

Implementation of a Voltage Sag Generator for Synchronous Generator Tests

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Abstract—A new Voltage Sag Generator (VSG) to test synchronous generators Fault Ride Through (FRT) capability as required by grid codes is proposed. This VSG consists of an electronically controlled tap changer transformer that takes into account the technological constraints of synchronous generators. A 10 kVA prototype has been assembled and tested. It has been demonstrated that this VSG reproduces faithfully the interactions between the generator and the grid during voltage sags.

Index Terms—Electronic Tap Changer Transformer, Voltage Sag Generator, Transient Stability, Fault Ride Through, Grid Codes.

I. INTRODUCTION

The increasing number of installed wind farms led the regulators to include new requirements in the grid codes to prevent a massive wind farm disconnection that could threaten the entire system [1]. One of these new requirements was the Fault Ride Through (FRT) capability, which consisted of voltage time profiles above which the wind generators must not trip from the grid in case of a voltage sag. FRT requirements were soon extended to synchronous generators too. However, the nature of the problem in synchronous generators was different from wind generators' one. Voltage sag will pull a synchronous generator out of synchronism if their duration is long enough. Therefore, this is more a transient stability problem [2] than a mere problem of protection relays settings or power converter capabilities. Transient stability is a complex problem that manifests as a steady increase in generator's angles.

Independently of the nature of the problem, generators' FRT capability has to be demonstrated prior to generator connection to the grid. Generator's FRT capability can be evaluated either through simulations or field tests. Usually Transmission System Operators (TSOs) demand just simulations using specific commercial software, where the model complexity and fault conditions are also predefined. Field tests provide high certainty of the generators' FRT compliance and simulation models validity. To carry out such a test a Voltage Sag Generator (VSG) is required. VSG can be either, reduced size to test scaled prototypes or full size to test actual generators.

This paper proposes and tests a reduced size electronic Tap Changer Transformer (TCT) as a VSG for synchronous generators. The paper is organized as follows. Section II. reviews the state of the art of VSGs. Section III. proposes the main features of a VSG to test synchronous generators. Section IV. introduces a TCT based VSG and presents the prototype. In section V. concept validation through

simulations and real tests are presented. Finally, section VI. draws out the conclusions.

II. VOLTAGE SAG GENERATOR'S STATE OF THE ART

VSGs can be classified either by their targeted equipment or by their own technology. Reviewed VSGs are mainly used to test electric equipment and sensitive loads for which there are a number of standards that measure and study the impact of voltage sags [3]. In addition, some research has been carried out to develop VSGs for wind generators. However, no development has been reported on VSGs to test synchronous generators.

Concurrently, the reviewed VSGs can be divided in five categories depending on their technology (Fig. 1): Tap Changer Transformer (TCT) based, Power Electronics (PE) based, Shunt/Series Reactance Switching (SSRS) based, Synchronous Generator (SG) based, and Induction Regulator (IR) based VSGs.

TCT based VSGs have been extensively reported for passive loads. However, none of them has been reported to test rotating machines. TCT based VSGs are able to produce fast and abrupt voltage sags. Moreover, they are able to operate in the four quadrants. This device can appear as an autotransformer too [4, 5]. A number of commutation technologies have been reported from electromechanical switches [5, 6] to solid state relays [4] passing through hybrid solutions to save energy. The switch choice is determined by the application. Electromechanical devices switching speed ranges from 10 to 60 ms, triacs [7, 8] commute at every zero crossing (10 ms at 50 Hz) and IGBTs [9] in less than 1 μ s. The later reference presents the same VSG concept but restricted to sensitive loads, without any mention to rotating machines' testing.

PE based VSGs have been widely proposed to test passive loads due to their high flexibility [10, 11]. Commercial products give wide functionalities as power corruptors (sags, swells, voltage disturbances, frequency disturbances, generation of harmonics, etc) [12-14]. They are usually based in either linear amplifiers or switched mode (PWM) IGBTs. Although most of them operate only in 2 quadrants, the technology to build 4 quadrant power converters exists and can be applied to develop a VSG. However, this technology has not been reported to be used to test rotating machines FRT capability.

SSRS based VSGs have been used to test electric equipment and passive loads [15-17]. They become the dominant solution to test wind turbines, provided that prototypes up to 5 MW have been built and tested [18]. Furthermore, there are some patents [19, 20], and even a short live commercial products

like the [21] related to wind turbines. They result from a combination of reactances and switches that are able to produce actual faults to earth with different voltage depths. Disturbances to the grid are minimized by means of series reactances. They are able to produce abrupt sags using similar switching technologies as the ones described for TCT based VSGs. Like them, they are able to operate in the 4 quadrants.

