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Optimization of FACTS Devices: Classification, Recent Trends, and Future Outlook

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Abstract— **Since the inception of industrialization, power system has been an indispensable aspect of economy. With the progression of time, technology has impalpably commingled into our lifestyle. Alongside blooming technologies, energy demand is proliferating and power companies are begetting energy at their best to quench it. Growing reliance on power system has brought its quality into more advertence. Various electronic devices and topologies have been invented to enhance power quality and reliability; numerous others are still underway. During the course, power system has grown to an intricate network of sources, loads and control devices, leading to various issues such as transmission congestion and high losses. This paper discusses ways to ameliorate congestion and gives an overview of relationship between our present energy resources and ecological threats like global warming. Moreover, it points out various power system problems such as energy losses and transients. The necessity of FACTS devices has also been elaborated alongside their classification and comparison. Finally, numerous topologies and optimization methods proposed in the technical literature have been classified and analyzed to alleviate power system conundrums, and a glimpse into future energy trends is presented.**

Keywords— FACTS devices, compensation techniques, power losses, voltage transients, optimization algorithms

I. Introduction

Power system is crucial to perform everyday activities in today's world. Industries, educational institutions, transportation services, health facilities, and research sectors, all need reliable power to function adequately. The cost and quality of energy supply play decisive role in determining the level of social security, quality of services, market value of goods, and economic prosperity of a country. In today's era of CC Cameras and online banking, higher is the reliability of power, higher is the level of social security. Analogously, lower is the price of energy, lower is the production cost, and thus higher is the profit in business. With recent advancements in technology, numerous avenues have been uncloaked; juxtaposed to that, multifold challenges have exacerbated. To support escalating energy demand, the number of power companies has metastasized over the past decades. But with the blooming energy market, competition is also getting fiercer. From economic point of view, power companies desire to transmit bulk power for higher gains; this often leads to congestion. To avoid congestion, expansion of transmission lines is a lucid remedy. However, due to the numerous reasons like the high cost required to construct new lines, environmental impacts, and health hazards to human and wildlife, it is quite a daunting task. The other panacea widely opted to ameliorate this issue is to use of Flexible AC Transmission System (FACTS) devices [1].

This paper is focused on the same topic: Section II depicts recent energy trends and ascribes FACTS devices to quench energy losses, reliability, voltage drop, transients, and other power system challenges; Section III elaborates contemporary use of FACTS devices, their types, uses, merits and limitations; Section IV portrays optimization methods, their applications, merits and limitations; Section V renders comparative overview of various FACTS devices and optimization techniques; Section VI is about future energy

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trends and state-of-the-art applications; and finally, Section VII draws the conclusion.

II. Recent Energy Trends

Number of industries and service sectors have surged up in recent years. As a result, global energy demand has continually escalated [2]-[4]. According to estimation of the International Energy Agency, throughout the globe, primary energy consumption accounted around 132,000 Terawatt-hours (TWh) in 2008 [2] and 158,000 TWh in 2012 whereas the supply was around 157,500 TWh in 2013. In 2014, coal amounted 155,481 TWh energy globally. In the year 2016, 82% of the energy was used for mostly heat and transportation [2]. Retrospection of global electricity consumption from 2000 to 2018 is portrayed in Figure 1, based on the data of IEA [5].

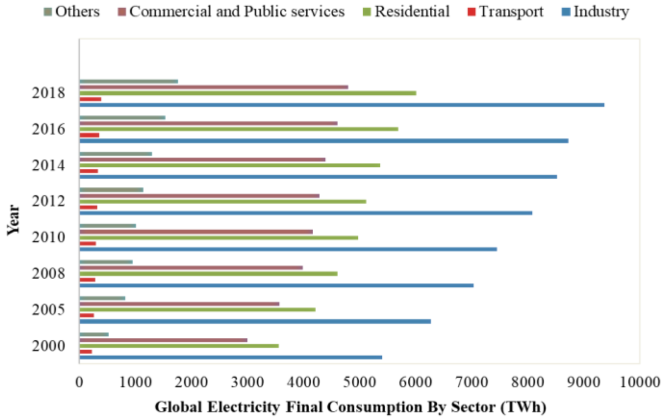

Fig. 1. Global electricity final consumption.

