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Testing and Validation of a 200 kVA SSSC Prototype for Power Flow Control

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Abstract. Power flow control in transmission networks requires new approaches to deal with the uncertainties in the power flow patterns caused by the massive integration of renewable energy generators and the difficulties for constructing new transmission corridors, due to environmental restrictions and social opposition. One solution explored nowadays by utilities is the installation of a Static Synchronous Series Compensator (SSSC). This paper presents a real test bench for an SSSC. The test bench allows verifying the real control devices of a substation and the PLC close-loop control of the SSSC. The proposed SSSC test bench is a scale FACTS device of a 50MVAs real SSSC that will be placed in the Spanish transmission grid. In this paper the design of the test bench is presented, including the main magnitudes of both grid and SSSC, along with the substation SSSC control scenario and the SSSC close-loop control strategy. Besides, the SSSC test bench dynamics and response has been validated using a model of the SSSC and its controls, developed in Matlab/SimPowerSystems. The paper shows the results of the simulation and compares them with the magnitudes measured in the test bench.

Key words

SSSC, test bench, Matlab, real implementation.

1. Introduction

In the last years, the control of the power flow in the transmission grids has become one of the hardest challenges of Transmission System Operators (TSO). The difficulties to construct new lines or even to re-power existing ones create an endless job for TSOs, due to environmental and social constraints. In case of constrains, the actual approach followed by TSOs is to change the topology of the grid by opening lines or to re-dispatch generation. Both solutions imply an increase in the operation cost and a decrease in security.

Flexible AC Transmission Systems (FACTS), firstly developed during the 1990's [1], are an alternative solution to control the power flow in a transmission grid, and nowadays they are been increasingly considered by TSOs. A FACTS device is defined in [2] as "A power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability". There are several types of FACTS devices, and they can be classified according to the way they are connected to the transmission system in series, parallel or series/parallel devices.

The SSSC is a series connected FACTS. It consists on a series connected transformer and a Voltage Source Converter (VSC), as shown in Fig. 1. The main application of the SSSC is to control the power flow in a transmission line by injecting a voltage in series with the line voltage. The injected voltage leads or lags the line current 90º, so it can be considered as a series reactor or a series capacitor.

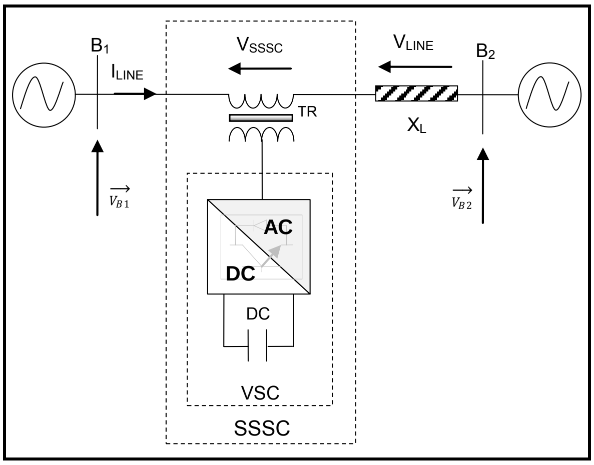

Fig. 1. Transmission line equivalent with a SSSC

This paper continues the work presented in [3] and [4] where the first installation of an SSSC in the Spanish transmission grid is described and the initial dynamic simulation studies are shown. Here, the test bench of a scaled prototype of the SSSC is shown, as well as the simulation model developed using Matlab with the purpose of validating the control strategy before carrying out the real tests.

The paper is divided into 7 sections including this introduction. In section 2 a description of the test bench is done, including the main parameters of the equipment. Sections 3 and 4 describe the control hierarchy and the control strategy, respectively. Section 5 contains the Matlab model and in Section 6 the results obtained in the simulation are compared with those provided by the test bench. Finally, Section 7 contains the conclusions.

2. Test Bench

The test bench of the SSSC is a reduced scale model of the 50MVA real SSSC that will be placed in the Spanish transmission grid. The rated power of the model is 200kVA.

