Lab-Scale TCR-Based SVC System for Educational and DG Applications

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***Abstract*—Motivated by the development of power semiconductor technologies, flexible ac transmission systems (FACTS) devices and their penetration in the field of electrical power systems, an educational challenge in complementing theoretical knowledge with practical experience is recognized. In this paper, the design and implementation of a lab-scale hardware and software setup is presented. Three small-scale devices, including a static VAr compensator (SVC) unit, a transmission line model, and a substation, are developed. The SVC unit is validated by obtaining its operating characteristic. The lab setup is presented as a platform to carry out different experiments related to the SVC operation. Safety considerations in the design are discussed. Steady-state and dynamic analysis are presented showing the consistency between theory and practice. The potential use of small SVC units on low-voltage distributed generation schemes is discussed.**

***Index Terms*—Distributed generation, education, flexible ac transmission systems (FACTS) devices, laboratory, power electronics, static VAr compensator (SVC).**

I. INTRODUCTION

THE great advantages of modern power electronic devices open up new application possibilities in different fields, like electrical power systems (EPS) and motor drives for electrical vehicles.

In the case of EPS, the development of flexible ac transmission systems (FACTS) devices is growing fast with the introduction of modern control techniques and new and improved power semiconductor devices [1]. Due to the lower costs of these devices, the penetration of these types of technologies in interconnected power systems has increased. This is also the case in Latin-American countries with high growth rates, where FACTS devices contribute to the dynamic performance of the system. In these countries, which mostly have longitudinal network structures, EPS are prone to experience reactive power control problems and voltage collapse [2]. This process is also reinforced by new requirements in power quality standards defined in grid codes [3], [4].

The increasing penetration of distributed generation (DG) in a global scale presents new challenges for power system operation and planning. In this field, power electronics can play a key role [4], [5].

Usually, these technologies are studied in a theoretical approach at university level, supported by computer simulation. However, the educational laboratory normally does not include prototype equipment where students can examine important phenomena as well as the interaction between these devices and an electrical system. This configures a new educational challenge in maintaining equilibrium between practical and theoretical knowledge related to technologies that will be used in future EPS.

In this context, based on the work presented by the authors in [6], this paper covers the design and implementation of hardware and software in a university laboratory to support and complement theoretical knowledge, by the construction of a basic FACTS device setup. For this purpose, three small-scale devices have been chosen: a three-phase thyristor-based static VAr compensator (SVC); a substation with electronic protection relay; and a transmission line modeled with concentrated parameters. Those devices configure a prototype setup currently located at the Energy Laboratory of the Electrical Engineering Department of the University of Chile. An MSC-TCR was designed and developed. Test results show the effectiveness of the design.

The paper is organized as follows. In Section II, a brief description of SVC technologies is presented and the DG application is discussed. Section III presents the design criteria for the proposed lab-scale SVC and substation. The implementation and validation of the SVC is shown in Section IV where the operational diagram of the device is obtained. In Section V, experimental results for steady-state and dynamic analysis are presented and discussed. The results of a survey for laboratory experience with the evaluation of students are presented. Finally, Section VI shows the main conclusions of the work and proposed future developments.

II. SVC TECHNOLOGIES

Historically, EPS operators have used different control options to ensure a reliable and economical operation. These conventional options include automatic generation control (AGC), excitation control by an automatic voltage regulator (AVR), transformer tap changers, and phase-shifting transformers, among others.

Some of the conventional control mechanisms are usually slow, while some are more oriented for other purposes, limiting their usage between multiple tasks. On the other hand, the development of power semiconductors, especially the thyristor, has

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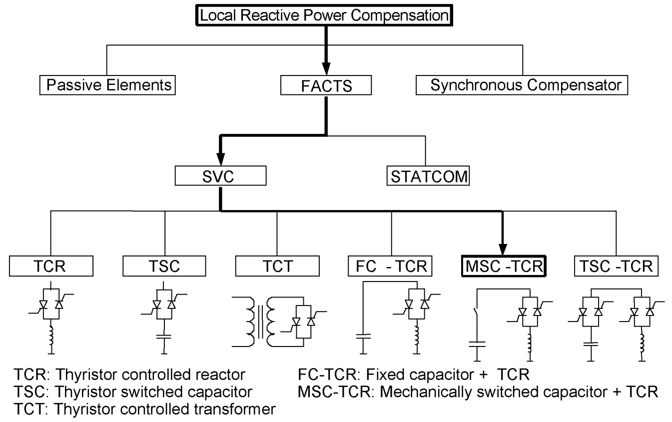

Fig. 1. Local reactive power compensation alternatives.

led to the development of FACTS devices, allowing an efficient use of the EPS capacity [7].

