A Review on Shunt Compensating Devices for Reactive Power Management

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Abstract
Since the last two decades, it has been observed that power quality as the key concern for power engineers. This has boosted up the use of Flexible AC Transmission Systems (FACTS) devices in the power system. Starting with static capacitors, FACTS devices cover the journey through synchronous condensers, Thyristor Controlled Reactors (TCR), Thyristor Switched Capacitor (TSC), Fixed-Capacitor Thyristor Controlled Reactors (FC-TCR) and Static Synchronous Compensators (STATCOM). Researchers have proposed various control strategies for all these devices and these schemes are running successfully over the period of time. The power quality issues like voltage sag/swell, power factor deviation, etc. can now be solved in fractions of seconds using these devices. This paper shows a review of the research done till now on reactive power compensation using shunt connected FACTS devices. In addition to the FACTS technology tools, this paper focuses on a detailed survey of applications of these tools for solving power quality issues and maintaining all the grid parameters well within the prescribed limits.

Keywords: *Shunt compensation, FACTS, Reactive Power Compensation, Power Quality, STATCOM*

INTRODUCTION

Generation and transmission of power requires all the components of power system to work in tandem so as to maximize the output. This demands very high level of control and protection schemes to work with maximum accuracy. The control scheme is developed based on either of the four key parameters of power system, namely, active power, reactive power, voltage and rotor angle.

Reactive power plays the major role in the process of power transmission. Ideally, the power system desires only active power to flow in the system but to maintain the voltage required to deliver active power, reactive power is a must. Most of the load comprises of motors, which require reactive power for their operation. This, in turn, deteriorates the power factor at the load end. Hence, the major problems being faced due to unbalance in power system parameters include voltage control at various load conditions, power factor improvement at load end and stability under transient and sustained disturbances. So, the control of reactive power is a must in order to maintain the power system parameters within allowable limits.

Reactive power compensation focuses on two major aspects, namely load compensation and voltage support. Load compensation includes power factor improvement, thereby, balancing the real power drawn from the grid and providing better voltage regulation for fluctuating loads. On the other hand, voltage support means the reduction in voltage fluctuations at the desired bus. This can be attained either by Series Compensation or Shunt Compensation. In this paper, however, shunt compensation is taken as key concern.

The constantly developing technology and increasing loads have brought about a paradigm change in the perception of customers and their willingness to receive quality power from the grid. The escalation in non-linear loads cause a high level of voltage harmonics to intervene the system, thereby, adding to the problem of reactive power compensation. An alert customer now asks for a power supply that is voltage regulated, balanced, flickers free, without harmonics and without any outages.

Ever since the AC transmission took a leap in early 19th century [19], the power engineers are facing trouble in maintaining the power quality parameters within prescribed limits. The concept and need of reactive power in the power system has always been a point of discussion. It has become more severe for engineers to focus more on controlling power quality issues at the transmission and distribution stage so that the generation is not affected. Keeping this point in view, a number of compensating devices have been proposed till date, the most ancient being static capacitors, proposed by Friedlander in 1970s [3] and the latest one is STATCOM, proposed by Padiyar in 2000 [15]. Out of these, STATCOM is still leading the technology [25,29,30,33].

Hingorani introduced the fundamental of custom power in 1995 [12]. The custom power devices deal with the issues related to distribution system by using power electronic converters and controllers. Smrithi K. successfully implemented an infinite level inverter based STATCOM in 2017 [25] which helps to minimize conduction and switching losses and hence to improve efficiency. Yushi Koyama also contributed by introducing transformer-less STATCOM in late 2017 [30].

In March 2018, Xuefeng Ge contributed by optimizing the operational performance of low-capacitance cascaded H-bridge (LC-CHB) STATCOM by using a flexible third harmonic control method, which could reduce the voltage stress on semiconductors during operation and the switching losses in consequence [33].

To summarize, the origin of compensation is reactive power compensation which was initially looked after by fixed capacitors, also known as passive capacitors. These capacitors were then replaced by Static VAR Compensators (SVCs) for reactive power compensation and voltage regulation at the customers' end. Some of the major drawbacks of these devices were: minimum limit of compensable reactive power below which these devices somehow failed to operate; slow dynamic response; injection of harmonics in the system due to the filters accompanying them; operation failure at low voltage conditions; and inability to provide load balancing and load levelling. The further development of STATCOM was efficient enough to overcome these problems.

