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Unified Power Flow Controller: A Brief Review on Tuning and Allocation for Power System Stability

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Abstract:

The Power System can become unstable due to disturbances. To enhance system stability the Unified Power Flow Controller (UPFC) is tuned and allocated in the System. In this paper, a brief review of UPFC tuning and allocation studies for power systems stability is presented. The databases consulted for literature are the IEEE Xplore, ScienceDirect, Google Scholar and IOP Publications. The search terms used are Allocation, Tuning, UPFC, Power System and Stability to find the literature used in this review. A total of 26 Journal articles and conference papers were found and reviewed based on tuning and allocation studies. The Researchers applied Fuzzy coordination, Genetic Algorithm (GA), Particles Swarm Optimization (PSO), Grey Wolf Optimization (GWO) and Linear Quadratic Tracker (LQT) to tune the UPFC for enhancing power system stability. For studies on UPFC allocation in power systems, the Researchers applied frequency response of power system transfer function, power flow, Tabu Search (TS), PSO and GA. For allocation based on optimization, the Researchers minimized power losses, voltage index and investment costs considering equality and inequality constraints.

Keywords: *Allocation of Unified Power Flow Controller, Tuning, Power System Stability.*

Introduction

The UPFC is one of the Flexible Alternating Current Transmission System (FACTS) devices connected to transmission lines to control voltages, and reactive power, reduced transient stability and mitigate oscillation (Shen et al., 2020). It contains two Voltage Source Converters (VSCs) as depicted in Figure 1. One of the Converter is connected in series to the receiving end of the line using a boost transformer while the other is connected in parallel to the sending end of the line using an excitation transformer. The two Converters have a common DC link via a Capacitor. The UPFC combines the capabilities of the Synchronous Series Static Compensator (SSSC) for voltage injection in the line and the Static Compensator (STATCOM) for reactive power control in the line. It is connected to the transmission line to mitigate power system insecurity (Padiyar, 2007).

The allocation of UPFC in the transmission line is to enhance power system security. There are different allocation methods such as frequency response of transfer function of power system, Fault Analysis, Newton-Rapson Power Flow, Optimal Power Flow, Parallel Tabu Search (PTS), PSO and GA. The allocation involves finding the buses at which the UPFC can be connected to derive both technical and economic advantages. The allocation of UPFC required appropriate models for different studies.

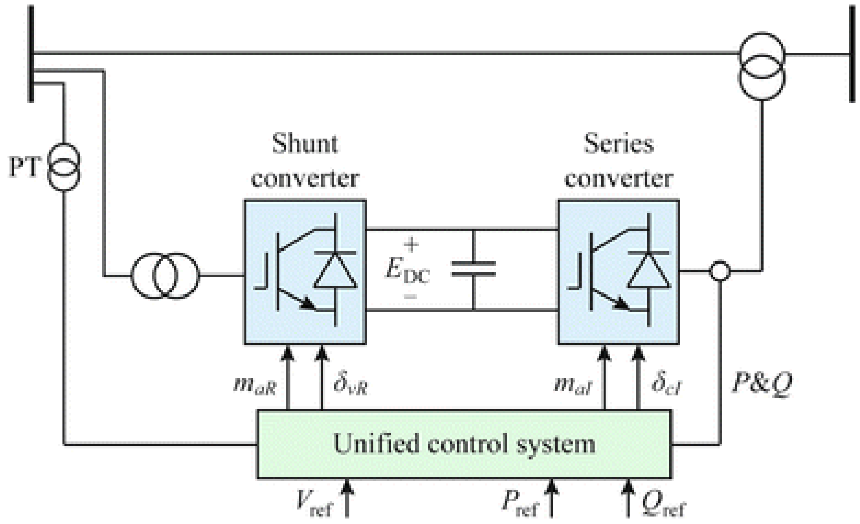

Figure 1. Unified Power Flow Controller (UPFC).
Source: Maza-Ortega et al. (2017)

Models of UPFC for Power System Study

For steady state, transient stability and eigenvalue studies of power systems the UPFC require suitable models (Nabavi-Niaki & Iravani, 1996). Figure 2 the series Converter control model of UPFC. The application of UPFC in power systems for active and reactive power control is presented in Equations (1) and (2) respectively (Connected, Converter & Zhao, 2008).

