STATCOM – A Preface to Power Quality in Power Systems Performance

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Abstract— **This paper investigates different types of Flexible AC transmission System (FACTS) controllers with focus on various operational and control aspects of static synchronous compensators (STATCOM) to different performance characteristics like power transfer capability, voltage regulation, reactive power management, stability limits, power factor improvement etc. In addition, various features related to STATCOM like converter topologies, reference compensating signal generation schemes, controllers, and generation of switching signals are reviewed.**

Keywords-Power Quality; STATCOM; Multilevel Voltage Source Converter; Harmonic

I. INTRODUCTION

Electrical power systems are stretching to their operational limits to meet growing demand. An added issue is power quality, as more and more nonlinear loads connect to the grid. Several large power swings and outages can be largely attributed to lack of awareness about system condition as well as inadequate understanding of power quality [1-2]. Several researchers have tried to address the issues that fall under the term of power quality. Even though there is not a strict universal definition, power quality can be considered as a set of various parameters like voltage/current magnitude variation, voltage fluctuation, voltage/current unbalance, harmonic voltage/ current distortion, high frequency voltage noise [3-4].

Flexible AC transmission systems (FACTS) due to their higher controlling capability and quick response have become an area of research with increased interest. Many researchers have developed FACTS controllers to mitigate different power system problems such as voltage unbalance, poor power factor, voltage sag/swell, reactive power compensation, harmonics etc. These controllers are adaptive to various operational conditions and competent to improve the usage of existing installations. This paper provides a thorough review on the topic, focused on Static Synchronous Compensators (STATCOM).

II. FACTS CONTROLLERS –TYPES & PERFORMANCE ANALYSIS

FACTS controllers due to their competency in governing the operation of transmission system by control of interdependent system parameters like power flow control, transmission capability, reactive power control, power quality improvement, etc. have become a key area of research. FACTS controllers were proposed in [5-8]. Depending upon the technological advancements FACTS controllers are segregated into two generations: the first that uses conventional thyristor switched capacitors, reactors tap changing transformers and the second that uses GTOs, MOSFETs, IGBTs etc. [9-18]. Both generations of FACTS controllers have distinct operating characteristics with the operation of first generation controllers restricted to reactive power control only, whereas the second generation controllers were able to control both active as well as reactive power flow, of the transmission system[19-21]. Based on connection with the grid, FACTS controllers are classified as series shunt and combined controllers. Figure 1 depicts statistics of FACTS controller installed worldwide. Performance analysis for different types of FACTS controllers is presented in Table I.

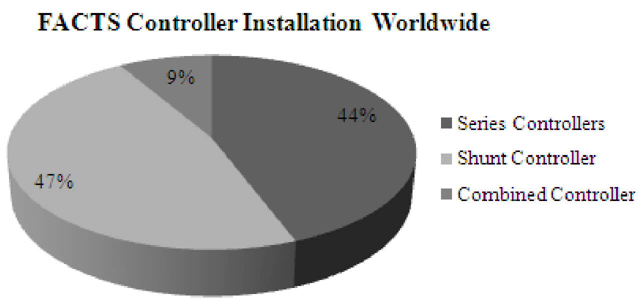

Fig. 1. FACTS Controller Installation Worldwide

III. DEVELOPMENT AND RESEARCH INTEREST OF STATCOM

STATCOM is the original shunt connected controller and falls amongst the FACTS Controllers. In 1976 Gyugyi anticipated the idea of power flow control through STATCOM. As per IEEE definition static synchronous compensator is competent to control capacitive or inductive output current independent of system voltage [1]. The entire power flow control is achieved by injection or absorption of controlled reactive power into/from the power system. At the time of lapse in system voltage STATCOM feeds reactive power (capacitive) and during increased system voltage STATCOM takes up reactive power (inductive) [2]. Figure 2 is an indicative of the research work being carried out in the area of STATCOM applications. It is clearly depicted from Figure 2 that most research work has been carried out on the usage of STATCOM for voltage control in power system. It is shown that STATCOM application for voltage control in power system has increased in the past decade. This also reflects the extensive utilization of STATCOM in power system stability and power quality issues. It is also shown that STATCOM application in renewable energy has also increased significantly.

