INVITED PAPER

Flexible AC Transmission Systems (FACTS) and Resilient AC Distribution Systems (RACDS) in Smart Grid

This paper provides comprehensive review of modern FACTS technology and its applications in smart grid and AC distribution systems.

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ABSTRACT | Transmission and distribution (T&D) networks are a critical part of the power grid. As moving towards a smart-grid, it is essential to modernize the T&D networks and make it "Smart-grid ready". The concept of flexible ac transmission systems (FACTS) has been well-known for three decades. Rapid advancements in power electronics technology in the past decades have led to a new generation of FACTS devices. The Modern FACTS technology helps the transition of transmission networks to "smart". With increasing penetration of distributed generation, the distribution network is seeing unprecedented variation in terms of its fundamental operation and control, from renewable energy integration to microgrid, from active control of power quality, volt/var and frequency to self-healing and islanding operation. As a key part of smart-grid at the distribution level, we summarize the current efforts as a concept of resilient ac distribution systems (RACDS). The concepts of both FACTS and RACDS for a smart grid are introduced in this paper. Different configurations, key benefits, operating principles and world-wide installations of FACTS and RACDS devices are presented in detail. The ongoing and future direction of R&D leading to newer generations of FACTS and RACDS are also discussed.

KEYWORDS | Flexible ac transmission; power electronics; resilient ac distribution; smart-grid

I. INTRODUCTION

The term "smart-grid" is often used to describe the grid of the future or the grid we are transitioning to. According to the IEEE smart grid initiative [1], "the smart grid is a revolutionary undertaking—entailing new communications-and-control capabilities, energy sources, generation models and adherence to cross-jurisdictional regulatory structures".

Since the introduction of the term "Smart-grid", it has evolved to include modernization efforts in generation, transmission and distribution of electric power in the power grid [2]. Throughout this paper, reference to a smart grid is made from the point of view of modernizing power transmission and distribution (T&D). In this regard, to ensure a smooth transition to a smart grid, it is essential to understand the limitations of the traditional transmission and distribution networks. Some of the existing limitations of the transmission and distribution networks are discussed in the following paragraphs.

Fig. 1 illustrates the transmission network of the contiguous United States. As it can be seen, the network is

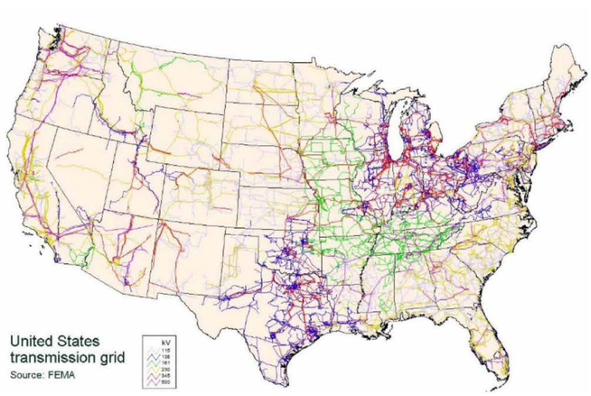

Fig. 1. ***Meshed, interconnected nature of transmission network in contiguous United States.***

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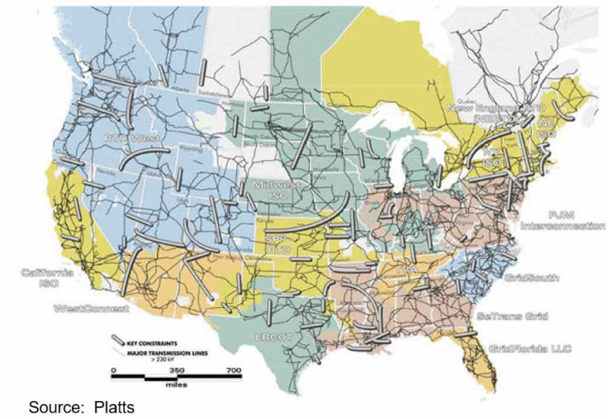


Fig. 2. ***Map illustrating transmission line congestion in North American power grid.***

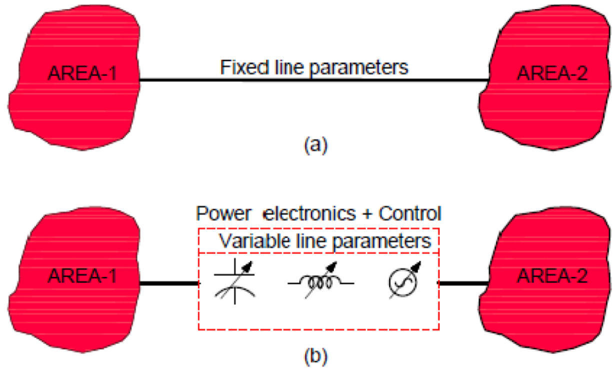


Fig. 4. ***Role of power electronics in FACTS: (a) transmission network without FACTS and (b) transmission network with FACTS.***

meshed, complex and seemingly hard to control. As of 2010, the U.S. power grid(s) consisted of an estimated 200000 miles of high-voltage transmission lines [3]. Due to their meshed structure, multiple paths for power flow exist between sending and receiving areas. Due to lack of control, some lines are overloaded while some are underloaded. This causes power flow paths to be congested or uncongested [4]. Fig. 2 illustrates some of the key congested paths in the North American Grid.

Yet another problem arises when power flows through long unintended paths. This is termed as loop flow [5]. Fig. 3 illustrates a real case of a loop flow encountered in the Michigan Upper Peninsula [6]. Power dispatched from generating stations to the loads in Ohio area finds an unintended path through the Upper Peninsula, causing an overloading of that part of the transmission network.

Majority of the states in the U.S. import power from the neighboring states to meet their local demand [7]. Additionally, majority of the wind power generated is in the central part of the country [8]. But, the main load centers are often located near the coasts. These factors further stress the transmission network and result in bottlenecks, which limit the penetration of renewable energy sources (RES).

Yet another limitation is the increasingly high cost to acquire right-of-way for constructing new lines. Also, as per the original design of the transmission system, transmission lines are to be loaded well below their maximum limits. Traditional coal-based generators were designed with a large amount of inertia to enhance the stability of the grid. However, with ever-increasing penetration of RES, and increasing retirement of coal-based power plants, such generous stability margins are difficult to be maintained.

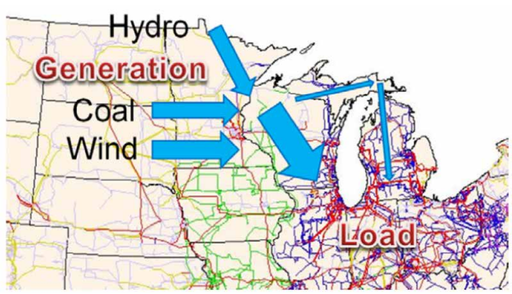


Fig. 3. ***A case of loop flow in Michigan Upper Peninsula [6].***

To transition into a smart grid, these are various critical issues in transmission systems that need to be solved. The flexible ac transmission system (FACTS) is considered a key aspect to facilitate this transition. In fact, its potential has been known for years. It has been listed as one of the top ten technological breakthroughs of the past decade [9]. 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" [10]. To illustrate the role of power electronics in FACTS, consider the illustration in Fig. 4. Fig. 4(a) shows a conventional transmission network transferring power between areas 1 and 2.

The various electrical parameters of the transmission line such as impedance, phase angle and voltage magnitude cannot be varied in real time. Fig. 4(b) illustrates a FACTS-based transmission network. By means of power electronics and control, the aforementioned line parameters can now be changed and voltage phases/magnitudes controlled in real time leading to several new degrees of freedom. The operation and benefits of FACTS will become clearer in the subsequent sections of this paper.

The following are some of the key roles of FACTS in a smart grid: a) increase penetration of renewable energy; b) improve power transfer capability; c) prevent loop flows; d) achieve fast dynamic voltage regulation and frequency control; e) balance power between parallel transmission paths to prevent overloading/underloading; and f) improve stability margins of existing grid.

