1.1 Voltage Regulation

It is well known that voltage control issues in power systems are related to reactive power compensation. The usual approach to reactive power management is to minimize reactive power transfer between different voltage levels. On the transmission level, the flat voltage profile is achieved when the line is naturally loaded. In this case the reactive power produced by the line capacitance corresponds to the reactive power absorbed by the line inductance. Line current and voltage are in phase in every point of the line and the losses are the lowest for a given power transfer. When the line is overloaded/underloaded, the consumption and generation of the reactive power do not match causing variation of the voltage. The role of compensator on the transmission level is to change the line parameters in order to match consumption and generation of reactive power [9]. Traditionally, this is achieved by inserting inductance and capacitance into the system, by synchronous condensers, or with static var system (SVS).

On the distribution level, the philosophy of the voltage regulation differs from that on the transmission level. Traditionally, reactive requirements of the loads and the voltage control are provided by combination of switched capacitors, load tap changing (LTC) transformers or line regulators. However, it has been recognized that LTC transformer can be a principal cause of voltage instability leading to voltage collapse [1]. It is incapable of stepless variation of voltage and has slow response.

The role of the ideal compensator is to change dynamically the line parameters in order to match instantaneously production and consumption of the reactive power on the point of its coupling with the grid. During the high load periods the reactive power consumed by the line inductance is higher then that supplied by the line capacitance and the compensator has to supply reactive power. On the other hand, the compensator has to absorb reactive power to prevent overvoltages that arise during light loads. Therefore, depending upon the line loading, the compensator has to function on either side: as a source of reactive power or as a sink of reactive power.

1.2 Needs for Dynamic Voltage Regulation

There are different reasons for fast, dynamic voltage regulation. Some of them are considered in the following subsections.

1.2.1 Fault Clearing

If the heavily compensated, overloaded line is subjected to sudden open circuiting due to the fault clearing, the line current is cut, so also is the voltage drop it causes. Because of the fast current change and line inductance, transient over-voltages arise. If the large number of slow acting compensation devices, previously providing reactive power, is still on line they also aggravate situation. A large amount of reactive power is released into the system tending to increase voltage to a dangerously high level. Therefore, under the fault conditions and the associated clearing process, the compensators must act fast to absorb reactive power to avoid insulation failures of the power system and compensation equipment.

1.2.2 Wind Farms

Larger numbers of wind farms, using induction generators, are being embedded into the distribution system, rising spectra of voltage issues on distribution feeders. The variable power output from induction generators is accompanied by variation in reactive power, causing voltage fluctuations which can seriously affect neighboring loads and even induction generators themselves. The wind farms often do not take part in voltage regulation, and they are being simply disconnected from the power system during the disturbances. To regulate voltage, the installation of dynamic voltage regulation device that can provide or absorb reactive power is required. Increase in number of wind farms, coupled with distribution grid with low short circuit capacity, will require installation of larger number of smaller sized Static Var Systems (SVS) on distribution level capable to provide efficient voltage regulation. Looking into the future, one can foresee that increase in number of wind farms coupled with distribution grid will require adequate voltage support on distribution level. It can be said that distributed generation shows need for distributed, distribution level, voltage regulation.

1.2.3 Induction Motors

Transient voltage instability or induction motor instability is another form of voltage instability that can lead to fast voltage collapse. For its prevention, dynamic voltage regulation is required. A closer look shows that induction motor loads behave as follows: Large industrial motors normally have under-voltage protection by which they are tripped as soon as the voltage drops to 30% to over 65%) [1]. Once they are tripped, they cease to be a problem to voltage recovery. This leaves the smaller motors which have thermal overload protection only. During the short circuit fault, or some other voltage disturbance these smaller motors are decelerated by the loads to low speeds. Upon the clearing of the fault, the still connected motors all accelerate at the same time drawing large currents from the transmission line because of the large slip s (low speed). The large accelerating motor current cause high voltage drop causing voltage collapse in week system or in system with lack of reactive power. Loads having low inertia as air conditioners and refrigerators are the most onerous.

