OVERVIEW OF FLEXIBLE AC TRANSMISSION SYSTEMS, FACTS

Introduction

The term ”FACTS” (Flexible AC Transmission Systems) covers several power electronics based systems used for AC power transmission and distribution. Given the nature of power electronics equipment, FACTS solutions will be particularly justifiable in applications requiring one or more of the following qualities:

-Rapid dynamic response
-Ability for frequent variations in output
-Smoothly adjustable output.

FACTS are a family of devices which can be inserted into power grids in series, in shunt, and in some cases, both in shunt and series. Important applications in power transmission and distribution involve devices such as SVC (Static Var Compensators), Fixed Series Capacitors (SC) as well as Thyristor-Controlled Series Capacitors (TCSC) and STATCOM.

SVC and SC have been utilized for a long time. The first SC installations came on line in the early 1950s. Among the pioneering countries are USA and Sweden. SVCs have been available for commercial purposes since the 1970s. Over the years, more than a thousand SVCs and SCs have been installed all over the world.

FACTS mainly find applications in the following areas:

- Power transmission
- Power quality
- Railway grid connection
- Wind power grid connection
- Cable systems

With FACTS, the following benefits can be attained in AC systems:

- Improved power transmission capability
- Improved system stability and availability
- Improved power quality
- Minimized environmental impact
- Minimized transmission losses

Power transmission under optimum conditions

A frequently occurring situation in a power system is the need to transmit more power over the system than it was originally designed for. In cases where there is a need to transmit more power, it is often a safe way out simply to build new transmission lines. This, however, may not at all be the best solution. Adding new lines may be too costly and time-consuming. Concessions for right-of-ways may be hard or impossible to come by. And last but not least, environmental aspects are much more important now than they used to be, and need to be properly addressed in conjunction with transmission development.

There are two typical cases in this discussion:

1) ***Greenfield projects*****:** a need to build new infrastructure, and then do it as economically as possible, both from an investment point of view, and from an environmental point of view. This means as few transmission lines as we can possibly get away with, without compromising our transmission goals.

2) ***Alleviation of transmission congestion*****:** we need to build away bottlenecks in existing transmission systems. This is very much on the EU agenda now, with the Energy Directive, which stipulates that each EU country should have the capacity to transmit at least 10% of its installed power to its neighbour countries (and even 20% in a certain perspective), to pave the way for the EU goal of free exchange of services and commodities inside the EU. In this discussion, of course, electric energy is treated as a commodity among others.

In either case, there is a lot to be gained, in economical terms just as well as environmental, if we can minimize the amount of transmission lines running through the countryside. This is exactly where FACTS is coming in.

Availability
With FACTS, availability and efficiency of power grids are improved, for existing just as well as new grids. When we say **availability**, of course, one comes to think of the several large and more or less dramatic **blackouts** in various parts of the world in recent years. The obvious question to be asked then is: **can FACTS help to prevent similar things to happen in the future?** The answer is that it will definitely play a role, and an important one, at that. And for sure, since blackouts in the majority of cases are caused by a deficit of reactive power, FACTS comes into the picture as a remedy in a natural way.

Power quality
Getting as much active power as possible over the grid with a minimum of transmission lines, and a minimum of losses, are crucial tasks, of course. There are other things that need to be looked after, as well, however: the power which eventually reaches the consumer must also be of sufficient quality. With this we mean that when we turn on the light at home, the voltage coming out of the socket should be fluctuation-free and free from harmonics, to make the flow of light smooth and comfortable, and free from intensity fluctuations. This, too, is a key task for FACTS to maintain. It is particularly important for residents living more or less close to heavy industrial plants such as steel works, because such plants emit a lot of disturbances which spread over the electrical grid, unless, as said, remedied by FACTS.

FACTS and Reactive Power
FACTS has a lot to do with **reactive power compensation**, and indeed, that used to be the term utilized for the technology in the old days. Reactive power appears in all electric power systems, due to the laws of nature. Contrary to active power, which is what we really want to transmit over our power system, and which performs real work, such as keeping a lamp lit or a motor running, reactive power does not perform any such work. Consequently, in a way one can say that the presence of reactive power in a grid makes it heavier for it to perform its task, i.e. transmit power from A to B (Figure 1), and consequently less efficient than would otherwise be possible. We can also refer to Lenz´ law, formulated already in the nineteenth century: Every change in an electrical system induces a counter-reaction opposing its origin.

