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Review

FACTS Providing Grid Services: Applications and Testing

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Abstract: The role of flexible alternating current transmission systems (FACTSs) in the provision of grid services is becoming increasingly important, due to the massive integration of intermittent renewable energy sources, energy storage systems, and the decommissioning of thermal plants. A comprehensive literature review of grid services offered by FACTS is performed, focusing on the different grid services that they can provide, such as power flow control, reactive power control, voltage control, power quality improvement, harmonic mitigation, improvement of transient stability, and damping of inter-area and intra-area oscillations. These grid services need to be realistically and economically validated in suitable testing environments. A review of relevant standards, guides, and the literature is performed, which covers the entire range from functional specification and factory testing up to the field testing of FACTS. Advanced industry practices, such as controller hardware in the loop (CHIL) testing of FACTS controllers by the manufacturer, and recent trends, such as CHIL testing of replica controllers by the owner, are underlined. Limitations of conventional testing and CHIL testing are explained and the use of power hardware in the loop (PHIL) simulation for FACTS testing is discussed. CHIL and scaled-down PHIL tests on a transmission static synchronous compensator (STATCOM) are performed and a comparison of the results is presented.

Keywords: FACTS; grid services; CHIL; PHIL; lab testing; field testing; standards; STATCOM; replica; review

1. Introduction

Power systems are subject to an unprecedented transformation, characterized by the wide integration of intermittent distributed generation, energy storage, consumer engagement, and the decommissioning of thermal plants, in order to meet environmental goals, while maintaining the quality of supply [1–3]. In this transformation, flexible alternating current transmission systems (FACTSs) can play an important role by facing several challenges of the transmission system [4]. They can offer a variety of grid services, such as power flow control, reactive power control, voltage control, power quality improvement, harmonic mitigation, improvement of transient stability, damping of inter-area and intra-area oscillations, and black-start capability, among others.

Many researchers have investigated various models and methods for the analysis of FACTS devices and their optimal operation and planning within power systems. In addition to research articles, there are also important review papers that summarize the research findings on FACTS devices and their grid services in a comprehensive manner. There are review articles devoted to the review of one particular FACTS device [5–7], and articles that review more FACTS devices [8–10]. The study of [5] reviews the models and methods of unified power flow controllers (UPFCs) in smart grids, sets the future research goals, and provides future research directions in this field. Another [6] provides a comprehensive review on static synchronous compensators (STATCOMs) and their future research potentials. Furthermore, [7] provides a systematic review of static phase sifters (SPSs), compares SPS configurations, and highlights their advantages and limitations. The work of [8] presents a bibliography review of FACTS applications for enhancing power quality and ensuring efficient utilization of energy in power systems with increased penetration of renewable energy sources. The work of [9] presents a review of methodologies for optimum allocation and coordination of FACTS devices and distributed generation units. Finally, paper [10] reviews electromagnetic transient models of FACTS devices that do not use voltage source converters and summarizes key characteristics of each model.

There is no review paper focused on the different grid services provided by various FACTS devices. This paper aims to cover this gap by providing a comprehensive review of the grid services offered by FACTS. These services include power flow control, reactive power control, voltage control, power quality improvement, harmonic mitigation, improvement of transient stability, and the damping of inter-area and intra-area oscillations. Due to space limitations, only a small set of representative research works is reviewed in Section 2 for each one of the different grid services offered by FACTS.

Moreover, suitable testing procedures and setups for testing grid services by FACTS are necessary. In the last decade, several standards and guides related to FACTS testing have been published. These include factory testing and field testing for specific types of FACTS, such as static var compensator (SVC) and STATCOM; however limited attention has been placed on grid services. A method for efficiently testing the provision of grid services is hardware in the loop simulation [11], where a hardware controller (controller hardware in the loop simulation, CHIL) or hardware power device (power hardware in the loop simulation, PHIL) is connected to a real-time simulated power system. Testing of the control systems of FACTS using CHIL simulation has been performed by manufacturers for several years and more recently by transmission system operators (TSOs).

Although there is a plethora of papers that have performed simulation studies of FACTS, limited experiences on hardware testing have been reported, concerning both laboratory testing and field testing. Most of these papers describe specific test cases for a specific FACTS device at a specific location (as described in Sections 3.1 and 3.2). A review on the testing of FACTS is still missing. This paper addresses this gap by reviewing papers, standards, and guides on the testing of FACTS. It efficiently presents all the different testing stages, including conventional testing, i.e., factory and field testing, and emerging industry practices, such as the CHIL testing of FACTS controllers by manufacturers and CHIL testing of replicas by utilities. Particular attention is placed on the testing of grid services.

The contributions of this review paper are manifold:

- It is the only review paper of the bibliography that is focused on the different grid services provided by various FACTS devices.
- It is the first paper that reviews the different testing stages of FACTS. It addresses conventional testing and advanced industry practices.
- It proposes the use of PHIL simulation for the testing of FACTS, as an additional stage before field testing, and presents laboratory results.

The structure of the paper is as follows: Section 2 presents a literature review on the grid services offered by FACTS. Section 3 reviews the conventional testing of FACTS, advanced industry practices, and recent trends. The CHIL and PHIL results of a STATCOM performing voltage control are presented and discussed. Section 4 concludes the paper and summarizes the main findings.

2. FACTS Providing Grid Services: A Review

FACTS devices are based on power electronics and are used in order to improve the control of electric power transmission systems in both steady state and transient state conditions [12]. FACTS devices also help increase transmission lines' power transfer capacity [12]. The ability of an alternating current (AC) transmission line to transfer AC electric power is constrained by various factors, including the thermal limit, voltage limit, transient stability limit, and short circuit current limit. These limits define the maximum power, called the power transfer capability, which can be transferred through the AC transmission line without causing damage to the transmission line and the electrical equipment.

A FACTS device provides control of one or more parameters of an AC transmission system. These parameters include the voltage magnitude, voltage angle, and the impedance of the transmission line. Through the control of these parameters, the FACTS device can control the real and reactive power flow, the voltage magnitude, and the shunt reactive power compensation. There are four different types of FACTS [12]:

1. Series devices. These are variable impedance devices that inject voltage in a series with the transmission line. Depending on the phase angle between the injected voltage and the line current, they can help control the real and reactive power. Examples of series devices include thyristor controlled series capacitor (TCSC), thyristor switched series capacitor (TSSC), and static synchronous series compensator (SSSC).
2. Shunt devices. These are variable impedance devices that inject current at the point of connection. Depending on the phase angle between the injected current and the line voltage, these devices can control the real and reactive power. Examples of shunt devices include SVC and STATCOM.
3. Series-series devices. These are a combination of series devices, where each series device provides series compensation for each line and also transfers active power among the transmission lines. An example of such a device is the interline power flow controller (IPFC).
4. Shunt-series devices. These are a combination of series and shunt devices, which are controlled in a coordinated way. An example of such a device is the UPFC, which is the most versatile among all FACTS devices, because it can control, selectively or concurrently, the real and reactive power flow via the transmission line, the bus voltage magnitude, and the compensation of reactive power [5].

In this section, representative research works are reviewed for each one of the different grid services offered by FACTS.