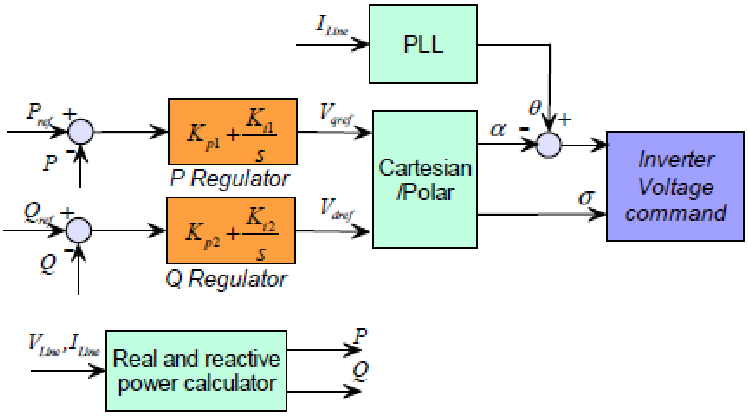

Figure 2. Model of Series Converter of UPFC.
Source: Connected, Converter & Zhao (2008)

$$\mathrm{P} = \frac{V_{sending} * V_{recieving} * \sin\delta_{sending}}{X_{tran.\ line}} \qquad (1)$$

$$\mathrm{Q} = \frac{V_{sending}(V_{sending} - V_{recieving}) * \cos\delta_{sending}}{X_{tran.\ line}} \qquad (2)$$

The magnitude of the series voltage inject in the transmission line by the series converter is presented in Equation (3).

$$V_{series} = m_{series} \frac{V_{DC}}{V_{base} 2\sqrt{2} n_{series}} \quad (3)$$

Figure 3 is the shunt Converter control model of UPFC (Connected, Converter & Zhao, 2008). The magnitude of shunt voltage inject in a bus by shunt converter is presented in Equation (4) (Connected, Converter & Zhao, 2008).

$$V_{shunt} = m_{shunt} \frac{V_{DC}}{V_{base} 2\sqrt{2} n_{shunts}} \quad (4)$$

And the UPFC shunt Converter decoupled Equations in the 0dq frame for power flow control are presented in Equation (5) – (8) (Parvathy & Thampatty, 2015).

$$V_{dsh} = V_{1d} + \frac{X_{sh}}{\omega} * \frac{\mathrm{d} I_{dsh}}{dt} + I_{dsh} R_{sh} - X_{sh} I_{qsh} \quad (5)$$

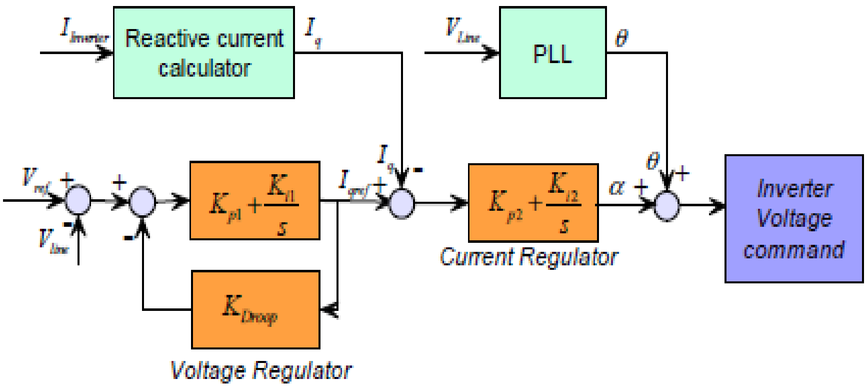

Figure 3. Shunt Converter Control Model of UPFC.
Source: Connected, Converter & Zhao, 2008.

$$V_{qsh} = V_{1q} + \frac{X_{sh}}{\omega} * \frac{\mathrm{d} I_{qsh}}{dt} + I_{qsh} R_{sh} + X_{sh} I_{dsh} \quad (6)$$

$$V_{sh\,rms} = \sqrt{[(V_{sh\,d})^2 + (V_{sh\,q})^2]} \quad (7)$$

$$P_{sh} = V_{dsh} i_{dsh} + V_{qsh} i_{qsh} \quad (8)$$

The above Series and Shunt models of the UPFC Converters are required for Voltage, Frequency and Transient stability control in Power Systems.

