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A Review Paper on the Role of FACTS and Resilient AC Distribution Systems in the Development of an Intelligent Power System

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ABSTRACT

Sensors, wireless communication technology and improvement of computer storage capacity together with FACTS and resilient AC distribution systems are critical elements to move the current power grid towards an intelligent and resilient power system grid. Now a day the flow of power is not limited only from generation to distribution. The smart grid concept allows power supplying also from the load side and this is due to the high penetration of renewable energy by electricity customers and penetration of distributed generation by the utility company at the load center. The distributed generation allow a bidirectional power flow and provides the reliability, voltage profile and efficiency of the system to improve when an autonomous system control, monitoring, and operation is properly done. To develop an intelligent power system grid, modernizing the transmission and distribution network, adopting energy efficient loads, introducing renewable energy technology to the grid and other measures are a priority. In addition to this installing FACTS and RACDS technology with intelligent load management techniques are mandatory. In this paper a review of modern and old FACTS and RACDS technologies are assessed and presented.

Keywords: Flexible ac transmission; Power Electronics; Resilient AC Distribution; Intelligent-grid

I. INTRODUCTION

An intelligent Grid consist of the traditional grid components, phasor measurement unit, advanced metering infrastructure, smart meter, information communication technology, digital fault detection and emergency restoration technology with a fully automated computer based control system and new technologies functioning coherently together that allows for two-way communication between the service provider and its customers [1]. In this paper, an intelligent power system grid is referenced in the view of modernizing the transmission and distribution network component of the power system. Smart grid is necessary due to the various constraints of the old grid technologies and its challenges. The existing grid now a day faces so many problems, such as:

- Phase unbalance in the transmission and distribution lines because of fault, long line length, and lack of load management system.
- The three phases of the transmission line and distribution feeders are not equally loaded due to multiple power flow paths, a weak grid and lack of flexible control system.
- A loop flow through long unintended paths is considered as a loss because it is unplanned [2].
- The transmission and distribution line capacity limit and the need of wide transmission corridor in the old grid system have a significant economic and environmental impact.

- When the penetration of renewable energy sources, and the retirement of coal-based power plants are increasing, the existing power system grid faces Power system stability problems.
- Frequent power interruption problem.
- The current distribution system has only less grid resiliency of DG penetration.

Because of the constraints and limitation of the existing grid system listed above, the limitation of fuel resource in the future together with high customer satisfaction need, the current power system grid fashion must be changed something which is smart by enhancing power system parameters control, operation and monitoring capability. So, the future grid technology must be introduced to handle all the problems explained before which is actually called an Intelligent Grid, the grid of the future. In the transformation from old power system grid to an Intelligent Grid of the transmission and distribution network, the contribution of newly emerging FACTS and resilient distribution system technology is very huge. As per IEEE, FACTS is defined as "a power electronics-based system and other static equipment that provide control of one or more ac transmission system parameters to enhance controllability and increase power transfer capability" [4]. The transmission line parameters (voltage, impedance, power flow, current and phase angle) are dynamically varied and controlled using FACTS.

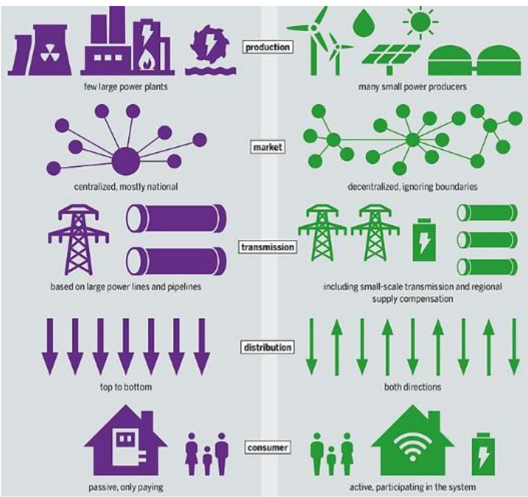


Figure 1.1 : Smart grid (right) versus conventional grid (left) [16]

Figure 1.1 demonstrates the basic differences of smart grid and the conventional grid. The smart grid contain FACTS controller in the transmission network, RACDS in the distribution system, DG power supply from load side and provides a bidirectional power flow and high level interaction of electricity customers in terms of system operation, energy management, and power generation.