TABLE I. PERFORMANCE ANALYSIS OF FACTS CONTROLLERS

	SVC	TCSC	TCPST	STATCOM	SSSC	UPFC	IPFC
MVA Capacity	Best	Best	Good	Better	Better	Better	Better
Reactive Power Control	Good	Better	Better	Good	Best	Best	Best
Voltage Control	Best	Good	Good	Best	Good	Better	Better
Thermal Stability	Good	Better	Good	Good	Better	Best	Best
Transmission Competency	Good	Best	Better	Good	Best	Best	Best
Transient Stability	Good	Best	Better	Better	Best	Best	Best
Investment Cost	Good	Good	Better	Better	Better	Best	Best
Converter Loss	Better	Good	Good	Better	Better	Best	Best
Expected Operational Life	Best	Better	Better	Best	Better	Better	Better
Installations till date	Best	Best	Better	Best	Better	Good	Good
Future Trends	Better	Better	Better	Best	Best	Best	Best

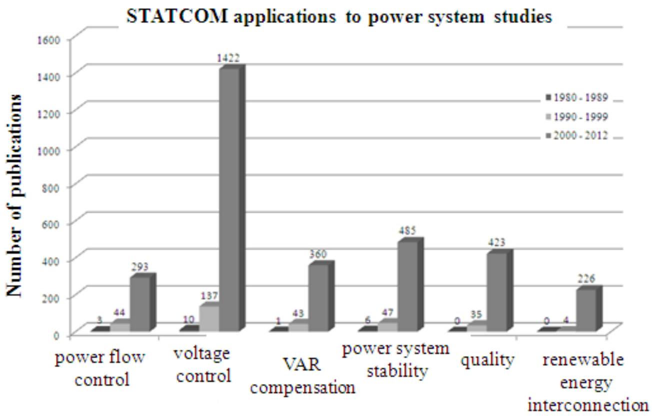

Fig. 2. STATCOM growth (publications in the IEEE/IEE library)

IV. STATCOM COMPONENT

STATCOM controllers achieve active as well as reactive power control by injecting current in to the line at the point of common coupling. Saha et al, have presented various topologies and control algorithms for STATCOM [22]. Also, the FACTS program sponsored by Electrical Power Research Institute (EPRI) identifies the significant challenges faced by the FACTS technology and their proposed solutions [23]. Various applications of shunt controllers have been studied and reported in literature [24-25]. Controllable reactive power can be generated by all types of DC to AC switching converters (voltage source and current source converters). However due to issues like high conduction losses, additional over voltage protection and higher voltage rating for the semiconductor in current source converter, voltage source converter is popular in power system application like FACTS controllers, especially STATCOM. A controlled three phase voltage of power frequency is produced by sequential switching of power semiconductor devices. The power flow either from line to controller or controller to line is due to DC charged capacitor at input side of converter. Each output voltage of converter is in phase with line voltage due to small tie reactance linking converter and line. Conventionally two-level VSC are used for STATCOM, however, nowadays multi-level VSC due to its modularity in structure and power handling capability are quickly replacing two-level VSCs for STATCOM [26-39].

A. Multilevel Voltage Source Converter Topologies for STATCOM

Multilevel converters have substituted the traditional converters due to structure modularity and low total harmonic distortion (THD). Components required per leg for different multilevel converter topology are listed in Table II.

TABLE II. COMPONENT PER LEG OF MULTILEVEL VOLTAGE SOURCE CONVERTER

Converter Type	Diode Clamp	Flying Capacitor	Cascaded
Main Switching Device	(m - 1) x 2	(m - 1) x 2	(m - 1) x 2
Main Diode	(m - 1) x 2	(m - 1) x 2	(m - 1) x 2
DC Bus Capacitor	(m - 1)	(m - 1)	(m - 1) / 2
Balancing Capacitor	0	(m - 1) x (m - 2) /2	0
Clamping Diode	(m - 1) x (m - 2)	0	0

