A COMPREHENSIVE REVIEW ON A D-FACTS CONTROLLER: ENHANCED POWER FLOW CONTROLLER (EPFC)

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ABSTRACT

Modern FACTS controllers are being used to control the power through the current power transmission system. The power transfer can be controlled by using these devices in an efficient and effective manner in transmission lines. FACTS controllers are having some downsides i.e. their bulky size, higher cost, reliability and break-in the transmission line, which makes it obsolete to use in modern power system network. These downsides can be fulfilled by a new compound which is scalable, light weighted and cost effective devices that are distributed-FACTS (D-FACTS). D-FACTS controllers are distributed version of conventional lumped FACTS controllers and their cost is low due to lower ratings of component and reliability also increases due to redundancy of devices. Enhanced Power Flow Controller (EPFC) is all a D-FACTS device which is a distributed version of thyristor controlled series controller. This paper discusses extensive review about the EPFC and its application.

KEYWORDS: *D-FACTS, TCSC, EPFC, FACTS CONTROLLER, POWER FLOW CONTROL*

I. INTRODUCTION

The demand of electrical energy is increasing day by day. In the developing countries like India, increasing demand rate is much higher and the generation of electrical energy is insufficient to achieve the increasing demand, so it is important to fulfil the gap of demand and generation by increasing the loading capability of transmission system or by developing the new transmission systems. Though, it's very challenging to develop the new transmission system due to the high capital cost, limited energy resources, and time and land restrictions [1, 2]. The increasing loads demand can be supplied by increasing the loading capability of existing transmission lines up to their thermal limits and decreasing the transmission lines losses [3-5]. About 2-3 decades ago, FACTS controllers were developed to increase the loading capability of transmission lines, as reactive power source and generator to the power system [6, 7]. The advantage of FACTS technology is their reliability, quick response, easy controlling and enhanced flexibility. There are various FACTS devices based on voltage source converters and current source converters *i.e*. Static Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Thyristor Controlled Series Controller (TCSC) and Unified/Interline Power Flow Controller (UPFC/IPFC) that are operating physically in the current power system [8]. These FACTS devices are connected in different type of connections with transmission lines *e.g*. shunt controllers, series controllers and their combinations of series-shunt controllers and series-series controllers [9].

Recently an alternative approach based on cost-effective and scalable series impedance device that named as D-FACTS has been presented [5, 10]. These D-FACTS devices are better in reliability, easy controlling, cost effective, and less weighted than conventional FACTS devices [11]. These D-FACTS devices have been emerged as an alternative approach instead of conventional FACTS devices for power flow control and enhancement of power transfer from generating station to receiving station. The one thing is also noticeable that saving of electrical energy by D-FACTS devices reflects on coal consumption and environmental pollution by minimizing transmission losses and enhancing the loading capability that is also a very good advantage [12].

EPFC is a series D-FACTS device which works on impedance injection in the transmission line and alters the transmission line impedance to enhance the power flowing through transmission line. This device is mounted on the transmission line as small modules by using single turn transformer (STT). These D-FACTS devices works on two modes of operation which are by-pass mode and compensation mode, during by-pass mode it bypasses the power under the fault conditions through the parallel connected back to back thyristor switches and during compensation mode of operation the transmission line impedance is compensated for power flow control. The TCSC is also a series FACTS controller which changes the line impedance of system. This paper mainly discusses about development of FACTS and D-FACTS controller along with EPFC which is a distributed version of TCSC topology [13, 14].

II. FACTS GENERATION WITH PROPOSED WORK IN INDIA

There are various FACTS controller in power systems which were generated in a specified time series are shown in figure 1 and proposed work of FACTS controllers are also presents in the tables 1 & 2.

2.1. Generation of facts devices and their classification

In last few decades due to rapid increment in power demand the traditional methodology of power system has changed. Now, for power flow increment and to fulfil the power demand FACTS controller has been introduced. These devices make better utilization of existing power transmission line and increases power transfer capacity up to thermal limit. The transmission line parameters like impedance, bus voltage, and phase angle can be changed by these devices in efficient manner [15, 16].

The subsequent generation of FACTS controllers [7, 17] are shown in figure 1.

