INAE Letters (2018) 3:41–64
https://doi.org/10.1007/s41403-018-0035-2

REVIEW ARTICLE

Optimal Allocation of Flexible AC Transmission System Controllers in Electric Power Networks

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Received: 19 October 2017 / Accepted: 20 March 2018 / Published online: 5 April 2018

Abstract

Due to increasing power demand, incorporation of prosumers, continuous expansion, competitive market and inherent limitations of alternating current, the management and operation of power system has become very complex. For economical, reliable and secure operation, the use of emerging technologies is unavoidable. Flexible AC transmission system (FACTS) is one of the emerging technologies which does not only solve the problems but also gives new directions in existing high voltage AC (HVAC) and high voltage DC (HVDC) power systems. However, allocation of FACTS controllers i.e., determination of optimal location, size, number and type of these devices with minimized cost is a difficult problem. This paper, in broader sense, discusses FACTS allocation for the solution of issues of power system. The benefits and objectives of optimal allocation of FACTS have been reviewed from view point of objective functions, decision variables, constraints and recent optimization algorithms.

Keywords FACTS · Economic dispatch · Stability analysis · Power oscillation damping

Introduction

Electrical energy is a key performance indicator of standard of modern living, economy, business and industry. National grid works as a backbone in transporting electrical energy from source of generation to consumer. Traditional power grid focuses on conventional controls in generation, transmission and distribution of the electricity (Fang et al. 2012). The electromechanical structure, one way communication, centralized generation, fewer sensors, manual checks/recovery cause the following issues;

- *Technical issues* Active/reactive power control, power factor, loop flows, congestion, power loss, capacity, load-ability, thermal limits, dielectric limits, line contingencies, overloads, stability, power oscillations, sub synchronous resonance, power quality, interfacing energy storage, distributed generation interconnection, etc.
- *Economic issues* Economic dispatch, spinning reserve, investment cost, operation and maintenance cost, power loss, corona energy loss, etc.
- *Environmental and regulatory issues* Effects of electric field, effects of magnetic field, radio interference, audible noise, step, touch and earth voltage, safety of human, beauty of nature, visual impacts, de-regulated market, continuous expansion, amount of land used, right of way, corona glow, ground currents and corrosion effects.

Transmission of AC power over long distances (Molburg et al. 2008) can be enhanced by improving thermal limits, real-time monitoring, up-rating lines and power equipment. However, these reinforcements are only cautionary measures, some may be very costly and others may not a permanent solution. On the other hand, conventional controllers like fixed/switched resistors, capacitors, inductors, phase-shifting and tap changing transformers (Rao 2009) are electro-mechanical in nature, very slow and subject to wear and tear. Hingorani et al. (1988) proposed power electronic based custom power devices to solve the issues of distribution system. Later on, he introduced the concept of FACTS as a complete power system control and solution philosophy (Hingorani et al. 2000). The electric power industry switched from conventional controllers to FACTS-controllers when

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researchers claimed about the superiority of power electronics controllers. These controllers received the support of electrical equipment manufacturers (Habur and O'Leary 2004), utilities (Renz et al. 1999; Fardanesh 2002; Acharya et al. 2005), researchers (Farkoush et al. 2016; Doerksen 2013; Tang 2010) and research organizations (Helbing and Karady 1994). The operating parameters (i.e., voltage, current, phase angle) of a power system depend on the network parameters (i.e., inductance, capacitance, impedance). FACTS controllers can control both types of parameters.

FACTS enhance power transfer capacity (Canizares et al. 1998), load-ability (Kazemi and Badrzadeh 2004; Singh et al. 2006; Duan et al. 2016), loading margin (Chang 2012), voltage stability (Obadina and Berg 1990; Mohamed and Jasmon 1996), transient stability (Chatterjee and Ghosh 2007; Xia et al. 2014), power oscillation damping (Farsangi et al. 2004; Magaji and Mustafa 2009) and utilization of existing network assets (Pilotto et al. 1997). FACTS reduce losses (Phadke et al. 2009; Yuvaraj et al. 2017), manage congestion (Wibowo et al. 2011) and improve power quality (Sarker and Goswami 2016). Moreover, FACTS can control voltage profile (Faried et al. 2009), convert DC to AC, deliver power more efficiently and reliably (Karami-Horestani et al. 2014), prevent cascaded outages, voltage collapse (Yorino et al. 2003) and blackouts (Moazzami et al. 2013). FACTS increase flexibility (Hingorani et al. 2000), security (Verma and Srivastava 2005) of the electrical system and satisfaction of consumer (Farhangi 2010). FACTS can interface with distributed generation (Aziz et al. 2013; Mahdad et al. 2009) like photovoltaic/solar parks (Shadmand and Balog 2014), wind forms (Wang and Hsiung 2011; Zhao et al. 2010), small hydro/hydrothermal units (De Oliveira et al. 2000) and energy storage systems (Bahmani-Firouzi and Azizipanah-Abarghooee 2014).

However, FACTS technology is in developing stage, the cost of FACTS devices is very high (Khan et al. 2015) and action of these devices is directly influenced by proper location, size, type, number (Halacli and Demiroren 2016) and parameter setting (Mokhtari et al. 2013). To utilize FACTS efficiently and to make them cost effective, follow issues of optimal allocation (Kavitha and Neela 2017) and control (Mahdad et al. 2009) are of vital importance.

- What types of FACTS controllers installed for better performance of power system?
- How to economically estimate the number or quantity of FACTS devices
- How to optimize the size, rating and capacity of FACTS controllers to be installed in practical networks for better performance?
- Where in the power grid, FACTS should be placed, located or installed for better performance of whole of the power system?
- How to coordinate dynamically and inter-act multiple FACTS in the network to better exploit FACTS devices to improve power system performance?
- How to set or adjust the parameters of FACTS in the power system to assure stability, security limits and service continuity.

The problem of finding the best type of FACTS controllers with the best size and with best quantity installed at the best location(s) of the existing power system is referred as "optimal FACTS allocation problem". This paper discusses, in a broader sense, the issues of national grid and reviews the literature of optimal allocation of FACTS controllers. Moreover, this paper reviews the literature from view point of objective functions in FACTS allocation problem, constraints, decision variables and recent optimization algorithms.

FACTS Controllers, Their Potential Benefits and Challenges

The FACTS controllers can be categorized as series, shunt, series–series and series–shunt types. These can also be categorized as 1st generation (thyristor based) and 2nd generation (converter based) controllers. Some major types of power controllers are shown in Fig. 1.

Static var compensator (SVC) can act as a source of reactive power as well as a sink of reactive power whose output is adjusted to exchange capacitive or inductive current (Hingorani et al. 2000; Song and Johns 1999). The primary purpose in a network is usually to control the voltage at weak points. Thyristor controlled series capacitor (TCSC) is a series type compensator and it is used to increase power transfer as well as to enhance system stability (Kazemi and Badrzadeh 2004). Thyristor-controlled phase shifting transformer (TCPST) is a commonly used series-shunt FACTS device (Kai and Kusic 1988). Through controlling the voltage phase angle, TCPST controls the power flow of the branch where it is located. It adds a quadrature component to the existing voltage in order to increase/decrease its phase angle.

Static synchronous compensator (statcom) is a solid state synchronous voltage source that is similar to a standard synchronous machine but without any rotating part (Barrios-Martínez and Ángeles-Camacho 2017). Basically statcom consists of three main parts; voltage source converter (VSC), step down coupling power transformer and a control system. As compared to SVC, statcom produces a balanced set of sinusoidal voltage with very fast control over phase angle as well as amplitude (Song and Johns 1999). Static synchronous series compensator (SSSC) is also a VSC based converter that is serially connected to a transmission line

