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Practical Power Flow Controller Brings Benefits Of Power Electronics To The Grid

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The use of electrical energy is increasing worldwide and so are its various sources from traditional to renewable. In order to accommodate the increasing demand for electricity, new alternative energy sources such as solar, wind and so on can be built. While such projects can be accomplished in a matter of months, these new sources also create demand for greater capacity in the power grid's transmission system. This is due to the fact that alternative energy sources are frequently located away from population centers.

Unfortunately, the conventional approach to expanding the transmission system consists of building new high-voltage transmission lines, which may take years to complete. Therefore, the immediate solution is to utilize the existing transmission system more efficiently. One way is to identify the underutilized transmission lines and increase their power flows to the lines' rating limits. This can be achieved using a full power electronics-based solution, an electromechanical solution or a hybrid of the two.

This article discusses the evolution of the power electronics inverter-based solution, explaining its interesting capabilities and also why its adoption to date has been limited. Then a new solution known as the *SMART Power Flow Controller* (SPFC) is introduced.[1,2] The SPFC offers the choice of either a low-cost electromechanical design using impedance-regulating transformers and mechanical load tap changers (LTCs) or a power electronics-based design that replaces the mechanical LTCs with thyristor-based LTCs.

At the heart of the SPFC is the Sen Transformer (ST), a new family of impedance-regulating transformers. Successful installation of an ST will give utilities the capability of a full-featured power flow controller that increases power flow in an underutilized line, decreases power flow in an overloaded line, controls the active and reactive power flows as desired, or limits fault currents, just to name a few. The almost instantaneous addition of transmission capacity will result in the acceleration of the adoption of alternative energies, thereby reducing the carbon footprint.

The power flow control techniques described in this article are applicable in electric transmission lines as well as various other applications such as motor drive, flicker control, harmonic mitigation, and so on.

Principles Of Power Flow

An electric power grid is a network of interconnected transmission and distribution lines that carries electrical energy from the generating points (power sources) to the points of use (loads) as shown in Fig. 1. In normal operation, the supply of electricity is matched with its demand at the loads and power losses in various components such as transmission lines, transformers, generators, etc.; throughout the process, the highest reliability is maintained. The flow of electricity in a particular line depends largely on its impedance. If the impedance of a line is larger compared to that of the lines connected in parallel, the current and the resulting power flow through the high-impedance line is lower compared to that in the neighboring lines and vice versa.

Sometimes it is desirable to decrease the impedance of a particular line so that more current can flow through the line up to the allowable limit. This results in higher line utilization, meets greater customer needs, integrates new sources of energy, and avoids building of new transmission lines, at least for the time being.

Sometimes it is the opposite when it is desirable to increase the impedance of a particular line so that less current can flow through the line. This is particularly important when a line becomes overloaded with a level of current that can trip it or a fault current that must be limited. If an overloaded line trips, its current will be redirected in the available lines proportionately, depending on the lines' impedances. This may cause a previously underloaded line to become overloaded and tripped, which may create a possible cascaded failure of the grid, resulting in a blackout.

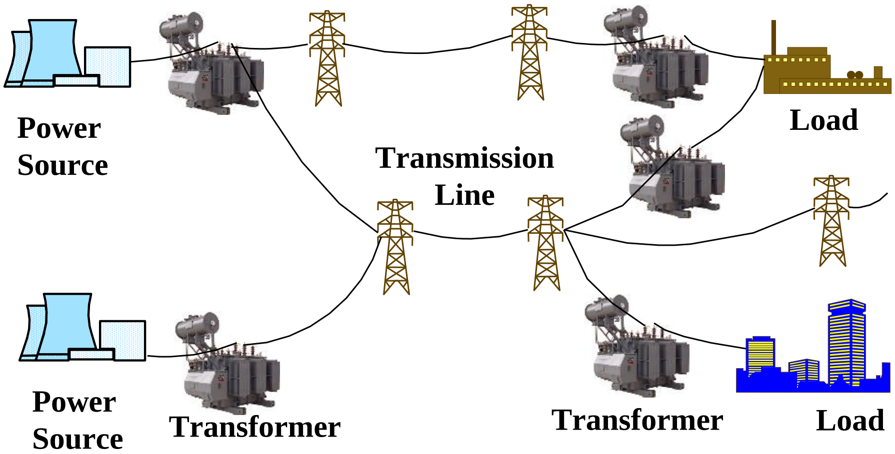

Fig. 1. Part of a large interconnected transmission system supplying electric power from the power sources to the loads.