While the transmission network is responsible for transporting bulk power from generating stations to the distribution substations, the distribution network is responsible for delivering power to consumers. As of 2010, there was an estimated 5 million miles of distribution lines in the U.S. power

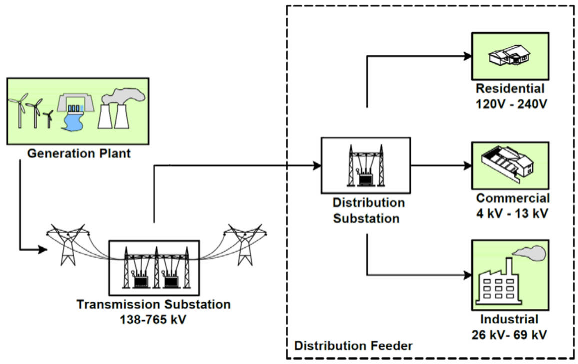


Fig. 5. ***General layout of the power distribution network.***

grid [3]. With such an extensive network, the distribution network forms an extremely important part of the grid. The general layout of the distribution system is illustrated in Fig. 5. Unlike the traditional transmission network, the traditional distribution network for the most part uses a radial, ring or interconnected architecture as shown in Fig. 6 [11]. The limitations of existing transmission networks were discussed so far. Some of the limitations of the existing distribution network are explained in the following paragraphs.

In the U.S., 90% of the power outages occur in distribution systems [16]. In a period from 2003 to 2012, 80% of the overall power outages have been due to severe weather [14]. In a radial architecture, as shown in Fig. 6(a), an entire feeder is often cutoff in the event of weather related faults/natural disasters [12]. This leads to loss of power to all the consumers receiving power from the same feeder. In a case of multiple parallel feeders from a single source, voltage sags are observed by loads connected in a feeder due to faults in neighboring

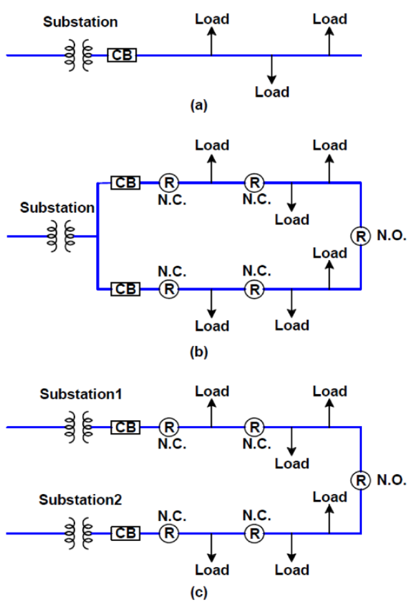


Fig. 6. ***Different types of distribution network architecture: (a) radial, (b) ring, and (c) interconnected.***

feeders [13]. In the so-called ring and interconnected structure Fig. 5(b) and (c), parallel or meshed operation is prohibited because a slight voltage difference could result in huge circulating current. The normally open recloser at the end of the feeders is for maintenance. Although, each voltage sag event typically lasts for less than 167 ms, repeated voltage sags have led to disruption to industries receiving power from the distribution system [13]. Therefore, improving grid resiliency is a critical aspect of the U.S. energy infrastructure.

As per the presidential policy directive in [15], resiliency is defined as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions…". Since distributed generation (DG) is located closest to the consumer, improving penetration of distributed energy resources (DER) by incorporating numerous micro-grids into the grid is widely expected to improve grid-resiliency [17], [18].

As per the Department of Energy [19], "A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid". A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode".

However, the present distribution network is not designed to accommodate high levels of DG penetration. Unlike Europe, the standards in the North American grid require quick disconnection of the DG sources from the distribution network in the event of a fault [20]. This severely limits the ability of the DGs to offer grid resiliency. Additionally, with increasing penetration of solar PV and other renewable DG sources, it is essential to enable bidirectional power flow through the distribution network. Interconnection between feeders to effectively route power and make efficient use of energy storage can go a long way in improving grid resiliency. The intermittent nature of these sources also causes voltage fluctuations at the distribution level. Conventional voltage regulators that use mechanical switches or on-load tap changers cannot respond fast enough to regulate voltage [23]. Increasing levels of industrial loads and electric transportation leads to further stress on the distribution network. Similar to FACTS, we propose and summarize the ongoing modernization efforts in distribution systems as resilient ac distribution systems (RACDS). 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, which includes microgrids, the use of RACDS devices (FACTS-like control devices at distribution levels), and meshed distribution systems (looped feeders and local generations). Analogous to the FACTS illustration in Fig. 4, by means of power electronics and control, RACDS renders a resilient distribution network.

Some key roles of RACDS in a smart grid are to: 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 in case of emergency/blackouts 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, etc.) in the distribution network.

The main aim of this paper is to emphasize the importance of FACTS and RACDS in the smart grid. The operating principle, various configurations, evolution of the modern FACTS and RACDS technology, examples of worldwide installations and future perspectives in this area will be described in the following sections.

II. FACTS CONFIGURATIONS IN THE SMART GRID

Fig. 7 illustrates an "ideal" interconnected transmission network within a smart grid. The possible locations where installation of FACTS could be beneficial for the grid are marked. As the name suggests, FACTS is a flexible ac transmission system, whereas individual pieces of equipment contributing to the overall FACTS system are referred to as FACTS devices.

To fully appreciate the benefits of FACTS, the different physical parameters of the transmission network have to be introduced. Transmission lines and underground cables are essentially a distributed network of inductors and capacitors. However, from an operation point of view, an overhead line can be considered predominantly inductive. An underground cable is predominantly capacitive. Real power, *P* flowing through a transmission line interconnecting any two areas in a synchronous grid is determined by the following expression:

$$\mathbf{P} = \frac{\mathbf{V_{SO}} \mathbf{V_R}}{\mathbf{X}} \mathbf{Sin}\delta \tag{1}$$

Here, $\mathbf{V_{SO}}$ and $\mathbf{V_R}$ represent the voltage magnitudes at the sending and receiving ends, respectively. **X** represents the equivalent impedance of the line and δ the phase angle difference between the sending and receiving ends. The reactive power, **Q** is determined by the following expression:

$$\mathbf{Q} = \frac{\mathbf{V_R}}{\mathbf{X}}(\mathbf{V_R} - \mathbf{V_{SO}}\cos\delta) \tag{2}$$

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. In the smart grid illustration shown in Fig. 7, each area may receive power from both conventional sources and renewable energy sources. Bulk industrial loads and the distribution network are some of the typical loads.

In Fig. 7, two key locations for FACTS can be observed: one at the interface/point of coupling (PCC) between the sources/loads and their corresponding area and the other along the transmission line. For each of these locations, a few different configurations of FACTS are possible, which are illustrated in Fig. 8.