2.1. Power Flow Control

The power flow control services include:

- Control of power flow [13–18]. The split TCSC provides better power flow control services than the single TCSC [13]. An adaptive TSSC with discrete nonlinear control provides power flow control and improves power system transient stability [14]. An SSSC with an oscillation damping controller simultaneously achieves power flow control and low frequency oscillation damping in a system with a wind farm [15]. The modular multilevel converter-based UPFC regulates the power flow of the power system in both steady state and transient state conditions [16]. A hybrid UPFC, composed of a smaller capacity UPFC and a larger capacity Sen transformer, provides the same services of active and reactive power flow control, with the advantage of much lower installation costs [17].
- Congestion management [19–22]. A method for the optimum location of TCSC relieves congestion in both the normal state and contingency state with single line outage [19]. An analytical method determines the optimum location of the TCSC and SSSC and relieves congestion in both the normal state and contingency state with a single line fault [20]. A pricing-based method finds the optimum location of the UPFC that mitigates line congestion and minimizes system operation costs [21]. A sensitivity-based optimization method finds the optimum location and rated capacity of the UPFC that minimizes congestion costs [22].
- Reactive power dispatch (RPD) [23–26]. RPD is a grid service that simultaneously minimizes reactive power flow in lines, total active power loss in transmission lines, and voltage deviation in buses. The optimal allocation of four TCSCs and three SVCs at the IEEE 30 bus system significantly reduces the total reactive power flow in lines [23]. The optimal reactive power allocation of three

different FACTS, namely TCSC, SVC, and thyristor controlled phase angle regulator (TCPAR), shows that a SVC is slightly better in the improvement of the voltage profile, while a TCPAR is better in reducing the total active power loss [24]. In comparison with the case without a UPFC, the optimal allocation of one UPFC provides a greater reduction of transmission lines' total active power loss and buses' voltage deviation for both the IEEE 57-bus and the IEEE 118-bus test systems [25]. In an AC-DC power system with 96 AC buses and two DC terminals, the optimal allocation of one UPFC, under contingency conditions, has a significant impact on the minimization of power loss and voltage deviation [26].

- Available transfer capability enhancement [27–33]. The available transfer capability (ATC) measures the capability of interconnected power systems to transfer electric power from one power system to another through the transmission lines. The increase of ATC is important because it helps transfer low cost energy to the loads. FACTS devices can increase the ATC by redistributing power flows. The optimal allocation of one UPFC increases the ATC for the IEEE reliability test system as well as for a 196-bus power system in North America [27]. Since series FACTSs help increase the ATC, it is proposed that these devices should be simultaneously optimized with power generation in a market environment [28]. The UPFC provides a higher increase of the ATC in comparison to STATCOM and SSSC [29], and in comparison to a SVC and thyristor controlled phase shifter (TCPS) [30]. The optimal allocation of multiple FACTS, namely TCSC, TCPS, SVC, and UPFC, provides a significant increase of the ATC [31].
- Power loss reduction. Several research works have shown the use of FACTS devices for the reduction of total active power loss [23–26,30,34].
- Load curtailment minimization. An optimally allocated UPFC is more effective than an optimally allocated TCSC in the minimization of load curtailment on IEEE 14-bus and IEEE 30-bus test systems [35].
- Minimization of wind power curtailment [36–39]. Wind power curtailment is minimized by an optimally allocated TCSC [36] and an optimally allocated distributed power flow controller [37]. An optimally allocated SVC is more effective than an optimally allocated TCSC in the minimization of wind power curtailment [38]. The combined optimal allocation of SVC and TCSC significantly reduces wind power curtailment [39].

2.2. Voltage Control

The voltage control capability of the SVC was investigated and a reactive power dispatch model was developed that restores the SVC operating point and regulates the bus voltage [40]. A photovoltaic inverter is controlled as a STATCOM and provides voltage control in power distribution systems [41]. The limits of the UPFC were included into a steady state power flow model, which was validated by simulations that highlight the capabilities of a UPFC for coordinated voltage control and power flow control [42]. An optimization methodology was developed that identifies the optimal parameter settings of one UPFC and manages to relieve voltage violations and overloads that are caused by line outages [43]. A probabilistic methodology improved the steady state bus voltage profile by optimally sizing the TCSC, STATCOM, and UPFC [44].

2.3. Improvement of Power Quality

FACTS devices, such as SVC, STATCOM, and UPFC, offer significant power quality services to the grid, including enhancement of the power system reliability and mitigation of voltage sags, harmonics, and unbalance [8,45–49]. The capability of the SVC, STATCOM, and dynamic voltage restorer (DVR) to mitigate voltage sags, harmonics, and unbalance was shown in [45]. Distribution STATCOM and SVC minimize voltage sags and the economic losses in power distribution systems [46]. SVC, STATCOM, and DVR minimize economic losses due to voltage sags [47]. An appropriate control strategy allows the UPFC to provide harmonic isolation in case of nonlinear loads [48]. In order to improve the reliability problem that is due to the loading of a transmission line, a UPFC was installed on that line and, as a result, power system reliability as improved [49].

2.4. Improvement of Power System Stability

FACTS devices offer significant stability services, including:

- Damping of inter-area and intra-area oscillations [50–52]. A nonlinear control method of UPFC and STATCOM was developed for damping inter-area oscillations, which was validated on a power system with 16 generators and 68 buses [50]. A single FACTS device (STATCOM, UPFC, or multi-terminal UPFC) successfully damps inter-area oscillations and intra-area (local) oscillations [51]. The UPFC provides robust damping of inter-area oscillations at different load conditions [52].
- Transient stability improvement [53–58]. The coordinated control of STATCOM and generator excitation achieves transient stability and voltage regulation [53]. A hardware in the loop validation verified the transient stability enhancement obtained by a wide-area controlled SVC [54]. STATCOM in combination with energy storage system enhances the transient stability of power systems with induction generators and synchronous generators [55]. UPFC offers vast improvement of first swing transient stability [56,57]. The coordinated use of SSSC, TCSC, and STATCOM improved the transient stability of a power system with photovoltaics and wind farms [58].
- Voltage stability improvement [59–64]. Eigen-value analysis or modal analysis can be applied to identify buses (locations) sensitive to voltage collapse and buses where power injections are the most beneficial. Modal analysis identifies the optimum location of SVC for voltage support [59]. Optimally allocated UPFCs enhance power system voltage stability under single outage contingency criterion [60]. The coordinated optimal allocation of SVCs and TCSCs enhance security against voltage collapse by keeping bus voltages and ensuring voltage stability margins [61]. In case of low loads or low voltages, regarding voltage stability, the SSSC is superior to the controllable series compensator (CSC) [62]. An analytical method was used estimate the efficiency of CSC, SSSC, SVC, and STATCOM for voltage stability enhancement [63].

2.5. Multiple Grid Services

The coordinated use of multi-type FACTS devices offers multiple grid services [65–69]. The multiple grid services are mathematically formulated as multi-objective optimization problems. An optimally allocated UPFC simultaneously minimizes total active power loss and maximizes power system predictability in systems with a high penetration of wind power [65]. In these systems, predicting the system state is very difficult due to the uncertainties in wind power generation.

An optimally allocated UPFC simultaneously minimizes transmission lines' total active power loss and maximizes the voltage stability limit [66]. The best results are obtained when the transformer taps are optimized in combination with the optimization of the UPFC location and parameter settings.

Optimally allocated TCSCs and SVCs simultaneously minimize the total active power loss, minimize load voltage deviation, and maximize static voltage stability margin, considering single outage contingency criterion, line thermal limits, and bus voltage limits [67].

An optimally allocated hybrid flow controller (HFC), phase shifting transformer (PST), and UPFC simultaneously minimize total active power loss, total fuel cost, and cost of FACTS installation, and maximize power system loadability [68]. The HFC provides better results in comparison with PST and UPFC.

Optimally allocated TCSC, SVC, and UPFC simultaneously minimize total active power loss, and minimize system operation cost that includes the cost of FACTS, the energy loss cost, and the congestion cost [69]. The FACTS' location, size, and parameter settings are optimized in combination with existing reactive power sources.

3. Current Practices and Future Trends in the Testing of FACTS

3.1. Conventional Testing of FACTS

The testing of distributed energy resource inverters according to ancillary service requirements has been well established recently. Several standards and guidelines are in place stating requirements and respective testing procedures [70,71]. Factory testing takes place at manufacturer's facilities, compliance testing at independent accredited institutes, and, finally, commissioning testing occurs in the field. On the other hand, the testing of FACTS is more challenging mainly due to their high rating and large size. For example, the typical capacities of recent transmission STATCOMs applied in the USA are +/−100 to +/−200 MVAr with some large units reaching +/−250 MVAr, while SVCs can have capacities up to 500 to 600 MVAr [4]. For this reason, most of the studies on FACTS preform digital simulations, while fewer involve laboratory or field tests.