Power flow in a line is inversely proportional to its reactance. The control of power flow in a line has been practiced for decades using a variable inductive/capacitive reactance in series with the line. Considering the line is inductive in nature, a series-connected inductor decreases the power flow in the line by increasing the effective line reactance between its two ends. A series-connected capacitor increases the power flow in the line by decreasing the effective line reactance between its two ends.

This series-connected reactance does not need to be a physical inductor or capacitor; it can be a compensating voltage source that leads the prevailing line current by 90º and acts as a virtual inductor; the same compensating voltage source can be programmed to lag the prevailing line current by 90º to act as a virtual capacitor.[3] The advantage of using an emulated series capacitor over an actual series capacitor is the avoidance of creating any resonance with the line inductance.

This concept was further advanced to "emulate a series impedance" by placing the series-connected compensating voltage as shown in Fig. 2. The figure shows a simple power transmission system with a sending-end voltage (V_s), a receiving-end voltage (V_r), the voltage (V_X) across the line reactance (X), a series-connected compensating voltage ($V_{s's}$), the modified sending-end voltage ($V_{s'}$), and the line current (I). The active and reactive power flows at the receiving-end are P_r and Q_r, respectively.

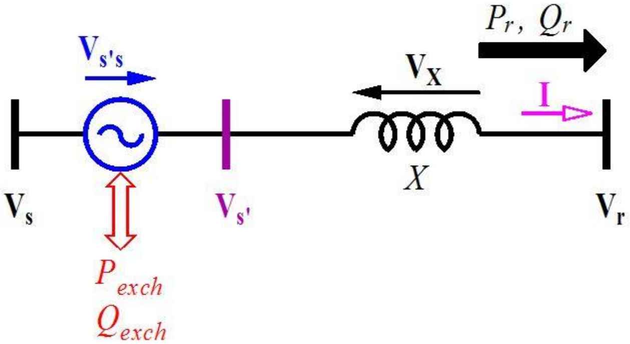

Fig. 2. A simple power transmission system with series-connected compensating voltage, $V_{s's}$.[4]

The impedance emulation allows the modified sending-end voltage ($V_{s'}$) to be at a specific magnitude and a specific phase angle required for specific active and reactive power flows in the transmission line. For the desired amount of active and reactive power flows, the compensating voltage is of a specific magnitude ($V_{s's}$) and at a specific phase angle with respect to the line voltage. The compensating voltage ($V_{s's}$) is at any phase angle with respect to the prevailing line current (I) from 0º to 360º and, therefore, exchanges with the line both active power (P_{exch}) and reactive power (Q_{exch}).

These exchanged active and reactive powers (P_{exch} and Q_{exch}) emulate in series with the line a capacitor (*C*) or an inductor (*L*) and a positive resistor (+*R*) or a negative resistor (–*R*). If the compensating voltage is decomposed, the in-phase or out-of-phase component with respect to the line current emulates a positive resistor or a negative resistor. A positive resistor (+*R*) absorbs active power from the line; a negative resistor (–*R*) delivers active power to the line.

The quadrature component with respect to the line current emulates an inductor if the voltage leads the current or a capacitor if the voltage lags the current. An inductor (*L*) absorbs reactive power from the line and, in the process, decreases the power flow of the line; a capacitor (*C*) delivers reactive power to the line and increases the power flow of the line.