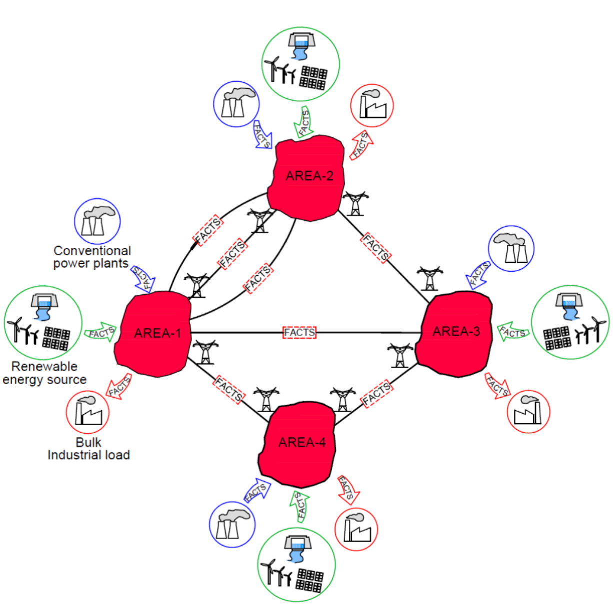


Fig. 7. ***Illustration of the transmission network in a smart grid.***

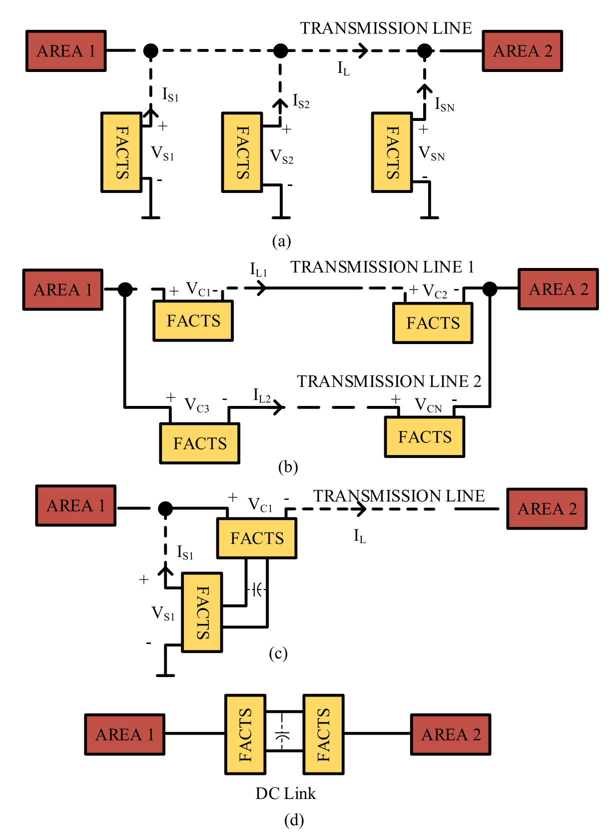


Fig. 8. ***Different configurations of FACTS for the smart-grid: (a) shunt, (b) series, (c) series-shunt, and (d) back-to-back.***

A. Shunt Compensation

The role of FACTS at the interface between RES and the transmission network cannot be overstated. FACTS plays a key role in enabling renewable energy interconnection to the transmission network. It also enables RES to meet grid code requirements and helps increase the penetration. The configuration illustrated in Fig. 8(a) is widely used for this purpose. This type of configuration is called "shunt compensation", where the FACTS device is controlled to dynamically inject/absorb reactive power to ensure voltage stability at PCC. In shunt compensation, the FACTS device essentially behaves as reactive power generator, injecting reactive power (+Vars) or absorbing reactive power (−Vars). Consider the grid integration of offshore wind power, in which the interconnection is almost always through underwater cables. As described before, the capacitive nature of these cables leads to a charging current being drawn (or injection of reactive power into the grid) [21], [22]. The charging current will be drawn from the transmission network leading to a low power factor. In larger wind farms, this could lead to voltage instability. During temporary faults on the transmission system, the shunt configured FACTS device can be controlled to regulate voltage at the interface by regulating the flow of reactive power. This enables large solar and wind farms to achieve "fault ride through" capability. Requirement to ensure high power factor, voltage stability and fault ride through capability for interconnecting wind power is now a grid code requirement in several countries [26].

By integrating battery energy storage with the shunt configured FACTS device, the device is no longer just a reactive power generator. Active power can be injected/absorbed to/from the grid. The FACTS device can then be used to provide backup power or frequency control for the transmission network [29]. Improving voltage stability at the PCC is also beneficial for the conventional power plants and loads. By providing voltage support, it aids in recovery during faults and helps avoid cascaded blackouts. By controlling the FACTS device to inject reactive power, the power transfer capability and the dynamic stability margin of the network are also significantly improved [27], [28]. Some industrial loads such as arc furnaces draw huge surge currents in a short instant of time. This could lead to low power factor, instability and low power quality for other loads connected to the network. By controlling the shunt configured FACTS device to compensate the surge currents, the stability and power quality would not be affected.

Fig. 8(a) illustrates the shunt configured FACTS device located along the transmission line. By controlling the device to inject reactive power along the transmission line (preferably at the middle of each section), the power flow capability of the line can be increased significantly [28]. This is instrumental in relieving congestion, enhancing dynamic stability and better utilization of the transmission network.

B. Series Compensation

When a FACTS device is placed in series with the transmission line at one or more locations, it is termed as series compensation. This configuration is shown in Fig. 8(b). The series configured FACTS device can be used to dynamically vary three different parameters of the transmission system: phase angle, voltage magnitude, and impedance. By increasing the phase angle difference or by reducing the impedance, more power can be transmitted through the line. By reducing the phase angle difference or by increasing the impedance, power flow through the line can be reduced. The dynamic power flow control is based on (1).

The ability to dynamically control power flow through the line enables efficient power routing and is instrumental in eliminating problems such as congestion and loop flows. Additionally, by adjusting the impedance in parallel paths (as shown in Fig. 7), power flow through individual paths can be balanced or regulated. Overloading/underloading of lines can be prevented. Congestion and loop flow can be reduced. The detailed operating principle of series compensation is described in [30]. The great advantage of series compensation is that only a fractionally rated device is needed to control the full system power.

While the series compensation can be used for power flow control, any change in power flow through the line leads to a change in reactive power requirement from the end generators. The end generators must be capable of supplying/absorbing this additional reactive power to enable power flow control. When used for impedance control, the series configured FACTS device needs only reactive power exchange with the transmission line. However, when used for phase shifting, the device may need to exchange active power. Additional energy storage devices or alternate source of active power source may be needed in such cases.

C. Shunt-Series Configuration

This configuration uses a combination of shunt and series configured FACTS devices. The shunt-series configuration is illustrated in Fig. 8(c). By coordinating the control between the shunt and series FACTS devices, all the transmission line parameters, viz. phase angle, impedance and voltage, can be varied either individually or simultaneously. This makes it the most versatile power flow control device. Much like the operation of the series configuration discussed before, the phase angle/voltage/impedance variation is introduced here by the series configured device. The role of the shunt configured device is two-fold: it supplies the necessary reactive power that would otherwise be drawn from the transmission network for power flow control, and it provides active power required by the series configured device to perform voltage and phase angle control. This leads to the capability to perform independent power flow control of real and reactive powers. The shunt configured device can also be controlled to regulate the voltage at area 1. This is suitable for installation in any kind of transmission network as it does not rely on the network to provide the additional Q to achieve power flow control.

The detailed operating principle is described in [31] and [32]. The capabilities of the "shunt-series" configurations are essentially a superset of the capabilities of all other configurations described so far.

D. Back-to-Back Configuration

The back-to-back configuration consists of two converters connected as shown in Fig. 8(d). This configuration has its roots in the conventional high voltage dc (HVDC) transmission system. Nonetheless, it has the ability to achieve power flow control and is included in the FACTS category. By controlling the voltage magnitude and phase angle on the ac terminals of either converter, the power flow from the sending end to receiving end can be controlled. Additionally, due to the presence of the intermediate dc link, the power flow control is independent of the frequency and phase angle difference of the ac voltage on either ends. Each converter in the back-to-back configuration is also capable of regulating the voltage at the corresponding end by injecting/absorbing reactive power. This leads to a similar functionality as the shunt configuration.

The back-to-back configuration is the perfect candidate for controlling power flow in an interconnection of two asynchronous grids. While it is also capable of achieving a similar functionality for synchronous grids, it needs two fully rated converters, thus not an optimum solution in terms of the efficiency, overall size and cost.

III. RACDS CONFIGURATIONS IN THE SMART GRID

Fig. 9 illustrates an "ideal" interconnected distribution network within a smart grid. The potential locations for installation of RACDS are marked. Compared to the traditional distribution network, there are significant differences in the corresponding network of the smart-grid. Distributed generation (DG) sources enter the system from the low voltage side. This is an entirely opposite approach in comparison to the traditional "top-down" centralized approach. Also, DG sources are all dispersed and their power levels also vary widely depending on local consumers. Depending on targeted functionality by RACDS, different levels of resiliency can be imparted to the power grid. Hence, RACDS is classified based on their functions and roles.