The SVC is one of the first FACTS devices. This local compensation system uses shunt connected elements that absorb or inject reactive power, like controlled reactors and switched capacitors. The SVC aims to maintain a set point of one or more elements of the power equation. Typically, the SVC modifies the voltage at the supply point. The SVC is characterized by fast response time, low power losses, high reliability, and low maintenance.

Nowadays, control capability is made possible by the use of thyristors, which are operated as power switches, among other advanced power semiconductor devices [8]. The thyristor provides current control by continuously changing the firing angle in the case of a reactor, or discretely changing the on-state periods in the case of a capacitor.

The SVC family is summarized in Fig. 1.

Apart from SVC, there are other local compensation topologies both in shunt and series configuration. Thyristor-controlled series capacitor (TCSC) and static synchronous series compensator (SSSC) are examples of the series compensation that optimizes power flow. Also a voltage source converter (VSC) configuration using gate-turn-off thyristors (GTO) or isolated gate bipolar transistors (IGBT) is an alternative to efficient shunt compensation. This FACTS device is named STATCOM, and reaches better performance than the SVC, acting as a synchronous compensator with no inertia, drawing from or injecting reactive power into the network [7]. The unified power-flow controller (UPFC) is the most complete compensator that joins the capabilities of an SSSC and a STATCOM, and offers full control over the parameters of the power equation.

Previous experiences on educational applications with the described devices are presented in [9]–[11].

Reference [9] presents a schematic of a reconfigurable VSC-based FACTS laboratory including data acquisition, processing, and signal generation. This laboratory is oriented to complement software simulation for university research and flexible development of new control methods. Experimental results clearly prove the correspondence between theory and practice.

In [10], experimental results on a lab-scale single-phase TCSC are presented. The work is focused on improvement in teaching and training about FACTS devices. The full functionality of the device and its performance is presented through using steady-state and harmonic content analysis in different operational conditions.

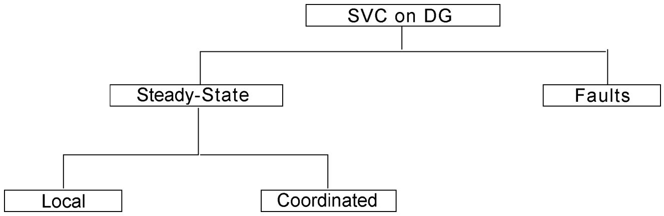

Fig. 2. SVC application on DG networks.

The concept of the blue-box module is presented in [11]. These are devices that are pre-built but not hidden from the students. The blue-box concept is applied not only in energy alternating/direct current conversion but also in other electrical experiments. All the components create a valuable teaching aid on power electronics and electric machines.

In the general area of power and energy systems, there also exist recent successful experiences of educational laboratories. Drexel University [12], Illinois Institute of Technology [13], and University of Puerto Rico-Mayaguez [14], among others, share the objective of improving the undergraduate and graduate curricula, by means of a variety of activities on power systems design and operation, electric machines and drives, and power electronics.

Distributed Generation (DG): On practical networks, at low voltage levels, one or more SVC units of power rate similar to a lab-scale unit can be used. The SVC units could support power quality requirements by voltage regulation needs at low voltage level distribution networks. This is also valid for distribution networks with integration of DG. The impact of an SVC unit can be approached in two different states: steady-state and fault conditions (see Fig. 2).

A small distribution network could use SVC units interacting on the spread points of connection. Lack of local VAr compensation can be a limiting factor of some DG technologies, such as the induction machine directly coupled to the grid and the permanent magnet synchronous machine. In this case, reactive power compensation and/or voltage regulation could be carried out using a small-scale SVC unit coupled to the DG point of connection.

On the other hand, when the compensation is not local, the SVC unit can work as a coordinated distributed resource that receives reactive power setpoints depending on the power quality requirements of the network feeder. The SVC units can be located on strategically predefined points of the distribution network to mitigate several unbalance problems, minimize negative-sequence currents, and do power factor correction [15].

Furthermore, despite the limited reactive capacity of the unit, owing to the passive elements used in its design, the use of one or more SVC units during a fault may help meet grid codes, as in the case of German transmission system, including fault ride through and voltage maintaining [4].

This aspect is especially important because of the high penetration of renewable energies, with wind generation as the most mature and widely applied technology. An SVC unit with similar characteristics can improve steady-state and dynamic behavior of wind generators [16].

III. Design Criteria for a Lab-Scale SVC

The design of a lab-scale SVC is conditioned by factors ranging from economical aspects to very detailed electrical specifications and pedagogical approaches. The design criteria definition has a tremendous impact in the way the SVC unit performs on an educational environment. In this section, the main design criteria used in this project are presented and discussed.

A. SVC Topology Selection

A first selection criteria looks for a good trade-off among theoretical description, robustness of design, and implementation costs.