The impedance emulation technique offers an independent control of active and reactive power flows that can optimize the power flows as desired. It not only increases power flow in underutilized lines, it also limits power flow in overloaded lines that might have tripped and led to a cascaded failure, even a possible blackout. It can maximize the revenue-generating active power flow while minimizing the reactive power flow that results in lower losses and higher efficiency in the grid, and lower wholesale electric market costs to loads. Note that the reactance emulation technique either increases or decreases both active and reactive power flows simultaneously; therefore, the line cannot be optimized for the highest active power flow at the lowest reactive power flow.

For over 100 years, the traditional solutions in power system applications have been the voltage regulator (VR) and the phase angle regulator (PAR), each of which uses a transformer and mechanical LTCs. The response time in this case is dependent on the speed of the mechanical LTCs, which is typically in seconds. But due to the availability of high-power semiconductor switches, it is now feasible to design power system compensators, such as VR, PAR, and the reactance regulator (RR) that leverage the speed and functionality of power semiconductors for high-voltage transmission system applications.

Such power electronics-based solutions can be divided into two categories—those using (1) inverters and those using (2) thyristor-controlled switches. The inverter-based system provides a response time in milliseconds. The thyristor-based system is a hybrid system that can be used where the needed response time is less demanding and is measured in cycles rather than milliseconds.

When comparing the traditional mechanical LTC-based solution with the two types of power electronics-based solutions, there are tradeoffs to be made. In particular, as the response speed of the solution increases from slow (seconds) to medium speed (cycles) to fast (milliseconds), there is a corresponding increase in the solution’s cost (installation and maintenance), complexity, component obsolescence and non-portability.

In the traditional approach of converting ac power into dc, transmitting it in dc, and converting it back to ac, where mercury valves were used, they are being replaced with thyristor-controlled switches. There is also a concerted effort to use inverter-based solutions in these applications. Advances in power electronics have made it possible to develop flexible alternating current transmission systems (FACTS) controllers, which are defined as “alternating current transmission systems incorporating power electronic based and other static controllers to enhance controllability and increased power transfer capability.”[8]

These controllers have shown that the transmission lines can be used to their fullest extent through independent control of active and reactive power flows. FACTS controllers can increase power flow through desired transmission paths, which improves line utilization. Also, grid congestion is avoided by redirecting the excess power flows from overloaded lines to underloaded lines.

In the last two decades, a great deal has been learned about the true needs of the utility for its everyday use and they are:

- High reliability with the lowest number of components that are free from becoming obsolete;
- Fast enough response for utility applications;
- Easy relocation to wherever the controller 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, high power density, small footprint and portability; and
- 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.

The objective of this article is to explain how a practical solution to enhance the controllability in an electric power system satisfies both functional and cost requirements.

Evolution Of The SMART Power Flow Controller

In 1998, a power electronics inverter-based power flow controller was demonstrated for the first time at American Electric Power's Inez substation. In the most general form, this type of controller can be programmed to operate as an impedance emulator; however, in a special case, it can be programmed to operate as a reactance emulator as well.

The reactance emulation technique allows the active and reactive power flows to change simultaneously, meaning both powers either increase or decrease as shown in Fig. 3; therefore, the line cannot be optimized for the highest active power flow that generates the most revenues at the lowest reactive power flow.

