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Smart Wires and Modular FACTS Controllers for Smart Grid Applications: A Review

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Abstract

Flexible AC Transmission System (FACTS) controller has got unanimous acceptance in the electric power industry due to their power control capability especially in transmission and sub transmission networks. These FACTS devices play a decisive role in stability enhancement and effective asset utilization. The controllers suffer from grave drawbacks such as colossal size, poor reliability, high cost, and unavailability of experienced personnel for operation and maintenance, which makes them unapt to be used in smart grid and modern power system applications. These inadequacies are effectively assuaged by the distributed FACTS devices, which are proliferated along the transmission lines, are said to be portable, cost-effective, highly reliable, and easy to maintain. This paper explores an exhaustive review of the smart wires and modular FACTS controllers with their application in smart power networks.

Keywords: Power flow control; FACTS; Smart Wires; Distributed FACTS Controller

1. Introduction

Modern interconnected power networks accommodate a variety of distributed generating sources such as PV/Wind [1-2]. These sources create various power quality issues such as change in fault current level [3], voltage variation [4-5], harmonics [6-7], and harmonics resonance [8]. These sources are located at different places and transmit bulk power over long distance transmission lines. The aging transmission lines operate at their thermal limits and are close to stability margin. Moreover, the congestions and bottlenecks in lines reduce the power transfer capacity and increases the risk of cascaded blackout. The transmission lines have no provision to control the power, but by coincidentally changing the

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line parameters, the power flow through the lines can be controlled. The remedial solution that can address the above issues effectively is the FACTS devices [9-10].

The FACTS devices have got wide spread application to improve the performance of electrical power system such as power flow control, congestion relieving, damping power oscillations, voltage and reactive power control, power factor correction, power quality conditioning and enhancement, steady state and transient stability improvement, voltage stability improvement, line loadability enhancement, losses reduction and operational efficiency improvement [11-16].

The FACTS devices can be attached in series, parallel or series–parallel mode to the transmission network depending upon the application. In modern FACTS devices, power electronic switches (Gate Turn Off Thyristor- GTO, Insulated Gate Bipolar Transistor- IGBT) are invariably used to control the power flow [17]. This paper presents the extensive survey of the newly developed Distributed static series FACTS devices called DFACTS, and their construction and applications in modern power system.

The thyristor-controlled series compensating FACTS devices utilize the principle of line impedance control and are frequently used in steady state power flow regulating applications. The application of these devices is well accepted for damping control and stability improvement [18-20].

In transmission networks, the wind energy contribution has increased many fold in past years, therefore, the existence of series compensating FACTS devices for transmission expansion planning is further appreciated [21-22].

The FACTS controllers are useful in power control due to their fast dynamic response, and flexible and controllable operations [23]. These FACTS devices are capable to accomplish the modern power grid goals but have got less relevance due to their bulky size, higher fault current, higher insulation stress on the power electronics components, less reliability, high cost and unavailability of skilled manpower to maintain and operate them. Moreover, installation of FACTS devices in all possible areas is not an economical and viable solution. The alternate solution which can address the above issues is distributed FACTS technology called Distributed Static Series Compensator (DSSC).

The distributed control and monitoring of entire transmission system using sensor and communication technology has got motivation. This employs smaller units clamped on the transmission lines in place of a big unit. This paper presents an extensive review of the distributed FACTS controller and their applications in smart power system era. The remaining paper is organized as follows. Section II briefly describes the philosophy of compensation as applied in transmission systems. Section III is devoted to the distributed FACTS technology state-of-art. Section IV presents extensive application of distributed FACTS controllers in power industry. Finally, Section V concludes the paper.

2. The Philosophy of Compensation

In a simple two bus system as shown in Fig. (1), the real and reactive power flow can be expressed by equations (1) and (2).