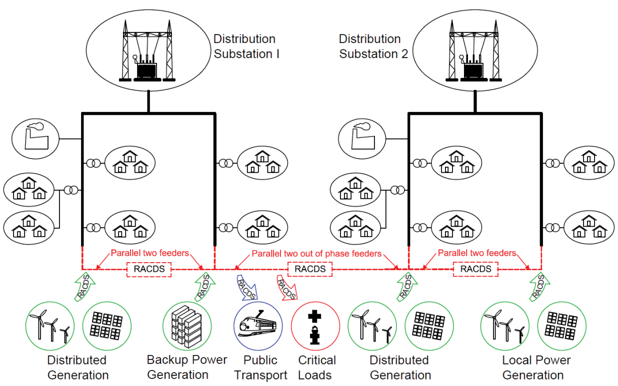


Fig. 9. ***Illustration of the distribution network in a smart grid.***

A. RACDS: Micro-Grids

A micro-grid is essentially a RACDS. Local generation, load management and energy storage forming a micro-grid to enhance the resiliency and controllability. Unlike the centralized generation mechanism, the local generation requires power electronics to interface with the distribution system. Residential solar PV panels are commonly connected to the system via micro-inverters. Voltage generated by "small-wind" turbines requires a power converter/inverter system to convert the variable output voltage and frequency to desired distribution level voltage. Local battery energy storage systems also require an inverter to serve as an interface to the micro-grid. Micro-grids improve resiliency and controllability, and the interface power electronics are classified as controllable RACDS devices.

B. RACDS: Controllable Distribution Network

To further improve resiliency of the power grid, local generation and storage from individual micro-grids must be transferred upstream through distribution network [17], [18]. In order to achieve this, individual micro-grids need to be interfaced to the distribution network. Increasing penetration of DGs leads to a changing voltage profile on the distribution feeders [33]. Additionally, due to the intermittent nature of renewable energy sources, dynamic fluctuation in the voltage profile is also common. Therefore, there is a need to regulate voltages along individual feeders. This leads to a scenario similar to that of FACTS, the parameters of a network are altered to achieve a controllable network. Devices capable of providing FACTS-like control in a distribution network also fall under the RACDS configuration.

Fig. 10(a)–(c) illustrates different configurations of RACDS devices in the distribution network.

Fig. 10(a) illustrates shunt compensation using a RACDS device. The RACDS device close to Feeder-1 can be controlled to regulate the voltage at the feeder and ensure that the voltage-variation is within required limits. As in the case of shunt compensated FACTS, a RACDS device injects/absorbs reactive power to regulate the voltage along the distribution feeder. In a case of DG interconnection, a shunt connected RACDS device must be capable of fast dynamic response. Several shunt configured RACDS devices may be placed along the distribution feeder to regulate voltage along the entire path. Many RACDS functions could also be implemented by DG interface inverters such as in PV and wind power.

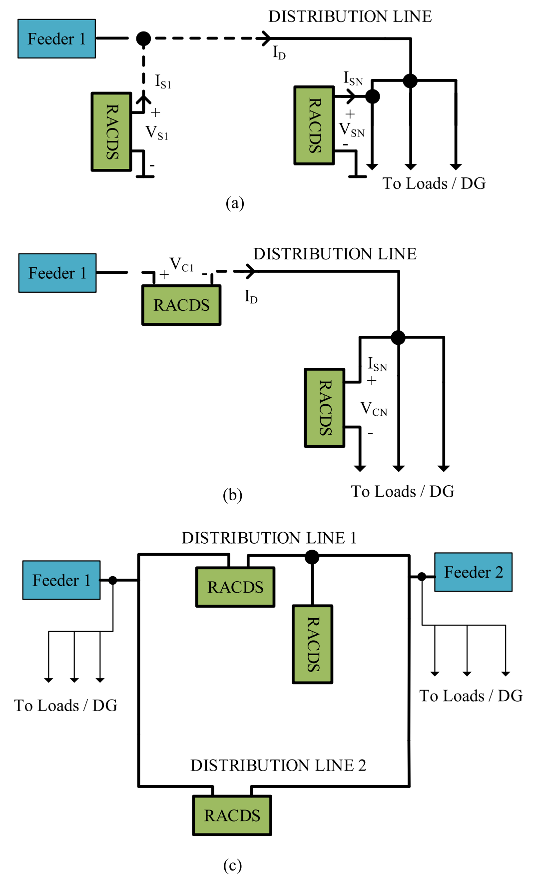


Fig. 10. ***Different configurations of RACDS in the smart-grid: (a) shunt, (b) series and shunt, (c) series and series-shunt.***

Some bulk industrial loads connected to the distribution feeder may cause large unbalance in individual phase voltages. This can potentially lead to loss in power quality and can affect other loads in the system. In such cases, a RACDS device can be used to provide variable controllable impedance/voltage in each phase. This leads to automatic load balancing and improves the network resiliency. Some loads may also draw a large amount of pulse current. In such cases, the RACDS device should be controlled to deliver this current transient and ensure a quality power supply for the network.

A series RACDS device is illustrated in Fig. 10(b). In ring and interconnected feeders, an adjacent feeder's fault can cause voltage sag by 50% [13]. In these circumstances, the series RACDS device can be controlled to dynamically compensate the voltage sag by injecting voltage in-phase with the feeder voltage. However, in order to generate an in-phase voltage, the RACDS device needs either energy storage or a path to receive real power from the feeder.

Today's distribution networks do not support bidirectional power flow. However, with increasing penetration of DG sources, the distribution network must be capable of bidirectional power flow. By controlling the phase angle of the series configured RACDS device, power flow from DGs back to the grid can be established. The usage of series configured RACDS devices could essentially introduce power flow control in the distribution network.

C. RACDS: Meshed Distribution Systems

The next level of grid resiliency is achieved by moving towards a meshed and parallel distribution network. A key requirement for meshed networks is interconnection. Much like interconnected areas in a transmission network, a meshed distribution network is based on interconnected feeders. In existing distribution networks (Fig. 6), the so-called interconnection achieved by means of a normally open switch/recloser is not a "real" interconnection, thus cannot be used for sharing local generation, storage and load resources among feeders. The switch is only closed during a power outage from one feeder or in order to isolate faults. Additionally, a small voltage difference in phase and/or magnitude between feeders results in huge circulating current, thus forbidding interconnection or parallel operation of active feeders. A series or series-shunt configuration of RACDS device [illustrated in Fig. 10(c)] should be used to achieve interconnection or paralleling. In such cases, the series configured RACDS device is controlled to dynamically compensate the voltage difference and enable the interconnection and power exchange/sharing. If there are multiple parallel paths for interconnection, the series RACDS device can be used to dynamically vary the impedance on each path to ensure a desired sharing of power among these parallel paths. By increasing the number of interconnected feeders in the distribution network, a meshed distribution network is possible in the near future.

IV. EVOLUTION OF FACTS AND RACDS

The concept of FACTS was first introduced in the 1980s [24]. Traditional FACTS devices based on thyristors and passives were large, heavy and slow in dynamic response. Since then, rapid advancements in power electronics technology have paved the way to a modern generation of FACTS and RACDS devices. These modern devices are based on IGBTs, with much faster dynamic response and smaller size and weight. They are much better suited for the smart-grid. Although almost all new installations are based on modern FACTS and RACDS, for a foreseeable future, both technologies will co-exist and best use of both the technologies is critical for the development and well-being of the smart-grid. In this section, some of the key features of both traditional and modern devices are described.

A. Traditional FACTS and RACDS

Although FACTS and RACDS devices may have different roles in the power grid, the technology, configuration and basic structure of these devices are identical to each other.

Traditional FACTS and RACDS devices use a combination of passive components and thyristors. The passive components include inductors, capacitors and zig-zag (or phase-shifting) transformers. Fig. 11 illustrates the circuit building blocks of some of the traditional FACTS devices. The devices illustrated in Fig. 11(a), (b), (d), and (e) are suitable for shunt compensation. In Fig. 10(a) and (b), current I_F is controlled by controlling the turn-on instant of thyristors. By controlling I_F, a variable impedance is achieved. If the equivalent impedance is capacitive, the device is supplying/generating Vars. Otherwise, the device is absorbing/consuming Vars.

Alternatively, the thyristor can be used to just switch the passive device into and out of the system. In such a case, several such blocks in parallel can lead to a step-wise variation in impedance. In view of this, the device in Fig. 11(a) is termed as thyristor controlled reactor (TCR) or a thyristor switched reactor (TSR) depending on the control of thyristor. Similarly, the device in Fig. 11(b) is termed as thyristor switched capacitor (TSC) [28]. The device in Fig. 11(d) is a combination of a fixed capacitor and a TCR. Such combinations between different types of passive and thyristor controlled impedances offer a greater range of variable impedance, spanning from inductive to the capacitive region. Static Var compensator (SVC) is the commercial term used when one or more thyristor-based controllable impedances are used in a shunt configuration as a FACTS/RACDS device. However, the connection of these devices to transmission/distribution lines often requires passive filters for harmonics and transformers for voltage stepping up.