So, as a consequence, if we can minimize the flow of reactive power over the transmission system, we can make the system more efficient and put it to better and more economical use.

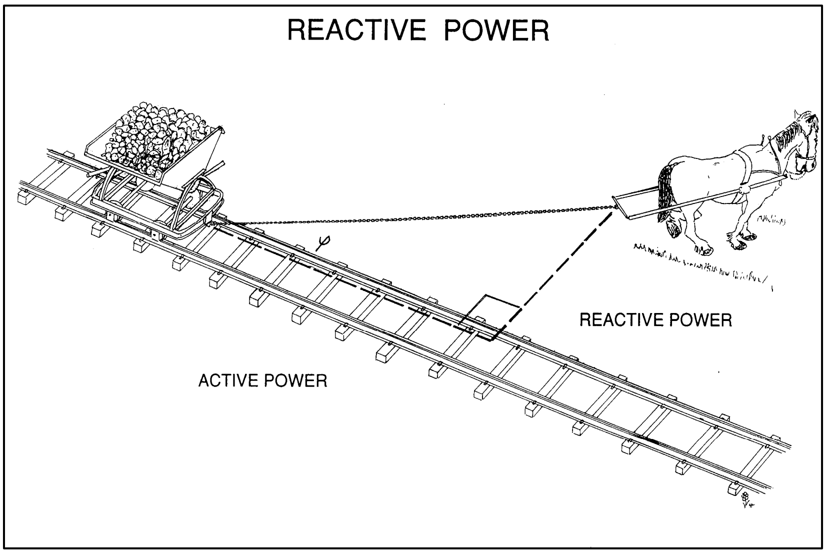

Fig. 1: There is potential for more efficient use of this line!

We cannot altogether do without reactive power, though, because it is intimately linked with grid voltage (500 kV, 400 kV, 220 kV, etc). To get the correct grid voltage, we need the right amount of reactive power in the system. If there is not enough reactive power, the voltage will sag. And vice versa, if there is too much of it, the voltage will be too high. So, to have it in the right amounts at all times, and in the right places of the grid, that is the task to be performed by means of Reactive Power Compensation.

Reactive power balance is important also from another point of view: it ensures that valuable space in transmission lines and equipment such as transformers is not occupied by "idle" reactive power, but rather available for a maximum of useful, active power (Fig. 2).

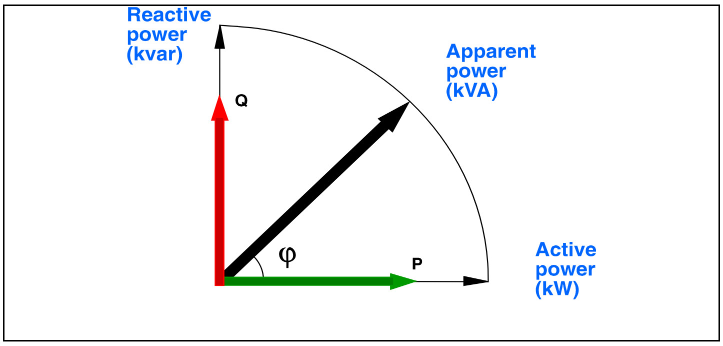

Fig. 2: Reactive power steals precious space in power lines and equipment.

Here it should be pointed out that a reactive power compensator needs to be fast, i.e. fast response is a key characteristic of the device. This is particularly crucial in situations where some fault appears in the grid. In such a situation, it will often be a matter of milliseconds for the Reactive Power Compensator, i.e. the FACTS device, to go into action and help restore the stability, and the voltage of the grid, in order to prevent, or mitigate, a voltage collapse.

Quite in general, there is a tendency for a deficit of reactive power close to large, electricity consuming areas, as well as close to large, electricity consuming industry enterprises, such as steel works, petrochemical complexes, and large mine complexes. That means that in such cases, reactive power needs to be added. Vice versa, there is usually a surplus of reactive power at the end of long, lightly loaded transmission lines and cables. Here, reactive power may need to be compensated away. In either case, and particularly when the reactive power is fluctuating with time, FACTS is the solution.

Losses

Maintaining proper balance of reactive power in the grid is important also from another point of view: too much reactive power flowing in the grid also gives rise to losses, and losses cost money which is always, at the end, charged to the customer. To prevent such losses, it is important that reactive power is not permitted to flow over long distances, because losses grow with the distance that the reactive power is flowing over. Instead, reactive power should be inserted where it is needed, i.e. close to large cities and/or large industry enterprises. This, too, is a task for FACTS.