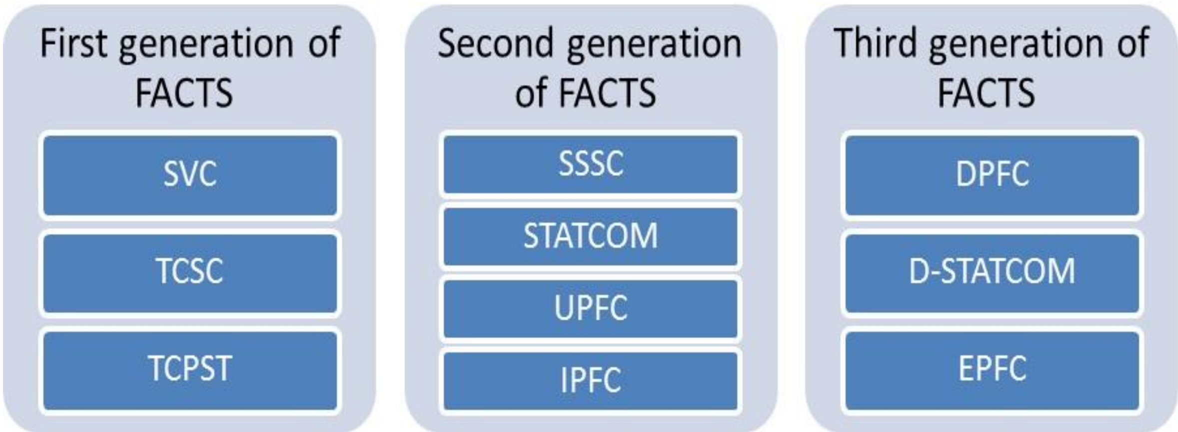

Figure 1. Generation of FACTS devices

The FACTS controller can be categorized mainly into four categories as shunt controller, series controller, combined series-series controller and combined series-shunt controllers. This classification is based on the connections of FACTS controllers with transmission lines. For switching of these FACTS controllers power electronics switches like thyristor, MOSFET, GTO and IGBT are used [13, 14].

By using different FACTS controllers, power transfer capacity through transmission lines can be increased in such a manner that their thermal limit do not get violated, losses minimized, power transfer increases, stability margin increases [18-20] *etc*.

Main different objectives of FACTS controller in power systems:

- To increase voltage stability limits of system

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- To mitigate sub synchronous resonance problems in the system
- To improve the damping of existing system
- To decrease short circuit currents of transmission line of system
- To improve transmission line's transient stability limits in system

FACTS devices are typically high-power, high-voltage power controllers, operating at 138–500 kV and 10–300 MVA, that are used to enhance power flow in the transmission and distribution network [3]. Shunt devices such as the static VAR compensator (SVC) and STATCOM, have been most widely used for reactive VAR compensation and voltage support for power system. Series devices such as the TCSC and the SSSC can be used for controlling active power flow on transmission lines. Series-shunt devices such as the UPFC can be used for voltage support and controlling of active power flow both with maximum flexibility, and higher cost.

2.2. Proposed work on facts in India

The demand of reactive power deteriorates the voltage profile and can cause system to make unstable and decreases the reliability. To overcome this problem some reactors (controlled and switchable) were proposed for reactive power support and to strengthen the voltage profile in the grid at different voltage levels [16]. STATCOM controllers are proposed at some strategic locations for dynamic voltage support in India which are 220 kV voltage level and their estimated cost is 57.70 crore rupees each as shown in table 1 [21].

Table 1. Suggested STATCOM installation projects in India

State	Sub-Station Location	MVAR ratings
Jammu-Kashmir	Budgam s/s	(+)125/(-)25
Jammu-Kashmir	Udhampur s/s	(+)125/(-)25
Rajasthan	Tinwari s/s	(+)50/(-)100
Andhra Pradesh	Urvakonda s/s	(+)100/(-)100
Maharashtra	Vita/Pandharpur s/s	(+)50/(-)100
Karnataka	Chitradurga s/s	(+)50/(-)100
Gujarat	Radhanpur s/s	(+)50/(-)100
Tamil Nadu	Theni s/s	(+)100/(-)50
Tamil Nadu	Kodikuruchi s/s	(+)100/(-)50
Tamil Nadu	Udaythu s/s	(+)100/(-)50

The STATCOM controller installation project is accounted around 704 crore rupees and these STATCOM controllers will be located at different proposed places from north to south in India. These controllers are cheaper instead of SVC at same rating when both are shunt connected controllers and used for increase power transfer and reactive power compensation. Some Bus reactors (controlled and switchable) are proposed at strategic locations for dynamic voltage support in which and 21 nos. are switchable bus reactors in India as shown in table 2.