1) Diode Clamped Multilevel Converter

Extensive number of clamping diode and balancing of DC link voltage are the two major issues that made diode clamped multilevel inverter less popular. Diode-clamped converter with virtual vector based modulation [40] and space vector pulse width modulation [41] for DC link voltage balancing algorithm has been proposed with experimental results. Dupuis and Okou have proposed a novel approach for DC link voltage balancing based on sub-controller [42]. STATCOM output voltage is supposed to be controlled by: terminal voltage sub-controller, neutral-point sub controller alleviate neutral point and two more auxiliary controllers maintain DC capacitor voltage [42]. A method to find the state space model for a general N-level diode clamped converter evaluated with simulation can be found in [43]. Voltage balancing between different capacitors with the use of an auxiliary capacitor in diode clamped multilevel converters is discussed and compared with traditional methods [44-45]. A combine diode-clamp cascade multilevel converter topology is suggested, where multilevel principal synthesizes output voltage with sub-harmonic PWM technique [46] and advantage of fewer numbers of clamping diodes helps in cost and size reduction [47]. Increased use of power electronics application, wind energy application and solar photovoltaic application, multi-level converters are designed for specific duty cycle, optimal balancing strategy, reduced switching strategy and specific modulation approach [48-54].

2) Flying Capacitor Multilevel Converter

With the large amount of energy storage capability during power outage, prevalent real and reactive power flow control and low harmonic content the flying capacitors multilevel converters have been accepted in FACTS control application. The only difficulty is that the excessive number of storage capacitors complicates converter control for real power transmission and capacitor voltage balancing issue [55-56]. The conventional flying capacitor multilevel converter performance can be improved by replacing the clamping capacitors by a number of series connected half bridge cells which will generate voltage at the converter output [57]. The measurement of voltage and selection of suitable switching states can control harmonic content of generated wave form, switching frequency and load impedance. A closed loop control based on phase shifted SPWM strategy with adjustment in switching time of selected switching states or selective harmonic elimination pulse-width modulation control has improved the self-balancing characteristics of the converter [58-60] and this can be achieved by adding two low frequency switches and capacitors [61]. The combined conventional flying capacitor multilevel converter with two level bridges is proposed in [62] and its soundness is checked with simulation. Also semi bridge converter with reduced switch count and free phase leg structure is used for unity power factor application [63].

Output voltage vector method for swapping of two switch modes which uses charging current in flying capacitor multilevel inverter is developed and simulation results are derived [64]. The number and size of flying capacitor limits use of converter. As a solution of this converter with multiple duty cycles with modulation technique in direct response to the capacitor voltage is explored [65-66]. A synchronous reference frame control is also broadly used to control power flow and DC bus voltage unbalance. Ghias et al. have carried out the simulation for back to back flying capacitor converter with reduced DC bus capacitance [67]. A work has been done on average models in abc and dq0 coordinates which will improve the performance of flying capacitor multi-level converters [68-69].

3) Cascaded Multilevel Converter

Cascaded-multilevel voltage source converter with separate DC source is proving itself an appealing concept due to its modularity in structure [70-72]. Peng et al. have proposed a cascaded 11-level inverter with a control scheme in which swapping pulses P1-P5 at every half cycle makes all DC capacitor voltage equally charged and discharged [73]. Instead of using DC voltage source of same magnitude if a DC voltage source of magnitude ratio 1:2:4:8, the traditional 9-level inverter is switched to 31-level inverter [74]. A six stage, 31-level converter of 30 kV with minimum step of 2 kV is simulated and tested on hardware of Railway Power Compensators [75]. Due to generation of medium/ high voltage capacity directly at converter output allows to eliminate the coupling transformer [76]. While in [77], a cascaded transformer for multi-level converter is suggested. This is the concept where, each level of the converter is transformer connected. This idea works for equal power sharing and losses estimation for multi-level converter. In [78] two structures for 11 kV and 33 kV are proposed with 81 and 27 levels. Here two comparative studies are carried out. The one with all cascaded converter of equal size cell and the other with the selection of cell size made on the basis of its DC-link voltage. In terms of their losses results, it is shown that the 27-level, 33 kV converters are superior with equal sized cell while the 81-level, 11 kV converters are good with ternary sequence selection of DC-link voltage. Instantaneous power theory for reference current extraction has been executed for multi-level inverter used in wind mill. The approach of the author is to analyze dynamic response of STATCOM for constant speed wind turbine [79]. Modular structure of cascaded multilevel inverter with two full-bridge units in parallel with two half-bridge units with single control loop to control both DC link voltage [80] and to improve power factor [81] has been obtained.