To survey the publications on FACTS devices till date, as searched on IEEE and SCOPUS database, following is the result obtained:

Table 1: *Facts and Figures*

Database	Conference	Journal	Book	Article
IEEE	43377	14086	480	291
SCOPUS	6630	7201	220	259

As on 15th February, 2018

CONCEPT OF SHUNT COMPENSATION

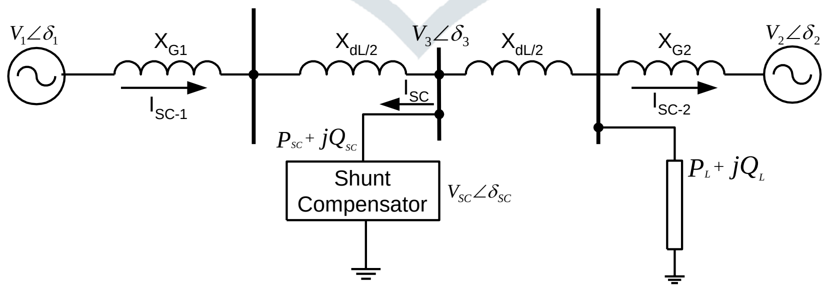

Fig. 1: An ideal Shunt Compensator connected to Transmission

Fig.1 shows a double generator system and a transmission line where an ideal shunt compensator is connected to the middle of the line. The generators have an equivalent reactance of X_{G1} and X_{G2} while the transmission line has an equivalent reactance of X_{dL}. The voltages at Point of Common Coupling (PCC) of the generators are given as $V_1\angle\delta_1$ and $V_2\angle\delta_2$. The shunt compensator connected in the middle of the line is a voltage source that is continuously controlled to $V_{SC}\angle\delta_{SC}$. The power factor of the load deteriorates when inductive load is connected in the system.

If pf reduces, the ampere burden of the equipment increases for a particular value of active power required. With increase in current, the ohmic losses of the system increases, which results in generation of unwanted heat in the system. The cross-section of the conducting parts of the system may also have to be increased for carrying extra ampere burden, which is not economical in the commercial point of view. Another major disadvantage, is poor voltage regulation of the system, which is mainly caused due to poor power factor. Hence, reactive power compensation is required.

The purpose of shunt compensation is to increase the steady state power transfer capability and to improve the voltage profile along the line. The shunt compensating devices act as a current source which injects leading or capacitive reactive current during heavy load conditions and lagging or inductive reactive current during light load conditions.

The shunt compensation can be achieved by using Flexible AC Transmission System (FACTS) devices. FACTS devices are electrically switched power-electronics based devices. These devices operate using high level control schemes. Better the control scheme used, higher is the efficiency and better is the performance of the compensating device. Since most of the loads are inductive in nature, the researchers introduced the synchronous condensers and static capacitors which were switched into the system as per the requirement [3,7,13].

SYNCHRONOUS CONDENSER AND STATIC CAPACITORS

Synchronous condenser is a DC-excited synchronous motor, whose shaft spins freely. The field winding of the motor is controlled by a voltage regulator either to generate or absorb reactive power as needed to adjust the grid's voltage, or to improve power factor. As the field excitation is increased, the reactive power is more furnished and the performance becomes better and more efficient.

The major advantage of this mechanism is that the precision level of correction required is very high. The kinetic energy stored in the rotor of the machine can help stabilize a power system during rapid fluctuations of loads such as those created by short circuits or electric arc furnaces. Large installations of synchronous condensers are sometimes used in association with high-voltage direct current converter stations to supply reactive power to the alternating current grid [3,13,19].

Because of the high cost and high size with increasing rating of the synchronous condensers, their application became economically adverse in the system. Also, due to the rotating parts involved, synchronous condensers possess higher energy losses. These disadvantages were overcome by using static capacitors [3,13]. These capacitors are connected in shunt to improve the reactive power demand at the load end, as shown in fig. 2.

