IET Smart Grid

Review Article

Unified power flow controllers in smart power systems: models, methods, and future research

eISSN 2515-2947
Received on 12th April 2018
Revised 29th September 2018
Accepted on 31st October 2018
E-First on 23rd January 2019
doi: 10.1049/iet-stg.2018.0065
www.ietdl.org

Pavlos S. Georgilakis[1] ✉, Nikos D. Hatziargyriou[1]

[1]*School of Electrical and Computer Engineering, National Technical University of Athens (NTUA), 9 Heroon Politechniou street, Athens, Greece*

✉ *E-mail: pgeorg@power.ece.ntua.gr*

Abstract: Power flow control has become increasingly important in recent years in the area of smart power systems that have to integrate increased shares of variable renewable energy sources. The unified power flow controller (UPFC) provides in real-time, simultaneously or selectively, active and reactive power flow control as well as voltage control in smart power systems. Several models and methods have been suggested for the control, analysis, operation, and planning of UPFCs in smart power systems. This study introduces a review of the state-of-the-art models and methods of UPFCs in smart power systems, analysing and classifying current and future research trends in this field.

1 Introduction

Smart power systems use state-of-the-art power electronics and information and communication technologies to improve power system control, security, reliability, and power quality with the optimal use of resources to provide economical electricity to the consumers. Flexible alternating current (ac) transmission system (FACTS) incorporates power electronic-based controllers to enhance controllability and increase power transfer capability. FACTS controllers are very useful in smart power systems in order to successfully integrate the increased shares of variable renewable energy sources. FACTS controllers include a static var compensator, a thyristor-controlled series capacitor, a static phase shifter (SPS), a static synchronous compensator (STATCOM), a static synchronous series compensator, and a unified power flow controller (UPFC). The most versatile FACTS controller is the UPFC since it is able to control, concurrently or selectively, the active and reactive power flow through the transmission line, the voltage magnitude, and the shunt reactive power compensation.

A lot of research works investigate FACTS controllers and their applications to power systems. Review papers for FACTS controllers are split into two categories: the first category reviews several FACTS controllers [1–3], and the second category is dedicated to the review of only one FACTS controller [4, 5]. More specifically, Faruque *et al*. [1] review electromagnetic transient models for FACTS; Singh *et al*. [2] review the impact of FACTS controllers and distributed generation on power systems; Gandoman *et al*. [3] review FACTS for power quality and efficient utilisation of renewable energy systems; Iravani and Maratukulam [4] review alternative semiconductor converter topologies feasible for SPS; and Singh *et al*. [5] review STATCOM controllers.

The above bibliography review indicates that there is no review paper dedicated on UPFC to cover the control, analysis, operation, and planning of UPFCs in smart power systems. This study covers this bibliography gap and introduces a taxonomy of models and methods for the control, analysis, operation, and planning of UPFCs in smart power systems, offering a unified presentation of a relatively large number of selected research works [6–190].

The contributions of the study are manifold:

- It introduces a comprehensive review covering the control, analysis, operation, and planning of UPFCs in smart power systems.
- It introduces several well-designed taxonomies for UPFC, which can help understand intriguing relationships among many variables and concepts in the field. These taxonomies include converter topologies for UPFCs, applications of UPFCs and D-UPFCs, steady state models and dynamic models for UPFCs, control methods for UPFCs, allocation methods for UPFCs, and simulation tools for UPFCs. For example, according to the introduced taxonomy, the UPFC control methods include linear and linearised control, advanced control, decoupled control, vector control, preventive control, coordinated control, sliding mode control, robust control, adaptive control, hybrid control, and intelligent control that consists of neural network (NN), fuzzy logic, genetic algorithm, particle swarm optimisation (PSO), and hybrid systems.
- It provides future research directions and sets the future research goals of cost reduction, new cost-effective UPFC topologies, and architectures with experimental validation, UPFC control algorithms with reconfigurable architecture, wide area coordinated control algorithms, new models, methods, and simulation tools for the integration of UPFCs into smart power system operations and planning.
- It serves as a guide to aid researchers and engineers on the available models and methods as well as the future research trends in the control, analysis, operation, and planning of UPFCs in smart power systems.

This paper is organised as follows. Sections 2 and 3 outline the UPFC technology and classify the converter topologies for UPFCs, respectively. Section 4 classifies the applications of UPFCs in smart power systems. Sections 5 and 6 provide an outline and taxonomy of steady state and dynamic models for UPFCs, respectively. Sections 7 and 8 outline and classify the control and allocation methods for UPFCs, respectively. Section 9 discusses the simulation tools for UPFCs. Section 10 proposes future research ideas, and Section 11 concludes.

2 Technology

The UPFC consists of one shunt and one series converter that share a back-to-back common direct current (dc) link provided by a dc storage capacitor, as shown in Fig. 1. These two converters are switching voltage source converters (VSCs) having semiconductor devices with turn-off capability. Active power flows between the series and shunt ac terminals through the common dc link. However, reactive power does not flow through the dc link, i.e. each converter independently supplies or absorbs reactive power.

The series converter controls the active and reactive power of the transmission line by injecting an ac voltage with controllable magnitude and phase angle.

The shunt converter supplies or absorbs the active power required by the series converter. Moreover, the shunt converter can supply or absorb reactive power, thus providing shunt reactive power compensation.

3 Converter topologies

Converter topologies for UPFC are classified as (i) multi-pulse converters and (ii) multi-level converters. For a given power, the multi-pulse converter has better total harmonic distortion but higher transformer complexity than the multi-level converter. Multi-level converters for UPFC are classified as: (i) multipoint-clamped converters (MPCs) or diode-clamped converters [45]; (ii) chain converters or cascade converters [80, 184]; and (iii) nested-cell converters or flying capacitor converters [64]. The UPFC projects at Inez and Kangjin use three-level MPCs because this topology provides a large range of voltage control [27].

A chopper stabilised diode-clamped seven-level converter UPFC is studied in [45]. A UPFC using three neutral-point-clamped (NPC) multilevel converters is investigated in [61]. A UPFC based on flying capacitor multi-level VSCs with phase-shifted sinusoidal pulse width modulation (SPWM) control using insulated gate bipolar transistor (IGBT) technology is studied in [64]. Conceptual design of a UPFC with SPWM control with VSCs using either gate turn-off thyristors or IGBTs is presented in [20].

In comparison with the conventional UPFC with two VSCs and two transformers, the transformer-less UPFC, composed of two cascade multi-level converters, has significant advantages over the conventional UPFC, such as low cost, low weight, high reliability, and fast dynamic response [179, 184, 185].

4 Applications

The world's first UPFC was installed at Inez substation in eastern Kentucky to increase power transfer capability and provide voltage support [16, 27, 37]. Applications of UPFC in transmission systems include: (i) power flow control and congestion management [6, 55, 57, 75, 83, 93, 124, 138, 140, 183, 189]; (ii) reactive power compensation and control [19, 118, 186]; (iii) voltage control [7, 31, 41, 47, 48, 96, 137, 190]; (iv) power transfer capability enhancement [13, 44, 77, 156, 168]; (v) power loss reduction [57]; (vi) load curtailment reduction [182, 187]; (vii) power quality improvement [137, 174]; (viii) power system reliability enhancement [105, 125]; (ix) harmonic mitigation [10]; (x) improvement of transient stability [8, 18, 21, 86, 94, 112, 138, 145, 167]; (xi) damping inter-area and intra-area oscillations [28, 29, 40, 52, 67, 76, 111, 115, 118, 119, 121–123, 127, 146, 147, 151]; (xii) damping of sub-synchronous resonance [87, 153, 159].

The UPFC is also used in power distribution systems, where it is sometimes called distribution-UPFC (D-UPFC). The applications of D-UPFC include voltage control of distribution system when voltage sags and swells occur [96]; line loss minimisation in loop distribution systems [163]; and voltage regulation in all nodes with simultaneous line loss minimisation in loop distribution systems [134].

5 Steady state models

5.1 Power flow models

An approximate ac power flow model and a dc power flow model are developed that ignore the resistance of UPFCs and transmission lines [73]. The dc power flow model proposed in [73] was used to derive modified distribution factors that model the impact of UPFC on transmission system usage [84]. A UPFC power flow model is proposed for the case in which the UPFC simultaneously controls the active and reactive power as well as the voltage magnitude [9].

The general UPFC power flow model, composed of two voltage sources and two impedances, is suitable to control individually or in any combination the active and reactive power as well as the voltage magnitude [14, 42]. This power flow model is used as a basis to define a dispatch strategy to maximise the voltage stability limited power transfer capability of a UPFC [88]. A variation of the general UPFC power flow model [14] is proposed considering

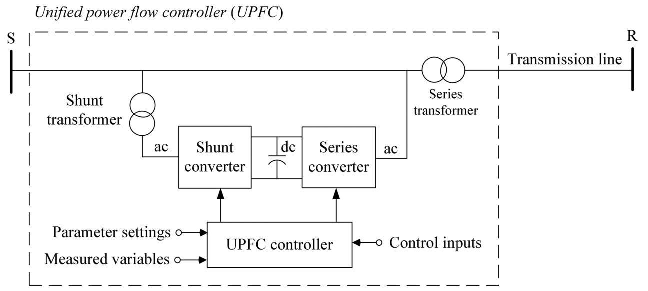

Fig. 1 *Structure of UPFC located at the sending bus S of a transmission line*

variable series impedance and decoupling of real power exchange of series and shunt converters [135]. In the power flow model proposed in [14], the capacity limit of the shunt converter is incorporated [50]. The power flow model proposed in [14] is used in a probabilistic power flow model that is solved by Monte Carlo simulation [158].