Frequency, Rotor and Voltage Stability in Power System

The power system stability can be subdivided into frequency stability, rotor angle stability and voltage stability (Kundur et al., 2004) as depicted in Figure 4.

The system frequency instability is a result of power fluctuation at the generation units (Lotfy et al., 2018), or due to a change in the load profile. The frequency stability is studied for the long-term and short-term duration.

Rotor Stability in Power System

Rotor stability is the study of electromechanical oscillation of the machines in a power system, largely caused by non-equilibrium between the input mechanical torque and output electrical torque of the machines. The rotor stability is classified into small disturbance angle stability and transient stability. The rotor stability of machines in power systems can be determined analytically using Equation (9) (Mi, Wang & Wang, 2018).

$$\frac{Hi}{\pi fi}\frac{d^2\delta i}{dt^2} + Di\frac{d\delta i}{dt} = (Pmi - Pei)\ in\ pu \qquad (9)$$

Where, Hi is the inertia constant of the ith machine in MJ/MVA δi is the ith machine rotor angle in electrical degree ° pu. The fi is the frequency of the ith machine in hertz. Di is the damping factor of the ith machine, P_{mi} is the mechanical input power of the ith machine in megajoules and P_{ei} is the electrical power output in megawatts of the ith machine all in pu. And t represents time in seconds.

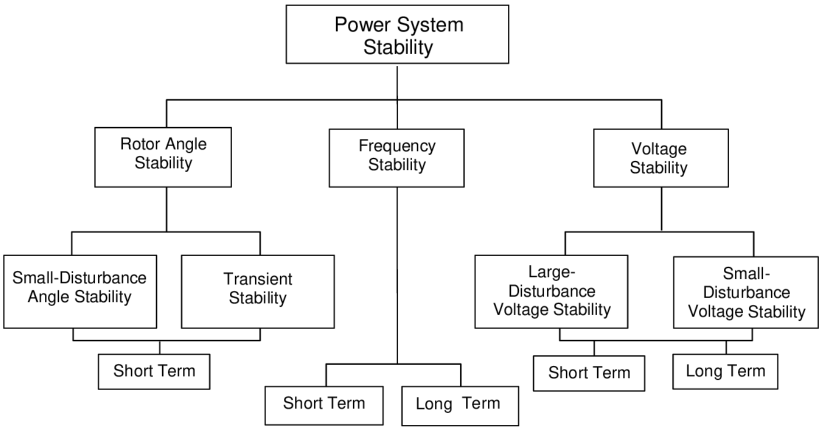

Figure 4. Classification of Power System Stability
Source: Kunder et al., 2004

Transient Stability of Power System

Transient stability is defined as the ability of synchronous machines in the power system to continue running in an organized manner, within a small period following a big disturbance (Mahdad & Srairi, 2013). The most common causes of transient instability in the systems are the application and clearance of faults; energizing and de-energizing of transformers; huge loads; transmission lines and generators outages. The transient stability of machines in two or single-infinite bus systems can be determined using swing Equation 10 (Duong et al., 2015).

$$\frac{d\omega_r}{dt} = \frac{1}{2H}(T_m - T_e) \qquad (10)$$

H is the generator inertia constant in MJ/MVA, ωr is the rotor angular speed in radians per second, Tm is the generator input toque (mechanical), Te is the generator output toque (electrical) and t represents time in seconds.

For one or two-machine infinite bus systems, their transient stability can be assessed using the equal area criterion from the power load-angle characteristics of the bus system represented by Equation (11).

$$\int_{\delta 01}^{\delta 1}(Pm1 - Pe1)\, d\delta 1 + \int_{\delta 02}^{\delta 2}(Pm2 - Pe2)\, d\delta 2 = 0 \qquad (11)$$

Voltage Stability in Power System

The Power System is said to be in voltage instability if a disturbance causes a gradual and uncontrollable reduction of voltage (Periyasamy, Selvan & Kumaresan, 2013). The integration of wind power generation in the power system can introduce small signal instability in the system (Chandra, Kumari & Sydulu, 2014), while the high penetration level of wind power generation in the distribution system can cause changes in voltage, frequency and angle stability in the distribution system (Van Thong et al., 2004). The voltage instability analysis in a power system is classified into steady-state and transient-state studies (Periyasamy, Selvan & Kumaresan, 2013), but the steady-state analysis gives better insight into reactive power problems.