The global electricity consumption was 12,116 TWh in 2000 and 15,105 TWh in 2005 [2],[4]. In 2008, the net global electricity consumption was 17,451 TWh, while in 2009, it was 17,349 TWh and 18,553 TWh in 2010. The consumption further climbed to 19,123 TWh in 2011 and 19,576 in 2012. It continually rose higher and reached 20,053 TWh in 2013 and 20,302 TWh in 2014. The global electricity generation in 2018 was 26,700 TWh; out of which coal and gas contributed more than half of the total [2], [4]. Globally, renewable energy sector experienced significant growth in the year 2019 [5].

Observation of global scenario reveals that, congestion of transmission lines is getting worse in developed countries whereas losses are immensely high in under-developed and developing countries, causing huge economic losses. Due to unreliable supply of power from national grid, the industries in poor countries are often forced to use secondary sources of electricity such as diesel generators. This increases their production cost and raises selling price of goods retrograding their already demurred position in the global market. According to the World Bank, almost 789 million people live in places with no access to power grids and nearly 3 billion people still use traditional means of fuel like wood for cooking their meals and heating purposes [6]. As compared to values of year 2015, current estimations depict that more than a quarter rise in worldwide energy utilization is likely before 2040. With polluting sources like coal and oil being the major suppliers of energy, detrimental effects in human lives, ecology and carbon cycle of the planet are being prognosticated [2], [7]. Figure 2 illustrates the global annual fossil CO_2 emissions as obtained from data of [8].

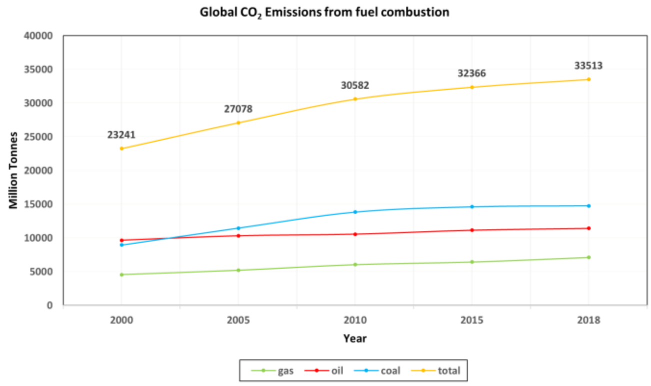

Fig. 2. Global annual fossil CO_2 emissions.

With the escalation in energy demand, lots of people yet to be supplied with electricity and renewable energy sources contributing only a small fraction in the energy market; thus, the environmental impacts will gradually rise. In its special report of 2018, the IPCC has already forecasted the impacts of global warming and has accentuated the measures to be adopted to check it by 2050 via zero emission strategies. The report further inferred that earth has warmed one degree more in recent centuries, which might trigger cataclysmic natural disasters and serious biodiversity loss [9]. This shows our current status owing to polluting sources of energy like fossil fuels.

In order to pass the ordeal of global warming, various sectors are collaborating with each other; people are paying attention to cleaner means of energy, smart grids are being designed, energy losses are being minimized, energy efficient approaches are being investigated, and distributed energy resources are being successively joined. In order to do so, FACTS devices are widely used [10].

III. Facts Devices

A large number of sources, loads and controllers are successively joined to constitute a power grid. The sources and control circuits are mostly pre-determined, whereas loads are continually varying and largely unforeseen. Loads can be of various types, i.e., resistive, capacitive or inductive. In case of resistive loads, phase balance is not an issue. But in case of inductive and capacitive loads, current and voltage are not in phase and power factor drops below its nominal value. To improve this, compensation is required. If proper compensation techniques are deployed, power factor becomes close to the unity. If sufficient supply of reactive power is not maintained in the grid, it causes low voltage levels at the receiving end, and at worst, might even cause blackouts. To prevent this and maintain reliability of the grid, FACTS devices are extensively deployed.