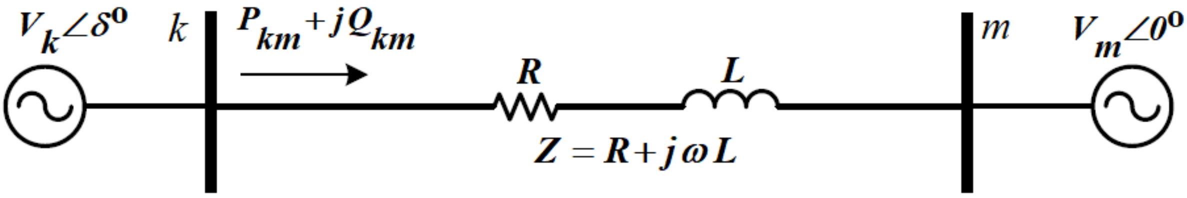

Figure 1. Schematic of Two Bus System

$$P_{km} = \left[\frac{V_k\, V_m \cos(\theta-\delta)}{|z|}\right] - \left[\frac{V_2^2 \cos(\theta)}{|z|}\right] \quad \text{Watt/phase} \tag{1}$$

$$Q_{km} = \left[\frac{V_k\, V_m \sin(\theta-\delta)}{|z|}\right] - \left[\frac{V_2^2 \sin(\theta)}{|z|}\right] \quad \text{Watt/phase} \tag{2}$$

where, P_{km} and Q_{km}: Real and reactive power flow form bus k to m, V_k and V_m : Voltage magnitudes, δ : Phase angle difference between the voltages, z: Line impedance, θ: Impedance angle.

In transmission lines, the resistance value is much lesser in comparison to inductance. Therefore, above equations can be reduced to equations (3) and (4).

$$P_{km} = \frac{V_k\, V_m \sin(\delta)}{X} \tag{3}$$

$$Q_{km} = \frac{V_k\, V_m \cos(\delta)}{X} - \frac{V_2^2}{X} \tag{4}$$

where, X is the line reactance.

Above equations show that the power flow through the network essentially depends on the power line inductive reactance and, therefore, control of line impedance can provide a dominant means of power flow control [24-28]. Hence, the real and reactive power can be varied by changing the reactive impedance of the power line. The reactive impedance is reduced by introducing capacitive element to proliferate the active power through the lines. Higher value line reactance decreases useful power through the transmission line. The equivalent circuit with capacitance element in the line and its phasor diagram are shown in figs. 2(a) and 2(b) respectively [29].

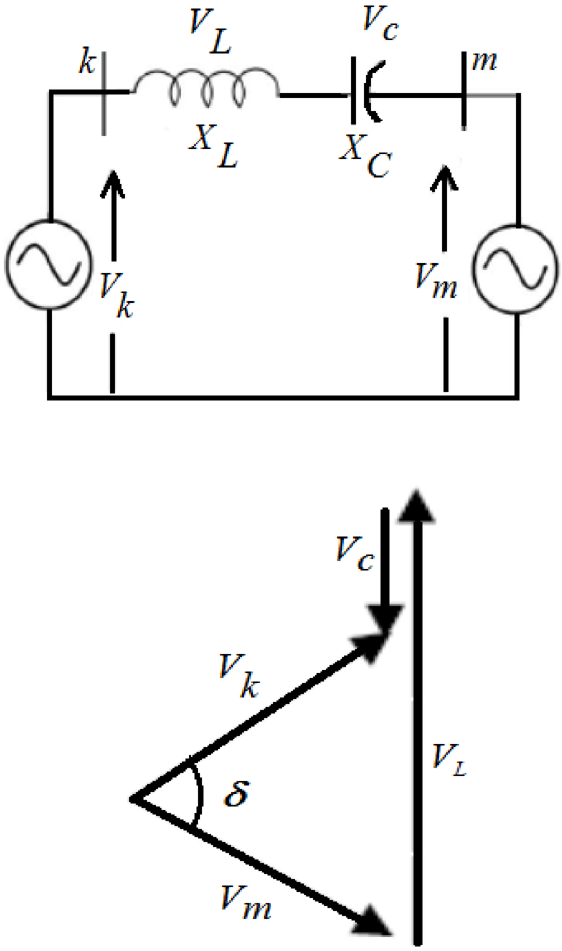

Figure 2. (a) Equivalent circuit capacitor compensated two bus system (b) Phasor diagram