Table 2. Suggested switchable bus reactors Installation projects in India

State	Sub-station Location	No. of units
Rajasthan	Bhadla, Akal, Bikaner, Jaisalmer	4
Maharashtra	Alkud	1
Gujarat	Solar Park-II	1
Andhra Pradesh	Kondapur, Hindupur	2
Karnatka	Davangiri, Hiriyur	2

D. Divan and H. Johal gave a term Distributed-FACTS in 2007 that has been emerged as a new technology for power flow control through transmission line instead of conventional FACTS controller. The D-FACTS controllers has advantages over conventional FACTS controllers as D-FACTS are cheaper and distributed over whole transmission line in small modules. The main advantage is that D-FACTS controllers don't require any break-in the transmission line and existing transmission network can be used to increase the power flow.

III.D-FACTS AND COMPARISION WITH CONVENTIONAL FACTS

In this section, the series D-FACTS controller and their working method have been explained followed by their comparisons with conventional FACTS controllers. The EPFC controller is also defined with its working methods.

3.1. Series D-FACTS controller

The transmission lines reactance is assumed to be purely inductive in nature. The impedance of line can be changed by injection of series passive capacitive or inductive elements in the transmission line and power flow transfer can be changed [7, 18, 19]. D-FACTS device can be used to change the series impedance of transmission line. D-FACTS are the advanced FACTS technology which is distributed over the whole transmission line as small modules between the small span of transmission lines as seen in figure 2 and they can offer series capacitive or inductive reactance in the line through STT [3, 20].

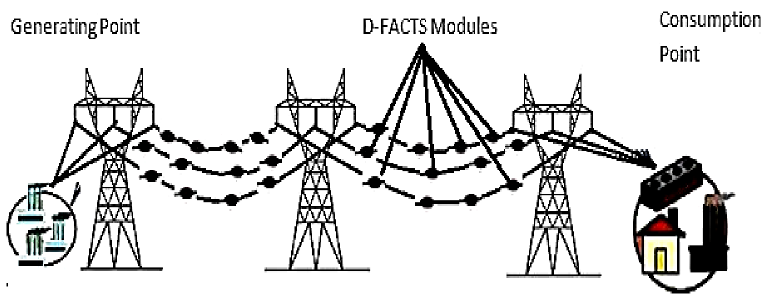

Figure 2. D-FACTS module connected on transmission lines

The conventional series FACTS devices like TCSC and thyristor controlled PST (TCPST) can control the power flow in transmission line by changing phase angle (δ) and line Impedance (Z) [22, 23]. But conventional FACTS devices increase the cost and complexity of the system because they require break in the line and a high voltage platform. For this control, series D-FACTS devices emerged as a substitute to control the power flow between lines which is a cost effective and simple device [24]. Figure 2 shows the D-FACTS modules connected on a power transmission line to control the power flow by changing the line impedance. Every module is rated about 10 kVA and floats on line both electrically and mechanically over transmission line. A large number of modules are working together to change the impedance or they can leave it unchanged. These modules work at extremely low cost and have high system reliability and there is no effect on system operation of some modules failure.

These D-FACTS devices are connected on transmission line by using a STT where transmission line acts as primary winding of transformer and secondary of transformer is connected with an inductor and a capacitor, both inductor and capacitor are connected parallel to each other with the secondary of STT. Inductor has back to back connected power electronic switches (IGBT or Thyristor). By using power electronics switches, injection of inductor can be controlled in circuit by firing pulses and the impedance of secondary side connected circuitry can be changed as shown in figure 3 and this secondary impedance can be transferred to primary by multiplying the square of turn ratio of transformer, thus the line impedance can be changed.

The power transfer can be changed in parallel lines when one is under loaded and other is overloaded. The under loaded lines power transfer can be increased up to their thermal limits by decreasing the total impedance of transmission line and overloaded lines power transfer can be decreased up to their safe limits of power transfer capability by increasing the total impedance of transmission line. Thus D-FACTS devices are efficient, cheap, less complex and easy controlling devices than conventional FACTS devices.