In the test bench the SSSC is connected in series with a line which is represented by four reactors that can be short-circuited so that the amount of current through the SSSC can be controlled. Fig 2 shows the one line diagram where:

- V_{B1}, V_{B2} and V_{BSSSC} are the corresponding voltages at buses B_1, B_2 and B_{SSSC}
- V_{LINE} is the transmission line voltage.
- I_{LINE} is the line current.
- I_{BYPASS} is the current through the bypass breaker.
- I_{SSSC} is the SSSC current.
- TR is the ratio of the coupling transformer.
- VSC is the Voltage Source Converter.
- Xi are the series reactors (i = 1, 2, 3 and 4).

The main characteristics of the elements are shown in Tables I to IV.

Table I. – Source Parameters

DESCRIPTION [Magnitude]	VALUE
Power [kVA]	1000
Frequency [Hz]	50
Voltage (ph-ph) [V]	690

Table II. – Coupling Transformer Parameters

DESCRIPTION [Magnitude]	VALUE
Power [kVA]	217
Frequency [Hz]	50
Primary Voltage (open winding) [V]	550
Nominal Primary Winding current [A]	120
Secondary Voltage (open winding) [V]	732
Transformer Ratio (RT)	0.758
Leakage Inductance [%]	6

Table III. – Voltage Source Converter Parameters

DESCRIPTION [Magnitude]	VALUE
Power [kVA]	197
Output Voltage (per phase) [V]	732
Max. current RMS [A_{SEC}]/ [A_{PRIM}]	97.5/130
THD [%]	< 3

Table IV. – Line Reactor Parameters

DESCRIPTION [Magnitude]	VALUE
X1 Inductance [mH]	3.2
X2 Inductance [mH]	7.5
X3 Inductance [mH]	7.5
X4 Inductance [mH]	15
Frequency [Hz]	50
Reactors maximum current [A]	120

Table V. – Transmission Line Parameters

DESCRIPTION [Magnitude]	VALUE
Nominal line voltage (V_{LINE}) [V]	1000
Nominal line current [A]	50
Max. line current [A] (Breaker Trip)	135

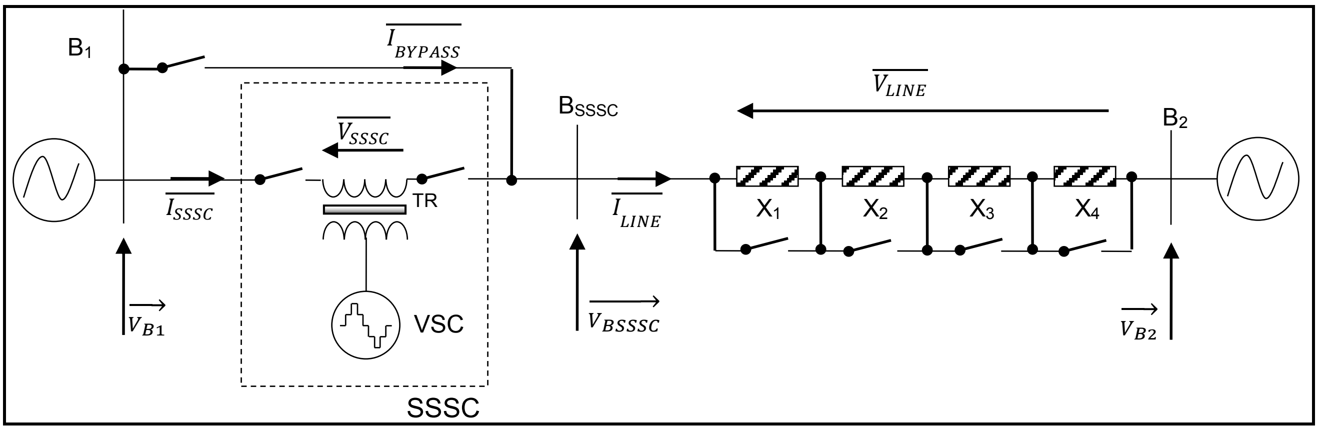

Fig. 2. Test bench oneline diagram

The voltage in B2 is equal to the voltage in B1 but 120º delayed. V_{B1} corresponds to the phase "A" of the laboratory power supply and the V_{B2} is the phase "B" voltage of the laboratory supply. Thus, the total voltage between B1 and B2 buses is 690 Vac (the phase to phase voltage of the laboratory source).