In practice, digital simulations (e.g., transient stability, dynamic performance) are used for the functional specification of a FACTS device, which refers to the definition of equipment requirements, typically performed by the buyer (typically the TSO) or a consultant [72]. IEEE 1031: 2011 [73] proposes an approach to prepare a specification for a transmission SVC using conventional thyristor technology, which can be partly used for STATCOM and other devices. The guide describes newer developments in SVC component equipment and, particularly, control systems and also the latest practices for SVC applications among other topics. Similarly, IEEE P1052/08 [74] aims to assist users in specifying the functional requirements for transmission STATCOMs, using forced commutated technology based on voltage source converter topologies. The guide covers specifications, applications, engineering studies, main component characteristics, system functions and features, factory testing, commissioning, and operations of the STATCOM systems. It addresses the following functions: Reactive power compensation, voltage regulation and control, transient and dynamic stability, and control and protection.

The manufacturing of the device, based on the specification, is followed by factory testing at the facilities of the manufacturer. This includes the testing of the valves as the most critical component. Standards for the testing of valves are IEC 61954:2011 [75] for the thyrisors of SVCs and IEC 62927:2017 [76] for voltage source converter valves of STATCOMs. More specifically, IEC 61954:2011 defines the type, production, and optional tests on thyristor valves used in thyristor controlled reactors, thyristor switched reactors, and thyristor switched capacitors, forming part of SVCs. Type tests aim to verify that the valve design meets the requirements specified (e.g., dielectric and operational tests), production tests aim to verify proper manufacturing (e.g., voltage withstand check), and optional tests are additional to the type and production tests (e.g., voltage transient test). IEC 62927:2017 applies to self-commutated valves for use in voltage source converters for STATCOMs. It includes type tests (e.g., dielectric, operational and electromagnetic interference tests) and production tests (e.g., voltage withstand check) for air insulated valves. Moreover, the manufacturer also tests all other components of the FACTS device (e.g., transformer, circuit breakers, etc.) according to their respective standards. Particular attention needs to be paid to the testing of the control system, which includes dynamic performance tests and protection system tests, among others. More information on the testing of the control system is provided Section 3.2.

When factory testing by the manufacturer is completed, field testing follows in order to verify the specified performance in real operating conditions. It should be noted that this is an important step as in many cases, FACTS are built to satisfy the needs of specific projects. According to IEEE 1303:2011 [77], a field testing program for SVCs should include the following: Equipment tests within the SVC system, tests of the various subsystems that comprise the SVC system, commissioning tests for the complete SVC system, and acceptance testing of the complete SVC system. Equipment, subsystem, and commissioning tests are usually performed by the supplier, while the acceptance tests are performed by the buyer or user. The standard provides general guidelines and criteria for the field testing of SVCs, before they are placed in-service. It identifies the main elements of a field testing program so that the user can formulate a specific plan that is most suited for his/her own SVC. Parts of the standard are useful for compensator systems using gate turn-off thyristor technology (STATCOM) or other semiconductor devices, such as insulated gate commutated transistors.

Apart from the aforementioned standards and guides, which focus on SVC and STATCOM, other relevant standards and guides have been published. IEEE 1676:2010 [78] defines control architectures for high-power electronics. It covers FACTS, high voltage direct current (HVDC) systems, distributed generation, and energy storage, among others, with a power range from hundreds of kW to thousands of MW, but with emphasis on 1 MW to hundreds of MW. IEEE 1534:2009 [79] provides recommended practices for specifying TCSC installations used in series with transmission lines. Ratings for TCSC thyristor valve assemblies, capacitors, and reactors as well as TCSC control characteristics, protective features, testing, commissioning, training, operation, etc. are addressed in this standard. IEEE P2745.1 [80] provides functional requirements for UPFCs, using modular multilevel converters (MMCs), including application conditions, system architecture, function requirements, performance requirements, primary equipment requirements, control and protection requirements, testing, etc. Concerning the testing of valves, IEEE 857:1996 [81] and IEC 60700-1:2015 [82] provide recommendations for the type testing of thyristor valves for HVDC power transmission systems. IEC 62501:2009 [83] deals with the testing of self-commutated converter valves, for use in voltage source converters for HVDC power transmission.

In the literature, a plethora of papers performing simulation studies of FACTS is available, as shown in Section 2. On the other hand, limited experiences on hardware testing are reported. Indicative papers are presented next. Concerning lab testing, [84] explains the difficulty of testing HV thyristor valves, due to the increasing capacity of FACTS devices. A synthetic test setup was applied, where the large current and the high voltage are generated by different power supplies. Moreover, test facilities that can perform operational tests on thyristor valves are reported (e.g., [85]). In [86], real scale validation tests in the laboratory of a large 40 MVAr voltage source converter for a SSSC were carried out. The device is formed by four 3-level 10 MVA inverters, and a series of tests was carried out, including dynamic performance and harmonics. In [87], the performance of prototype tests of a 26 MVA STATCOM and a 13 MVA back-to-back, comprising smaller units connected in parallel, is described. A scaled-down setup for testing series connected FACTS (e.g., SSSC, UPFC, TCSC) was proposed in [88].

Experiences of field testing of FACTS can be found in the literature, starting from more than 20 years ago [89]. Aspects of the planning and execution of the commissioning and testing of +300 MVAr (capacitive) to −100 MVAr (inductive) SVC are described in [90]. Challenges concerning the commissioning and testing of the SVC connected to a relatively weak grid are reported, while considerations on the impact of the tests on transmission and distribution system equipment, generating facilities, and customers are provided. Dynamic performance tests were performed, by varying the reference voltage of the SVC, due to the difficulty of controlling the grid voltage in the field. In [91], a comparative analysis between field tests during commissioning of a −50/+70 MVAr SVC and computer simulations was carried out. The tests included the application of steps in the reference voltage of the SVC and the switching off a capacitor bank among others. In [92], a 1 MVA FACTS device, entitled "power router", designed for power flow control was tested in the field, including dynamic tests. In [93], a large load disturbance test on an HV line with a TCSC was performed (by opening-reclosing of a circuit breaker) combined with a wide area measurement system (WAMS). The field tests and simulations showed that the current issue of a transmission bottleneck of hydroelectric power could be resolved. Additional experiences on the field testing of FACTS have been reported e.g. [94–96].

From the above review, it is clear that important progress in the development of appropriate setups and procedures for laboratory/factory and field testing of FACTS has been performed. However, the standards and guides cover only some types of FACTS devices, while grid services are not thoroughly addressed. Due to the large rating of FACTS devices, it remains a challenge to fully validate all the device functionalities, and especially grid services provision, in the laboratory. For example, inverters that are interfacing distributed generation are typically tested in the lab by a grid simulator that can simulate several network conditions (e.g., voltage dip, frequency rise, etc.). However, such devices are hard and expensive to build for high ratings. Moreover, conventional lab testing treats the FACTS device as an independent component, while neglecting interactions with other devices (e.g., distributed generation, other FACTS, etc.) and the overall power system. This is becoming increasingly important due to the need of FACTS to provide advanced grid services in the complex contemporary environment. On the other hand, field tests can validate the performance of FACTS in actual conditions; however, limitations are present, such as limited flexibility and repeatability, as well as the possibility of adversely influencing network equipment. Digital real-time simulation is a promising tool that can tackle some of the aforementioned limitations. Its use for the lab testing of FACTS will be discussed in the following section.

3.2. Hardware in the Loop Testing of FACTS

Real-time hardware in the loop (HIL) simulation is gaining significant attention as an advanced power system testing method [11,97–100]. It allows the connection of a physical device to a power system that is simulated in real-time in a digital real-time simulator (DRTS). Exhaustive testing can be achieved in realistic, flexible, controllable, and repeatable conditions that allow de-risking equipment. The two main categories of HIL simulation are shown in Figure 1. In CHIL simulation, a hardware controller is connected to a simulated system executed in the DRTS. In PHIL simulation, a physical power device (e.g., motor, inverter) is connected to a real-time simulated system. In PHIL simulation, a power interface consisting of a power amplifier and sensor is required in order to connect the hardware under test with the DRTS. The voltage of the common node between the simulation and hardware is amplified and applied on the hardware under test. The measured current of the hardware under test is fed back to the DRTS and is inserted in a controllable current source in the real-time simulation. Stability and accuracy issues arise during PHIL simulation due to the non-ideal power interface, which needs to be considered.

