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A Comprehensive Review on Various FACTS Devices and Application of Different AI Techniques in Their Operations for Progressive Electric Power System Operations

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Abstract: The growth and demand for electric power with the huge construction cost of new power networks has been the biggest challenge for the efficient power supply. FACTS devices are utilized to take care of this issue to improve static and dynamic effectiveness of the system. This analysis targets different FACTS devices, their configuration, controlling, comparative analysis & applications for power quality improvement. The escalation in power demand results in unstable voltage, surge in losses inclusive of degrading the power quality of network. Optimal deployment of FACTS devices helps to increase the stability of system including resolving power quality concerns. Various new technologies like Genetic Algorithm, Whale Optimization Algorithm, Brain Storm Optimization, Immune Algorithm, Fuzzy Logic Controller etc. are also studied for the various operations of FACTS devices. A literature study of various FACTS devices; challenges and corresponding solutions along with the application of intelligent techniques in their operations has been carried out in this work for improving the power system governance for power system control and its management.

Keywords: Flexible AC Transmission System (FACTS); Static Synchronous Series Compensator (SSSC); Thyristor Controlled Series Compensator (TCSC); Static VAR Compensator (SVC); Distribution Static Compensator (DSTATCOM); AI Techniques, power system operations

1. INTRODUCTION

Power quality is the major problem for modern consumers [1]. The rapid increase in demand is increasing the problems of power quality. Whenever there is any kind of disturbance like change in load, faults, flicker, voltage sags etc. power system stability is affected which causes unstable voltage, increase in losses, reduce the power flow capability of power system[2]. Due to this; many loads are adversely affected.

Many conventional devices used for power quality enhancement like capacitor and reactor of shunt and series type and also synchronous phase modifier and on load tap changing transformer[3] are used in the system. Due to the various disadvantages of conventional method, they do give an efficient output. So, modern devices called FACTS devices are replacing the conventional devices.

Their principle of operation is on basis of power electronics. They are used to add the power flow competence of system which makes the network more stable. These devices absorb or deliver reactive power. Line compensation results in improved system reliability and voltage control, increased power flow capacity and decreases temporary and transient over voltages. These are connected in power system in four ways i.e. series, shunt, series - shunt or series- series. Series linked devices are namely TCSC and SSSC; shunt associated devices are SVC and STATCOM, and series- shunt combination device is UPFC [4,5].FACTS devices can also be classified on the ground of thyristor and voltage source converter where VSC are more reliable than thyristor based in applications demonstrating better results regarding solutions to power quality issues. For the most part, the power converters are extensively arranged as voltage source converter and current source converter yet voltage source converter is favored over current source converter because in the later there is problem of reverse power flow and its cost is also very high[5].

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Implementation of various methodologies such as ANN for controlling the FACTS devices had given a very good result in power system governance which makes the system more robust and efficient. Genetic Algorithm [6] is utilized to determine the optimum location so as to increase the flow of power into the system. This approach has resulted in improved performance and stability of power system. The modern approach of Fuzzy logic and ANN controller also enhanced stability. To dampen low frequency perturbations, [52] implements a completely adaptive multiple-input-multiple-output neuro-fuzzy mechanism for multi-type FACTS. There in neuro-fuzzy system, the new adaptive strategy combines the complementary characteristics of locally tunable fuzzy bsp-line membership functions and strong wavelet neural architecture. Within two-area power grid, a neuro-fuzzy wavelets-based supplementary regulation of STATCOM is proposed in [53]. The suggested controllers' output is evaluated using the traditional TSK regulation and then a wavelet neural structure is incorporated to modify the TSK controlling resulting in enhancement in the operation. An optimal ant colony implemented static compensator is used to create a revolutionary control method for damping low-frequency fluctuations including voltage deviations for multi-machine power system in [54].In [55], the GA method is implemented to search the best STATCOM position for IEEE 30 bus configuration resulting in improvement of bus voltages.More technologies like Brain Storm Optimization (BSO), Whale Optimization Algorithm (WOA), Fuzzy Logic Control, Immune Algorithm, are also studied for different FACTS devices which fulfills the need of power system i.e. good power quality performance and hence increases the system stability [7,8].

2. CLASSIFICTION OF FACTS DEVICES

Facts devices are basically four types as. These are given as: Series Compensation Devices, Shunt Compensation Devices, Series-Shunt Compensation Devices and Series-Series Compensation Devices which are further classified as given in Figure.1

2.1 SERIES COMPENSATION DEVICES

Series compensation is used to transmit actual power at a particular voltage in the system. Through optimally locating devices, system losses are reduced and flow capacity in the network increases. These controllers add the voltage in series with the network; thus improving voltage profile. They are implemented for long distant transmission lines.

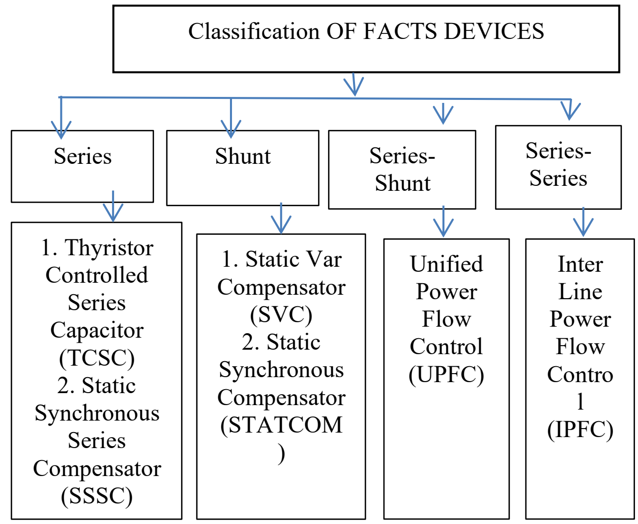

Figure 1. Categorization of FACTS Devices

2.1.1 SSSC (STATIC SYNCHRONOUS SERIES COMPENSATOR)

Towards fulfilling the objectives of boosting the efficiency of the current network; the SSSC was applied to various utilizations of the power systems [8]. It is connected in series and SSSC contains a converter on one side link with a DC source and linked on the other by a coupling transformer to transmission system as depicted in Figure.2. The SSSC regulate movement of electric power in transmission system by modifying the reactance from capacitive to inductive and vice versa as referred in Figure.2 and Figure.3.