In 2016 the applications of unified STATCOM-Fuel cells for improving the transient stability of power systems were reviewed in Morris et al. (2016). In 2018 the authors Pertl, Weckesser and Rezkalla reviewed the conventional and renewable-based methods for improving the transient stability in power systems (Masood et al., 2020). The applications of FACTS for improving power quality in smart grids with renewable energy systems were reviewed by Gandoman et al. (2018). It was in 2018 the authors (Venkateswarlu et al., 2018) reviewed the applications of VSC, a subsynchronous damping controller for damping torsional interactions in power systems. In 2020 the allocation of FACTS devices in power systems using metaheuristic optimisation techniques was reviewed by Okampo, Nwulu and Bokoro (2022). In 2020 a review on improving the power performance using FACTS was presented in Singh and Kumar (2020). In 2022 the review on Computational Methods in Power System Stabilizer for Damping Power Oscillations was presented in Devarapalli, Sinha and García Márquez (2022). In 2023 the methods of power system static security assessment and improvement were reviewed in Hailu, Nyakoe and Muriithi, (2023). The objective of this review paper is to summarise the articles and papers published on tuning and allocation of UPFC for enhancing power system stability.

Previous Studies of UPFC Tuning to Enhanced Power System Stability

A GA-tuned UPFC device was connected between the Point of Common Coupling (PCC) and a bus to support the voltage at PCC and limit the rotor speeds of the Wind Turbine (Jayashri & Kumudini Devi, 2009). The UPFC reduced the transient voltage at PCC and restored it to 100%. But the GA has a slow speed and contradictory response time as a result of a random execution process (Sinha & Chandel, 2015). The Fuzzy-based tuning of the UPFC-based Power Oscillation Damping (POD) Controller was applied to a three Machine nine-bus system (Pradesh & Dist, 2009) to mitigate the power system oscillation during a three-phase fault. The method involves the modification of the amplifier section of the POD Controller using Fuzzy Coordination Controller. The system was modelled with and without the developed controller model. Different case studies were simulated in a MATLAB/Simulink environment during a three-phase fault. The developed controller controlled the power flow and consequently mitigated the flickers and the voltage sags in the system. The critical clearance time of machines in a transmission line under different types of short circuit faults, improved in Rohan, N.D.G. and Thakur, V. (2012) using the UPFC to provide reactive power support. The method is based on a two-machine power system without a single load.

The authors in Qader (2015) applied the peaking and tracking of the PI controller, the Linear Quadratic Tracker (LQT) to optimise the performance of UPFC for mitigating power system instability in steady state operation. The method involved the development of a system model based on UPFC and PI controller, which was simulated in MATLAB/ Simulink environment. The method is capable of controlling load flow, reducing voltage flickers and current harmonics in the system under short circuit conditions. But the LQT applied is not suitable for minimizing an objective function with constraints involving decouple equations of series and shunt converters of UPFC. Furthermore, Linear programming is only suitable for solving linear equations with constraints (Mahmoud Pesaran, Phung, & Vigna 2017). The oscillation in a Single Machine Infinite Bus System (SMIB).was damped in Mallick, R.K. & Nahak, N. (2016) using GWO-tuned UPFC. The tuning was formulated as the minimization of Integral Time Absolute Error (ITAE) of the generator's angular speed as presented in Equation (12) considering constraints presented in Equations (13) - (15).

Objective function:

$$J = \int_0^{tsim} t|e(t)|dt \tag{12}$$

Constraints:

$$K_i^{min} \leq K_i \leq K_i^{max} \tag{13}$$

$$T_{1i}^{min} \leq T_{1i} \leq T_{1i}^{max} \tag{14}$$

$$T_{2i}^{min} \leq T_{2i} \leq T_{2i}^{max} \tag{15}$$

Where, T_{1i}^{min} *and* T_{1i}^{max} are the minimum and maximum values of damping of the controller. While K_i^{min} *and* K_i^{max} are the minimum and maximum values of the damping controller.