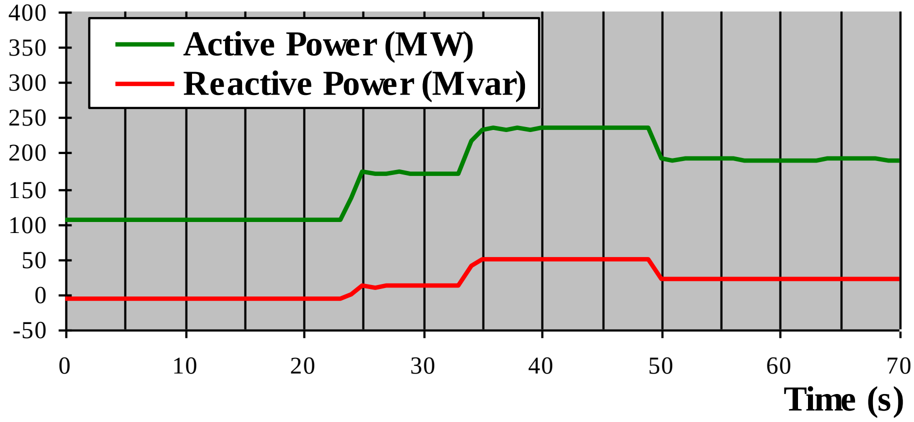

Fig. 3. Simultaneous power flow control by reactance regulation.[5]

In contrast with reactance emulation, the impedance emulation technique allows the active and reactive power flows to change independently, meaning as desired, as shown in Fig. 4. While maintaining unity power factor load, the active power flow in the line is varied at different levels, such as 145 MW, 65 MW, 240 MW, and 145 MW, respectively. While increasing or decreasing both active and reactive power flows simultaneously with the use of a series reactance compensator is undesirable, controlling the active and reactive power flows independently is highly desirable. This independent control can be accomplished using either an inverter-based unified power flow controller (UPFC) or a transformer/LTCs-based Sen Transformer (ST).

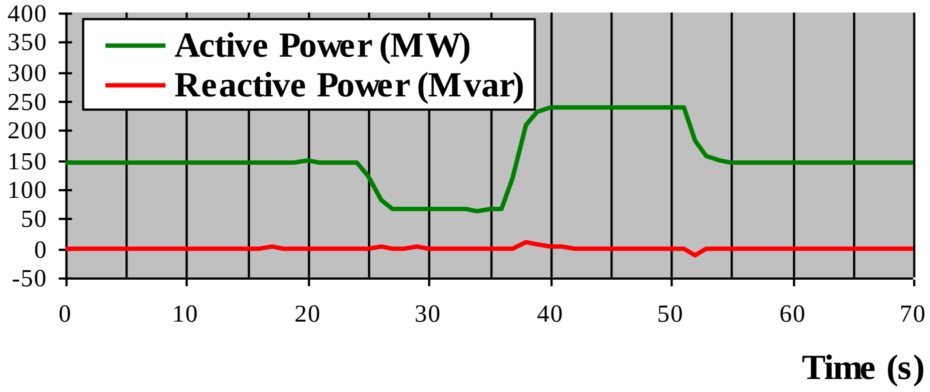

Fig. 4. Independent power flow control by impedance regulation.[5]

Fig. 5 shows the circuit diagram of a UPFC used in this application. The UPFC consists of two units—shunt and series: the shunt unit consists of an inverter and a transformer that is connected in shunt to the line; the series unit consists of an inverter and a transformer that is connected in series with the line. The inverters are connected together with a joint dc link capacitor. The series-connected compensating voltage ($V_{s's} = V_{s'} - V_s$) is of variable magnitude and phase angle and it is also at any phase angle with the prevailing line current. Therefore, it exchanges active and reactive powers with the line. The exchanged active power (P_{exch}) flows bidirectionally through the shared link to and from the same transmission line under compensation.

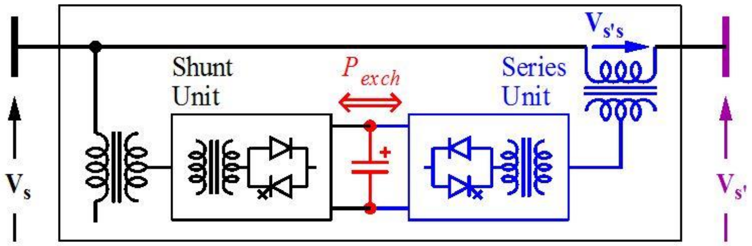

Fig. 5. Unified power flow controller (UPFC).[4]

In the last two decades, a great deal has been learned about the true needs of a utility for its everyday use and they are (a) high reliability, (b) low installation and operating costs, (c) component non-obsolescence, and (d) easy relocation to adapt to changing power system's needs. The inverter-based UPFC is capable of providing responses in the range of milliseconds. However, experience has shown that the response time needed in most utility applications is seconds rather than milliseconds (see Figs. 3 and 4 again.) In other words, the fast response cannot be utilized in order to assure continued operation under contingencies (i.e. all the possible variations in the number of lines connected as a network at different times.) Nevertheless, the cost of a UPFC is about the same, whether it is used in slow-response or fast-response applications.

