EXPERIMENTAL VALIDATION OF MV GRID REACTIVE POWER COMPENSATOR BASED ON A FOUR LEVEL POWER ELECTRONIC CONVERTER

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ABSTRACT

The present paper is focused on the development and the experimental validation of an electronic voltage regulator/reactive power compensator based on a multilevel converter, designed to operate in the medium voltage distribution network. The new operation requirements of the electric system justify more and more the introduction of equipment based on power electronics adapted to medium voltage (MV) distribution networks. This electronic equipment allows optimising the power quality and the operation conditions of the distribution networks. In this paper, a device based on a four-level converter is shown. A first experimental validation of a 300kVAR prototype of the system has been carried out. The experimental results show the correct operation of the reactive power compensator, under different working conditions and meeting the power quality requirements.

INTRODUCTION

The new operation requirements of the electric system, justify more and more the introduction of equipments based on power electronics adapted to medium voltage (MV) distribution networks [1-5].

One of the technical solutions to operate in the medium voltage distribution networks is the multilevel converter [6-7]. In this paper, a four level converter based device is shown. In [8] and [9] the limitations of the DC bus capacitors voltage balancing are explored under different operation conditions for this multilevel topology. The work presented in this paper, implements a control for this topology achieving a correct operation behavior, in a medium voltage distribution network. The device regulates the reactive power injection to the distribution network, allowing to perform the following functions:

Grid voltage regulation: It controls the grid voltage rms value in a continuous way. For that purpose, it boosts and reduces the voltage at the connection point of the device, within its optimum operation range. This functionality contributes to compensate the voltage variations of the network, improving the power quality of the grid.

Reactive power regulation: It contributes with reactive power in order to control the reactive power flow of the system. This functionality improves the management of the distribution network.

Power factor regulation: It allows improving the power factor in the connection point of the device, increasing the efficiency of the distribution network.

In Figure 1, the per phase equivalent circuit of the system is shown, connected to a radial distribution network.

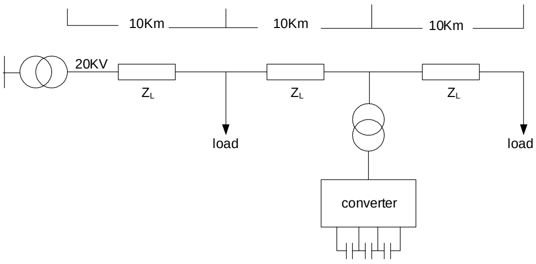

Fig. 1.Radial distribution network and connection of the device simplified schema.

REACTIVE POWER COMPENSATOR

Compensation schema

The reactive power compensator is connected in parallel to the grid as shown in the next figure. By means of a transformer the grid voltage (20 kV) is reduced to the operation voltage of the converter, 6.3 kV. The compensator is composed by a Multilevel NPC inverter based on IGBT semiconductors.

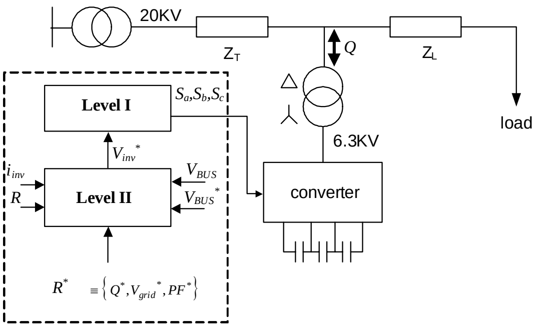

Fig. 2.Simplified schema of the compensator.

The converter contributes with inductive or capacitive reactive power to the grid (Q), in order to meet several network requirements, such as voltage regulation (V_{grid}), power factor control (PF), etc…

The system is not equipped with a passive front end, hence it is not capable to contribute with active power to the grid.

In order to fulfill all the control requirements, the system presents two control strategy levels [10]:

1. Control level I: At this low control level, the voltage references for the inverter are transformed into pulses for the IGBTs of the converter. The inverter voltage references are generated by the control level II, in order to meet the power control requirements. This control is based in a space vector modulation technique [9].
2. Control level II: At this higher level, the power that the system exchanges with the network is controlled. The reactive power (or the PF or the V_{grid}) is controlled to its demanded reference, and the active power is controlled indirectly by controlling the DC bus voltage of the converter. If the system is in the steady state, it does not transmit active power and the DC bus voltage mean value is kept constant.