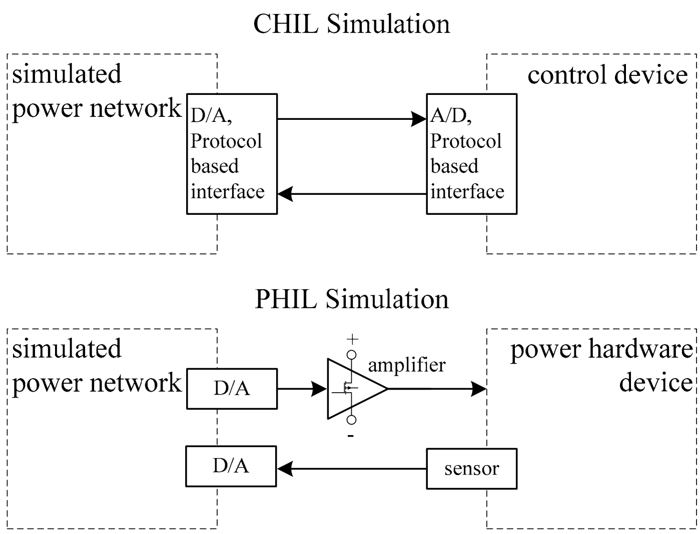

Figure 1. Basic topologies of controller hardware in the loop (CHIL) and power hardware in the loop (PHIL) testing [101].

Decades ago, analogue simulators or transient network analyzers (TNAs), composed of scaled-down physical models, were used for FACTS and HVDC controller testing, which were simplified and presented limited flexibility [102,103]. The emergence of digital real-time simulation allowed a realistic representation of the network and FACTS converter, allowing efficient testing of FACTS controllers and thus leading to fewer problems at the commissioning phase and field operation. This allowed the optimal tuning of the controller parameters, debugging, and repairing. Since then, several HVDC and FACTS manufacturers have been using digital-real-time simulation, and specifically CHIL simulation, for dynamic performance and factory acceptance tests [102,103]. It should be noted that the possibility of using digital real-time simulation for FACTS controllers testing is mentioned in guides/standards [73]. The FACTS actual control system is connected to a DRTS that simulates the power network and also the FACTS power circuit (valves, filters, circuit breakers, etc.) [104]. The actual control system receives measurements from the simulated VTs/CTs, sends firing pulses to the simulated converter, and trip commands to simulated breakers. More recently, voltage source converters, which are part of certain FACTS devices, have made use of MMCs, which can include hundreds of sub-modules, therefore requiring hundreds of input/output channels and posing additional challenges for testing and real-time simulation. Indicative examples of CHIL testing of FACTS are briefly presented below. In [105], an SVC controller intended to damp sub-synchronous oscillation was tested using CHIL simulation. In [106], comparisons between CHIL tests and field tests of an SVC were performed. The CHIL tests allowed the efficient tuning of the SVC controller, as well as effective fault tracing. A wide-area control of a STATCOM using a hybrid CHIL and software-in-the loop configuration was validated in [107]. The transient stability enhancement using a wide-area controlled SVC was investigated in a CHIL configuration [54]. Additional applications of CHIL simulation for the testing of FACTS and HVDC controllers are reported in [108].

A more recent trend is the CHIL testing of replicas of the control system of HVDC and FACTS devices by utilities, mainly TSOs. The complexity and increasing importance of HVDC and FACTS in contemporary power systems, the difficulty of maintaining simulation models (e.g., black box models provided by the manufacturer)—leading to differences between the modeled controllers and the actual controllers in the field—and the need to test control changes in a safe environment before field implementation are key drivers for this development [102,103,109]. Certain utilities operate a DRTS, and obtain from the HVDC or FACTS manufacturer a replica of the control/protection system, which is an exact copy of the actual control/protection system installed on site [110]. Moreover, the human–machine interface of the replica offers the same functionalities with the one installed in the field [102]. CHIL platforms with hardware replicas of the control system allow the investigation of system events and the optimum tuning of the control and protection systems [111]. Moreover, interactions between several HVDC systems and FACTS devices can be studied (e.g., provided by multiple vendors), maintenance can be supported, future software updates can be validated, and the training of engineers can be facilitated [112]. As a major source of modeling uncertainty is removed, such platforms are considered to be a reliable tool for longer term studies [109,111].

The application of CHIL simulation for FACTS testing is an industry practice, either with factory testing of the control system by the manufacturer, or in cases with the testing of a replica by the utility. On the other hand, the use of PHIL simulation for testing of FACTSs has been much less explored. PHIL simulation has been successfully used in the testing of PV inverters, wind generation systems, motors, drives, etc., and is also under consideration for standardized testing [97,99,113]. Concerning FACTSs, PHIL simulations were performed in [114]; however, a hardware PV inverter was used, while a D-STATCOM was simulated in the DRTS. PHIL simulation for studying the synchronization issues of voltage source converters, including STATCOMs, was performed in [115]. Contrary to CHIL simulation, where only the control system is tested, in PHIL simulation, the hardware power device is tested, which includes both the control system and power circuit. PHIL simulation can test the actual end-product that is going to be installed in the field, which is not possible with CHIL simulation. Physical valves, filters, circuit breakers, etc. are used, instead of a real-time simulation model. In this way, complex interactions of the actual device with other simulated power system components (e.g., distributed generation, FACTS from different vendors, etc.) within the power system can be examined. This is increasingly important for testing the grid services provided by FACTSs. Therefore, it is suggested that efficient PHIL tests could reduce the need for some of the field tests, or reveal hidden issues prior to field testing. On the other hand, the performance of PHIL testing of full-scale transmission FACTSs is difficult, as a power amplification unit is required with at least the same rating as the hardware under test. PHIL simulation capabilities in the 5 MVA [97] and 7 MVA [116] range have been reported, while the rating of AC grid simulators (that can be used as power amplifiers) is constantly increasing (e.g., 12 MVA or higher [117]). However, reaching the rating of large transmission FACTSs is not feasibly nowadays. One solution would be the PHIL testing of each converter separately, if the transmission FACTS is composed of different converters. Another approach would be the PHIL testing of a scaled-down model of the FACTS device. Initial results of this approach are presented in Section 3.3.2. Special investigations are necessary to ensure that the scaled-down model adequately represents the full-scale device. It should also be noted that the non-ideal power interface used in PHIL simulation can, in certain cases, render the experiment unstable or compromise the accuracy, therefore, attention should be paid to this issue [118,119].

Figure 2 summarizes the development and testing stages of FACTSs that were described in Section 3.1 (i.e., functional specification, factory testing, and field testing), including advanced approaches, such as the CHIL testing of the control system by the manufacturer and the CHIL testing of a replica controller by the owner, as presented in Section 3.2. Moreover, the option of performing the proposed PHIL tests (full scale or scaled-down) is included as a new step after the CHIL testing by the manufacturer.

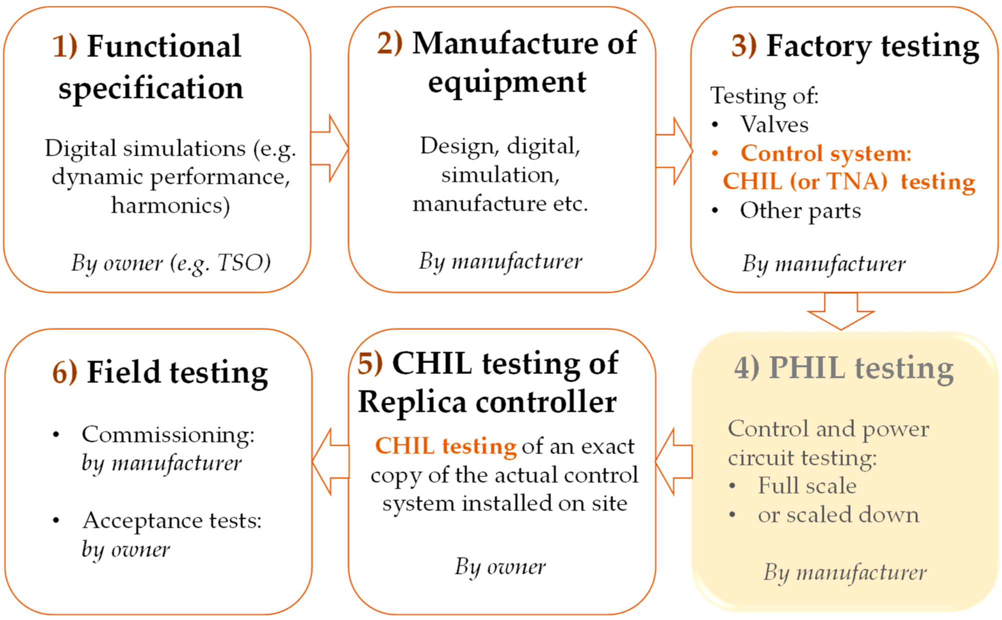

Figure 2. Process from the functional specification to field testing of flexible alternating current transmission systems (FACTS), including the proposed PHIL testing stage.