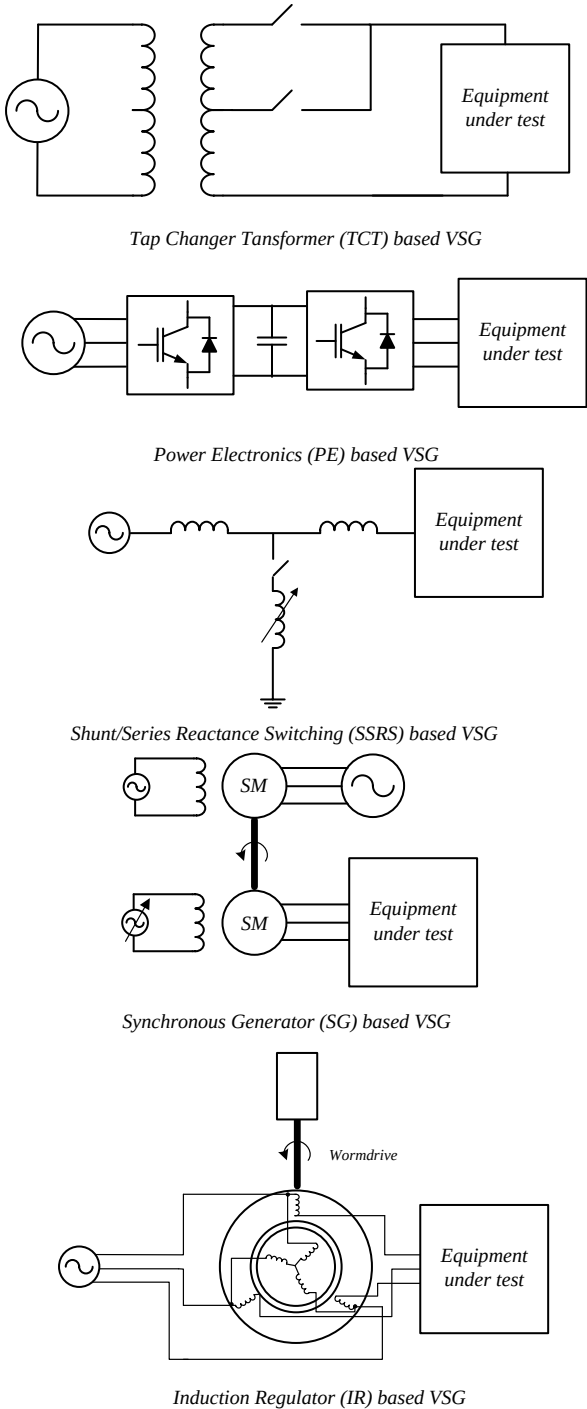


Fig. 1. Technologies for VSGs.

SG based VSGs are able to control frequency and voltage through their mechanical input and excitation system. The slope of the voltage drop is limited by the generator time

constants. Smooth recoveries are also possible. They can operate in the four quadrants and may appear as a three phase synchronous generator [22] or as three single phase synchronous generators to allow independent control of each phase like in [23]. They can be driven by diesel engines [24] or by another electric machine directly connected to the grid [22]. They have been used to test passive loads [23, 24] and wind generators [22]. They should have enough inertia to test other synchronous generators in order to avoid oscillations between the two machines.

An IR based VSG is based on the old idea of using a wound rotor induction machine as a variable transformer before TCTs appeared. In this application, the rotor is not allowed to move freely and its position is controlled by a worm drive. Furthermore, the rotor windings are connected to the stator windings in such a way that the output voltage depends on the rotor position. Therefore, a continuous output voltage regulation is obtained. They are still used in sensitive applications with special voltage demands. As a VSG it is used to test wind generators in combination with solid state relays to obtain a fast voltage drop and a smooth recovery [25, 26]. This device can be used to test passive loads too.

Table I and **¡Error! No se encuentra el origen de la referencia.** summarize the state of the art of the use of VSGs to test electric equipment/sensitive loads and wind generators, respectively.

TABLE I. VSGs FOR ELECTRIC EQUIPMENTS & SENSITIVE LOADS

Technology	Articles	Patents	Commercial VSGs
TCT	[4]	[5-9]	N/A
PE	[10, 11]	N/A	[12, 27]
SSRS	[16, 17]	[15]	N/A
SG	[24]	N/A	[23]
IR	N/A	N/A	N/A

TABLE II. VSGs FOR WIND GENERATORS

Technology	Articles	Patents	Commercial VSGs
TCT	N/A	N/A	N/A
PE	N/A	N/A	N/A
SSRS	[18]	[19, 20]	[21]
SG	N/A	[22]	N/A
IR	[25]	[26]	N/A

Table III summarizes the different VSGs technologies vs. the different loads and how they might be used. Shadowed box is where the contribution of this paper is located.