The GWO tuning halves the damping of real power and rotor speed deviations in the system compare to PSO tuning. Only short-term voltage stability study was considered, neglecting long-term voltage stability study.

In Firouzi, M., Gharehpetian, G.B. & Salami, Y. (2017) the Unified Inter-phase Power Controller (UIPC) was connected to PCC where the SCIG wind farms were tied to the grid, to control the reactive power consumption of the farms. The UIPC improved the transient stability of the wind farms. The authors redesigned the reactive and active power control loops of the UIPC. The redesign enables low voltage fault ride-through capability of the wind farms.

The researchers applied Fuzzy coordination, GA, GWO and LQT to tune the UPFC for enhancing power system transient stability, sub-synchronous stability, and reduced power system oscillation as summarized in Table 1. But the GA has high complexity, high computational time and premature convergence. The LQT is a linear quadratic programming method, which is not suitable for minimizing objective functions with constraints involving decouple equations of series and shunt converters of the UPFC. Linear programming is suitable for application to linear equations with constraints (Mahmoud Pesaran, Phung, & Vigna 2017).

Previous Studies of Allocation of UPFC Devices for Power System Stability

The Parallel Tabu Search (PTS) Algorithm was applied in Mori and Goto (2000) to find the optimal locations of UPFC in the IEEE 30 bus power system and the optimized UPFC parameters. The allocation problem was formulated as maximization of power transfer and minimization of active power losses considering active, apparent and voltage limits. The method provided a better Power Transfer Capability of the systems than TS and GA. The parameters of PTS, TS and GA were provided. The best locations and control signals of UPFC were selected using the frequency response of close-loop and open-loop transfer functions of a linearized Phillips-Heffron model of a three-machine power system (Ramírez & Coronado, 2002). The allocation reduced the damping oscillations in the three-machine power system. But the best investment cost of UPFC devices was not investigated. The optimal locations and parameter settings of UPFC in a modified 14-bus system were determined in Bhowmik, Chakraborty & Das (2013) using the PSO. The optimization was formulated as the minimization of active power loss and system cost with power mismatch and bus voltage limits as constraints. But in the method, the sensitivity factor was used to convert the multi-objective function to a single-objective function.

The Newton-Rapson power flow embedded and optimal allocation and parameter settings of UPFC in Jaiswal & Shrivastava (2014) were applied to improve the bus voltages and minimized power losses in an IEEE 33 Radial Distribution System. In the allocation, the power limit and voltage stability constraints were considered. The bus voltage angle limits were not considered. The authors in Firouzi, M., Gharehpetian, G.B. & Salami, Y. (2017) the Unified Inter-phase Power Controller (UIPC) was connected to PCC where the SCIG wind farms were tied to the grid, and operated in reactive and active power control modes. The UIPC improved the transient stability of the wind farms. The authors redesigned the reactive and active power control loops of the UIPC. The redesign enables low voltage fault ride-through capability of the wind farms.

An Optimal Power Flow in a MATPOWER environment was applied to maximize the social welfare, and the generation and UPFC investment cost in a deregulated electricity market (Dawn & Tiwari, 2015). The method involved the optimal allocation and parameter setting of UPFC in a 14-bus system considering voltage magnitude and voltage angle limits as constraints. The approach is applied to a small-scale power system. In Zeinhom (2017) the reactive power consumption in a 380kV 400 km double circuit transmission line provided by Fixed Series Capacitor (FSC) was reduced by replacing the FSC with UPFC optimally allocated in line using the GA. In the allocation, the generation cost, UPFC investment cost and active loss were minimized. In the method, the voltage profile and stability margin were not studied. The PSO was applied to allocate the UPFC in 30 IEEE bus power system (Steffy Amirtham & Uma, 2016) to control active, reactive power flow and improve voltage profiles in the system under a contingency scenario. The allocation was formulated as a minimization of generation cost considering active and reactive power mismatch as constraints. The PSO, UPFC parameters and IEEE system data were not provided for repeating the method. The voltage instability in 14, 30 and 57 bus systems due to changing load was reduced in Das et al. (2018) by optimal placement of UPFC at the receiving ends of the most stressful line buses in the systems using the Newton Rapson Flow Study software. The placement is formulated as a minimization of generation cost considering transmission line, load bus, generated power, and transformer tap settings as constraints. The multi-objective function was not formulated and the system data are not provided. A modified power flow Algorithm and PSO were applied in Blanas, Karafotis, & Georgilakis (2018) to find the optimal locations and parameter settings of UPFC in 39 and 118 bus systems. The placement problem was formulated as a minimization of generation cost considering active and reactive power mismatch as constraints. The model of the UPFC applied by the authors was simplified for easy insertion into the power flow algorithm. The UPFC devices were allocated in the 500 kV transmission lines in (Shen et al., 2020) to enhance the power system capacity during fault. In the approach, the UPFC with high capacity is located in the heavy-loaded line while the one with less capacity is connected at the low-loaded line. The approach involved multiple calculations. The authors in Rashed et al. (2012) applied Differential Evolution (DE) Algorithm to determine the optimal placement of UPFC in 14 and 30-bus systems.

