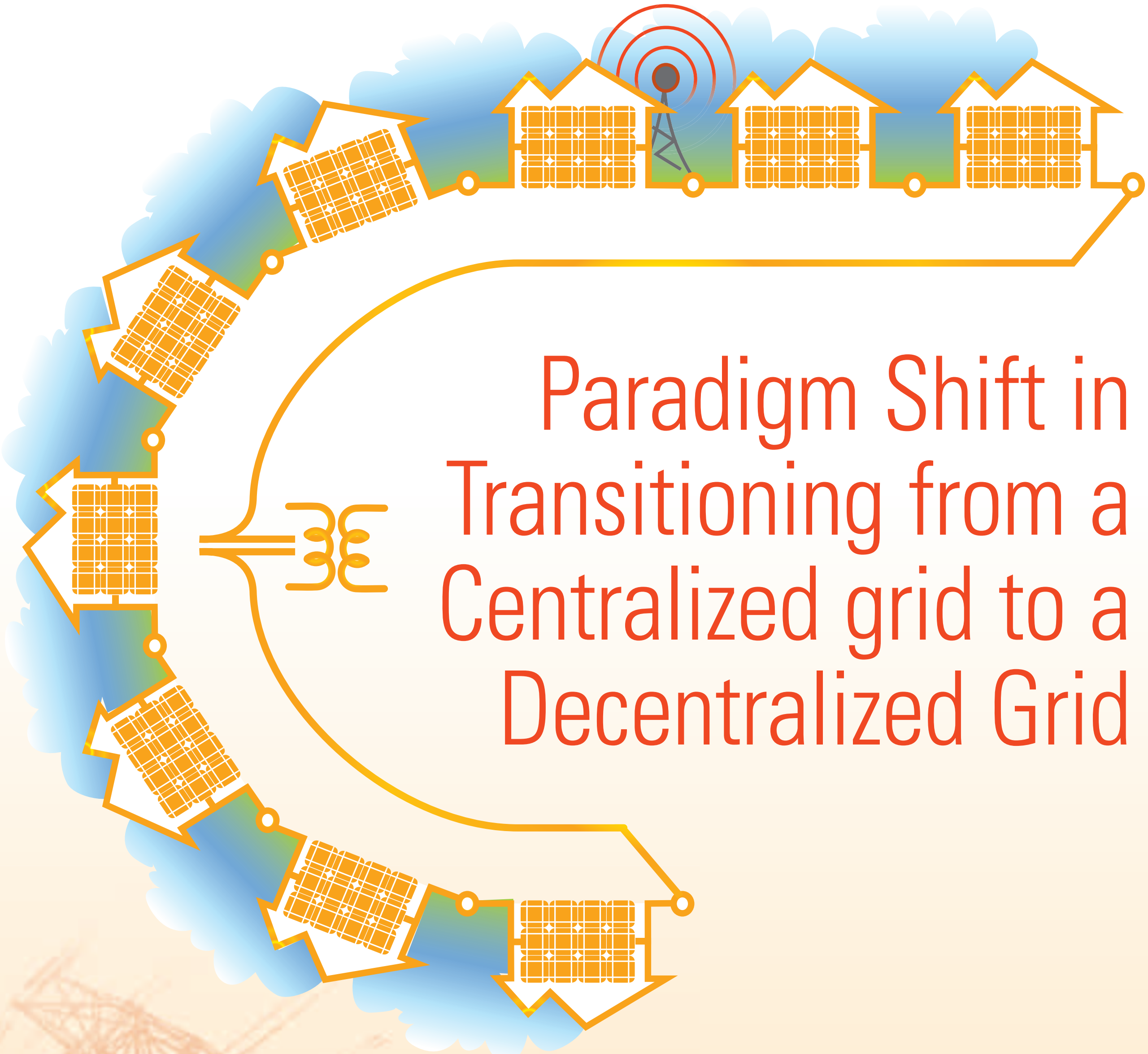
The cost of electricity
- Increasing electricity costs and their impact on the economy
- The impact of shale gas availability

The role of nuclear power is being re-considered
- Reliable cost-effective base power with low carbon emissions
- Nuclear plant lifetime, license extensions, changing economics.

(*) Canadian Academy of Engineering, 2012, Canada: Winning as a Sustainable Energy Superpower

Higher Performance Expectations while being subjected to increasingly catastrophic risks like incidences of extreme weather, physical and cyber attacks, the intermittency of distributed renewable energy sources.

What do these developments mean to the Canadian electricity supply system now and in the future? In this issue and the next we will explore some of these issues, their implications, and potential solutions.



Paradigm Shift in Transitioning from a Centralized grid to a Decentralized Grid

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Canada's electrical grid has evolved over the last century through the provinces' economies, geographies and climates. While generation capacity in certain provinces has been dominated by hydroelectric power, other provinces have used nuclear or fossil fuel-based energy generation, while still others have attempted to tap into renewable sources of energy. The transmission side has seen its own share of peculiarities, reflecting Canada's vast and demanding geographical and climate conditions. Different urbanization patterns in Canada have influenced the distribution system design. Developing Canada's future Smart Grid will require attention paid to the same realities and patterns of its existing electrical grid while responding to the challenges of providing power to the country as a whole.

Smart Microgrids form an interconnected network of distributed energy systems (loads and resources) that can function connected to or separate from the overall electricity grid.

The central issue is that Canada's current centralized grid system is being challenged by increasing demand, rising costs, tightening supply, declining reserve margins and the need to minimize environmental impacts. At no time in its century-long history, has the Canadian utility industry had to confront so many diverse and concurrent challenges, as it does now. At the core of the crisis is the inability of Canada's electrical grid to respond to such challenges without a major paradigm shift, resulting in new approaches, topologies and architectures of its entire business, operational and technological processes.

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Such a change is often described as an evolutionary process which helps Canadian utilities transform their legacy grid into Smart Grid. This evolutionary process is often envisioned as strategic implants of distributed control and monitoring systems within and alongside existing electricity infrastructure. Such functional and technological growth will warrant pockets of distributed intelligent systems emerging across diverse geographies. This organic growth shall allow the utility industry to shift more of the old grid's load and functions onto the new grid, thus improving and enhancing their critical services. These Smart Grid embryos, known as Smart Microgrids, will facilitate distributed generation and cogeneration of energy. They will also provide for the integration of alternative sources of energy and management of the system's emissions and carbon footprint. They will enable utilities to make more efficient use of their existing assets through demand response, peak shaving and service quality control.