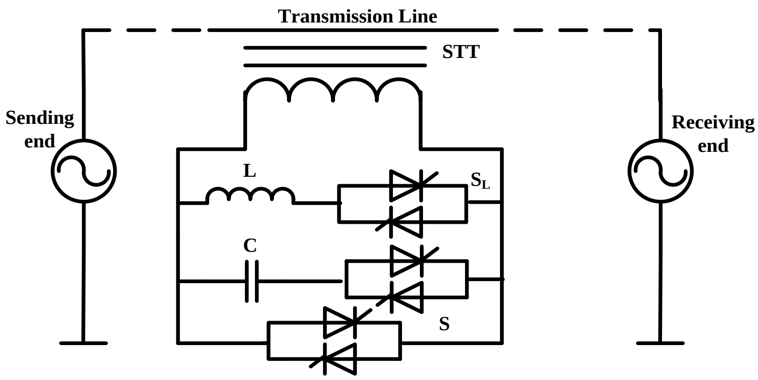

Figure 3. Simplified schematic of a D-FACTS device

3.2. Comparison between conventional FACTS and D-FACTS

There are so many advantages of conventional FACTS devices in the power system [23-25] and it has been also technically proven but the D-FACTS devices have some extra benefits like cost effectiveness, less weighted, easily controllable, reliable, doesn't require break-in the line, less maintenance, less repair time *etc.* On the basis of these benefits the D-FACTS devices can be proven much beneficiary instead of conventional FACTS controllers [4, 26] which are listed in table 3 and it is shown that the cost of D-FACTS controller is cheaper than the conventional facts devices. The cost of different FACTS devices and EPFC are shown in figure 4 [27-33] and it is observed that EPFC is cheaper than other conventional FACTS controllers.

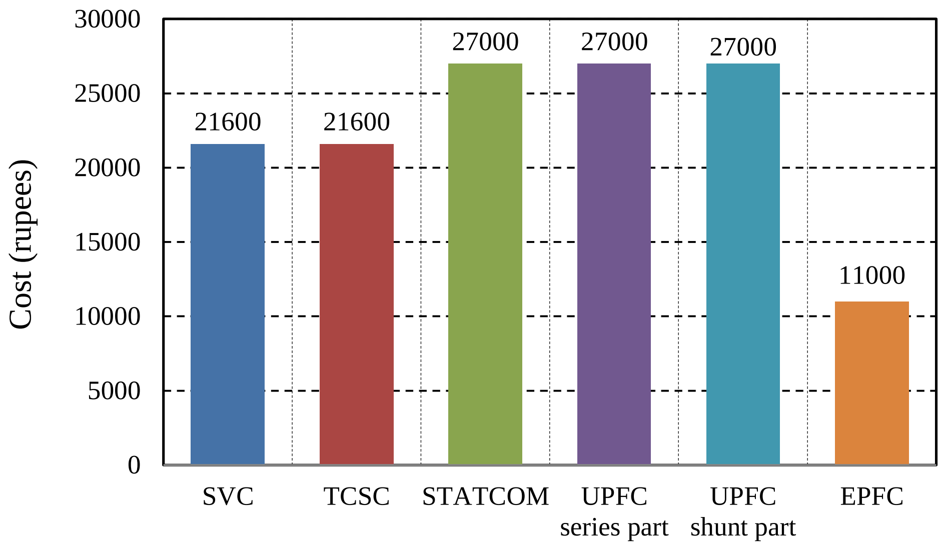

Figure 4. Cost comparison of Various conventional FACTS and controller

The static data for power rating and weight is also an issue for the less use of conventional FACTS rather than D-FACTS controllers as shown in table 4 by comprising conventional FACTS and D-FACTS devices [9, 11] and it has been shown that D-FACTS controllers are light in weight so these can be mounted on transmission lines.

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3.3. Enhanced Power Flow Controller (EPFC)

EPFC is a kind of D-FACTS controller which is distributed version of TCSC FACTS controller. The simplified schematic diagram of proposed EPFC is shown in figure 5 where a STT is connected with transmission line. The shunt connected inductor and capacitor are connected with secondary of STT with switch (S_L) and (S_C) and it is also shown that switch (S_L) is controlled with conduction angle control technique switch (S_C) is normally closed and switch S is normally remains open. The switch S is also connected in parallel with inductor and capacitors which is used in by-pass mode of operation.

Table 3. Comparision between conventional FACTS and D-FACTS

Characteristics	Conventional FACTS	D-FACTS
Break-in the Line	Required	Doesn't Require
Cost	Very costly than D-FACTS	Cheap
Size	Larger than D-FACTS	Small modules
Nature	Lumped	Distributed over whole Line
Weight	Higher than D-FACTS	Very less around (50-60) per module
Best Location to use	Can be used on line any where	Used on very small span of line about (1-2 mile for each module)
Control arrangements	Complex	Easy
Maintenance	Required and costly	Doesn't require, if required not too costly
Repair Time	Mean time to repair is much	Repaired single module which doesn't affect the line performance so no time required
Conventional transmission line	Cannot be used, it requires some changes.	Conventional transmission line can be used
Effects of fault on devices	May get damaged	By-passes the current so no chances to get damaged
Single point failure effect	Entire system may get damaged	No effect of single point failure
Future up-gradation	Not compatible	Compatible and easily upgradable
Work force	Skilled workforce required	Doesn't require because it can be repaired in factories as it is small in size

The EPFC mainly changes the impedance of transmission line by controlling the effective impedance by continuously varying the conduction angle (σ) of thyristor switch. EPFC is mounted on transmission line and connected in series to alter the transmission line impedance. Switch (S_C) is always turn on means capacitor is normally connected in parallel with secondary of STT.