Fig. 3 shows the line equivalent (LINE) and the VSC cubicles are shown. The line equivalent cubicles contain the coupling transformer, the line reactors, the necessary breakers and the current and voltage transformers.

Fig. 3. Laboratory cubicles

The control system is placed in another cubicle with various auxiliary contacts whose purpose is to simulate the signals from the Uninterruptible Power Supply (UPS) and other Programmable Logic Controllers (PLC).

3. Control Hierarchy Description

In this section the control hierarchy of the test bench is described. The aim is to integrate a complete substation control scenario with the SSSC control PLC. A laptop is used to control the Bay Control Unit (BCU) and the PLC of the SSSC, as shown in Fig.4.

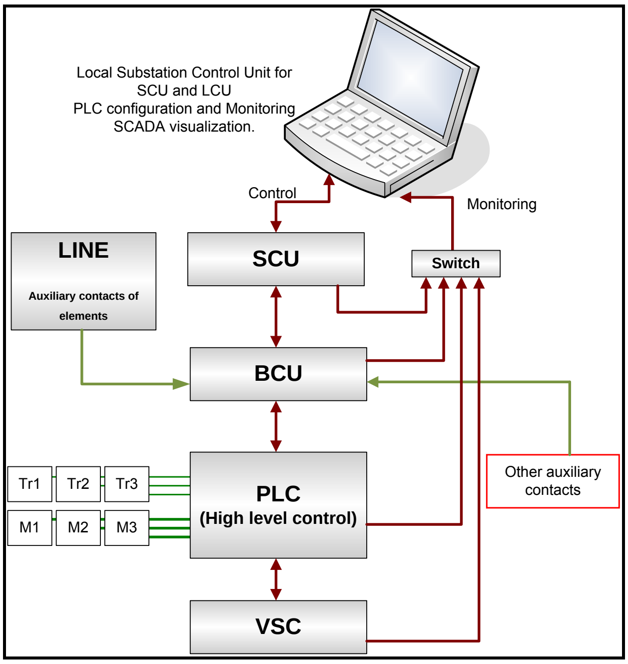

Fig. 4. Control Hierarchy

The main components of the control system are:

- LINE is the cubicle that represents the behaviour of the equivalent power system. It contains the breakers, the auxiliary contacts of the breakers for SCADA representation, measurements and the coupling transformer.
- The Substation Control Unit (SCU) is in charge of communicating with the central dispatch and controlling every BCU behind.
- The BCU is the control unit in charge of controlling the breakers and ground breakers, sending the set-point and operation mode to the PLC of the SSSC and sending the states and measurements of the system to the SCU.
- The PLC of the SSSC is prepared to receive measurements from the field via the multimeters M_1, M_2 and M_3, and the current transducers T_{R1}, T_{R2} and T_{R3}. The PLC controls the voltage set-point to the VSC by a multi-objective PI controller.
- M_1 is a multimeter that measures the voltage at B_1 and the current through the coupling transformer.
- M_2 is a multimeter that measures the voltage at B_1 and the current through the SSSC bypass.
- M_3 is a multimeter that measures the voltage at B_2 and the current in the line.
- T_{R1}, T_{R2} and T_{R3} are current transducers that measure the line current.
- The VSC is the Voltage Source converter that imposes in the secondary of the coupling transformer the required voltage.

4. SSSC Control

The SSSC can be connected in Static or Dynamic configuration. When the VSC is switched off, the SSSC is connected in “Static mode” and the total series imposed reactance (X_{STATIC}) is equivalent to the leakage reactance of the coupling transformer and the reactance of other reactors in the secondary of the coupling transformer.

In contrast, when the equipment is configured in “Dynamic mode”, the total imposed impedance (Xsssc) can be dynamically modified, according with the equipment limits shown in Fig 5.

Once the SSSC is in dynamic mode, it can operate in four close loop operation modes:

- Power limitation: The line power is limited to the set point value. Only inductive behaviour is possible.
- Power regulation: The line power is fixed to the set point value. Both inductive and capacitive behaviour are possible.
- Series reactance regulation: The imposed series reactance is fixed to the set point value. Both inductive and capacitive behaviour are possible
- Maximum power limitation: It imposes the maximum reactance value in series in the line. Only inductive behaviour is possible.