At the core of this evolutionary process is therefore the ad hoc integration of complementary components, subsystems and functions under the pervasive control of a highly intelligent and distributed command and control system, developed by assimilating Smart Microgrids. Smart Microgrids form an interconnected network of distributed energy systems (loads and resources) that can function connected to or separate from the overall electricity grid. The emergence of Smart Microgrids across the utility's network will eventually transform the Utility's Centralized Grid into a Distributed (and yet interconnected) network of Smart Microgrids.

The United States Department of Energy's 2035 Vision for the Electricity Grid of Future identifies the need to develop innovative technologies and solutions for the following three areas of the electricity grid:

1. Optimized utilization of assets and increasing system efficiency

2. Large scale integration of Clean Energy Sources (80% by 2035)

3. Allowing 100% customer participation in energy transactions

One of the basic premises of Smart Microgrids, is of course their ability to partially or fully generate the energy they require using their locally available resources; most often out of renewable sources of energy. However, what hinders wider adoption of renewable sources of energy, such as wind, solar, biomass, and wave/tide, is not solely their diffuse nature or higher cost, but also the absence of suitable devices, interface standards, application protocols, integration systems, reliable storage, appropriate policies and efficient transmission/distribution infrastructure. In particular, utility's distribution system should adopt a topology required to support two-way flow of information and power. Unfortunately, the legacy grid's architecture is not conducive to support such approaches. A new paradigm in substation design, architecture and protocols are required to help the grid take the first step towards decentralization.

As such, DOE advocates significant departure from utility's hierarchical architecture, positioning Distribution Substations as "Energy Hubs". The impact of that approach is significant, as Substations could no longer operate as a "flow-through" layer in service/energy delivery, but have to be a hub where available system energy and user demand are corroborated, service needs are rationalized and stakeholders are engaged.

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The interior hallway of one of the buildings.

View into the telecommunications room.

Following Dr Molaug's excellent presentation some conference attendees were invited to visit the site. What followed was fascinating adventure into the heart of a mountain that conjured up my Norwegian childhood memories of trolls and their magic realms.

Electricity is supplied by two independent feeds at 220KV. In addition there is emergency power available provided by a set of Perkins diesel powered generators. Due to the distance from the substation with the generators and the step-down transformers the supply cables to the interior of the mountain still run at 2.2KV to minimize transmission losses.

Following the tour of the external buildings we proceeded to the main facilities located inside the mountain. Knut Molaug had access to this part of the facility through a biometric scanner located about 200 meters inside the mountain. From the inside he opened a massive blast door, an inheritance left from the military past. It was about 9 by 14 feet of two foot thick concrete moving slowly on a track. As we entered we were reminded that the air inside had reduced oxygen as a precaution against catastrophic fires.

We walked through the halls on both levels. Everywhere there were remains of the original purpose of the installation being removed and upgraded to house modern computation and data storage installations.

After our intriguing visit into the heart of Green Mountain we got out into the daylight. This time the trolls let us go.

The tour of the facility gave us an insight into the workings of a modern data storage facility that embodies all of the current criteria of such a facility: remote, efficient, secure and reliable. Other facilities exist, but most do not fulfill the criteria as fully as Green Mountain.

All of us were impressed with the facility and we were thankful that Knut Molaug took the time to give us such an interesting tour of a modern data center. ■

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[1] http://lostimagesofww2.com/photos/places/magi-not-line.php

[2] http://www.battlefieldsww2.com/Dora_Trondheim.html

[3] http://www.tourmycountry.com/austria/flak-towers-vienna.htm

[4] http://greenmountain.no*

[5] http://smedvig.no

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To realize that vision, significant research in new and innovative substation command and control, and data collection and decision support systems would be required. In particular, an environment is required to develop the following technologies:

- **Development of Intelligent Optimization and Conservation Systems for Efficient Delivery of Services to Consumers**
- **Development of Command & Control Technologies for Substations operating as an Energy Hub**
- **Development of reliable communication technologies, protocols and systems to enable end-to-end integration of the utility system, from source to socket, supporting energy transactions between all stakeholders in the utility network. Stakeholders who could be consumers, as well as producers of energy.**

It is time for Canadian technologists, engineers, utilities and researchers to work together and begin the process of developing the blueprint for Canada's future Smart Grid; a modern, resilient and reliable Grid, capable of supporting our country's diverse geography, economy and urbanization patterns.

Suggested Readings

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2. US Dept of Energy, "Visioning the 21st Century Electricity Industry: Strategies and Outcomes for America", Feb 2012
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Adaptive Energy Ecosystems

– Improved Operability, Efficiency and Economics for Electricity and Gas Infrastructure

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Ontario is working to manage periods of surplus baseload generation (SBG), often from emissions free nuclear power, and increasingly from intermittent renewable sources such as wind power. Thus for a 'Smart Grid' energy storage is essential. Gas energy storage offers the equivalent of a system-wide, distributed storage system during periods of surplus power, off-peak power periods, or when system operators need to immediately absorb spikes in generation during high wind periods. The convergence of the electrical grids with the natural gas distribution/storage infrastructure increases the potential flexibility for managing intermittent renewable supplies. Renewable Natural Gas and Power-to-Gas (PtG) energy storage solutions offer the ability to improve the economic and technical management of surplus off-peak power, and intermittent renewable energy. New, adaptive infrastructure like electrolyzers allows simultaneous grid stabilization, seasonal storage of bulk power, geographic transmission of energy and dispatchable regeneration of distributed renewable energy. This is achieved by bridging the electricity and gas-pipeline infrastructure together into a seamless "energy grid". The challenge is developing the gas interchangeability standards and predictive system modeling that enables researchers, planners, system operators, and industry to realize the full technical and economic potential. By establishing bidirectional energy flow between electricity grids and gas pipelines, along with the flexibility to interchange conventional natural gas with renewable gases, consumers will have access to increased renewable energy supplies at a lower cost. This has near-term potential because much of the existing energy infrastructure exists. Renewable gases, like Power-to-Gas conversion of renewable power to hydrogen, is just optimizing the existing gas distribution and electricity network capabilities to limit waste and exports to harvest more renewable energy for Ontario. The scale of improved renewable energy integration is potentially in the TWh range offering very compelling environmental gains. In addition to the economic and environmental benefits, optimizing existing infrastructure by deferring the building of new transmission will result in increased public acceptance on energy issues as pressure for new-build energy infrastructure is reduced.

Seasonal energy storage and energy distribution are required and renewable natural gas and hydrogen can provide this storage vector as they can be generated via bio-gas and electrolysis from off-peak electricity, and then stored with natural gas in existing long term underground storage facilities. Driven by the proliferation of intermittent renewable energy sources – such as wind and solar, the onset of the emerging smart grid and a shift to electric and plug-in vehicles, as well as fuel cell vehicles in the future, energy storage will play a large role in the electricity grid of the future. To make the energy network "smart", energy storage will need to be deployed, including the existing gaseous energy storage and existing thermal power plant infrastructure that can operate on renewable fuel.