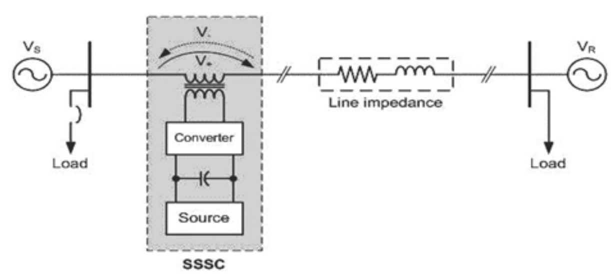

Figure 2. SSSC

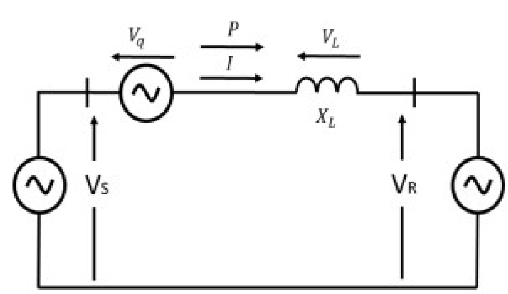

Figure 3. Power Flow in Transmission System

$$P = \frac{V_s V_r}{X_l} \sin\delta \quad (1)$$

$$Q = \frac{V_s V_r}{X_l}(1-\cos\delta) \quad (2)$$

$$P = \frac{V_s V_r}{X_l}\sin(\delta_s-\delta_r) = \frac{V^2}{X_l}\sin\delta \quad (3)$$

$$Q = \frac{V_s V_r}{X_l}(1-\cos(\delta_s-\delta_r)) \quad (4)$$

$$\delta = \delta_s - \delta_r \quad (5)$$

$$V_s = V_r = V \quad (6)$$

Power flow expressions in eq.3 and eq. 4 become

$$P_q = \frac{V^2}{X_{eff}}\sin\delta = \frac{V^2}{X_l(1-\frac{X_q}{X_l})}\sin\delta \quad (7)$$

$$Q_q = \frac{V^2}{X_{eff}}(1-\cos\delta) = \frac{V^2}{X_l\left(1-\frac{X_q}{X_l}\right)}(1-\cos\delta) \quad (8)$$

In above equations X_{eff} is the total reactance of the system between source and receiver ends together with the corresponding “variable reactance” infused by net injected voltage (V_s) by the SSSC. It can be concluded that SSSC has benefit of changing the reactance in parallel line load sharing. A sinusoidal AC voltage relating in series with SSSC can be injected in the transmission line having power movement capability in the system line and can be used for voltage control enhancement and enhancement of voltage constancy by damping power oscillation. In the operation of SSSC; GA based control strategy[9] is being incorporated to manage the behavior of the power system stabilizer mostly with SSSC’s unit there in attenuation of electromechanical localized oscillatory patterns and in the management of unreliable modes induced by generation load difference and also fault situations. The adjustment of operation of the integrated supplementary controller uses the synchronized operation of both SSSC and PSS units. Because the optimum management of these two devices' parameters interferes with their efficiency, creating optimum control environments for their operation is critical, and this has been accomplished using genetic algorithm.Genetic algorithm is an optimization algorithm for general purposes based on natural function (FF) to evaluate any solution generated by assigning a quality value. The process starts with the first random population produced and assessed. Three simple genetic operators perform genetic assessments given below:

Step1: Select parents.
Step2: Processing of crossover.
Step3: Process of mutation.
Step4: Newly created population for a further evolution.
Step5: Stopping and reach optimal solution.

Also PI (real power flow performance index) compassion based methods are used for power flow. In SSSC basically fuzzy logic controller [10] based PI controller are used for enhancement voltage of transmission line. Improved Harmony search algorithm (HIS) [11] is applied to identify correct SSSC position including model parameters with in electrical systems. An OPF approach with the optimized SSSC model is verified utilizing HIS optimization approach on recommended IEEE 30 bus topology. It clearly establishes the supremacy of the OPF approach established utilizing IHS methodology compared to conventional approaches reported in literature.

2.1.2 TCSC

It is a device that is utilized fundamentally to lessen transmission line reactance as depicted in Fig.4. Accordingly, the transient and voltage strength in transmission network is generously increased [12]. This device controls the measure of line compensation and also has the capability to work in different modes. These attributes are very essential; as the loads changes continually and can’t generally be anticipated.

The principle of thyristor controlled arrangement is to vary the fundamental frequency voltage of the capacitor which is in series compensated line by altering the firing angle. This alters the effective value of capacitive reactance which is connected in series [13].

A TCSC comprises of an arrangement of capacitor and thyristor controlled reactor as depicted in Figure.4 below:

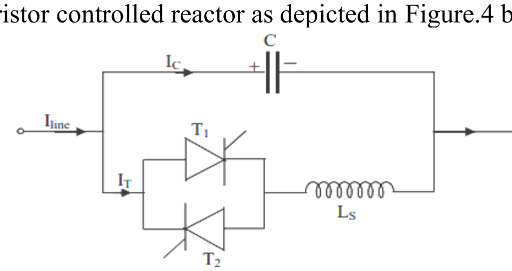

Figure 4. TCSC

The TCSC operates in three different modes [14].

- **Blocking mode**: Firing pulse is blocked to the thyristor. When a blocking command is given, the current reaches zero and thyristor gets turn off. Thus TCSC is reduced to capacitor only.
- **Bypass mode**: When the voltage across the thyristors becomes zero, the gate pulses are applied which results in a flow of current which is sinusoidal in nature and passes via thyristors. The TCSC is reduced to a parallel capacitor-inductor configuration.

$$Zeq = \left(\frac{j}{\omega C}\right) \| (j\omega L) j\left(\frac{1}{\omega C-\frac{1}{\omega L}}\right) \quad (9)$$

If $\omega C - \frac{1}{\omega L} > 0$ contribute capacitive reactance of variable nature

If $\omega C - \frac{1}{\omega L} < 0$ contribute inductive reactance of variable nature.