Hingorani and Gyugyi are credited for introducing the concept of FACTS in 1999 [1]. Optimal utilization of existing infrastructures of power system can be achieved using FACTS devices [11]. Also, they can alleviate efficiency of energy utilization, mitigate power losses and transients, enhance the quality, foster harmonic reduction, power factor correction, etc. [12], [13]. Therefore, applications like standalone microgrids with renewable energy utilization using photovoltaics, wind, biomass, micro-hydro systems, AC-DC hybrid topologies, etc. have cropped up recently [12], [14].

From the evolution point of view, FACTS controllers can be grouped into first and second generations. The first generation included thyristor switched capacitors, reactors and quadrature tap changing transformers [15]. The second generation included Gate Turn Off (GTO) thyristor switched converters as Voltage Source Converters (VSCs) [16]. FACTS devices have four popular compensation topologies:

A. *Series compensation*: In this technique, the power system and FACTS devices are in series to each other. For any inductive load, current lags voltage. The voltage drop due to the effect of inductive load is $V_d = I(R\cos\varphi + X_L \sin\varphi)$. If any capacitance "$c$" with reactance X_c is connected in series to the line, the new reactance will be X_L -X_c , and voltage drop is reduced. FACTS devices based on series compensation topology are Interphase Power Controller (IPC), Thyristor Controlled Phase Angle Regulator (TC-PAR), Thyristor Switched Series Capacitor (TSSC), TCSC, Thyristor Switched Series reactor (TSSR), SSSC, Thyristor Controlled Series Reactor (TCSR), etc.

B. *Shunt compensation*: In this compensation topology, the connection between power system and FACTS devices is made in a parallel fashion. Shunt connected FACTS devices reduce unwanted reactive power flow and network loss, keep the contractual power exchange with balanced reactive power, improve power quality (during demand fluctuations), static and transient stability, etc. [17]. Shunt compensation involves shunt capacitive compensation and shunt inductive compensation. FACTS devices based on shunt compensation topology are Dynamic Voltage Restorer (DVR), Distributed Static Synchronous Compensator (DSTATCOM), SVC, Mechanically Switched Capacitor (MSC), Thyristor Switched Reactance (TSR), Thyristor Switched Capacitor (TSC), STATCOM, etc.

C. *Series-Series compensation*: In this technique, real and reactive power are controlled parameters, the voltage and phase angle are controlled via compensation. IPFC, Generalized IPFC (GIPFC), etc. use series-series compensation.

D. *Series-Shunt compensation*: They deploy both series and shunt connected devices. FACTS devices based on this topology are UPFC, Generalized UPFC (GUPFC), United Power Quality Conditioner (UPQC), Unified Dynamic Quality Conditioner (UDQC), Hybrid Power Flow Controller (HPFC), Thyristor Controlled Phase Shift Transformer (TCPST), etc.

Some popular FACTS devices are described as follows:

GUPFC: It is a comparatively robust, multipurpose, FACTS device proposed in 2000 A.D by Fardanesh [18]. It can simultaneously tune all parameters of voltage, impedance, and phase angle; and can efficiently govern the active power control as well as the reactive power control of multiple circuits [19]. In [20], ability of GUPFC to control voltage and active cum reactive has been demonstrated. Furthermore, alleviation of the problems like low voltage and energy losses has also been shown by the authors.

IPC: It has the ability to control active and reactive power; and makes use of the Phase Shifting Transformers (PSTs) [1]. It can effectively govern the power flow in addition to suppressing the fault current [21].