Stemming from increased penetration of intermittent renewables, grid operators will have increased need to control power fluctuations, grid frequency, etc. and energy storage is an alternative to curtail renewables or operating thermal

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plants in the off-peak periods to control system stability. By converting "excess" renewable energy and surplus baseload power into 'stored energy' via an energy hub, the constraints on increased renewable energy deployment are lifted and costly infrastructure additions (i.e. electric transmission towers and lines) are not required. Through the convergence of the electric distribution grid with the gas distribution and storage infrastructure, Ontario can achieve more flexible and adaptive operations across multiple vectors in the provincial energy system. Ontario's electricity sector is blessed with a relatively low-carbon electricity grid; however, with over 50% of the energy supplied by nuclear energy the grid has less operational flexibility to balance supply and demand during off-peak periods. Balancing the grid will be even more challenging when the existing 2,000+ MW of variable generation, like wind, is expanded to 10,000 MW of variable generation by 2018. Simply, there are and will continue to be short periods when the intermittent nature of new renewable power sources will result in surplus electricity supply being available to the grid and this surplus is a necessary and expected result of Ontario's diverse portfolio of power sources and the need to ensure peak system capacity at all times. With additional quantities of wind power, solar power, must-run hydroelectric power, the province can anticipate significant periods of surplus power going forward. To maintain electricity grid reliability, surplus electricity conditions are balanced by exporting power at low or zero prices to neighbouring states. In 2011, the Independent Electricity System Operator (IESO) reported 9 TWh of "net" electricity exports, or approximately 6.3% of Ontario's annual electricity consumption. For Ontario consumers this represents an outflow of high-value, renewable or non-carbon-emitting energy from wind, solar, biogas and nuclear. Consumers pay a premium for this high-value energy, but with no practical means of storing this quantity of surplus energy. In some circumstances, nuclear plants vent this energy in the form of heat/steam as an alternative to generating power.

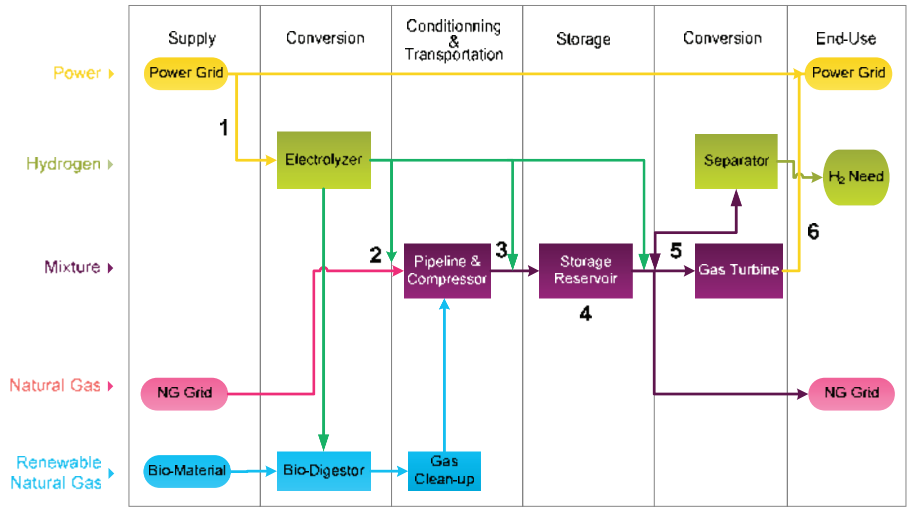

Figure 1: Basic Concept Illustration for RNG and Power to Gas

The peak, daily capacity for existing gas storage systems is so large it could accommodate the entire daily energy output from Ontario's nuclear fleet.

By contrast, Ontario's natural gas infrastructure can accommodate the equivalent of 80 TWh of energy that can be stored for many months. To offer a sense of scale for this energy storage, this is the equivalent of approximately 55% of the provinces annual electricity consumption. The peak, daily capacity for existing gas storage systems is so large it could accommodate the entire daily energy output from Ontario's nuclear fleet. This can be repeated for months without the need to discharge the stored energy. However, this surplus power must be converted to a gas to access this existing and cost-effective infrastructure. As a gas, surplus energy can be stored, transported and converted to dispatchable, renewable power using existing pipelines, storage and Combined Cycle Gas Turbines (CCGT). Using CCGTs with renewable fuel could optimize these assets for lower overall costs of operation.

New technologies allow Ontario to consider options for generating renewable energy directly as a gas. This includes renewable natural gas from biogas supplies injected into pipelines and storage systems. This renewable energy offers flexible end-use because it can be delivered to consumers as green power, green heat or green transportation fuel. Direct-to-gas renewables are only one means of increasing renewable integration with the provincial economy. Renewable gas can also be generated from surplus renewable electricity with utility-scale electrolyzers. This power-to-gas solution converts surplus renewable power to hydrogen gas that can be injected into the natural gas infrastructure. Historically, pipelines would be a one-way flow of electrical energy from intermittent renewables, but using the power-to-gas solution Ontario's pipeline infrastructure can be integrated with the electricity grid for bidirectional energy flows to absorb and potentially store surplus power; or use the natural gas distribution system to move the energy to another location where it can then be used to generate electricity or heat on demand. The only new infrastructure required in the system is the electrolyz-

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er. With this addition the vast natural gas infrastructure can offer the electricity system a very large, distributed, energy storage network that can also transport energy from one area of the province to another while shifting the time between generation and end-use from hours, days or months.

Renewable natural gas (RNG), also known as bio-methane, is a high BTU gas with gas quality comparable to that of conventional natural gas, upgraded from biogas produced at landfills and anaerobic digesters on farms [1]. Biogas is produced from the breakdown of organic matter via anaerobic digestion. As long as the feedstock contains carbohydrates, proteins, fats, cellulose and hemicellulose as main components, any type of biomass can be used as feedstock to the production process: agricultural residues, cow, pig and chicken manure are but a few examples. The exact composition and methane yield of biogas depends on the feedstock composition, the digestion system used and the retention time. Biogas occurs naturally from municipal solid waste, wastewater treatment, animal waste and food processing residues through fermentation processes. Historically, the gas produced was either vented to the atmosphere or gathered and flared. In recent decades, as the energy content of biogas became appreciated (its methane content is about 50% to 60%), it was increasingly used as a fuel for on-site power generators, combined heat and power generators or dual fuel engines [2]. In addition to on-site use for power generation, upgraded biogas, renamed renewable natural gas because of its composition, can be transported and distributed through the existing natural gas network to end-users. Treatment is required to meet the quality requirements of different gas appliances, reduce risks to pipeline integrity and human health. Carbon dioxide—a significant gas by-product from fermentation—is removed, as are other impurities or contaminants. Germany, Sweden and Switzerland all have defined quality standards for biogas injection into the natural gas grid, typically the upgraded gas, named as RNG, must have a methane content of more than 95% [2]. In 2012, the Canadian Gas Association gathered a panel of contributors to publish informative, non-binding guidelines on the quality of the RNG that can be injected into existing natural gas and distribution systems [3]. The delivery and use of RNG compares favourably to conventional natural gas, because, over its lifetime, this fuel emits less green-