Utilizing this concept, Divan et al., [30] developed low-priced, miniature, and light weight single phase distributed devices named Distributed Flexible AC Transmission Systems (DFACTS), which provide many prospective advantages in the operation of power system [31-33]. The major benefit of these devices is that with respect to the length of the power lines, these are effortlessly mounted on the lines without changing its structure.

A DFACTS device essentially varies the actual impedance of the line by providing voltage drop in 90^0 with current either in lagging or leading directions. The line current leads or lags the voltage by 90^0 according to relation,

$$V = IZ \quad \text{or } V = jI\,X_L = -j\,I\,X_C$$

where, Z - Impedance, X_L- Inductive reactance, and X_C - Capacitive reactance of power line.

3. The Distributed Facts Technology Overview

The basic force behind the technology lies in the fact that current is continuously sensed and compared with a reference value, and according to the difference of current, the line impedance is regulated. The main components of distributed FACTS unit are one-turn transformer, PWM inverter, feedback with associated control and communication module. These components are located in a modular box like arrangement and can be easily clamped on the transmission line as shown in Fig. 3. The primary component of transformer is one-turn and secondary is the transmission line itself where the controlled voltage is injected directly by the transformer. The voltage injected by the distributed FACTS module is such that it neutralizes the inductive or capacitive effect of the line [34-35]. A communication channel serves to control these modules remotely [36].

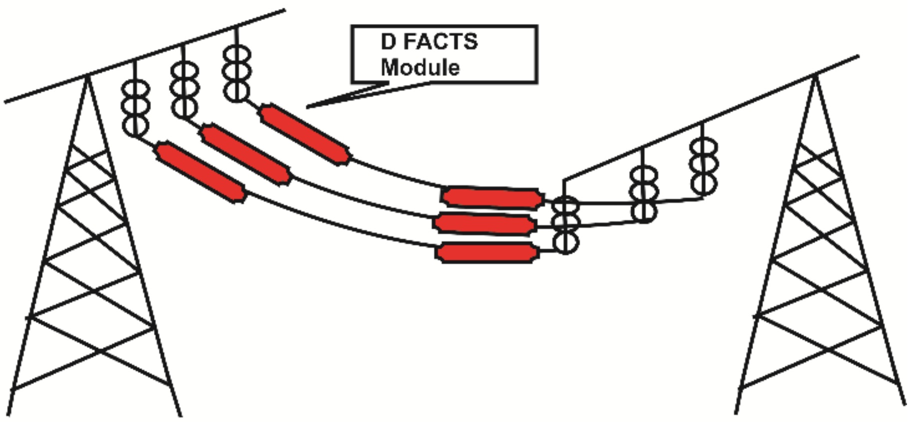

Figure 3. The Single-Phase distributed FACTS Modules

The fig 4 shows the schematic of distributed FACTS (DSSC) module [29-30]. The distributed FACTS device transfers power flow from over-burdened line to less-loaded line by regulating the line impedance. This power flow re-routing increases power transfer limits of the line and subsequent lines utilization. The distributed FACTS device has the capability to provide inductive and capacitive compensation of the line. The capacitive compensation of under-loaded lines allow more current to flow through it, while the inductive compensation of over-utilized lines allow less flow of current. In both the scenarios, the surplus power is routed through less loaded line and makes the overloaded lines free from congestion. The general schematic of Distributed Series Impedance (DSI) is presented in Fig. 5. [38]