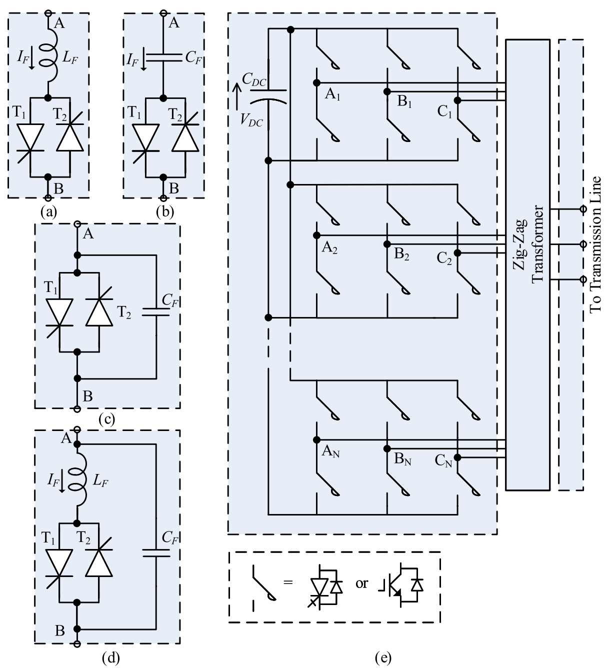


Fig. 11. ***Basic building blocks of Traditional FACTS and RACDS devices: (a) TCR, (b) TSC, (c) TSSC, (d) TCSC, and (e) multi-pulse converter.***

The devices in Fig. 11(c) and (d) are also suitable for series compensation (described in Sections II and III). When the thyristors in Fig. 11(c) are OFF, the capacitor C_F is switched into the line. When either of the thyristors is ON, the capacitance is bypassed. This type of device is termed as thyristor switched series capacitor (TSSC).

The device in Fig. 11(d) is termed a thyristor controlled series capacitor (TCSC) when used in series configuration. All the types of thyristor-based devices discussed so far rely on the thyristor switching to control the impedance. They can also be replaced with GTOs to achieve more control. However, each of the thyristor-based or GTO-based devices discussed so far has a time-delay of 8 ms to 16 ms (one-half to one-cycle) for turning ON and turning OFF the thyristors as they are often dependent on zero-crossing of the current.

Fig. 11(e) illustrates a multi-pulse converter-based FACTS device. Here, multiple six-pulse inverters are connected in parallel to a transmission line via a zig-zag transformer. By controlling the voltage magnitude and phase angle, the device can achieve variable impedance, phase angle and voltage control. Configurations such as shunt, series and shunt-series all can be realized using this structure. The shunt-series configuration of two VSCs connected back-to-back is commercially known as "unified power flow controller (UPFC)" [40]. Although this structure offers faster dynamic response (~5 ms) [34], its overall response is limited by the response time of the six-step operation of each VSC. Also, the size, efficiency and modularity of the overall system are all limited by the requirement of zig-zag transformers. There are very few installations of this type of FACTS devices.

The detailed operating principle of multi-pulse and other VSC based shunt compensators are described in [34]–[39]. Examples and descriptions of different installations are provided in later sections of this paper.

B. Modern FACTS and RACDS

In the early 1990s, two types of cascaded multi-level inverters (CMI) were introduced [41], [42]. This was a breakthrough in terms of moving away from the multi-pulse converter technology that has several limitations as described earlier. The basic building block of the CMI proposed in [41] is a string of IGBT based single-phase full-bridge voltage source converters (H-bridge inverter). Fig. 12 illustrates such a string using H-bridge inverters. Each H-bridge cell is called a submodule (SM). Two key differences between the multi-pulse converter structure and the CMI are the absence of the interfacing zig-zag transformers and fixed six-step operation versus pulsewidth modulation. This leads to a much lighter, modular and compact structure, better efficiency and dynamic response (~1ms) [41]. Additionally, the complexity in control and operation is minimized [43].

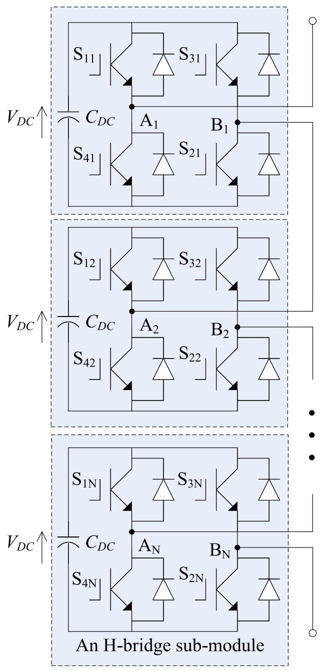


Fig. 12. ***Cascaded H-bridge structure to generate staircase voltage waveforms.***

There are two different CMI configurations as shown in Figs. 13 and 14. All shunt compensation functions can be realized using either structure. By appropriately controlling the voltage magnitude and phase angle at the terminals, the CMI can provide continuously variable VAR compensation, voltage regulation and harmonic current compensation. Its ultra-fast response times (<1 ms) makes the CMI a preferred choice for smart-grid.

The delta connected CMI configuration illustrated in Fig. 14 can achieve all the features of the Wye connected configuration.

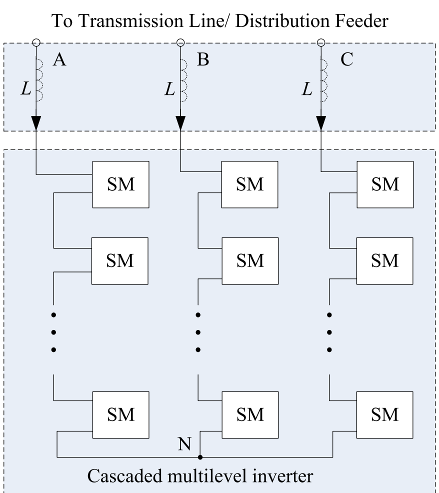


Fig. 13. ***Wye connected cascaded multi-level inverter (CMI) in shunt configuration.***

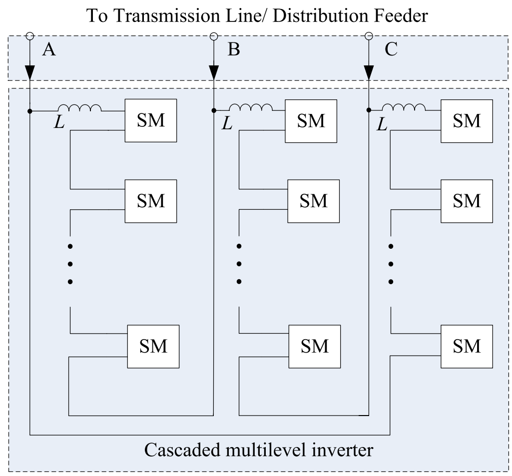


Fig. 14. ***Delta connected CMI in shunt configuration.***

Additionally, by controlling the delta configuration to behave like a variable impedance in each phase independently, it has the ability to generate negative sequence reactive power. This is a key benefit for correcting unbalance due to loads such as underground railway and steel mills in the transmission and distribution networks. The detailed operation and control of the delta-connected shunt configuration for load balancing are described in [44].

Another benefit of the CMI-based structure is that it can easily be integrated with battery energy storage (BESS) at the submodule level. This was proposed in [45] and [46]. Other active power sources such as PV modules can also be integrated with the submodule. Fig. 15 illustrates such a CMI sub-module.

The BESS integrated shunt compensation can be used to provide backup energy for the distribution network or an islanded network. It can also be used to provide frequency and voltage control to the power grid. The control and operation of BESS-based shunt compensators for these purposes are investigated in [47]–[50]. The CMI-based shunt compensators are commercially known as static synchronous compensators, or "STATCOMs".

The CMI structure can also be integrated into a series configuration [46]. Fig. 16 illustrates the ability of CMI to directly connect to the transmission line/distribution line for FACTS and RACDS applications, respectively.