The placement was formulated as a minimization of UPFC cost, active and reactive power losses in the systems considering active, reactive, bus voltage and bus voltage angle as inequality constraints. The DE provided better results than the PSO. The UPFC were allocated in a 118-bus system (Mortazavian et al., 2012) by minimizing the bus voltage indices of the system using an Improved Specific Coefficient Algorithm (ISCA), Specific Coefficient Algorithm (SCA) and Genetic Algorithm (GA) considering bus voltage index limits. But two coefficients were applied in the method to convert the multi-objective function to a single-objective function. The Newton Rapson Load flow study and allocation of UPFC in an IEEE 30 bus system were applied in Sarkar (2013). The allocation reduced the power losses and improved the system bus voltages compared to untuned UPFC. But the method involved complex computation. In Kumar & Srikanth (2017) the hybrid Cuckoo Search-Firefly technique was applied to find the best buses and UPFC parameter settings in an IEEE 14 bus and a 30-bus test system. The multi-objective function formulated consists of minimization of voltage deviation and device cost considering power loss, and reactive and active power injections as constraints. The hybrid technique outperformed the Cuckoo Search (CS), the hybrids Firefly-Bat and the GSA-Bat algorithms.

The optimal locations and UPFC and SVC parameter settings in a 39 IEEE bus system were determined using Cuckoo Search (CS), Adaptive Cuckoo Search (ACS), Dragonfly Algorithm (DA) and Gravitational Search Algorithm (GSA) in Taleb et al. (2019). The problem was formulated as minimization of active, reactive power losses and UPFC cost considering maximum power flow, active, reactive power mismatch. The simulation result indicated that the allocation of UPFC increased the system bus voltages. But a single objective function was applied to solve a multi-objective function.

The active power flow sensitivity index approach was applied in Rajderkar & Chandrakar (2021) to optimally allocate the UPFC devices in an IEEE 30 bus system. The magnitude of the series insertion voltage control parameter of UPFC was the constraint parameter The allocation reduced the overloading in the system and reduced the cost of investment. The approach involved complex computation. The authors in Amarendra, A., Srinivas, L.R. & Rao, R.S. (2022) allocated the UPFC devices in an IEEE 300 bus system using Red Deer Algorithm (RDA). The allocation was formulated as minimization of power loss, voltage deviation, severity index, congestion index, fuel cost and installation cost considering FACTSS Device Capacity, Feeder Capacity, Bus Voltage, and Real and Reactive Power Limits as constraints. The allocation improved the system's security, reliability and stability. In Reddy, Rao & Rao (2022) the authors allocated the UPFC in the 5, 14 and 30 IEEE bus systems using the ISCA. The allocation improved the system bus voltages and power flow compared to SCA and the GA. The allocation was formulated as the minimization of UPFC cost, power loss, and voltage profile deviation in the systems considering maximum and minimum voltage limits as constraints. Tables 2 and 3 contain the summary of articles and papers on the Allocation of UPFC Devices in power systems for Power System Stability.