The theoretical descriptions of TCR and TSC show that these devices are not as flexible as FC-TCR, MSC-TCR, and TSC-TCR. The limiting factor for each one is the excluding capacitive or inductive current. The cases of TSC and TSC-TCR have additional complexity related to the firing of capacitors. The topology of TCT involves a special design of transformer, which increases the cost.

Another selection criterion is related to the existence of SVC units installed in the Chilean Interconnected Systems. Offering students a discussion on the technologies that will be part of the future professional practice is crucial. There are MSC-TCR units installed in several substations of the longitudinal system structure, allowing power factor correction and voltage support.

By these criteria, in the case of Chile, the most convenient SVC topology is the MSC-TCR.

B. Pedagogical Approach

Instead of the typical commercial or industrial equipment, which is not student-oriented, the system should be planned with online measurements, transparency of the unit parts, easy access to different devices of the system, and the possibility of modification and replacement of any module.

All lab setup components must be designed to allow per-unit comparison and dimensional analysis between a realistic, practical installation and the lab setup.

These characteristics allow the students to make consistency check from theory to practice with an easy, systemic approach. Additionally, real contact with the whole process, which is not possible on industrial installations, is achieved. Consequently, the following learning objectives, complementary to those covered in theoretical lectures, can be achieved.

- General topology: instead of a virtual or software-simulated arrangement of different modules, they should be seen in an experimental setup as a scaled version of the expected setup in a real substation for a specific SVC topology. The arrangement could also be changed to observe different behaviors.
- Start sequence of the system: the start-up sequence should be studied, including the transient effects on the network.

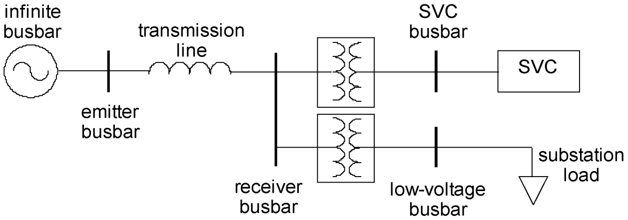

Fig. 3. Single-line diagram of the lab setup.

- Steady-state operation: the setup should allow observation of multiple steady-state conditions (i.e., voltage regulation) that can be easily compared to theoretical analysis.
- Dynamic conditions: with the help of the developed measurement system, the dynamic behavior of the SVC should be analyzed for several scenarios: suddenly load changes, short-circuits, and unbalances. All the results could be compared with the associated theoretical analysis, verifying similitude and explaining differences.
- Harmonic distortion: as with other power electronic devices, the presence of the SVC in a network impacts the quality of the voltage and current waves. The harmonic distortion could be measured and studied with suitable lab instruments (spectrum analyzer/power system analyzer).
- Creativity: the lab setup encourages the creativity of the students by proposing new operating conditions.

C. Global Layout Design

The minimal equipment needed to represent the behavior of a real EPS is composed of the following:

- Infinite busbar: point of connection with a short-circuit level bigger than levels involved in application.
- Transmission line: 4-pole element that allows different configurations of its parameters (R, L, and C).
- Substation with step-down transformer: asubstation is necessary for short-circuit tests, which can be made on the safe, low-voltage side.
- SVC: the device being tested, and described below.
- Measurement equipment and protection system: A group of measurement devices is needed to monitor the significant variables.

This layout is shown in the single-line diagram of Fig. 3.

D. Needed SVC Layout

The hardware layout used in the lab-scale SVC should be similar to those presented in the literature (see Fig. 4). This includes the following modules.

- *Voltage measurement*: it is coupled by a potential transformer, and has an RMS integration circuit (or algorithm in case of digital calculation).
- *Voltage regulator*: it sends control signals to follow a voltage reference at the point of measurement.
- *Distribution unit*: it calculates firing angle α and the number of capacitors to get the desired susceptance B.
- *Trigger synchronization*: it fires thyristors maintaining synchronization with the network.
- *TCR modules and capacitor modules*: the former is built around a reactor using silicon controlled rectifiers (SCR)

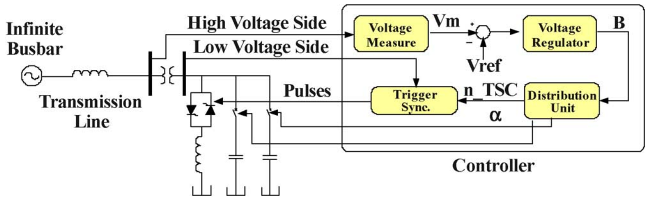

Fig. 4. Block diagram of the SVC unit.

to control the circulating current. The latter is built around capacitors controlled by circuit breakers (this conforms a discrete-step capacitor bank).

Per-unit system should be selected according to the local network.