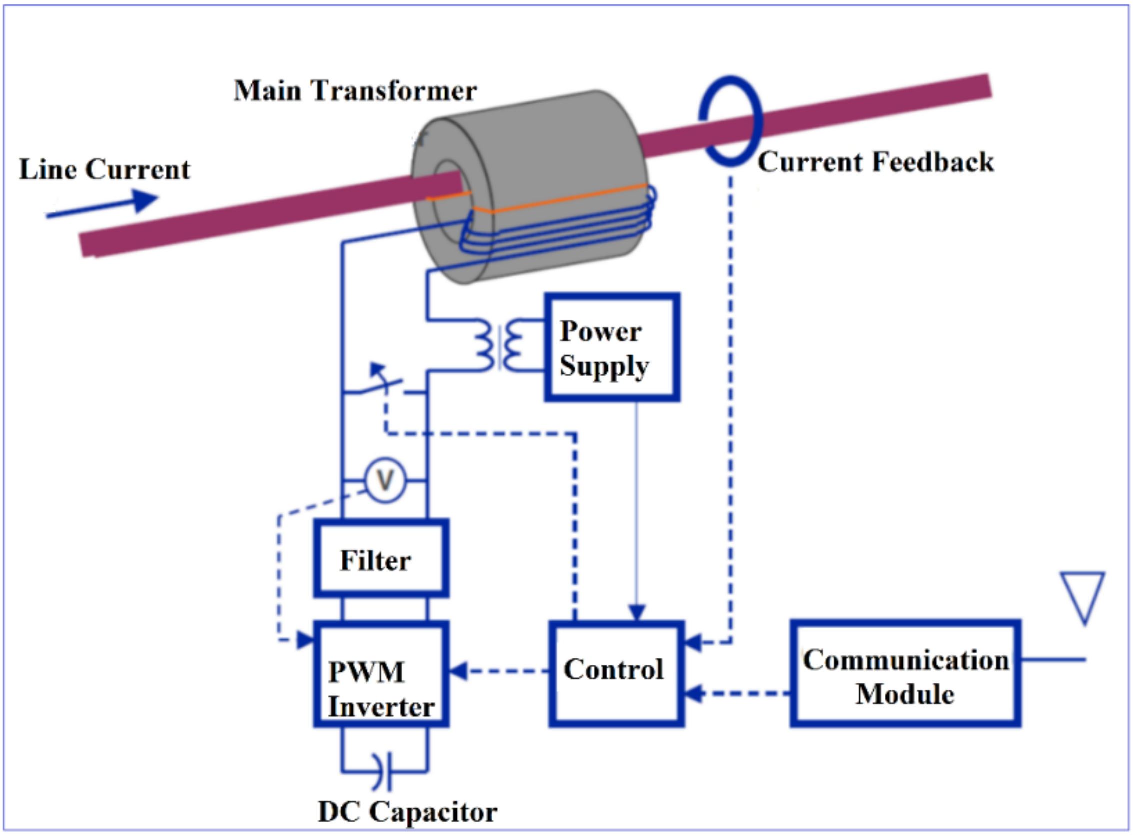

Figure 4. DSSC circuit representation [27-28, 37]