Therefore, it is desirable to redesign the independent power flow controller to meet the functional requirements of providing responses in seconds, which will make it less expensive than the inverter-based solution. This was the thinking behind the development of the ST, which costs a fraction of what the UPFC costs. Moreover, the ST, in its basic form, uses time-tested components, such as a transformer and mechanical LTCs that are proven to be reliable.

The ST uses a shared magnetic link between primary and secondary windings as shown in Fig. 6. A three-phase voltage is applied in shunt to three primary windings that are Y-connected and placed on each limb of a three-limb, single-core transformer. On the secondary side, three induced voltages from three windings that are placed on three different limbs are combined, through series connection of the associated windings, to produce the compensating voltage ($V_{s's}$) for each phase. The number of active turns in the three windings can be varied with the use of LTCs. As a result, the composite voltage becomes variable in magnitude and variable in phase angle in the range of 0º to 360º.

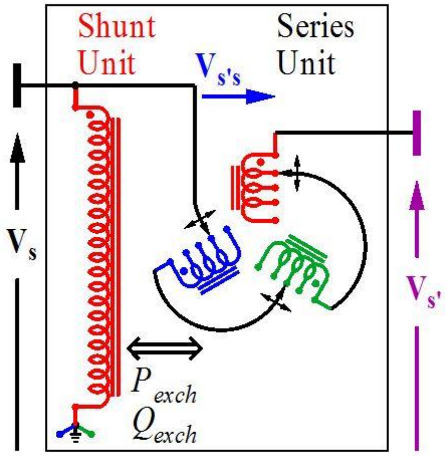

Fig. 6. Sen Transformer (ST).[4]

The dynamic performance of an ST is limited by the speed of operation of the mechanical LTCs, which is in seconds—a level of performance that is acceptable in most utility applications. However, if faster response is desired, the mechanical LTCs can be upgraded with power electronics-based LTCs as shown in Fig. 7. This version is used in a thyristor-controlled Sen Transformer (TCST).

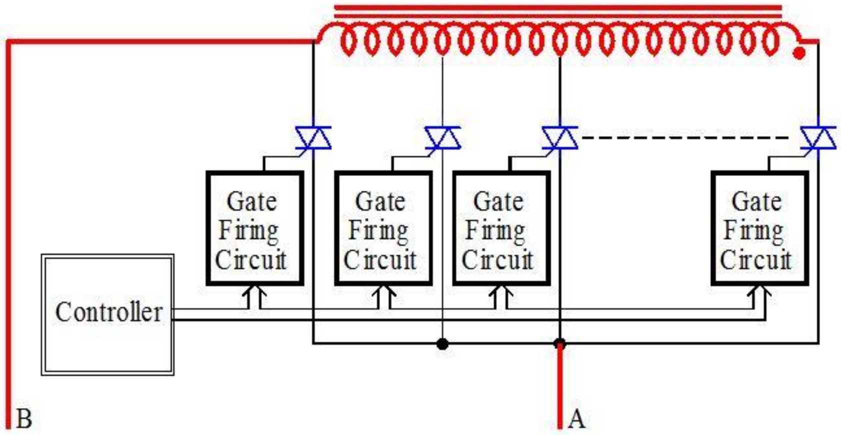

Fig. 7. Thyristor-controlled load tap changer.

Fig. 7 shows the schematic diagram of a thyristor-controlled load tap changer (LTC). A transformer winding is tapped at various places. Each of the tapped points is connected to one side of a back-to-back thyristor (triac) switch. The other side of each triac switch is connected at point A. Depending on which thyristor is on, a variable number of turns between the on-switch and one end of the winding become active; the voltage between points A and B can be varied between zero and the full-winding voltage with available steps in between.