The addition of two controllable diodes in each cell to reduce voltage ripple is a novel technique proposed in [82]. Multilevel converters made of cascaded cells energy storage systems integrated with conventional topology or with integer/non-integer DC voltage ratio or dynamically varying voltage ratio have made multi-level converter application more attractive [83-86]. A concept of sub-multilevel converter blocks is explored with reduced number of switches and capacitors through experimental result in [87-89]. An asymmetrical 147-level converter topology with sub-multi-level arrangement is proposed. The objective of this converter is to improve its' performance for DVR. Together with conventional number of switches at each level, two additional switches between two DC sources are used to generate more number of level in [90]. Reference [91] deals with the elimination of DC components of current in coupling transformer secondary due to core saturation issues. Authors have proposed two methods to achieve this: either reduce the positive half cycle area by keeping the negative half cycle area constant or reduce the positive half cycle area by increasing the negative half cycle area. Experimental results are derived for 154 kV, ±50 MVAR, T-STATCOM.

A digital controller parallel to PD and repetitive control is simulated by Xu et al. in [92]. To achieve DC link voltage regulation, low THD, redundancy and reductions in cost; modular multilevel converter topologies like single star bridge cells, single delta bridge cells, double star bridge cells etc. for drives and PV solar system are discussed in [93-94]. The multilevel converter topology generally uses the fundamental switching frequency modulation method and the high frequency PWM method [95]. An accurately designed switching scheme can further reduce converter losses, size of inductor and DC capacitor. As a harmonic elimination technique, it gives better result compared to other techniques, but its complexity in deciding the parameter rating increases as the levels of the inverter increase [96-98]. Reference [99] shows the comparative simulation studies of Sine-Wave Pulse Width Modulation (SPWM) and Optimized Hybrid Phase Disposition Method (OHPDPWM) to measure the effectiveness of STATOM control. DC voltage balancing with phase shifted sinusoidal pulse width modulation (PS-SPWM) technique for cascaded multilevel converter by means of experimental result is proposed in [100-103]. This scheme helps out to eliminate weighty transformer and reduces converter power loss. Sinusoidal pulse width modulation (SPWM) with carrier phase-shifting, unipolar phase-shifting, reversing voltage etc. for STATCOM to reduce THD and switching frequency is discussed in [104-106].

B. Controller Design for STATCOM

For ease the following section is arranged as;

- Pole placement controller technique
- PI / PID/ PD controller technique
- DC-link balancing controller technique
- Hysteresis band controller technique

This however, doesn't mean that the above mentioned controller techniques are the only solutions. Researchers are continuously updating previous concepts by amalgamating existing one. Pole placement controller design with two set of controller gain i.e. first gain, by the use of linear matrix inequalities (LMIs) to meet design specification and second gain, by the use of zero set to meet overall system voltage control [107], first gain with one modulation index for steady state and second gain with adaptive modulation index for transient [108], combine Linear-Quadratic Regulator (LQR) [109] etc. are discussed for improving the operation of STATCOM.