TABLE III. VSGs TECHNOLOGIES VS. TEST LOADS

Test Load Technology	Elect. Equip. Passive load	Wind Gen.	Synch. Gen.
TCT	♦	0	0
SSRS	♦	♦	0
PE	♦	0	0
SG	♦	♦	x
IR	0	♦	x

- ◆ RESEARCH, PATENT OR COMMERCIAL PRODUCT
- NO RESEARCH, PATENT OR COMMERCIAL PRODUCT, BUT POSSIBLE USE
- ✕ TECHNOLOGY CANNOT BE USED TO TEST LOAD

III. VSGs FOR SYNCHRONOUS GENERATORS

The specifications and design of a VSG for synchronous generators are conditioned by its response to voltage sags. During a voltage sag, the generator terminal voltage is reduced and so does the electromagnetic torque, whereas the mechanical torque from the turbine remains constant and consequently the generator accelerates. Meanwhile, the generator core suffers a demagnetization that causes a sudden current increase that the VSG should withstand. If the sag is long enough, the generator loses synchronism and it is disconnected from the grid. If not, the generator will experience electromechanical oscillations that are transmitted to the grid through the VSG. The oscillations and the critical clearing time are influenced by the grid's Short Circuit Capacity at the connection point. The lower the impedance added by the VSG, the better the grid emulation. Therefore, the main conditions of a VSG to test a synchronous generator should be:

1. Not disturbing the grid during the sag test.
2. Operating in the four quadrants in order to transmit the power from the generator to the grid.
3. Not braking the generator.
4. Being able to withstand both, the current peaks during the sag and the power oscillations after the sag clearing.
5. Emulating the grid behavior.

VSGs developed to test electrical equipment and sensitive loads (

Table I), cannot be used as they are not able to transfer the power flow from the tested generator to the grid (2nd condition).

SG based VSGs are not suitable to test synchronous generators, provided that they do not fulfill the 5th condition. Interconnected grids have an equivalent inertia that is considerably greater than the inertia of a single generator. If the inertia of the SG based VSG is not large enough compared to the one of the Synchronous Generator under test, significant oscillations will appear between both machines, disturbing their response and exhibiting a poor emulation of the grid.

IR based VSG don't respect the 5th condition as the fault recovery profile in a network is abrupt.

PE, SSRS and TCT based VSGs seem to be the best choices to test synchronous generators. The three technologies require enough transient overcurrent capability in order to withstand the synchronous generator response (4th condition).

A PE based VSG with 4 quadrants operating capability fulfill the 5 conditions. They could be operated under sophisticated control schemes that are able to produce almost any kind of disturbance. Two quadrants operating power converters with the addition of a shunt resistance to dissipate the active power that cannot be transmitted into the grid are not suitable as VSGs for synchronous generators. They would behave as the braking resistor used to brake the generator for transient stability improvement of [28].

SSRS based VSGs create an actual fault and they have been used to test wind generators [18-21]. SSRS based VSGs are placed between the grid connection point and the generator under test. They include a series connection reactance to limit the fault current and to avoid disturbing the grid. In other words, they decouple the test from the grid. This fact is irrelevant when testing wind generators as most of them belong to the Synchronous Generators with Full-Power Converters (SGFC) and Doubly Fed Induction Generators (DFIG) technologies that are already decoupled from the grid due to their power electronic converters. However, a large connection reactance may modify the response and the critical clearing times of a synchronous generator directly connected to the grid. This fact can be a limitation when testing synchronous generators.