The simulated transient responses of P_r and Q_r in a transmission line with the use of a transformer and mechanical LTCs-based ST and an inverter-based UPFC are shown together in Fig. 8. The natural power flows until $t = 5$ s. Then, a series-connected compensating voltage ($V_{s's}$) of magnitude 0.2 p.u. is applied at a phase angle of 300º at $t = 5$ s and at a phase angle of 240º at $t = 14$ s. While keeping the phase angle at 240º, the magnitude of the compensating voltage is increased to 0.4 p.u. at $t = 23$ s. The power flow in the line due to the application of the UPFC is changed smoothly whereas that due to the application of the ST is changed in multiple steps. Regardless of how the transitions take place, the steady-state power flow is the same in both cases.

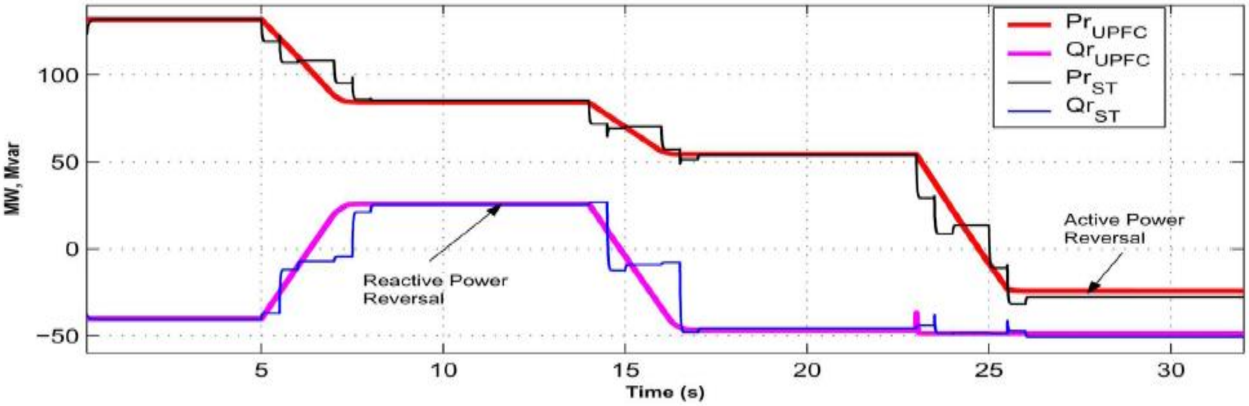

Fig. 8. ST simulation results superimposed on UPFC simulation results.[6]

Preliminary examination of an ST and a UPFC shows that the available control region, represented by the active and reactive (*P*-*Q*) plane for the two power flow controllers is virtually the same as illustrated in Fig. 9. The ST is more than 99% efficient, since power flow through the ST encounters only one stage of loss (see Fig. 6 again.) In contrast, there are four stages of losses in the UPFC —two in the inverters and two in the coupling transformers (see Fig. 5 again.)

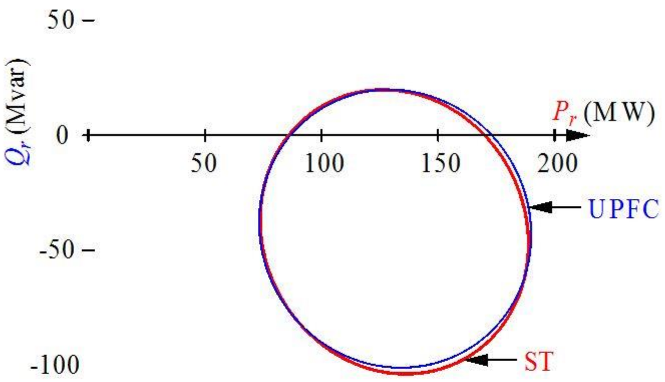

Fig. 9. Range of active and reactive power flow with the operation of an ST and a UPFC.[7]

A comparison of the sizes and footprints of the Westinghouse-built UPFC and the ST is shown in Fig. 10.