Technology underlying FACTS

<u>SVC</u>

An SVC is based on thyristor controlled reactors (TCR), thyristor switched capacitors (TSC), and/or Fixed Capacitors (FC) tuned to Filters. A TCR consists of a fixed reactor in series with a bi-directional thyristor valve. TCR reactors are as a rule of air core type, glass fibre insulated, epoxy resin impregnated.

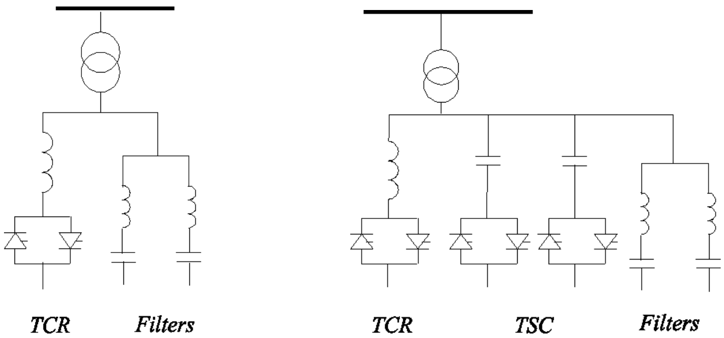

Fig. 3a: TCR / FC configuration. Fig. 3b: TCR / TSC configuration.

A TSC consists of a capacitor bank in series with a bi-directional thyristor valve and a damping reactor which also serves to de-tune the circuit to avoid parallel resonance with the network. The thyristor switch acts to connect or disconnect the capacitor bank for an integral number of half-cycles of the applied voltage. A complete SVC based on TCR and TSC may be designed in a variety of ways, to satisfy a number of criteria and requirements in its operation in the grid. Two very common design types, both having each their specific merits, are shown in Fig. 3a and 3b.

Series Capacitors (SC)

Of course, a series capacitor is not just a capacitor in series with the line. For proper functioning, series compensation requires control, protection and supervision facilities to enable it to perform as an integrated part of a power system. Also, since the series capacitor is working at the same voltage level as the rest of the system, it needs to be fully insulated to ground.

The main circuit diagram of a state of the art series capacitor is shown in Fig. 4. The main protective device is a varistor, usually of ZnO type, limiting the voltage across the capacitor to safe values in conjunction with system faults giving rise to large short circuit currents flowing through the line.

A spark gap is utilized in many cases, to enable by-pass of the series capacitor in situations where the varistor is not sufficient to absorb the excess current during a fault sequence. There are various bypass solutions available today like spark gap, high power plasma switch, power electronic device, etc.

Finally, a circuit breaker is incorporated in the scheme to enable bypassing of the series capacitor for more extended periods of time as need may be. It is also needed for extinguishing the spark gap, or, in the absence of a spark gap, for by-passing the varistor in conjunction with faults close to the series capacitor (so-called internal faults).

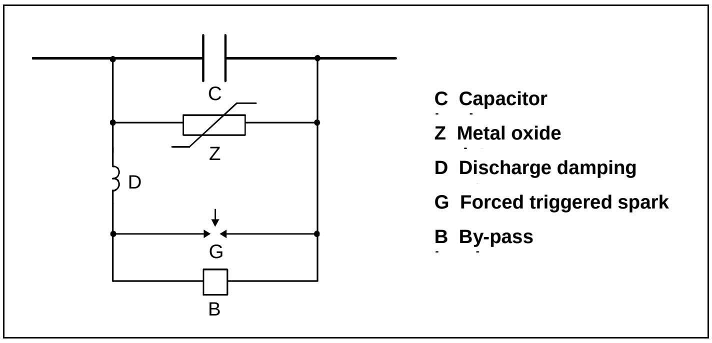

Fig. 4: Main configuration of a Series Capacitor.

Controllable series compensation

Though very useful indeed, conventional series capacitors are still limited in their flexibility due to their fixed ratings. By introducing control of the degree of compensation, additional benefits are gained.

State of the art controllable series compensation is shown in Fig. 5. Here, the introduction of thyristor technology has enabled strong development of the concept of series compensation. Added benefits are dynamic power flow control, possibility for power oscillation damping, as well as mitigation of sub-synchronous resonance (SSR), should this be an issue.