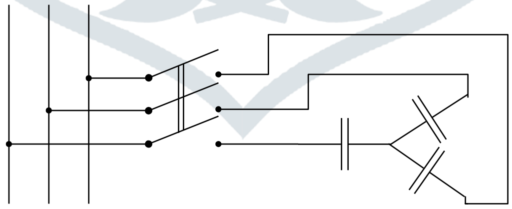

Fig. 2. Shunt Static Capacitor

The Shunt Static Capacitor reduces the reactive current flowing through the system. This, in turn, reduces line current of the system, improves voltage level of the load, reduces system losses, improves power factor of the source current, reduces the load of the alternator and hence, the capital investment per megawatt of the load [3,13]. The shunt capacitor basically draws a fixed value of leading current which is superimposed on the load current. This reduces the reactive power of the load and improves the power factor of the system [3,7,13].

In order to achieve a continuous control over reactive power, thyristor-controlled reactors were introduced as the first FACTS device by G. K. Dubey in 1983 [7].

THYRISTOR CONTROLLED REACTOR

Thyristor controlled reactor (TCR) consists of a reactance connected in series with a bidirectional thyristor, as shown in fig. 3. TCR is a phase-controlled device which allows the value of delivered reactive power to be continuously adjusted to meet varying system conditions. TCR can be used for limiting voltage rise on lightly loaded transmission lines.

With its introduction in early 80s [7], it is still being implemented in most of the countries in the world and running successfully [26]. However, due to the discontinuity in load current, it introduces very high harmonics in the system [7].

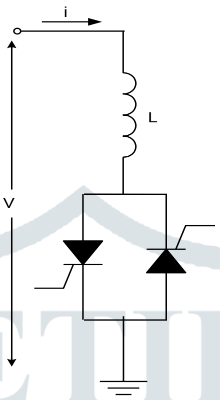

Fig. 3. Thyristor Controlled Reactor

Various control schemes have been developed in order to mitigate these harmonics. Two of the most popular schemes were proposed by Bohmann and Lasseter in 1987. They proposed two schemes, first, by developing a Fourier matrix model for the TCR whereas, the second, by using state variable analysis to write the circuit equations for the TCR [10]. The first method worked well in many situations including investigating the effects of ambient harmonics. However, the accuracy of this method decreases near resonance points. The second method was successful enough to resolve this issue.

With various control schemes coming on the way, the latest one was proposed by Sankar Das, Debashis Chatterjee and Swapan Kumar Goswami in 2017 [26]. The proposed scheme uses a single-equivalent delta-connected thyristor-controlled reactor (TCR) along with a combination of Y- and Δ-connected thyristor switched capacitors (TSC). This reduces effective number of switching devices, cost, complexity, and space requirement compared to the conventional SVC-based schemes [21]. An optimized switching function is adopted in the proposed scheme for reduction of additional injected harmonics by TCR. The optimized switching angles are computed offline using gravitational search algorithm and stored in the processor memory for online application.

TCR was capable enough to inject inductive reactive current at PCC, but the problem was still existing when the transmission line was lightly loaded. Some mechanism, other than a static capacitor, was required to automatically detect the amount of capacitive current existing in the system and absorb the excess reactive power. Thus, in 1981, Thyristor Switched Capacitor (TSC) was introduced by S. Torseng [6].

THYRISTOR SWITCHED CAPACITOR

As shown in fig.4, Thyristor Switched Capacitor (TSC) consists of a capacitor connected in series with a back-to-back connected thyristor and a small inductor in series with the combination to mitigate the harmonics.

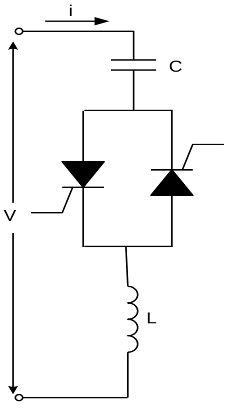

Fig. 4. Thyristor Switched Capacitor

In [6], the author has explained the operation and control of TCR and TSC individually. In order to obtain flexibility, the author has, then, proposed a combination of both these devices and control of the combined compensator hence obtained. According to his study, this combination was technically and economically more efficient than individual devices connected to the system.