In the environment of damping power systems oscillations, two controllers which regulate DC voltage and AC voltage using the optimal pole shifting (OPS) technique [110] are proposed. Also, the same concept but with fixed modulation index (MI) and variable dc capacitor voltage reference is implemented for STATCOM in [111]. Single machine infinite bus and two area four machine system for damping control by the nonlinear matrix inequalities is proposed in [112] with tested closed-loop performance under three phase fault and small signal disturbances. Reference [113] has come up with the exact linearization method to transform the nonlinear three-dimension equations with proportional integral control. Simulation results are derived for STATCOM operation for three phase ground fault too. A $H\infty$ loop shaping technique [114] for voltage magnitude and angle controller is identified and compared with a PID controller using pole placement method for gain derivation. Rule based controller, which utilizes fuzzy logic, bang-bang, root counting theory, self-tuning PI with particle swarm optimization etc. are proposed over a fixed parameter PI control to enhance the improved performance of controller [115-117]. Behavior of SSSC and STATCOM on single machine infinite bus [118] and SVC and STATCOM with usual lead – lag controller [119] with particle swarm optimization for dynamic stability performance has been proposed. The result proves that the SSSC offers fast dynamic recovery amongst all three. An adaptive PI controller is designed to maintain the voltage at point of common coupling for a range of instability. For the intended change in the gain of PI controller a cautious study of previous gain, practical gain and global is done for the algorithm [120-121].A self-tuning STATCOM with PI controller based on real time data adoption and gain setting with pole placement technique for different loading condition is designed and simulated [122-123]. A direct axis current control for any PI, PID or Adaptive mechanism is proposed in [124]. Simulation results are compared for controller output voltage variations when reactive power demand does not exceed limits and when reactive power demand exceeds them.

Particle swarm optimization technique for AC/DC voltage regulation, AC/DC damping controller, power system stabilizer on the single bus system with several fault condition with simulation result is investigated in [125]. In [126] transient stability is improved using Euler-Lagrange method based on passivity, where setting of PI controller Kpd=0.01, Kid=0.3, Kpq=2 and Kiq=10 and in [127-128] a back to back STATCOM based on passivity controller with PWM based rectifier section and multipulse inverter section is proposed. Whereas in [129] sliding mode technique is adopted where inner loop performs for switching of VSC and outer loop performs for AC and DC side voltage control. A decoupled controller with pole placement technique having an inverter voltage of 480 V and a reference reactive power of 1000 VAR is tested for reactive power change up to 5000 VAR. While doing so the capacitor voltage variation is very small [130]. A various approach supporting zero set technique, additional current feedback, phase-lead compensation, and series passive compensation, shunt active compensation etc. are conceded to study system dynamic [131-135]. In the case of [136] CT behavior is analyzed for cascaded multilevel inverter feedback loop. Voltage compensation at far end of line is experimented by 8 kVA, 415 V STATCOM. The results are strongly matched with speculative framework as voltage sag is reduced by 39% for the STATCOM designed at 25% of rated load [137], while in [138] an attempt to integrate power converter with digital controller equipped with optical interface is described. This local controller is also capable of sensing signal and sending them back to the power converter via a serial port.

Mohan et al. have worked out the issues related to practical implementation of STATCOM for voltage regulation through estimation of load conductance with feedback control. They have modeled STATCOM as an instantaneous reactive current source which controls DC bus voltage with tolerable value of charging and discharging current [139-143]. Singh et al. has come up with low THD, 48–pulse, voltage source converter. The uniqueness is achieved by 8 set of double star connected 2–level converter topology. The phase angle difference between two star connections can control reactive power [144].

DC capacitor voltage balancing with swapping switching pattern for fixed time period only has been proposed in [145-148]. Here two series H-bridge five level converter is simulated and tested on prototype. At some instant the swapping of switch may introduce redundant switching loss and phase shift in voltage. This limitation is overshoot by small signal model and dead band controller where controller is designed to work in capacitive, inductive and standby mode with changing frequency of 120 Hz [145 –148].

A wide area control technique for 12-bus STATCOM is proposed in [149] capable of controlling large power disturbance. At the time of operation, the controller generates two signals, one for AVR of generator and second for STATCOM. These will together look up the damping of generator rotor during interruption and restoration too whereas in [150] an automatic gain controller is designed for a gain $0< k\leq 1$. Stability enhancement with less variation in DC voltage is the key issue while designing a controller. In [151–154] an attempt to offer the solution for the above said problem via modified invasive weed optimization (MIWO) algorithm, back to back STATCOM or loop-shaping technique is presented. A repetitive controller is endowing with the conventional PI controller to trail or refuse the signal with moderate steady state error. For abrupt changes in load the output of the repetitive controller is constant which offers effectiveness in power factor improvement and DC voltage stabilization [155]. STATCOM controller based on RL trial and error is designed. The data is monitored online through six layer fuzzy neural network controller [156]. Floating of DC voltage is a challenging issue for today's FACTS Controllers. In [157-161] the focus is on how to improve the drift in voltage for diode clamped multi-level converter by space vector modulation techniques.