The four level converter and the filter

Using a multilevel converter topology solves the difficulty that represents the direct connection of a converter to a distribution network. This topology allows dealing with high voltage levels as well as to improve the quality of the provided waveform. This feature reduces the filtering requirements working at low switching frequencies and consequently improving the efficiency of the system.

The voltage supported by the power semiconductors in the multilevel NPC topology is a fraction of the DC bus. Considering this voltage relation, the DC bus voltage has been sized using the power semiconductors that allow to reach the application's voltage specifications.

The selected converter topology is a four level NPC inverter (Fig 3). The static switches are IGBT modules that meet the specifications mentioned previously. In order to achieve reduced harmonic current spectra, a filter is required between the converter and the grid. In the present research study, a transformer that provides the filter and the voltage level conditioner functionalities has been used. The sized transformer's leakage inductance fulfills the attenuation specifications.

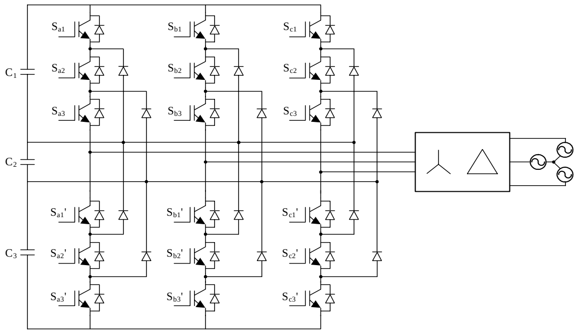

Fig. 3. Four level NPC converter and the filter.

EXPERIMENTAL VALIDATION

In this section, the experimental validation of a 300kVAR prototype of the system is carried out. First of all, the main characteristics of the system are described. After that, the experimental results are shown.

Description of the system

In the next table the most interesting, maximum rated values of the reactive power compensator are presented. As mentioned before, it is mainly composed by two different elements, i.e. the four level NPC converter and the transformer.

Table I.

Nominal ratings of the Transformer

Rated power	300 kVA
Rated primary voltage (Δ)	20 kV
Rated secondary voltage (Y)	6.3 kV
Secondary side equivalent inductance	12.7 mH

Nominal ratings of the Converter

Rated power	300 kVA
DC bus voltage	12 kV
Output voltage	6.3 kV
IGBTs	200 A/ 6.5 kV
DC bus capacitors	600 μF

In the four level NPC converter topology, in each leg of the converter, the IGBTs and the diodes turns between ON and OFF state, in order to achieve the demanded voltage level at the output. There are some combinations, where a part, or the total DC bus voltage has to be distributed between more than one IGBT. It is desired that one third of the total DC bus voltage drops through each IGBT. Taking into account the close distance between the maximum IGBT voltage (6.5kV) and the total DC bus voltage (12kV), it arises the necessity of additional hardware components to ensure the balanced voltage distribution of the IGBTs.

In the present paper, a solution to this problem based on snubbers is adopted. Adding a snubber to each IGBT, the balanced voltage distribution of the IGBTs is achieved not only in dynamic situations, but in static situations too.

Experimental results

The experimental results show the correct operation of the reactive power compensator, under different working conditions, due to the testing facilities requirements.

The behavior of the system, is studied at three different stages:

1. Connection of the device to the grid. When the converter starts operating, since the voltages of the DC bus capacitors experiment a considerably high increment, the voltage balancing algorithm must guarantee that the three voltages track close enough the reference value. On the other hand, the currents of the converter must be maintained within the nominal values too, in order to ensure that the connection is made in a safe manner.
2. Steady –state operation conditions. When the device works under normal operation conditions, injecting the demanded reactive power, the response capacity of the system to changes in the references, as well as the quality of the generated reactive power, must be supervised.

3. Disconnection of the device from the grid (Inhibition of the IGBTs). Finally, when it is desired to perform a disconnection of the device, the designed snubbers play a very important role, because they must guarantee the absolute absence of overvoltages in the elements of the device, especially in the IGBTs.

The experimental results shown below, are focused on demonstrating the desired behavior of the device, in the mentioned three stages.