- **Vernier operating mode:** The firing angle is varied from 0^0 to 90^0 in this mode and are further categorized as[15]:

*1) Capacitive*boost*mode:*

Thyristor is given a pulse that has forward voltage when the V_C becomes zero. So a current pulse flows via parallel inductive branch. This current pulse is applied to line current, bringing about a V_C that to the voltage created by the line current which expands the capacitor's peak voltage in relation to thyristors branch charge. The fundamental voltage likewise gets increment relatively to the charge. This is the standard operating method of TCSC.

*2) Inductive*boost*mode:*

The line current is less than the current in the thyristor branch in this mechanism. The thyristor current distorts sinusoidal waveform of capacitor voltage. Due to the poor waveform, this method is not preferred for steady state operation. Oscillations of power in the systems may occur during the heavy power transfer. These oscillations are due to the occurrence of faults, line switching or a sudden change in output. By modulating the reactance of one or more different interconnecting power lines, damping can be done; hence the oscillations are reduced. Assume that the speed be η_1 and rotor angle be Φ_1 of machine $SM_1$and η_2 and Φ_2 respectively of machine SM_2 in consideration with Figure.5.

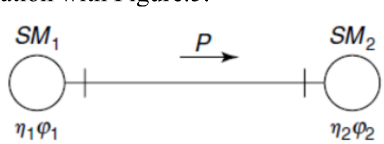

Figure 5. Transmission Line

If the speed of SM_2 is less than SM_1, i.e. $\Delta\eta$ is negative, and then the power in the line increases and when the $\Delta\eta$ is positive then the power in the line decreases. Figure.6 shows the rotor angle deviation [16].

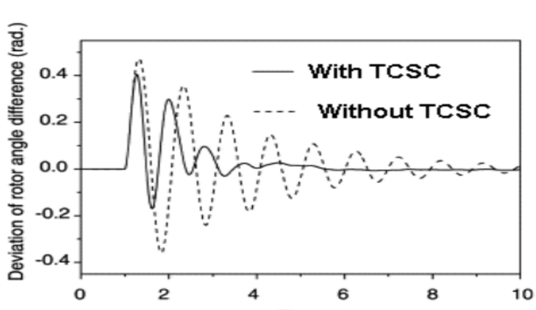

Figure 6. Damping using TCSC

Advantages of the TCSC can be summarized as :

- It increases power flow capacity.
- System stability increases.
- System loss gets reduced.
- Voltage profiles of the lines are improved.
- Suppression of sub synchronous oscillations.

Whale optimization technique -: This algorithm solves the issues of reactive power requirements concerning voltage stability of the systems by using the TCSC. Optimal location of TCSC was calculated using the VCPI process [17]. The most important finding is that the suggested solution by WOA reveals fewer variations that are not caught in the local minima and give positive attributes of convergence addressing the issue of reactive power allocation in power networks efficiently. This algorithm consists of two main stages and corresponding process is demonstrated in Figure.7

Stage1: Seeking for prey is done in this phase. It is also known as exploration phase. The search agent's location is changed depending on a randomly elected search agent, rather than the best search agent retrieved.

Stage2: Encircling of prey and spiral updation of location is carried out. It is also known as exploitation phase.

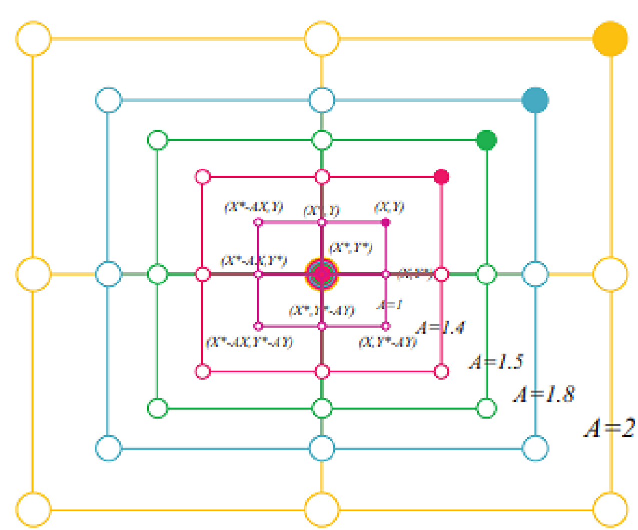

Figure 7. WOA Expedition System(X^* Denotes Arbitrary Chosen Inspection Agent)

Imperialistic Competitive Algorithm-: This technique is used for optimizing the allocation TCSC and to enhance static safety in power systems. For an Indian utility; neyveli coal power industry 23 bus networks; the proposed approach has been evaluated [18]. It can be concluded that utilizing this approach; total true power losses are curtailed while preserving the voltage regulation among total buses as well as thermal limit amongst all power lines within the prescribed tolerance boosting the performance of power network.

2.2. SHUNT COMPENSATION DEVICES

These are the FACTS tools that are used to manage the stress level, reducing the losses through optimally locating the FACTS devices in the electrical network.

2.2.1 STATIC VAR COMPENSATOR

SVC as depicted in Figure.8 is a collection of electrical devices capable of controlling voltage, harmonics, power factor and system stability to provide quick KVAR power on HVAC systems [19].

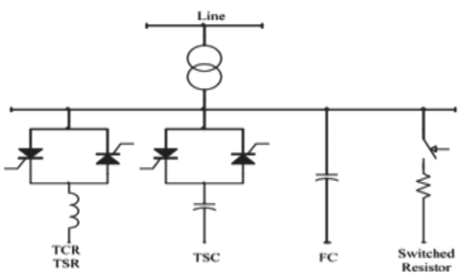

Figure 8. Static Var Compensator

Working Principle: If the bus voltage declines below a certain value, the SVC delivers reactive power and thus boosts the bus voltage again to final optimized voltage value. As the bus voltage rises, the static var compensator absorbs reactive power and the required bus voltages are accomplished [20].Static Var Compensators (SVC) have parallel connection of the condenser filter banks and air-core reactors. Air core reactor are series attached to thyristor. Control of thyristor firing angle will regulate the current of the air core reactors. The air-core reactor has linearity in Static Var Compensator [21].By regulation of thyristors. It is suitable for absorbing reactive power.

The condenser can give sample quantity of capacitive KVAR to the system and remove the undesirable harmonic. The filter consists of components such as condensers, reactors and resistors, giving the entire system capacitive reactive power [22-23].

