Design, Control and Simulation of a Grid Emulator for Standards Requirements Based Compliance Testing of Grid Connected Photovoltaic Inverters

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***Abstract*--The main purpose of this study is the design and performance investigation of a test bench reproducing grid behavior in both ideal conditions and in presence of normative faults. It is able to generate different types of disturbed grid voltages as symmetrical and unbalanced voltage sags, frequency variations and harmonic disturbances. Taking into account the Tunisian grid specifications as well as national and international standards requirements, the designed grid emulator aims to test performances of single and three-phase utility-interconnected photovoltaic inverters existing in the Tunisian local market.**

***Index Terms*—Grid emulator, photovoltaic inverter, standards requirements, ideal grid conditions, normative faults.**

1. INTRODUCTION

Nowadays, electrical power generation based on renewable energy sources becomes one of the biggest concerns because of the fuel sources lack, polluting effects and raised price. In the Tunisian case, for example, national plans are targeting, by 2030, to achieve 30% of the electrical power generation based on distributed renewable energy including 10% of photovoltaic systems conditioned by grid connected inverters. Indeed, the utility-interconnected devices such as photovoltaic inverters are submitted to compliance tests, due to power quality evolving concerns in grid codes, national and international standards. The main objective of these tests is to study and propose better solutions and recommendations for renewable energy integration problems [1]. One of the major technical issues is islanding. It is defined as a potentially hazardous phenomenon in which a distribution generation continues to dispatch power to a portion of the system while that portion is electrically separated from the main power system. Such isolated islands may cause serious damages for maintenance personnel, customer equipments and grid utility. Thus, the islanding prevention for utility-interconnected photovoltaic inverters is an important performance test to be carried out. Consequently, referring to both the European and Tunisian Standards, respectively EN 62116 and NT 67.53, a normative test bench, depicted in Fig. 1, is needed [2]-[3]. It is composed of 4 parts: an AC energy supply: the Grid, a DC energy source: a photovoltaic generator, a load emulator and a supervision system. The presented test bench aims to evaluate the equipment under test (EUT) performances based on normative conformity under various grid conditions [2]. The EUT, in the present study, is the photovoltaic inverter. However, a real grid cannot be used because of its output voltage inflexibility. Therefore, a grid emulator (GE) is required to reproduce grid behavior, both in ideal conditions and in the presence of normative faults. In fact, the sinusoidal voltage waveform will be generated with high flexible programmability of given network characteristics [4]. For this purpose, this paper focuses on the design of a grid emulator, to be included in the normative photovoltaic inverter test bench, taking into account Tunisian grid specifications and national and international power quality standards.

This paper is organized as follows. Firstly, in section II, standards requirements in ideal grid conditions and in presence of grid faults are presented. Then, in section III, the study and design of the proposed grid emulator power topology and control strategy are detailed. Section IV exposes and discusses the simulation results in order to validate the designed GE. Finally, a conclusion and some future works are given.

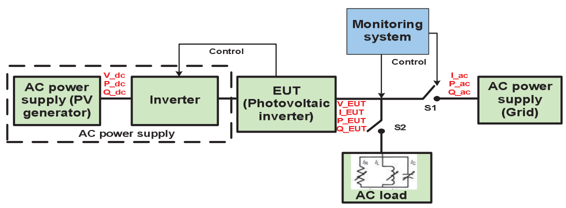

Fig. 1. Test bench for compliance testing of grid connected photovoltaic inverters [2]

2. Standards Requirements

In recent years, grid codes and international standards concerns are still evolving. In this context, the proposed grid emulator is designed within a normative test bench for compliance testing of photovoltaic inverters to be commercialized in the Tunisian local market.

Hence, studies of international standards dealing with grid emulating aspects and photovoltaic grid inverter tests, lead to the definition of the grid emulator to be designed taking into account both ideal and grid faults operating conditions.

A. *Ideal grid Conditions*

In this case, the grid emulator should be able to generate a perfect sinusoidal voltage waveform with a tolerance range as imposed in the European Standard EN 62116 [2]. The output characteristics are presented in Table I.