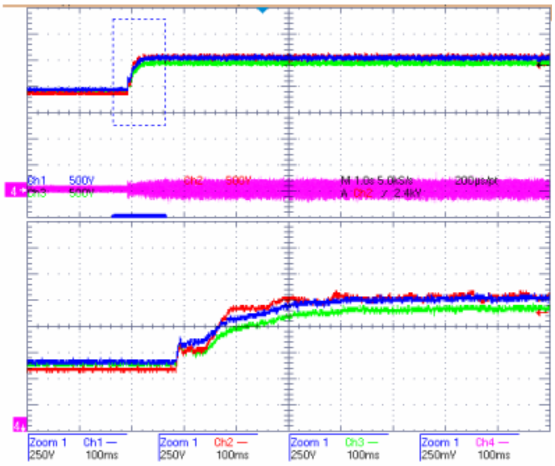

Fig.4. Connection of the converter to the grid with initial references Vbus = 7850 V and Q = 60 kVAR. CH1(1:1000V): Vc1, CH2(1:1000V): Vc2, CH3(1:1000V): Vc3, CH4(1V:10A): Ia

In figure 4, the voltages of the three DC bus capacitors are shown together with the current exchanged by the converter with the grid through the phase a. A initial DC bus voltage is achieved by means of a static pre-charge from the grid through the diodes of the converter. During the connection of the converter, a DC bus voltage step (7.850 kV) from its initial value is required. With this DC bus voltage value, the device is able to exchange 300 kVAR (inductive or capacitive) reactive power, with a 20 kV grid. On the other hand, the reactive power reference at the start has been set to 60 kVAR. A smooth evolution of the voltages and the current is noticed, with an absolute absence of overcurrents or overvoltages.

According to the experimental tests described before, figure 5 shows the steady state operation conditions of the compensator. 200kVAR (inductive) of reactive power are demanded. So, with a 4kV voltage at the low side of the transformer, the current has a maximum fundamental component value of 28 A. On the other hand, with 7.850kV in the DC bus, the inductive current demand implies that the converter generates a fundamental component voltage waveform smaller than the grid voltage.

The current distortion is provoked by high and low frequency harmonics. The high frequency harmonics (they appear in groups around the multiples of the switching frequency, i.e. 3kHz) are filtered by the equivalent resistance-inductance of the transformer. On the other hand, the effect of the low frequency harmonics will be reduced, increasing the current fundamental component, in other words, increasing the reactive power exchanged with the network. The THD of the current, at nominal reactive power (300 kVAR) is 9 %. Simulation results of the 3 MVAR device, have shown that the THD of the current is less than 1.5 % at nominal power.

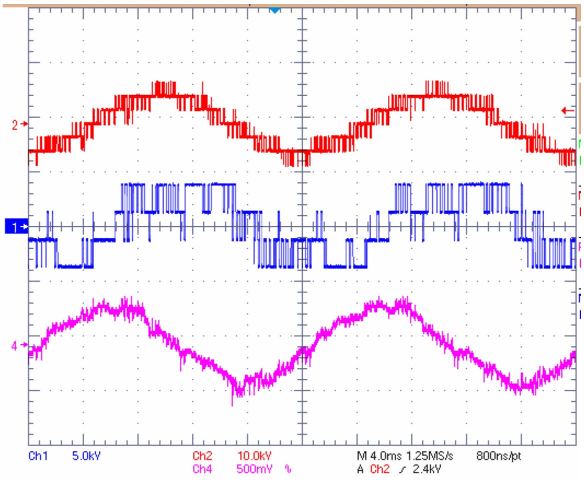

Fig.5. Steady state operation at V_{bus}=7850V and Q=200kVAR (inductive).CH1$_{(1:1000V)}$: $V_{phase\ a}$, CH2$_{(1:1000V)}$: V_{ab}, CH3$_{(1V:10A)}$: I_a.

Finally, to conclude with the described experimental tests, the correct voltage distribution of the IGBTs is shown at steady state operation, and under a disconnection of the device.

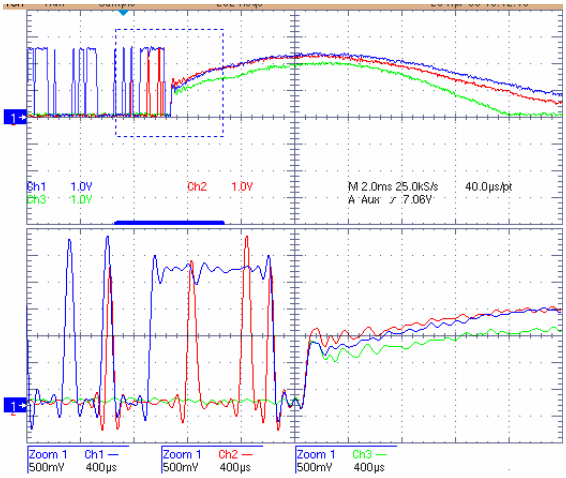

Fig.6. Inhibition of the compensator from the operation conditions: V_{bus}=7850V and Q=200kVAR (inductive).CH1$_{(1:1000V)}$: $V_{CE\ Sa1}$, CH2$_{(1:1000V)}$: $V_{CE\ Sa2}$, CH3$_{(1:1000V)}$: $V_{CE\ Sa3}$.