IV. ELECTRONICALLY CONTROLLED TAP CHANGER TRANSFORMER AS A VOLTAGE SAG GENERATOR

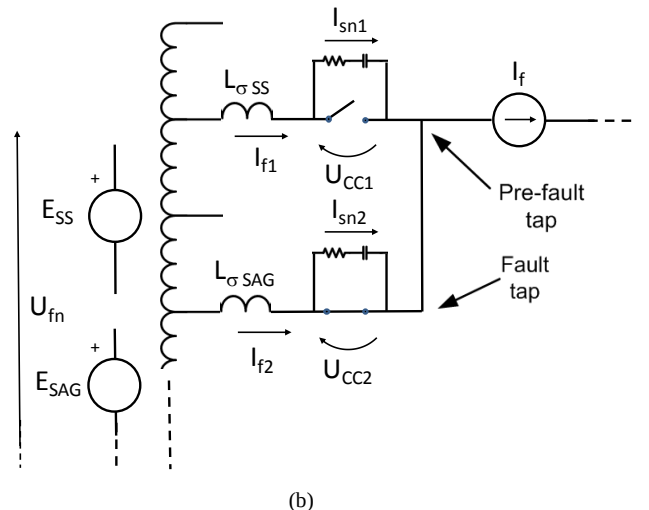
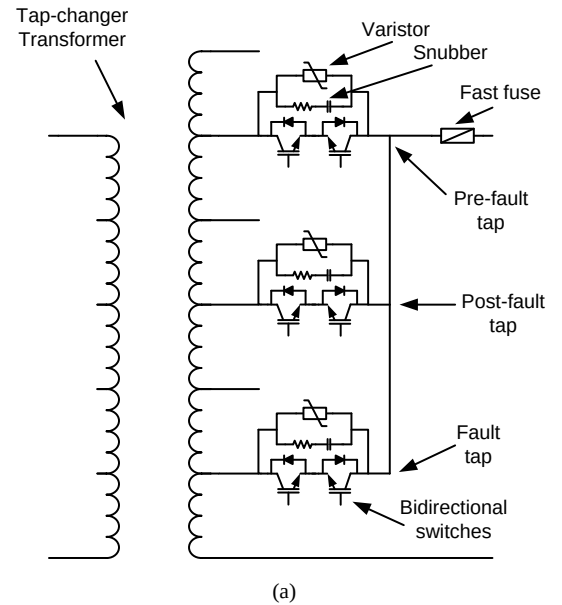


Fig. 2. (a) Equivalent single phase diagram of the VSG. (b) Simplified equivalent tap commutation circuit.

The continuous improvement on semiconductors voltage and current capabilities has triggered the development of electronically controlled on load Tap Changer Transformers (TCT) of increasing powers to operate and control the distribution network [29-31]. This development makes it also possible to build full size TCT based VSGs to test synchronous generators. The concept discussed in this paper is similar to the ones proposed in [5-9] but adapted to synchronous generators. A 10 kVA small size prototype, being the first one of its kind, has been developed to assess its adequacy to generate voltage sags and emulate the grid.

A. Hardware

Fig. 2a and Fig. 3 depict, respectively, the equivalent single phase diagram and a picture of the setup. The prototype consists of a three phase 10 kVA 230V/230V transformer and 3 sets (one set for each phase), of 3 bidirectional switches (one for the pre-fault, one for the fault and one for the post-fault periods). Although the taps in this design are discrete and fixed, continuous tap selection can be installed in future designs. The available taps produce 1.1, 1.0, 0.7, 0.5, 0.3, 0.2, 0.1 and 0.05 pu voltages at the secondary of the transformer allowing different configurations of voltage sags. The taps are manually connected to the bidirectional switches prior to the test depending on the test requirements. Moreover, the independent control of each bidirectional switch enables to emulate balanced and unbalanced voltage sags.

Each bidirectional switch is made up of a pair of IGBTs in back-to-back configuration (with both emitters connected), a snubber network and a varistor. The two latter components are aimed to protect the IGBTs from switching overvoltages, being the varistor a back up protection as long as its time constant is slower than the snubber's. The back-to-back IGBT switch provides faster response and easier control than a Triac. The transient current rating of the IGBT is an important parameter because during a voltage sag the synchronous generator stator current can reach peaks of 5 to 10 pu's in the generator basis. This response is completely different from the passive loads' and wind generators' and must be addressed when designing a VSG. Additionally a fast fuse has been installed to protect the IGBTs from permanent overcurrents.

B. Control and tap commutation

A simple state-machine control method is used to control the switching sequence of the VSG. It has been implemented in a DS1103 Dspace platform with a sampling frequency of 10 kHz. Although more complex sags are possible, for the sake of simplicity the control of a balanced three phase voltage sag with equal pre- and post-fault voltages is presented in this section. Fig. 4 depicts the state-machine diagram for this case. During the initial or Shutdown state (S0) every tap is switched off and the synchronous generator remains disconnected from the grid. To connect the generator to the grid, the operator switches on the pre-fault control signal (rising edge sw_1) and the transition from Shutdown (S0) to Prefault (S1) state is performed in the next sampling period. The pre-fault or steady state tap (tap_{ss}) at rated voltage is switched on, whereas the fault tap (tap_{sag}) remains off. Then, the synchronous generator

is synchronized to the grid through the VSG and driven to its steady state condition. Once the test operating conditions are verified, the operator can switch on the sag control signal (rising edge sw_2) that is synchronized to a predefined synchronizing signal (in this study, the rising edge of the zero pulse of the encoder that measures the generator speed) in order to ensure the repeatability of the test and to control the trigger phase. This maneuver enables to pass from Prefault (S1) to Sag (S2) state. Pre-fault tap is switched off and fault tap is switched on in this state. This state is kept for the predefined sag time and then the system goes automatically to the pre-fault state.