- Voltage level: instead of working at medium-voltage levels (tens of kilo-volts) as many FACTS devices do, the lab-scale SVC works on a low-voltage level network (380 [V] phase to phase in the case of Chile).
- Power level: this level can be arbitrarily defined, and consecutively gives the base for the currents that circulate in the lab-scale model.

There are also special considerations for measurement transformer (PT and CT).

E. Safety Considerations

A well-designed setup has to avoid the exposure of the students to high voltage and deal with other safety concerns such as heat sources, quality of materials, weight, mobility, etc. Consequently, the proposed design incorporates the following considerations.

- The laboratory infrastructure where the set-up will operate should fulfill the basic safety requirements (isolation, grounding, emergency equipment, and procedures).
- Exposure of students to high voltage must be avoided. The SVC unit and the substation should be fully protected using transparent isolating materials, like acrylic boxes.
- Connectors to be used should comply with international standards, and do not affect accessibility to the system (contact with energized points is avoided).
- Installation of measurement instruments should be supervised by a laboratory assistant.
- Power and control signals should be isolated.

IV. IMPLEMENTATION AND VALIDATION OF DESIGN

A. General Description

To implement the system, three custom-made devices are created.

- Substation: The substation includes a bank of three single-phase 220/40 [V] transformers that allows different Yy and Yd connections, and is equipped with switches and logic circuits to represent real circuit breakers. The substation is complemented with an industrial electronic relay, configured to protect the substation under fault conditions. The equivalent series reactance of each transformer is 4.64 [Ω].
- Transmission line: A concentrated parameters π-model transmission line lets the student configure the component values for different length representations. The transmission line has a current capacity of 1 [A] that matches the reactive power capacity. The selected parameters for the model are $\mathrm{L_{series}} = 32$ [mH], $\mathrm{R_{series}} = 2.5$ [Ω], and $\mathrm{C_{shunt}} = 3$ [μF].
- SVC Unit: all blocks are built with mixed analog and digital components, including logic gates, microcontrollers, and operational amplifiers, among others. This gives a flexible unit that is also built in a modular way. To have a representative model of a real system and to obtain similar per-unit parameters, the reactive power capacity of the SVC is approximately 0.62 [pu] of injection and 0.55 [pu] of absorption.

The modules that build up the SVC unit are the following.

- Step-down transformer: as part of the SVC unit, a 380/110 [V] Yd1 transformer is used to trap the 3rd harmonic frequency component and its multiples. Sometimes, the SVC operates with constant overvoltage for a long time. It is not desirable for the transformer to operate on such saturated conditions. Thus, the transformer is designed for operating voltages up to 1.1 [pu]. The equivalent series reactance of the transformer is 6.14 [Ω].
- Inductors: as part of the SVC unit, iron core inductors are designed not to saturate in the voltage operation range, so their behavior is similar to real air core inductors. The inductance of each reactor is 0.18 [H]. The reactors are delta-connected.
- Delta-connected capacitor banks: each capacitor bank is designed to match half of the reactive power absorption limit of the inductors. Each bank has capacitors of 31.5 [μF]. There are two capacitor banks in the unit.
- Thyristors: the power semiconductor components of the TCR are oversized in current capacity (25 [A]). The fire of the thyristors is based on optocouplers.
- Control and data collection modules: composed by few microcontrollers with local measurements, the control and data collection modules allow different control strategies to be programmed and tested in-place. It is also possible to do an external control of the unit supported by a computer, using a serial port for sending the data collected from the sensors and receiving actuator signals. As part of the control module, an LCD screen is installed to show the most important variables.
- Rule-based control algorithm: the developed control and monitoring algorithms are presented in Fig. 5.

Finally, it is important to point out that the design allows the use of other voltage levels performing the following minor changes: measure transformers, inductors and capacitors ratings, and controller/monitoring source code adjustment.

B. Control Algorithm

The control algorithm is based on a synchronization stage followed by the activation or disconnection of the capacitor banks using a hysteresis scheme. The firing angle is sent to the trigger

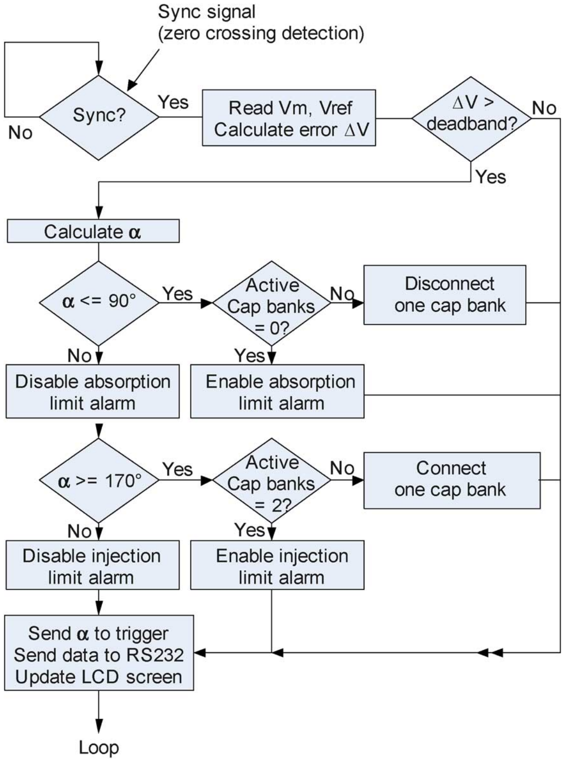

Fig. 5. SVC control loop (distribution unit).