TABLE I

GRID EMULATOR CHARACTERISTICS IN IDEAL GRID CONDITIONS [2]

Parameters	Symbol	Characteristics
Rated output line-to-neutral voltage	V_{ac}	230 V_{rms} ± 2%
Frequency	f	50 Hz ± 0.1 Hz
Voltage THD	THD_U	<2.5%
Phase angle	Φ_{ac}	120° ± 1.5°
Rated current	I_{ac}	0 A …25 A
Rated power	P_{ac}	0 kW …6 kW

B. *Grid Faults Conditions*

Several grid faults are defined and presented in many standards which deal with power quality issues, such as EN50160, VDE126 and CEI61000. In the case of the Tunisian grid, the national energy provider bases his grid studies on the European Standard EN50160 [5]. Each grid fault is characterised by a specific output signal waveform with a prescribed tolerance range. Those specifications are presented respectively in Tables II and III.

TABLE II

INDIVIDUAL HARMONIC VOLTAGES AT THE SUPPLY TERMINALS [5]

Odd harmonics				Even harmonics	
Not multiple of 3		Multiple of 3			
Order h	Relative voltage (%)	Order h	Relative voltage (%)	Order h	Relative voltage (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6…24	0.5
13	3	21	0.5		
17	2				
19	1.5				
23	1.5				
25	1.5				

TABLE III

GRID EMULATOR CHARACTERISTICS IN PRESENCE OF GRID FAULTS [5]

Description	Parameters	Symbol	Value
Frequency variation	Power frequency	f	50Hz -6% +4%
Voltage magnitude variations	Output voltage	V_{ac}	230 V_{rms} ±10%
Rapid voltage changes	Long term severity	P_{lt}	< 1
Supply voltage sags	Duration	Δ_t	< 1s
	Depth	V_{ac}	< 60%
Short interruptions of supply voltage	Duration	Δ_t	< 3min
Long interruption of supply voltage	Duration	Δ_t	> 3min
Temporary power frequency overvoltages	Output voltage	V_{ac}	< 440 V
	Duration	Δ_t	5s
Transient overvoltages	Output voltage	V_{ac}	< 6k V_{rms}
	Duration	Δ_t	ms-µs
Supply voltage unbalance	Voltage unbalance	V_U	< 2%
Harmonic voltage	Output voltage	V_{ac}	See Table II

3. Study and Design of the Grid Emulator

The objective of this section is to present the GE design methodology. The first subsection aims to study its power topology. Then, the second part presents the proposed control strategy.

A. *Power Topology Study*

In this subsection, first, according to a deep bibliographic study, different power electronics solutions based GE, developed by researchers, are presented. Second, a comparative analysis is carried out to conclude to the GE power topology to be adopted. The related filters design is then detailed.

1) *Existing Grid Emulator Power Topologies:* The grid emulators were developed basing on four topologies: thyristor-controlled-reactor-based, transformer-based, generator based and linear-amplifier-based ones [6]. With the advent and the evolution of power electronics, the voltage source inverters (VSI) based systems are becoming a very competitive realization technique of the grid emulators. In this context, four power electronic topology based grid emulators are presented in Fig. 2, Fig. 3, Fig. 4 and Fig. 5. Each of these GE structures has its own advantages and drawbacks. Indeed, the three-level neutral point clamped voltage source converter presented in Fig. 2 is able to reproduce balanced and unbalanced faults with high voltage resolution but it uses a big number of switches which is economically unsuitable [7].

The second topology, based on voltage source inverter cumulation, and presented in Fig. 3, is able to generate transient low frequency faults and high order harmonics but it presents an interaction between the two used inverters [8]. The third solution, depicted in Fig. 4, is based on two three-phase three-leg converters. Such an emulator can produce voltage and frequency variation and harmonic faults. But, it is not able to generate single phase and unbalanced grid faults. This topology is then limited to the generation of balanced three phases [9]. The last topology presented in Fig. 5 is based on two three-phase four-leg converters. It allows generating single and three-phase, balanced and unbalanced grid faults, voltage and frequency variation as well as harmonic disturbances [10]. This structure can be used to reach the desired standard requirements. But it will rather be modified to make it more economically suitable.