In Figure 1.2, the FACTS devices are installed at the generation and transmission network whereas the RACDS are installed at the distribution system for control of power system parameters. The key roles of FACTS technology in the development of an intelligent power system grid is summerized as:

- improve penetration of renewable energy based distributed generation and energy storage system/;
- increase the power transfer capability or loadability of the transmission line;
- prevent loop flows in a ring system;
- provide fast voltage profile improvement and frequency control;
- balance power between the three phases of a single line and parallel transmission paths to prevent overloading/ underloading; and
- prevent the system from voltage collapse.

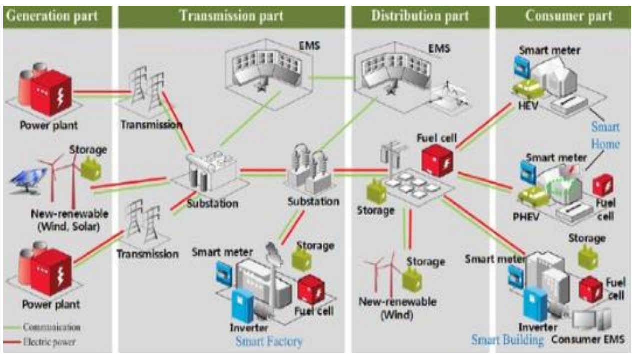
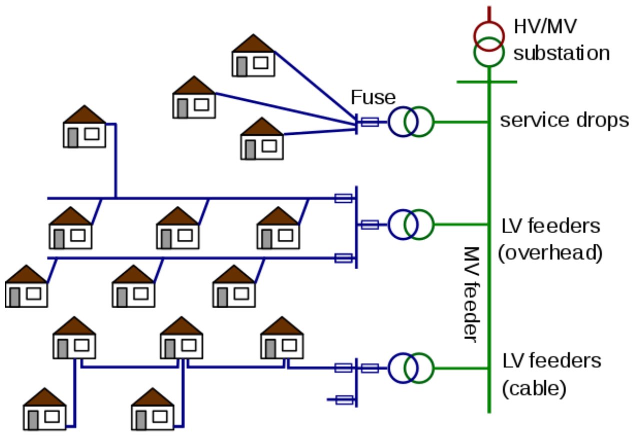


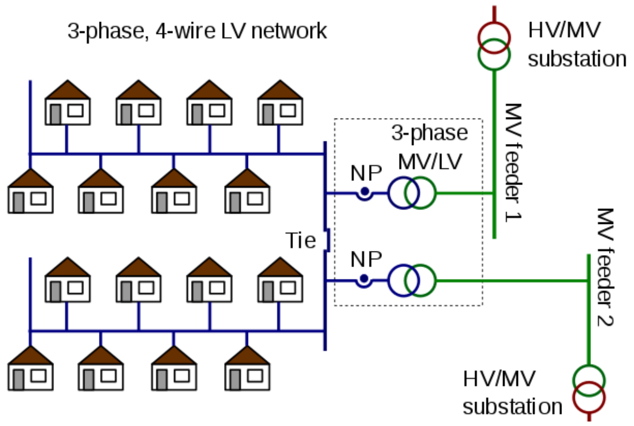
Figure 1.2. Power system network connectionin a smart grid. [17]

The distribution network supply power to consumers. So, this network should be reliable to dispatch power to the end users. There are two ways to make the distribution network as smart as possible.

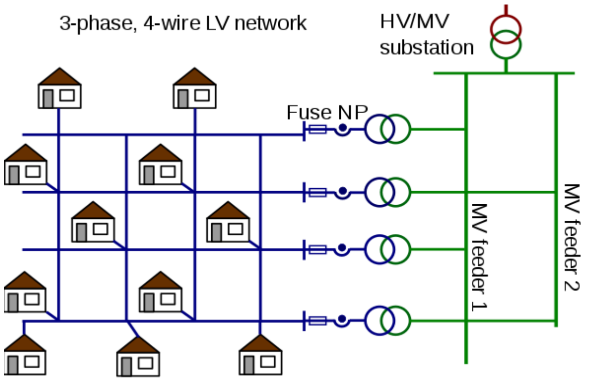
- Choosing the right distribution network topology providing maximum supply reliability and effctive controllability.
- Install RACDS to easily control and monitor the status of the distribution network operation.



a) Radial distribution network



b) Parallel distribution network



c) Ring distribution network

Figure 1.3 : Distribution feeder's layout. [18]

The ring and interconnected distribution network topology allows the customers connected to the utility with multiple interconnection path. This will boost the system reliability and reduces the outage rates. Like FACTS effert in transmission network, resilient ac distribution systems (RACDS) play a promising impact on modernization of distribution network. The RACDS concept is to systematically improve resilience of distributed systems by employing power electronics for DG integration, voltage/ var/frequency control, and efficient consumption of electricity by loads.