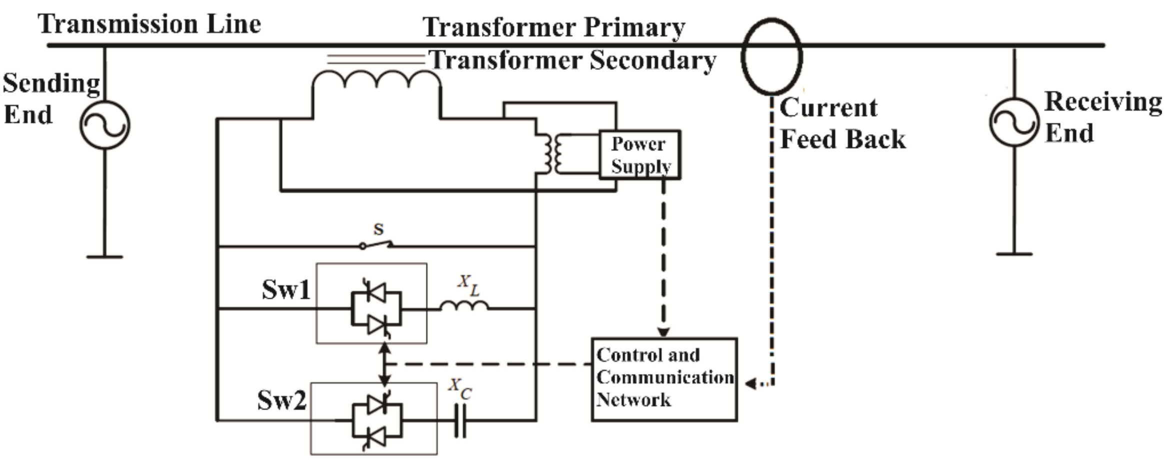

Figure 5. General schematic connection of DSI device [30, 38]

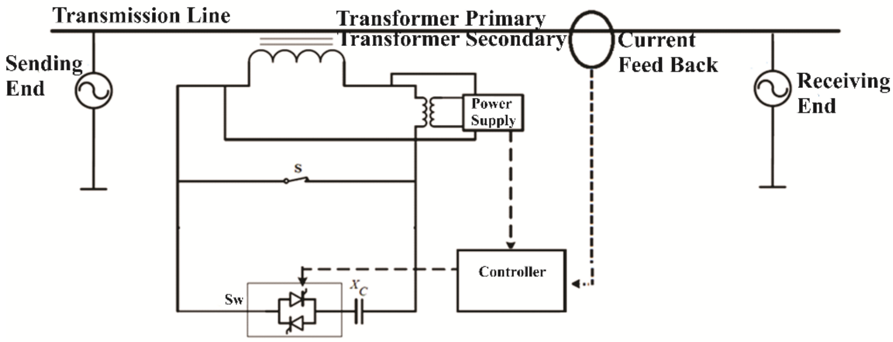

Figure 6. General schematic connection of DSR device [30, 38-39]

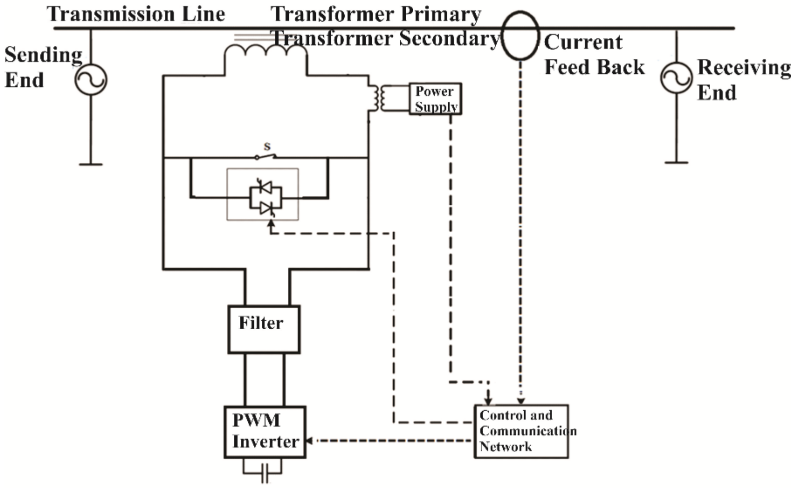

Figure 7. General schematic connection of DSSC device [27-28, 30, 37]

Fig. 5 shows the connection schematic of DSI distributed FACTS modules in a power transmission line to achieve the power flow control by changing the line impedance. The single turn transformer assists distributed FACTS devices for series injection, where the line conductor acts as primary winding of transformer. The secondary circuit contains a by-pass switch S along with two switches SW1 and SW2. These switches are controlled by a communication assisted controller in order to inject the effective inductance and capacitance into the lines. The switch S is used to by-pass the transformer under no compensation requirement and a current feed-back is provided to observe the on-line power status.