IPFC: IPFC has a typical feature of controlling power in numerous transmission lines and is therefore widely opted for series compensation in electrical networks [22]. It consists of series and shunt converters and can efficiently establish balance in terms of real and reactive power flow among transmission lines [23]. IPFC minimizes the cost of energy generation and reduces the power losses that occur in electrical networks by adjusting the parameters via compensation techniques [24]. In addition to these, it can also enhance voltage profile of the power system.

DVR: It has the ability to maintain voltage of the load side within certain range even while there is disturbance in voltage of the source. DVR uses the concept of "Dynamic voltage restoration" for overcoming voltage surges that occur in electrical networks [25]. In order to govern the real power as well as the reactive power of the distribution system, the parameters of the injected voltage can be varied by using DVR [26]. The negative impacts of voltage surges and change in harmonics can be alleviated to a great extent with the use of DVR [27]. Although DVR offers protection against power quality disturbances, when incipient voltage conditions are present, it might trigger cascading interruptions.

SVC: SVC can effectively monitor reactive power and is commonly employed for maintaining the voltage within prescribed limits and also for reducing the frequency distortions [28]. SVC can absorb as well as generate reactive power in its two different modes of operation. It can be used as a source of ideal reactive power when connected to the bus, and as variable admittance if connected to transmission lines [29]. SVCs are also deployed to smooth flicker voltage in industries [30]. They are widely used to ameliorate power losses, as well as to maintain reactive power, voltage levels and frequencies of the electrical networks at their desired levels [31].

SSSC: SSSC is based on series compensation topology and can inject an almost sinusoidal voltage in the power system in which it is used [32]. SSSC can compensate the reactive power in large quantity in order to alternate the direction of power in the circuit [32]. Its unique feature of changing the reactance without any effects to the current makes it very effective as a power control device [33]. SSSC is an adamant controller against frequency distortions [34].

VSC: VSCs are self-commutated converters that connect HVAC and HVDC systems using power electronic devices like IGBTs. A typical VSC contains one significantly large capacitor which can supply sufficient current for regulating the switching sequence [1]. VSC can effectively govern the parameters of load voltage.

UPFC: It is a multipurpose FACTS device which has the ability to supply reactive power on a need basis to the network in which it is used [35]. It can regulate active power as well as the reactive power. It is regarded by many experts as one of the most comprehensive FACTS devices, and is often considered as the third generation FACTS device [36]. UPFC offers system stability, improved voltage profile, relief from congestion problems and better safety of the electrical network [37].

TCPAR: It uses phase-shifting transformer and thyristor switches for regulating the parameters of power system. One of the striking features that TCPAR offers is: regulation of the power flow without affecting power stability in that particular network [38]. It can also be employed for adjusting power flow after contingencies due to faults in the system [39].

STATCOM: It is based on shunt compensation topology. It can supply as well as consume the reactive power, to and from the electric circuit [40]. It can successfully regulate power factor and voltage of the power system [41]. Additionally, it can be deployed to mitigate fluctuations in the system frequency, compensate the reactive power when it changes rapidly, and also to maintain the voltage within prescribed safe limits [42].

TCSC: TCSC is a modern FACTS device based on series compensation techniques. TCSC can support inductive as well as capacitive compensation of the transmission lines [43]. Power system becomes less prone to frequency disturbances and loadability enhancement is also facilitated by the use of TCSC [44], [45].

IV. Optimization Methods

FACTS devices are efficient in solving power system problems. However, they are expensive and their installation cost is often higher than the rate of return from the energy they saved, causing economic loss. Thus, selecting the proper number and type of these devices is a challenge. In order to mitigate this, various optimization techniques have been proposed by notable scientists and engineers in recent decades. Optimization provides objective assessment of various factors in order to assist the decision makers.

Based on the objectives, optimization techniques can be single-objective or multi-objective. Single objective techniques are simple, fast, and cost-effective; and they give a single solution. On the contrary, a multi-objective optimization approach assesses numerous conflicting objectives. It yields a set of compromised solutions or a pareto optimal front of parallel alternatives, which are better equipped and better suited for implementation in complex real-world situations.