RACDS includes microgrids, FACTS-like control devices at distribution levels, and meshed distribution systems (looped feeders and local generations). Analogous to the FACTS illustration in Fig. 2.1, by means of power electronics and control, RACDS renders a resilient distribution network.

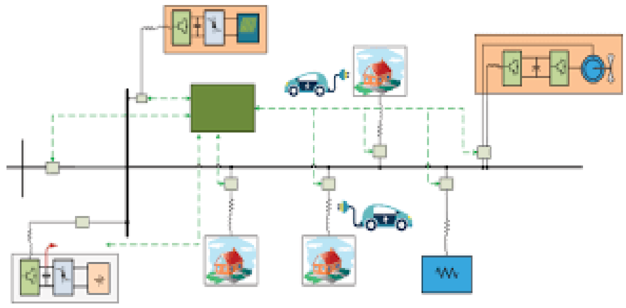


Figure 2.1 : Illustration of the RACDS in a Smart Grid.

The key roles of RACDS in the transformation of a current grid into smart grid are: a) facilitate interconnection between feeders to improve grid resiliency; b) enable and increase penetration of distributed generation sources; c) use battery energy storage and voltage restorers to provide fast, dynamic voltage and frequency support during emergency and voltage sags due to sudden variation in source/ load profile; d) mitigate power quality issues to ensure reliable power supply to critical loads; and e) facilitate the increasing penetration of electric public transportation (electric cars, underground rails) in the distribution network.

1. FACTS and RACDS Configurations in Smart grid

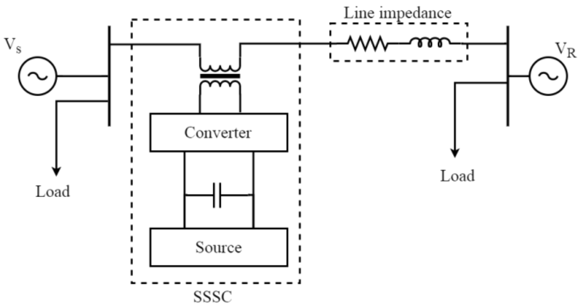
The transmission line has predominately a distributed inductive and capacitive parameter. A long lossless three phase transmission line power flow between two terminal points (generation to load) can be expressed as:

$$P_{ij} = \frac{V_i V_j}{X} \sin(\delta_i - \delta_j) \quad (1)$$

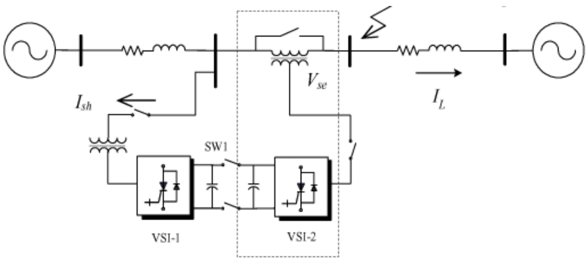
$$Q_{ij} = \frac{V_i}{X} (V_i - V_j \cos(\delta_i - \delta_j)) \quad (2)$$

Both (1) and (2) share the same parameters: voltage magnitudes, phase angle difference, and impedance. Using FACTS devices, one or more of these parameters are dynamically controlled. Two key locations for FACTS can be observed: one at the point of coupling (PCC) between the sources/ loads and their corresponding area and the other along the transmission line.

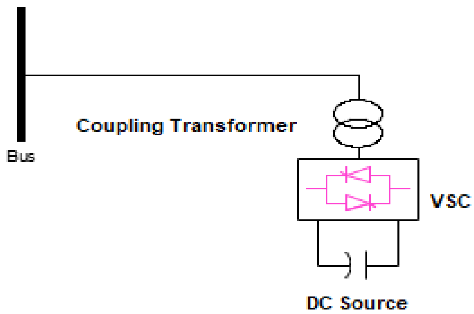
The most common FACTS used for Smart Grid application are HVDC Link, STATCOM, SSSC, UPFC, IPFC and GUPFC. The STATCOM is self-commutated power electronics-based shunt compensator used for power flow control to improve the capacity of the transmission line [5, 6].



a) Serial FACTS configuration [19].



b) Serial-Shunt FACTS configuration [19].