1.2.4 Prevention of Overvoltages

For minimizing overvoltages due to load rejection and switching operations the dynamic voltage regulation is required. It is done with SVC (TCR). The example of SVC to prevent overvoltages are ABB installations of SVC (four TCR 75 Mvar each) in the

Mexican power system (1982 Temascal), installation of SVC in Indian (Kanapur 1992)power system, installation of SVC in Namibia (520 km radial line -SVC 250 Mvar inductive-80 Mvar capacitive).

1.3 State of Art Devices

1.3.1 Reactive Power Management

Traditional means of reactive power management and voltage support/control, apart from generator itself, have been synchronous condensers switched/fixed capacitors and inductances. The synchronous condensers have been connected on transmission and sub-transmission voltage levels to improve voltage profile under varying load conditions and contingency situations over the last 80 years [9]. Their advantage is possibility to provide and absorb continuously reactive power enabling smooth voltage control over wide range of operating conditions. Their main drawbacks are rotational instabilities and high maintenance requirements due to rotational parts. For economical reason their application on sub-transmission voltage levels has been replaced by fixed/switched capacitor banks. In spite of their low cost, the capacitor banks have drawbacks of slow response, introduction of harmonics due to switching operation of the breaker and possibility of resonance with the rest of the power system. Moreover, they occupy a large amount of real estate and they cannot provide stepless voltage control. As the breaker has limited life (typically 2000 to 5000 switching operation) they are not suitable for systems where frequent capacitors switching is required.

Developments in solid-state technologies, micro-processor technologies and Flexible AC Transmission Systems (FACTS) have led to the application of power electronic based switching devices for reactive power management and voltage control. Due to their fast switching capability and voltage and current ratings they can provide fast and accurate dynamic voltage control at transmission and distribution levels. The power electronic based FACTS devices can overcome the traditional compensators drawbacks and with their fast dynamics they can significantly improve power system stability and voltage profile. Power switching device can undertake a role of breaker and be used for fast switching in/out of capacitor banks and inductance. These devices called Static VAr Compensators (SVC) provide advantage of fast response and no wear and tear. They consist of Thyristor Switched Capacitor (TSC) /Fixed Capacitors (FC)/Switched Capacitors (SC) and Thyristor Control Reactor (TCR).

Power electronic converter can be applied to provide voltage support. They shape DC voltage and produce AC voltage of controllable amplitude and phase. In this case they simulate AC source and we talk about Static Synchronous Compensator or STATCOM. The voltage support can be also provided with HVDC back to back configuration if the power converters forming HVDC consist of full controllable power switching devices.

1.3.2 Shunt FACTS Controllers

The Thyristor Switched Capacitors – Thyristor Control Reactor (TSC-TCR) is a mature FACTS controller [9-16] based on proven and reliable technology. The first installation date from 1978 near Rimuski, Quebec. The compensator is used for performance evaluation and is applied for regulation of 230 kV transmission voltage. The installation consist of 93.6 Mvar fixed capacitors bank wye-connected and 93.6 Mvar TCR delta-connected. Later the same principles are applied to provide dynamic voltage regulation and voltage support at five intermediate points along 1000 km of Hydro-Quebec's long transmission lines enabling delivery of James Bay power [12]. Today, TCR-TSC/SC/FC are routinely installed on transmission level to provide transmission voltage regulation of long lines [17,18]. TSC-TCRs have fast response, but they have some serious drawbacks as high cost, possibility of resonance with the rest of the power system, introduction of harmonics and larger installation area. Moreover, they behave as a variable admittance.

Their reactive power output is largely dependent on the system voltage. Therefore, if the line voltage goes down, the reactive power supplied by the shunt capacitors also reduces.