The SSSC operates, according to its operation mode, with a set point of series reactance value or a power value.

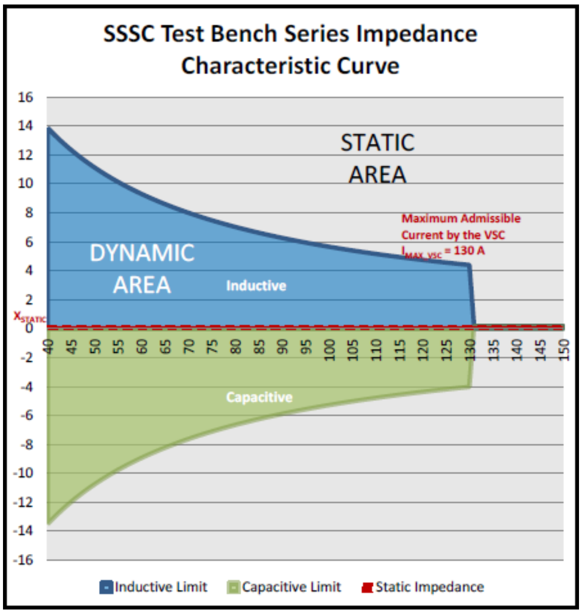

Fig. 5. Characteristic curve of the SSSC in the test bench

5. Test Bench and SSSC Control Validation

The test bench has been implemented in Matlab using the SimPowerSystems toolbox. The aim of this model is to verify the obtained electric magnitudes and dynamics of the test bench.

The laboratory source has been modelled as an ideal source, the line load has been modelled as a series RLC branch and the SSSC is modelled as an ideal coupling transformer with 3 single phase voltage sources. In Fig 6 the MatLab model is shown.

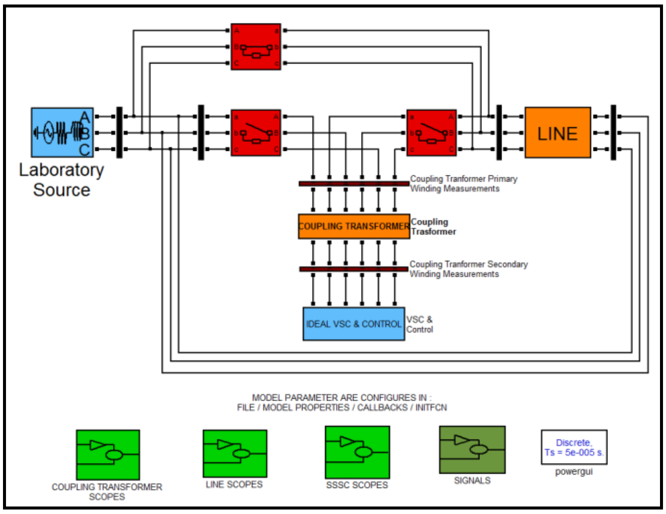

Fig. 6. Test bench model in Matlab

6. Results

Table VI shows the line current and the voltage magnitude measured in the test bench, with the coupling transformer bypassed, for different configurations of the line reactors. When the reactors configuration goes up to 140A the main breaker is triggered.

Table VI. – Test Bench Measurements with SSSC in Bypass

TEST BENCH MEASUREMENTS - BYPASS CLOSED					
Connected Reactors					
X1	*X2*	*X3*	*X4*	*Phase Current A [A_{RMS}]*	*Voltage (B_1) [V]*
X	X	X	X	67,5	703
X	X	X		139	690
X	X		X	85,7	695
X		X	X	87,2	695
X			X	128	690
	X	X	X	75	700
	X	X		Test Bench Breaker Trip	695
	X		X	99	695
		X	X	101	695
			X	Test Bench Breaker Trip	695

Table VII shows the line current RMS and peak values measured in the test bench for different reactor configurations, with the coupling transformer connected and the SSSC in "Static mode".