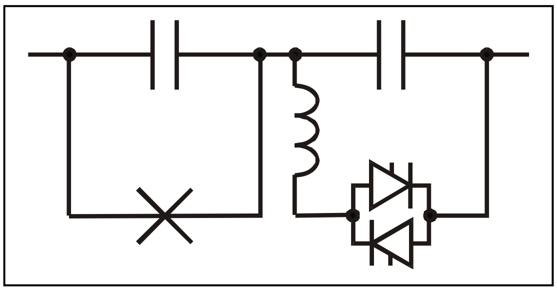

Fig. 5: Controllable Series Compensation.

STATCOM

A Static Compensator consists of a voltage source converter, a coupling transformer and controls (Fig. 6). In Fig. 6, I_q is the converter output current and is perpendicular to the converter voltage V_i. The magnitude of the converter voltage and thus the reactive output of the converter (Q) is controllable. If $V_i > V_T$, the STATCOM supplies reactive power to the ac system. If $V_i < V_T$, the STATCOM absorbs reactive power.

State of the art for STATCOM is by the use of IGBT (Insulated Gate Bipolar Transistors). By use of high frequency Pulse Width Modulation (PWM), it has become possible to use a single converter connected to a standard power transformer via air-core phase reactors. The core parts of the plant are located inside a prefabricated building. The outdoor equipment is limited to heat exchangers, phase reactors and the power transformer. For extended range of operation, additional fixed capacitors, thyristor switched capacitors or an assembly of more than one converter may be used.

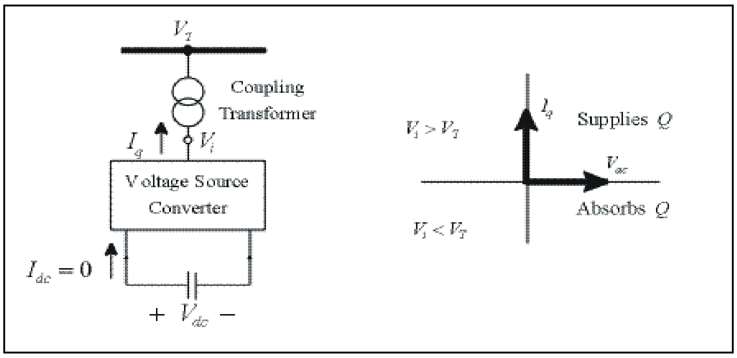

Fig. 6: STATCOM.

The semiconductor valves in a STATCOM respond almost instantaneously to a switching order. Therefore the limiting factor for the comple plant speed of response is determined by the time needed for voltage measurements and the control system data processing. A high gain controller can be used and a response time shorter than a quarter of a cycle is obtained.

The high switching frequency used in the IGBT based STATCOM concept results in an inherent capability to produce voltages at frequencies well above the fundamental one. This property can be used for active filtering of harmonics already present in the network. The STATCOM then injects harmonic currents into the network with proper phase and amplitude to counteract the harmonic voltages.

By adding storage capacity to the DC side of STATCOM, it becomes possible not only to control reactive power, but also active power. As storage facility, various kinds of battery cells can be used, depending on the requirements on the storage facility. The result, STATCOM with energy storage (Fig. 7), is expected to come into use in years to come as dynamic storage facility particularly of renewable energy (wind, solar).

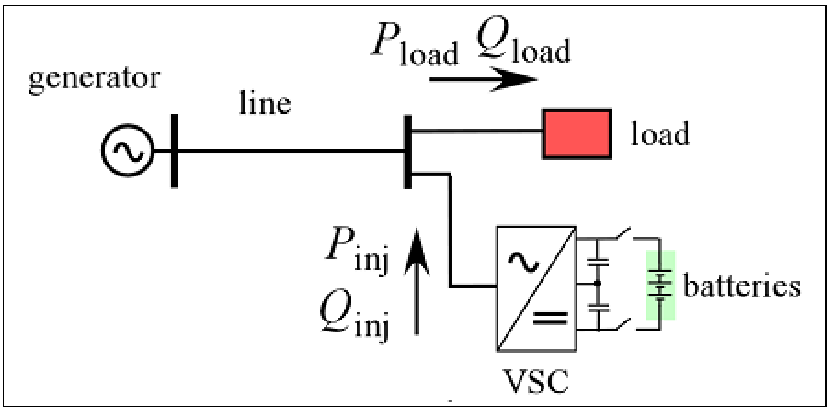

Fig. 7: STATCOM with energy storage.