house gas emissions, and the source of energy used is local and based on renewable biological processes. But, for the natural gas sector, policy directives that stipulate the share of energy to be supplied from low carbon sources, analogous to the Renewable Portfolio Standards (RPS) that exist for power generation, are not yet common in all jurisdictions. Therefore, most biogas produced is directed toward power generation instead of being upgraded to RNG. The price differential between natural gas and electricity, as manifested through the spark spread, has also contributed to this trend [1]. Even so, in Germany, the top biogas producer country in Europe, where 4000 agricultural biogas production units were placed on farms at the end of 2008, the share of RNG in natural gas fuel increased from 6% to more than 15% in the year 2012 [4]. In a 2011 report on potential production of RNG from waste in Ontario, it was estimated that, in the long term, up to 6% of Ontario's current residential, commercial and industrial consumption of natural gas can be met by RNG production within the province [5].

Utility-scale energy storage is a topic that has gathered significant research interest in the past decade, especially in jurisdictions where power grid reliability is tested, with a significant and rising share of intermittent renewable power generation. The inherited operating paradigm of the power grid is such that fluctuating power demand is met by adjusting the supply of power. Given that the output of renewable energy (RE) power generators, such as wind turbines and photovoltaic cells, cannot be readily dispatched, utility-scale energy storage has been proposed as a tool to maintain grid reliability at the required level, while enabling the integration of RE sources [6]. Acting as a dispatchable load and power generator, an energy storage facility can divert energy from the power grid during times of surplus – when wind power is plentiful, but the demand is low – and deliver energy to the power grid during the time of need, keeping the energy in storage in between. The energy storage technologies that are frequently reviewed and studied for such purposes include: pumped hydro, Compressed Air Energy Storage (CAES), various types of battery storage, including repurposed electric vehicle batteries, flywheels, advanced capacitors and superconducting magnetic energy storage (SMES) [7-12]. However, all these technologies have either high costs, durability issues, or low power storage densities.

The term "Power-to-Gas" is used to describe the process of converting electrical energy into a gaseous form, making storage and transportation via the existing natural gas infrastructure possible, bridging the power grid with the gas grid. It is a novel concept which emerged from Germany in the last four years, but before that, a wide array of similar processes was also proposed in Europe, under different names; NaturalHy (Using the Existing Natural Gas System for Hydrogen), Renewable Power Methane are two examples [13, 14]. In its current form, Power to Gas is a largely industry-led initiative; among its champions are large European utility companies such as E.ON, EnBW and GDF Suez [15]. Note that this technology is now being demonstrated by RH2-Werder/Kessin/Altentreptow (RH2-WKA) at a 140MW wind farm in the German municipality of Grapzow (Mecklenburg-Vorpommern District) and with a 1MW electrolysis system supplied by Hydrogenics. The system includes a 1MW Power-to-Gas system unit producing 210Nm3 of H2 per hour. There is the option to use the hydrogen in an internal combustion engine to produce electricity or be injected directly

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By establishing adaptive energy ecosystems, where gas pipelines and electricity transmission are integrated for bi-directional energy flows and seasonal storage, the provincial energy market will achieve improved system operability, greater system efficiency, and an overall reduction in emissions.

into the local natural gas grid depending on operational needs. The hydrogen compression and storage system stores up to 27MW Hr-1 of energy and dramatically increases the overall efficiency of the wind park by tapping into wind energy which otherwise would be shed or lost because of the lack of electrical demand, as such there is significant saving of carbon dioxide each year.

In the first step of the Power to Gas process, electricity, especially surplus electricity from renewable sources, is used in electrolysis to produce hydrogen from water. This natural gas hydrogen mixture can be transported directly to customers where it can be used as a mixture.[16] Large-scale, industrial, electrolysis technology is critical for the true convergence of the natural gas and power grids. Electrolysis-based hydrogen storage technology brings with it unsurpassed energy storage capacity, timescale, and dynamic responsiveness for grid stabilization. Informational and control systems for power and gas grids can be networked to manage this energy flow from power to gas, and then from gas back to power when, and where, these energy conversions are most beneficial to the provincial power grids. A very limited number of academic publications have considered this concept [17-22]. In natural gas engines and natural gas turbines it is found that adding hydrogen to natural gas results in a cleaner, more efficient burn. The energy yield of the process increases, and emissions are generally reduced. Hydrogen assists the complete combustion of methane, decreasing unburned hydrocarbon and carbon monoxide emissions. Although in gas turbines, nitrogen oxide emissions may increase with the addition of hydrogen, they can be offset by adjusting reactor temperature and excess air ratio. It is found that excess air ratio also proves to be important in determining process efficiency and emissions. [22 - 24]. In a potential second scenario, carbon dioxide gas is captured from natural or industrial sources, in preparation for the next step. Then, hydrogen and methane are combined in a reactor to undergo catalytic methanation, in which methane and water are released. In the last stage of the process, the methane produced is injected into the natural gas network to be stored, and transported to users. This process would typically be considered where the renewable gas injection into the pipeline would exceed 10% by volume; however, today's technology costs and lower system efficiencies make this process more of a medium to long-term opportunity.

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In a variant of the Power to Gas process, the electrolytic hydrogen is not used to produce synthetic methane; instead, it is directly injected into the natural gas network as an additive; the resulting mixture, hydrogen-enriched natural gas (HENG) can be used as natural gas, as long as the gas composition meets end-use appliances' requirements and does not threaten the structural integrity of network components. This direct hydrogen injection is appropriate where the renewable gas volumes are typically less than 10% by volume, and this process is preferred due to technological simplicity and higher system efficiencies (>85% conversion efficiencies). In another variant, hydrogen is kept separate from natural gas in a dedicated storage space and delivered to higher-value uses, before becoming mixed with natural gas in the gas grid. The Power to Gas concepts connect the two previous themes of Renewable Natural Gas and Energy Storage: in this concept, synthetic methane is produced from water and carbon dioxide using renewable power, making it a synthetic version of RNG; also, large-scale energy storage is achieved by storing excess power, in the form of synthetic methane, within the existing natural gas network. More interestingly, Power to Gas closes the loop between two critical and extensive infrastructures which are already closely coupled, through the wide use of gas-fired power generators. In addition to the benefits of renewable natural gas and large-scale energy storage, such bidirectional conversion between key energy vectors is expected to improve the utilization of assets in both energy networks and to increase supply reliability through supply redundancy. The challenge is two-fold. While initial market penetration of renewable gases can occur today, achieving the maximum system integration, renewable penetration levels, and consumer economics will require predictive system operability modeling to assess and plan, how the energy systems (gas and electricity) can be optimized for geography, time, and energy supply/demand mixes. Industry and technology developers can use research activities and results to define the techno-economic benefits of adaptive and integrated energy infrastructure that span both electricity and natural gas grids. There are still a number of technical issues to be investigated [25], but 'Power to Gas' is a technology that is ready for commercialization. With the development of polymer electrolyte membrane (PEM) electrolyzers there will become available even higher efficiencies and lower cost hydrogen.