A power injection model (PIM) is developed and a power flow method is proposed for the case in which the control parameters of UPFC are known [38, 103] or unknown [34, 41, 46, 47, 59]. The PIM model of UPFC has to be carefully used to ensure stable operation [104]. The rules for handling the internal limits of UPFC are incorporated into the PIM-based power flow method [48]. The current-based power flow model of the UPFC considers the current of the series converter as a variable, allowing easy manipulation of current limitations in optimal power flow (OPF) [149]. A power and current injection power flow model is proposed for the centre-node UPFC [169].

A UPFC power flow model using auxiliary capacitors is proposed to handle UPFC constraints [43]. A graphical method determines the entire operating range of the UPFC and incorporates all relevant UPFC limits for any point of UPFC installation in the transmission line [72]. An indirect power flow model is proposed, where an existing system with UPFCs is transformed into an augmented system without UPFCs, thus enhancing the reusability of existing power flow codes [113].

A power flow model, combing power and current injections, is proposed for the generalised (multi-line) UPFC (GUPFC) [181]. The advantages and disadvantages of various power flow models are analysed in [170].

5.2 OPF models

An OPF model shows that UPFC regulates power flow and concurrently minimises power losses [15]. A nonlinear OPF model, simulating different operating modes of UPFCs, is formulated and solved using Newton's method [22]. An OPF model for the generalised UPFC is formulated and solved using the interior point method (IPM) [58]. An active and reactive OPF model for the UPFC is solved by IPM [65]. The state estimation of power systems with UPFCs is formulated as a nonlinear optimisation problem and is solved by IPM [82]. An OPF model, solved by Newton's method, provides optimal reference inputs to UPFC [102]. An OPF model for the UPFC is solved by bat algorithm [172].

5.3 Steady state harmonic models

A modular harmonic domain modelling method for the UPFC has been proposed and validated using time domain simulation [95]. A UPFC model in the form of equivalent impedance is proposed for harmonic analysis [176].

6 Dynamic models

UPFC dynamic models are necessary to understand and control the interactions between the power system and the UPFC. The development of UPFC dynamic models is challenging, due to the difficulty in the analysis of VSCs of the UPFC, since VSCs include both discrete time events and continuous time dynamics because the operation of VSCs and UPFC is based on a switching process.

6.1 Small signal dynamic models

Linearised small-signal dynamic models for UPFC are developed for eigenvalue analysis, e.g. to investigate low-frequency electromechanical modes and torsional oscillatory modes [9, 11]. UPFC power frequency models for a single machine to infinite bus (SMIB) system are proposed in [8, 11]. A linearised Phillips–Heffron dynamic model of a multi-machine power system with a UPFC is developed [32] and applied to damp power system oscillations [52]. A conceptually simple, linearised dynamic model, with fast convergence characteristics is developed and applied for inter-area power oscillation damping [76].

A UPFC power frequency model including dc link capacitor dynamics for the multi-machine power system is proposed in [49]. An analytical dynamical model for unbalanced UPFC operation is derived and tested on a SMIB system [63]. A fast time domain method is proposed for the periodic steady state solution of systems with consideration of UPFCs control and switching (commutation) process [110]. The modal series analytical method is proposed to analyse small signal oscillations and to study the nonlinear interaction between the UPFC and the rest of the power system [173].

6.2 Transient stability models

A state space transient stability model of the UPFC is proposed in [9, 11]. A transient power flow model for UPFC is developed and used to design the capacitance of the dc-link capacitor [60].

6.3 Fault analysis models

For multi-machine systems with UPFCs, an energy function is developed and applied for direct estimation of the critical clearing time [90]. A fault analysis model is developed to quantify the impact of UPFC on the performance of the distance relay during power swing [188].

In a transmission line with a UPFC, the fault location is identified by a differential equation-based impedance calculation method in combination with wavelet transform for fault transient analysis [114]. An analytical approach calculates the impacts of UPFC and offshore wind on distance relay tripping characteristics [164]. In a transmission line with a UPFC, fault analysis is implemented by fast discrete orthonormal Stockwell transform in combination with support vector machines [171], and by sparse S-transform [177].

6.4 Dynamic harmonic models

A dynamic harmonic domain model for the GUPFC is developed and used to analyse the transient and steady state response of GUPFC to voltage disturbances [154].

7 Control methods

Linear and linearised control methods are simple, easy to implement, and reasonably effective. Traditional linear proportional–integral (PI) control is typically optimised (tuned) around a single operating point; however, it is less effective as the system conditions move from the tuned operating point. Nonlinear control methods are computationally more complex; however, they are relatively independent of a particular operating point. There are two general approaches for dealing with parameter uncertainties: adaptive control and robust control. In adaptive control, the parameters are identified online and then are used to tune the controller. In robust control, a fixed controller is used, which is typically designed considering the worst-case uncertainties.

7.1 Linear and linearised control

The feedback linearisation method tries to cancel the nonlinearities of the system. Linear quadratic control (based on feedback linearisation) shows very good performance in regulating the shunt converter of the UPFC [12]. A direct feedback linearisation is applied for coordinated excitation and UPFC control to improve transient stability and voltage stability on a single-machine single-load power system [56]. A feedback linearisation control method for the UPFC enables independent control of real and reactive power [107, 118]. A feedback linearisation control is proposed for damping inter-area oscillations using UPFCs with ultra-capacitors [123]. An adaptive input–output feedback linearisation control is proposed for damping low-frequency oscillations in power systems with multiple machines and multiple UPFCs [146].

A multivariable PI controller successfully fulfils the power flow and voltage control functions of UPFC [66]. An instantaneous power theory based PI control scheme for UPFC is proposed for power flow control under both steady state and transient conditions [69]. The mixed sensitivity based $H\infty$ in the linear matrix inequality framework is used for the design of a UPFC as a damping device and is applied in a two-area power system to damp inter-area oscillations [67]. A UPFC damping controller, designed based on modal control theory using the linearised equations of the power system, simultaneously improves power flow control and stability of a combined wave and wind energy system connected to a bulk power system [152]. To ensure the dc link voltage stability under faults, a NPC multi-level UPFC is proposed with decoupled power linear controllers in combination with the real-time generation of pulse-width modulation (PWM) and balancing of dc link capacitor voltages using both converters [161].

7.2 Advanced control

7.2.1 Decoupled control: Independent control of real and reactive power allows operation under unbalanced conditions [33]. Decoupled control of real and reactive power through a transmission line using a PWM-based UPFC is studied [68].

7.2.2 Vector control: Vector control of UPFC ensures the independent control of active and reactive power [19, 35].

7.2.3 Preventive control: A proposed predictive control scheme for UPFC provides better transient performance in comparison with decoupled control [17]. Preventive control actions, by adjusting the UPFC reference signals, are proposed to enhance power system static and dynamic security [75].

7.2.4 Coordinated control: The coordinated control of UPFC and power system stabiliser (PSS) enhances power system small signal stability [71]. An active power coordination controller is proposed to avoid excessive instability of the UPFC dc link capacitor voltage during transient states [81, 101]. A reactive power coordination controller is also proposed to reduce UPFC bus voltage excursions during reactive power transfers [81]. An interaction indicator is proposed that shows if the interactions among multiple control functions of the UPFC cause power system stability problems [85].

7.2.5 Sliding mode control: An advanced nonlinear direct power control, based on sliding mode control theory, is proposed for the UPFC with a matrix converter (vector switching converter) [129, 160], as well as for the UPFC with a neutral point clamped converter [143]. A terminal sliding mode controller for the UPFC with an adaptive observer is proposed to operate under transient and steady state conditions [162].

7.2.6 Robust control: A robust $H\infty$ UPFC controller improves power system stability [53]. A nonlinear finite time controller, based on direct Lyapunov stability theory, needs significantly reduced convergence time and is robust against parameter uncertainties [141, 151]. A nonlinear dynamic control for a UPFC is proposed that effectively damps oscillations over a wide range of operating conditions [115].

7.2.7 Adaptive control: To improve transient stability, in the conventional PI controller of UPFC, a self-tuning controller is added, which is composed of an adaptive constrained recursive least squares identifier and a pole shift controller [157]. A discrete control strategy, by adaptively operating the UPFC, improves transient stability [91].

7.2.8 Hybrid control: A combined linear and nonlinear control strategy for the UPFC helps improve transient stability [70]. An advanced control, which combines phase angle control and cross coupling control, achieves a quick response of active and reactive power without power fluctuations [39, 60], as well as improved transient performance [98].