While managing voltage stability or reactive power compensation, inverter losses and harmonics in a STATCOM controller is also a question of research. A multilevel inverter with harmonic elimination method is one of the suggested solutions. But these can malpractice with the change in load condition. In [162-164] the authors had put on the concentration on current harmonics due to resonance, DC voltage ripple due to firing angle of each switch, consequence of coupling transformer. Also a square-wave controller with current feedback and phase lead compensation is proposed. Differential algebra [165] and a loop shaping method with use of hysteresis band are worked out where pre and post comparator shaped to provide a preferred open loop [166-167]. The best input signal is chosen by inspection. Here a complex perturbation is used to compute optimal control. A seven level cascaded multilevel converter is design as standalone system or H-bridge building blocks technique for 1.5 MVA. This model is capable of handling 4.5 to 30 MVA by adding more number of H-bridges [168-169].

In [171], a ±75 KVAR, 50 Hz, angle-controlled STATCOM was put up for minute operating rang of angle difference between converter voltage and system voltage. The value of angle is set (- 1.5°, 1.5°), hence state-space averaging principal provides more accurate results for reactive power compensation [170]. Similarly root locus method [171] and dynamic voltage controller configurations with negative sequence component and phase voltage magnitude is suggested for steady state and dynamic stability [172-173]. An adaptive control that counts the ambiguity in the parameter variation is designed and tested for power factor improvement. Author has also compared adaptive controller test results with conventional vector control test results which satisfy the performance of STATCOM in both the case [174-175]. A comparative analysis is conceded for voltage source converter (VSC) in shunt and series connection applications. Along with this radial basis function network based VSC is proposed and compared with PI controller based VSC for STATCOM, SSSC and UPFC [176-177].

High power multipulse, multipoint clamped and chain converter topologies are analyzed on basis of no. of devices, total harmonic distortion, component sizing, capability of voltage control and DC voltage drift. Later on, generalized N-converter module for H-bridge is presented which uses voltage and current harmonic component to stabilize the DC capacitor voltage. Experiments were executed for two and three modules where second harmonic of line voltage has been adopted for injected component [178-180]. H-bridge cascade multilevel STATCOM with low voltage and 11 kV power rating hardware has been jointly developed by University of Newcastle and ResTech Pty Ltd. Voltage balancing is done by arranging the DC capacitor voltage in incremental order. This will decide the sequence of phase leg to generate the output based on instantaneous real power flow [181-184]. A nonlinear controller based STATCOM on multi-machine power system is designed and simulated for three-phase to ground fault at two different nodes [185]. A special purpose STATCOM for Spallation Neutron Source power beam accelerator at Oak Ridge National Laboratory has been effectively implemented for full rated power [186]. Also for regulation of bus voltage a system stabilizer based on STATCOM is designed on computational optimization approach [187]. ±100 MVAR, 132 kV, 48–pulse, 2-level STATCOM is designed to locate at midpoint of line. The reason behind midpoint location is that it requires only four transformers which further reduces size and cost [188].

In [189] superconducting magnetic energy storage coil is integrated with STATCOM operation for three phase to ground fault. The operation of the proposed STATCOM is simulated for voltage control as well as frequency control model. A space vector based 3–zone, 5–zone and 7-zone, PWM technique has been carried out by Narayanet al. The proposed work is to reduce current ripple for inverter used in high-tension lines [190]. Few converters reported for Adjustable speed drives (ASDs), are also reviewed to analyze their probable application in STATCOM. A concept of 5-level inverter has been implemented by cascading one 2-level and one 3-level inverters [191]. Mahadevan et al. team has suggested phase-shifted dual source matrix converter topology [192]

V. CONCLUSION

By looking at the number of papers published in recent years, it is easy to conclude that a variety of FACTS controllers is available for evaluating performance in large power systems.

The research and development activity to obtain accuracy has adequately crossed the threshold. A trend of having more and more advanced FACTS controllers is evident. This paper provides a brief summary of different FACTS controller types and a focus on STATCOM topologies and their control strategies.

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