By establishing adaptive energy ecosystems, where gas pipelines and electricity transmission are integrated for bidirectional energy flows and seasonal storage, the provincial energy market will achieve improved system operability, greater system efficiency, and an overall reduction in emissions. There is an expected significant reduction in greenhouse gases, as CO2 free nuclear and wind power that is currently shed or sold at a deep discount will now be effectively used and emission reductions for Ontario validated. This will ultimately result in improved consumer economics through more efficient use of energy resources. The use of hydrogen blends in the natural gas combustion process has been shown to have air emission reduction benefits. Since much of the infrastructure already exists, there is only a modest capital investment required. The existing energy storage and distribution infrastructure is simply being used in new and adaptive ways. Ontario has all the key conditions and industrial expertise to deliver on this transformative convergence of infrastructure for smart-energy-grid renewables. Repurposing existing gas grid assets for new services such as energy storage for intermittent power has the potential to provide significant value to ratepayer benefits for both electricity and gas consumers.

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LTE for Smart Grid Communication

The Canadian Outlook

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Communication infrastructure requirements for various smart grid applications are now well known and LTE cellular technology is being seriously considered by many utilities around the world due to its appealing cost, performance and sustainability benefits. While most utilities prefer to deploy their own communication infrastructure for security and performance guarantee reasons, Canadian utilities are currently investigating beneficial scenarios where LTE technology can be combined with the other already deployed broadband technologies. This article discusses the feasibility of using LTE technology for smart grid applications in current Canadian settings as well as the extended vision of sharing spectrum with the public safety band.

The term smart grid has been coined for a long time. According to the CEA (Canadian Electricity Association) [1], a smart grid is nothing but a modern electricity system which uses monitoring, sensors, communications, automation and computerized processes to improve reliability, efficiency, and flexibility. In essence, a smart grid is a set of intelligent information based applications made possible by increased automation of the electricity grid encompassed by underlying automation techniques.

This article is an overview of how LTE (Long Term Evolution) technology can be used as the communication infrastructure needed to support common smart grid applications significant to Canadian utilities. Moreover, it discusses the various networking scenarios that would involve LTE. The focus of this article will be on the grid's distribution network while most of the discussed facts will apply to the transport and generation scenarios (see Fig. 1).

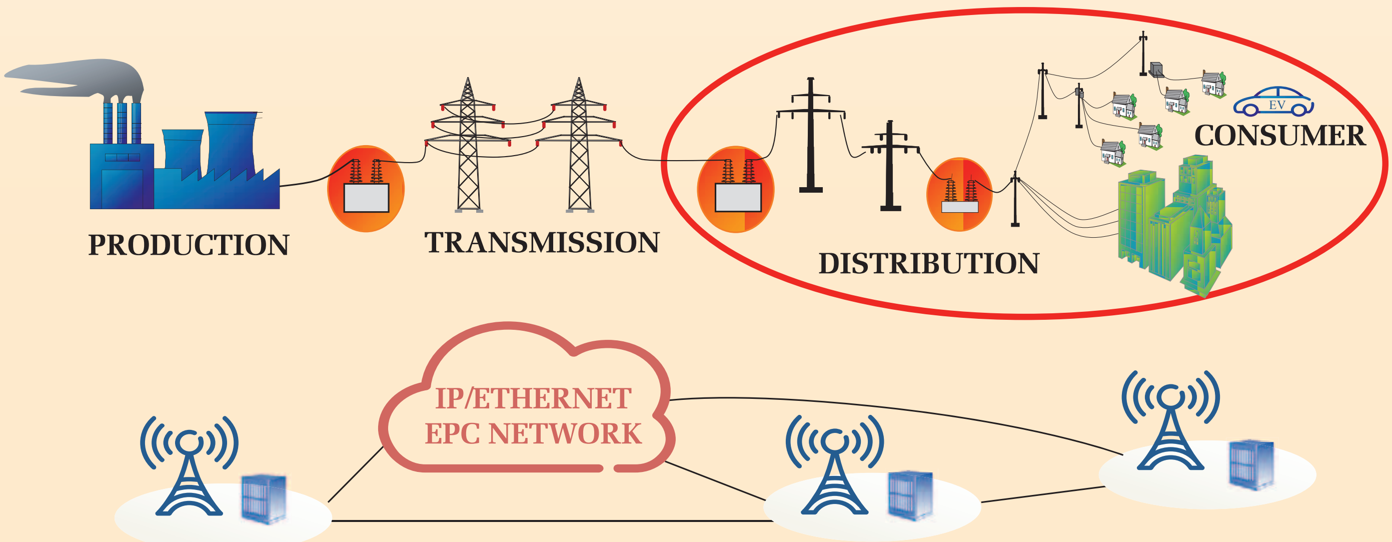
Canadian utilities – today's reality

Canadian electricity companies are mainly hydroelectric followed by nuclear and then fuel based. This distinction plays a role on the smart grid applications that are most significant in Canada.

Smart grid applications– latency classification

The International Electrotechnical Commission (IEC) classifies smart grid application types based on their latency requirements. This classification is summarized in Table 1 [4]. This classification is used to select the viable communication media that are suitable for each type of application within and between substations. The applications requiring 10ms or less latency are better served with optical fiber media. The others can be served with broadband wireless technologies such as LTE.

Fig. 1 Electrical grid sub-division and focus area



Fallback scenarios from private to public or public to private could be considered. This type of redundancy could be extremely useful and again will be enabled by multi operator SIM technologies.