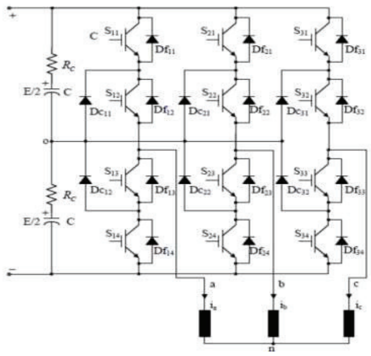

Fig. 2. Three-Level Neutral Point Clamped Voltage Source Converter (3L-NPC-VSC) based Grid Emulator [7]

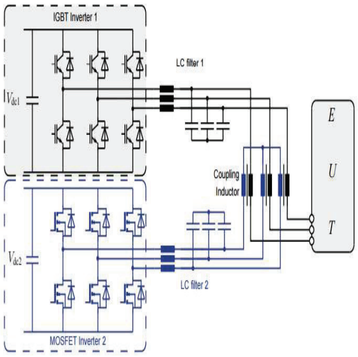

Fig. 3. Voltage Source Inverter Cumulation based Grid Emulator [8]

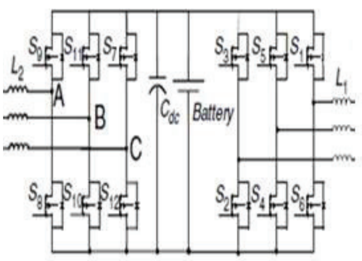

Fig. 4. Two conventional three-phase three-leg converters based Grid Emulator [9]

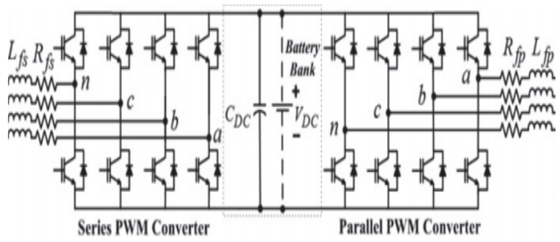

Fig. 5. Two three-phase four-leg converters based Grid Emulator [10]

2) The Adopted Grid Emulator Design: The grid emulator design adopted in this study is described by Fig. 6. It is characterised by a back-to-back inverter topology. In the grid side, a conventional three-phase three-leg AC/DC converter is used. In the Equipment Under Test (EUT) side, a three-phase four-leg converter is adopted in order to generate balanced and unbalanced faults [11].

The used four-leg Voltage Source Inverter (VSI), involves one more leg than the conventional three-leg inverter which provides a way for the zero-sequence currents in case of unbalanced, single and three-phase loads [12].

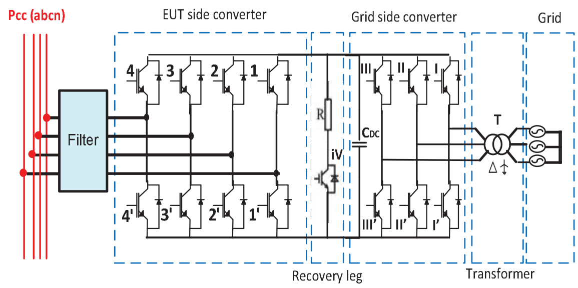

Fig. 6. The Adopted grid emulator topology

3) The GE AC and DC Filters Design: The grid emulator topology is based on power converters generally characterized by their high harmonics range. Then, the use of LCL filters is required in order to deal with grid codes and international standards requirements. The filter design is carried out basing on high filtering performances and by ensuring low weight, size and cost. Indeed, the designed LCL filter is characterized by a supplementary inductance for the fourth converter wire as presented in Fig. 7. This design aims to ensure the EUT side converter output voltage filtering and to meet the filter resonance frequency condition [13]. On the other hand, the designed grid emulator has to generate harmonic faults with a range up to 25 according to the EN50160 Standard [5]. Then, the filter resonance frequency should be in respect with the equation 1. Moreover, the filter inductances and capacitances are sized according respectively to equations 2 and 3 [14].