However, TSC is a device in which only two states of operation are possible, i.e., ON or OFF. The continuous range of operation is not available as far as TSC is concerned. That is why, in 1992, D.A.N. Jacobson and R.W. Menzies proposed a scheme having fixed filter capacitors connected in parallel to a Gate Turn-Off (GTO) thyristor-based voltage source converter [11]. The authors have proved the efficiency of this combination. Considering the control complexity involved in TSC-TCR combination, fixed capacitor in parallel to another inductor-based compensator was technically a better option.

In addition to this, all this survey shows that TCR can work well as far as voltage profile needs to be regulated. In 1985, Haque and Malik introduced the concept of Fixed-capacitor Thyristor Controlled Reactor (FC-TCR) which not only serves the purpose of TCR, but also improves the power factor [8,9].

FIXED CAPACITOR THYRISTOR CONTROLLED REACTOR

Earlier industries used to prefer shunt compensating capacitors in series with harmonic suppressor inductors for regulating power factor and terminal voltage in case of non-linear loads [1,5,7,8]. In this technique, the value of capacitor and inductor depends on load impedance and firing angle of thyristor. But changing capacitance of the capacitor with change in firing angle is not preferable. So, researchers suggested the need for an arrangement which provides continuous variation of inductance while keeping capacitance constant [7,8].

Fig. 5 shows the mechanism with thyristor-controlled reactor and shunt capacitor which is superior in performance as compared to mechanical switches and synchronous condensers [1,5,8]. Later, researchers have used self-saturating reactors, having inherent control, shunt capacitors and filters for the purpose [2,4,7].

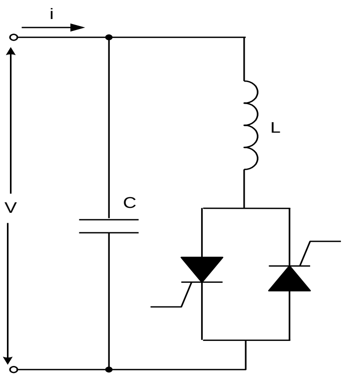

Fig. 5. FC-TCR Approximate Circuit

In 1985, S. E. Haque and N. H. Malik in [7,8] have given a detailed analysis of the basic functioning of FC-TCR circuit. They have proposed an approximate circuit and an exact circuit and performed the analysis of both, taking reference from [1,2,4,5].

In 1987, the same researchers have proposed an LC filter in place of fixed capacitor in order to mitigate the harmonic oscillations caused by fixed capacitor [9]. This technique is named as Fixed Filter Thyristor Controlled Reactor (FF-TCR). As per their research, this scheme proved to be efficient enough to maintain power factor at unity irrespective of the firing angle of the thyristor and supply impedance. This scheme was discussed in a number of research articles and discussions [14,16,17,23], but considering the complexity involved, in 2013, AMOJ Pasupuleti concluded that FC-TCR is preferred over FF-TCR [23].

Later in 2017, Gajanana Abhyankar, K. N. Shubhanga and H. Girisha Navada proposed a three-phase SVC setup [28] developed at power systems laboratory at NIT Karnataka. The authors have discussed various case studies which they had conducted on SVC under steady state. Reactive power computation is being demonstrated through harmonic analysis. The major achievement is the data acquisition system built to ease the steady-state analysis of SVC, which can be used to capture the transient response of SVC.

In 2000, K. R. Padiyar introduced the concept of Static Synchronous Compensator (STATCOM) [15], which proved out to be more efficient than SVC in further researches [25,29,30,33].

STATIC SYNCHRONOUS COMPENSATOR

In his research in 2000, Padiyar introduced STATCOM to the world [15], which is a Voltage Source Converter (VSC) based device as shown in fig. 6. His study gives the detailed analysis of a STATCOM, its circuit and control strategy used for its operation.

The proposed topology has a six-pulse inverter using PI current control. Earlier Hingorani proposed hysteresis current control for SVC based FACTS devices [12] but this scheme was too slow to respond to dynamic changes [15]. A number of researchers proposed various topologies and control techniques to improve the performance of STATCOM [18,20,22,24-27,29-33]. In 2006, thyristor-based STATCOM was introduced to enable self-commutation of the converter switches [18].