Type/Application	Performance class	Latency Requirements
Type 1-Fast messages:		
Type 1A "trip":	P1 - P2/P3	10ms - 3ms
Type 1B "Others":	P1 - P2/P3	100ms – 20 ms
Type 2- Medium speed messages:		100ms
Type 3- Low speed messages:		500ms
Type 4- Raw data messages:	P1	10ms
Type 5- File transfer functions:		>=1000ms
Type 6- Time synchronization messages		Accuracy ±1ms or ±0.1ms

Table 1 IEC61850-5 Latency requirement classification for substation applications [4]

Based on this table the various transmission applications of smart grid can be mapped to the different types. On the other end, distribution applications, such as demand-response, asset use efficiency, and electrical vehicle applications transactions require 0.5 to 5 seconds latency. Others like DA (Distribution Automation), VVC (Volt-Var Control), fault location and distributed generation applications have transactions latency in the range of 0.1 to 60 seconds.

Characteristics of Canadian Utilities

More than 60% of Canadian production is hydroelectric [5]. This is an important factor to consider because some of the popular smart grid applications are not as critical for hydroelectric generation plants. Hydroelectric production can be more rapidly adjusted to fill the demand. The main smart grid use cases for the distribution network in Canada are AMI (Advanced Metering Infrastructure), distribution power loss reduction through VVC and improvement on the installed grid control and monitoring equipment to reduce outages duration, i.e. DA. The latency requirements of these applications make broadband wireless technologies very suitable from a cost/performance view point.

On another note, interoperability is a key requirement for Canadian utilities. Canadian utilities value for example the Interoperability Framework by the GridWise Architecture Council [3]. Other guiding bodies include, EPRI, IEC, NIST/SGIP and IEEE. LTE technology's interoperability and future proof properties are in line with Canadian utilities' inclination towards standard and interoperable technologies.

Current communication infrastructures

Canadian utilities currently use a range of communication technologies for various applications. These include optical communication, BPL (Broadband over Power Line), Satellite, Microwave, 900MHz wireless mesh, cellular 3G, mobile broadband LTE and WiMAX (Worldwide Interoperability for Microwave Access). These technologies are often selected depending on the range of applications they can cover as well as characteristics such as performance, cost, open standards and availability of equipment, in particular LTE UEs (User Equipment).

LTE Technology Possibilities and Promises

LTE is the latest 3GPP standard in use for mobile communication technology. The LTE initial standard is officially called by the 3GPP document Release 8. LTE's benefits include global standardization and future proofness, a secure ecosystem, rapid deployment with plug and play features, scalable bandwidth, simplified IP based architecture, multi-antenna support for a very low latency and QoS based (Quality of Service) and policy based traffic handling.

LTE supports peak data rates of 150Mbps downlink and 50Mbps uplink (in a 20MHz spectrum, although carriers of as low as 1.4 MHz, 3MHz, 5MHz, 10MHz and 15MHz are possible with LTE). Enhancements are achieved when advanced antenna technologies (e.g. MIMO) are used. An LTE cell can cover up to a 100 km area although best performance is achieved within a 30 km reach. LTE inherently supports interworking with existing 3GPP networks as well as non-3GPP networks (see Fig. 2).

The LTE's EPC (Evolved Packet Core) is a flat IP-based multi-access core network which makes it very suitable for interworking with, and migration from, existing technologies. The PDN-GW (Packet Data Network Gateway) can serve as such an interconnection point for 3GPP and non-3GPP access networks.

A list of further improvements of LTE is summarized in reference [2]. LTE-A or LTE-Advanced relates to Releases 10 and 11. LTE-A release 10 enhances the radio access technologies of LTE with the improved spectrum flexibility of carrier aggregation, enhanced multiple antenna transmission and relaying functionality allowing use of LTE as wireless backhaul media (as opposed to only network to UE media). LTE release 11 will include functionality for CoMP (Coordinated Multi Point) Tx/Rx for the deployment of low power network nodes under macro node coverage.

LTE release 12 and beyond is referred to as LTE-B and will address new use cases such as MTC (Machine-Type Communication) and NSPS (National Security and Public Safety) services. LTE-B will include further enhancements to multiple-antenna and CoMP technologies as well as advanced terminal receivers with always-on signals. The benefits are expected not only for macro deployments, but also for deployments with low power nodes. LTE-B will address device to device (D2D) discovery and communication, a feature highly anticipated for national safety as well as smart grid applications.

LTE for Canadian Utilities

In Canada, like many other countries, smart grid deployments included other broadband technologies (i.e. pre-LTE era technologies). To face this reality, LTE technology can be introduced in three deployment scenarios, one being a private LTE network, another using operator owned public LTE networks and a third one, and the most desirable one, being a shared network scenario with public safety LTE deployments.

Private LTE network

In this scenario, the utility company will be in charge of deploying and operating its own LTE network. This has the advantage of full network control and access to configuration parameters. Private deployments are favored for reasons of robustness and availability,

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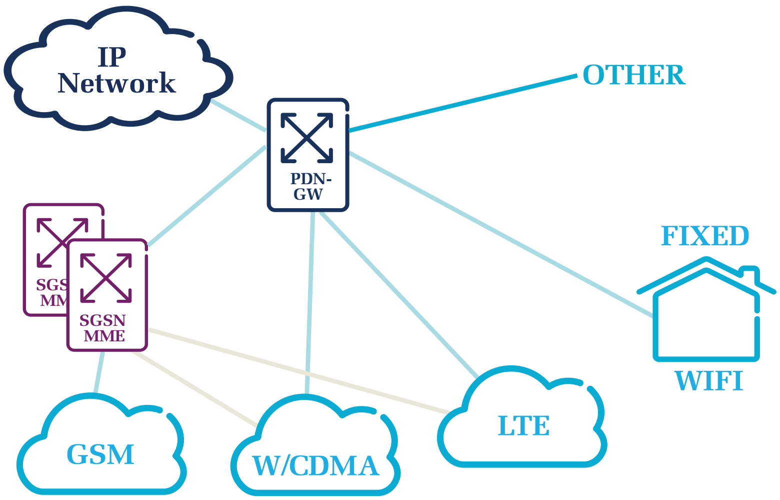

Fig. 2 EPC inter-working with various access networks.

which are not yet explicitly available in current public SLAs. This comes at the greatest cost of green field deployment and spectrum acquisition as well as considerable network under-utilization. The former is less of a problem when it comes to base station site acquisition as utilities have thorough infrastructure that can be leveraged for this mean. This type of deployment can inter-operate with existing infrastructures (e.g. WiMAX). In such an example, the WiMAX's ASN-GW (Access Service Network Gateway) can be interconnected to the EPC's PDN-WG, with possible interconnection to the EPC's PCRF as well.

even more common in the near future by allowing for multi operator SIM support. Currently the biggest concern of utilities with public network operators is the service availability, as well as lack of differentiated SLA for M2M type applications and corresponding QoS configuration, although the technology is available.