c) Shunt FACTS configuration

Figure 2.2 : Different configurations of FACTS for the smart- grid development

A UPFC is a series-shunt device consists of two back-to-back linked self-commutating converters operated from a common DC link and connected to the AC system through series and shunt coupling transformers. Within its operating limits, a UPFC can independently control three power system parameters [7–9]. Unlike the STATCOM, SSSC, or UPFC, which can control the power flow in a single transmission line only, the IPFC or GUPFC can address the problem of compensating a number of transmission lines simultaneously at a given substation. The IPFC is a series compensating device employs a number of DC-to-AC converters linked together at their DC terminals, each providing series compensation for a different line. The converters are connected to the AC system through their series coupling transformers [10]. The GUPFC is a series-shunt compensating device used to control five power system parameters at a specified substation. In AC transmission, the lengths of transmission links are limited by stability considerations. No such limitation exists for DC transmission. In this context, a high-voltage DC (HVDC) link (back-to-back) can be used to interconnect two AC substations that are separated by very long distances. A HVDC link can be used to improve system reliability by interconnecting two asynchronous AC systems [11].

In Fig. 2.3, the location of RACDS installation is clearly indicated. Such type of distribution system transforms us from the current grid to the smart grid concept in the distribution network. The penetration of RES can be increased and supports the grid when it faces scarcity of supply in the top-down power flow approach. RACDS is classified based on their functions and roles. It is functioned as Micro-Grids, Controllable Distribution Network, and Meshed Distribution Systems for smart Grid development.

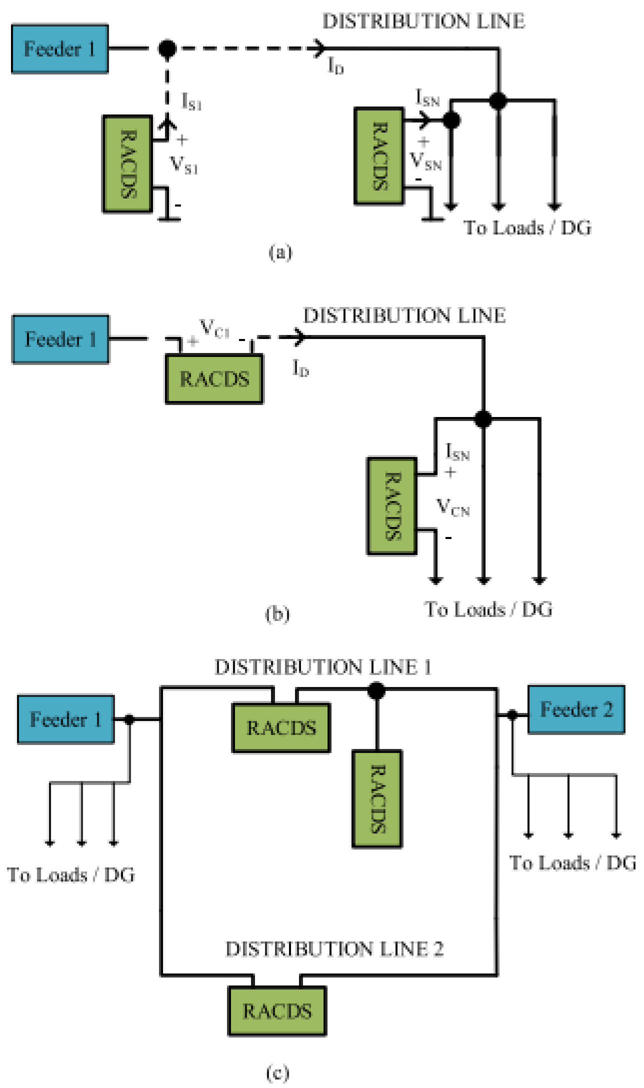


Figure 2.3 : Different topology of RACDS in the smart-grid: (a) shunt, (b) series and shunt, (c) series and series-shunt [20].

The microgrid is also known as the local grid, which contain local generation and local load with emergency energy storage system for a better resilient distribution network. The power electronics device, RACDS is used as an interfacing medium between the energy storage system and the DG units with the microgrid and its integration with the national grid. Higher wind and solar power penetration into the national grid through the distribution system affects the voltage profiles of the grid. So, the series, series-shunt, series and series-shunt configuration of RACDS produces a controllable distribution network. The controllable distribution network maintains the voltage profile, phase angle and power flow at each feeder within the standard value during the existence of fault in the distribution network and high penetration of RES available in the system.