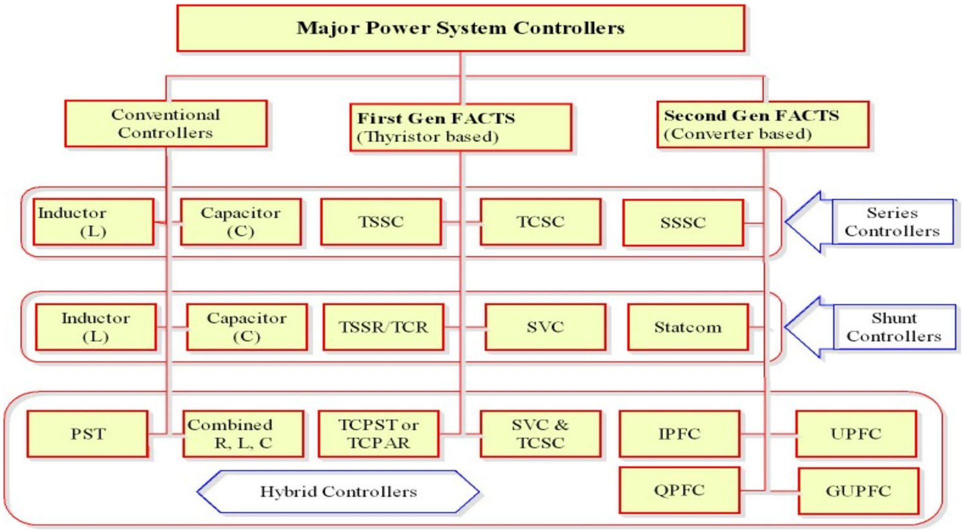


Fig. 1 Classification of power system controllers

through a transformer (Hingorani et al. 2000). As compared to TCSC, SSSC produces a balanced set of sinusoidal series voltage with faster control over phase angle as well as amplitude (Song and Johns 1999; Morsali et al. 2016). A unified power flow controller (UPFC) is capable of both supplying and absorbing real and reactive power. It consists of two voltage source converters (VSC). One of the two converters is connected in series with the transmission line through a series transformer and the other in parallel with the line through a shunt transformer. The dc side of the two converters is connected through a common capacitor, which provides dc voltage for the converter operation (Hingorani 2007; Edris 1997). As the series branch of the UPFC injects a voltage of variable magnitude and phase angle, it can exchange real power with the transmission line and thus improves the power flow capability of the line (Rajabi-Ghahnavieh et al. 2015). The shunt converter exchanges a current of controllable magnitude and power factor angle with the power system.

Interline power flow controller (IPFC) is a combination of two or more separate SSSCs. The simplest one consists of two converters which are connected in series with two transmission lines via transformers. The DC terminals of the converters are connected together via a common DC link. IPFC is a unified series–series controller that significantly controls power flow in multiple lines (Hingorani 2007; Edris 1997) rather than control of power flow in a single line as by UPFC or SSSC. Due to high cost, quality issues and reliability concerns, deployment of FACTS in distribution system (D-FACTS) is increasing as compared to transmission system (Sarker and Goswami 2016). Being light in weight, D-FACTS devices can clamp onto lines rather than a separate building. Furthermore, D-FACTS devices are very much faster, can communicate with other devices or a central control for distribution automation and SCADA and integrate DGs (Aziz et al. 2013), ESS (Bahmani-Firouzi and Azizipanah-Abarghooee 2014) and renewable power sources such as wind, solar (Shadmand and Balog 2014), small hydro (Chaudhry et al. 2016) with power system.

Potential Benefits of FACTS

The FACTS controllers can:

- Minimize the electrical length of transmission lines, power flow loops, losses, voltage violations, operations of tap changing transformer and shunt capacitors.
- Manage congestion and reduce overloading.
- Enhance capacity of lines to their thermal limits and increase load-ability.
- Can force current flow in cold weather conditions to prevent ice formation.
- Provide dynamic reactive power support, voltage regulation and control power flow dynamically to reduce disturbances. Direction of power flow can be changed easily.
- Can be switched in the line instantly to reduce fault current and short circuit levels.
- Prevent the power system from large power swings, blackouts and cascading outages.
- Can counter sub-synchronous resonance problem and damp low frequency oscillations.
- Withstand contingencies and load cannot cause voltage collapse.
- Improve power quality by 3-phase voltage balancing, mitigate flicker and work as active harmonic filters to control wave shape of voltage and current.
- Control power dynamically and reduce operating margin or spinning reserve.

- Provide greater flexibility and stability in interfacing energy storage systems and energy sources (solar, wind, small hydro).
- Can be used as high power–frequency converters in megawatt range and synchronize power sources operating at different frequencies.
- Required rating of FACTS is less than 100% of the transmission throughput rating.
- Have cost five to seven times lower than HVDC for the same throughput.

Challenges for FACTS Devices

The price of semiconductor switches, power transformers, inductors and capacitors have not decreased as were predicted. The ESS are also are very much costly (Muyeen et al. 2009). The cost of FACTS controllers is two to three times higher than conventional controllers (Eslami et al. 2012). The voltage and current rating of FACTS components i.e., thyristors, ETO, IGBT, etc. in FACTS (de Souza et al. 2008) is limited. The cascaded multilevel converters have to be used in high power applications. It is quite difficult to diagnosis reason of malfunctioning of electronic equipments in FACTS (Lotfifard et al. 2013). Each fault in power system also requires very specific measurement from one or multiple substations and ends of the line. Electronic switching components in FACTS inject harmonics into the grid (Kezunovic 2011) and potentially produce voltage distortions (Colak et al. 2016). Especially, TCR and TSC permit continuous inductive compensation and discontinuous capacitive compensation, respectively (Carrasco et al. 2006). Similarly, SVC produces 3rd, 5th and 7th harmonic currents into the power supply system (Colak et al. 2016) and current compensation capability of SVC becomes smaller at lower voltage (Kulkarni and Udupi 2010) because it operates in continuous compensation. TCSC, TSSC and SSSC cannot be handle transmission angle problems. For instance, the prevailing transmission angle may not be compatible with the transmission requirements of a given line (Glanzmann 2005) and it may vary with daily or seasonal system loads (Gavrilovic et al. 2003). A statcom is superior to SVC in terms of its stability margin and response time but statcom and other VSC based controllers (SSSC, UPFC and IPFC) suffer from higher cost, higher loss and complex control strategy (Jiang et al. 2011). The lifetime of a standard voltage source PWM inverter is affected by the electrolytic capacitor used in power decoupling (Blaabjerg et al. 2004). In multi-level PWM inverters used for high power applications, higher switching losses and unbalanced voltage occur due to the series-connected string of switches (Kjęr and Blaabjerg 2003). In addition to the issues discussed, FACTS have also following challenges when used in power systems;

- Power transmission systems are designed and constructed to use symmetrically and handle bi-directional power flow. The action of distance-relay depends upon the impedance of the line to be protected and tells the location of fault in zones. When a controller is installed on existing line, it significantly changes the effective impedance of the line/zones to be protected; this in-turn leads malfunctioning and disrupts the performance of protective relays especially distance relays.
- The distribution system is originally designed to handle unidirectional power flow (asymmetric) from utility to end users. The addition of D-FACTS with ESS and renewable energy sources lead to flow bi-directional power. This feature also affects and disrupts the performance of protection system. Due to bi-directional power flow, FACTS normally increase short circuit currents.
- If FACTS are not properly sized and located, they may lead to over-voltages, excessive power losses and may also cause stability issues.
- Power oscillation damping controller can be attached to the reactive power control loop for overcoming the interference between active power modulation and shaft torsion modes oscillation (Pillai et al. 2002). However, they introduce oscillations to the terminal voltage for a while before it dies out (Padiyar and Prabhu 2006).
- The steady state models cannot be used to study real time operations of power system. Moreover, un-coordinated design may deteriorate the power system performance. So, transient modeling and coordinated design of these devices is another requirement (Shayeghi et al. 2010a).
- Transient over load capability of devices is not as much as generators or other transmission equipment.
- Long term reliability and equipment life is not well established.
- Technology is continuously changing and still under research.

Previous Reviews and Contribution of Present Review

In order to differentiate our work from the existing work, we review the existing surveys conducted on FACTS allocation in electric power networks. Moreover, we highlight the inherent peculiarities of power systems which render the FACTS allocation schemes applicable to distribution and renewable generation. A comparative summary of existing surveys is shown in Table 1.

The work in Germond (2002) is very short and tutorial type and no classification of optimization algorithms has been provided. In Singh et al. (2009), the authors discussed component ratings, size and capacity of statcom in real world but focused on design, control issues, network

Table 1 Existing reviews/surveys related to FACTS allocation

References	Opt. type	OFS	OF	Application/objective	Con	Tool	Decision variable	FACTS type
Germond (2002)	No	GA	Single	Load ability	No	No	Location	SVC and TCSC
Singh et al. (2009)	No	No	No	Multi	No	Yes	Rating/size	Statcom
Singh et al. (2010)	Yes	Multi	Multi	POD, stability	No	No	Placement	All
Singh (2011)	No	No	No	Stability	No	No	Placement	All
Eslami et al. (2012)	No	No	No	Multi	No	No	Placement	All
Sautua (2013)	Yes	Multi	Multi	MOO	No	No	Location	Multi type
Dixit (2014)	No	No	Conv. multi	Stability, min loss	No	No	Size and placement	TCSC
Dubey et al. (2014)	No	Heuristic	Multi	Multi objective	No	No	Placement and sizing	SVC and statcom
Jamhoria and Srivastava (2014)	No	No	Multi	Multi objective	No	No	Size and Location	TCSC
Chindhi et al. (2013)	Yes	No	Multi	Multi objective	No	No	Location	(HPFC), (UPFC)
Singh et al. (2015a)	Yes	Yes	Multi	Multi	Yes	No	All	
Jordehi (2015)	No	PSO	Single	Multi	Yes	No	Location	Multi type

OFS optimization function specific, *OF* optimization function, *Con* constraints

architectures, their potential application areas and the future research avenues. In Singh et al. (2010), the authors focused on the problems of voltage profile, security, small signal stability, transient-stability, power transfer capability and load-ability and damping of power system oscillations with some methods of placements. In Singh (2011), author presented a comprehensive review on enhancement of power system stability. FACTS devices have been considered only for placement, there is no much information on optimization based methods and algorithms. In Eslami et al. (2012), the authors presented an extensive analysis on the research for power system stability using FACTS devices. However, a very little literature about location and feedback signals in designing of FACTS controllers was discussed.