A variant of this scenario is a mix of private and public deployment. Fallback scenarios from private to public or public to private could be considered. This type of redundancy could be extremely useful and again will be enabled by multi operator SIM technologies.

> LTE technology can be introduced in three deployment scenarios, one being a private LTE network, another using operator owned public LTE networks and a third one, and the most desirable one, being a shared network scenario with public safety LTE deployments.

Public LTE network

This scenario seems like the most reasonable one for Canadian utilities in the short run. Certainly less critical smart grid applications could be supported by public operator LTE networks. An example would be the AMI infrastructures where the primary requirement is the periodic relay of meter readings from collectors to the back office. New, more time critical, applications could be developed as operators offer new SLA's for specific M2M use cases and/or as the utilities migrate towards their own private LTE network. Soft SIM (Subscriber Identity Module) technology will make such transitions

Private Virtual Network Operator (PVNO)

This scenario is one of the most promising ones as a follow through with scenario B. A PVNO is nothing but an adaptation of an MVNO (Mobile Virtual Network Operator) for private use. Like MVNOs, a PVNO does not have a mobile license or mobile infrastructure, but has its own HSS (Home Subscriber Server), SIM/IMSI (International Mobile Subscriber Identity) range, billing system and core network which gives a large degree of control and management of resources. A PVNO deployment often avoids SIM lock-in by making use of embedded SIM concepts. A PVNO eliminates security and authentication issues as both SIM and HSS belong to the PVNO. Moreover, using multiple networks will provide redundancy and a more reliable PVNO. Utilities can deploy and manage their own PVNO or request the services of a PVNO service provider.

Semi-private LTE network shared with Public Safety

This last scenario is being touted in general in the United States where the public safety departments have been granted a block of 20MHz within the 700MHz band but there are currently issues with deployment costs of an LTE based Public Safety Network. One very beneficial scenario would be the split of the cost and network between utilities and first order public safeties. This is a logical strategy that could leverage on utilities' widespread grid infrastructure where substations, high voltage line towers and poles can be strategically used as base station sites. The other gain for utilities would be the avoidance of bidding on LTE spectrum or waiting for future government allocations.

LTE – Desired Enhancements

As discussed in Section II.A, current LTE performance is suitable for most smart grid applications not related to grid protection. To reach the next class of latency would be improbable by any mobile broadband technology. Despite this, improving LTE latency could provide a margin and anticipate future applications in a new latency class not yet determined.

Causes of latency in LTE networks include

- The idle to connected stated delay.
- Random access delay
- Scheduling and HARQ (Hybrid Automatic Repeat Request) retransmissions
- Latency introduced by the UE
- Non-differentiation of traffic

Delay improvement can be achieved either by configuration (e.g. use of proprietary QoS class profiles), or may require changes to the 3GPP standards. This usually comes with cost, such as increased power consumption at the UE, underutilization of resources and increased complexity.

There are other architectural changes that could improve latency and be more suitable for smart grid deployment, like colocating the P-GW and S-GW.

The true concern in Canada is the deployment scenario of choice which varies between using a public infrastructure and PVNO concepts, or the potential of network sharing with the public safety's upcoming infrastructure in the 700 MHz band.

Finally end user equipment for smart grid applications needs to focus on latency criteria and ruggedness. While the market for such UEs was initially slow there are a number of UEs being currently advertised. Many smart grid applications rely on Ethernet connectivity creating the need for LTE UEs to offer Ethernet connectivity on the client side. LTE UEs can also be enhanced to noticeably improve latency.

This paper sheds light on the Canadian perspective of using LTE technology for smart grid applications. Overall LTE technology is sufficient for most of the current applications. With upcoming enhancements LTE will be even more suitable for MTC and future smart grid applications. The true concern in Canada is the deployment scenario of choice which varies between using a public infrastructure and PVNO concepts, or the potential of network sharing with the public safety's upcoming infrastructure in the 700 MHz band.

Acknowledgment

The authors would like to thank their parent companies for supporting this work, in particular from Ericsson Pierre Boucher, Mike Sisto, Andre Perreault, Pierre Fitzgerald, Ven Sampath, Andre Beliveau and from IREQ Marie Rochefort and Jean Goulet. Moreover, the authors would like to thank Sylvain Morin of IREQ, as well as Issa Al-Fanek of Ericsson RAN customer unit team for their close involvement in this work.

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SMART Power Flow Controller

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SMART power flow controller (SPFC) enhances the controllability in an electric power transmission system by using functional requirements and cost-effective solutions. If the requirement is to reduce the reactive power flow in a transmission line within a permissible limit and increase active power flow to the line's thermal limit, SPFC controls the flows of active power and reactive power in a line independently. Reduction of reactive power flow reduces losses in a transmission line, thus increasing the system's efficiency. If the requirement is to avoid grid congestion, SPFC redirects the excess power flow from an overloaded line to underloaded lines, instead of tripping the overloaded line when the power flow is needed the most. If the requirement is not to trip an overloaded line in order to avoid a possible cascaded failure and a blackout, SPFC limits the power flow in the overloaded line.

Advances in power electronics have made it possible to control the flows of active power and reactive power independently in an electric transmission line as shown in Fig. 1. An independent power flow controller redirects power flow through the desired transmission path that is otherwise underloaded or overloaded due to free flow of power.

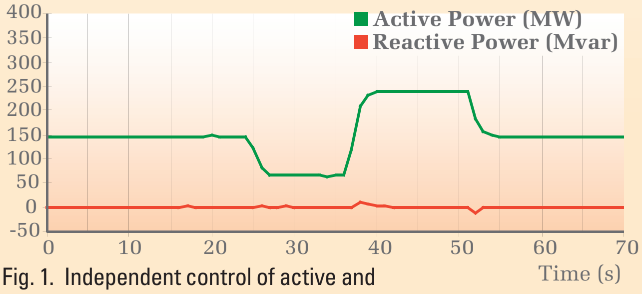

Fig. 1. Independent control of active and reactive powers in a 138-kV transmission line.