$$25.f < f_{res} < \frac{f_{sw}}{2} \tag{1}$$

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_x + L_n + L_{x'}}{C_x.L_{x'}.(L_x + L_n)}} \tag{2}$$

$$C_x = \frac{\Delta.P}{V^2_{ac}\omega_1} \quad (3)$$

where

f : is the Grid frequency

f_{res} : is the filter resonance frequency

f_{sw} : is the switching frequency

x : denotes respectively the a, b and c phases

L_x : are the EUT side converter filter inductances

$L_{x'}$: are the PCC side filter inductances

L_n : is the PCC side neutral filter inductance

C_x : are the AC filter capacitances

P : is the output rated power

Δ: is a relative power value assumed to ensure a capacitive reactive power at a rated load less than 5% of the output rated power

V_{ac} : is the Line-to-neutral RMS grid voltage

ω_1 : is the fundamental Grid pulsation

Regarding the DC bus, it is designed to provide sufficient energy to the EUT side converter to generate the appropriate output signal. The DC bus voltage sizing is then given by equation 4 [15].

$$V_{DC} = \frac{2\sqrt{2}}{m} V_{ac\max} \quad (4)$$

where

$V_{ac\max}$: is the maximum line-to-line RMS grid voltage

m : is the modulation index of the Grid side converter

On the other hand, the DC bus capacitance value is designed using equation 5 basing on the approach presented in [16].

$$C_{DC} = \frac{2.E_{DCres}}{U^2_{DC\max} - U^2_{DCn}} \quad (5)$$

where

E_{DCres} : is the DC bus Energy reserve

$U_{DC\max}$: is the maximal DC link Voltage

U_{DCn} : is the nominal DC link Voltage

According to the described AC and DC filter design methodology, the LCL filter parameters are given in Table IV.

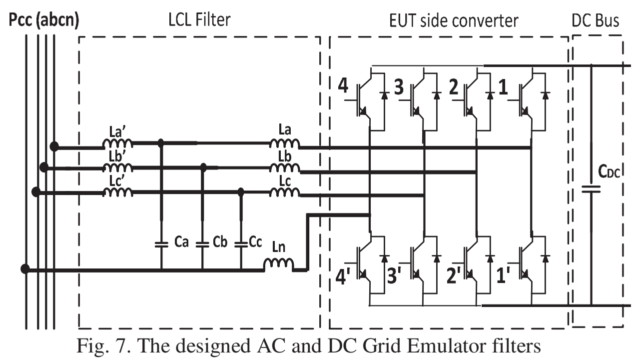

Fig. 7. The designed AC and DC Grid Emulator filters

TABLE IV

THE DESIGNED LCL FILTER PARAMETERS

Parameter	Symbol	Value	Unit
Grid frequency	f	50	Hz
Switching frequency	f_{sw}	15	kHz
Line-to-neutral RMS grid voltage	V_{ac}	230	V
Maximum Line-to-neutral RMS grid voltage	$V_{ac\max}$	253	V
Modulation index	m	0.9	
AC filter inductance	L_x	1.8	mH
	$L_{x'}$	1.8	mH
	L_n	1.8	mH
AC filter capacitance	C_x	27	µF
Minimum DC bus voltage	V_{DC}	800	V
DC bus capacitance	C_{DC}	1100	µF

B. *The Control Strategy Study*

1) *The Grid Side Converter Control Strategy:* As a conventional three-phase three-leg converter is adopted in the grid side, a classical PI controller, used generally for current-controlled inverters, is designed such that the reactive power flux does not disturb the grid and the DC link voltage is well controlled [17]. The control strategy is developed in the dq frame as depicted in Fig. 8.