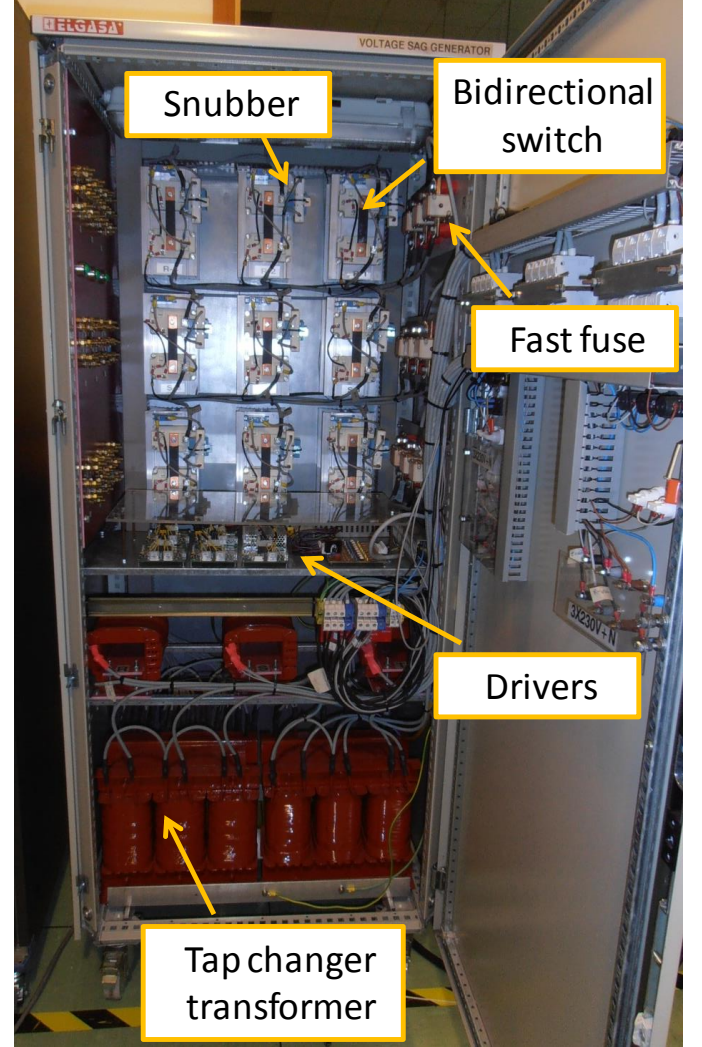


Fig. 3. Detail of the prototype

Commutation time between pre-fault tap and the sag tap is far less than the nominal period of the network (about 500 μ s in the prototype). Therefore, synchronous generator can be considered as a constant current source and the secondary of the transformer as a constant voltage source with the instantaneous values of the sinusoidal current and voltage at the moment of commutation (see Fig. 2b). The leakage inductances of the taps in series with the secondary constant voltages limit the rate of change of the current transfer between the taps. The IGBT switching on and off times are

very short and similar (respectively 710 ns and 930 ns in the prototype) and it causes a smooth current transfer between the two taps through the snubber network of the IGBT that switches off. This snubber limits the overvoltage across the bidirectional switch (less than 1.5 pu of the line voltage in the prototype). Note that commutation time is negligible compared to the time constants involved in the electro-mechanical transient of study. Experimental validation is shown in Fig. 8 in section V.

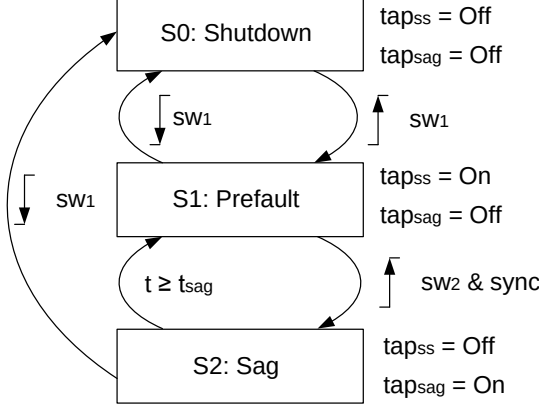


Fig. 4. VSG control scheme with the same steady state tap for the pre-fault and post-fault periods.

C. Components sizing

Components can be classified as operative and protective. The limitations of the former are the specifications of the later. Limitations should meet the compromise between component protection and test insusceptibility.

1) Operative components

The transformer has the same ratings as the generator under test (10 kVA). The overloading capability was defined by simulation in EMPT, for a voltage sag of 0.05 pu of retained voltage, that yielded a peak of 283 A. This current value during 1 second has been taken as a reference provided that it is consistent with the expected subtransient current of the generator (5-10 times the rated current). The overvoltage capability has been limited to a maximum of 1000 V as it is typically demanded in low voltage standards.

IGBTs have been sized taking into account both voltage and current. The Semikron SKM600GA12V (600A, 1200 V) IGBT was selected.