A review has been presented in Sautua (2013) regarding optimal allocation of FACTS. The researchers divided the optimization techniques in four methods; classical optimization methods, technical criteria based methods, simulation based methods, heuristic and meta-heuristic methods. In Dixit (2014), authors reviewed optimal placement, sizing and proper installment of FACTS devices for minimization of transmission loss and enhancement of stability of power system. Similarly, in another survey paper (Lotfifard et al. 2013), authors reviewed heuristic optimization techniques used for optimal location and sizing of SVC and STATCOM. FACTS allocation with respect to applications, decision variables, optimization, tools and constraints have not been considered in detail. Jamhoria and Srivastava (2014) reviewed optimal placement and sizing of TCSC. Different optimization techniques with single objective as well as multi objective were discussed in optimal power flow, voltage stability, transient stability enhancement, congestion management, loss minimization. In another review (Chindhi et al. 2013), authors focused on placement and comparison of HPFC, UPFC and Sen-transformer. In the most recent survey (Singh et al. 2015a), different FACTS technologies and their impact on power systems have been discussed and analyzed. The allocation problem is categorized from perspective of the used optimization algorithms, objective functions, constraints, decision variables and used technology. Jordehi (2015a) reviewed the applications of PSO for FACTS allocation problem. The objectives, parameter selection, objective handling strategy, constraint handling strategy and discrete variable handling strategy discussed deeply. Considering the described reviews already done on FACTS allocation problem, the current review distinguishes from those reviews in the following terms.

- Unlike previous reviews, in this review, a comprehensive classification of available research on problems of conventional grid and FACTS controllers will be done.
- In this review, FACTS allocation with respect to power system objectives and constraints will be discussed.
- Unlike most of previous reviews, in the current review, allocation problem with respect to applications, decision variables and tools will be discussed.
- In most of previous reviews, a very limited number of optimization algorithms, applied to allocation problem, have been reviewed, however, in the current review, a very extensive and diverse set of recent optimization algorithms, applied to optimal FACTS allocation problem, will be reviewed.

Problems of HVAC Transmission

Technical debates on HVDC and HVAC transmission have been reported in Hammerstrom (2007) and Taylor et al. (2016). Thomas Edison (1847–1931) and Nicolas Tesla

(1856–1943) were pioneers of DC and AC, respectively. Edison was being self-educated and working at Cooper Union lit the world Pearl Street in New York on September 4, 1882 with 110 V DC (Kalair et al. 2016; Wang et al. 2013) and gave a bright future for DC system (Wang et al. 2013; Baldwin 2001). Tesla (Carlson 2013) was a graduate from Graz University of technology, Austria. He invented the AC for twentieth century by creating the major electrical change (Cheney 2011) i.e., lighting World Columbian exposition fair Chicago on 16 November, 1893 by two phases, 240 V, 25 Hz AC supply (Cheney 2011). Edison 1st invented the lamp and then designed DC motor while Tesla built AC motor. General Electric Company left back the Edison's DC and Westinghouse Company backed the Tesla's AC as AC/DC rotary converters were designed to interconnect both AC and DC systems. American companies continued generation and distribution of power at 110 V DC as well as 110 V, 25 Hz (AC) while European at 110 V DC and 110 V, 16.7 Hz (AC) but after World War-II, Americans shifted to 3-phase 120/230 V (60 Hz) while Europeans started 3-phase 120/230 V (50 Hz) and later on 3-phase 230/400 V (50 Hz). As the AC voltages were stepped up/down with transformer, so AC network began to expand vastly. War of DC and AC currents between Edison and Tesla changed into the war of high voltage AC and DC transmission. It is often said that 50 Hz power supply is 10–20% less efficient than 60 Hz power supply. In case of AC, cables charge and discharge due to capacitance during every cycle, but in case of DC, cables charge only once or at the time of switching. Theoretically, a transmission system can be loaded up-to its thermal limits but practically it is only true in case of HVDC whereas in HVAC, power transfer is limited due to line reactance, thermal limits, dielectric limits and stability limits (Beaty 2006). HVDC transmission lines are recognized as an efficient alternative of HVAC lines (Hammerstrom 2007; Taylor et al. 2016). HVDC transmission is also more economical than HVAC beyond 600 km (Rao 2009). A comparison (Molburg et al. 2008) is shown in Table 2.

Review from View-Point of Objectives in FACTS Allocation Problem

In this section, some literature on FACTS allocation problem is reviewed from the viewpoint of decision variables, constraints and objectives present in objective function.

Economic Dispatch/Minimize the Cost

Cai et al. (2004) analyzed optimal location and size of FACTS for economic generation and dispatch. The authors proposed TCSC to relieve congestion (Javaheri and Goldoost-Soloot 2012) and enhanced the security (Bathina and Gundavarapu 2014), of power system considering generation

Table 2 Comparison for HVAC and HVDC transmission systems

S. no.	Characteristic	HVAC transmission	HVDC transmission	System preferred
1	Power transfer	Low and limited	High	HVDC
2	Power control	Slow, difficult	Fast, accurate	HVDC
3	Frequency disturbance	Can transfer	Reduced	HVDC
4	System support	Oscillatory	Excellent pod	HVDC
5	Transient performance	Poor	Excellent	HVDC
6	Fault levels	Increased	Un-changed	HVDC
7	Power swings	Long time	Quick damping	HVDC
8	Submarine cables	Charge/discharge	No charge/discharge	HVDC
9	Multi-terminal	Economical	Costly	HVAC
10	Reactive power flow	Occurs	Not-possible	HVDC
11	Cascaded tripping	Likely	Avoided	HVDC
12	Frequency conversion	Not possible	Possible	HVDC
13	Back-to-back	Not possible	Possible	HVDC
14	Spinning reserve	Not reduced	Reduced	HVDC
15	Transient stability	Less than half of thermal limit	Very high, up-to thermal limit	HVDC
16	Congestion and loop flows	Depend on path impedance	Do not occur	HVDC
17	Protection	Difficult	Easy	HVDC
18	Breakers	Simple	Special	HVAC
19	Right of way	More	Less	HVDC
20	No. of conductors	Six	Two	HVDC
21	Skill and cost	Medium	High	HVAC

cost. In Rahimzadeh and Bina (2011), the authors developed a new objective function to manage congestion and placement of statcom and SSSC. If a congested line is managed so that the difference of nodal prices is decreased, the congestion of transmission lines is decreased too. In Milanovic and Zhang (2010), authors formulated objective function to reduce overall financial losses in the network due to voltage sags by using SVC, statcom and DVR. The cost of the individual devices along with their installation costs and annual maintenance are taken into account in the optimization procedure (Hooshmand and Ezatabadi 2010). Yousefi et al. (2013) developed an objective function consisting of network active-power loss, cost of SVCs, voltage deviation and power-flow limits violation. The FACTS allocation with minimum cost, discussed in Cai et al. (2004), Javaheri and Goldoost-Soloot (2012), Bathina and Gundavarapu (2014), Rahimzadeh and Bina (2011), Milanovic and Zhang (2010); Hooshmand and Ezatabadi (2010), Yousefi et al. (2013) Balamurugan et al. (2015), Alabduljabbar and Milanović (2010), Krishnan et al. (2016), Bhattacharyya and Gupta (2014) and Bhattacharyya and Kumar (2016) is shown in Table 3.

Minimize Loss and Voltage Deviations

In Singh et al. (2015b), the authors addressed ORPD problem to minimize power loss and absolute value of total voltage deviations without FACTS device at IEEE-30, -57 and 118-bus systems. In Roy et al. (2011), the authors discussed the objective of real power loss and voltage deviations using multiple TCSC and TCPS devices at IEEE 30-bus system. Abdelaziz et al. (2011) formulated objective to minimize the total losses and number of TCSCs at modified IEEE 30-bus system. Taher and Afsari (2014) formulated an objective function to minimize the size of D-statcom, voltage deviation and power loss in distribution network. The studies reviewed are listed in Table 4.

Maximize Capacity and Load-Ability of Lines to Thermal Limits

In Alabduljabbar and Milanović (2010), the placement of SVC, TCSC, TCVR and TCPST for increasing available transfer capability (ATC) was discussed. Jirapong and Ongsakul (2007) discussed the same objective to minimize the loss, voltage difference index and to maximize power index by utilizing FACTS controllers.