2) *The EUT Side Converter Control Strategy:* A three-phase four-leg converter is used in the EUT side. Its control strategy is ensured in order to maintain the output voltages equal to the reference ones to emulate both ideal grid operating conditions, as depicted in Table I, and disturbed grid operating conditions, as presented in Tables II and III. The EUT side converter control strategy, as depicted in Fig. 9, is based on a two control loops cascade. The external loop aims to control the grid emulator output voltage in the EUT side. The internal loop controls the grid emulator output currents and generates then the inverter voltages references. In this case, using a resonant controller allows tracking sinusoidal inputs, introducing an infinite gain at the resonant frequency and eliminating steady-state error. This strategy requires less computational resources and execution time than conventional PI based controllers [18]. The resonant controller used in this study is defined as show in equation (6).

$$G_{PR}(s) = K_p + K_i \frac{s}{s^2 + \omega^2} \quad (6)$$

where

K_p and K_i are respectively the proportional and integral gains,

ω is the resonance frequency.

4. Simulation Results

In this section, simulation results, using the PSIM software package, are presented and discussed, in order to validate the designed GE performances. The simulated system includes the designed GE connected to a three-phase RL load and a given photovoltaic inverter (EUT).

Three GE operating conditions are then analyzed: ideal grid conditions, voltage sag fault occurrence and unbalance voltage disturbances. The simulation results are respectively presented in Fig. 10, Fig. 11 and Fig. 12.

The simulated waveforms, for the three studied cases, are organized as follows.

The first curves depict the DC bus voltage reference and response. A progressive capacitance charge reference is taken into account to reach the desired DC bus voltage of 1000V.

The second simulation waveforms are one-phase GE output line-to-neutral voltage and its reference.

Furthermore, the third curves present the three phases line-to-neutral voltages variations.

Finally, the last waveforms present the output current responses to the grid operating condition variations which are respectively:

- A load variation at t=0.4s in case of normal grid operation,

- A voltage sag occurrence at t=0.5s,

- A voltage unbalance occurrence at t=0.5s.

Indeed, the three cases of the emulated grid voltages are simulated as follows:

- The ideal sinusoidal voltage waveform depicted in Fig. 10, during 0.8s, is generated with a 230V rated line-to-neutral voltage, a 50Hz rated frequency and a 120° phase angle. The voltage references are generated according to the EN 62116 Standard requirements [2].

- In Fig.11 and Fig. 12, the voltage sag grid fault and the unbalance voltages disturbance simulation results are presented during 0.2s. Their specifications are based on the EN 50160 Standard [4]. The voltage sag is generated during 0.1s with a depth of 50% and respect of the phases balance. On the other hand, the unbalance has been reproduced on the phase 'a' with a 10% overvoltage of the rated voltage.

The obtained results demonstrate that the designed GE emulate in an accurate way the grid behavior and is able to reproduce the grid faults as they are defined by the standard requirements. Indeed, the GE output voltages and the desired references are in good agreement. These results show the effectiveness of the designed GE in both, ideal and faulty grid conditions.