One of the most versatile FACTS devices is a STATCOM [20-28]. It is basically alternative voltage source behind reactance. Its application can vary depending on the needs of power system where it is to be installed. In transmission system, it can be considered as transmission expansion alternative to provide big savings. It can be used to stabilize the system and improve damping, or to support the voltage profile [16-28]. In distribution system, STATCOM can be applied for power factor correction of the load, or for voltage regulation. Moreover, it can be used as dynamic supplement to shunt capacitors because of high price of switching devices for high MVA ratings, or it can act alone as individual unit. The STATCOM itself, in spite of numerous advantages over traditional compensators, has some serious limitations. The main building block of the STATCOM is Voltage Source Converter (VSC). When applied in transmission system, the rating of switching devices can be a problem. Moreover, in order to produce output voltage and current low in distortion, the switching frequency has to be increased which implies higher switching losses. The numerous efforts have been undertaken in order to overcome these limitations. The solution of this problems has been seen in different multi-pulse arrangements of power converters, putting switching devices in series [29] or in the various multilevel topologies [30-40]. The power switching devices evolve in the direction of increased voltage and current ratings, and switching frequency with decrease in switching losses. The promising power electronic switching devices for high voltage and high power applications are GTO (Gate Turn Off Thyristor) and IGBT (Insolated Gate Bipolar Transistor). Their present voltage and current ratings are about 6 kV, 6 kA for GTO and 1.7 kV and 0.8 kA for IGBT. Switching frequency is of order 5 and 20 kHz for GTO and IGBT respectively. Development target maximum voltage and current rating of GTO is about 10 kV and 8 kA while for IGBT is of order 3.5 kV and 2 kA.[41]. It is anticipated that higher frequency switching modulation strategies will be applicable on transmission level in recent future [42-46]. That would make their application in power system even more attractive, especially on transmission level making STATCOM an attractive alternative to new transmission line installation. The main advantage of STATCOM over its traditional counterparts (TSC-TCR) is in its intrinsic possibility to provide voltage independent reactive output so that voltage profile of line can be supported even up to higher power level as compared to TSC-TCR of the same rating. In case if the maximum rating of the STATCOM has been reached, the STATCOM will continue to supply rated reactive power while TSC reactive output decreases proportionally to square of the line voltage.

1.3.3 Static Var Systems

In this work the term Static VAr System (SVS) is treated as a continuously controllable source of reactive current. It represents a combination of switched capacitors (SC), switched inductance (for economy), thyristor switched capacitor (TSC), thyristor control reactors (TCR) and SVCs or STATCOMs (to give continuously adjustable control between the capacitor steps). Some of above mentioned configurations are displayed on the Fig. 1. The power electronic switching devices allow fast action and fast adaptation to current loading condition in order to alleviate transients and to relax power system.

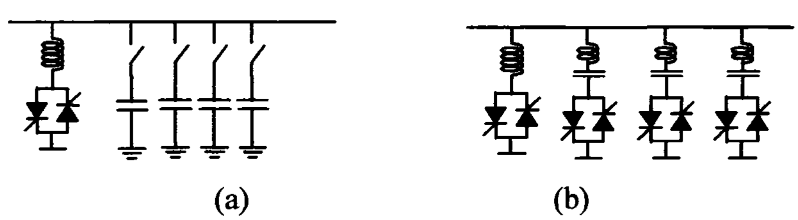

Figure 1 Different arrangements of static var compensators: a) TCR with switched capacitors, b) TCR-TSC.

1.3.4 Positioning of SVS

Historically, synchronous condensers, connected at the sub-transmission and transmission buses, have been used to supply the continuously adjustable capacitive or inductive currents to support the voltages at the load centers [9]. Because of the precedence set by synchronous condensers, the SVSs which have largely supplanted them, still tend to be situated at the sub-transmission and transmission buses. Even the term FACTS tends to impose application on transmission level. However, SVSs are suited to distribution bus voltages and sizes. This is because they are based on solid-state technologies, which have grown from the application of thyristors, gate-turn-off thyristors (GTOs) and insulated gate bipolar transistors (IGBTs) to variable speed AC motor drives. The controllers of SVS such as the Static VAR Compensators (SVCs) and the STATic COMpensator (STATCOM), are solid-state switch technologies pushing upwards to the higher MVA ratings of power utilities. In fact, this has been one motivation of multi-level converter research. A few manufacturers have already mastered the technology of connecting GTOs or IGBTs in series to increase the voltage ratings of STATCOMs to distribution voltage levels. Recent examples are following ABB installations (SVC light - that is ABB trade mark for STATCOM): *Hagfors, Sweeden* -STATCOM (based on IGBT technology together with PWM) rated 44 Mvar directly connected at voltage 10.5 kV via its phase reactor and *Moselstahlwerk* in Trier -STATCOM rated at 20 kV, 38 Mvar is directly connected at 20 kV votage via its phase inductor [47,48].