The proposed method was tested with different locations of TCSC, SVC, TCPST and TCVR at IEEE 30-bus, 345 kV Taiwan power system. Rao et al. (2016) calculated static as well dynamic ATC based on continuous power flow, linear sensitivity methods, iterative methodology and constant power model without and with FACTS devices. The results show that ATC increases in the presence of UPFC and Sen Transformer. The objectives of power transmission loss, power flow in the transmission lines and voltage difference between buses were discussed in Huang and Huang (2014). The capacity was maximized by optimal allocation of FACTS devices. In Ghahremani and Kamwa (2013) and Srikumar et al. (2014), authors proposed TCSC for maximizing load-ability of transmission lines. The articles reviewed are shown in Table 5.

In Ara et al. (2012), the authors formulated objective function to minimize the total fuel cost, load-ability and power loss with and without considering cost of installation of FACTS.

Minimize Overloads and Manage Congestion (N – 1 Contingency Analysis)

Line outage contingencies in power systems are likely to result in line overloads, bus voltage deviations and excessive line loss. TCSCs effectively relieve overloads and line outage contingencies. The problem has been discussed in articles as shown in Table 6.

Enhance Steady State and Voltage Stability

Steady state stability is the ability (Zhang et al. 2006) of the power system to continue synchronous operation of machines when subjected to a small disturbance. In power networks, voltage instability occurs when some disturbance such as load variation, line trip, and generator outage occurs in overloaded line (Ahmad et al. 2014b). A higher probability of voltage instability results when transmission lines are more heavily loaded nearer to their upper limits of stability (Ahmad et al. 2014a). A variety of traditional control strategies, such as load shedding, energy rescheduling, economic dispatch (Rabiee et al. 2012), conventional controls (Zhang et al. 2010) and series/shunt capacitors, have been used to maintain voltage stability. In Saravanan et al. (2007), the location of UPFCs is investigated for voltage stability dynamically. A few articles studied on the topic are well elaborated in Table 7.

Sedighizadeh et al. (2013) proposed reactance model and injected power model of TCSC and SVC to enhance voltage stability and minimized active power loss, voltage stability index and voltage deviation. In Kumar and Srikanth (2015) and Gopinath and Kumar (2016), the optimal location and sizing of UPFC was proposed to enhance the dynamic stability. Phadke et al. (2012) proposed optimal placement and sizing of shunt FACTS to enhance stability in terms saddle-node bifurcation and minimized voltage deviation. Dutta et al. (2016a, b) investigated stability of power system by minimizing loss, voltage deviation and voltage stability index. In Dutta et al. (2016a), optimal location of

Table 3 Minimize cost (active power/economic dispatch)

Objective	Type of FACTS	Decision variable	Test system	Solution algorithm	Findings/application	References
Minimize generation cost, investment cost, operation cost, etc.	Multi type	Location, rating, type	14 bus	GA	An effective and practical method in large power systems	Cai et al. (2004)
	TCSC	Locating and sizing	14 bus	HSA	HSA gives better size of TCSC that lead to more saving when compared with PSO and CRCM	Javaheri and Goldoost-Soloot (2012)
	TCSC	Location	5, 14, 30-bus	FFA	FFA produces better results and has fast computing than GA and DE	Bathina and Gundavarapu (2014)
	TCSC and others	Location and number	5 bus	DE	TCSC and DE gives better result than all types of FACTS with EP	Balamurugan et al. (2015)
	SVC, TCSC TCVR/TCPST	Location and type	39 bus	OPF and GA	Increased power and improved damping of electromechanical oscillations.	Alabduljabbar and Milanović (2010)
	Statcom and SSSC	Location and number	14, 30 and 118 bus	MINP, SQP and GA	Analysis with converter power loss, optimal operation by SQP and placement by GA	Rahimzadeh and Bina (2011)
	SVC, TCSC and UPFC	Location	4-bus, 24-bus	EP	Total overloads and total SOL were reduced. Real power contracts were established	Krishnan et al. (2016)
	SVC, DVR and statcom	Type, size, locations	10 bus	Niching GA	Larger the investment/mitigation measures, the bigger the reduction in costs	Milanovic and Zhang (2010)
	SVC and statcom	Size, rating and cost	57-bus	(BF-PSO) MINLP	For reactive power planning (RPP), bus facing minimum voltage is selected.	Hooshmand and Ezatabadi (2010)
	SVC and TCSC	Placement and location	30 bus	Fuzzy GA, EA and PSO	Weak node detection and simultaneous optimal parameter settings in a power system	Bhattacharyya and Gupta (2014)
	SVC and TCSC	Location	30 and 57 bus	GSA	GSA based approach is compared with GA, DE, PSO	Bhattacharyya and Kumar (2016)
	SVC	Location and size		NSGA II	System security, power flows and voltages in steady sate by non-dominated sorting genetic algorithm	Yousefi et al. (2013)

Table 4 Minimize loss and voltage deviations

Objective	Type of FACTS	Decision variable	Test system	Solution algorithm	Findings/application	References
Minimize loss, voltage deviation and size/no of FACTS	Nil	Nil	30, 57, 118-bus	ALC-PSO	An effective and fast method for solving the ORPD problem in large power systems	Singh et al. (2015)
	TCSC, TCPS	Placement	30-bus	Biography based	BBO approach is better than PSO, real-coded GA, and DE	Roy et al. (2011)
	TCSC	Location, no	30-bus	GA	TCSCs sized, located and selected to improve performance and system stability	Abdelaziz et al. (2011)
	Dstatcom	Location, size	33, 69-bus	Immune algorithm	Overall 10.9 and 18% power loss reductions in distribution systems	Taher and Afsari (2014)
	UPFC, IPFC, OUPFC	Location, placement	5, 14 bus	Sensitivity analysis	FACTS device are capable of controlling both active and reactive power	Rao and Rao (2015)
	UPFC, TCSC, IPFC	Location	30 bus	CS and GA	Cuckoo search (CS) and GA ensure good stability and better convergence	Akumalla et al. (2016)

statcom was suggested at IEEE 30-bus and IEEE 57-bus while in Dutta et al. (2016b), optimal allocation of SVC and TCSC was worked out at IEEE 14-bus and 30-bus systems. In Moazzami et al. (2013), the authors investigated stability improvement in terms of vulnerability of system, reactive power generation and cost of SVC, TCSC and statcom.

Transient Stability Improvement

The ability of the power system to continue synchronous operation of machines when subjected to sever/large disturbance is called transient stability (Kundur et al. 2004). The system reaction involves large excursions of machine rotor angles and whenever corrective actions fail, synchronism is lost (Kundur et al. 1994). If system has low transient stability, major blackout can occur during contingency/fault condition. If the system experiences no blackout, low transients can break the rotor of the generators. SVC and statcom are highly efficient in improving the transient stability of the system (Hingorani et al. 2000). The shunt FACTS controllers give highest benefit of increase in power transfer when located at the intermediate of the line (Rashid 2009; Ooi et al. 1997). The maximum capacity is based on location and model of short transmission line. Panda and Patel (2007, 2009) proposed location of shunt FACTS devices with exact line modeling to improve transient stability of longer transmission lines. Table 8 shows articles reviewed on the topic of FACTS allocation from view point of transient stability.

Dezaki et al. (2013) proposed objective function of the transient stability in terms of capacity and phase angle with optimal allocation of SSSC at 6-bus and 57-bus system. Aghaei et al. (2016) analyzed an appropriate criterion for the transient-stability evaluation in term of CTEM that has a linear performance over a wide range of the system changes. Jain et al. (2009) analyzed the structure to preserve energy function by placement of statcom and UPFC at 39-bus and 246-bus system.