7.3 Intelligent control

7.3.1 Neural network (NN): A radial basis function NN (RBFNN) controller for the UPFC using a direct adaptive control scheme improves transient stability [54, 94]. An on-line trained RBFNN controller for the UPFC is used for power flow control and voltage support [130]. Continually online trained NN controllers for the UPFC using an indirect adaptive control scheme improve damping during transient and dynamic control [89]. An optimal NN controller for UPFC, using wide area signals, enhances damping of inter-area and intra-area modes of oscillations [111].

7.3.2 Fuzzy logic: A Mamdani type fuzzy logic controller for UPFC improves transient stability [21]. A Takagi–Sugeno-type fuzzy logic controller for UPFC significantly reduced inter-area and local mode oscillations [40]. Fuzzy logic controllers improve the dynamic response of the UPFC during faults and unbalanced network conditions [132].

7.3.3 Genetic algorithm (GA): A UPFC, tuned by a GA, damps the rotor speed oscillations of fixed speed wind turbines [116].

7.3.4 Particle swarm optimisation (PSO): PSO is proposed for the individual design of the UPFC and PSS to damp low-frequency oscillations [100]. PSO computes the optimal parameter settings of the output feedback UPFC controller for damping of electromechanical oscillations [121, 122, 127].

7.3.5 Hybrid systems: Two online trained fuzzy NN controllers for the UPFC are proposed to improve power system dynamic control performance [106]. An adaptive neurofuzzy inference control system for the UPFC independently controls the real and reactive power flow over a wide range of possible operating points and extreme conditions [136]. A decision tree-induced fuzzy rule-based relaying scheme is proposed that provides robust protection to the transmission line including UPFC and wind farm [166]. An intelligent damping controller for the UPFC includes a functional link Elman NN, a genetic ant colony optimisation algorithm and a PI derivative linear damping controller [175]. A hybrid GA in combination with the gravitational search algorithm is proposed for tuning damping controller parameters for a UPFC [178]. A UPFC based on the fuzzy logic controller, with its rules being derived from sliding mode control theory, improves transient stability [180].

8 Allocation methods

UPFCs are expensive, so their optimal location has to be determined. The UPFC allocation methods are classified as analytical, numerical, and heuristic. An exhaustive search analytical method guarantees the finding of the optimal UPFC allocation; however, it necessitates huge computational time for large real-world power systems.

Nonlinear programming is the most efficient among the available numerical methods for UPFC allocation.

Heuristic optimisation methods are usually robust and find near-optimal solutions for complex and large-scale UPFC allocation problems. Generally, heuristic methods require high-computational time; however, this limitation is not necessarily critical in UPFC allocation problems.

Table 1 introduces a taxonomy of models and methods for optimal allocation of UPFCs in power systems.

8.1 Analytical methods

The maximum power transfer is analytically calculated considering UPFC location and constraints [62]. An exhaustive search finds the optimal number, location, size, and parameter settings of multiple UPFCs [144].

8.2 Numerical methods

An augmented Lagrange multipliers method computes the optimal location of the UPFC [36]. An exhaustive search in combination with nonlinear programming finds the optimal number, location, and parameter settings of UPFCs [131].

Table 1 Taxonomy of models and methods for optimal allocation of UPFCs

Reference	Published	Number of UPFCs	Design variables	Load profile	Objective	Objective Function	Method
[36]	September 1999	multiple	location + size	two load levels	single	min cost	Lagrange multipliers
[57]	June 2001	single	location + settings	one load level	single	min power loss	practical heuristic
[78]	June 2004	single	location	one load level	single	max voltage stability	practical heuristic
[92]	September 2005	single	location	one load level	single	max voltage stability	practical heuristic
[93]	February 2006	single	location + settings	one load level	single	max social welfare	practical heuristic
[99]	February 2007	single	location	one load level	single	min operational cost	practical heuristic
[117]	March 2009	single	location + settings	three load levels	single	min generation cost	practical heuristic
[124]	July 2010	single	location + size	multi-load level	single	min congestion cost	practical heuristic
[131]	February 2011	multiple	number + location + settings	one load level	single	min operational cost	nonlinear programming
[140]	July 2012	single	location + size + settings	multi-load level	single	min total system cost	PSO
[144]	October 2012	multiple	number + location + size + settings	one load level	single	max social welfare	exhaustive search
[148]	March 2013	single	location + settings	one load level	single	max damping ratio	genetic algorithm
[165]	November 2014	single	location + size	one load level	single	max loading margin	practical heuristic
[167]	January 2005	single	location + size	one load level	single	min power loss	hybrid heuristic
[182]	July 2016	single	location + settings	one load level	multiple	multi-objective with weights	hybrid heuristic
[187]	October 2016	multiple	location + settings	one load level	single	min load curtailment	practical heuristic

8.3 Heuristic methods

8.3.1 Genetic algorithm (GA): GA computes the optimal location and control parameters of a UPFC to maximise the damping of electromechanical oscillations [148].

8.3.2 Particle swarm optimisation (PSO): PSO is proposed to find the optimal location and size of a single UPFC to manage congestion and minimise total system cost [140].

8.3.3 Hybrid heuristic methods: An artificial bee colony algorithm finds the optimum location and gravitational search algorithm finds the optimum size of a UPFC [167]. A hybrid imperialist competitive algorithm and pattern search method finds the UPFC location and the minimum load shedding to prevent voltage collapse [182].

8.3.4 Practical heuristic algorithms: A sensitivity-based method is proposed to find the suitable location of a single UPFC [57]. A heuristic approach, based on voltage stability indicator, is proposed to find the suitable location of a single UPFC, considering also a list of the most severe contingencies [78, 92]. A sensitivity based approach finds a suitable location and an OPF provides the parameter settings of a single UPFC [93]. A sensitivity-based screening technique computes the suitable location of a single UPFC [99]. A sensitivity method finds the optimal location and an IPM finds the optimal size of a UPFC [124]. A sensitivity method finds the location and size of a UPFC to enhance static voltage stability [165]. A sensitivity method finds the location of UPFCs to minimise load curtailment [187].

9 Simulation tools

In UPFC research and development, simulation tools have been proved very useful by implementing various tasks, including the validation of various UPFC steady state models, dynamic models, converter topologies, and control methods. Indicative applications of selected simulation tools are presented in the following.

An EMTP simulation tool has been used to validate steady-state and dynamic UPFC models [9] and to verify various UPFC control methods [7, 10, 12, 23, 26].

The PSCAD/EMTDC simulation tool has been used to validate a transient stability UPFC model [60]; to verify various UPFC control methods [24, 35, 89]; to analyse the dynamic performance of a UPFC with H-bridge modules [79, 109]; to validate an analytical frequency response characteristics of the UPFC [74]; to compute the optimal location of a single UPFC, considering critical line contingencies and a system loading distribution factor [117]; and to study a UPFC topology based on two shunt converters and a series capacitor [128].

A Matlab/Simulink simulation tool has been used to validate a steady state [30] and a dynamic UPFC model [87]; to verify various UPFC control methods [25, 120, 150]; to study power system protection in the presence of UPFC [97, 142, 155]; to analyse the dynamic performance of a UPFC without a dc link capacitor [108]; and to show that a UPFC topology with only four IGBT switches for each one of the shunt and series converters improves system transient stability [133].

PowerWorld simulation tool has been used to compute available transfer capability in power systems with UPFCs [77] and to validate a current-based power flow model for UPFC [149].

A real-time power system simulator, interfaced through the hardware in the loop with multiple UPFCs, is capable of rapidly testing UPFC control interactions [126].

10 Future research

10.1 Cost reduction

In the smart power systems era, the ever increasing penetration of variable energy resources is expected to increase the need for widespread use of UPFC technology. Such a need would require research and development efforts to reduce UPFC equipment cost, which includes the cost of design, materials, and manufacturing. As an example, economies of scale and new semiconductor materials with reduced cost and appropriate technical characteristics for use in UPFC would help decrease UPFC equipment cost.

10.2 Topologies

Research and development on topologies can help reduce cost and improve UPFC performance. As an example, the dc link UPFC (Fig. 1) is the standard topology. An alternative topology called the ac link UPFC has been introduced [139]. A detailed comparison (cost, size, and complexity) of the ac and dc link UPFC is proposed as a future research.

10.3 Experimental validation

Various models and methods have been developed for power systems with UPFCs. It would be interesting these models and methods being verified not only through software simulation but also using actual equipment or laboratory prototype or real-time hardware in the loop simulations.

10.4 Models and simulation methods

For a widespread application of UPFCs, new models, appropriate for UPFC feasibility studies, have to be developed. Moreover, new methodologies and algorithms are needed for the integration of UPFCs into smart power system operations. Another research area is to study the effect of UPFCs on the different types of power system protection.

10.5 Control methods

Control methods are needed to replace very specific UPFC control algorithms, which are obsolete with changes to the smart power system, with control algorithms having a reconfigurable architecture. UPFC control algorithms have to use data from phasor measurement units (PMUs). To maximise power system benefits, there is a need to develop a wide area coordinated control algorithms that would leverage the complementary characteristics of multiple UPFCs, PMUs, and other new control technologies.