Fig. 6 shows a schematic representation of an easy version of Distributed Series Reactor (DSR) based distributed FACTS device [38-39]. It requires no communication network, and the control strategy is also comparatively simpler than DSI. Switches turn on when the current in any line increases to a predetermined value, causing the impedance to gradually change and then the current is diverted to a less loaded line. In this approach, switches are turned on in a regular manner and allow the power line to function as current limiting conductor. Inductance of the line changes in accordance to the variation in the current [40].

The Distributed Static Series Compensator (DSSC) based distributed FACTS device is shown in Fig. 7. This module has inbuilt communication capability. It consists of a small single phase inverter and a single turn transformer along with control circuitry and power supply. The weight and size of the module is low, and therefore it can be easily suspended from the power line [41].

In the above DSSC module, the use of high turn radio transformer helps to increase the current magnitude in the lines and simultaneously the voltage correction capability reduces for the same power inverter rating. Hence, a greater number of DSSC devices are required to control active power flow through lines.

The design aspects for the development of hardware module according to transmission grid parameters and influence of these devices on the power grid performance is presented and the laboratory prototype of DSSC module is shown in Fig. 8 [42-43]. Further, the simulation of the technology, hardware testing, and practical viability studies are discussed in [48].

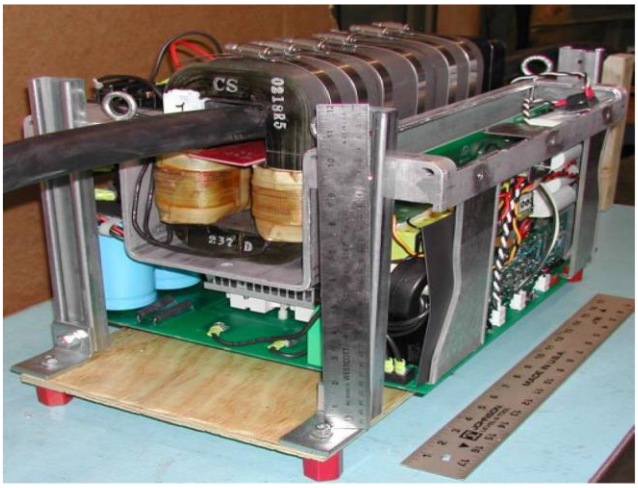

Figure 8. DSSC Laboratory prototype [42-43]

In the light of above, another breakthrough came in the power flow controller technology with the development of Emitter Turn Off (ETO) based Voltage Source Inverter (VSI). The concept of using ETO in VSI overcomes the limitations as mentioned of earlier DSSC. In addition, the module is flexible, modular, and light in weight, hence a single module is sufficient to control the power in place of large number of modules [44 - 46].

In order to address the reliability issues and maintenance problems, the inverter-less model of static series compensator as shown in Fig. 9 is proposed in [47]. This module is prepared by modifying the Distributed Series Reactance (DSR) module. It includes two AC switches, an AC capacitor, and a communication channel.

The connection schematic of distributed FACTS devices in the transmission system is shown in Fig. 10. Many advantages are associated with distributed FACTS technology in comparison to conventional FACTS technology. Multiple voltage source converters eliminate the need of transformer in DSSC, as the distributed FACTS devices permit flexible and real-time control of grid operations, as per the patent published in 2017 [51]. It is expected that the distributed FACTS technology perform promising roles to meet the smart grid objectives [49].