There are two popular schemes in multi-objective optimization. The first one is a dominated sorting, where certain objectives are given more priority over other objectives. The second one is non-dominated sorting, where no particular objective is sacrificed to give more priority to others.

Based on their development, optimization techniques can be broadly categorized as shown in Figure 3.

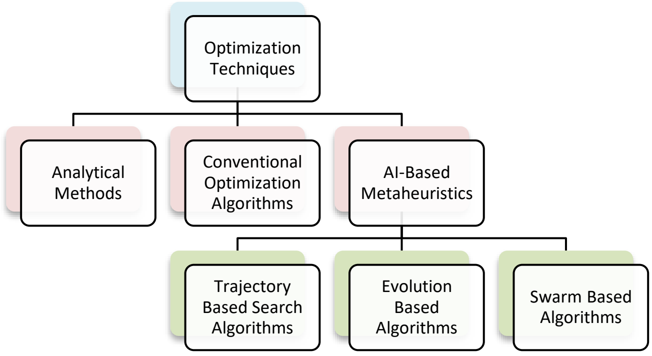

Fig. 3. Classification of Optimization Techniques.

A. *Analytical methods:* Initial methods used for mitigating power system problems and enhancing FACTS device performances were mostly analytical in nature. They include Model Analysis (MA) method, Index Method (IM), Controlling Method (CM), Residue Analysis (RA) method, Numerical Optimization (NO) method, Eigenvalue (EV) method, Sensitivity-based Method (SM), etc. Analytical approaches render clear information about the economic and technical outcomes from the designed model; and they are quite helpful to design a future framework for certain objectives. However, their application to large networks becomes very difficult and their accuracy in such cases is not high.

B. *Conventional Optimization Algorithms (COAs):* COAs mainly rely on arithmetic programming approaches. They include Newton method, Linear Programming (LP) method, interior point method, branch and bound method, Stochastic Load Flow (SLF) method, non-linear programming, Mixed Integer Non-Linear Programming (MINLP), Adaptive Control Law (ACL) method, Dynamic Programming (DP), Optimum Power Flow (OPF) method, Modified Mixed-Integer Non-Linear Programming (MMINLP), etc. They are much faster in working and have a higher efficiency in finding local optimal solutions. However, they often suffer trapping while searching for global optimums.

C. *AI-based Metaheuristics*: Unlike normal heuristic programs which are mostly problem dependent, metaheuristic techniques are problem independent and they can be applied to a broad range of problems. Metaheuristic algorithms can be further divided into three sub-categories:

1) *Trajectory-based search algorithms:* Trajectory optimization techniques are based on finding the best route to reach a certain goal by deploying the algorithm. Trajectory-based algorithms include Simulated Annealing (SA), Tabu Search (TS), Variable Neighborhood Search (VNS), Guided Local Search (GLS) algorithm, Iterative Local Search (ILS), etc.

2) *Evolution-based algorithms:* These algorithms are based on evolution theory. They include a selection of the best candidates who undergo crossover and

mutation and breed children. Based on the performances to fit desired objectives, criteria of selection are made. Selected candidates are bred for certain generations and final generation of best candidates is obtained. Evolution-based algorithms include GA, Adaptive Evolutionary Algorithm (AEA), Differential Evaluation (DE), Clonal Selection Algorithm (CSA), Harmony Search (HS) algorithm, Memetic Algorithm (MA), Backtracking Search Algorithm (BSA), Stochastic Fractal Search algorithm, Across Neighborhood Search (ANS) algorithm, Symbiotic organism search (SOS) algorithm, etc.