10.6 Allocation methods

To maximise power system benefits, it is needed to coordinate the allocation of UPFCs, PMUs, capacitors, protection devices, and other FACTS controllers. Moreover, the reviewed allocation methods consider only loads with constant active and reactive power; however, more accurate load models have to be considered using more general and practical load models.

10.7 Simulation tools

The forthcoming smart power system is a large cyber-physical system (CPS) with many sensors, controllers, and information and communication technologies. The simulation tools have to be upgraded in order to model and simulate together all these new technologies of the CPS.

10.8 Collaboration

To accelerate the widespread application of UPFC, a research collaboration among academic institutions, power system operators, and UPFC manufacturers should be encouraged.

11 Conclusions

This study introduces a thorough description of the state-of-the-art models and methods for the analysis and control of UPFCs in smart power systems, analysing and classifying current and future research trends in this field. The most common applications of UPFCs include active and reactive power flow control, voltage control, reactive power compensation, improvement of transient stability, and damping of inter-area and intra-area oscillations. The most frequently used methods for the control of the UPFC are intelligent control schemes as well as various advanced control techniques. The most frequently used techniques for the solution of the UPFC allocation problem are various practical heuristic algorithms. Future research areas include UPFC equipment cost reduction, new cost-effective UPFC topologies, and architectures with experimental validation, UPFC control algorithms with reconfigurable architecture, wide area coordinated control algorithms, and new models, methods, and simulation tools for the integration of UPFCs into smart power system operations and planning.

12 Acknowledgment

This research was co-financed by the European Union and Greek National Funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE (project code: T1EDK-00450).

13 References

[1] Faruque, M.O., Dinavahi, V., Santoso, S., *et al.*: 'Review of electromagnetic transient models for non-VSC FACTS', *IEEE Trans. Power Deliv.*, 2005, **20**, (2), pp. 1065–1079

[2] Singh, B., Mukherjee, V., Tiwari, P.: 'A survey on impact assessment of DG and FACTS controllers in power systems', *Renew. Sustain. Energy Rev.*, 2015, **42**, pp. 846–882

[3] Gandoman, F.H., Ahmadi, A., Sharaf, A.M., *et al.*: 'Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems', *Renew. Sustain. Energy Rev.*, 2018, **82**, pp. 502–514

[4] Iravani, M.R., Maratukulam, D.: 'Review of semiconductor-controlled (static) phase shifters for power system applications', *IEEE Trans. Power Syst.*, 1994, **9**, (4), pp. 1833–1839

[5] Singh, B., Saha, R., Chandra, A., *et al.*: 'Static synchronous compensators (STATCOM): a review', *IET Power Electron.*, 2009, **2**, (4), pp. 297–324

[6] Gyugyi, L.: 'Unified power-flow control concept for flexible AC transmission systems', *IEE Proc. C*, 1992, **139**, (4), pp. 323–331

[7] Gyugyi, L., Schauder, C.D., Williams, S.L., *et al.*: 'The unified power flow controller: A new approach to power transmission control', *IEEE Trans. Power Deliv.*, 1995, **10**, (2), pp. 1085–1097

[8] Mihalic, R., Zunko, P., Povh, D.: 'Improvement of transient stability using unified power flow controller', *IEEE Trans. Power Deliv.*, 1996, **11**, (1), pp. 485–492

[9] Nabavi-Niaki, A., Iravani, M.R.: 'Steady-state and dynamic models of unified power flow controller (UPFC) for power system studies', *IEEE Trans. Power Syst.*, 1996, **11**, (4), pp. 1937–1943

[10] Enslin, J.H.R., Zhao, J., Spee, R.: 'Operation of the unified power flow controller as harmonic isolator', *IEEE Trans. Power Electron.*, 1996, **11**, (6), pp. 776–784

[11] Smith, K.S., Ran, L., Penman, J.: 'Dynamic modelling of a unified power flow controller', *IEE Proc. Gener. Transm. Distrib.*, 1997, **144**, (1), pp. 7–12

[12] Lombard, X., Therond, P.G.: 'Control of unified power flow controller: comparison of methods on the basis of a detailed numerical model', *IEEE Trans. Power Syst.*, 1997, **12**, (2), pp. 824–830

[13] Bian, J., Ramey, D.G., Nelson, R.J., *et al.*: 'A study of equipment sizes and constraints for a unified power flow controller', *IEEE Trans. Power Deliv.*, 1997, **12**, (3), pp. 1385–1391

[14] Fuerte-Esquivel, C.R., Acha, E.: 'Unified power flow controller: a critical comparison of Newton–Raphson UPFC algorithms in power flow studies', *IEE Proc. Gener. Transm. Distrib.*, 1997, **144**, (5), pp. 437–444

[15] Noroozian, M., Angquist, L., Ghandhari, M., *et al.*: 'Use of UPFC for optimal power flow control', *IEEE Trans. Power Deliv.*, 1997, **12**, (4), pp. 1629–1634

[16] Rahman, M., Ahmed, M., Gutman, R., *et al.*: 'UPFC application on the AEP system: planning considerations', *IEEE Trans. Power Syst.*, 1997, **12**, (4), pp. 1695–1701

[17] Papic, I., Zunko, P., Povh, D., *et al.*: 'Basic control of unified power flow controller', *IEEE Trans. Power Syst.*, 1997, **12**, (4), pp. 1734–1739

[18] Limyingcharoen, S., Annakkage, U.D., Pahalawaththa, N.C.: 'Effects of unified power flow controllers on transient stability', *IEE Proc. Gener. Transm. Distrib.*, 1998, **145**, (2), pp. 182–188

[19] Schauder, C.D., Gyugyi, L., Lund, M.R., *et al.*: 'Operation of the unified power flow controller (UPFC) under practical constraints', *IEEE Trans. Power Deliv.*, 1998, **13**, (2), pp. 630–639

[20] Mwinyiwiwa, B., Ooi, B.T., Wolanski, Z.: 'UPFC using multiconverter operated by phase-shifted triangle carrier SPWM strategy', *IEEE Trans. Ind. Appl.*, 1998, **34**, (3), pp. 495–500

[21] Limyingcharoen, S., Annakkage, U.D., Pahalawaththa, N.C.: 'Fuzzy logic based unified power flow controllers for transient stability improvement', *IEE Proc. Gener. Transm. Distrib.*, 1998, **145**, (3), pp. 225–232

[22] Ambriz-Perez, H., Acha, E., Fuerte-Esquivel, C.R., *et al.*: 'Incorporation of a UPFC model in an optimal power flow using newton's method', *IEE Proc. Gener. Transm. Distrib.*, 1998, **145**, (3), pp. 336–344

[23] Song, Y.H., Liu, J.Y.: 'Electromagnetic transient simulation studies of sinusoidal PWM unified power-flow controllers', *Euro. Trans. Electr. Power*, 1998, **8**, (3), pp. 187–192

[24] Toufan, M., Annakkage, U.D.: 'Simulation of the unified power flow controller performance using PSCAD/EMTDC', *Electr. Power Syst. Res.*, 1998, **46**, (1), pp. 67–75

[25] Padiyar, K.R., Kulkarni, A.M.: 'Control design and simulation of unified power flow controller', *IEEE Trans. Power Deliv.*, 1998, **13**, (4), pp. 1348–1354

[26] Sen, K.K., Stacey, E.J.: 'UPFC – unified power flow controller: theory, modeling, and applications', *IEEE Trans. Power Deliv.*, 1998, **13**, (4), pp. 1453–1460

[27] Schauder, C., Stacey, E., Lund, M., *et al.*: 'AEP UPFC project: installation, commissioning and operation of the ±160 MVA STATCOM (phase I)', *IEEE Trans. Power Deliv.*, 1998, **13**, (4), pp. 1530–1535

[28] Wang, H.F.: 'Damping function of unified power flow controller', *IEE Proc. Gener. Transm. Distrib.*, 1999, **146**, (1), pp. 81–87

[29] Padiyar, K.R., Rao, K.U.: 'Modeling and control of unified power flow controller for transient stability', *Int. J. Electr. Power Energy Syst.*, 1999, **21**, (1), pp. 1–11

[30] Keri, A.J.F., Mehraban, A.S., Lombard, X., *et al.*: 'Unified power flow controller (UPFC): modeling and analysis', *IEEE Trans. Power Deliv.*, 1999, **14**, (2), pp. 648–654

[31] Morioka, Y., Kato, M., Mishima, Y., *et al.*: 'Implementation of unified power flow controller and verification for transmission capability improvement', *IEEE Trans. Power Syst.*, 1999, **14**, (2), pp. 575–581

[32] Wang, H.F.: 'Applications of modelling UPFC into multi-machine power systems', *IEE Proc. Gener. Transm. Distrib.*, 1999, **146**, (3), pp. 306–312

[33] Sonnenmoser, A., Lehn, P.W.: 'Line current balancing with a unified power flow controller', *IEEE Trans. Power Deliv.*, 1999, **14**, (3), pp. 1151–1157

[34] Fang, W.L., Ngan, H.W.: 'Control setting of unified power flow controllers through a robust load flow calculation', *IEE Proc. Gener. Transm. Distrib.*, 1999, **146**, (4), pp. 365–369