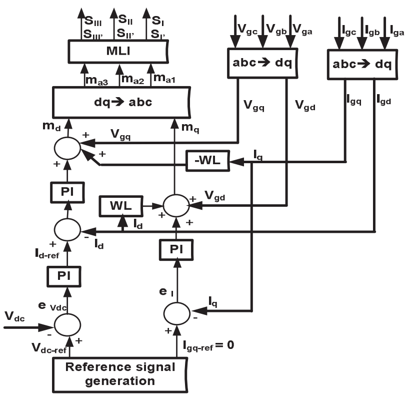

Fig. 8. Grid side converter control strategy

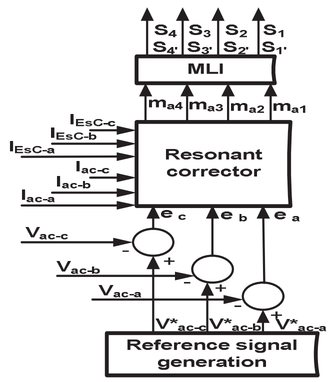

Fig. 9. EUT side converter control strategy

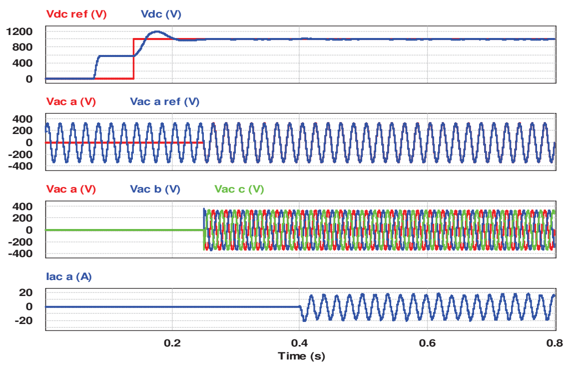

Fig. 10. Simulation results of the proposed grid emulator connected to the EUT (photovoltaic inverter) and three phase RL load in ideal grid operating conditions

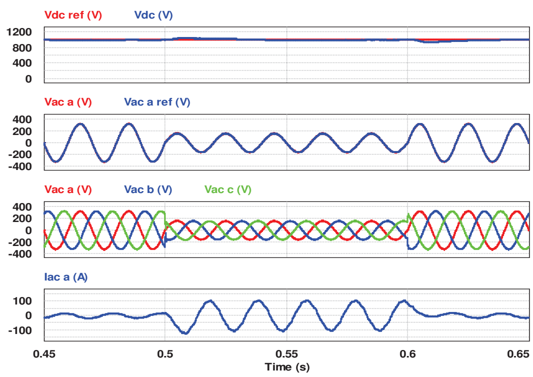

Fig. 11. Simulation results of the proposed grid emulator connected to the EUT (photovoltaic inverter) and three-phase RL load in presence of voltage sag conditions

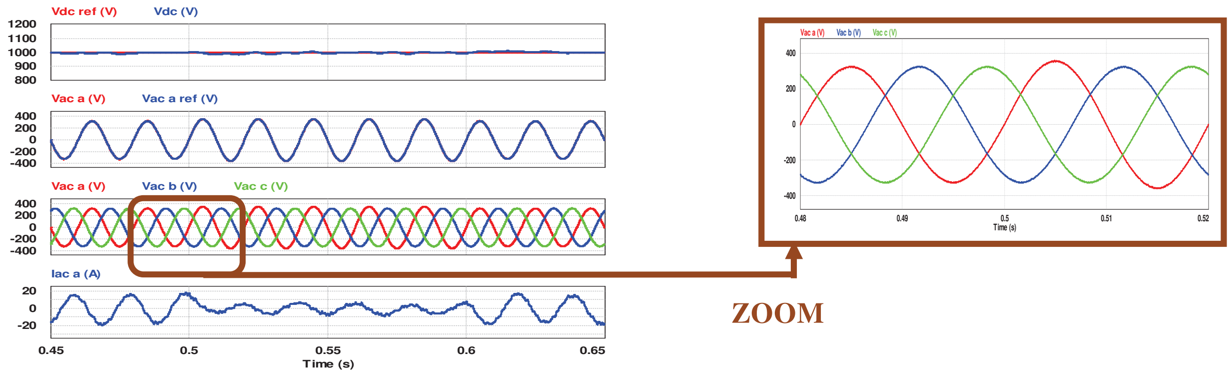

Fig. 12. Simulation results of the proposed grid emulator connected to the EUT (photovoltaic converter) and three phase RL load under unbalance fault conditions

5. Conclusion

This paper presents the design methodology of a Grid Emulator (GE) dedicated to the emulation of the Tunisian grid behavior basing on the EN 50160 Standard requirements. The designed emulator will be developed to test grid connected photovoltaic inverters performances according to the Tunisian market and grid requirements. The GE power range considered is up to 6kVA. First, a bibliographic study has been conducted to identify the different emulator topologies developed by researchers as well as the standard requirements to be considered both in ideal grid operating conditions and in presence of normative faults operating conditions. Second, the adopted GE topology has been presented, analysed and sized both in terms of power and control design. Finally, simulations have been carried out to validate the proposed GE design. An experimental setup is being developed to validate the accurate operating of the designed grid emulator according to the Tunisian grid standard requirements.

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