3.3. Testing Results

Laboratory testing of a transmission STATCOM providing voltage control was carried out. First, the controller of a 100 MVA STATCOM was tested in a CHIL configuration. Then, a physical scaled-down model of the STATCOM (1 kVA) was tested in a PHIL configuration.

3.3.1. Controller Hardware in the Loop Tests

The Electric Energy Systems laboratory of the National Technical University of Athens (NTUA) operates a DRTS by RTDS Technologies Inc. (including 2 GPC processors), which allows the simulation of switching phenomena in small time-steps in the range of 1 to 4 µs. A transmission system was designed in the DRTS, as shown in Figure 3. A 3-level 3-phase DC/AC voltage source converter of a 100 MVA STATCOM, including DC bus, filters, and transformer, was simulated in the DRTS, while its control algorithm was executed on a hardware controller. Voltage and current measurements from the real-time simulation were fed to the hardware controller, which returned the modulation signal to the simulated DC/AC converter. It should be noted that the conversion of the modulation signal to PWM pulses was performed in the real-time simulation, in order to match the operation of the actual voltage source converter used for PHIL tests in Section 3.3.2. The control algorithm of the STATCOM aims to provide dynamic and steady state voltage control by comparing the locally measured grid voltage (bus 2) with a reference voltage and providing or absorbing reactive power. The model of the STATCOM was based on [120] using the following values for the proportional integral (PI) controller of the outer AC voltage control loop: K_i = 1000, K_p = 10.

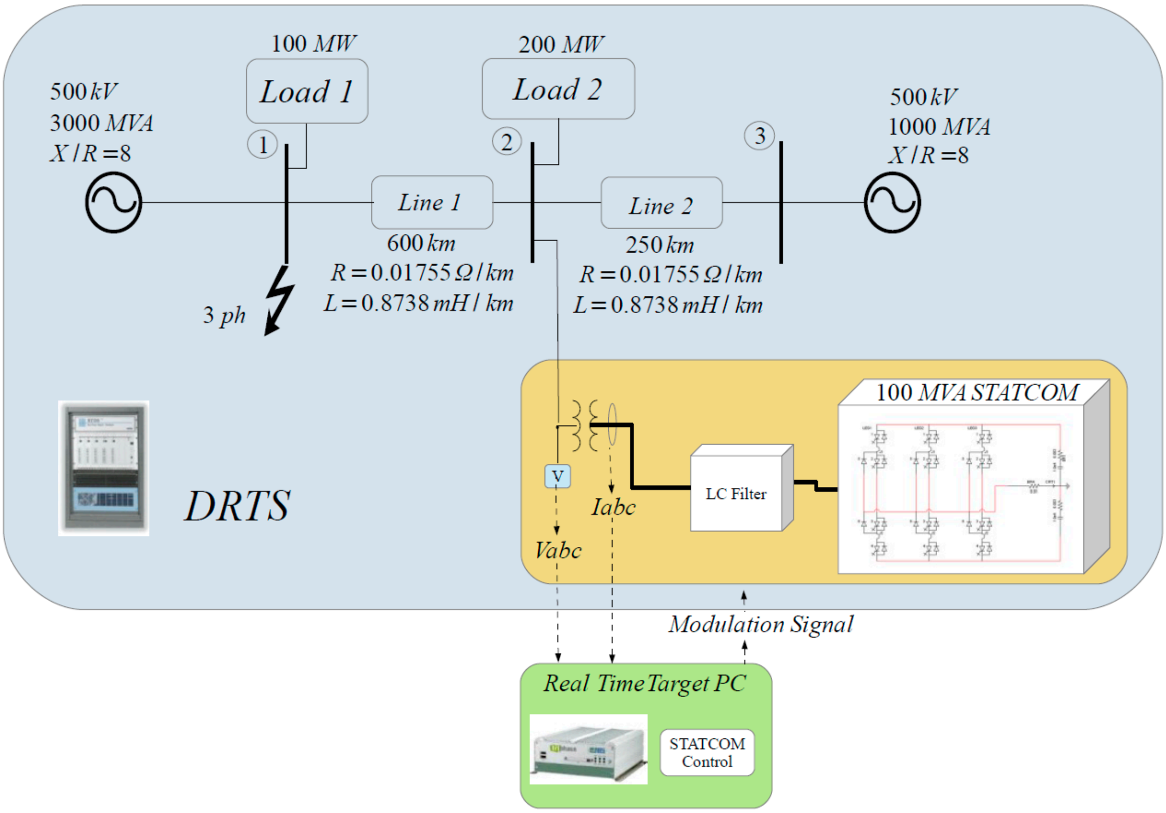

Figure 3. CHIL test setup for the STATCOM controller.

A 3-phase symmetrical fault occurred at bus 1, which was cleared after 13 cycles (fault impedance equals to 100 Ohm resistive). CHIL tests were performed and the results are described below. The 3-phase current at the faulted bus is shown in Figure 4. Figure 5 shows the increase of the current of the STATCOM during the fault in order to provide voltage control, where only one phase is shown in order to facilitate comparison with the PHIL tests in Section 3.3.2 (in the PHIL test, a hardware single-phase voltage source converter was used).

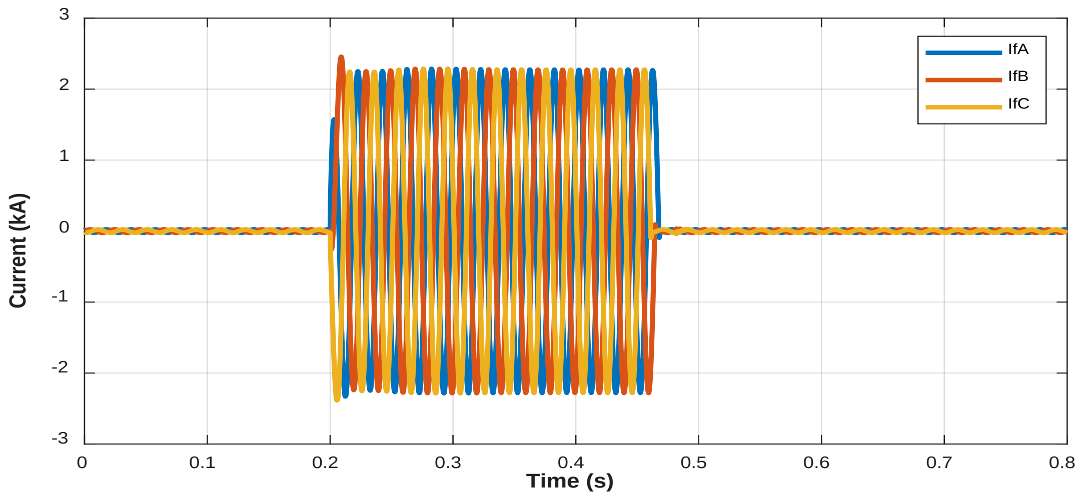

Figure 4. Current at the faulted bus (CHIL test).