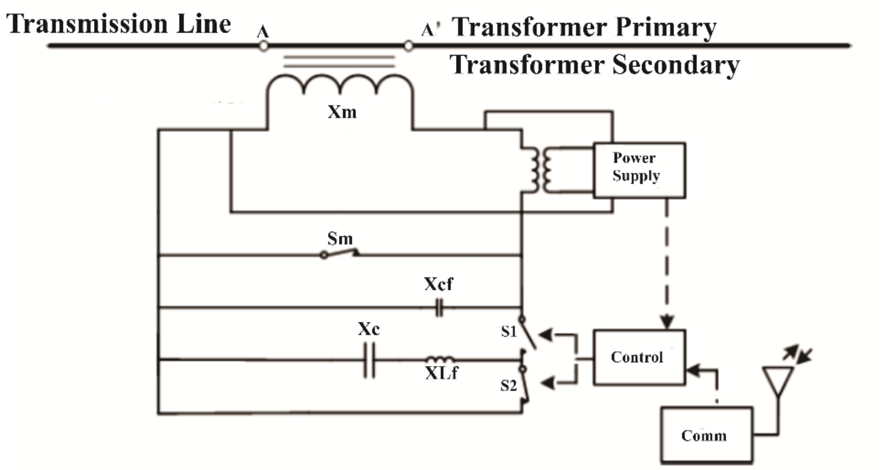

Figure 9. Inverter-less static series compensator [47]

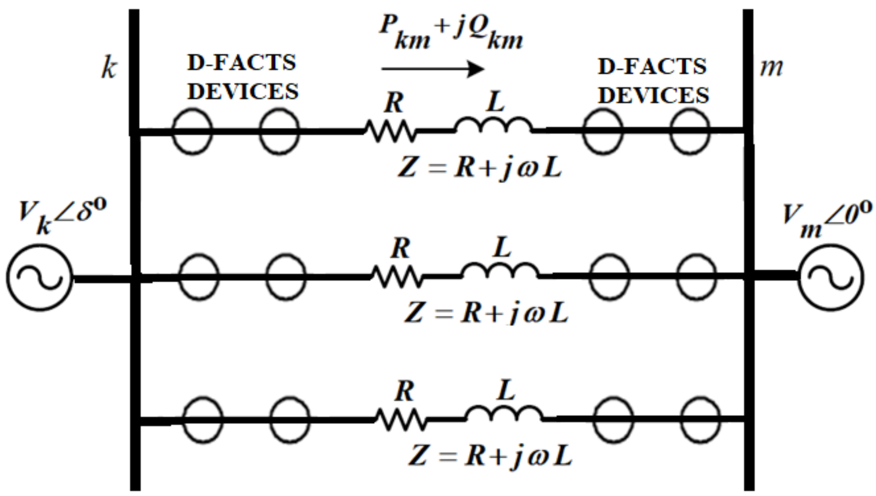

Figure 10. The connection schematics of distributed FACTS devices

Future grids accommodate renewable energy sources, where bi-directional power flow is obvious. It has been observed that the mechanical or passive control of grid components cannot work reliably under such situation and cannot fulfil the future grid objective. Therefore, the active control using distributed power electronics has been presented in [50]. This is a low cost solution to achieve the precise and effective control of the grid components.

4. Distributed Facts Application Review

The optimal operation is one way to regulate the power flow through transmission lines [52-53]. The applications of DFACTS technology to regulate the power flow have been investigated and validated in various studies [54]. The active power regulation in the standing transmission lines is done utilizing the DFACTS modules. It is observed that DFACTS device has the capability to regulate the power by varying the line impedance and improves power transfer capacity of the power lines. Moreover, it assists the operation of the system during contingencies [54] and finally reduces the transmission investment cost [30-33].

In 2012, in Brazil the impact study of distributed FACTS device in transmission expansion, financial and operational studies has been performed [55]. The distributed FACTS devices work as a smart transmission wire to offer the economical solution of power regulation through the transmission lines. By fitting these devices, the transmission utility gets rid from new lines installation [56-58]. The series converter of UPFC has been modified using the DFACTS idea and a controller named Distributed Power-Flow Controller (DPFC) is developed to regulate the transmission line power

[59]. In this controller, the series converter is energized by the 3rd harmonic current which offers the advantage that DC connection between series and shunt converters can be avoided. It offers cost-effective solution due to smaller size component and high reliability, because of the unavailability of series converter. A three phase model of distributed FACTS device is developed and implemented in Newton's algorithm to obtain power flow solution. IEEE 30 node and 5 node standard system is used to authenticate the viability of algorithm. However, a convergence difficulty is detected due to unknown initial parameters [60]. A simulation based study is conducted to explain the operation of DFACTS device. The power flow results, before and after distributed FACTS device are presented in [61].