The TCR is controlled for continuous operation with the correct firing angle input, while the TSR is controlled without the control of the firing angle. TSR and TSC both aim to regulate the issue of voltage instability by delivering and consuming the KVAR power in the device. This FACT device stabilizes the voltage by simultaneously absorbing and discharging reactive power [24].

The V-I properties of SVC are graphs of junction voltages and current. V_{ref} is the voltage at the SVC's terminals as it does not consume or produce any KVAR power at all. The source voltage value will vary between lowest and highest thresholds [25]. The slope or decline in the characteristic V-I is the connection between the degree of change involved and the current magnitude change over the linear control spectrum as demonstrated by Figure. 9.

$$k_{si} = \frac{\Delta V}{\Delta I} \tag{10}$$

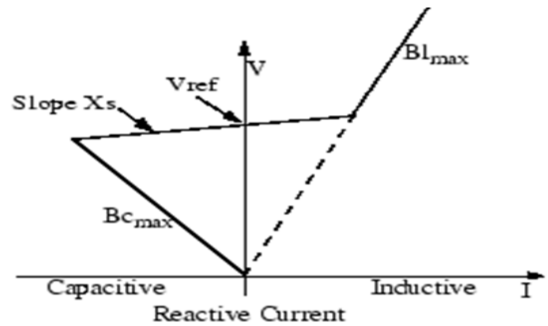

Figure 9. V-I Characteristics of SVC

$$V = \begin{cases} Vref + Xs.I & \text{For SVC in regulation range} \\ -\frac{1}{Bcmax} & \text{For SVC totally capacitive} \\ \frac{I}{Blmax} & \text{For SVC totally inductive} \end{cases} \tag{11}$$

Where,

V = reference voltage

Xs = Slope or droop reactance

Bc_{max} = Maximum capacitive susceptance

Bl_{max}= Maximum inductive susceptance

Pbase = Three-phase base power.

SVCs are used for:

1. SVC are used to boost power transmission in long lines.
2. It is used for low frequency oscillation damping (corresponding to the electromechanical modes)
3. Improvement of stability (both steady and transient) with rapid voltage regulation
4. Damping oscillations in sub-synchronous frequencies.
5.

Following conclusions can be drawn regarding SVC benefits:

- This helps to improve efficiency, since stable voltage means higher power utilization.
- Reduces KVAR power usage, resulting in lesser losses and tariff improvements.
- Balanced asymmetric loads minimize device losses and require lower rotating machinery stress.
- Making better use of equipment.
- Minimize voltage fluctuations and light flicker
- Reduces Harmonic Distortion.

SVC with fuzzy wind farm grid integration controller has been applied using the PI-based controller SVC which can effectively control the grid voltage [26]. ANFIS controller was engineered using transitory-response sheet for the SVC system as well as the PID controller which does have a short-circuit failure in three phases for the system under analysis. The recommended SVC model and the developed PID damping controller are capable of mitigating synchronous generator oscillations; thereby improving the network performance under examination.

Symbiotic organism search (SOS)-: This methodology proposed an iterative population based approach which needs no unique algorithm control parameters as seen in other approaches [27] dealing with non-linear optimization challenge addressing both inequality and equality constraints of the system. The efficacy of the suggested SOS algorithm is evaluated on the updated IEEE-30 bus as well as IEEE-57 bus configuration systems that integrate 2 kinds of FACTS tools respectively, thyristor-controlled condenser series but also thyristor- directed phase shifter over fixed positions. The OPF issue of this research has been developed with four specific objective roles viz. (a) lowering fuel prices, (b) mitigating significant power failure transfer, (c) decreasing emissions and (d) lowering the overall economical including environmental expenses.

BSO algorithm-: The BSO (Brain storm optimization) is used to get both the SVC's optimum placement and capacity. BSO's outcomes are achieved by using IEEE 57 bus system. The presented BSO solution gave better stress profile, less device losses and lowering voltage fluctuations [28]. Entities in BSO are clustered and deviated in the searching space using the divergent and convergent operations simulating human process of brainstorming.

A brainstorming algorithm follows these steps:

Step 1: Collect a brainstorming g people with as many different backgrounds as possible.

Step 2: Develop lots of thoughts as per the rules.

Step3: Many, say 5 or 7, clients act as problem owners, say every owner, ideas as better solutions

Step 4: Using the concepts obtained in Step 3 as hints that are more probable than other idea, and create more ideas as per Table 2 rules.

Step 5: Have owners come up with much superior ideas, as they perform in Phase 3

Step 6: Choose an thought by possibility, using the object's functions and appearance as hints, generate more ideas in accordance with the Table rules.

Step 7: Some better ideas are opted by owner

Step 8: A good enough solution can possibly be obtained by considering and/or combining the ideas produced.

2.2.2 STATCOM (Static compensator)

The STATCOM as depicted in Figure. 10 [29] works on the principle that a controllable alternating voltage is produced by a voltage supply inverter to create active power conversation between transmission system and STATCOM by the voltage across the network [30]. The STATCOM produces AC voltage at the connection to the transmission system causing a variable magnitude current. This injected current through line voltage is nearly in quadrature, emulation of a capacitive or inductive reaction at the power transmission connection point as referred in Figure.11 [31].The basic parts of the STATCOM are voltage-source converter, coupling transformer and a dc link capacitor [32]. When transients periods are over (steady state) power transmits between the STATCOM and transmission system frequently using this arrangement.