Power Oscillations Damping (POD)

The voltage instability, small signal local oscillations, asynchronous inter-area oscillations and the hidden failures of relays are the main reasons for cascaded outage and blackout (Pourbeik and Gibbard 1998). PSSs are

Table 5 Maximizing available transfer capacity and load-ability

Objective	Type of FACTS	Decision variable	Test system	Solution algorithm	Findings/application	References
Max TTC, ATC and load ability	Multi-type	Placement	30, 118-bus	HEA	HEA integrates EP, TS and SA enhances more TTC than others and hence efficient	Jirapong and Ongsakul (2007)
	SSSC, UPFC statcom	Location	30, 57 bus	Firefly algorithm	Scheduling of generator is decided to decrease the system severity	Rao et al. (2016)
	TCSC, SVC TCPST, TCVR	Type, location	30-bus, 345 kV	Ant and HSA	Improves steady state control and transfer capability of Taiwan power	Huang and Huang (2014)
	Multi type	Allocation type, no		GA	Simulation and testing FACTS in PSs using GUI, a user friendly tool	Ghahremani and Kamwa (2013)
	TCSC, SVC	Location	14 bus	OO	Loading capacity enhanced by OO is greater than PSO	Srikumar et al. (2014)
	TCSC	Location, size	6, 30 and 118 bus	Min cut, KCI	Maximizes load ability with reduced search space and clear formulation	Duong et al. (2014)
Min losses and change in powers	PST, HFC, UPFC	Location setting	14-bus	GAMS, e-constraint	HFC gives best satisfaction based on technical and economical aspects	Ara et al. (2012)

Table 6 Minimize overloads and manage congestion (N − 1 contingency analysis)

Objective	Type of FACTS	Decision variable	Test system	Solution algorithm	Findings/application	References
Minimize overloads, voltage deviations and losses	TCSC	Allocation		TLBO, LWS	TLBO is better than GSA, NLP, PS and FSO for $N-1$ and $N-2$ line contingencies	Jordehi (2015b)
	TCSC, SVC	location and setting	57 bus	BSOA	Better voltage profile and lower voltage deviations during contingencies	Jordehi (2015c)
	D-TCSC	Allocation	14, 118-bus	ELPSO	D-TCSC's are better for $N-1$ and also for simultaneous outage of four branches	Jordehi et al. (2015)
	TCPST, TCSC	Allocation	39 bus	ICA	ICA is better than ABC, GSA, EP and bat swarm optimization	Jordehi (2016)

Table 7 Enhance steady state Stability

Objective	Type of FACTS	Decision variable	Test system	Solution algorithm	Findings/application	References
Min losses, voltage deviation and voltage stability index	SVC, TCSC	Location, setting	14 and 30 bus	NDSPSO, fuzzy	Scheduling and utilization of the power system	Sedighizadeh et al. (2013)
	UPFC	Location, size	14 and 30 bus	Hybrid of ABC,GSA	Maximum power loss bus is identified for fixing UPFC	Kumar and Srikanth (2015)
	UPFC	Location, capacity	14 and 30 bus	CS and MFA	Enhanced searching capability, degradation in complexity	Gopinath and Kumar (2016)
	SVC, statcom	Placement, size	14 and 57 bus	Fuzzy-GA	Min size of the shunt devices, max distance to saddle-node bifurcation,	Phadke et al. (2012)
	Statcoms	Location	30 and 57 bus	CRO	CRO is robust and suitable for sizing and locating statcom	Dutta et al. (2016a)
	SVC, TCSC	Allocation	14 and 30 bus	QOCRO	Higher quality solution in reasonable computational time with FACTS	Dutta et al. (2016b)
Min VI, VAr and cost	SVC, TCSC statcom	Location, size	39 bus	APSO	Min vulnerability index (VI) and blackouts to improve stability	Moazzami et al. (2013)

commonly used to damp out oscillations (Martins and Lima 1990). However, FACTS controllers provide much better damping of oscillations than PSS. The usefulness of damping is based on parameter setting and location of FACTS (Okamoto et al. 1993). Tuning of parameters is proposed in Son and Park (2000) for weakly damped inter-area mode. Chaudhuri and Pal (2004) and Farrangi et al. (2004) selected appropriate feedback signals to FACTS devices for improving the damping. Martins and Leonardo (1990) suggested placement of PSS and SVC to improve damping using zeros of the transfer function. The placement of SVC, TCSC TCVR and TCPST for enhancement of POD was also studied in Ni (1998). Martins and Lima (1990) and Okamoto et al. (1995) considered the placement of SVC and TCSC based on single operating order but did not addressed placement of UPFC. Kumar et al. (2007), a new set of controllability indices were proposed for placement of the UPFC, TCSC and SVC for critical contingencies. The objective of small signal stability was investigated in Mondal et al. (2012) using allocation of SVC and TCSC controllers. TCSC controller is better than SVC in mitigating the problem even during higher loading. In Farsangi et al. (2007), SVCs were analyzed to damp out power oscillations effectively. In Kumar (2010), authors discussed and compared a number of control methods for damping unwanted electro-mechanical oscillations. Different types of PI controllers have been proposed in Jiang et al. (2010) to control operation of UPFC and IPFC for damping power oscillations (Fujita et al. 1998). PI controllers are usually designed based on linear model and certain conditions of the network. Such PI controllers may not have an appropriate dynamic response (Jiang et al. 2011) with different loading situations and disturbances Shayeghi et al. (2010c). The auxiliary damping controllers i.e., FACTS are added to PI controllers to inject additional stabilizing and damping signals (Arabi et al. 2002). In Hameed et al. (2008), a self-tuned fuzzy PI controller was suggested for TCSC to improve power system dynamic performance. The progress of articles reviewed and discussed on the topic of POD is given in Table 9.

The damping of oscillations was improved significantly through the fast control of UPFC and IPFC (Isazadeh et al. 2016). Shayeghi et al. suggested optimal tuning of PSS, TCSC (Shayeghi et al. 2010a, b) and UPFC (Shayeghi et al. 2010c) for improving the objective of POD in terms of settling time and overshoots.

Table 8 Enhancing transient stability

Objective	Type of FACTS	Decision variable	Test system	Solution algorithm	Findings/application	References
Min rotor angle deviation	SVC, statcom	Location, size	2 area machine	GA	Improved stability of two hydraulic generating units of 1400 and 700 MVA	Panda and Patel (2007)
Min invest. cost, settling time and overshoots	SVC	Size, site, no and setting	39 bus, 10 machine	MOPSO	SVC can improve greatly the transient stability of the multi-machine system	Gitizadeh et al. (2014)
Min function of capacity and phase angle	SSSC	Allocation	6 and 57 bus	SA and GA		Dezaki et al. (2013)
Min CTEM, CTKE and CCT	SVC, TCSC, UPFC	Type	3, 39 and 145 bus	Simulation, Lyapunov	Results of energy functions for direct and simulation methods are almost equal	Aghaei et al. (2016)
preserve energy function	Statcom, UPFC	Placement	39 and 246 bus	SA	Potential energy, contributed by facts influenced the transient stability	Jain et al. (2009)

CTEM corrected transient energy margin, *CTKE* corrected transient kinetic energy, *CCT* fault critical clearing time

Power Quality and Interfacing PS with ESS, DGs and DFIGs

Energy storage applications deliver short-term power to improve quality, voltage support and frequency support for renewable generation smoothing and end user energy management (Bahmani-Firouzi and Azizipanah-Abarghooee 2014). The power quality improvement and integration of FACTS devices with renewable energy sources reviewed is shown in Table 10.

The role of FACTS devices for the dynamic stability of power system is investigated in Kumar and Khan (2008) using a variable speed doubly-fed induction generator model. The impact of FACTS parameters and short circuit faults on wind turbine induction generators were discussed in Grainger et al. (2014).

Methods and Techniques Used in FACTS Allocation Problem

FACTS allocation problem is a nonlinear, highly constrained, multi-objective, mixed-integer, multimodal problem and finding global solution is very difficult. The solution approaches applied to FACTS allocation problem are discussed in this section.

Analytical and Numerical Techniques

Sensitivity based, loss sensitivity, index based, Eigen-values based, e-constraint and modal analysis are analytical and numerical based methods. In Krishnan et al. (2016), the authors proposed severity index to indicate most sensitive line in case of single contingency. In Rao and Rao (2015), authors proposed sensitivity index for optimal placement of UPFC, IPFC and OUPFC. The objective function is differentiated with respect to angle of injected voltage and verified on 5 bus and 14 bus system. The authors proposed sensitivity based method in Preedavichit and Srivastava (1997) for finding the optimal location of FACTS devices. Song et al. (2004) have applied an analytical method in order to minimize the security indices. In Rao et al. (2016), the authors proposed SA for the evaluation of ATC using statcom, SSSC and UPFC. The power-transfer-distribution factors based and novel current based model was developed and tested on 30-bus and 57-bus systems. In Aghaei et al. (2016), the authors also proposed SA for allocation of SSSCs to enhance the stability and capacity. The proposed method does not require exact modeling and limit on number of SSSCs. The method was tested on 6-bus and 57-bus system.

Kumar et al. (2007) proposed a set of loss sensitivity and controllability indices for optimal placement of UPFC, TCSC and SVC. The optimal placement based on proposed indices is also effective in critical contingency situations.