[35] Makombe, T., Jenkins, N.: 'Investigation of a unified power flow controller', *IEE Proc. Gener. Transm. Distrib.*, 1999, **146**, (4), pp. 400–408

[36] Fang, W.L., Ngan, H.W.: 'Optimising location of unified power flow controllers using the method of augmented Lagrange multipliers', *IEE Proc. Gener. Transm. Distrib.*, 1999, **146**, (5), pp. 428–434

[37] Renz, B.A., Keri, A., Mehraban, A.S., *et al.*: 'AEP unified power flow controller performance', *IEEE Trans. Power Deliv.*, 1999, **14**, (4), pp. 1374–1381

[38] Song, Y.H., Liu, J.Y., Mehta, P.A.: 'Power injection modeling and optimal multiplier power flow algorithm for steady-state studies of unified power flow controllers', *Electr. Power Syst. Res.*, 1999, **52**, (1), pp. 51–59

[39] Fujita, H., Watanabe, Y., Akagi, H.: 'Control and analysis of a unified power flow controller', *IEEE Trans. Power Electron.*, 1999, **14**, (6), pp. 1021–1027

[40] Mishra, S., Dash, P.K., Panda, G.: 'TS-fuzzy controller for UPFC in a multimachine power system', *IEE Proc. Gener. Transm. Distrib.*, 2000, **147**, (1), pp. 15–22

[41] Song, Y.H., Liu, J.Y.: 'Steady-state power flow and voltage control by unified power-flow controllers, part 1: modelling and algorithms', *Euro. Trans. Electr. Power*, 2000, **10**, (1), pp. 53–57

[42] Fuerte-Esquivel, C.R., Acha, E., Ambriz-Perez, H.: 'A comprehensive Newton–Raphson UPFC model for the quadratic power flow solution of practical power networks', *IEEE Trans. Power Syst.*, 2000, **15**, (1), pp. 102–109

[43] Arabi, S., Kundur, P., Adapa, R.: 'Innovative techniques in modeling UPFC for power system analysis', *IEEE Trans. Power Syst.*, 2000, **15**, (1), pp. 336–341

[44] Billinton, R., Fotuhi-Firuzabad, M., Faried, S.O., *et al.*: 'Impact of unified power flow controllers on power system reliability', *IEEE Trans. Power Syst.*, 2000, **15**, (1), pp. 410–415

[45] Chen, Y., Mwinyiwiwa, B., Wolanski, Z., *et al.*: 'Unified power flow controller (UPFC) based on chopper stabilized diode-clamped multilevel converters', *IEEE Trans. Power Electron.*, 2000, **15**, (2), pp. 258–267

[46] Fang, W., Ngan, H.W.: 'A robust load flow technique for use in power systems with unified power flow controllers', *Electr. Power Syst. Res.*, 2000, **53**, (3), pp. 181–186

[47] Song, Y.H., Liu, J.Y.: 'Steady-state power flow and voltage control by unified power-flow controllers, part 2: applications', *Euro. Trans. Electr. Power*, 2000, **10**, (2), pp. 81–85

[48] Liu, J.Y., Song, Y.H., Mehta, P.A.: 'Strategies for handling UPFC constraints in steady-state power flow and voltage control', *IEEE Trans. Power Syst.*, 2000, **15**, (2), pp. 566–571

[49] Huang, Z., Ni, Y., Shen, C.M., *et al.*: 'Application of unified power flow controller in interconnected power systems–modeling, interface, control strategy, and case study', *IEEE Trans. Power Syst.*, 2000, **15**, (2), pp. 817–824

[50] Yuryevich, J., Wong, K.P.: 'MVA constraint handling method for unified power flow controller in loadflow evaluation', *IEE Proc. Gener. Transm. Distrib.*, 2000, **147**, (3), pp. 190–194

[51] Dash, P.K., Pradhan, A.K., Panda, G.: 'Distance protection in the presence of unified power flow controller', *Electr. Power Syst. Res.*, 2000, **54**, (3), pp. 189–198

[52] Wang, H.: 'A unified model for the analysis of FACTS devices in damping power system oscillations – part III: unified power flow controller', *IEEE Trans. Power Deliv.*, 2000, **15**, (3), pp. 978–983

[53] Vilathgamuwa, M., Zhu, X., Choi, S.S.: 'A robust control method to improve the performance of a unified power flow controller', *Electr. Power Syst. Res.*, 2000, **55**, (2), pp. 103–111

[54] Dash, P.K., Mishra, S., Panda, G.: 'A radial basis function neural network controller for UPFC', *IEEE Trans. Power Syst.*, 2000, **15**, (4), pp. 1293–1299

[55] Mwinyiwiwa, B., Lu, B., Ooi, B.T.: 'Multiterminal unified power flow controller', *IEEE Trans. Power Electron.*, 2000, **15**, (6), pp. 1088–1093

[56] Chen, H., Wang, Y., Zhou, R.: 'Transient and voltage stability enhancement via co-ordinated excitation and UPFC control', *IEE Proc. Gener. Transm. Distrib.*, 2001, **148**, (3), pp. 201–208

[57] Verma, K.S., Singh, S.N., Gupta, H.O.: 'Location of unified power flow controller for congestion management', *Electr. Power Syst. Res.*, 2001, **58**, (2), pp. 89–96

[58] Zhang, X.P., Handschin, E., Yao, M.: 'Modeling of the generalized unified power flow controller (GUPFC) in a nonlinear interior point OPF', *IEEE Trans. Power Syst.*, 2001, **16**, (3), pp. 367–373

[59] Fang, D.Z., Fang, Z., Wang, H.F.: 'Application of the injection modeling approach to power flow analysis for systems with unified power flow controller', *Int. J. Electr. Power Energy Syst.*, 2001, **23**, (6), pp. 421–425

[60] Fujita, H., Watanabe, Y., Akagi, H.: 'Transient analysis of a unified power flow controller and its application to design of the dc-link capacitor', *IEEE Trans. Power Electron.*, 2001, **16**, (5), pp. 735–740

[61] Soto-Sanchez, D.E., Green, T.C.: 'Voltage balance and control in a multi-level unified power flow controller', *IEEE Trans. Power Deliv.*, 2001, **16**, (4), pp. 732–738

[62] Cai, H., Qu, Z., Gan, D.: 'Determination of the power transfer capacity of a UPFC with consideration of the system and equipment constraints and of installation locations', *IEE Proc. Gener. Transm. Distrib.*, 2002, **149**, (1), pp. 114–120

[63] Stefanov, P.C., Stankovic, A.M.: 'Modeling of UPFC operation under unbalanced conditions with dynamic phasors', *IEEE Trans. Power Syst.*, 2002, **17**, (2), pp. 395–403

[64] Xu, L., Agelidis, V.G.: 'Flying capacitor multilevel PWM converter based UPFC', *IEE Proc. Electr. Power Appl.*, 2002, **149**, (4), pp. 304–310

[65] Cazzol, M.V., Garzillo, A., Innorta, M., *et al.*: 'Unified power flow controller (UPFC) model in the framework of interior point based active and reactive OPF procedure', *Int. J. Electr. Power Energy Syst.*, 2002, **24**, (6), pp. 431–437

[66] Wang, H.F.: 'Interactions and multivariable design of multiple control functions of a unified power flow controller', *Int. J. Electr. Power Energy Syst.*, 2002, **24**, (7), pp. 591–600

[67] Pal, B.C.: 'Robust damping of interarea oscillations with unified power-flow controller', *IEE Proc. Gener. Transm. Distrib.*, 2002, **149**, (6), pp. 733–738

[68] Garcia-Gonzalez, P., Garcia-Cerrada, A.: 'Detailed analysis and experimental results of the control system of a UPFC', *IEE Proc. Gener. Transm. Distrib.*, 2003, **150**, (2), pp. 147–154

[69] Haghighat, H., Seifi, H., Yazdian, A.: 'An instantaneous power theory based control scheme for unified power flow controller in transient and steady state conditions', *Electr. Power Syst. Res.*, 2003, **64**, (3), pp. 175–180

[70] Xie, H., Song, Y.H., Yokoyama, A., *et al.*: 'Integrated linear and nonlinear control of unified power flow controllers for enhancing power system stability', *Electr. Power Compon. Syst.*, 2003, **31**, (4), pp. 335–347

[71] Fang, W., Ngan, H.W.: 'Enhancing small signal power system stability by coordinating unified power flow controller with power system stabilizer', *Electr. Power Syst. Res.*, 2003, **65**, (2), pp. 91–99

[72] Bebic, J.Z., Lehn, P.W., Iravani, M.R.: 'P–δ characteristics for the unified power flow controller – analysis inclusive of equipment ratings and line limits', *IEEE Trans. Power Deliv.*, 2003, **18**, (3), pp. 1066–1072

[73] Alomoush, M.I.: 'Derivation of UPFC DC load flow model with examples of its use in restructured power systems', *IEEE Trans. Power Syst.*, 2003, **18**, (3), pp. 1173–1180

[74] Papic, I., Gole, A.M.: 'Frequency response characteristics of the unified power flow controller', *IEEE Trans. Power Deliv.*, 2003, **18**, (4), pp. 1394–1402