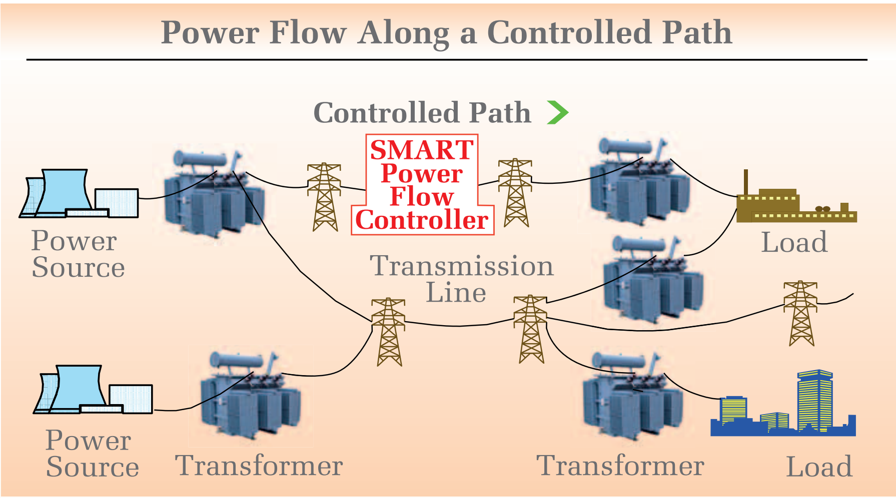

Fig. 2. Power flow along a controlled path.

- **specific** (independent power flow control)
- **measurable** (low-cost and high efficiency)
- **attainable** (demonstrated concept by Westinghouse)
- **relevant** (efficient power grid)
- **timely** (contemporary)

The power electronics-based power flow controller, such as Unified Power Flow Controller (UPFC) is capable of providing responses in the range of milliseconds; however, the experiences from the last two decades show that the needed response time is in seconds in most utility applications as shown in Fig. 1. Therefore, it is desirable to redesign the independent power flow controller that meets the functional requirements to provide responses in seconds, which will reduce the cost to a fractional amount of the cost of power electronics-based solutions. This was the motivation to develop a SMART power flow controller whose objectives are as follows. [2]

SMART power flow controller

A SPFC, shown in Fig. 2, modifies the effective impedance (both resistance and reactance) of the transmission line between its two ends, which results in an independent control of active and reactive power flows in the line so that the useful active power flow is maximized while the less desirable reactive power flow is minimized in the controlled path.

Independent control of active and reactive power flows leads to:

- **reduction** in reactive power flow, resulting in a reduction of losses in generators, transformers, and transmission lines, which increases the overall system's efficiency
- **freeing up** the generators, transformers, and transmission lines to carry more active power

- **power flow** through the desired transmission paths that have high impedances, low power flow, and low line utilization

- **avoidance** of grid congestion by redirecting excess power flow from an overloaded line to underloaded lines, instead of tripping the overloaded line when power flow is needed the most

- **delayed** construction of new, expensive, high-voltage electric transmission lines.

The objective of this paper is to present the highlights of a SPFC that is a new technology and offers essential features, such as:

- **high reliability** with the lowest number of components that are free from becoming obsolete

- **fast enough** response for utility applications

- **easy relocation** to wherever it is needed the most, since the need for power flow control may change with time due to new generation, load, and so on

- **lowest installation** and operating costs with the highest efficiency

- **interoperability** so that components from various suppliers can be used, resulting in a global manufacturing standard, ease of maintenance, and ultimately lower cost to consumers.

Sen Transformer

The Sen Transformer (ST), shown in Fig. 3, can be designed to meet the objectives of a SPFC and the requirements to provide an independent power flow control at the lowest price. The ST consists of three primary windings that are Y-connected and placed on each limb of a three-limb, single-core transformer. As the primary voltage is applied, three induced voltages from three windings, on the secondary side, that are placed on three different limbs are combined, through series connection of the associated windings, to produce the compensating voltage (Vs's) for each phase. The number of active turns in the three windings can be varied with the use of load tap changers (LTCs). As a result, the composite voltage becomes variable in magnitude and variable in phase angle in the range of 0º and 360º, which is the key to an independent control of active and reactive power flows in a transmission line.

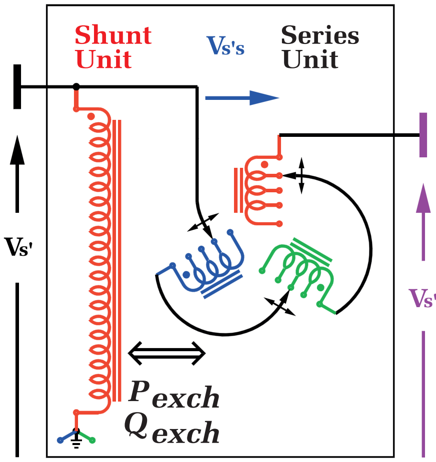

Fig. 3. Sen Transformer.

The simulated transient responses of active and reactive powers (Pr and Qr) in a transmission line due to the use of ST and the power electronics-based solution (UPFC) are superimposed and shown in Fig. 4. The natural power flows until t = 5 s. A series-connected compensating voltage (Vs's) of magnitude 0.2 pu is applied at a phase angle (b) of 300° at t = 5 s and 240° at t = 14 s. While keeping the phase angle at 240°, the magnitude of the compensating voltage is increased to 0.4 pu at t = 23 s. The line power due to the application of the UPFC is changed smoothly where as that due to the application of the ST is changed in multiple steps.

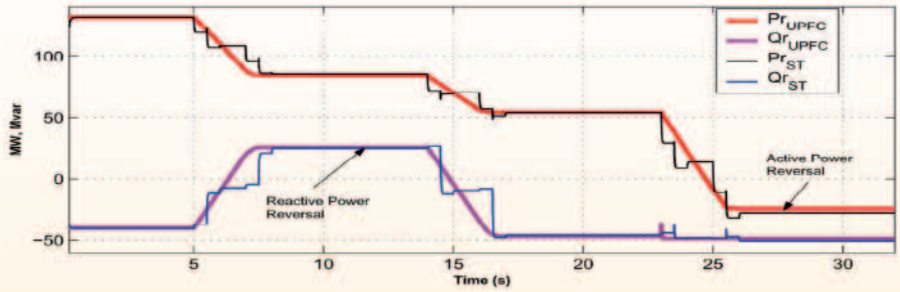

Fig. 4. ST simulation results superimposed with the results from power electronics-based solution (Faruque & Dinavahi-2007).

The merit of the ST is that it allows an independent control of active and reactive power flows in the line, similar to the UPFC. The UPFC can offer faster response (in ms at a given constant line impedance), but this capability cannot be utilized, as shown in Fig. 1, in order to assure continued operation under contingencies. In most utility applications in which the fast response is not required, the ST presents an economically attractive solution for power flow enhancement when compared with the UPFC, which has higher installation and operating costs than ST.

The power industry is in constant search for the most economic way to transfer bulk power along a desired path. This can only be achieved with the use of an independent power flow controller. Although the power electronics-based power flow controllers are capable of providing responses in the range of milliseconds, the experiences from the last two decades show that the needed response time is in seconds in most utility applications. A new concept in power flow control that is reliable, efficient, cost-effective, free from component obsolescence, portable, and based on proven technology should be exploited to meet today's utility's power flow control needs.

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