Table 9 Enhancing power oscillation damping

Objective	Type of FACTS	Decision variable	Solution algorithm	Findings/application	References
Max damping of small signal oscillations	SVC, TCSC UPFC	Location	Loss sensitivity	UPFC settles down oscillations in 9 s, TCSC or SVC in 13 s at 39 and 68 bus	Kumar et al. (2007)
Maximize the damping ratio	SVC, TCSC	Location, setting	PSO	TCSC is better than SVC for higher loading and mitigating small signal stability problem	Mondal et al. (2012)
Max voltage stability and damping oscillations	SVC at 14 bus	Placement size, setting	GA,MA	Best stabilizing signal, controllability and observe-ability using 2× SVCs	Farsangi et al. (2007)
Max damping of power oscillations	SVC, TCSC, statcom UPFC	Rating, type	PSO, Eign. Ana	The rating of SVC is found between −50 and +50 MVAR by using load flow study	Kumar (2010)
Min square of error between P_{ref} and P_{act} power	TCSC	Location	STFPIC	greater penalty on large errors and STFPIC quite effective in POD	Hameed et al. (2008)
Min angle, frequency and voltage deviations	IPFC and UPFC	Location, size	ANFIS MsPSO	Iranian power grid and New England power system selected to install CSC (200 MVA)	Isazadeh et al. (2016)
Minimize a function of settling time and overshoot	TCSC	Optimal tuning	PSO	TCSC has excellent capability in damping inter-area oscillations and enhances stability	Shayeghi et al. (2010a)
Minimize a function of settling time and overshoot	TCSC	Optimal tuning	PSO, GA	PSO is superior to the genetic algorithm based damping controller	Shayeghi et al. (2010b)
Minimize a function of settling time and overshoot	UPFC	Optimal tuning	QPSO	QPSO based UPFC has excellent capability in damping low frequency oscillations	Shayeghi et al. (2010c)

The proposed method was tested for power oscillations damping at 68-bus and 39-bus. Farsangi et al. (2007) proposed modal analysis and GA to damp out the inter area oscillations using SVC. The MA is best in finding location while GA is best in finding the optimal size of SVC. In Kumar (2010), the authors proposed Eigen Analysis to calculate the dynamic ratings of TCSC, UPFC, SVC and statcom. In Ara et al. (2012), the authors proposed e-constraint approach using GAMS in Matlab. The proposed method is tested on IEEE 14 bus system with PST, HFC and UPFC.

Classical Optimization Based Techniques

NLP, MINLP, ordinal optimization (OO), Newton–Raphson method, OPF based, quadratic programming (QP) and sequential QP are classical methods. In Kumar and Gokulakrishnan (2011), the authors proposed SQP for stability assessment using SVC and statcom in the area of wind power. The proposed method was tested for a 3-phase short circuit without and with FACTS controllers in the power network. In Rahimzadeh and Bina (2011), authors proposed GA and SQP to solve a MINP related optimization problem for optimal allocation of FACTS devices in power systems. In GA, the location of FACTS devices are represented by chromosomes having integer numbers while the length of each chromosome represents the number of FACTS device. In Krishnan et al. (2016), authors suggested NR method for contingency analysis and transient stability study. In Duong et al. (2014), the authors proposed minimum cut methodology to determine best location and applied Kirchhoff's

Table 10 Power quality and capacity enhancement with FACTS, DG, DFIG and ESS

Objective	FACTS/DG/ESS	Decision variable	Solution algorithm	Findings/application	References
Max load-ability within allowed voltage	SVC	Number at 14 and 140 bus	GA	An existing 140-bus improve the voltage stability and the voltage profile of the power network according to the utility regulations	Amaris and Alonso (2011)
Increase load-ability and voltage stability	UPQC and DG	Allocation	SPAC model	Tested at 33 node and 69 node, efficient in under voltage mitigation, beneficial for DG units	Taher and Afsari (2012)
Improve voltage and current profiles, reduce power loss and cost	UPQC	Location and size	DE	DE is a nearer to global optimal in minimizing the OF than GA and I in radial distribution	Ganguly (2014)
Max voltage stability, min power loss and VAr investment cost	SVC and DGs	Location, 140 bus	GA	Improves the voltage stability, reduces active power losses as well as the cost of SVC in wind forms	Alonso et al. (2012)
Min cost of generation	TCSC	Location capacity	Monte Carlo, DE	A high penetration of renewable generation	Galloway et al. (2010)
Min cost of power loss, cost of UPQC and cost of interruption	UPQC	Location, number	CSO	UPQC with Cuckoo Optimization algorithm gives better results in distribution network	Sarker and Goswami (2016)
Min oscillations of PCC voltage and Rotor angle deviations	Statcom, SVC and DFIGs	Transient ratings	SQP	Statcom is cost effective for stabilizing rotor oscillations of induction generator in wind form	Kumar and Gokulakrishnan (2011)
Improve rotor speed stability and angle stability	FACTS, DFIGs	Transient ratings		Enhancement of rotor speed stability of induction generators and angle stability of synchronous generators	Kumar and Khan (2008)

current law to determine the best setting of TCSC. Ara et al. (2012) used NLP and MINLP for finding the optimal location and best setting of FACTS.

Artificial Intelligence Based Techniques

Heuristic Approaches

GA, PSO, EA, harmony search algorithm (HSA), TLBA, GSA, CRO, QOCRO and BSOA are heuristic approaches. In Cai et al. (2004), authors proposed GA to determine the optimal location and suitable type of FACTS device from TCSC, SVC, UPFC and TCPST. In Amaris and Alonso (2011), authors proposed GA using SVC for maximizing power generation from wind turbines. An existing 140-bus power system is used to validate the performance and effectiveness. In Alonso et al. (2012), GA was validated at 140 bus power system with wind farms using FACTS units due to its effective speed and simplicity. Alabduljabbar and Milanović (2010) proposed GA and OPF to allocate SVC, TCSC, TCVR, and TCPST. The placement methods not only considered different costs simultaneously but also increased power transfer in the lines and damping of electro-mechanical oscillations. The authors studied GA for minimizing the total loss and improving the load-ability of the lines using TCSC (Abdelaziz et al. 2011). The approach was tested on 30-bus system for optimal number and optimal compensation level of TCSC. The authors proposed GA (Ghahremani and Kamwa 2013) to search the suitable location and determine the best sizes of SVC, TCSC, TCVR, TCPST and UPFC. A GUI was presented with the FACTS toolbox up to 300-bus system to maximize the load-ability. In Amaris and Alonso (2011), authors proposed GA using SVC for maximizing power generation from wind turbines. An existing 140-bus power system is used to validate the performance and effectiveness. In Alonso et al. (2012), GA was validated at 140 bus power system with wind farms using FACTS units due to its effective speed and simplicity. In Panda and Patel (2007), the authors proposed GA for placing statcom in order to improve transient stability. The proposed method was tested at two-area test system for determining the optimal allocation.

In Kumar (2010), PSO was proposed to solve the optimization problem and EA analysis to perform calculations in time domain. The dynamic ratings of TCSC, UPFC, SVC and statcom were determined in a multi machine power system. Mondal et al. (2012) proposed PSO to tune the parameters of TCSC for damping power oscillation. The performance of the PSO based controller is evaluated in a four-machine power system and compared with GA in terms of robustness subjected to the different types of disturbances. Shayeghi et al. (2010a) also proposed PSO for coordinated control of PSS and TCSC as an efficient damping controller. The proposed optimization problem with time domain-based multi-objective function is tested under different operating conditions. It has good robust performance for damping low frequency inter-area oscillations. Javaheri and Goldoost-Soloot (2012) proposed HSA with sensitivity factors for to mitigate congestion using TCSC. The concept of HSA is derived from musical practice for searching an ideal state of harmony (Lee and Geem 2004). Line outage sensitivity factors can reduce the solution space and point out suitable lines for placement of TCSC. The simulation results on 14-bus system show the effectiveness of HSA over PSO. In Balamurugan et al. (2015), authors proposed EP and DE algorithms for optimal placement of multi-type FACTS. The proposed approaches were compared for minimizing the costs, overloads, excess power flow and maximizing the benefit.

In Bhattacharyya and Kumar (2016), GSA was proposed to maximize power transfer capacity using FACTS devices. The proposed approach is compared with GA, DE, and PSO at 30-bus and 57-bus system. The authors outlined BBO in Simon (2008) and implemented in Roy et al. (2009, 2010, 2011), and for optimal reactive power dispatch using multiple TCSC and TCPS devices. This approach studies optimal setting of control variables for minimizing power loss and voltage deviations. The approach was tested at 30 bus and compared to PSO, GA and DE. In Taher and Afsari (2014), authors proposed biologically inspired Immune Algorithm (IA) to search the best location and determine the best size of D-statcom. The proposed approach minimizes the cost of installation and power loss within the constraints of the objective function. The proposed approach was tested on 33-bus and 69-bus distribution systems.

The authors proposed TLBO using TCSC (Jordehi 2015b) to decrease overload, power loss and voltage deviations. Optimal settings of TCSC contingencies show that TLBO is more efficient than GSA, FSO, PS and NLP in solving these problems. The authors proposed BSOA (Jordehi 2015c) to find optimal setting and location of TCSC and SVC for the objectives of voltage profile, losses and overloads. The results of proposed method at IEEE 57-bus system shows that BSOA is better than PSO, GA, DE, SA, hybrid of GA and PS, backtracking search algorithm and GSA. In Dutta et al. (2016a), CRO was proposed to find the optimal location of statcom at IEEE 30 bus and IEEE 57 bus systems. The results show effectiveness of the proposed method and better performance when compared with PSO, DE, etc. Dutta et al. (2016b) proposed QOCRO to find optimal location of FACTS device. The proposed concept successfully speeds up the convergence of conventional CRO to decrease power loss, improve the voltage stability and voltage profile.