[75] Bruno, S., La Scala, M.: 'Unified power flow controllers for security-constrained transmission management', *IEEE Trans. Power Syst.*, 2004, **19**, (1), pp. 418–426

[76] Son, K.M., Lasseter, R.H.: 'A Newton-type current injection model of UPFC for studying low-frequency oscillations', *IEEE Trans. Power Deliv.*, 2004, **19**, (2), pp. 694–701

[77] Sawhney, H., Jeyasurya, B.: 'Application of unified power flow controller for available transfer capability enhancement', *Electr. Power Syst. Res.*, 2004, **69**, (2), pp. 155–160

[78] Visakha, K., Thukaram, D., Jenkins, L.: 'Application of UPFC for system security improvement under normal and network contingencies', *Electr. Power Syst. Res.*, 2004, **70**, (1), pp. 46–55

[79] Han, B.M., Baek, S.T., Kim, H.J., *et al.*: 'Novel unified power flow controller based on H-bridge modules', *Electr. Power Syst. Res.*, 2004, **70**, (1), pp. 64–75

[80] Wang, J., Peng, F.Z.: 'Unified power flow controller using the cascade multilevel inverter', *IEEE Trans. Power Electron.*, 2004, **19**, (4), pp. 1077–1084

[81] Kannan, S., Jayaram, S., Salama, M.M.A.: 'Real and reactive power coordination for a unified power flow controller', *IEEE Trans. Power Syst.*, 2004, **19**, (3), pp. 1454–1461

[82] Xu, B., Abur, A.: 'State estimation of systems with UPFCs using the interior point method', *IEEE Trans. Power Syst.*, 2004, **19**, (3), pp. 1635–1641

[83] Tumay, M., Vural, A.M., Lo, K.L.: 'The effect of unified power flow controller location in power systems', *Int. J. Electr. Power Energy Syst.*, 2004, **26**, (8), pp. 561–569

[84] Alomoush, M.I.: 'Impacts of UPFC on line flows and transmission usage', *Electr. Power Syst. Res.*, 2004, **71**, (3), pp. 223–234

[85] Wang, H.F., Jazaeri, M., Cao, Y.C.: 'Operating modes and control interaction analysis of unified power flow controllers', *IEE Proc. Gener. Transm. Distrib.*, 2005, **152**, (2), pp. 264–270

[86] Gholipour, E., Saadate, S.: 'Improving of transient stability of power systems using UPFC', *IEEE Trans. Power Deliv.*, 2005, **20**, (2), pp. 1677–1682

[87] Padiyar, K.R., Prabhu, N.: 'Investigation of SSR characteristics of unified power flow controller', *Electr. Power Syst. Res.*, 2005, **74**, (2), pp. 211–221

[88] Wei, X., Chow, J.H., Fardanesh, B., *et al.*: 'A dispatch strategy for a unified power-flow controller to maximize voltage-stability-limited power transfer', *IEEE Trans. Power Deliv.*, 2005, **20**, (3), pp. 2022–2029

[89] Venayagamoorthy, G.K., Kalyani, R.P.: 'Two separate continually online-trained neurocontrollers for a unified power flow controller', *IEEE Trans. Ind. Appl.*, 2005, **41**, (4), pp. 906–916

[90] Azbe, V., Gabrijel, U., Povh, D., *et al.*: 'The energy function of a general multimachine system with a unified power flow controller', *IEEE Trans. Power Syst.*, 2005, **20**, (3), pp. 1478–1485

[91] Krishna, S., Padiyar, K.R.: 'Discrete control of unified power flow controller for stability improvement', *Electr. Power Syst. Res.*, 2005, **75**, (2), pp. 178–189

[92] Thukaram, D., Jenkins, L., Visakha, K.: 'Improvement of system security with unified-power-flow controller at suitable locations under network contingencies of interconnected systems', *IEE Proc. Gener. Transm. Distrib.*, 2005, **152**, (5), pp. 682–690

[93] Verma, K.S., Gupta, H.O.: 'Impact on real and reactive power pricing in open power market using unified power flow controller', *IEEE Trans. Power Syst.*, 2006, **21**, (1), pp. 365–371

[94] Mishra, S.: 'Neural-network-based adaptive UPFC for improving transient stability performance of power system', *IEEE Trans. Neural Netw.*, 2006, **17**, (2), pp. 461–470

[95] Collins, C., Watson, N., Wood, A.: 'UPFC modeling in the harmonic domain', *IEEE Trans. Power Deliv.*, 2006, **21**, (2), pp. 933–938

[96] Lee, K., Koizumi, H., Kurokawa, K.: 'Voltage control of D-UPFC between a clustered PV system and distribution system'. Proc. IEEE Annual Power Electronics Specialists Conf., Jeju, South Korea, June 2006, pp. 1–5

[97] Zhou, X., Wang, H., Aggarwal, R.K., *et al.*: 'Performance evaluation of a distance relay as applied to a transmission system with UPFC', *IEEE Trans. Power Deliv.*, 2006, **21**, (3), pp. 1137–1147

[98] Fujita, H., Akagi, H., Watanabe, Y.: 'Dynamic control and performance of a unified power flow controller for stabilizing an AC transmission system', *IEEE Trans. Power Electron.*, 2006, **21**, (4), pp. 1013–1020

[99] An, S., Condren, J., Gedra, T.W.: 'An ideal transformer UPFC model, OPF first-order sensitivities, and application to screening for optimal UPFC locations', *IEEE Trans. Power Syst.*, 2007, **22**, (1), pp. 68–75

[100] Al-Awami, A.T., Abdel-Magid, Y.L., Abido, M.A.: 'A particle-swarm-based approach of power system stability enhancement with unified power flow controller', *Int. J. Electr. Power Energy Syst.*, 2007, **29**, (3), pp. 251–259

[101] Liu, L., Zhu, P., Kang, Y., *et al.*: 'Power-flow control performance analysis of a unified power-flow controller in a novel control scheme', *IEEE Trans. Power Deliv.*, 2007, **22**, (3), pp. 1613–1619

[102] Nguyen, T.T., Nguyen, V.L.: 'Representation of line optimisation control in unified power-flow controller model for power-flow analysis', *IET Gener. Transm. Distrib.*, 2007, **1**, (5), pp. 714–723

[103] Vural, A.M., Tumay, M.: 'Mathematical modeling and analysis of a unified power flow controller: a comparison of two approaches in power flow studies and effects of UPFC location', *Int. J. Electr. Power Energy Syst.*, 2007, **29**, (8), pp. 617–629

[104] Zarghami, M., Crow, M.L.: 'The existence of multiple equilibria in the UPFC power injection model', *IEEE Trans. Power Syst.*, 2007, **22**, (4), pp. 2280–2282

[105] Aminifar, F., Fotuhi-Firuzabad, M., Billinton, R.: 'Extended reliability model of a unified power flow controller', *IET Gener. Transm. Distrib.*, 2007, **1**, (6), pp. 896–903

[106] Ma, T.T.: 'P-Q decoupled control schemes using fuzzy neural networks for the unified power flow controller', *Int. J. Electr. Power Energy Syst.*, 2007, **29**, (10), pp. 748–758

[107] Saravanailango, G., Nagamani, C.: 'A non-linear control technique for unified power flow controller based on feed-back linearization', *Electr. Power Compon. Syst.*, 2008, **36**, (4), pp. 432–447

[108] Geethalakshmi, B., Dananjayan, P.: 'Investigation of performance of UPFC without DC link capacitor', *Electr. Power Syst. Res.*, 2008, **78**, (4), pp. 736–746

[109] Han, B.M., Ledwich, G.: 'Dynamic performance analysis of novel unified power flow controller with computer simulation and scaled-model experiment', *Euro. Trans. Electr. Power*, 2008, **18**, (3), pp. 250–265

[110] Segundo, J., Medina, A.: 'Periodic steady-state solution of electric systems including UPFCs by extrapolation to the limit cycle', *IEEE Trans. Power Deliv.*, 2008, **23**, (3), pp. 1506–1512

[111] Ray, S., Venayagamoorthy, G.K.: 'Wide-area signal-based optimal neurocontroller for a UPFC', *IEEE Trans. Power Deliv.*, 2008, **23**, (3), pp. 1597–1605

[112] Hao, J., Shi, L.B., Ni, Y.X., *et al.*: 'Improvement of transient stability by unified power flow controller based on Hamiltonian system theory', *Euro. Trans. Electr. Power*, 2008, **18**, (6), pp. 617–635

[113] Bhowmick, S., Das, B., Kumar, N.: 'An indirect UPFC model to enhance reusability of newton power-flow codes', *IEEE Trans. Power Deliv.*, 2008, **23**, (4), pp. 2079–2088

[114] Samantaray, S.R., Tripathy, L.N., Dash, P.K.: 'Differential equation-based fault locator for unified power flow controller-based transmission line using synchronised phasor measurements', *IET Gener. Transm. Distrib.*, 2009, **3**, (1), pp. 86–98

[115] Guo, J., Crow, M.L., Sarangapani, J.: 'An improved UPFC control for oscillation damping', *IEEE Trans. Power Syst.*, 2009, **24**, (1), pp. 288–296