Conclusion

From the literature reviewed the researchers applied Fuzzy coordination, GA, GWO and LQT to tune the UPFC and Power Damping Oscillator for enhancing power system transient stability, sub-synchronous stability, and reduced power system oscillation. The power system they considered contained active loads and paid less attention to industrial loads. The GA has high computational time and premature convergence. The LQT is a linear quadratic programming method, not suitable for minimizing objective functions consisting of decoupled equations of the UPFC. The researchers' allocation methods such as frequency response of power system transfer function, power flow, Tabu Search PSO and GA. For optimization allocation methods, they minimized power losses, voltage index and investment costs considering equality and inequality constraint. The limitations of optimization allocation methods are (1) Coefficients were used to convert multi-objective to single-objective functions, (2) Simplified UPFC model was used and (3) Complex computation.

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Appendix 1

Table 1. List of Articles and Papers on the Tuning of UPFC for Enhancing Power System Stability

Ref.	FACTS/ Tuning Techniques	Stability problem	Disturbance/ Reaction	Power Systems	Methodology	System stability enhanced
Jayashri. & Kumudini Devi, (2009)	Genetic Algorithm tuned UPFC	Voltage and Rotor speed stability in steady state	Solid three-phase fault closed to PCC leading to line isolation	Grid-connected SCIG wind energy converter	GA-tuned UPFC was connected between the PCC and the second bus.	The transient voltage at PCC and reactive power consumption of the Wind Turbine at PCC were reduced
Pradesh, A. & Dist, C. (2009)	UPFC-based Fuzzy coordination Controller	System Oscillation	Three phase faults	Three Machine 9-bus power system	Modification of amplifier section of POD Controller using Fuzzy coordination Controller.	Reduction of voltage sags.
Rohan, N.D.G. & Thakur, V. (2012)	Untuned UPFC	Transient stability	Application of L-G, L-L, L-L-G and L-L-L-G faults at the bus at 0.1 second	Two-machine power system	Reactive power compensation at PCC using UPFC.	Enhanced critical clearance time in the system in the range of 10.62% to 13.98%
Qader, M.R. (2015)	Linear Quadratic Tracker tuned UPFC	Steady stability, Voltage flicker and harmonics	Application Short circuit fault	UPFC-based Controller connected to a transmission line	Peaking and tracking the PI controllers of UPFC using an LQT	Voltage flicker and harmonics were reduced
Mallick, R.K. & Nahak, N. (2016)	GWO tuned POD Controller of UPFC	System Oscillation	Increment of mechanical input power by 10% step increase.	Single Machine Infinite Bus System (SMIB).	GWO minimized the Integral Time Absolute Error (ITAE) of the generator's angular speed.	The settling time of the GWO-based POD controller was halved (50%) compared to PSO in active power and generator speed deviations.
Firouzi, M., Gharehpetian, G.B. & Salami, Y. (2017)	UIPFC	Steady and transient stability of power system connected to a wind farm.	Application of three-phase fault	SCIG Wind Farms integrated into two area power system	UIPC act as STATCOM to provide active and reactive power control to wind farm	Improved transient stability of wind farms integrated into the power system.

Table 2. Summary of Articles and Papers on the Allocation of UPFC Devices in Power Systems for Power System Stability