2) Protective components

Protective components protect not only the VSG integrity but also the generator and the grid from undesirable overvoltages and overcurrents.

C120H D 40 A Schneider circuit breakers have been selected to trip during permanent faults but not to trip during the test. Their rated current allows a permanent overcurrent of 160%. The D curve guarantees that the instantaneous tripping will not happen below 10 times the rated current.

A supplementary protection to the IGBTs against accidental short circuits between taps has been added. They are fast fuses (300 A) whose rated current is below the IGBTs rated current.

Snubbers have been sized to offer a high impedance in steady state and a low one during transients. The resistance was fixed in 1 Ω as a compromise between voltage drop and

current capability during transients. A high overloading capability of 10 times the rated current has been chosen. The capacitance was sized through simulations to damp the switching oscillations in less than 1 ms and to limit the voltage peaks below 1000 V. A value of 1.2 μF was obtained. The steady state impedance of the snubber is 2.65 k Ω .

Varistors are conceived as a backup protection to the IGBTs and the transformer insulations. They are sized by the voltage and the power. The SIOV high energy B40K420 EPCOS varistors have been selected. They guarantee a clamping voltage at 420 V_{RMS} , which is below the specified limit, and are able to dissipate 910 J during 2 ms far enough to cope with the energy stored in the windings.

V. VSG PROTOTYPE TEST AND VALIDATION

A. Description of the Test Bench

The best way to check the performance of the proposed TCT based VSG prototype is using it to evaluate the FRT capability of an actual synchronous generator. A test bench has been assembled as shown in Fig. 5, to produce voltage sags and reproduce the fundamental dynamics of a power plant for the transient stability phenomena in a system equivalent to the one shown in ¡Error! No se encuentra el origen de la referencia..

The test bench is made up of a synchronous generator a turbine simulator (induction motor + flywheel + power drive), a step up transformer, a bus fed static excitation system (transformer + rectifier), the voltage sag generator under test, and a SCADA system implemented in the Dspace DS1103 platform at a sampling frequency of 10 kHz. Test bench's rated power is 10 kVA, whereas the rated voltages at each of the transformer's sides are respectively 230 V and 400 V. The shaft line rotates at 1500 rpm.

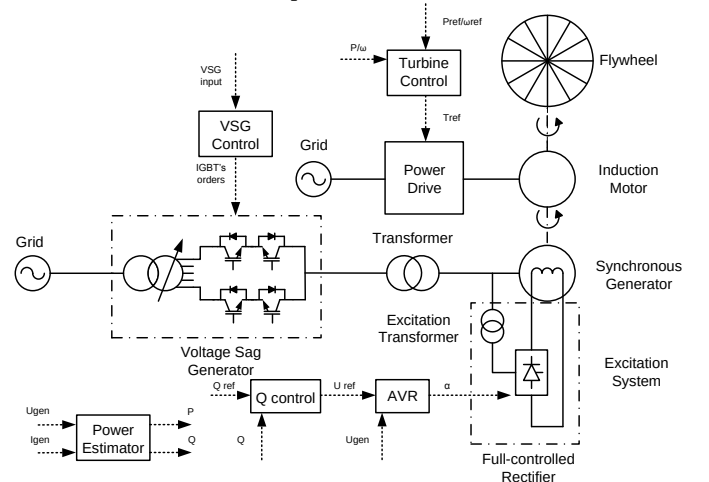


Fig. 5. Test bench layout.

B. VSG Prototype Tests

The performance of the TCT based VSG prototype is displayed by means of voltage sag with a retained voltage of 0.05 pu during 400 ms.

Prior to the voltage sag, the synchronous generator was delivering 0.85 pu and 0.50 pu of active and reactive power, respectively. The two upper subplots from Fig. 7 display the

measured voltage at the VSG input (grid side) and the VSG output (generator side), respectively. The two lower subplots from Fig. 7 represent the synchronous generator's terminal voltage and stator current. It can be noted that distortion of the grid is minimum during the voltage sag. Furthermore, the sag is perfectly rectangular at the output of the VSG. Both voltages are free from harmonics due to the VSG concept as long as it is free from high frequency switching power electronics.