[116] Jayashri, R., Devi, R.P.K.: 'Effect of tuned unified power flow controller to mitigate the rotor speed instability of fixed-speed wind turbines', *Renew. Energy*, 2009, **34**, (3), pp. 591–596

[117] Singh, J.G., Singh, S.N., Srivastava, S.C.: 'Optimal placement of unified power flow controller based on system loading distribution factors', *Electr. Power Compon. Syst.*, 2009, **37**, (4), pp. 441–463

[118] Ilango, G.S., Nagamani, C., Sai, A., *et al.*: 'Control algorithms for control of real and reactive power flows and power oscillation damping using UPFC', *Electr. Power Syst. Res.*, 2009, **79**, (4), pp. 595–605

[119] Pandey, R.K., Singh, N.K.: 'UPFC control parameter identification for effective power oscillation damping', *Int. J. Electr. Power Energy Syst.*, 2009, **31**, (6), pp. 269–276

[120] Singh, J.G., Tripathy, P., Singh, S.N.*, et al.*: 'Development of a fuzzy rule based generalized unified power flow controller', *Euro. Trans. Electr. Power*, 2009, **19**, (5), pp. 702–717

[121] Shayeghi, H., Shayanfar, H.A., Jalilzadeh, S.*, et al.*: 'Design of output feedback UPFC controller for damping of electromechanical oscillations using PSO', *Energy Convers. Manage.*, 2009, **50**, (10), pp. 2554–2561

[122] Shayeghi, H., Shayanfar, H.A., Jalilzadeh, S.*, et al.*: 'A PSO based unified power flow controller for damping of power system oscillations', *Energy Convers. Manage.*, 2009, **50**, (10), pp. 2583–2592

[123] Zarghami, M., Crow, M.L., Sarangapani, J.*, et al.*: 'A novel approach to interarea oscillation damping by unified power flow controllers utilizing ultracapacitors', *IEEE Trans. Power Syst.*, 2010, **25**, (1), pp. 404–412

[124] Chong, B., Zhang, X.P., Godfrey, K.R.*, et al.*: 'Optimal location of unified power flow controller for congestion management', *Euro. Trans. Electr. Power*, 2010, **20**, (5), pp. 600–610

[125] Rajabi-Ghahnavieh, A., Fotuhi-Firuzabad, M., Shahidehpour, M.*, et al.*: 'UPFC for enhancing power system reliability', *IEEE Trans. Power Deliv.*, 2010, **25**, (4), pp. 2881–2890

[126] Wang, K., Crow, M.L., McMillin, B.*, et al.*: 'A novel real-time approach to unified power flow controller validation', *IEEE Trans. Power Syst.*, 2010, **25**, (4), pp. 1892–1901

[127] Shayeghi, H., Shayanfar, H.A., Jalilzadeh, S.*, et al.*: 'Tuning of damping controller for UPFC using quantum particle swarm optimizer', *Energy Convers. Manage.*, 2010, **51**, (11), pp. 2299–2306

[128] Sadigh, A.K., Hagh, M.T., Sabahi, M.: 'Unified power flow controller based on two shunt converters and a series capacitor', *Electr. Power Syst. Res.*, 2010, **80**, (12), pp. 1511–1519

[129] Monteiro, J., Silva, J.F., Pinto, S.F.*, et al.*: 'Matrix converter-based unified power-flow controllers: advanced direct power control method', *IEEE Trans. Power Deliv.*, 2011, **26**, (1), pp. 420–430

[130] Farrag, M.E.A., Putrus, G.: 'An on-line training radial basis function neural network for optimum operation of the UPFC', *Euro. Trans. Electr. Power*, 2011, **21**, (1), pp. 27–39

[131] Ara, A.L., Kazemi, A., Nabavi Niaki, S.A.: 'Modelling of optimal unified power flow controller (OUPFC) for optimal steady-state performance of power systems', *Energy Convers. Manage.*, 2011, **52**, (2), pp. 1325–1333

[132] Saribulut, L., Teke, A., Tumay, M.: 'Dynamic control of unified power flow controller under unbalanced network conditions', *Simul. Model. Pract. Theory*, 2011, **19**, (2), pp. 817–836

[133] Baskar, S., Kumarappan, N., Gnanadass, R.: 'A novel component minimized converters for unified power flow controller', *Int. J. Electr. Power Energy Syst.*, 2011, **33**, (4), pp. 923–932

[134] Sayed, M.A., Takeshita, T.: 'All nodes voltage regulation and line loss minimization in loop distribution systems using UPFC', *IEEE Trans. Power Electron.*, 2011, **26**, (6), pp. 1694–1703

[135] Tiwari, R., Niazi, K.R., Gupta, V.: 'Variable series impedance model of a unified power flow controller for load flow analysis', *Electr. Power Compon. Syst.*, 2011, **40**, pp. 74–92

[136] Farrag, M.E.A., Putrus, G.A.: 'Design of an adaptive neurofuzzy inference control system for the unified power-flow controller', *IEEE Trans. Power Deliv.*, 2012, **27**, (1), pp. 53–61

[137] Elgamal, M.E., Lotfy, A., Ali, G.E.M.: 'Voltage profile enhancement by fuzzy controlled MLI UPFC', *Int. J. Electr. Power Energy Syst.*, 2012, **34**, (1), pp. 10–18

[138] Wang, K., Yan, B., Crow, M.L.*, et al.*: 'A feedback linearization based unified power flow controller internal controller for power flow control', *Electr. Power Compon. Syst.*, 2012, **40**, pp. 628–647

[139] Mancilla-David, F., Venkataramanan, G.: 'Realisation of an ac link unified power flow controller', *IET Gener. Transm. Distrib.*, 2012, **6**, (4), pp. 294–302

[140] Hajforoosh, S., Nabavi, S.M.H., Masoum, M.A.S.: 'Coordinated aggregated-based particle swarm optimisation algorithm for congestion management in restructured power market by placement and sizing of unified power flow controller', *IET Sci. Meas. Technol.*, 2012, **6**, (4), pp. 267–278

[141] Ajami, A., Shotorbani, A.M., Aagababa, M.P.: 'Application of the direct Lyapunov method for robust finite-time power flow control with a unified power flow controller', *IET Gener. Transm. Distrib.*, 2012, **6**, (9), pp. 822–830

[142] Ahsaee, M.G., Sadeh, J.: 'New fault-location algorithm for transmission lines including unified power-flow controller', *IEEE Trans. Power Deliv.*, 2012, **27**, (4), pp. 1763–1771

[143] Verveckken, J., Silva, F., Barros, D.*, et al.*: 'Direct power control of series converter of unified power-flow controller with three-level neutral point clamped converter', *IEEE Trans. Power Deliv.*, 2012, **27**, (4), pp. 1772–1782

[144] Tiwari, P.K., Sood, Y.R.: 'Efficient and optimal approach for location and parameter setting of multiple unified power flow controllers for a deregulated power sector', *IET Gener. Transm. Distrib.*, 2012, **6**, (10), pp. 958–967

[145] Therattil, J.P., Panda, P.C.: 'Non-linear dynamic modeling and adaptive control of a power system with unified power flow controller', *Electr. Power Compon. Syst.*, 2012, **40**, (14), pp. 1544–1561

[146] Shojaeian, S., Soltani, J., Markadeh, G.A.: 'Damping of low frequency oscillations of multi-machine multi-UPFC power systems, based on adaptive input-output feedback linearization control', *IEEE Trans. Power Syst.*, 2012, **27**, (4), pp. 1831–1840

[147] Taher, S.A., Hemmati, R., Abdolalipour, A.*, et al.*: 'Comparison of different robust control methods in design of decentralized UPFC controllers', *Int. J. Electr. Power Energy Syst.*, 2012, **43**, (1), pp. 173–184

[148] Hassan, L.H., Moghavvemi, M., Almurib, H.*, et al.*: 'Application of genetic algorithm in optimization of unified power flow controller parameters and its location in the power system network', *Int. J. Electr. Power Energy Syst.*, 2013, **46**, pp. 89–97

[149] Pereira, M., Zanetta, L.C.: 'A current based model for load flow studies with UPFC', *IEEE Trans. Power Syst.*, 2013, **28**, (2), pp. 677–682

[150] Kasinathan, P., Vairamani, R., Sundramoorthy, S.: 'Dynamic performance investigation of *d–q* model with PID controller-based unified power-flow controller', *IET Power Electron.*, 2013, **6**, (5), pp. 843–850

[151] Shotorbani, A.M., Ajami, A., Aghababa, M.P.*, et al.*: 'Direct Lyapunov theory-based method for power oscillation damping by robust finite-time control of unified power flow controller', *IET Gener. Transm. Distrib.*, 2013, **7**, (7), pp. 691–699

[152] Wang, L., Li, H.W., Wu, C.T.: 'Stability analysis of an integrated offshore wind and seashore wave farm fed to a power grid using a unified power flow controller', *IEEE Trans. Power Syst.*, 2013, **28**, (3), pp. 2211–2221