Meta-Heuristic Approaches

Fuzzy logic (FL), GA and variants, PSO and variants, FFA, ANN, ABC, EP and DE are meta-heuristic approaches. In Bathina and Gundavarapu (2014), the authors proposed FFA to solve the problem of optimal placement of a TCSC. The proposed method was tested at 5 bus system, IEEE 14 bus system and the modified IEEE 30 bus test systems. Milanovic and Zhang (2010) proposed Niching GA (NGA) for optimal placement and sizing of SVC, statcom and Dynamic Voltage Restorer (DVR). The purpose of the scheme is to reduce losses and the overall cost. The method was tested on 295-bus and 278-branch system. In Hooshmand and Ezatabadi (2010), the authors proposed FACTS with BF oriented by PSO (BF-PSO). The simulation were carried out at IEEE 57 bus test system and compared with PSO and GA. In Ghahremani and Kamwa (2013) and Srikumar et al. (2014), authors proposed NSGA II for solving multi-objective problem of optimal location and ratings of SVC.

In Chen et al. (2013), the authors developed ALC-PSO that tunes the lifetime of the leader adaptively as per leader's leading authority. Singh et al. (2015b) proposed ALC-PSO for the solving ORPD problem in electric system and minimized power loss and absolute value of total voltage deviations. The proposed method was tested on IEEE standard 30 bus, 57 bus and 118 bus system. Jordehi et al. (2015) proposed enhanced leader PSO (ELPSO) to minimize power loss, power flow violations and voltage deviations using D-TCSCs. ELPSO and eight other optimization approaches tested at IEEE 14-bus and 118-bus systems with N – 1 contingency conditions for outage of 4 × branches simultaneously. The results are batter in terms of lower power flow violations, voltage variations and power loss. Jordehi (2016) proposed ICA using TCPSTs and TCSCs to minimize overloads and voltage deviations during line outage contingencies and demand growth. In Moazzami et al. (2013), the authors proposed APSO to determine the most economic and cost effective bus for load shedding. The proposed method also prevents the system instability and blackout situation in power systems. In Gitizadeh et al. (2014), authors proposed MOPSO for finding optimal rating, placement and parameter setting of SVC to enhance power system stability. In Phadke et al. (2012), authors proposed a Fuzzy-GA framework to address the problem of optimal location of shunt FACTS devices. The method minimizes the bus voltage variation and maximize loading margin simultaneously and was tested at 14-bus and 57-bus system. The authors proposed ANFIS and MsPSO (Isazadeh et al. 2016) to avoid shutdown scenarios. The different configurations of UPFC and IPFC were investigated for damping of power oscillations.

Hybrid Approaches

GA and DE along with FL was proposed for the optimal placement and setting of TCSC and SVC (Bhattacharyya and Gupta 2014). The fuzzy membership functions with Eigen value analysis are utilized for the selection of weak buses for the placement of SVCs while the locations of TCSCs are determined by the power flow in lines. A combination of CS and GA is proposed in Akumalla et al. (2016) to find optimum placement of UPFC, TCSC and IPFC in a multi-machine power system. The purposed hybrid approach speeds up the convergence and improves the quality of solution through expanded search space. The simulation results of proposed method on IEEE 30 bus network show good stability, better convergence, simultaneous and efficient use of several kinds of FACTS controllers. In Huang and Huang (2014), authors proposed a hybrid approach that combines HSA and an ant system for the optimal solution of FACTS allocation problem. The proposed approach is verified on 30-bus and 345 kV Taiwan power system. The results show better steady-state control of power systems and improvement in the total power transfer capacity.

A new hybrid evolutionary algorithm combining EP, TS, and SA methods (Jirapong and Ongsakul 2007) was proposed for improving power transfer capacity. In Sedighizadeh et al. (2013), the authors also proposed a hybrid approach which combines FL with NSPSO algorithm for the solution of multi-objective FACTS allocation problem. The active power loss and voltage stability index were minimized by using reactance model of TCSC and power injection model of SVC. In Kumar and Srikanth (2015), authors proposed a hybrid approach integrating ABC and GSA for optimal placement and sizing of UPFC to improve the dynamic stability. The optimal location is searched out by using ABC algorithm and the required optimal number of the UPFC by using GSA. The highest power loss bus is recognized as favorable location for placement of the UPFC, because the generator failure affects the constraints regarding voltage, real/reactive power flow and power loss. The performance has been verified by comparing with ABC and GSA. In Galloway et al. (2010), the authors proposed DE algorithm and Monte Carlo simulation technique for minimizing cost in DG and finding the optimal location, respectively. These techniques together are called renewable uncertainty-based optimal allocation techniques. The operation with FACTS devices gives highest benefit in terms of reducing cost of generation. In Chaudhry et al. (2017), authors have proposed a novel hybrid technique for energy mix cost reduction and proved that chaotic DE hybridized with SQP works efficiently. It can also be implemented on FACTS allocation effectively.

Case Study: IEEE-14 Bus System

The IEEE-14-bus power system is widely used in validation of FACTS devices. This system consists of generator buses, load buses along with twenty power transmission lines. Bus-1 is the slack/reference bus. A base of 100 MVA has been considered and single line diagram of this power system is shown in Fig. 2. The data of Buses, shunt capacitor, load, generators reactive power limits are given in Table 11 and lines data with transformer taps settings have been provided in Table 12.

We have employed different optimization techniques on the case study with and without FACTS controllers. The average and optimal results provided by the different computational techniques without FACTS and with FACTS controllers are shown in Figs. 3 and 4, respectively.

In the case study results we have observed that the recursive technique Sequential Quadratic Programming is better than classical Newton's method. While the evolutionary techniques Partial Swarm Optimization and Differential Evolution outperform the SQP. But the most optimal results are provided by the hybrid technique of DE and SQP.

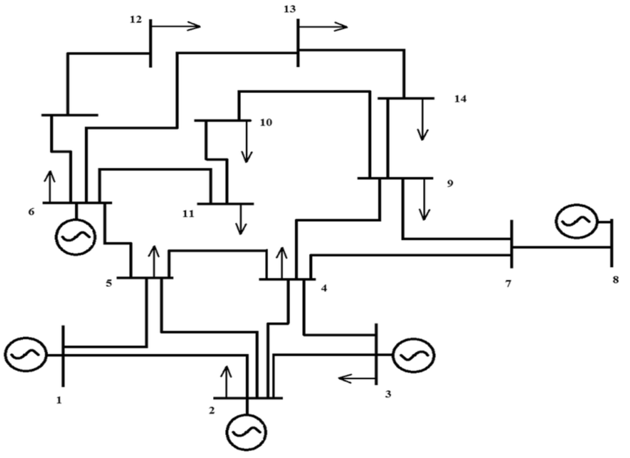


Fig. 2 Single line diagram of IEEE-14-bus system

Weakness of the Existing Research Work and Guidelines for Future

After reviewing the existing works on FACTS allocation problem, following is being provided as weakness of the existing research works and guidelines for research in future.

- Almost all the existing works, attempt to find optimal placement or location of FACTS and some find size of FACTS but do not find optimal number and type of FACTS. Development of efficient approaches capable of finding optimal type, size and number of FACTS is recommended.
- The utilities as well suppliers mostly employ experience based conventional approaches rather than modern approaches for allocation of FACTS. Even in many countries, particularly in developing countries like Pakistan, the power generation, transmission and distribution is totally without any FACTS. Transmission system operators and sub station operators switch on conventional fixed capacitors and inductors for compensation which is time consuming along many other drawbacks. Convincing the utilities and suppliers in different countries

Table 11 Buses data IEEE-14-bus system

Bus no.	Bus code	Voltage magnitude	Angle (°)	Load		Generator				Injected MVAR
				MW	MVAR	MW	MVAR	$Q_{\min}$	$Q_{\max}$	
1	1	1.06	0	30.38	17.78	40	−40	0	0	0
2	2	1.045	0	0	0	232	0	−40	50	0
3	2	1.01	0	131.88	26.6	0	0	0	40	0
4	0	1	0	66.92	10	0	0	0	0	0
5	0	1	0	10.64	2.24	0	0	0	0	0
6	2	1.07	0	15.68	10.5	0	0	−6	24	0
7	0	1	0	0	0	0	0	0	0	0
8	2	1.09	0	0	0	0	0	−6	24	0
9	0	1	0	41.3	23.24	0	0	0	0	0.19
10	0	1	0	12.6	8.12	0	0	0	0	0
11	0	1	0	4.9	2.52	0	0	0	0	0
12	0	1	0	8.54	2.24	0	0	0	0	0
13	0	1	0	18.9	8.12	0	0	0	0	0
14	0	1	0	20.86	7	0	0	0	0	0