Table 4. Comparison between FACTS and D-FACTS on the basis of weight and power

Constraints	Conventional FACTS	D-FACTS
Power rating	10-300 MVA per module	10 kVA per module
Weight	280-300 kg /10 kVA (average data)	50-60 kg. per module

Total inductive and capacitive reactance of EPFC is given by X_l and X_c respectively and X_{leak} is the leakage reactance of STT. The EPFC works in two modes of operations which are discussed below:

3.3.1. By-pass mode

The device operates in by-pass mode during fault condition and the device can be saved from damage due to high fault currents. The fault currents can be of 50000 A (75000 A peak), which can cause damage to the switches and control circuitry so this is very important to switch over to bypass mode whenever fault takes place. During this mode of operation no current flows through inductor and capacitor. Because the current is very high so it can cause harm to enhanced power flow controller. During faulty condition or strokes period secondary protection is provided as a break-over device that is attached between outer casing of transformer and cable to provide different path. Than Effective inserted reactance ($X_{inserted}$) in line during by-pass mode is:

$$X_{inserted} \cong X_{leak} \quad (1)$$

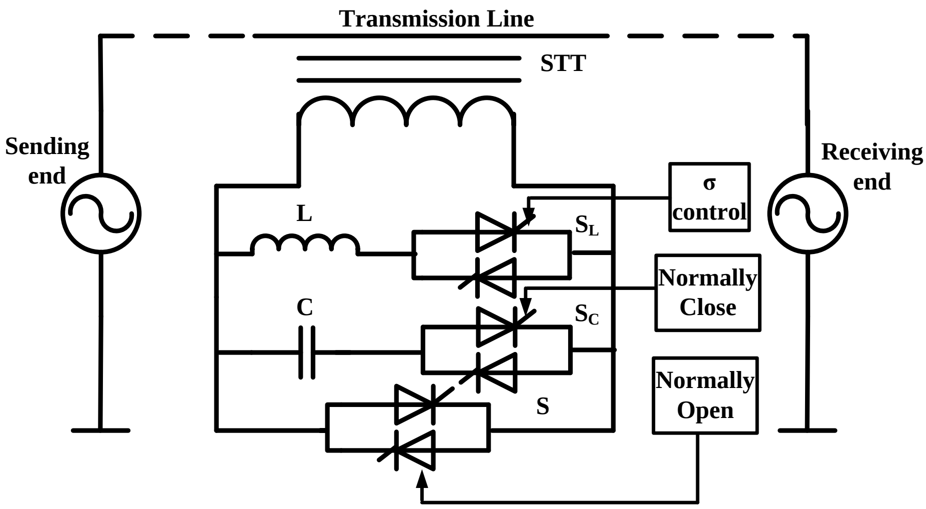

Figure 5. Simplified schematic of the proposed EPFC

3.3.2. Compensation mode

Capacitor is normally connected during the compensation mode and the inductance is connected with back to back thyristor switches which are controlled by conduction angle control technique. The conduction angle control feedback is given by feedback of control circuitry. During the compensation mode the switch (S) is normally disconnected and switch (S_C) is also connected and switch (S_L) controls the total effective impedance insertion of EPFC. The series capacitance insertion of EPFC affects the transmission line currents. Once an EPFC is inserted in transmission line the current doesn't remains sinusoidal due to the switching of EPFC and parallel combination of L and C. The total effective inserted reactance ($X_{inserted}$) in line during this mode is given by:

$$X_{Inserted} = X_{line} + (X_l \| -X_c) \quad (2)$$

when, $X_L > X_C$ then only EPFC works in capacitive mode of operation and when $X_L < X_C$ than EPFC works in inductive mode of operation and when these are equal than causes a sub synchronous problem.

IV. CONCLUSIONS

This paper presents a review on new approach to control power flow in transmission and distribution lines. D-FACTS controller uses economically available low power devices that offer the potential to reduce the cost of power flow control. Series VAR compensation using D-FACTS controller would help utilities to improve grid congestion, accepts delay in construction of new transmission lines, and increases system capability. D-FACTS device doesn't require change in utility structure and operate separately, with or without communications. These devices can operate with or without communication and continues the operation of the system during contingency periods. Under contingency periods the modules can return back to bypassed mode of operation. The high consistency, lesser cost and durability of these new devices makes them all the more eye-catching to use in power system.

In D-FACTS devices, the EPFC is a new power controlling device, which is distributed version of TCSC FACTS controller. This changes transmission line impedance to improve the power transfer capability and has smooth controlling of power flow.

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