Table VII. – Test Bench Measurements with SSSC in Static

TEST BENCH MEASUREMENTS - TRANSFORMER CONNECTED (STATIC)					
Connected Reactors					
X1	*X2*	*X3*	*X4*	*Phase Current A [A_{RMS}]*	*Phase A [A_{PEAK}]*
X	X	X	X	66,45	104
X	X	X		134,8	220
X	X		X	84,6	130
X		X	X	86	132
X			X	122,8	195
	X	X	X	74	110
	X	X		Test Bench Breaker Trip	
	X		X	98	155
		X	X	98,6	152
			X	Test Bench Breaker Trip	

In Fig.7 the PLC power and line current variables are shown. This capture corresponds to the static configuration of the SSSC. The upper graph shows the power variables and the lower graph the line current. The power set point value (blue) is 50 kVA and the value measured (green) is 77.9 kVA. In this situation, the line current is 66.2 A.

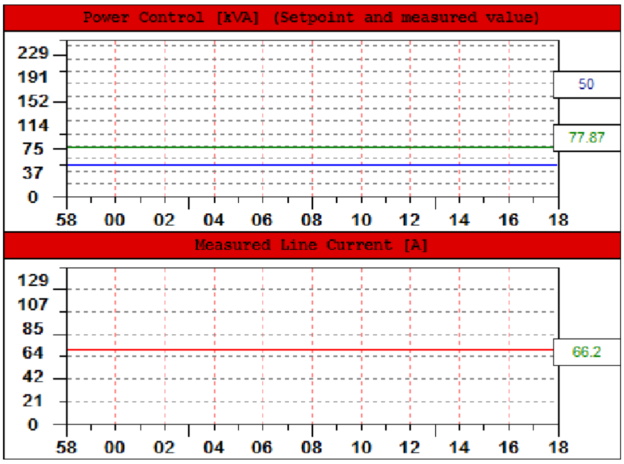

Fig. 7. PLC in static configuration

Once the SSSC is in static mode, it starts the synchronization to dynamic mode. The SSSC test bench has been tested and its functionality has been approved by the customer. During the validation stage many tests have been done such as:

- All the transition possibilities from one compensation mode to another.
- Change of the Set point in every compensation mode.

- Load change (by changing the line impedance)
- SSSC disconnection during a line fault
- SSSC reconnection.

In the next figures two examples of different tests simulated in Matlab and reproduced in the test bench are shown. In Fig. 8 and 9 the SSSC response to an impedance set point change is shown. The impedance is changed from 4 Ohm (inductive) to -2 Ohm (capacitive). In both cases the scope windows show 20 seconds of simulated/measured values. In the top of the Fig. 8 the Matlab results are shown, and in the bottom the measured impedance response in the test bench. The Matlab value after 20 seconds is -1.92 Ohm whereas the value obtained in the test bench is -1.96 Ohm.

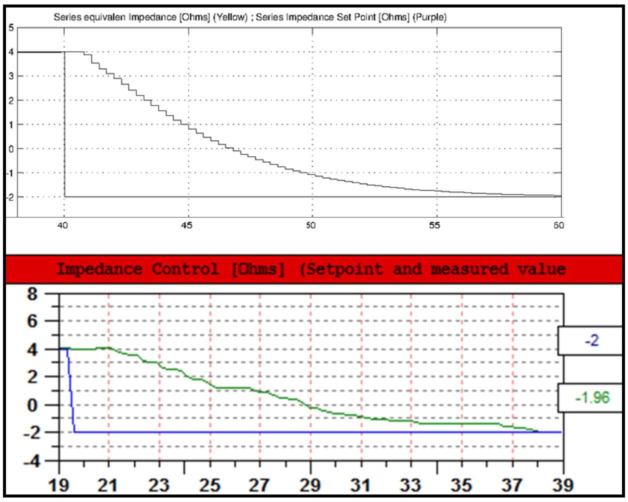

Fig. 8 Matlab (top) and SSSC test bench (bottom) response to an impedance set point change.