Impact of FACTS in interconnected networks

The benefits of power system interconnection are well established. It enables the participating parties to share the benefits of large power systems, such as optimization of power generation, utilization of differences in load profiles and pooling of reserve capacity. From this follows not only technical and economical benefits, but also environmental, when for example surplus of clean hydro resources from one region can help to replace polluting fossil-fuelled generation in another.

For interconnections to serve their purpose, however, available transmission links must be powerful enough to safely transmit the amounts of power intended. If this is not the case, from a purely technical point of view it can always be remedied by building additional lines in parallel with the existing, or by uprating the existing system(s) to a higher voltage. This, however, is expensive, time-consuming, and calls for elaborate procedures for gaining the necessary permits. Also, in many cases, environmental considerations, popular opinion or other impediments will render the building of new lines as well as uprating to ultra-high system voltages impossible in practice. This is where FACTS is coming in.

Examples of successful implementation of FACTS for power system interconnection can be found among others between the Nordic Countries and between Canada and the United States. In such cases, FACTS helps to enable mutually beneficial trade of electric energy between the countries.

Other regions in the world where FACTS is emerging as a means for AC bulk power interchange between regions can be found in South Asia as well as in Africa and Latin America. In fact, AC power corridors equipped with SVC and/or SC transmitting bulk power over distances of more than 1.000 km are a reality today.

FACTS for minimizing grid investments

It has been mentioned that an important incentive for considering FACTS in grid planning is its being an economically as well as politically and environmentally attractive alternative to larger, more costly and more time-consuming investments in extended transmission networks, i.e. basically more lines. Thus, for instance, it can be shown that the cost of installing series capacitors as means for improving the power transmission capacity of existing lines amounts to only a fraction of the cost for installing one or several new lines. This is valid for all existing transmission voltages and for all transmission distances where series compensation comes into consideration.

By considering series compensation from the very beginning, power transmission between regions can be planned with a minimum of transmission circuits, thereby minimizing costs as well as environmental impact from the start.

Conclusion

Power supply industry is undergoing dramatic change as a result of deregulation and political and economical driving forces in many parts of the world. This new market environment puts growing demands for flexibility and power quality into focus. Also, trade of electric power between countries is gaining momentum, to the benefit of all involved. This calls for the right solutions as far as power transmission facilities between countries as well as between regions within countries are concerned.

As indicated by the acronym, FACTS stands for flexibility in AC power systems. Properly utilized, this offers benefits to users of a variety of kinds. Without the need to reinforce the grid by means of additional or upgraded existing lines and/or substations FACTS brings about:

-An increase of synchronous stability of the grid;
-Increased power transmission capability;
-Increased voltage stability in the grid;
-Decreased power wheeling between different power systems;
-Improved load sharing between parallel circuits;
-Decreased overall system transmission losses;
-Improved power quality in grids.

The choice of FACTS device in each given case may not be obvious but may need to be made the subject of system studies, taking all relevant requirements and prerequisites of the system into consideration, so as to arrive at the optimum technical and economical solution. In fact, the best solution may often be a combination of devices.

From an economical point of view, more power can be transmitted over existing or new transmission grids with unimpeded availability at an investment cost and time expenditure lower, or in cases even much lower than it would cost to achieve the same with more extensive grids. Also, in many cases, money can be saved on a decrease of power transmission losses.

From an environmental point of view, FACTS enables the transmission of power over vast distances with less or much less right-of-way impact than would otherwise be possible. Furthermore, the saving in transmission losses may well bring a corresponding decrease in need for generation, with so much less toll on the environment.

Finally, a rough and quick guideline to the use of FACTS in various applications:

Issue	**Device**	**Comment**
Steady-state voltage control	SVC SC	Continuous control inherent Continuous control inherent
Dynamic and Post-contingency voltage control	SVC STATCOM	Compact design
Improvement of steady-state load sharing	SC	Very low losses
Transient stability improvement	SC SVC	Inherently self-regulating
Power oscillation damping	SVC TCSC	Location critical Insensitive to location and load type
Power quality improvement	SVC Statcom	Voltage fluctuation mitigation Flicker mitigation
Sub-synchronous resonance mitigation (if an issue)	TCSC	

Terminology:

SVC	Static Var Compensator
SC	Series Capacitor
STATCOM	Static Compensator
TCSC	Thyristor-controlled Series Capacitor