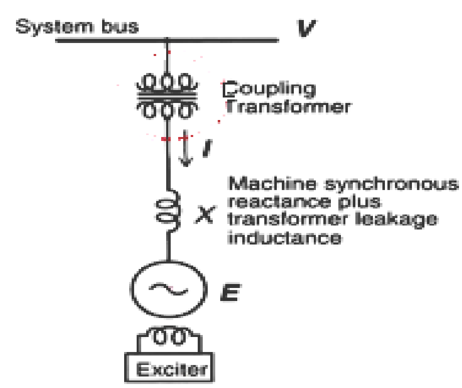

Figure 10. STATCOM

$$I = \frac{V-E}{X} \tag{12}$$

$$Q = \left(\frac{1-\frac{E}{V}}{X}\right)V^2 \tag{13}$$

If voltage after process of the STATCOM switching is equal that of the connected device, STATCOM does not interpose any KVAR power to the system when net amount of current is zero [33]. The facts devices (STATCOM) will continue to plunge KVAR power to the network when the output voltage of STATCOM becomes less than the ac system (inductive) [34]. If output voltage of STATCOM is higher than ac voltage of system (capacitive) the device can produce reactive power. In addition, it is observed that the current inserted by the STATCOM is in a 90° phase displacement with the voltage of the ac device, and can either be leading or lagging [35]. The role of the condenser is to ensure that the inverter receives a unceasing dc voltage at all times. Any electro-mechanical fluctuations that are created in the multi-machine electrical grid, which have the greatest influence on the power grid, may be greatly reduced by utilizing STATCOM.

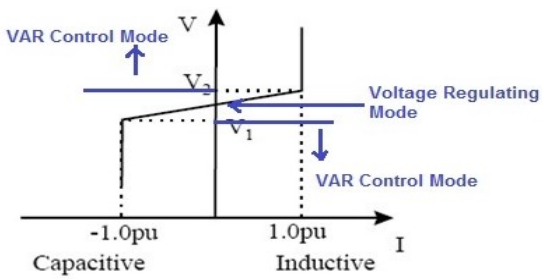

Figure 11. VI characteristic of STATCOM

NSGA-II meta-heuristic algorithm: The NSGA-II as demonstrated in Figure.12 meta-heuristic algorithm is one of the most flexible and efficient algorithms to resolve optimizations of multi-objectives and NSGA optimization approach [36] was used to figure out multi-objective optimization problems. It was used to address the multi-objective issue of planning of reactive power allocation in order to reduce the shunt compensation expenditure costs including fluctuations in mean load bus voltage. This algorithm applies for optimum location of STATCOM in IEEE 30 bus topology. It can be inferred that analytical methods provide comprehensive knowledge about reactive power control scheme installations and have technological and economic advantages in varying scenarios.

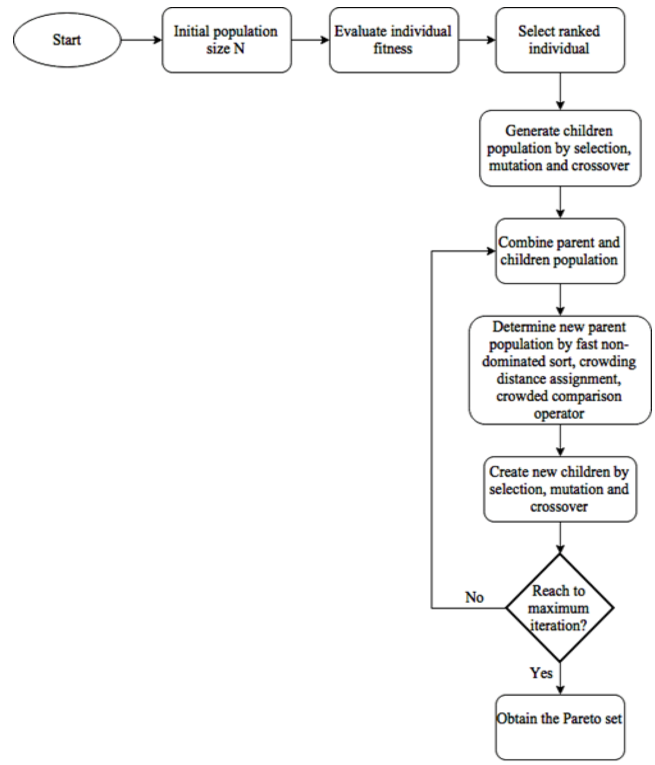

Figure 12. NSGA-II Meta-heuristic Flowchart

2.2.3 DSTATCOM

This FACTS device is a counterbalancing tool utilized to monitor KVAR power discharge in the distribution network. This is a shunt compensation system mounted at load end to increase the power factor (PF) and voltage control. DSTATCOM shown in Figure.13 is an modern power electronic unit that give us reactive power balancing, remove harmonic, source current balancing and other solutions related to power quality [37].

Due to its remarkable features like it give swift response, adaptability, easy to implement, it is used for vital load response requirements as well as for the amelioration of voltage sags and swells; leading or lagging reactive power supplies.

DSTATCOM contains a voltage reference converter, DC capacitor, coupling inductor or coupling transformer and a controller [38].

OPERATING PRINCIPLE:

DSTATCOM operate in three modes: [39]

Capacitive mode: When inverter voltage is greater the network voltage current will run from DSTATCOM to alternating current network; that means Distribution STATCOM delivers the current into the system, and the unit is capacitive reactive

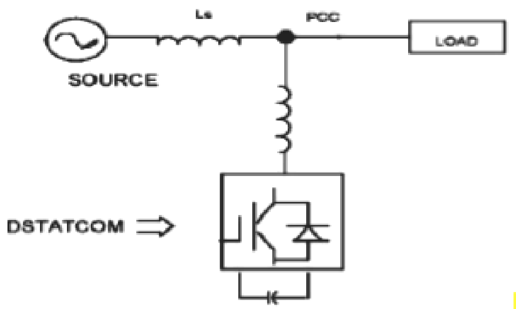

Figure 13. DSTATCOM Structure

- **Inductive mode:** Current runs from the alternating network to the DSTATCOM if voltage of inverter is lesser as compared to voltage of the network, DSTATCOM consumes inductive reactive power.

- **Floating mode:** When inverter response voltage equivalent to the voltage of the network, KVAR power is zero, and the D-STATCOM neither delivers nor consume the reactive power.

DSTATCOM CIRCUIT DESCRIPTION:

In circuit given in Figure.14; three step value of V and I is measured. From concept of the instantaneous KVAR power theory for a balanced three-phase network, the quadrature component of the voltage is forever zero; the active and kVAR power given by DSTATCOM in the device can be expressed as reference frame dq [40].