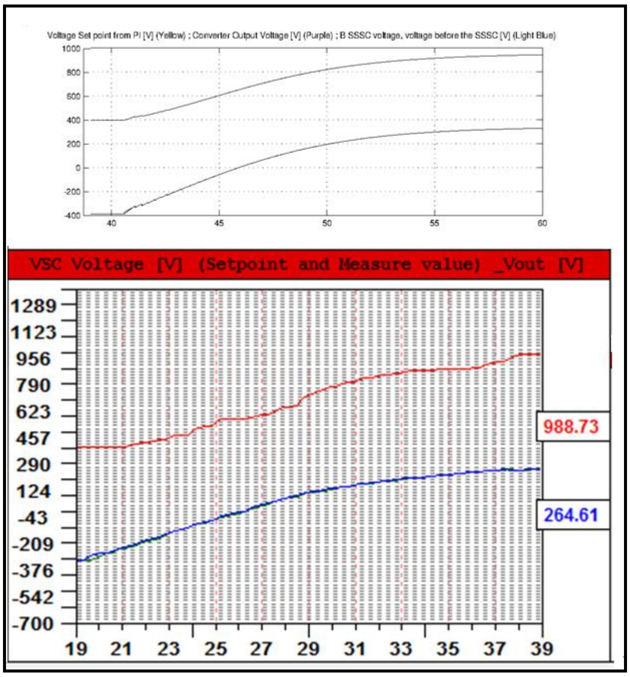

Fig. 9 Matlab (top) and test bench (bottom) B_{SSSC} voltage comparison for an impedance set point change

For each graph in Fig. 9, the upper line represents the voltage in the bus B_{SSSC}, and the lower line the output voltage of the SSSC. The B_{SSSC} final voltage in Matlab is 958 V whereas the value measured in the test bench is 988.73 V. The difference between measurement and simulation is close to 3%. For the SSSC voltage, the result is similar.

Fig. 10 and 11 show the results for a test in power regulation mode in Matlab and the test bench, respectively. In both figures there are 4 graphs, from top to bottom:

- Power set point and measured value.
- Impedance set point and measured value.
- Measured line current with transducers, with multimeter and current used for control loop.
- Converter voltage set point (ph-ph), SSSC output voltage (ph-ph) and B_{SSSC} voltage (ph-ph).

In this test, the SSSC is regulating the line power to 185 kVA. At t = 40 s the line power set point is changed to 36 kVA. After 10s, the line power reaches the set point value. The final (t=60s) impedance value is close to 3 Ohm, the line current is 47 A, the SSSC ph-ph voltage - 240 V, the SSSC series voltage (ph-L) is 138 V and the B_{SSSC} ph-ph voltage is 460 V, approximately.

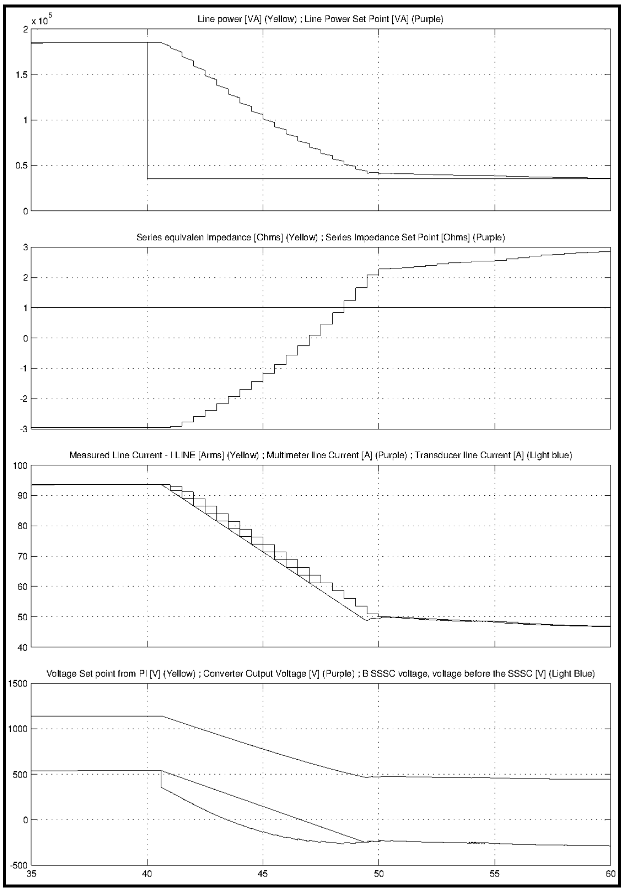

Fig. 10 Matlab results for power regulation mode

In Fig 11 the SSSC test bench results for the same test case are shown. The results obtained at the end of the test are shown on the right. The test bench results show the same dynamic response obtained in the Matlab simulation and the final test values are within the same 3% difference of previous test case.