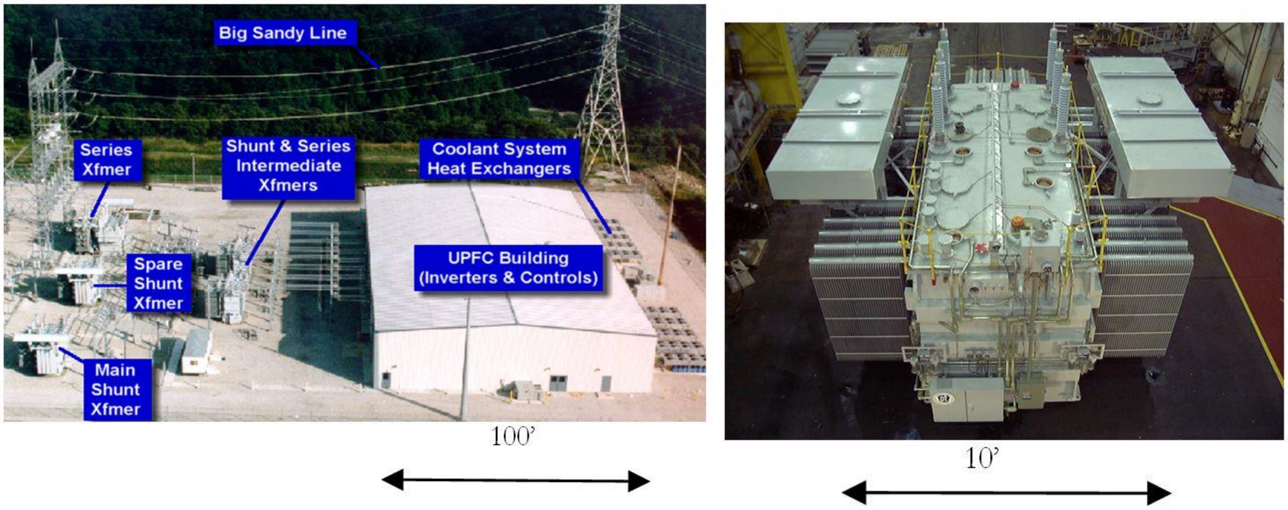

Fig. 10. A Westinghouse-built UPFC at the AEP Inez substation[8] *(left image) versus a comparably rated ST (right image).*

The objectives of a SMART power flow controller (SPFC), shown in Fig. 11, are as follows.

S—specific (design a power flow controller that meets utilities' needs);

M—measurable (high reliability, high efficiency, low carbon footprint, low cost, component non-obsolescence, high power density, small footprint and portability);

A—attainable (demonstrated theory by Westinghouse, which was cost-prohibitive for commercialization if inverter-based UPFC is used);

R—relevant (for efficient power grid);and

T—timely (contemporary for national grid modernization.)

If the requirement is to reduce the reactive power flow within a permissible limit while maintaining the voltage stability and to increase the revenue-generating active power flow in an existing underutilized transmission line up to the line's rating limit, the SPFC controls the flows of active power and reactive power independently. Flexible power routing with the use of the SPFC creates immediate capacity to absorb alternative energy sources into the grid.

If the requirement is to avoid grid congestion, the 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 to not trip an overloaded line in order to avoid a possible cascaded failure of the grid and a resulting blackout, the SPFC limits the power flow in the overloaded line at the maximum allowable level.