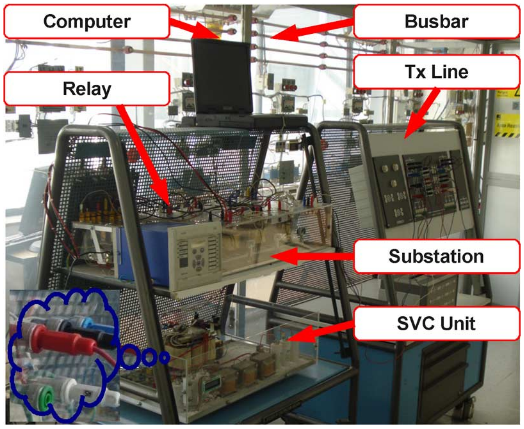

Fig. 6. Physical arrangement of the modules that conforms to the lab setup.

synchronization unit in this stage, as well as the switched capacitor states.

In case the voltage error goes beyond the deadband, a new firing angle is calculated. If the angle reaches a limit, then capacitors are switched accordingly.

The trigger synchronization unit (not shown in Fig. 5) selects the trigger sequence for the thyristors. The sequence starts at the time indicated by the zero crossing signal, provided by the synchronization stage.

C. Layout

The LCD screen shows the state of the unit, and the control variables are shown in a computer with a graphical user interface. For a complete time-domain system study, eight synchronized oscilloscope channels are needed. The substation is equipped with a MiCOM P-141 industrial relay [17], which serves as another data acquisition device and plays an important role on the short-circuit test.

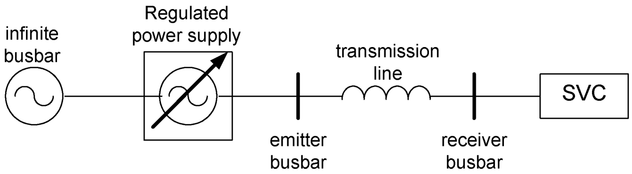

Fig. 7. Lab configuration for the SVC unit validation.

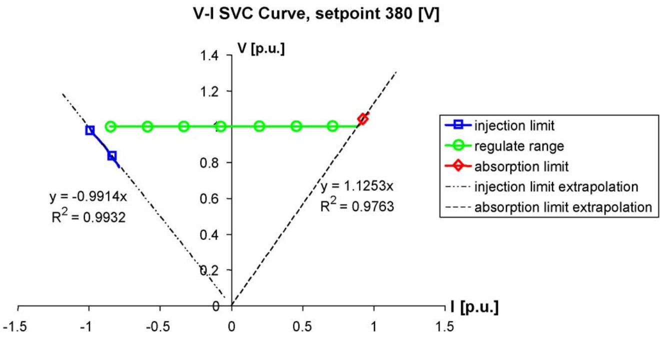

Fig. 8. Operation curve of the SVC unit.

To carry out the theoretical and experimental comparison, a data acquisition and monitoring system is included in the lab setup. The graphical computer interface is made on Matlab-Simulink, communicating by a serial port with the data collection module.

The computer is mounted within a laboratory rack, among other small-scale devices, as shown in Fig. 6. The selected base voltage is 380 [V], and base power is 1000 [VA]. As can be observed, the point of common coupling (three-phase busbar) is fully isolated using an acrylic board. Both the SVC unit and the substation are effectively enclosed in acrylic boxes. The interconnection cables comply with the CAT-III (600 V) standard. Resistive loads (located in the back) are connected to the low voltage side of the substation (40 Vrms).

D. Validation

The validation of the lab setup is accomplished using the configuration shown in Fig. 7. In the validation setup, the transmission line is configured to represent a 32 [km] line for a base voltage of 110 [kV] and a base power of 100 [MVA]. The regulated voltage source shown in Fig. 7 is used to maintain a constant voltage at the test area, independent of the variations in the network. The operation curves of Figs. 8 and 9 are obtained at high-voltage side and low-voltage side, respectively. These operation curves describe the capability of the SVC unit in the V-I plane, which is limited by the passive components' curves (shown as extrapolations). These curves agree with the literature [7]. On Fig. 9, the slope of the operation curve is caused by the transformer's impedance.