2. Evolution of FACTS and RACDS

There are two basic FACTS and RACDS technology used for series, shunt and series-shunt compensation: the traditional FACTS and RACDS technology and the modern FACTS and RACDS technology. The traditional FACTS and RACDS technologies include, thyristor-controlled series compensator (TCSC) and thyristor switched series compensator (TSSC) both used for series compensation; thyristor-controlled reactor (TCR) and thyristor switched capacitor (TSC) used for shunt compensation. Those traditional devices have the following common features:

- Large in size and heavy in weight
- Slow response for dynamic parameter changes made up of thyristor switch and passive devices such as inductor, capacitor and zigzag transformer.

The modern FACTS and RACDS technologies include, static synchronous compensator (STATCOM) used for shunt compensation; unified power flow controller (UPFC) and generalized power flow controller (GUPFC) used for series-shunt compensation; static synchronous series compensator (SSSC) and interline power flow controller (IPFC) used for series compensation. Those RACDS and FACTS devices have the following common features:

- Compacted in size and light in weight.
- Much faster dynamic response for a disturbance.
- Made up of self-commutated IGBT and IGCT switch and a dc link at the output terminal.

3. Facts and RACDS Installations

The CMI based traditional and modern FACTS and RACDS are installed in different countries for reliability and power quality improvement; for integration of renewable energy resource to the main grid; for power system stability and transmission capacity improvement of smart grid development.

The SVC and TCSC from the traditional FACTS and battery energy storage systems (BESS), dynamic voltage restorer (DVR) and the STATCOM from modern FACTS and RACDS are some of the lists discussed in this paper.

3.1. Traditional FACTS Installations

SVC is the most common FACTS installed both in industrial, railway traction loads, and utility application for power quality improvement, power factor correction, stability maintenance and power flow control with an estimated world total capacity exceeding 90Gvar [12]. Some of the installations of SVCs in industries and railways include: 34.5 kV, 90 MVAr SVC at Cascade Steel Rolling Mills, USA [13]; and 132 kV, -267/345 MVAr SVC at Power link Substation, Queensland, Australia [14].

The series connected TCSCs have been mostly used in transmission systems (230-500 kV) for: 1) increasing the power transfer capability and transient stability; 2) damping power oscillation between interconnected areas; and 3) providing power flow control. As of 2009, there are 13 installations of TCSCs worldwide 2 GVAr [15].

3.2. Modern FACTS Installations

The CMI based shunt compensator or "STATCOM" has undergone commercialization by manufacturers worldwide. There are an estimated 26 major STATCOM installations (excluding small installations with less than 25 MVAr) around the world. The total installation capacity of STATCOMs is over 20 GVAr.

The battery energy storage systems (BESS) integrated with STATCOM are also being installed in transmission systems. The major applications of BESS installations are for: 1) cost saving by load leveling; 2) providing storage for intermittent renewable energy sources; 3) maintaining stability by providing voltage and frequency support; and 4) reducing or eliminating outages.

3.3. RACDS Installations

Different RACDS devices like Dynamic Voltage Restorer (DVR) and BESS have been installed as power quality devices at both customer (120 to 480-V) levels and distribution voltage (6 to 69-kV) levels. The DVR is a series connected RACDS device which provides protection to sensitive loads against voltage sags. The DVR has been installed to protect critical loads in the food processing, semiconductor, paper, textile and utility sectors.

4. Future Perspectives

The present and traditional limitation of FACTS and RACDS devices are modified to become the future smart devices. The major target of the future FACTS and RACDS devices are reliability, low cost, fast dynamic response, light weight and compacted and independent operation for power flow control. The future FACTS devices are discussed below.

4.1. Transformer-Less UPFC

The present UPFC technology is a back-to-back integration of series and shunt compensator for independent power flow control. This type of UPFC configuration raises the cost and size of the compensator due to the availability of specialized coupling transformer. A 2-MVA prototype has recently been tested for a 13.8-kV distribution level application. The proposed configuration can also be extended to transmission applications. It can be seen that no interfacing transformers are needed.

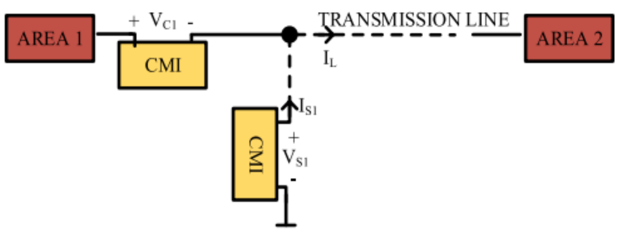


Figure 5.1 : Basic configuration of Transformer-less UPFC [20].