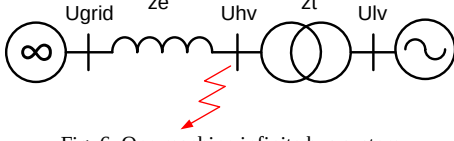


Fig. 6. One machine infinite bus system

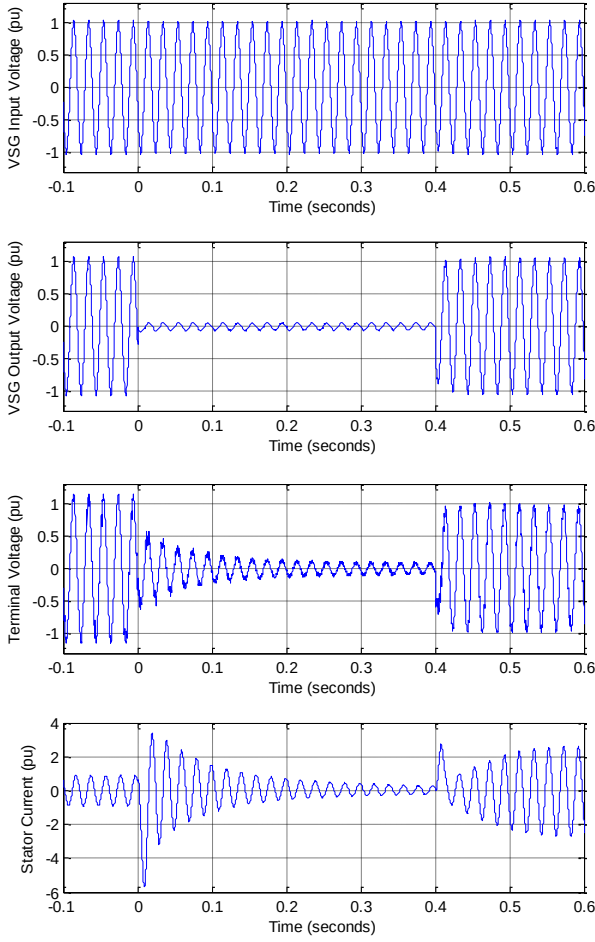


Fig. 7. Detail of instantaneous voltages at VSG input (grid side), VSG output (generator side), synchronous generator terminal voltage and synchronous generator stator current during a sag of 0.05 pu of retained voltage and 400 ms of duration.

Fig. 8 displays an oscilloscope capture of the first millisecond of the sag (pre-fault switch switches off, whereas fault switch switches on). It shows the tap commutation detail using a high speed 10 channels Yokogawa DL850 SScopeRecorder at a rate of 5 MS/s. The switching time was done coincidentally with the current peak of phase as it is the

most demanding one. The signals shown in Fig. 8 are indicated in Fig. 2b.

As stated in section IV.B, the transition from pre-fault tap to fault tap is fast and smooth (oscillations are damped out within 500 μ s).

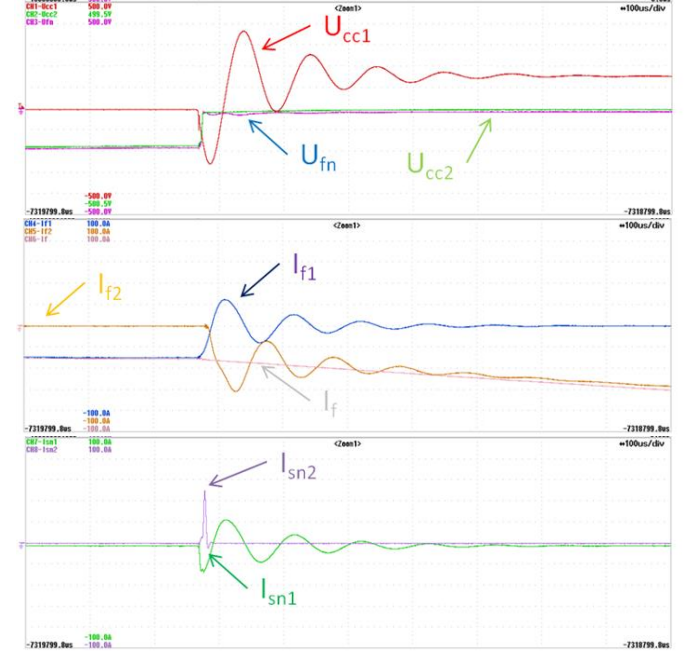


Fig. 8. Tap commutation detail (1 ms) captured by the oscilloscope captures (up to down): collector-collector voltages (U_{cc1} & U_{cc2}) and VSG output voltage (U_{fn}); current through the pre-fault and sag taps (I_{f1} & I_{f2}) and phase current (I_f); current through the snubbers (I_{sn1} & I_{sn2}).

C. VSG Prototype Validation

Experimental results are compared to simulations. The voltage sag is simulated as a three phase to earth short-circuit through a pure reactance at the transformer's high voltage side (Fig. 6). The generator has been modeled as a 3rd order salient pole generator with saturation and the rotor has been modeled as a 4th order two lumped masses model. Therefore, the stator fluxes time derivatives are neglected. Consistently with the later assumption, only the algebraic equations of the network are considered. A 2nd order AVR model has been used. Neither PSS nor governor has been included.