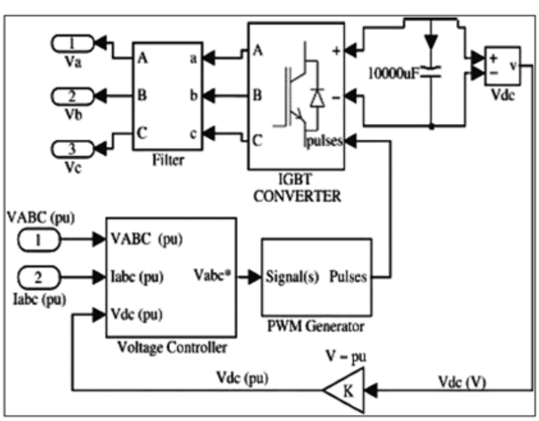

Figure 14. DSTATCOM Controller

DSTATCOM CONTROL ALGORTITHM

A DSTATCOM control algorithms given in Figure. 15 are executed in the steps below:

1. Measuring the voltages and current of system and conditioning the signal
2. Reimbursing signals calculation.
3. Formation of proper triggering angles of switching devices.
4. Most significant part of DSTATCOM control is the generation of correct PWM firing.

Control of DSTATCOM:

Three phase value of voltage and current are estimated .The voltage quadrature component is always at zero from the principle of the IRP theory for a balanced 3φnetwork, real (p) and KVAR power (q) provided in the device by DSTATCOM may be demonstrated as reference frame dq[40].

$$p = V_d I_d + V_q V_q \quad (14)$$

$$q = V_d I_d - V_q V_q \quad (15)$$

If device voltage stays unchanged, vq=0, Id and Iq thoroughly define the instant value of the active and KVAR power deliver by DSTATCOM. Thus the determined instantaneous three phase current converts from abc to dqo 41].Two independent PI regulators control the direct-axis component Id and the q-axis component Iq. We will obtain instant Id reference and instant Iq reference by regulating the dc voltage. Instant current tracking regulations are thus attained with the use of four PI regulators. The phase locked loop (PLL) is utilized to configure the regulated loop with the alternating supply to function within the abc to dqo standard frame active and KVAR powers p and q split into an standard and an oscillatory part.

$$q = \bar{q} + \tilde{q} \quad (16)$$

$$p = \bar{p} + \tilde{p} \quad (17)$$

Here p or q are the average part of real and KVAR powers and the oscillatory part. The requite currents are measured to counter balance instant KVAR power and the oscillating part of the instant real power [42]. Hence reference source current component described as:

$$\begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} \quad (18)$$

Such currents can be converted to a-b-c to measure the reference currents in the a-b-c coordinate.

$$\begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \\ i_{s0}^* \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (19)$$

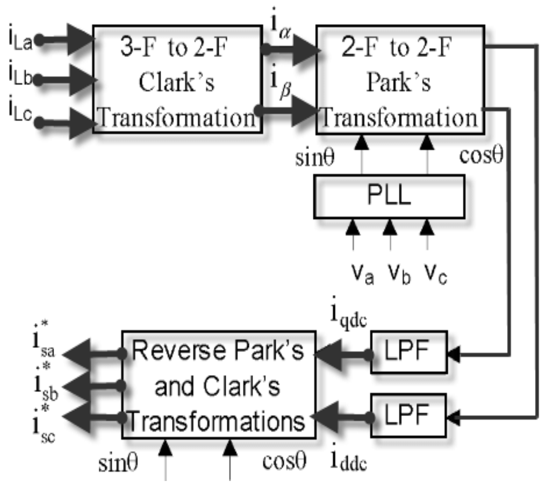

Figure 15. Block Diagram for Controlling of DSTATCOM

CONTROL TECHNIQUES FOR DSTATCOM,:

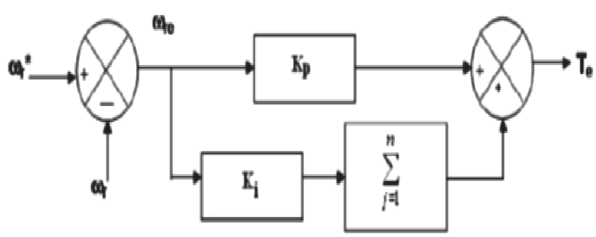

Figure 16. PI-Controller Block Diagram

The controller output speed (torque command) depicted in Figure. 16 can be described as follows at n-th instant:

$$T_e(n) = T_e(n-1) + K_p\omega_{re}(n) + K_i\omega_{re}(n) \quad (20)$$

Where Te(n) =nth instant output torque of the controller, K_p & K_i = proportional and integral gain constants, respectively [43].
The torque control limit is defined as:

$$T_{e(n+1)} = \begin{cases} T_{emax} & \text{for } T_{e(n+1)} \geq T_{emax} \\ -T_{emax} & \text{for } T_{e(n+1)} \leq -T_{emax} \end{cases} \quad (21)$$

Numerous techniques such as hit and trial technique and development technique-based searching can select PI controller gains. The mathematical values for these gains rely on the ratings of the machine [44].

Following advantage and disadvantages can be inferred:

- PI controller integral term lowers the steady-state error to nil.
- In case of disturbance data lack of derivative action, system in the steady state may become more stable. This is because derivative operation in the inputs is more prone to expressions of higher frequencies
- Absence of derivative operation, so the system can take longer to reach set point.

PI CONTROL

The algorithm of Proportional-Integral (PI)[45] evaluates and sends each sample time (T); a output of controller (CO) signal .The parameters of tuning and error of controller , e(t), influence the PI algorithm's computed CO.
To adjust this, PI controllers have two tuning parameters, though it is less challenging than the PID controller with three parameters
Integral PI controller operation eliminates variance, which is a significant downside for a P-only system. PI controllers therefore provide sophistication and a capability balance which makes them perhaps the most largest commonly utilized algorithm for controlling.

$$CO = CO_{bias} + K_c e(t) + \frac{K_c}{T_i}\int e(t)dt \quad (22)$$

Integral operation is the final termination of the above equation. The purpose is to continuously merge or add the error, e(t), over time.
Kc·e(t), sums up or deducts CO_{bias} at each time t, depending on the controller error size e(t).The sum of CO_{bias} will expand or shrink instantly and in proportion as e(t) increases or decreases. Past record of controller error and current trajectory have no effect on proportional term estimation.
The integral term assesses the past record of the error or the duration and degree to which the process variable was over time from the fixed point. Integration implies adding up constantly. Integrating error over time means we are summarizing the past record of controller error up to, beginning from when the controller was converted to automatic for the first time.