In figure 6, the collector-emitter voltages of the three IGBTs located above in the phase a, as well as the current of the phase a are shown. The voltages of the rest three IGBTs of the same phase, together with the rest of the IGBTs of the other two legs (b and c) present equivalent behavior due to symmetry.

The first part of figure 6, shows a proper static and dynamic voltage distribution among the three IGBTs, since the voltage is reasonably equally distributed between them. On the other hand, in the second part of figure 6, an inhibition of the IGBTs is performed. Due to the fact that the current can not suddenly disappear, it flows through the snubbers, provoking a short voltage oscillation among the IGBTs that is kept within the maximum permitted voltage values, and at the same time under balanced conditions.

It has to be pointed out, that the inhibition test has been carried out at severe working conditions, since the current that the compensator was treating in the disconnection moment was considerably high. In general, for safety reasons and if it is possible, it is recommended to perform the disconnection of the device at the minimum currents, i.e. compensating zero reactive power. However, thanks to this experiment, it is shown that the device is safely protected even under severe disconnection conditions.

FIELD INSTALLATION

The system will be connected to a 20 kV medium voltage radial distributed network, located in the north of Spain. The connection will be made by means of the corresponding MV switchgear. The selected configuration is implemented by means of a shunt connection cubicle. A MV fuse and a switch with on load breaking capacity are used to protect the installation. It also presents a metering cubicle, providing voltage and current measurements using voltage and current transformers. The system is equipped with a monitoring function and its corresponding control. In figure 7 the device in a concrete envelope with dimensions 4460x2380x3045 mm is detailed.

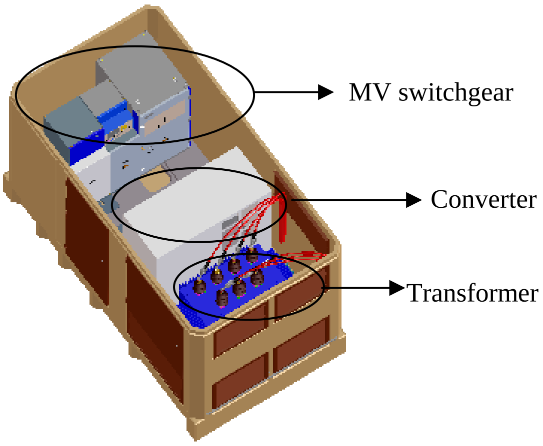

Fig.7. Concrete envelope of the device in field installation.

CONCLUSIONS

This work explores the capacity of a four level NPC based converter in a reactive power compensator application. The voltage range in what the device operates is within the medium voltage distribution networks. It is connected to the grid by a transformer that as well as adequate the voltage range level of the device to the grid, it fulfills the filtering functionality.

From the control aspects point of view, two different control levels strategies have been developed. Second control level strategy allows the control of the reactive and the active power exchanged by the device with the network. First control level strategy deals with the voltage balancing of the DC bus capacitors and the generation of the pulses for the IGBTs in order to create the desired converter's output waveforms.

Experimental results show the capacity of the system to operate under normal operation conditions, compensating reactive power in the whole range within its nominal ratings, and meeting the power quality requirements. Together with this, the proposed snubber topology has proved that guarantees the balanced voltage distribution requirements of the converter's IGBTs, under different operation conditions. This fact is very important in the multilevel topology solution for MV applications, where the voltage levels treated by the converter are very close to the voltage limit of the IGBTs. Finally, the experimental results have shown that the DC bus capacitors voltage balancing algorithm, must pay special attention in the connection of the device to the grid. If no especial effort is dedicated to this transient phenomenon, the voltages of the capacitors tends to unbalance, provoking a potential destabilization of the system and an increase of the voltage that appears in some IGBTs of the converter.

To conclude, the experimental results allow to initiate the validation of the device in field, in a radial distribution network.

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