A computer model is created for steady-state and dynamic simulation and comparison. The model is programmed in DIgSILENT PowerFactory software. Simulations of the unit shows a curve very similar to Fig. 8, but with a 30% greater regulation range. Table I shows the difference between current

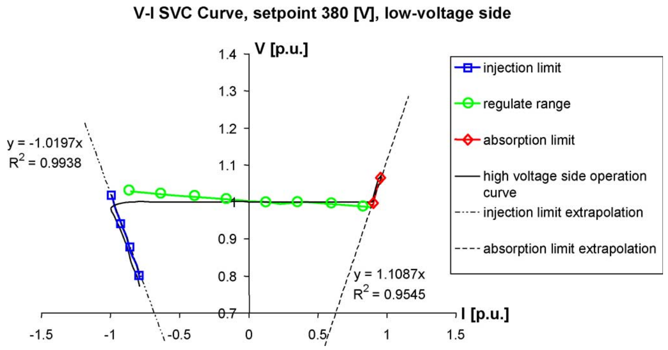

Fig. 9. Operation curve of the SVC unit, low-voltage side.

TABLE I
CURRENT AT HIGH-VOLTAGE SIDE OF SVC UNIT

	Injection limit	**Absorption limit**
DIgSILENT model	1,2015 [A]	1,0641 [A]
SVC Unit	1,0087 [A]	0,888 [A]
Difference	19,1%	19,8%

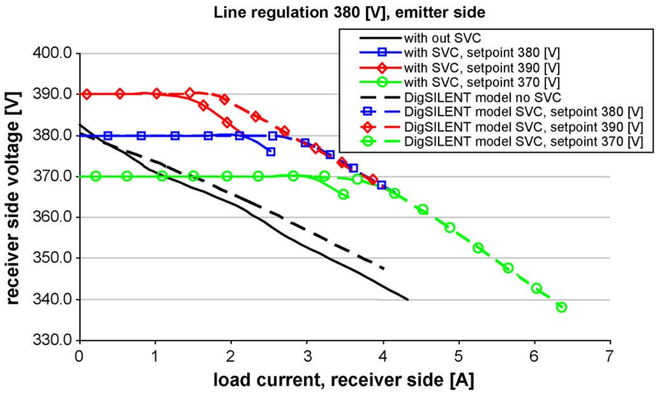

Fig. 10. Voltage regulation curves of the SVC unit and the model.

limits of the model and the physical unit. This difference is caused by the high series equivalent resistance of the step-down transformer which cannot be modeled because of its low X/R ratio.

It is important to emphasize that the SVC unit is part of a lab setup for educational purposes with specific learning objectives. The presence of a simulation model that runs and behaves almost as the real unit strengthens the link between theoretical and practical experience.

V. EXPERIMENTAL RESULTS

The results shown below are obtained by carrying out experiments using the validated SVC unit with the rest of the lab setup. These experiments can be reproduced by students following laboratory practices.

A. *Steady-State*

The voltage regulation test is carried out to observe the regulation capability of the SVC unit when different loads are applied to the system through the substation.

Fig. 10 shows the results of this test at 380 [V] on the emitter side, for different voltage set-points.

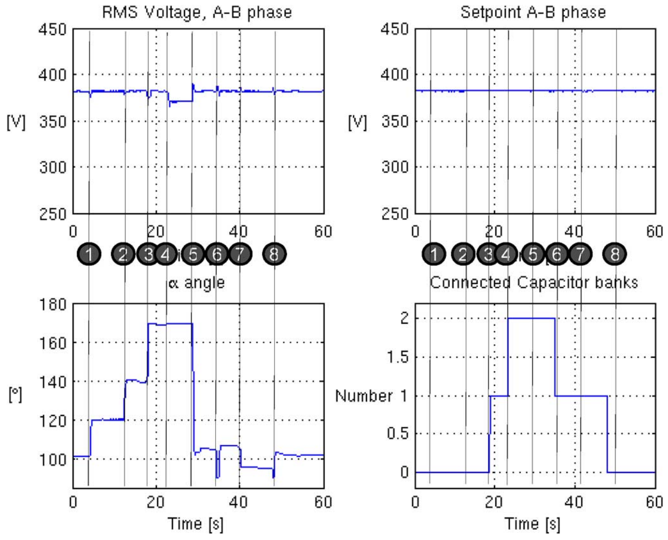

Fig. 11. Dynamic response of the SVC unit.

State changes: (1) Connection of substation, (2) Connection of load 1, (3) Connection of load 2, (4) Connection of load 3, (5) Disconnection of load 3, (6) Disconnection of load 2, (7) Disconnection of load 1, (8) Disconnection of substation.