Table 12 Lines data for IEEE-14-bus system

Line no.	Sending end bus	Receiving end bus	Resistance (p.u)	Reactance (p.u)	Half susceptance (p.u)	Transformer tap	MW limit (p.u)
1	1	2	0.01938	0.05917	0.0264	1	0.6
2	2	3	0.04699	0.19797	0.0219	1	0.7
3	2	4	0.05811	0.17632	0.0187	1	0.8
4	1	5	0.05403	0.22304	0.0264	1	0.5
5	2	5	0.05695	0.17388	0.017	1	0.4
6	3	4	0.06701	0.17103	0.0173	1	0.3
7	4	5	0.01335	0.04211	0.064	1	0.2
8	5	6	0	0.25202	0	0.932	0.5
9	4	7	0	0.20912	0	0.978	0.4
10	7	8	0	0.17615	0	1	0.2
11	4	9	0	0.55618	0	0.969	0.2
12	7	9	0	0.11001	0	1	0.2
13	9	10	0.03181	0.0845	0	1	0.2
14	6	11	0.09498	0.1989	0	1	0.3
15	6	12	0.12291	0.25581	0	1	0.2
16	6	13	0.06615	0.13027	0	1	0.2
17	9	14	0.12711	0.27038	0	1	0.2
18	10	11	0.08205	0.19207	0	1	0.2
19	12	13	0.22092	0.19988	0	1	0.2
20	13	14	0.17093	0.34802	0	1	0.2

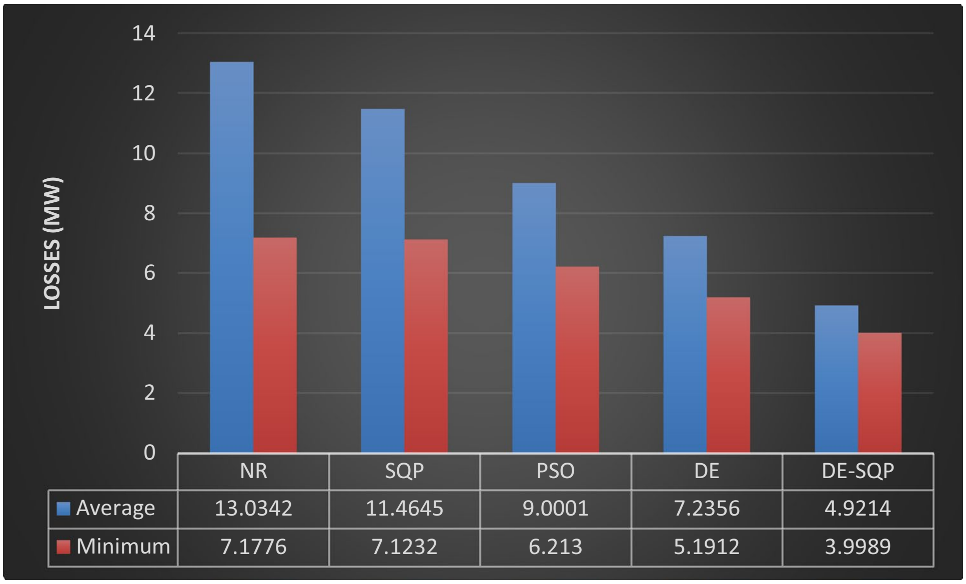
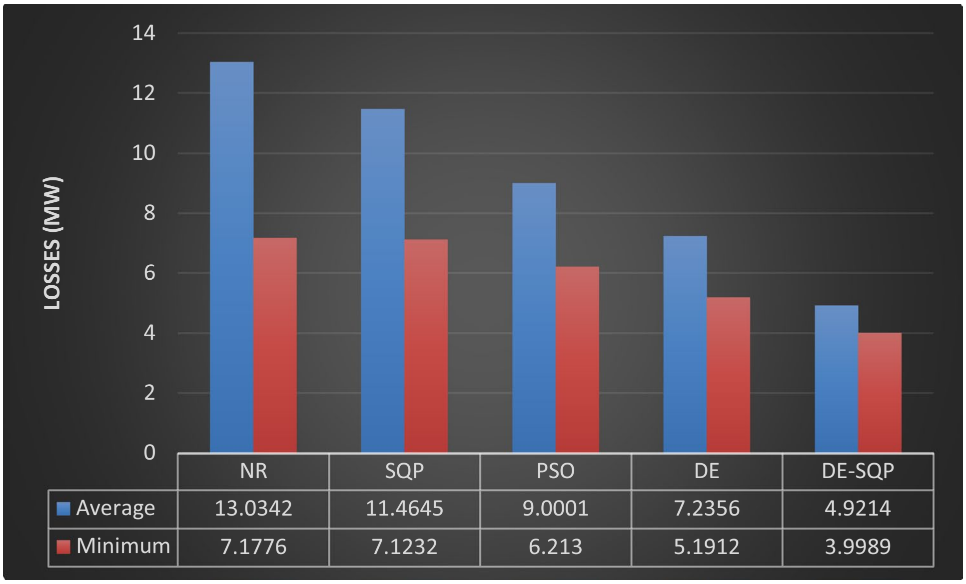


Fig. 3 Power loss without FACTS device (UPFC)

about the advantages of FACTS and encouraging them to use modern FACTS allocation approaches is highly recommended.

- Almost all existing research works, attempt to optimize simple steady state characteristics of transmission and distribution systems, while dynamic, transient and coordinated control issues of the system should be considered in multi-FACTS allocation.
- Shunt compensators are a source of reactive power and can be considered as Q-type FACTs. In order to reduce costs, a minimum number and size of fixed capacitors and fixed inductors in concert with FACTS devices is recommended in transmission and distribution systems in FACTS allocation approaches.
- The addition of energy storage systems along with FACTS can provide smooth output and quality power

Fig. 4 Power loss with FACTS device (UPFC)



and relieve intermittency of renewable energy-based FACTS, however, a very small portion of existing works have investigated FACTS allocation problem with energy storage systems. Using energy storage systems integrated with FACTS and thorough study of their effects on solution of FACTS allocation problem is highly recommended.

- A lot of the existing works analyze the optimization approaches for FACTS allocation problem on very small scale power systems. A geographically and country-wise power system bus data and transmission lines data should be collected, in which analysis of optimal size and optimal placement of different types and number of FACTS devices is recommended. This will make implementations and improvements very simple and fast.
- Full investigation of the effects of different models of FACTS is recommended with power system modeling, while load models such as constant impedance model, constant current model, etc., is recommended for future research in distribution system.
- Although a lot of research effort has already been put to develop efficient and powerful meta-heuristic optimization algorithms for solving allocation problem, there is still room for improvement. Developing more efficient meta-heuristic optimization algorithms with strong capability in discovery of global optimum is recommended for future research.
- In hybrids of sensitivity analysis and classic/heuristic/meta-heuristic optimization approaches, optimal size, location and type of FACTS are not found simultaneously. No doubt, the computational time of such approaches is less, however, the obtained solutions cannot be considered optimal. Therefore, more concise study on other optimization algorithms that simultaneously optimize size, type and location of FACTS is recommended.
- To provide a practical reasonable solution for FACTS allocation problem, all the associated economical, technical, geographical and environmental constraints must be included into study, whereas a large number of existing research works have neglected some of constraints. As an example, about in all the cases, the cost of power transformers, inductors and capacitors is not taken into account but cost of power electronic component is taken into consideration. Similarly right of way problems may not allow the installation of FACTS at certain buses of system, while in most of research such a constraint has been simply ignored. As another example, in most of the research works, design of power electronic components has been considered but ratings and size of electrical equipment i.e., power transformers, inductors and capacitors has not been considered.
- This review shows that different existing research works have used a number of different constraints, different decision variable and different objective functions. So comparison of the concert of different optimization approaches is unworkable. Comparison of different optimization approaches with same constraints, same decision variables and same objectives in FACTS allocation problem is recommended for research in future. A comparison can be prepared in terms of computational time, robustness, convergence speed and accuracy.

Conclusion

FACTS allocation is a hot topic for research in electric power systems and represents a challenging problem in power resources optimization. In this paper, the existing works on FACTS allocation have been studied from the viewpoint of applied optimization approaches, objectives, constraints, design variables and FACTS types. Based on the review of research works, the research shortcoming has been identified and some useful recommendations and suggestions for future study on FACTS allocation problem have been provided. As a major judgment of this review, it was searched out that although a lot of research attempt has already been put to extend powerful and efficient meta-heuristic-optimization approaches for solving FACTS allocation problem, there is still an opportunity for more efficient metaheuristic optimization approaches. Another effort of using hybrid of sensitivity analysis with classical/heuristic/meta-heuristic approach with strong capability and improvement in discovery of global optimum is recommended.

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