3) *Swarm-based algorithms:* In nature, various animals, insects and birds work together in swarms for finding food, migration, etc. Due to their combined group efforts, their efficiency and rate of success is higher than the ones doing it alone. This concept is used in swarm-based algorithms. Artificial buffalo optimization, seeker optimization algorithm, ant colony algorithm, immune algorithm, PSO, Artificial Bee Colony optimization (ABC), Gravitational Search Algorithm (GSA), firefly algorithm, teaching learning algorithm, chemical reaction optimization, water cycle algorithm, Coyote Optimization Algorithm (COA), Emperor Penguins Colony (EPC), Migrating Birds Optimization (MBO), Animal Migration Optimization (AMO), Grasshopper optimization algorithm, Hunting Search (HS) algorithm, Glowworm Swarm Optimization (GSO), Intelligent Water Drops (IWD), Joint Operations Algorithm (JOA), Salp Swarm (SS) optimizer, Grasshopper Optimization (GO) algorithm, Gray Wolf (GW) Optimizer, Ant Lion (AL) optimization technique, etc. are all examples of swarm-based algorithms.

Some animals involve group work for certain objectives and individual work for other objectives. Inspired from it, algorithms like Whale Optimization (WO) algorithm, Spider Monkey Optimization (SMO), etc. have been formulated for higher efficiency and success. Some other popular algorithms include computational simulations, Monte Carlo simulation, intelligent programming method, artificial neural network, fuzzy linear programming, etc.

V. COMPARATIVE OVERVIEW

Tables I and II present brief comparison of FACTS devices and heuristic algorithms respectively.

TABLE I. COMPARATIVE OVERVIEW OF FACTS DEVICES

FACTS Device	Reference	Features
GUPFC	[18], [19], [20]	Ability to damp power system oscillations; control voltage; control active and reactive power flow of multiple transmission lines; reduce harmonic distortion
IPC	[1], [21]	Control power flow; mitigate fault current
IPFC	[22], [23], [24]	Balance power between transmission systems; monitor real and reactive power flow; minimize power losses and generation cost; maximize loadability of system; transfer power from more loaded lines to less loaded or unloaded lines
DVR	[25], [26], [27]	Ability to generate or absorb controllable real and reactive power; mitigate voltage swells and distortions
SVC	[28], [29], [30], [31]	Can absorb or generate reactive power dynamically; power factor correction; dynamic and static security enhancement; voltage regulation; harmonics mitigation
SSSC	[32], [33], [34]	Ability to change reactance character from capacitive to inductive without changing line current; can alternate the power flow
VSC	[1], [46]	Ability to generate AC voltages without relying on AC system; rapid control of active and reactive power
UPFC	[35], [36], [37], [47]	Deploy active and reactive power control; improve system voltage stability; power angle stability and Damping system harmonics
TCPAR	[38], [39]	Ability to mitigate congestion issues; adjust power flow; reduce transmission losses
STATCOM	[40], [41], [42]	Supply inductive and capacitive reactive power; improve power factor; voltage regulation; dampen system oscillation; improve harmonic filtration
TCSC	[43], [44], [45]	Elimination of sub-synchronous resonance; damping active power oscillations; provide inductive or capacitive compensation; loss reduction; congestion relief

TABLE II. COMPARATIVE OVERVIEW OF HEURISTIC ALGORITHMS

Algorithm	Reference	Merits	Limitations
GA	[48], [49], [50]	Easy to use; high degree of randomness due to stochastic nature; good diversity of solutions to avoid trapping in local optimum	Highly dependent on crossover and mutation rate; slow convergence; no guarantee to find global optimum
PSO	[51], [52], [53]	Easy to implement; high chance of convergence; few parameters to be adjusted; less dependent on initial points	Slow speed of convergence; chance of trapping into local optima
GSA	[54]	High randomness of individual moves; better global exploration	Weak local search ability
Ant Colony Optimization	[55], [56]	Inherent parallelism; adaptability; positive feedback support; high chance of convergence	Difficult mathematical execution and analysis; slower convergence
Simulated Annealing	[57]	Statistically guarantees finding optimal solution; relatively easy coding	Does not specify explicitly when solution is found; repeated annealing is very slow
Cat Swarm Optimization	[58], [59]	Can easily modify tracing and seeking modes to balance exploration and exploitation; fast convergence	Chance of falling into local optima; premature convergence
Tabu Search	[60], [61]	Can intensify or diversify search; can escape local optimums; avoid reverting to old solutions; applicable to both discrete and continuous solutions	Number of iterations can be very high; has lots of tunable parameters