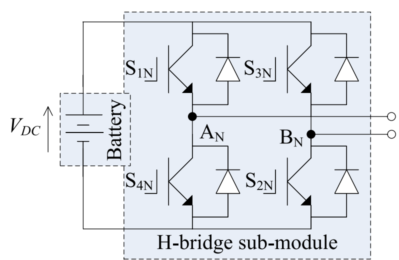


Fig. 15. ***Battery integrated sub-module (SM) for CMI.***

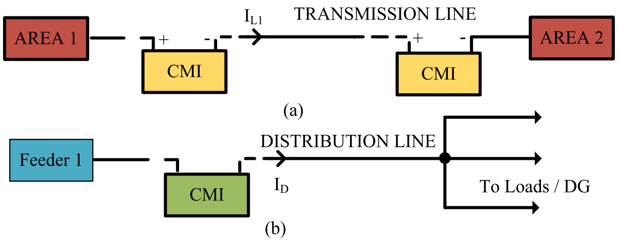


Fig. 16. ***Series compensation using CMIs: (a) FACTS application and (b) RACDS application.***

By appropriate control of the voltage magnitude and phase angle at the output terminals of the CMI string, dynamic variation in impedance, phase angle difference and/or voltage magnitude can be achieved. The control and operation of such a system used for impedance compensation is described in [51]. By integrating with battery energy storage, dynamic voltage restoration from voltage sags or swells at the feeder is made possible for RACDS applications. This is also known as "dynamic voltage restorer" [52], [53].

The ability to achieve a fully modular and compact structure, faster dynamic response, easy integration of battery energy storage, ability to directly connect to the power grid and elimination of zig-zag transformers has led to rapid commercialization of the CMI based technology. The CMI-based shunt compensators or "STATCOMS" are the mainstay of the modern FACTS and RACDS devices being installed today. Examples and description of different installations are provided in later sections of this paper.

In 2002, a modular multilevel converter (MMC) based back-to-back configuration was introduced [54]. The block diagram of a MMC converter is shown in Fig. 17.

Although it was proposed in [54] that individual submodules used half-bridge cells, it is preferred to use full-bridge (or H-bridge) cells as the submodule due to its superior dc side fault handling capability [56]–[59]. As per [57], out of the 95 MMC installations by Siemens from 2009 to 2013, 81 of them use full-bridge modules. The MMC structure is suited for HVDC transmission, in which two MMC converters are connected back-to-back via HVDC. By controlling the voltage magnitude and phase angle on the ac terminals of either MMC, the power flow from the sending end to receiving end or vice versa can be controlled.

Additionally, due to the presence of the intermediate dc stage, power flow control is independent of the frequency of the ac voltage on either ends. While the back-to-back configuration can function as a versatile FACTS device with ultrafast dynamic response in a synchronous grid, it requires two fully rated MMCs to carry the entire transmission line current. This leads to a larger footprint, higher cost and lower efficiency [60], [61]. However, the back-to-back configuration is an ideal candidate for achieving power flow control in an asynchronous tie and HVDC. The various commercial installations of different types of FACTS and RACDS devices are described in the next section.

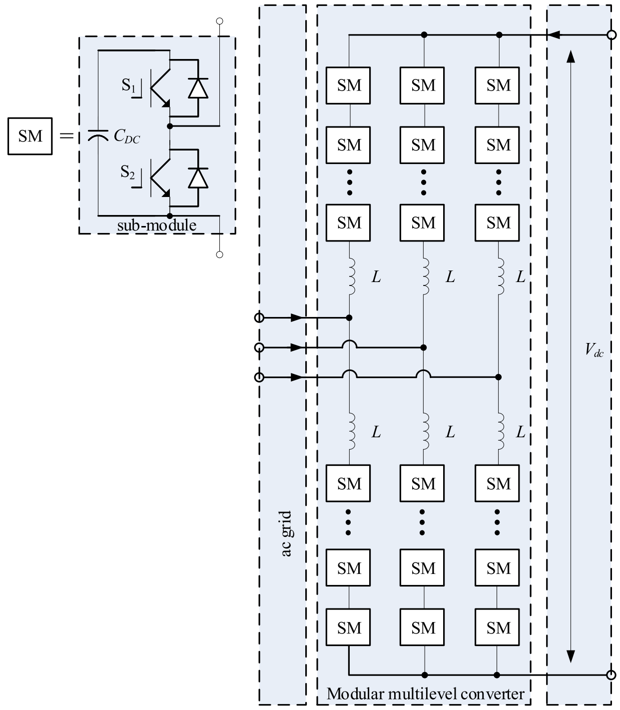


Fig. 17. ***MMC for back-to-back configurations.***

V. FACTS AND RACDS INSTALLATIONS

In this section, we provide an overview of different commercial installations of the FACTS and RACDS technology discussed so far. The growing popularity of CMI based devices is exemplified here.

A. Traditional FACTS Installations

Among FACTS, SVCs have been widely installed (within industry facilities and utility systems alike) with an estimated total capacity exceeding 90 Gvar [62]. The SVCs are recognized as an important power quality enhancement device for large industrial and traction loads. Many industrial loads such as arc furnaces often draw large pulses of reactive power, which create voltage fluctuation across other nearby loads. Therefore, the ability of SVCs to effectively compensate such random variations of reactive power is beneficial for flicker reduction, harmonics reduction and power factor correction for large industrial loads. Such power quality enhancements are essential for higher efficiency and productivity in industries. In addition, SVCs have also found its use in railway traction loads. Traction drives are large single-phase loads spaced apart at regular distances. The sudden variation of load in one phase creates an unbalance in the associated three-phase system leading to sudden voltage dips. Thus, SVCs provide load balancing and dynamic voltage support for such three phase systems. Some of the installations of SVCs in industries and railways include: 34.5 kV, 90 Mvar SVC at Cascade Steel Rolling Mills, USA [63]; 21 kV, 90 Mvar SVC at Ferriere Nord Steel plant, Italy [64]; 33kV, 180 Mvar Bao Steel group, China [65]; and 132 kV, -267/345 Mvar SVC at Powerlink Substation, Queensland, Australia [66]. The benefits of SVCs have been realized for power transmission systems as well. The major installations of SVCs in transmission systems are for: 1) increasing the transmission capacity of existing lines; 2) enhancing the transient stability of interconnected systems; 3) stabilizing voltages in weak systems; and 4) enabling interconnection of off-shore wind power to the transmission network.

Some SVC installations for increasing transmission capacity and stability of transmission systems include: 500 kV, −250/+250 Mvar SVC at Bom Jesus Da Lapa II substation, Brazil [67]; 525 kV, −110/+330 Mvar SVC at Devers Substation, Florida, USA [67]; 500 kV, −145/+575 Mvar SVC at Black Oak substation, Maryland, USA [65]. Similarly, some SVC installations are for enabling interconnection of off-shore wind farms to the grid: 230kV, −75/+150 Mvar SVC at Extremoz substation, Brazil [65] and 132 kV, −65/80.2 Mvar SVC at Radsted offshore wind farm, Denmark [67].

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 (total 2 Gvar) [68]. Some TCSC installations are: 230 kV, 45 Mvar TCSC at Kayneta substation, Arizona, USA [68], [69]; 500 kV, 208 Mvar TCSC at Slatt substation, Oregon, USA [68]; 420 kV, 112 Mvar TCSC at Purnea substation, India [68], [69]; and 500 kV, 326 Mvar TCSC at Yimin-Fengtun substation, Heilongjiang, China [68].

B. Modern FACTS Installations

The CMI based shunt compensator or "STATCOM" [41], [42] has undergone rapid commercialization by manufacturers worldwide. There are an estimated 26 major STATCOM installations (excluding small installations with less than 25 Mvar) around the world. The worldwide (completed and ongoing) installations of such CMI based STATCOMs are shown in Fig. 18. The capacity of each device is shown alongside the installations at their respective locations. The symbols in the map denote the usage of STATCOMs for utility application, offshore wind farm integration (or grid access) application, electric railway application, and industrial application. The individual capacities of some of the ongoing/ future projects include: 2 Gvar installation in Northern India [70]; 1.65 Gvar installation in Western India [71]; 290 Mvar installation in Race Bank and Burbo bank offshore wind farm, UK [72]; and 300 Mvar Lake Turkana on-shore windfarm, Kenya [73]. The total installation capacity of STATCOMs is over 20 Gvar.