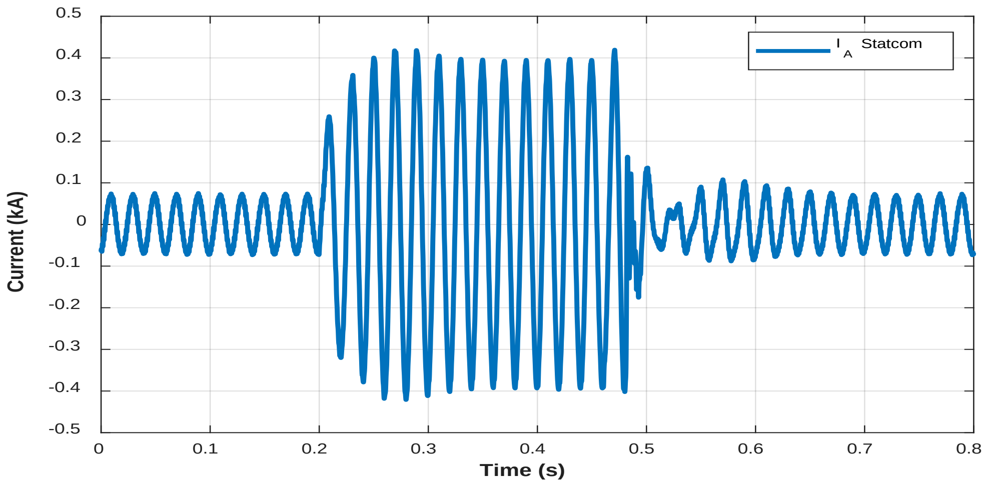

Figure 5. Current contribution of the STATCOM during the fault (CHIL test).

Figures 6 and 7 show the resulting voltages of bus 2 and bus 3 during the short circuit, with and without the STATCOM. The CHIL results show that the mitigation of voltage deviations in dynamic and steady state conditions by the STATCOM is clear. The voltage improvement is greater at bus 2, as this is the point of connection of the STATCOM. The dynamic behavior of the STATCOM influences the grid voltages shortly after fault clearance, however, without adverse effects. Figure 8 shows the reactive power provision by the STATCOM in steady state and dynamic conditions in order to mitigate the voltage sag. Naturally, the reactive power provision is reduced after fault clearance. Active power is absorbed by the STACOM in order to maintain a constant DC bus voltage and it is shown that the active power is increased when the reactive power provision rises.

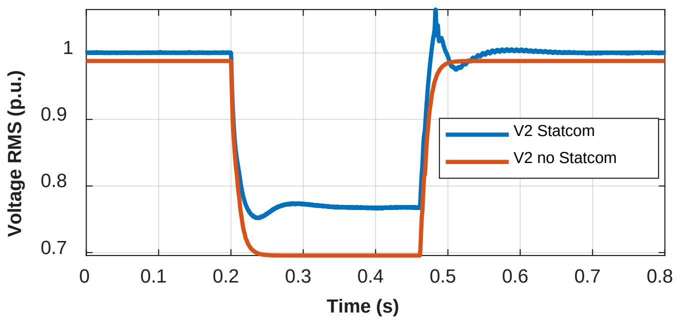

Figure 6. Voltage of bus 2 during the short circuit, with and without the STATCOM (CHIL test).

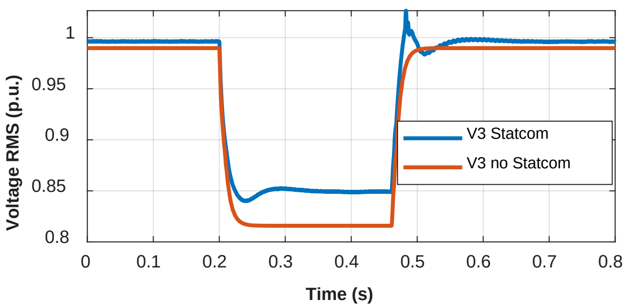

Figure 7. Voltage of bus 3 during the short circuit with and without the STATCOM (CHIL test).

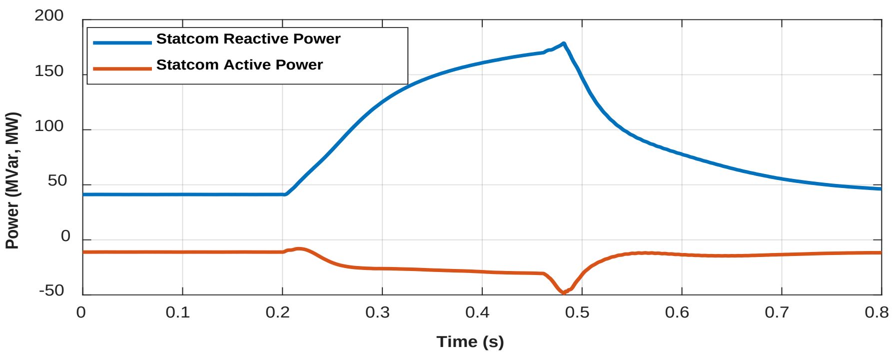

Figure 8. Active and reactive power of the STATCOM during the short circuit (CHIL test).

3.3.2. Power Hardware in the Loop Tests

After the successful completion of the CHIL tests, the hardware controller was connected to a physical voltage source converter in order to verify the performance of the device in a PHIL setup (Figure 9). As the rating of the transmission STATCOM is high (i.e., 100 MVA, 3-phase), it was not possible to perform full-scale tests. A small-scale 2-level voltage source converter (i.e., 1 kVA, 1 phase) was used in order to verify the performance of the full-scale device. The converter was connected to the real-time simulated system using a suitable power interface consisting of a fast and accurate linear power amplifier and a current sensor. The current sensor used was a current probe (Tektronix A622, scaling 100 mV/A), with a small time-delay and compatible output voltage range with the analogue input card of the RTDS. The high voltage of the transmission system was scaled down in the DRTS, in order to reach the low voltage level of the physical converter, while the actual current provided by the converter was scaled up in order to virtually increase the rating of the device, following a similar approach to [119]. Specifically, the voltage from the simulation was multiplied by the ratio of the nominal voltage of the hardware under test (V_{HW_n}) and the full scale device (V_{SW_n}) according to Equation (1). Similarly, the measured current of the hardware was multiplied by the ratio of the nominal current of the full scale device (I_{SW_n}) and the nominal current of the hardware under test

(I_{HW_n}) according to Equation (2). It should be noted that the single phase hardware under test (1 kVA) was seen as a 3-phase in the simulation (i.e., 3 kVA) by applying a similar approach to [114]:

$$a = \frac{V_{HW_n}}{V_{SW_n}} = \frac{400\ V}{500\ kV} = 0.0008, \tag{1}$$

$$b = \frac{I_{SWn}}{I_{HWn}} = \frac{100\ MVA/\left(\sqrt{3}{\cdot}500\ kV\right)}{3\ kVA/\left(\sqrt{3}{\cdot}400\ V\right)} = 26.67. \tag{2}$$