VI. FUTURE OUTLOOK

According to various reports by the IEEE, the World Bank and other organizations, the demand and generation of electricity is expected to escalate in the future. Electric Vehicles (EVs) are expected to gradually take over conventional diesel and petrol fueled vehicles. Currently, numerous researches are undergoing for developing better interface between the batteries of EVs and the power grid to support fast charging of batteries as well as for using them as energy sources during peak demand hours. This trend is expected to rise in coming years. Another idea of using rooftop solar panels connected to smart grid and dual payment mode is already getting popular; paramount rise in its use is expected in future. Renewable energy production is expected to rise vigorously in the coming decades and various projections have been made to mitigate global warming via zero carbon emission. In this respect, a paradigm shift in use of renewable energy and connection of distributed energy resources is being presaged.

Peeking into the future of optimization techniques, various forms of non-dominated sorting multi-objective optimization techniques and hybrid techniques are expected to gain more popularity because of their increased effectiveness, flexibility, and quick action on various problems. Regarding state-of-the-art FACTS devices, use of more generic FACTS devices such as UPFC and other variants is expected to rise in coming decades, attributing to their flexibility of automatically and selectively governing multiple power system parameters.

According to [62], nearly 27.8% of global energy is contributed by renewable energy sectors in 2020. It is expected to reach 30.2% in 2025, 32.8% in 2030, 35.4% in 2035 and 37.1% by 2040. In 2020, the final demand for electricity consumption is around 3,398 TWh in Europe, 10,410 TWh in Asia, 709 TWh in Africa and 22,536 TWh globally. In 2025, it is expected to elevate further and touch 3,528 TWh in Europe, 12,488 TWh in Asia, 867 TWh in Africa and 25,307 TWh globally. In 2030, the electricity consumption is expected to further escalate and reach 3,648 TWh in Europe, 14,826 TWh in Asia, 1,095 TWh in Africa and 28,513 TWh globally. In 2035, the trend will continue further until it reaches 3,793 TWh in Europe, 17,120 TWh in Asia, 1,392 TWh in Africa and 31,907 TWh globally. By 2040, the final demand for electricity consumption will have reached 3,985 TWh in Europe, 19,254 TWh in Asia, 1,789 TWh in Africa and 35,407 TWh globally [62].

As projected by [63], human population is likely to reach 9.7 billion by 2050 and the global electricity demand is estimated to reach around 48,800 TWh. As solar PV and battery storage are more likely to be cheaper in the future, their use is expected to rise significantly in majority of the large power consuming sectors. For 100% renewable energy usage and zero carbon emissions, it is projected that solar PVs will comprise more than two third, wind energy almost a fifth of the total energy, and hydropower and bioenergy are expected to contribute around 10% in 2050 [63]. Beyond 2030, solar PVs are expected to be highly competitive and have a generation increment from 37% of 2030 to about 69% in 2050 [63]. Compared to the current electrical systems with high energy input loss, total losses in the 100% renewable electricity system are expected to recede by half.

VII. CONCLUSION

In this paper, first, the global recent energy trends are discussed. Subsequently, the main power system challenges such as congestion issues and energy losses were portrayed alongside modern sources of energy attributing to ecological problems like global warming. Afterwards, different types of FACTS devices as suitable options to mitigate these issues were introduced. Moreover, the necessity of optimization for optimal allocation of FACTS devices was justified and various optimization techniques were classified. In addition, a short comparison between FACTS devices and popular optimization methods was performed, and energy projection till 2040 was described. Finally, a glimpse of future energy trend to mitigate global warming till 2050 was presented.

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