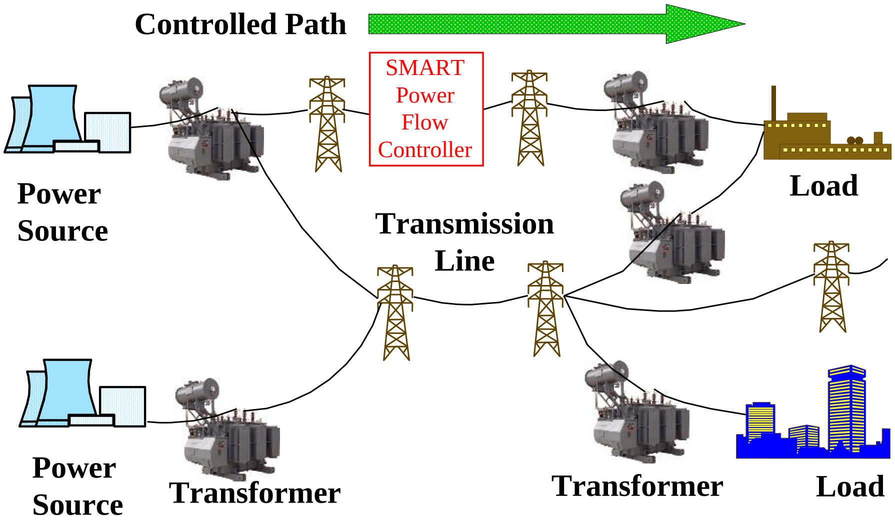

Fig. 11. Power flow along a controlled path.

Conclusion

The power industry's pressing need for the most economical ways to transfer bulk power along a desired path may relieve grid congestion in certain U.S. markets during peak hours and integrate renewable energy from wind, solar, and so on. Apart from building new transmission lines, it may be quicker and cheaper to utilize the existing transmission system infrastructure by harnessing the dormant capacity of the underutilized lines. This can only be possible through an independent control of active and reactive power flows in the transmission lines. 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 efficiency, thus low carbon footprint;
- 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 and creating possible blackouts when power flow is needed the most;
- Delayed construction of new, expensive, high-voltage electric transmission lines.

The SMART Power Flow Controller is proposed to enhance the controllability in the power grid on the basis of functional requirements and affordability. The Sen Transformer technology meets the immediate need of the utility in terms of maximizing the revenue-generating active power flow while providing the highest efficiency. The ST uses transformers and mechanical LTCs and offers high reliability, high efficiency, low cost, component non-obsolescence, high power density, small footprint and portability. The power electronics-based technology has the capability of providing fast (subcycle) dynamic response for a given transmission line impedance, although in a power flow controller the dynamic response of at least a few line cycles is necessary to operate safely under contingencies.

Most utility applications allow regulation of the power flow in the line(s) in a "slow" manner as permitted by the speed of operation of the mechanical LTCs. Applications that require faster response time can make use of a thyristor-controlled Sen Transformer that replaces the mechanical LTCs used in an ST, with power electronics-based LTCs. Both types of ST cover a wide range of requirements for power flow control in electric transmission lines. If needed, the power electronics inverter-based Unified Power Flow Controller can be used for the fastest response time in milliseconds.

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About The Author

Currently the chief technology officer of Sen Engineering Solutions, Kalyan K. Sen has spent 28 years in academia and industry. Sen who was selected to be a Westinghouse Fellow Engineer, was a key member of the FACTS development team at the Westinghouse Science & Technology Center in Pittsburgh. He contributed in all aspects (conception, simulation, design, and commissioning) of FACTS projects at Westinghouse. Sen conceived some of the basic concepts in FACTS technology. He has more than 25 patents and publications in the areas of FACTS and power electronics, including a book and two book chapters. He is a licensed Professional Engineer in the Commonwealth of Pennsylvania.

Sen received BEE, MSEE, and PhD degrees in electrical engineering, from Jadavpur University, Tuskegee University, and Worcester Polytechnic Institute, respectively. In addition, he received an MBA from Robert Morris University. A senior member of IEEE, Sen has served the organization in many positions. In 2003, he reestablished the Pittsburgh Chapters of the Power & Energy Society and the Industry Applications Society. Both Chapters received the "Outstanding Large Chapter" awards for their activities in 2004. Under his chairmanship, the

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