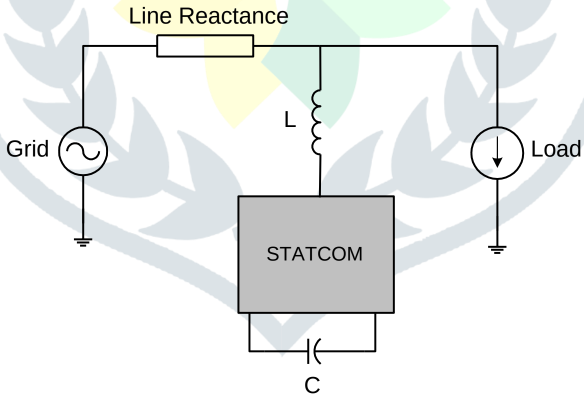

Fig. 6. STATCOM connected to Grid

In 2009, Bhim Singh and Srinivas introduced 12-pulse STATCOM in order to mitigate lower order harmonics [20]. In 2011, a hybrid control was proposed for STATCOM [22], which uses a digitally controlled oscillator (DCO) to synchronize the STATCOM with an AC system exhibiting the frequency variations. The control also schedules the firing of the converter valves in order to achieve the reactive power compensation level required in the connection bus of the AC system.

In 2013, Luis M. Castro and Enrique Acha proposed an advanced model of the STATCOM suitable for steady-state and dynamic simulations of large-scale power systems, which comprises of VSC in series with Load Tap Changer (LTC) Transformer [24]. Later in 2014, Yao Xu proposed Adaptive PI control of STATCOM which was capable to react to even a minute change in the grip parameters [27].

2017 proved out to be a year of advancements as far as STATCOM is concerned. An infinite level STATCOM was proposed by Smrithi K in 2017, which brought revolution in the FACTS family. It improves efficiency drastically by reducing the switching and conduction losses [25]. In the same year, a transformerless STATCOM based on hybrid cascade multilevel converter was proposed which is extremely low loss and small-sized STATCOM [30].

Recently in 2018, a flexible third harmonic voltage control of low capacitance cascaded H-bridge STATCOM has been proposed [33] which reduces the voltage stress on semiconductors during operation and thereby reduces the switching loss. This scheme reduces the capacitor peak voltage based on the injected capacitive reactive power during operation, and consequently, the switching losses can be reduced.

As far as recent installation of STATCOM is concerned, in July 2017, PowerGrid commissioned India's first STATCOM of ±100 MVAr capacity at 400 kV bus at 400/220 kV N. P. Kunta substation in Ananthapur district of Andhra Pradesh. N P Kunta substation is connected to 1500 MW Ultra Mega Solar Park (in phases). Solar is a variable renewable energy source which is dependent on time of day, locational, seasonal variations including weather conditions. Addition of a solar plant to 400 kV Grid results in Grid Voltage Instability. STATCOM improves Grid Voltage Stability by providing required Reactive Power Compensation based on different operational profile of Ultra Mega Solar Power Plant. It produces Reactive Power without employing separate capacitor or reactor banks and provides steady state and dynamic voltage control, transient & dynamic stability control and damping of power & sub-synchronous oscillations so as to provide quality power.

CONCLUSION

This paper has presented an inclusive review of shunt FACTS devices. Evolution and advancements of the FACTS devices such as synchronous condenser, shunt capacitor, TCR, TSC, FC-TCR and STATCOM have been presented. FACTS devices are used for solving various power system steady state control problems such as voltage regulation, transfer capability enhancement and power flow control. As supplementary functions, damping the inter-area modes and enhancing power system stability using FACTS controllers have been extensively studied and investigated. Generally, it is not cost-effective to install FACTS devices for the sole purpose of power system stability enhancement. Researchers are going for fast control strategies and the multi-functional use of voltage control, stabilization, reactive power compensation and unified power flow control. The emphasis of the presented analysis is on energy efficient utilization, loss reduction, voltage stabilization, power factor, power quality and harmonic reduction at the point of common coupling with nonlinear loads. The review reflects that the FACTS technology is still undergoing immense advancements in the control and configuration aspects. Future of FACTS devices is still interesting. With the emerging technologies of Smart grid and Electric vehicles, FACTS devices see a broad scope of applications in the power system. The latest FACTS devices currently present in market include FCTCR and STATCOM.

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