[153] Thirumalaivasan, R., Prabhu, N., Janaki, M.*, et al.*: 'Analysis of subsynchronous resonance with generalized unified power flow controller', *Int. J. Electr. Power Energy Syst.*, 2013, **53**, pp. 623–631

[154] Vyakaranam, B., Villaseca, F.E.: 'Dynamic modeling and analysis of generalized unified power flow controller', *Electr. Power Syst. Res.*, 2014, **106**, pp. 1–11

[155] Moravej, Z., Pazoki, M., Khederzadeh, M.: 'Impact of UPFC on power swing characteristic and distance relay behavior', *IEEE Trans. Power Deliv.*, 2014, **29**, (1), pp. 261–268

[156] Ahmad, S., Albatsh, F.M., Mekhilef, S.*, et al.*: 'Fuzzy based controller for dynamic unified power flow controller to enhance power transfer capability', *Energy Convers. Manage.*, 2014, **79**, pp. 652–665

[157] Malhotra, U., Gokaraju, R.: 'An add-on self-tuning control system for a UPFC application', *IEEE Trans. Ind. Electron.*, 2014, **61**, (5), pp. 2378–2388

[158] Galvani, S., Hagh, M.T., Sharifian, M.B.B.: 'Unified power flow controller impact on power system predictability', *IET Gener. Transm. Distrib.*, 2014, **8**, (5), pp. 819–827

[159] Golshannavaz, S., Aminifar, F., Nazarpour, D.: 'Application of UPFC to enhancing oscillatory response of series-compensated wind farm integrations', *IEEE Trans. Smart Grid*, 2014, **5**, (4), pp. 1961–1968

[160] Monteiro, J., Silva, J.F., Pinto, S.F.*, et al.*: 'Linear and sliding-mode control design for matrix converter-based unified power flow controllers', *IEEE Trans. Power Electron.*, 2014, **29**, (7), pp. 3357–3367

[161] Santos, N.M.R., Silva, J.F., Verveckken, J.*, et al.*: 'Enhancing the ride-through capability of DC-link voltage in NPC multilevel unified power-flow controllers', *IEEE Trans. Power Deliv.*, 2014, **29**, (4), pp. 1542–1550

[162] Shotorbani, A.M., Ajami, A., Zadeh, S.G.*, et al.*: 'Robust terminal sliding mode power flow controller using unified power flow controller with adaptive observer and local measurement', *IET Gener. Transm. Distrib.*, 2014, **8**, (10), pp. 1712–1723

[163] Sayed, M.A., Takeshita, T.: 'Line loss minimization in isolated substations and multiple loop distribution systems using the UPFC', *IEEE Trans. Power Electron.*, 2014, **29**, (11), pp. 5813–5822

[164] Dubey, R., Samantaray, S.R., Panigrahi, B.K.: 'Simultaneous impact of unified power flow controller and off-shore wind penetration on distance relay characteristics', *IET Gener. Transm. Distrib.*, 2014, **8**, (11), pp. 1869–1880

[165] Lee, S.H., Liu, J.H., Chu, C.C.: 'Modelling and locating unified power-flow controllers for static voltage stability enhancements', *Int. Trans. Electr. Energy Syst.*, 2014, **24**, (11), pp. 1524–1540

[166] Jena, M.K., Samantaray, S.R., Tripathy, L.: 'Decision tree-induced fuzzy rule-based differential relaying for transmission line including unified power flow controller and wind-farms', *IET Gener. Transm. Distrib.*, 2014, **8**, (12), pp. 2144–2152

[167] Kumar, B.V., Srikanth, N.V.: 'Optimal location and sizing of unified power flow controller (UPFC) to improve dynamic stability: a hybrid technique', *Int. J. Electr. Power Energy Syst.*, 2015, **64**, pp. 429–438

[168] Rajabi-Ghahnavieh, A., Fotuhi-Firuzabad, M., Othman, M.: 'Optimal unified power flow controller application to enhance total transfer capability', *IET Gener. Transm. Distrib.*, 2015, **9**, (4), pp. 358–368

[169] Kamel, S., Jurado, F., Mihalic, R.: 'Advanced modeling of center-node unified power flow controller in NR load flow algorithm', *Electr. Power Syst. Res.*, 2015, **121**, pp. 176–182

[170] Kamel, S., Jurado, F., Pecas-Lopes, J.A.: 'Comparison of various UPFC models for power flow control', *Electr. Power Syst. Res.*, 2015, **121**, pp. 243–251

[171] Moravej, Z., Pazoki, M., Khederzadeh, M.: 'New pattern-recognition method for fault analysis in transmission line with UPFC', *IEEE Trans. Power Deliv.*, 2015, **30**, (3), pp. 1231–1242

[172] Rao, B.V., Kumar, G.V.N.: 'Optimal power flow by BAT search algorithm for generation reallocation with unified power flow controller', *Int. J. Electr. Power Energy Syst.*, 2015, **68**, pp. 81–88

[173] Rodriguez, O., Medina, A., Andersson, G.: 'Closed-form analytical characterisation of non-linear oscillations in power systems incorporating unified power flow controller', *IET Gener. Transm. Distrib.*, 2015, **9**, (11), pp. 1019–1032

[174] Qader, M.R.: 'Design and simulation of a different innovation controller-based UPFC (unified power flow controller) for the enhancement of power quality', *Energy*, 2015, **89**, pp. 576–592

[175] Lin, W.M., Lu, K.H., Ou, T.C.: 'Design of a novel intelligent damping controller for unified power flow controller in power system connected offshore power applications', *IET Gener. Transm. Distrib.*, 2015, **9**, (13), pp. 1708–1717

[176] Martinez, M.M., Viveros, H.G.: 'Harmonic interaction of the unified power flow controller with the electrical network', *Int. Trans. Electr. Energy Syst.*, 2015, **25**, (11), pp. 3139–3154

[177] Tripathy, L., Samantaray, S.R., Dash, P.K.: 'Sparse S-transform for location of faults on transmission lines operating with unified power flow controller', *IET Gener. Transm. Distrib.*, 2015, **9**, (15), pp. 2108–2116

[178] Khadanga, R.K., Satapathy, J.K.: 'A new hybrid GA–GSA algorithm for tuning damping controller parameters for a unified power flow controller', *Int. J. Electr. Power Energy Syst.*, 2015, **73**, pp. 1060–1069

[179] Yang, S., Liu, Y., Wang, X., *et al.*: 'Modulation and control of transformerless UPFC', *IEEE Trans. Power Electron.*, 2016, **31**, (2), pp. 1050–1063

[180] Mohanty, A., Patra, S., Ray, P.K.: 'Robust fuzzy-sliding mode based UPFC controller for transient stability analysis in autonomous wind–diesel–PV hybrid system', *IET Gener. Transm. Distrib.*, 2016, **10**, (5), pp. 1248–1257

[181] Kamel, S., Jurado, F., Chen, Z., *et al.*: 'Developed generalised unified power flow controller model in the Newton–Raphson power-flow analysis using combined mismatches method', *IET Gener. Transm. Distrib.*, 2016, **10**, (9), pp. 2177–2184

[182] Moazzami, M., Morshed, M.J., Fekih, A.: 'A new optimal unified power flow controller placement and load shedding coordination approach using the hybrid imperialist competitive algorithm-pattern search method for voltage collapse prevention in power system', *Int. J. Electr. Power Energy Syst.*, 2016, **79**, pp. 263–274

[183] Reddy, A.K., Singh, S.P.: 'Congestion mitigation using UPFC', *IET Gener. Transm. Distrib.*, 2016, **10**, (10), pp. 2433–2442

[184] Peng, F.Z., Liu, Y., Yang, S., *et al.*: 'Transformer-less unified power-flow controller using the cascade multilevel inverter', *IEEE Trans. Power Electron.*, 2016, **31**, (8), pp. 5461–5472

[185] Liu, Y., Yang, S., Wang, X., *et al.*: 'Application of transformer-less UPFC for interconnecting two synchronous AC grids with large phase difference', *IEEE Trans. Power Electron.*, 2016, **31**, (9), pp. 6092–6103

[186] Dutta, S., Mukhopadhyay, P., Roy, P.K., *et al.*: 'Unified power flow controller based reactive power dispatch using oppositional krill herd algorithm', *Int. J. Electr. Power Energy Syst.*, 2016, **80**, pp. 10–25

[187] Singh, J.G., Qazi, H.W., Ghandhari, M.: 'Load curtailment minimization by optimal placement of unified power flow controller', *Int. Trans. Electr. Energ. Syst.*, 2016, **26**, (10), pp. 2272–2284

[188] Khodaparast, J., Khederzadeh, M., da Silva, F.F., *et al.*: 'Variation of UPFC controllable parameters during power swing and their impacts on distance relay', *IET Gener. Transm. Distrib.*, 2017, **11**, (7), pp. 1735–1744

[189] Song, P., Xu, Z., Dong, H.: 'UPFC-based line overload control for power system security enhancement', *IET Gener. Transm. Distrib.*, 2017, **11**, (13), pp. 3310–3317

[190] Li, J., Liu, F., Li, Z., *et al.*: 'Impacts and benefits of UPFC to wind power integration in unit commitment', *Renew. Energy*, 2018, **116**, pp. 570–583