Fig. 9 depicts the corresponding RMS values from measurements on Fig. 7 against the simulation results. Grid voltage is minimally distorted after the sag end as it was required in order not to disturb other equipments. Moreover, the rectangular voltage sag produced by the VSG resembles strongly to an inductive fault in the simulated network. Generator voltage and current excursions obtained using the proposed VSG together with the simulated fault are very similar proving the ability of the VSG to reproduce almost ideal grid faults. The high generator current peaks during and after the sag justify the election of components with high transient capabilities for the proposed VSG.

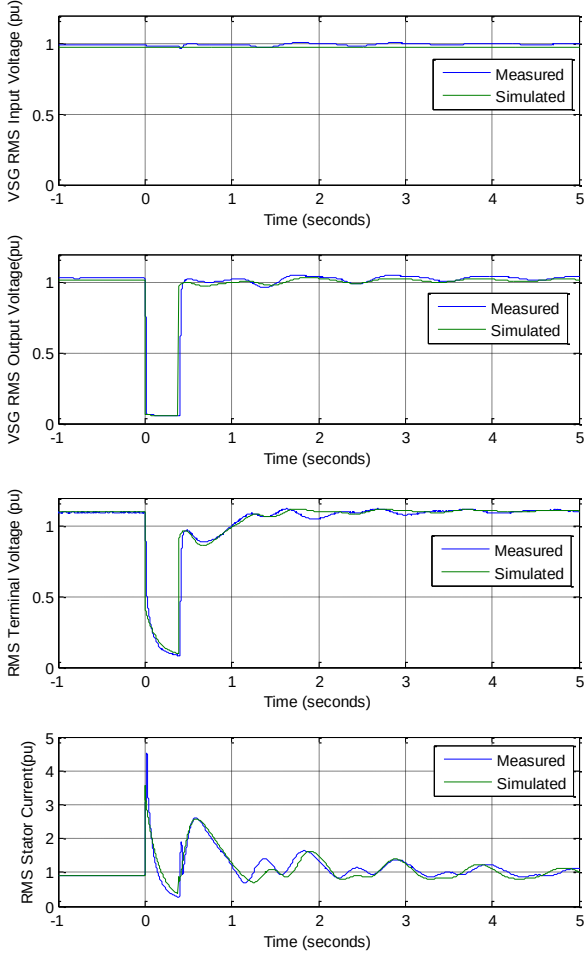


Fig. 9. RMS values at VSG input (grid side), output (generator side), synchronous generator terminal voltage and synchronous generator stator current during a sag of 0.05 pu of retained voltage and 400 ms of duration.

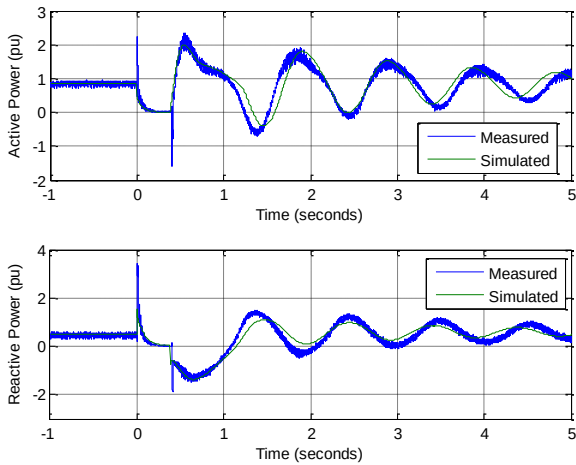


Fig. 10. Active and reactive power during a sag of 0.05 pu of retained voltage and 400 ms of duration.

Fig. 10 represents the active and reactive power of the generator. These two variables have an important impact on the VSG design, as long as the active power and current experience important excursions after the fault clearing and

their transient values can double the steady state ones. This figure demonstrates that the proposed VSG is able to operate in the four quadrants with important transient capabilities without disturbing the generator response.

VI. CONCLUSIONS

The proposed VSG is the first piece of equipment to test synchronous generators Fault Ride Through (FRT) capability. It copes satisfactory with the technological requisites of synchronous generators.

The proposed VSG is based on an electronically controlled Tap Changer Transformer (TCT). The taps are commuted by IGBT based bidirectional switches, which are controlled by a simple state machine that deals successfully with the switching problems. The design of the VSG guarantees the absence of harmonics and switching noise as long as no power converter is involved in the sag generation.

A small scale prototype has been assembled and tested. Moreover, it has been compared with a simulation of a power system and it reproduces faithfully the behavior of the grid during a three phase to earth short circuit.

Although only a three phase fault has been presented, the VSG design allows controlling the number of phases involved in the sag, the sag depth, the phase angle of the sag, the sag duration and the pre-fault, fault and post-fault voltage levels.

VII. ACKNOWLEDGEMENTS

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