Ref.	FACTS	Power System	Method/Algorithm	Objective Functions	Constraints	Performance	Limitations
Mori, H. & Goto, Y. (2000)	UPFC	30 IEEE bus System	Parallel Tabu Search	Maximization of ATC and minimization of power losses	Active, apparent and voltage limits.	Enhanced ATC of power systems	The parameters of optimization techniques are not provided
Ramírez, J.M. & Coronado, I. (2002)	UPFC	3-machine power system.	Frequency response of transfer function	Not applicable to the method-	Un-constraint	Damping oscillations	The UPFC investment was not study
Rashed et al. (2012)	UPFC	14 and 30 IEEE bus systems	DE	Minimize the active, reactive power losses and UPFC cost	Power, voltage, bus voltage angle inequality	Minimized active and reactive power loss	The multi-objective function was transformed into a single-objective function
Mortazavian et al. (2012)	UPFC	118 bus system	ISCA, SCA & GA	Minimize the bus voltage index	Bus voltage index limits	Improved bus voltages	Two coefficients were applied in formulating the objective function
Bhowmik, A.R., Chakraborty, A.K. & Das, P.N. (2013)	UPFC	Modified IEEE 14 bus System	PSO	Minimized power losses and total investment cost	Power mismatch and bus voltage limit	Minimized active power loss and reduced system costs.	The sensitivity factor was used to convert multi-objectives to a single objective function
Sarkar, M. (2013)	UPFC	IEEE 30 bus system	NRL flow study	Minimize the power losses	Limit of reactance	Reduced power losses and improved bus voltages	The method involved complex computation
Jaiswal, S.P. & Shrivastava, V. (2014)	UPFC	IEEE 33 Radial Distribution System	Newton-Rapson power flow	Minimized power losses	Max & Min power, voltage limits	Voltage profile and power losses	The UPFC investment and bus voltages were not studied.
Dawn, S. & Tiwari, P.K. (2015)	UPFC	Modified IEEE 14 bus System	Optimal Power Flow in MATPOWER	Minimization of generation and UPFC investment cost	Voltage magnitude and Voltage angle limits	Improved social welfare, reduced generation and UPFC investment cost	The approach is applied to small power systems.
Zeinhom, A.N. (2017)	UPFC	380kV 400 km double circuit transmission line	Replacement of FSC with UPFC allocated using GA	Minimized generation cost, UPFC investment cost and active power loss	Unconstraint	Reduced active power loss, Generation cost, and UPFC investment cost.	Voltage profile and stability margin are not studied

Steffy Amirtham, J. & Uma, V. (2016)	UPFC	30 IEEE bus System	PSO	Minimization of generation cost	Active and reactive power mismatch	Reduced generation cost	The PSO, UPFC parameters and power system data are not provided.
Das et al. (2018)	UPFC	14, 30 and 57 bus systems	Newton-Rapson Power Flow	Minimization of generation cost and improvement of voltage profiles.	Transformer settings, transmission line and load bus limits	voltage stability	Multi-objective function and system data are not provided.

Table 3. Summary of Articles and Papers on the Allocation of UPFC Devices in Power Systems for Power System Stability

Ref.	FACTS	Power System	Method/Algorithm	Objective Functions	Constraints	Performance	Limitations
Kumar, B.V. & Srikanth, N.V. (2017)	UPFC	IEEE 30 bus System	FA –CSA	Minimize the voltage deviation and cost of UPFC	Power loss; Active and Reactive Power Injections.	Hybrid CS-FA outperformed the hybrid FA-BA, GSA-BA and CS	The multi-objective function was transformed into a single-objective function
Blanas, O.I., Karafotis, A.P. & Georgilakis, P.S. (2018)	UPFC	39 and 118 IEEE Bus System	PSO	Minimization of generation cost.	Active and reactive power mismatch	Reduced generation cost	A simplified model of UPFC was used
Taleb et al. (2019)	UPFC & SVC	39 IEEE bus system	CS, ACS, DA and GSA	Minimize the active, reactive power losses and UPFC cost	max power flow, active, reactive power mismatch	Increased bus voltages	The multi-objective function was transformed into a single-objective function
Shen et al. 2020	UPFC	500kV power system	Fault Analysis	Not Applicable	Un-constraint	Transmission line Capacity	Involving multiple calculations
Rajderkar, V.P. & Chandrakar, V.K. (2021)	UPFC	IEEE 30 bus System	Active power flow sensitivity index	Not applicable to the method	The magnitude of the series insertion voltage control parameter of UPFC	Reduced overloading and investment cost of UPFC	The method involves complex computation

Amarendra, A., Srinivas, L.R. & Rao, R.S. (2022)	UPFC & DVR	IEEE 30 bus System	RDA, PSO and FA	Minimize the power loss, voltage deviation, severity index, congestion index, fuel cost and installation cost	FACTSS Device Capacity, Feeder Capacity, Bus Voltage, Real and Reactive Power Limits	Improved the system's security, reliability and stability	The multi-objective function was transformed into a single-objective function
Reddy, K.M.K., Rao, A.K. & Rao, R.S. (2022)	UPFC	IEEE 5, 14 and 30 bus System	ISCA, SCA and GA	Minimization the UPFC cost, power loss, and voltage deviation	maximum and minimum voltage limits	ISCA improved the system bus voltages and power flow compared to SCA and the GA	Multi-objective optimization was transformed into a single-objective function