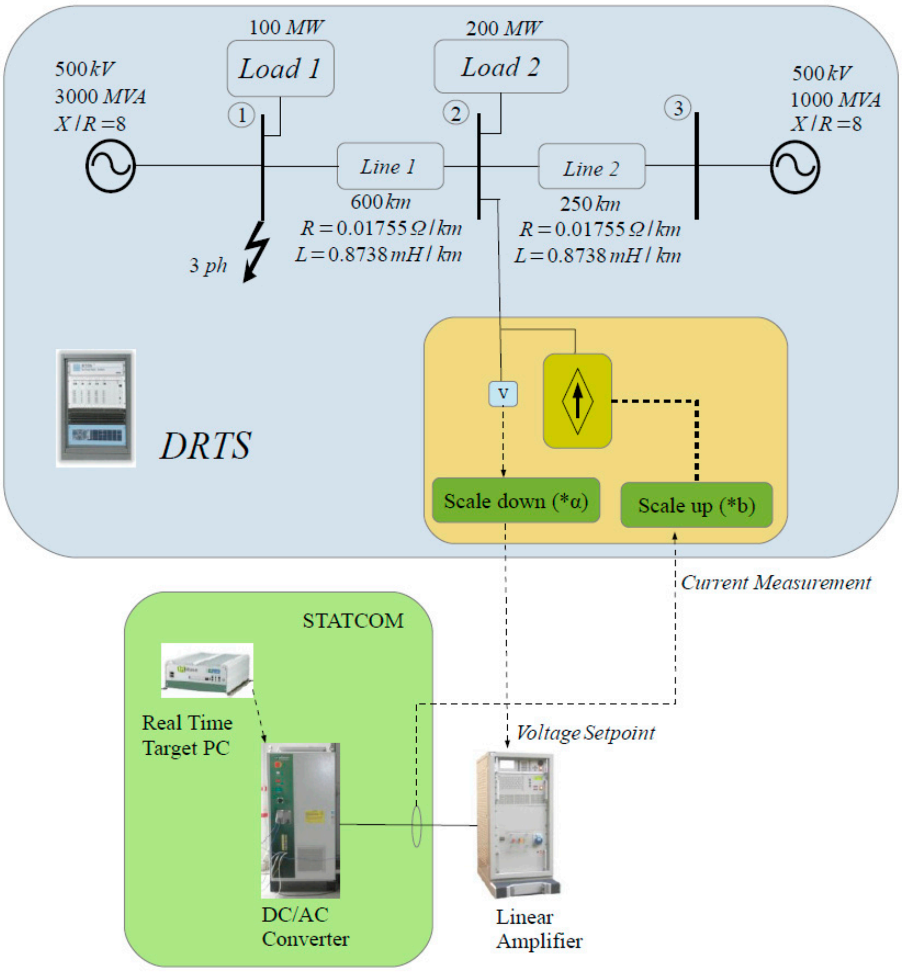

Figure 9. PHIL test setup of the scaled-down STATCOM.

The CHIL tests of Section 3.3.1 were repeated in a PHIL configuration. Figure 10 shows the current at the faulted bus during the short circuit in the PHIL test, which is very similar to the CHIL test. Figure 11 shows the current of the actual voltage source converter before, during, and after the fault is cleared, measured by the aforementioned current probe and obtained from the software of the DRTS. This current was scaled up in the DRTS and was injected in the simulated power system via a controllable current source.

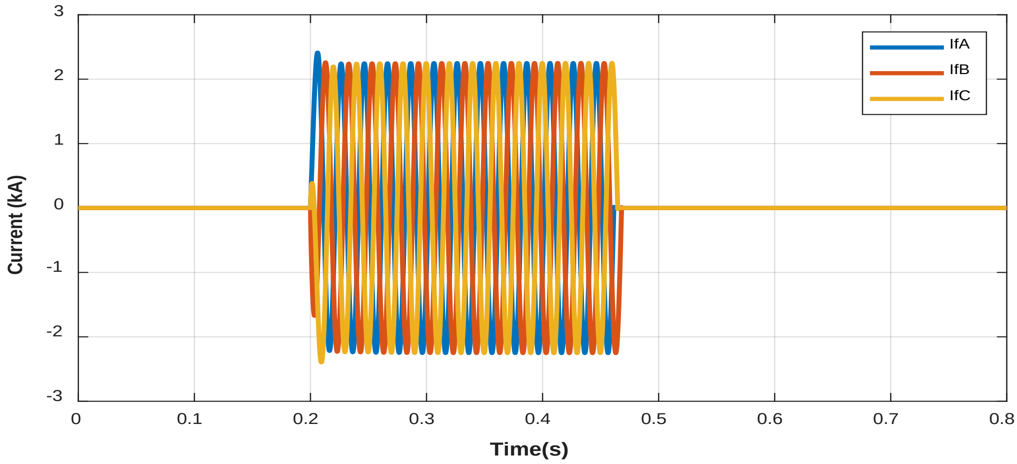

Figure 10. Current at the faulted bus (PHIL test).

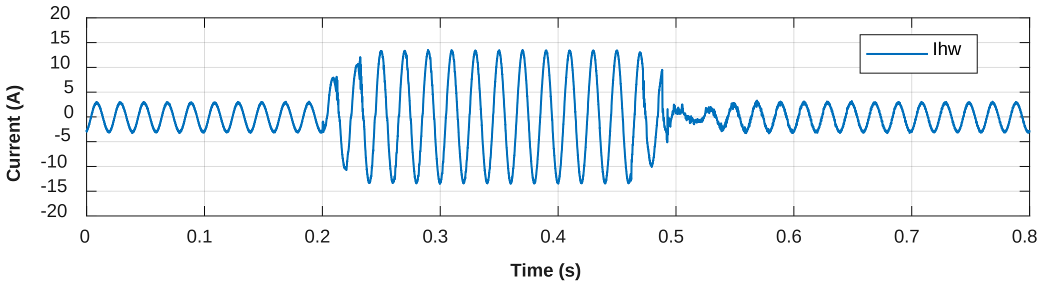

Figure 11. Current of the hardware voltage source converter during the short circuit (PHIL test).

The voltages of bus 2 and bus 3 during the short circuit, with and without the STATCOM, are shown in Figures 12 and 13. It is clear that the STATCOM manages to mitigate the voltage sag at both buses, similarly to the CHIL tests. The occurring voltages in the steady state and dynamic conditions are similar to the CHIL test (Figures 6 and 7), however, there is a smaller voltage improvement under dynamic conditions (around 2 p.u less at bus 2). The smaller voltage improvement is due to less reactive power provided by the converter in the PHIL test (Figure 14), compared to the CHIL test (Figure 8). The hardware voltage source converter exhibits additional constraints on its maximum admissible current, based on its actual switching devices and power circuit. In the CHIL test, where the voltage source converter was purely simulated, this was not considered accurately. Therefore, in the PHIL test, the less reactive current allowed to mitigate the voltage sag resulted in a smaller improvement of the voltage compared to the CHIL test.

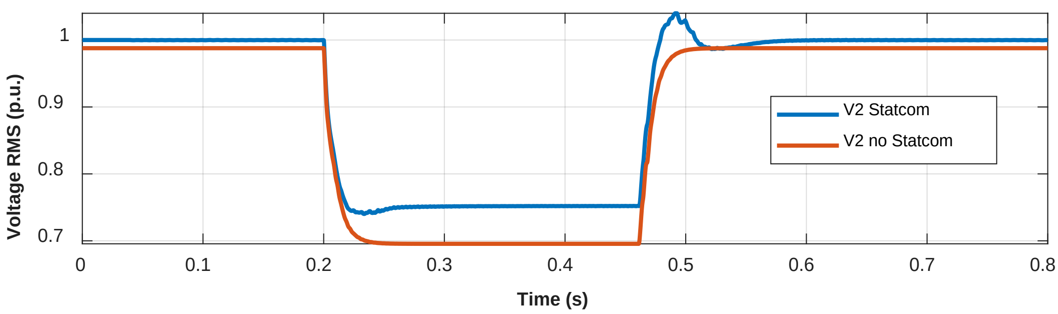

Figure 12. Voltage of bus 2 during the short circuit with and without the STATCOM (PHIL test).

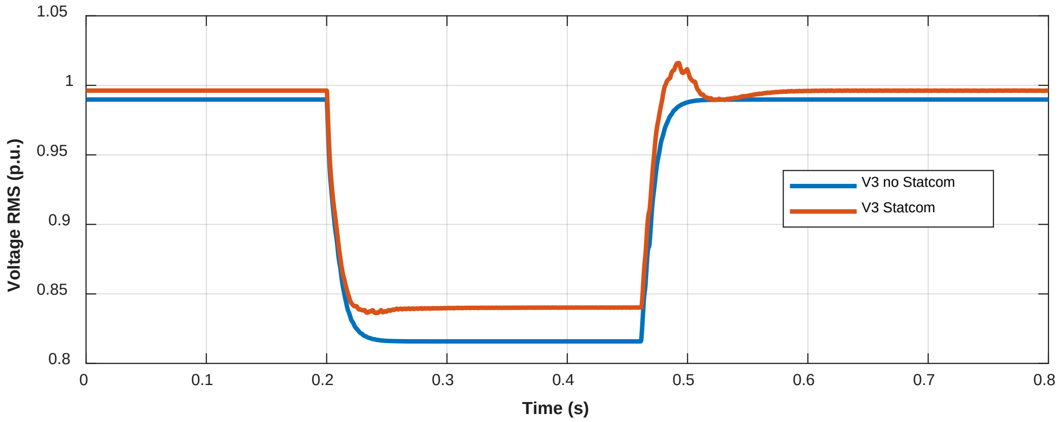

Figure 13. Voltage of bus 3 during the short circuit with and without the STATCOM (PHIL test).