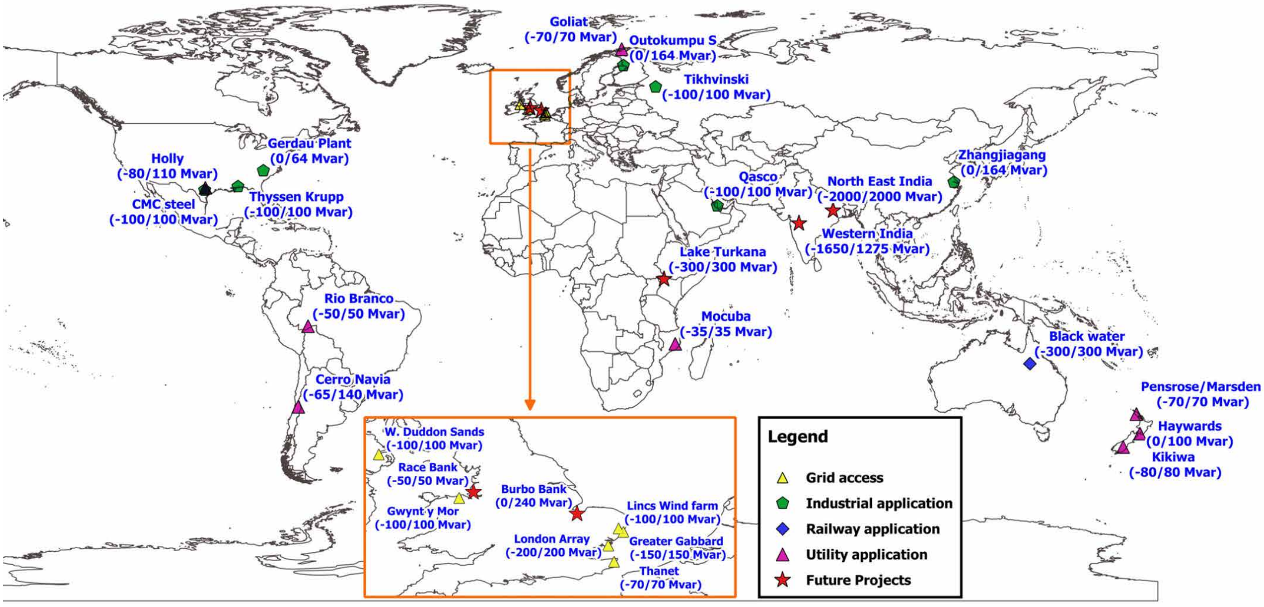


Fig. 18. *Worldwide installation of CMI based STATCOMs.*

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 levelling; 2) providing storage for intermittent renewable energy sources; 3) maintaining stability by providing voltage and frequency support; and 4) reducing or eliminating outages. Some of the BESS installations include: 40 MW Angamos BESS in Northern Chile [74]; 64 MW Laurel Mountain BESS in West Virginia, USA; 36 MW Notrees BESS, Texas, USA [75]; and 40 MW Golden valley electricity authority BESS, Fairbanks, Alaska, USA [76].

C. 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 [77]. Some of the installations include: 22-kV/5.25-MVA DVR at Power Cor distribution system at Stanhope, Victoria, Australia [78]; 11-kV/4-MVA DVR at Caledonian Paper plc, Irvine, Scotland [79]; and 25-kV/600-kVA DVR at North Lights Community College, British Columbia, Canada [77]. In 2011, the DVR proved its worth by protecting critical hospital loads at Sendai Microgrid, Sendai, Japan during a three-day power outage caused by earthquake [80].

BESS systems are installed at distribution feeders mainly for: 1) energy saving by providing load leveling at substation level; ii) improving the power factor of the feeder; iii) reducing outages by providing islanded mode of operation; and iv) integrating renewable energy resources. A small substation-scale 1MW Charleston NaS Energy Storage Project in North Charleston, West Virginia, USA, has demonstrated the load leveling and power factor improvement functionalities [81]. Similarly, the 200 kW BESS installation at Norfolk, England, has permitted the integration of renewable energy sources by leveling out the power fluctuations in a distribution network [82]. A BESS has also been installed for demonstration of micro-grid operations as in the case of 2 MW, Santa Rita Jail Smart Grid demonstration project, Almeda County, California, USA [83].

VI. FUTURE PERSPECTIVES

Reliability, size/weight, cost and dynamic response time of the system are the major driving factors for the development of modern FACTS and RACDS devices. As we continue to transition to a smart grid, these driving factors are predicted to be pursued in full-throttle. In view of this, there is continuous ongoing research to achieve FACTS and RACDS devices that are cheaper, lighter, faster and smaller. A few key R&D activities in this area and the problems they aim to solve are briefly described here.

A. Transformer-Less Unified Power Flow Controller

At present, the back-to-back MMC configuration is the preferred technology for achieving independent power flow control in a synchronous grid. However, as described before, this technology uses two fully-rated power converters leading to increased size, cost and power loss of the system. The traditional UPFC technology can achieve independent power flow control with fractionally rated back-to-back converters. However, the need for bulky zig-zag transformers and lack of modularity severely limit their applications. The quest to achieve fractionally rated power flow controllers has recently led to new inventions in this area.

A transformer-less unified power flow controller has been proposed in [84]–[88]. 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. Fig. 19 illustrates the overall configuration of the transformer-less UPFC in a FACTS application [84]. It can be seen that no interfacing transformers are needed. The photograph of the experimental prototype is illustrated in Fig. 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.

For many cases, the series CMI alone could achieve the necessary power flow control. The worst case phase angle difference in the transmission network is within +/−30 degrees [24]. Power flow control in such cases has been tested in [87]. Power flow control from 0 to 2 MVA has been implemented. The comparison between size and cost of the transformer-less UPFC and the back-to-back MMC for such a case is described in [60], [61]. Based on the analysis, the proposed transformer-less UPFC is expected to be $(1/4)^{th}$ in size and cost. Utilizing the series module alone

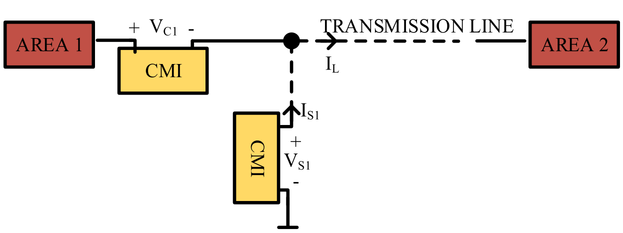


Fig. 19. ***Basic configuration of Transformer-less UPFC.***

Fig. 20. ***Photograph of the 2-MVA prototype at Michigan State University.***

leads to a reduction to $(1/8)^{th}$. Further research and development to deploy the transformer-less UPFC in the field is currently ongoing.

B. Compact-Dynamic Phase-Angle Regulator

Several instances in the power grid do not require a large variation in phase angle difference to achieve power flow control. Traditionally, phase angle regulators were achieved using phase-shifting transformers. This led to a large footprint and slow dynamic response. A low-cost, compact dynamic power flow controller has recently been invented [89]. The general structure of the proposed system along with the converter implementation is illustrated in Fig. 21. By using a "cross-coupled" winding structure and duty cycle control for the ac switches, dynamic phase angle control is achieved. Test results from a 12.7 kV, 1-MVA rated prototype illustrate the benefits of the technology [90]. The overall converter power rating is reported to be $(1/10)^{th}$ of the rating of the maximum power flowing through the line [89]. R&D efforts in scaling to a 138 kV transmission level are currently ongoing.

C. Distributed FACTS

FACTS devices for transmission systems often need a large platform. The high-voltage insulation requirements,

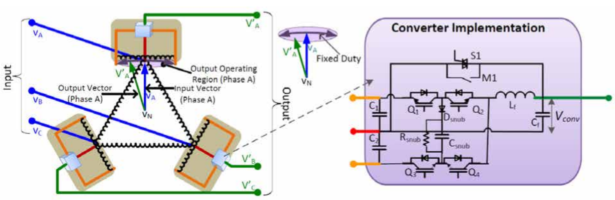


Fig. 21. ***Structure of Compact-phase angle regulator [89].***

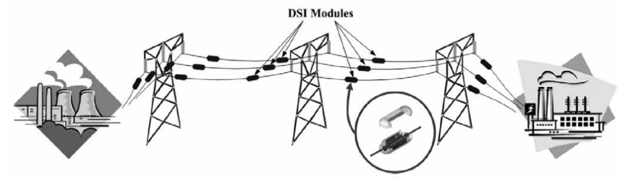


Fig. 22. ***Distributed FACTS illustrated in [91].***

construction and land costs lead to increase in the overall cost and complexity of the system. A recent invention, termed as "distributed FACTS" proposes to do away with the requirement for such a platform. Fig. 22 illustrates the distributed FACTS concept proposed in [91]. Compact, controllable floating reactors are distributed along the transmission line. Fig. 23 illustrates the implementation of these floating reactors.