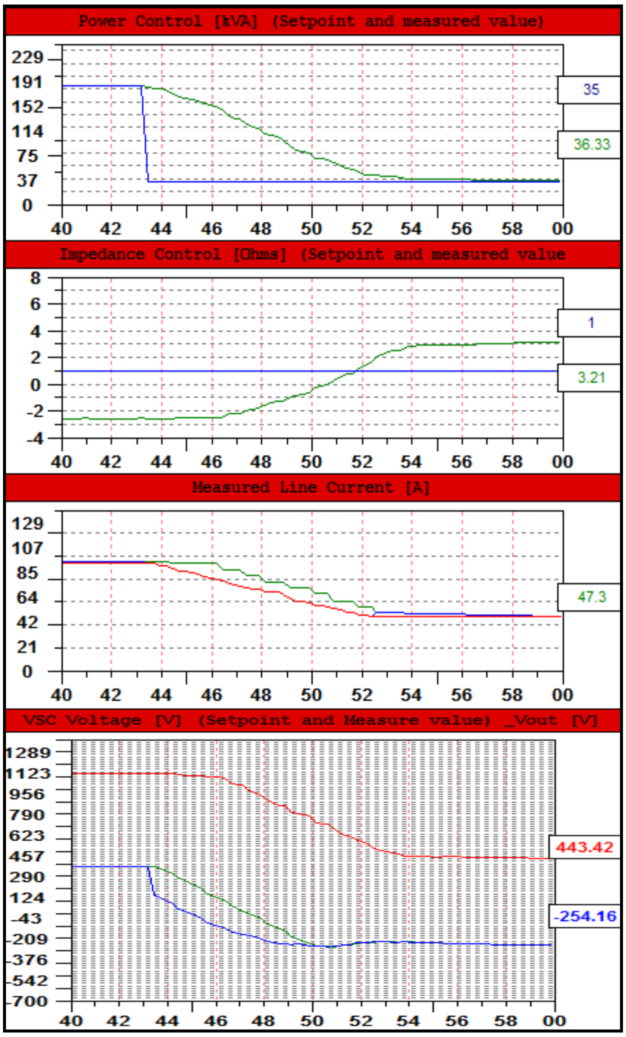

Fig. 11 Test bench results for power regulation mode

For example, during the test the SSSC output voltage has been limited by software. As seen in the fourth graph in Fig. 11, from t = 43 s to t = 50 s the voltage reference to the converter is greater than the SSSC imposed voltage. This result is in accordance with the Matlab simulation. The fourth graph in Fig. 10 shows that the SSSC voltage is limited to its maximum value during 7 seconds. After the limitation is released, the voltage set point to the VSC and the output voltage are equal.

7. Conclusion

In this paper the control system of a 50MVA SSSC has been studied with a Matlab model and the simulation results have been validated in a 200 kVA SSSC test bench. The results show a good agreement between the Matlab simulation and the test bench measurements.

During the validation of the SSSC test bench and the Matlab model some important considerations have been taken like implementing the time responses of the multimeters and current transducers and considering the communications delay time and priorities.

This study has allowed to highlight some important aspects of the SSSC control system, such as: the influence of the current transducers measurement and multimeters voltage measurement in the output voltage, the importance of a fast PI response to overcurrents to avoid a VSC trip, the importance to set appropriate proportional and integer gains depending on the measured error, the influence of an extremely fast voltage response of the SSSC transformer and the line reactances and the influence of the system communications priority on the PLC control strategy to ensure an appropriate response.

Finally, the test results show that the SSSC test bench fulfils the customer specifications due to its time response, electrical parameters, regulation mode, dynamics and control strategy.

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