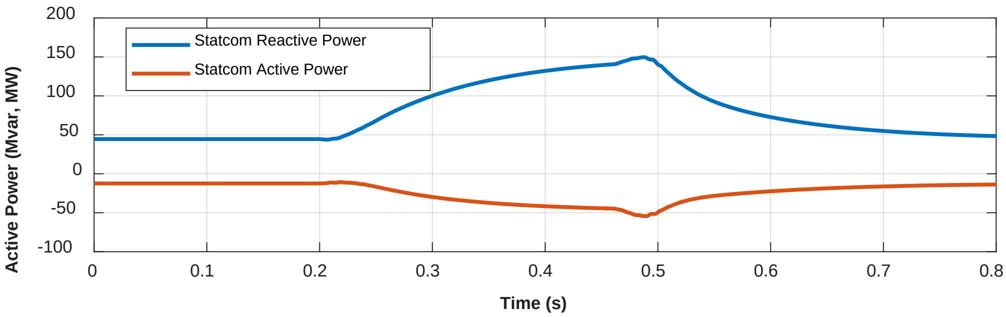

Figure 14. Active and reactive power of the STATCOM during the short circuit (PHIL test).

Finally, the aforementioned CHIL and PHIL test results were compared with pure digital simulations. In the pure digital simulations, the power system, the control algorithm of the STATCOM as well as its power circuit were simulated in real-time using the software of the RTDS (RSCAD). Figure 15 shows that the pure simulation and CHIL test result in very similar voltages at bus 2 with the operation of the STATCOM. Small deviations are shown shortly after fault clearance. On the other hand, the PHIL test results in a smaller voltage improvement, which is due to the less reactive power provided, as already explained. Similarly, Figure 16 shows the similar behavior of the current contribution of the STATCOM during the pure simulation and CHIL test. It is clear that the reactive current of the hardware voltage source converter (scaled up in the simulation) during the fault was smaller in the PHIL test. Moreover, the non-ideal behavior of the hardware device at fault clearance (t = 0.48 − 0.52 s) was shown in the PHIL tests.

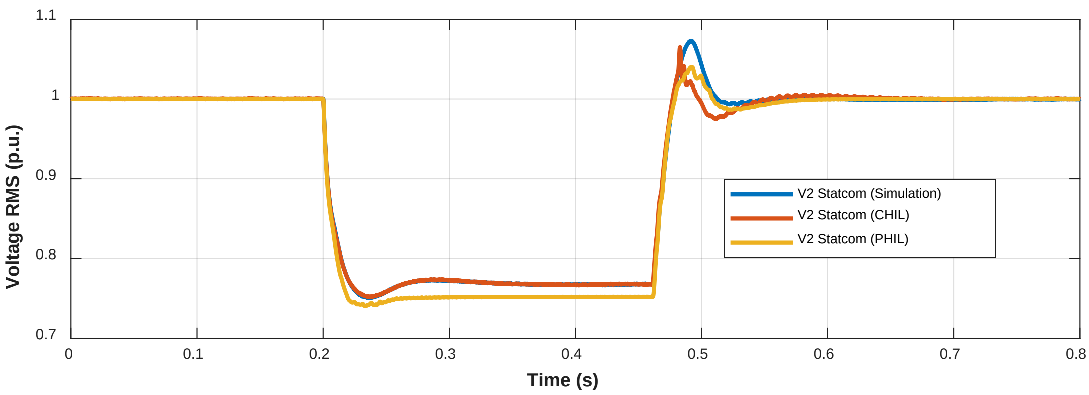

Figure 15. Voltage of bus 2: comparison of pure digital simulation, CHIL test, and PHIL test.

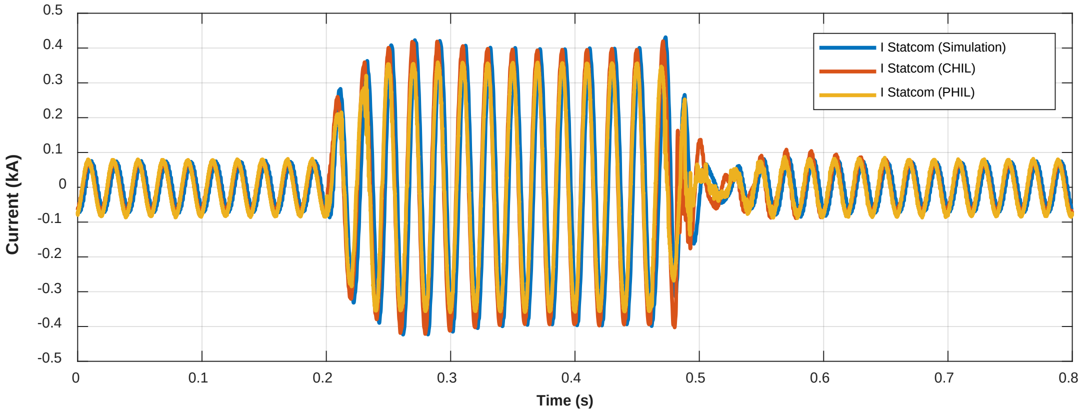

Figure 16. Current contribution of the STATCOM: comparison of pure digital simulation, CHIL test, and PHIL test.

4. Discussion

This paper addressed the provision of grid services by FACTS and their testing considering complex contemporary and future power systems. Several research articles, but also review papers summarize the research findings on FACTS devices and their grid services in a comprehensive manner. However, there is no review paper focusing on the different grid services provided by various FACTS devices. This paper aimed to cover this gap by providing a comprehensive literature review on the different grid services provided by various FACTS devices. Moreover, limited experiences on hardware testing of FACTS have been reported that mostly present specific test cases, for a specific FACTS device at a specific location, while a review on the testing of FACTS is missing. This paper addressed this gap by providing a literature review of standards, guides, and scientific papers on the testing of FACTS and presented an overview of all the different testing stages, including conventional testing and emerging industry practices. Moreover, PHIL simulation for the testing of FACTS was suggested as an efficient testing method prior to field testing.

Conventional laboratory testing of FACTS treats the device as an independent component, while neglecting interactions with other devices and the power system. On the other hand, field testing has limited flexibility and repeatability, as well as the possibility of adversely influencing network equipment. The advantages of CHIL testing of FACTS controllers to overcome the above limitations were explained, which is already a practice of manufacturers. It was explained that recently, owners of FACTS, like TSOs, obtain a replica of the control and protection system by the manufacturer and perform CHIL tests, in order to reduce modeling uncertainty in the long-term, provide optimal tuning of parameters, and facilitate maintenance and future updates. As CHIL simulation allows testing of only the control system and not the actual end-product, the use of PHIL simulation is suggested as a further step. PHIL simulation can test both the control system and power circuit (i.e., valves, filters, transformer, circuit breakers, etc.), reducing the uncertainty towards field testing. Full-scale PHIL testing of D-STATCOMs and relatively small transmission STATCOMs, if they consist of several converters that are tested separately, is feasible. However, the full-scale PHIL testing of large transmission STATCOMs is not feasible nowadays. Therefore, the execution of scaled-down PHIL tests was discussed. Indicative CHIL and scaled-down PHIL tests of a transmission STATCOM providing voltage control were performed. The CHIL and PHIL results presented a similar behavior at steady state and dynamic conditions. The differences were due to the current limitations of the hardware device that were not considered accurately in the CHIL tests. The CHIL and PHIL results were also compared with pure digital simulations.

In future work, PHIL testing of a full-scale D-STATCOM could be performed in a suitable laboratory in order to compare with conventional factory tests and CHIL tests. In this way, the specific benefits of performing PHIL simulation prior to field testing could be highlighted. Moreover, the effectiveness of scaled-down PHIL tests and their accurate representation of full-scale tests could be further investigated.

Author Contributions: P.K. and P.G. developed the main idea and structure of the paper. D.T.L. and V.K. performed the hardware in the loop tests. P.K. and P.G. wrote the paper. N.H. supervised the work and reviewed the paper.

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