1.3.5 Distribution Level SVS

Developments in solid-state technologies has enabled the SVSs to have fast voltage control at distribution levels. Smaller sized SVCs and distribution STATCOMs (D-STATCOMs) have been successfully developed, tested and applied, providing voltage regulation for large, fast fluctuating loads, such as, arc furnaces, arc welders, rolling mills and very large motors which start and stop frequently [49],[50]. In [51], it has been demonstrated that fast acting SVC can prevent voltage collapse due to induction motor instability. In [26] and [52], results of feasibility studies of distribution STATCOM application on Commonwealth Edison's power system have been described showing that performance of a STATCOM can benefit the system if STATCOM properly coordinated with existing voltage control equipment. The benefits include enhanced power quality, increased loadability while number of switching operations and LTC operations has been decreased, reducing maintenance requirement. Many companies have put D-STATCOM on the market, available with or without energy storage as option. Recent installation of D-STATCOM in BC Hydro System is described in [53], and installation of Distributed Superconducting Magnetic Storage System (D-SMES) in Entergy System for improvement of Voltage Stability has been reported in [54]. Most of the papers discussing application of distribution side dynamic voltage control consider only one SVS. The merits of removing voltage support from transmission side to distribution side of power delivery substation and dispersing it in the form of small size units have been investigated in [55-59].The preliminary findings based on reliability, lower VAr and transformer requirement favor distributed, distribution compensation.

1.4 Research Objectives

This research addresses voltage issues in modern power system. The main goal of this thesis is to investigate avenues that can lead toward economical and reliable voltage regulation of overall power system. Based on current state of development and actual problematic, as described above, the objectives of this research are as follows:

1. Enhancement of voltage stability of electric power grid.
2. Enhancement of voltage quality on distribution feeders.
3. Increase of transmission capacity of transmission system
4. Development of new control techniques for application of power electronic converter in voltage control (STATCOM)
5. Investigating the impact of shunt compensation on reliability
6. Investigating optimal positioning of voltage support devices

These issues are considered in detail in the work that follows.

1.5 Research Tools

As a music is made of tones and the poem from words, this thesis is made of the basic laws of circuit theory, namely, Kirchhoff's current and voltage laws together with vector diagrams. They are used as main research tools. For the realization of the dynamic study and enumerated objectives, standard simulation packages such as MATLAB, together with the newest available in power industry, HYPERSIM, software and simulator developed by IREQ, Hydro-Quebec's research institute, for real time, dynamic simulation of power systems. The simulator is state of the art equipment based on parallel processors. HYPERSIM is based on EMTP software mostly. The main advantage of HYPERSIM is availability of high precision models of lines, loads and SVCs based on many years of experience of R&D at IREQ. In this thesis HYPERSIM is used because it was available, not because it is required. However, importance of real time dynamic simulation is in fact that long term dynamic stability study can be performed to insure that there are no long term instabilities following contingency situations.

1.6 Outline of Thesis

The main contribution of this thesis is in proposing a new concept, namely, "Transmission Voltage Support Decentralization and Sustained Voltage Support of Transmission Lines from Distribution Level". It is demonstrated in this thesis that sustained voltage support of transmission lines can be provided, more efficiently, with large number of smaller sized distribution, distributed SVS scattered all around the main grid compared to smaller number of lumped SVS on transmission level. The term "more efficiently" means better voltage regulation for smaller cost or "to get more for less money". Finally, the obtained conclusions are verified with real time dynamic simulation using detailed modeling and professional, state of the art tool for simulation of power systems.

The structure of the thesis is as follows:

In Chapter 2 the principle of voltage drop and voltage support are discussed. In Chapter 3 the principles of operation of STATCOM are reviewed together with its control circuit. In Chapter 4 the advantages of removing voltage support from transmission level to distribution level are quantified on radial system using simplified model of the line. In Chapter 5 detailed modeling of lines is undertaken and voltage support on distribution level with N compensator is discussed. In Chapter 6, general equations allowing reactive power requirements are deduced. In Chapter 7 the voltage support required by a long, radial transmission line in feeding several remote load centers spaced along its length is addressed. It has been shown that it is feasible to use Static Var Systems (SVS) located on distribution buses of each of the load centers. Finally, in Chapter 8, the conclusions are drawn and suggestions for future work are given.