The curve of regulation without SVC unit shows a linear decrease of voltage on the receiver busbar. The SVC unit produces a shift of this regulation curve for the different set-points. The point from which every curve starts decreasing (parallel to the original regulation curve) is defined by the reactive power injection limit of the unit, showing better regulation range for the 370 [V] set-point than for the 390 [V] set-point. The curves in Fig. 10 do not show the reactive power absorption limit of the unit.

The results shown by the DIgSILENT simulation and the experimental results are also coherent for 370 [V] and 390 [V] at the emitter busbar. These results demonstrate the curve shift effect at reactive power limit condition.

B. *Dynamic Response*

In the dynamic test, three loads are connected at the substation in sequential steps and then disconnected in reverse order. The voltage at receiver busbar, the firing angle of the TCR, and the state of the discrete-step capacitor bank are shown in the Matlab-Simulink graphic computer interface.

The results of this test are presented in Fig. 11. It can be observed in this figure that for the connection of the three loads, the reactive power limit is reached and the desired voltage is not preserved. The voltage oscillations on state changes of the capacitor bank can also be observed.

C. *Short-Circuit*

In the short-circuit test, a three-phase-to-ground short circuit is applied to the low-voltage side of the substation. The initial condition of the system is composed by the current state of the SVC unit, the voltage set-point of 380 [V], and the load at the substation of 0.3 [pu] of active power. The results from the Matlab-Simulink graphical interface are presented in Fig. 12.

The protection relay sends the trip signal 685 [ms] after the beginning of the event. This relay is programmed to maintain

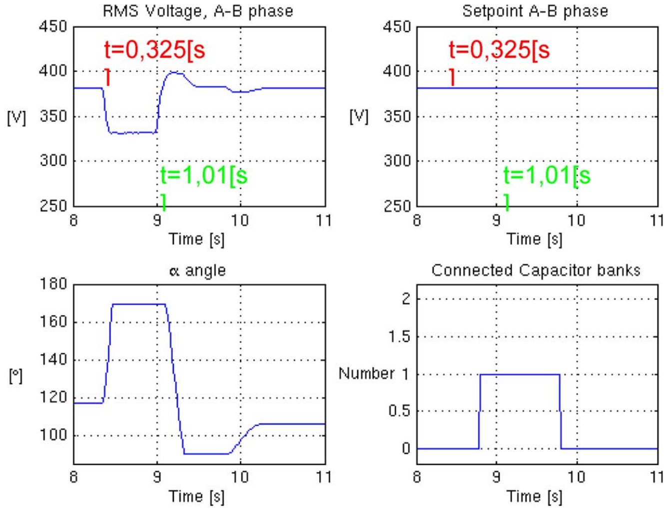

Fig. 12. SVC state during the short-circuit fault condition.

the fault condition for a longer time than the usual, to allow the students to observe the behavior of the system variables during the fault. The components of the system are oversized, ensuring proper operation during the fault.

During the fault, the SVC unit reacts to the voltage drop injecting all reactive power, which means connection of capacitor banks and maximum firing angle. The connection of the first capacitor bank occurs 400 [ms] after the beginning of the event. This action has little impact on the voltage at the point of connection of the SVC unit because the fault is close to this point.

When the fault is cleared, an overvoltage is generated for a few cycles due to the reactive power injection and the slow voltage measurement of the control module. The SVC control unit continues to follow the voltage set-point, disconnecting the capacitor bank and modifying the firing angle of the thyristors. The final state of the SVC unit is different from the initial state, because the relay has disconnected the substation, so the new load condition is null.

D. Harmonic Distortion

The harmonic distortion at any waveform can be observed directly with an oscilloscope, or indirectly with other devices like spectrum analyzers. Gathering all the information regarding harmonic distortion for different firing angles, it is possible to generate a harmonic pattern.

The harmonic content of the line current at the high-voltage side is shown in Fig. 13. The current does not have the 3rd harmonic, due to the use of a Yd transformer. Also the shape of the curves is similar to those expected by means of theoretical analysis. The case shown in Fig. 13 considers no connected capacitor banks. The maximum values of harmonic components are summarized in Table II.

E. Evaluation in the Classroom

At the Electrical Engineering Department of the University of Chile, the course that makes use of the laboratory is *Power Systems*. In this course, the students adequately understand the operation of a power system and the SVC laboratory experience provides the first-hand experience of an active compensation device. The course lectures include introduction to FACTS devices, mathematical description of an SVC, and fault calculations. Therefore, the students can observe the effects described in Section V, which motivates them to follow other courses covering specific topics in greater detail.