Different Technique of Tuning PI-now Controllers: There are different techniques used for PI-controller tuning like:

- Hit and error
- Continuous cycling method.

Hit and error

The equation of PI controller is:

$$p(t) = K_c\left[e(t) + \frac{1}{\tau_i}\int_0^t e(t)dt\right] \quad (23)$$

It is analyzed that this method take lots of time and requires a large number of iterations if the dynamics of the process are slow. Continuous cycling can be problematic, as the cycle is driven to the stability limit. Therefore, if external interruptions or system changes occur during the tuning of the controller, an unsafe operation or dangerous circumstances can occur. The tuning approach does not extend to open loop systems.

Application of Fuzzy Logic Controller:

FLC is implemented for better system's transient response. PI controllers with fixed parameter were implemented to control D-STATCOM. Because of its nonlinear nature, the average control efficiency could be inadequate. The regulation of direct and quadrature axis currents of STATCOM is suggested using a fuzzy-PI controller with a nonlinear and stable structure. It's operation is based on sets of rules that is easy to build for every number of inputs and outputs [46].

The FLC has been engineered to boost the working of controller. Membership functions or scaling factors are used for modulation of fuzzy controllers. The rules represents a control strategy, it is suggested that the rule base remain identical and that the tuning exercise concentrate on the scaling factors. The factors of scaling the model FLC are optimized utilizing the Gray Wolf Optimization (GWO) algorithm [47].For changing the scaling aspects of fuzzy logic controller ; implementation of the grey wolf optimization algorithm which is a wise option for finding the best tuning of parameter of fuzzy and minimization of error on various constrain sets which is explained as:

Step 1: Allocate variables for GWO. Gd-Design variable size, Gs-Search agents, vectors a, A, C, and max numbers of iterations are allocated.

$$\bar{A} = 2\bar{a}.\text{rand} - \bar{a} \quad (24)$$
$$\bar{C} = 2.\text{rand} \quad (25)$$

Step 2: Randomly generated wolves which can be presented mathematically, as

$$\text{Wolves} = \begin{bmatrix} G11 & G12 & G13 & \dots & G1n \\ G21 & G22 & G23 & \dots & G2n \\ . & . & . & \dots & . \\ . & . & . & \dots & . \\ Gm1 & Gm2 & Gm & \dots & Gmn \end{bmatrix} \quad (26)$$

Where, G_{mn} is the initial value of the n^{th} pack of the m^{th} wolves.

Step 3Each hunting agent's fitness is calculated using Equations (27)-(28).

$$\bar{D} = |\ \bar{C}.\bar{G_p}(t) - (t)\ | \quad (27)$$
$$\bar{G}(t+1) = \bar{G_p}(t) - \bar{A}.\bar{D} \quad (28)$$

Step 4: The hunting agents α (best), β (second best) and δ(third best hunting agent) are found by the Eqns. (29)-(34).

$$\bar{D}_\alpha = |\bar{C_1}.\bar{G}_\alpha - \bar{G}| \quad (29)$$
$$\bar{D}_\beta = |\bar{C_2}.\bar{G}_\beta - \bar{G}| \quad (30)$$
$$\bar{D}_\delta = |\bar{C_3}.\bar{G}_\delta - \bar{G}| \quad (31)$$
$$\bar{G}_1 = \bar{G}_\alpha - \bar{A_1}.(\bar{D}_\alpha) \quad (32)$$
$$\bar{G}_2 = \bar{G}_\beta - \bar{A_2}.(\bar{D}_\beta) \quad (33)$$
$$\bar{G}_3 = \bar{G}_\delta - \bar{A_3}.(\bar{D}_\delta) \quad (34)$$

Step 5 The current hunting agent 's location is modified using Equation (34).

$$\bar{G}(t+1) = \frac{\bar{G}_1 + \bar{G}_2 + \bar{G}_3}{3} \quad (35)$$

Step 6: Record the fitness level of all hunts.

Step 7: Values of $\bar{G}_\alpha$, $\bar{G}_\beta$ and $\bar{G}_\delta$ are updated

2.3. SERIES SHUNT COMPENSATOR

It is a shunt and series combination. So, they have the characteristics of all types of controllers and they are very helpful regarding improving the power flow capacity of system. Thus, it makes the network more stable and efficient.

2.3.1. UPFC (UNIFIED POWER FLOW CONTROL)

This is a kind of shunt series FACTS device. It exhibits the characteristics of both series and shunt devices where SSSC is a series controller and STATCOM is a shunt controller [48].These two converters given in Figure. 17 are connected through a DC condenser. The process of parallel inverter is to absorb or produce absorbing power to the line. The DC capacitor is charged by shunt controller to meet the power requisition and to compensate any real power [49].The inverter converts the actual power back and forth at ac terminal ;transform to dc power, which appears as active power needed at dc terminal.

$$V_{vR} = |V_{vR}|(\cos\theta_{vR} + j\sin\theta_{vR}) \quad (36)$$
$$V_{cR} = |V_{cR}|(\cos\theta_{cR} + j\sin\theta_{cR}) \quad (37)$$

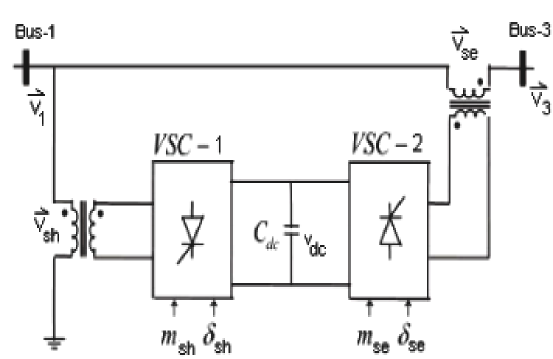

Figure 17. UPFC

Immune algorithm (IA)-:

This method is given to figure out optimization problems by implementing human immune system operating principle. This article discusses the implementation of the

immune algorithm (IA) for identify the best position of the UPFC to ensure desirable power flow and congestion control [50]. The immune algorithm was proposed to reduce the overall costs, including total real and KVAR power generation costs and the implementation costs of UPFC, taking into account the various faults associated with different line overload conditions. The tests are carried out on 4-bus, 14-bus IEEE as well as on 30-bus IEEE study platforms and and the outcomes are promising and would be helpful in electrical reconstruction for the optimum position of UPFC.
It is analyzed that to find out the most effective cost of the system, the following procedure is used. With the initial recognition of antigens, antibody populations are produced. After the production of antibodies, high affinity solutions are selected which will be used for crossover and mutation .The following procedure is used:
Step 1: Initially antigens are recognized.
Step 2: Antibody population are produced.
Step 3: Calculate affinity.
Step 4: Evaluate and select.
Step 5: Mutation and Crossover are done.
Step 6: Determination of optimum approach.