The DSSC analysis in terms of mathematical modeling and control is explored in [62], where the performance of model is investigated on IEEE 14 node standard system and particle swarm optimization (PSO) is applied to obtain the optimal devices to reduce the transmission line loading. The application of DSSC to solve the congestion and transient stability issues are presented in [63]. The DFACTS modules are installed at various places throughout the power network to control power flow through the lines. The controller is tested on 48 buses and 65 lines system installed in North American utility system. The efficacy of controller is judged by determining the sensitivities which relates the impact of variation in line impedance onto voltage and power flow quantities [64]. Again a model based study is executed to investigate the impact of distributed FACTS device on the transmission lines power transfer competency [65].

Voltage unbalancing is a big issue in power networks, which affect the operation of loads connected to it. Various methods have been adopted to improve the voltage in transmission and distribution systems. The variation in line impedances may cause voltage unbalancing in power system. However, this can be mitigated using transposition of conductors, however transposition alone is not sufficient to provide comprehensive voltage improvement. Hence, the distributed FACTS device is used in each phase to effectively improve the voltage unbalancing [66].

The DSR solution to control power flow and mitigate overloading contingencies is proposed in [67]. In order to investigate the role of distributed FACTS devices for power control, an experimental study is performed in [68]. The PWM control signal for converter power devices is generated using TMS320F2407 DSP processor to effectively vary the inductance of the lines. The transient effect of DFACTS modules on the power network is reported. The optimal location of distributed FACTS devices is another issue. The DSSC location to obtain the maximum reliability and enhanced line loadability is explored in [69], and Fuzzy inference system is used to get the best position of the modules. The Particle Swarm Optimization (PSO) is applied to find the optimal position of DFACTS modules. IEEE 39 standard node system is used to validate the results and to find the paramount position of these modules [70].

The influence of DFACTS devices cannot be speculated easily in modern complex and nonlinear power system. Therefore, a linearized power system model is developed to decide the best position and the impacts of DFACTS modules [71]. A simulation study with Fuzzy and Artificial Neural Network (ANN) controller is performed to investigate the application of distributed FACTS devices for transient stability improvement. It is reported that, the presence of distributed FACTS devices control the rotor angle and maintain the stability of the system

[72, 73]. The installation of these devices and their influence upon the power system parameters such as, voltage magnitude, angle, power injected into the nodes, power flow through the lines, active power losses with variation in impedance and location of these devices to control the power flow were discussed in [74-75].

A linear transmission line model is developed to deploy and operate distributed FACTS optimally. The power flow equations are linearized after a disturbance. Thus, the system operating points reduces to a set of linear coefficients. The study further eliminates the requirement of power flow solution [76]. The over and under compensation of lines is not desirable, due to the cost and operational motives and therefore, optimum placement of distributed FACTS devices is necessary to get the highest utilization of asset. This can be achieved by implementing optimization algorithms. Particle Swarm Optimization (PSO) and Mixed Integer Linear Programming (MILP) algorithms are implemented in [77-78] to obtain the optimum location of distributed FACTS devices.

5. Conclusion

This paper explores a comprehensive state-of-art and application overview of distributed FACTS technology in modern electric utility system. The existing FACTS controllers are insufficient to meet the goals of modern power system due to the various disadvantages associated with them. The distributed FACTS devices have proved their worth for performance improvement of transmission and sub transmission power system such as competency for power transfer, contingencies relieving, voltage balancing, stability and reliability improvement. Research is being conducted to increase the modularity of these devices and make them economical. Further, research is also carried out to address the post contingency scenario by providing the multi variable impedance power regulation to dispatch the optimal power. In the near future, the distributed FACTS controllers may supersede the conventional FACTS controllers and may be a milestone for the power industries to achieve the modern power system goals.

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