The reactors can either be switched into the line or bypassed by controlling switch S_m. This can provide a stepwise increase in reactance that can mitigate some congestion problems in the transmission network. Several installations are currently under way and more are expected in the near future.

D. Power Regulator for Parallel Feeders

There are always some voltage differences in magnitude and/or phase between feeders due to loading, legacy, or other problems. A small-difference can cause large circulating current if connecting two feeders together at their ends. The transformer-less UPFC described above can be used as a RACDS device, such as a power regulator to make parallel operation of feeders possible. Fig. 24 shows two cases that need a power regulator. In Case (a), the two feeders are 30° out of phase due to a legacy problem. A transformer-less UPFC based on two CMIs has been used and demonstrated in lab to connect them together to route power from one feeder to the other, share loads and/or backup power. In Case (b), the old feeder is an overhead line that has been used as a backup for the new feeder (an underground cable). Due to an increase of the local demand, the underground

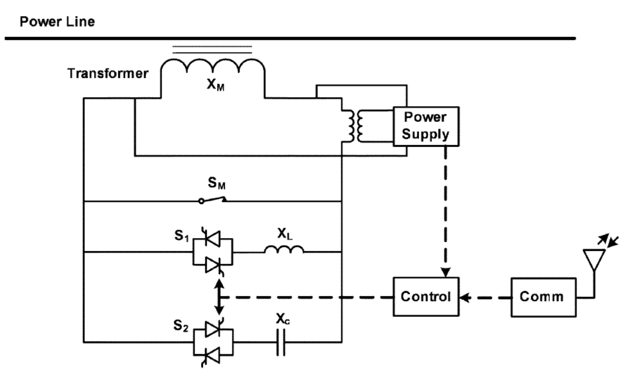
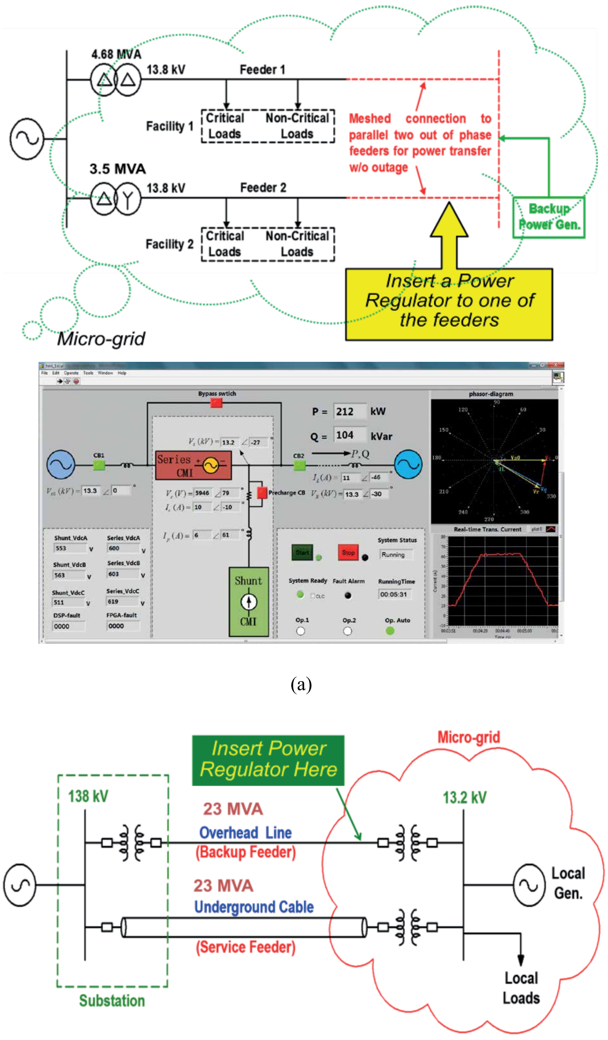


Fig. 23. ***Floating Reactor implementation in distributed FACTS [90].***



(a)

(b)

Fig. 24. ***Power Regulator to make parallel operation of feeders possible. Case (a): To parallel two out-of-phase feeders, route power from one feeder to the other, and share one backup power generator. Case (b): To parallel two extremely different feeders to share power flow.***

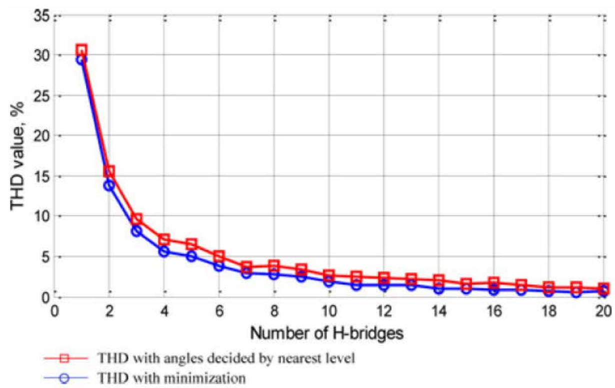


Fig. 25. ***THD (%) versus number of modules for direct connection of cascaded H-bridge to power grid [61].***

cable is overloaded whereas the overhead line feeder carries no load current because of impedance mismatch. A power regulator based on CMIs could be used for power sharing of these two extremely different feeders.

E. High Power Density CMIs

Majority of modern FACTS and RACDS devices use IGBT semiconductor switches. When using CMIs and MMCs for direct connection without transformers, the larger the number of modules, the smaller is the harmonic distortion (THD) [61]. However, as it can be observed from a case of H-bridge modules in [61], the change in %THD is negligible beyond about ten modules. This is illustrated in Fig. 25. But, since IGBTs have a maximum voltage rating of 1200 to 1700 V, larger than ten modules is always required to facilitate a direct connection to the grid voltage. The case described in [61] uses 20 H-bridge modules of 1200 V each to connect to a 13.8 kV system.

The number of modules may still be within 20 to 30 for distribution level RACDS applications even with 1200 and 1700-V IGBTs. However, as it can be seen from the installations in Section V, a direct connection of STATCOMs to transmission or subtransmission 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 subtransmission level. Recent R&D efforts in wide-band gap devices have led to initial prototypes of 10 kV and higher voltage rating Wide bandgap (WBG) semiconductor switches [92].

In the future, with commercialization of HV WBG switches, the number of modules (and hence complexity of the system) are expected to be minimized (tens instead of hundreds) and direct connection to sub-transmission level voltages may become practical. This can also improve the overall reliability of the system. The use of WBG devices also enables faster switching speed and reduced losses. Overall, WBG devices have a great potential to make big impact in realizing compact direct interfaced, naturally cooled FACTS and RACDS.

Although, cascaded multi-level inverters (CMIs) do not require active energy storage for STATCOM and power flow control applications, they require relatively large dc capacitors to maintain a constant dc side voltage. In order to increase reliability of individual CMIs, film capacitors are used. However, film capacitors are large and have very low power density. In view of this, there is continuous ongoing research to minimize the dc capacitance of single-phase inverter modules [93]. This has a great potential to reduce the size and cost of the overall system and dramatically increase the power density of the system.

VII. CONCLUSION

This paper has touched upon two important aspects of the smart-grid: the transmission and distribution networks. The need for a FACTS and a RACDS in a smart-grid has been discussed in great detail. Different configurations and technologies available for the installation of FACTS and RACDS have been marked out. Comparison between existing technologies and their suitability for a given application are also illustrated. Installation examples around the world illustrating the growing importance of power electronics in the grid are also illustrated. Ongoing and future research in this area that could lead to the next generation of FACTS and RACDS devices has been briefly described. A wealth of literature is included for reference and further interest. ■

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