The most utilized applications of UPFC recognized are:

- Voltage profile improvement.
- Fault current limiting.
- Reduces Damping oscillation in power flow.

2.4 SERIES-SERIESCOMPENSATOR IPFC:
A tool for increasing the reliability of the power network as shown in Figure.18. It incorporated IPFC based online damping testing recurrent neural topology controls for mitigation of power system fluctuations is explained in [51].
Configured control parameters for optimizing system per formance at IPFC are optimized using computational m odels. It can be inferred that multi - layer artificial neural structure that can be adjusted for evolving device conditions to effectively dampen the perturbations. This controlled mechanism is checked for machine load variations including fault in the power network and its output are contrasted to a controller's efficiency while the step correction procedure is used to determine the parameters. It can be demonstrated that suggested controller's superior robustness as well as stabilizing impact as contrasted with that of the system of phase compensation.

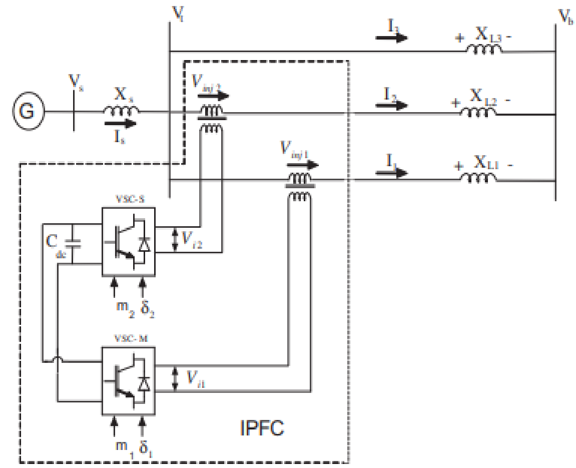

Figure 18. IPFC Connected to the Power System Network

3. FACTS ADVANTAGES IN POWER SYSTEM SUMMARIZATION:

- System losses are reduced.
- System stability is increased.
- Voltage flicker is controlled by using STATCOM most effectively.
- Power flow in transmission line is enhanced.
- Better stability

3.1 COMPARISON BETWEEN VARIOUS FACTS

TABLE1. Explains the important attributes of different FACTS devices which are considered for analysis and corresponding results are tabulated.
TABLE2. Highlights the key issues of various FACTS devices which are investigated and corresponding solutions are also suggested based on comprehensive analysis.

TABLE.1 IMPORTANT ATTRIBUTES OF DIFFERENT FACTS DEVICES

4. CONCLUSIONS

This work attends the comprehensive study of FACTS with their comparison and corresponding benefits are also discussed. The FACTS provides many benefits like voltage enhancement, reactive power enhancement, voltage profile consistency at heavy loads etc. FACTS devices are very cost effective when compared to the installation of new power generation system for enhanced power flow and to enhance the static and dynamic capacities of the network. Optimal placement of these devices using various new technologies leads to enhanced stability and productive operations. The application of FACTS devices can be used for maintaining a good voltage figure including good power quality, harmonics reduction, and losses minimization and to increase the system stability.

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TABLE.2 KEY ISSUES OF VARIOUS FACTS DEVICESM AND CORRESPONDING SOLUTIONS

Sl. no	Issues	Devices	Solutions
1	Parallel line loading	TCSC,UPFC	Series line reactance is modified
2	Fault after power run communion	SSSC,UPFC	Reorganize the system
3	Flow of power in opposite direction	SSSC,UPFC	Modified Phase angle
4	High loads low voltage	STATCOM	Sending reactive power
5	Minimum loads with high voltage	STATCOM, SVC	Absorbing reactive power
6	High voltage after failure	STATCOM, SVC	Absorbing reactive power
7	Weak voltage after failure	SVC, STATCOM	Sending reactive power and preclude overloading
8	Transmission overloading circuit	UPFC, TCSC, SSSC	Reducing overload
9	Parallel line fluctuation	TCSC, SSSC,UPFC	Circuit loading is minimised

SSSC led to improvement in dynamic and transient stability of extra high voltage transmission line inclusive of damping fluctuations in voltage. SVC and TCSC enhances the limit of line power improving system stability. UPFC implementation compensates voltage and current associated power quality concerns. D-STATCOM can provide compensation of voltage increment and decrement from specified levels and maintains profile of voltage. STATCOM enhances the regulation of power flow. Artificial intelligence technologies are becoming common for addressing a plethora of issues in power systems, including monitoring, planning, scheduling, forecasting, and so forth to fulfil the increase in demand of load. Implementation of various intelligent methodologies like Artificial Neural Network (ANN) and fuzzy logic control, genetic algorithm etc. are fault tolerant; capable of understanding and adapting to new data for controlling of FACTS devices and having fast processing speed which is very helpful to maintain good power quality of system leading to better efficiency and

S.NO	Attributes	Devices				
		TCSC	SSSC	STAT-COM	SVC	UPFC
1.	Power back up control	✓	✓			✓
2.	Voltage level enhancement			✓	✓	✓
3.	Forced response commutated		✓	✓		✓
4.	Forced com mutated		✓	✓		✓
5.	Vsc	✓	✓	✓		✓
6.	Current inverter	✓	✓		✓	
7.	Dynamic inverter	✓	✓			✓
8.	Damping fluctuation	✓	✓	✓	✓	✓
9.	Limiting Fault current	✓				✓
10.	Voltage controlling	✓	✓	✓	✓	✓

enhanced operation and resulted in skilful power system control along with its productive management.

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