When used for power flow control, the series configured CMI dynamically injects a series voltage to the transmission line. The shunt configured CMI is then used to inject/absorb the change in reactive power in the transmission network due to the power flow through the line (P). This enables independent control of powers through the line. Both CMIs exchange only reactive power with the transmission/ distribution network. So, no active energy storage is necessary. The proposed transformer-less UPFC is expected to be (1/4)th in size and cost.

4.2. Dynamic Phase Angle Regulator

The low cost and compacted dynamic phase angle regulator has a faster dynamic response for the phase angle change in the transmission network than the traditional phase shift transformer to restore the phase angle error. It uses a "cross-coupled" winding structure and duty cycle control for the ac switches to achieve dynamic phase angle control.

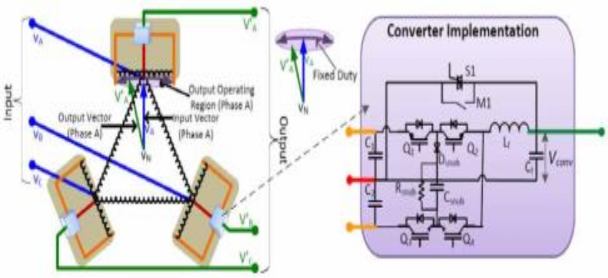


Figure 5.2 : Structure of Compact-phase angle regulator. [20]

4.3. Distributed FACTS

The cost requirement for transmission corridor, the insulation criteria and transient event like lightening affects the design, construction and installation of transmission system. So, to mitigate such problems compact, controllable floating reactors are distributed along the transmission line. The reactors can either be switched into the line or bypassed by controlling switch S_m.

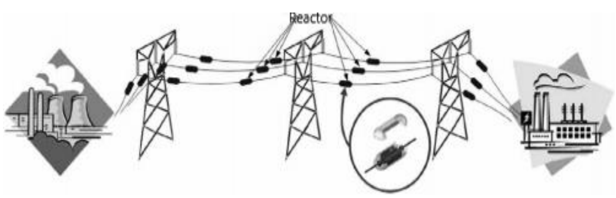


Figure 5.3 : Distributed FACTS illustrated [20].

4.4. High Power Density CMIs

Due to the low voltage rating (1.2kV-1.7kV) of an IGBT CMI and MMC's, a high density (large number of) H-bridge module is required to directly connect the converters with the grid. This connection helps us to achieve a low level of %THD.

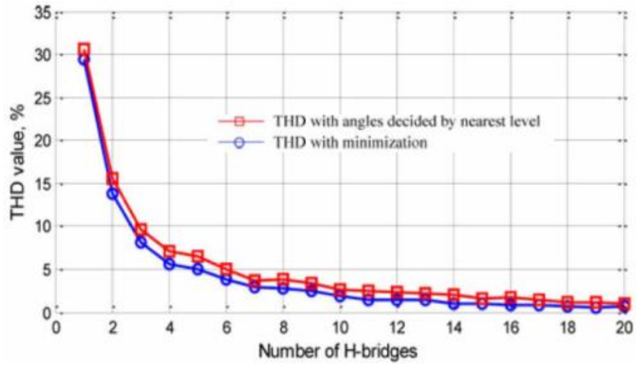


Figure 5.4 : THD (%) versus number of modules

The number of modules may still be within 20 to 30 for distribution level RACDS applications even with 1.2 and 1.7kV IGBTs. However, as it can be seen from the installations in Section 4, a direct connection of STATCOMs to transmission or sub-transmission level voltages would become impossible. Hypothetically, should such a connection be made using existing IGBT based technology, it could lead to hundreds of modules. This leads to an extremely complex system and reliability issues that are associated with such a system. Hence, a step-down transformer is still required for interfacing the STATCOMs to the transmission level or sub-transmission level.

II. CONCLUSION

In this paper a short and brief description of FACTS and RACDS device used for Smart Grid development is presented. The history, configuration and installation and gaps of RACDS and FACTS in the traditional and modern grid are also discussed. The future FACTS and RACDS technology including DVR, transformer less UPFC, distributed FACTS, dynamic phase angle regulator and high power density CMI's are also included to show the future trends of FACTS and RACDS.

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