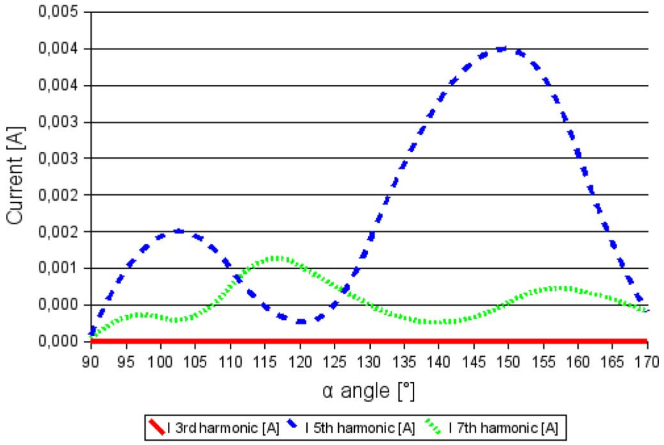

Fig. 13. Harmonic content of line current at high-voltage side of SVC unit.

TABLE II
HARMONIC CONTENT OF LINE CURRENT OF SVC UNIT (AS PERCENT OF FUNDAMENTAL)

	5th	**7th**	**11th**
Theoretical maximum	7,6%	3,85%	1,5%
Experimental maximum	7,11%	5%	unnoticeable

With the intention of incorporating an objective evaluation of the proposed laboratory equipment, a demonstrative laboratory practice has been carried out since 2007. A 40-min presentation reviews the main theoretical concepts, the historical background, and a description of the components and stages of the setup. Then, the equipment is exhibited and the experiments are carried out.

In fall 2009, 16 responses to the survey were received. According to the qualitative levels defined in the survey, the general evaluation of laboratory experience was *very good*. The students found that the proposed objectives were achieved with a *good* level of detail. They recognized most of the concepts presented during the experience, finding a clear link with the theory presented in previous courses. Moreover, they clearly understood the purpose of an SVC in a power system and each of the subcomponents of the device. Also, the practice showed how different disciplines (control systems, digital electronics, power electronics, and information technology) converge in order to deal with real problems in power systems.

The survey included 12 questions with *agree/disagree* scale, as well as fields for comment and observations. The results are summarized in Table III, and can be accessed on [18].

For future practices, the students recommended a more detailed comparison with other technologies and theoretical background. Also, some improvements for the visualization of the results in the laboratory (diagrams, simulations, and cameras) were suggested.

TABLE III
EVALUATION RESULTS FOR FALL 2009 SURVEY

Evaluated Topic	Agreement pct.
Objectives fulfillment	86.6%
Level of details on covered topics	75%
Students' understanding	60.4%
Theory linkage	83.3%
SVC role on EPS	89.6%
SVC components	77.1%
EPS familiarization	95.8%
Lab infrastructure	92.8%
Visual aids	92.8%
Safety level	76.9%
Lab equipment	95.2%
General evaluation	85.40%

VI. CONCLUSIONS AND FUTURE WORK

This paper presents a group of custom-made devices that make up a lab setup to carry out experiments with an SVC unit. These devices are arranged in a modular way and allow students to get involved in all stages of the system and become familiar with the future professional practice. Each module is briefly described and implemented with components of easy-access, low-cost, and simple design.

The operation curve of the SVC is obtained for the validation of the unit. Different experimental tests are performed for steady-state condition, dynamic response study, and harmonic distortion analysis.

The implemented small-scale SVC unit works by following the expected behavior of theoretical development. This unit, with the other devices of the lab setup, generates a powerful educational tool for electrical engineering students in a safe environment. As presented in the previous section, feedback from the class reinforces the educational purpose of the SVC unit, provided that more than 85% of the students expressed a positive general evaluation on the conducted survey.

The final lab-scale SVC unit is characterized by its low cost and high effectiveness on a small local network, as demonstrated by the results. Thus, lab-scale SVC can find industrial use in the field of DG located at the low-voltage level of distribution networks. Some constraints presented in the design criteria (Section II) of the lab-scale SVC unit could be suppressed for the DG network. For example, pedagogical concepts could be replaced by industrial requirements and standards fulfillment, as the IEEE 1547 [19].

As future work, an upgrade in the control algorithm is proposed. It is desirable to develop PI, PID, and fuzzy logic control algorithms either into the microcontroller or through the computer interface. The first choice is adequate for the independent functioning of the unit. The last choice is well-suited for student analysis and is an easy parameter modification in the Matlab-Simulink environment.

Another recommendation for future work is harmonic content handling. This topic can be approached by harmonic filters which can be designed and validated using the SVC unit as a platform to analyze the results.

Finally, improvements must be done in the areas pointed out by the students on the laboratory evaluation. These areas include visualization aids and technological comparison. The former requires an approach not only from an engineering point of view but also from a design and even artistic standpoint. The later requires new equipment to be added to the laboratory, and is an expected part of the laboratory acquisitions plan.

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