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Chapter 9

Low Voltage DC System with Storage and Distributed Generation Interfaced Systems

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Additional information is available at the end of the chapter

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1. Introduction

The complexity of the problems related to the generation, transport and utilization of energy increased in the last decades, with the intensification of the global problems regarding environment protection, climatic changes and the exhaust of the natural resources. In addition, the European Union is facing some specific problems, the most important being the one linked to the nowadays high dependency of the imported energy resources. Placed under the pressure of the agreements assumed through Kyoto protocol, The European Union launched in 2000 the third Green Paper "Towards an European strategy for security of supply". The necessity that the renewable sources to become an important part of the energy generation sector it is highlighted. An important increase of their share it is planned. In particular the place of the new sources in a liberalized energy market is discussed, as well as their purpose as main promoters of the "distributed generation"(DG) concept. The interconnection of the storage systems and distributed generation units in the existing power system affects the classical principles of operation for this latter. From the utility point of view, the operation of the these sources in parallel with the power system presents a high interest, as leads to the diminution of the transport capacity, permits the voltage regulation, maintains the systems stability, increases the equipments lifetime. Moreover, the actual trend of increasing installation of these units implies the establishment of their impact on the operation of the power system and on the power quality.

In the last years, the electrical industry sector is suffering important changes: besides the structural changes induced by the deregulated energy market, important developments of the customers installations and devices are taking place. In parallel to these aspects, energy and environmental considerations encourages the spread use of the renewable energy

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sources and the utilization of higher energy efficiency levels, recurring at distributed generation (DG) [1].

These bring to the question if the present distribution networks are still the most adequate to satisfy the nowadays demands. The major part of the DGs and storage systems are generating dc power or require an intermediate dc stage before power injection in a possible ac network. These considerations brought to the possibility to use dc distribution networks, in the presence of sensitive loads and distributed generation. The low voltage dc system ensures a stable voltage level for the supplied customers, connected at the dc bus through ac-dc or dc-dc converters. The choice of the most suitable equipments, which respond to the requirements of an optimum operation of the entire system, is necessary. For guaranteeing the correct and robust operation of the system is essential to adopt adequate control logic for obtaining the best system performances.

2. DC system layout

The profusion of dc power (internally used by various customers facilities based on electronics, present in the conversion state of the UPSs and generated or used in the energy conversion stage by some distributed energy sources) has opened the door for the consideration of a dc distribution system, where all the converters and distributed energy sources are connected. The possible use of a dc distribution network for residential customers has been analyzed in [2], which illustrated the suitability to directly supply with dc power some specific customers. Low voltage dc distribution systems, where the various converters are connected to the main dc bus, were proposed for navy applications, or, for the industrial sector, the supply of variable speed drives.

The main purpose of the dc distribution system is to ensure a high degree of power quality and supply reliability for the customers supplied by it. Also, the network is thought to facilitate the interconnection of the distributed generators and of the storage systems [3]. The dc distribution system, illustrated in Fig. 1, presents a series of advantages with respect to the ac network. The distributed generation units can be interconnected directly with the dc system or through only one ac/dc converter, avoiding in this way the many conversion stages that reduce the system reliability and are responsible for higher power losses. Storage energy systems, for the power quality improvement, can also be interconnected directly or through inverters with the dc distribution system. Also, is not required to realize the synchronization between the generators and the dc network and the control of the system is simpler, as it is not necessary frequency regulation for the islanding operation [4].

The dc bus is the only common point for all the converters. Hence, the control of every converter is based on the dc voltage feedback that is compared with a reference value, in correspondence with every device converter.

The low voltage dc distribution systems must fulfill the following requirements [5], [6]:

- the dc system, with distributed generators and storage systems interconnected, must have a stable operation during ac grid-connected and islanding functioning;
- should deliver premium voltage quality and should ensure high supply continuity for the ac and dc loads;
- the dc system should be expandable: by adding supplementary loads and energy sources, the control strategy must be redesigned in a small manner;
- the electric safety should be ensured respecting the existing standards.

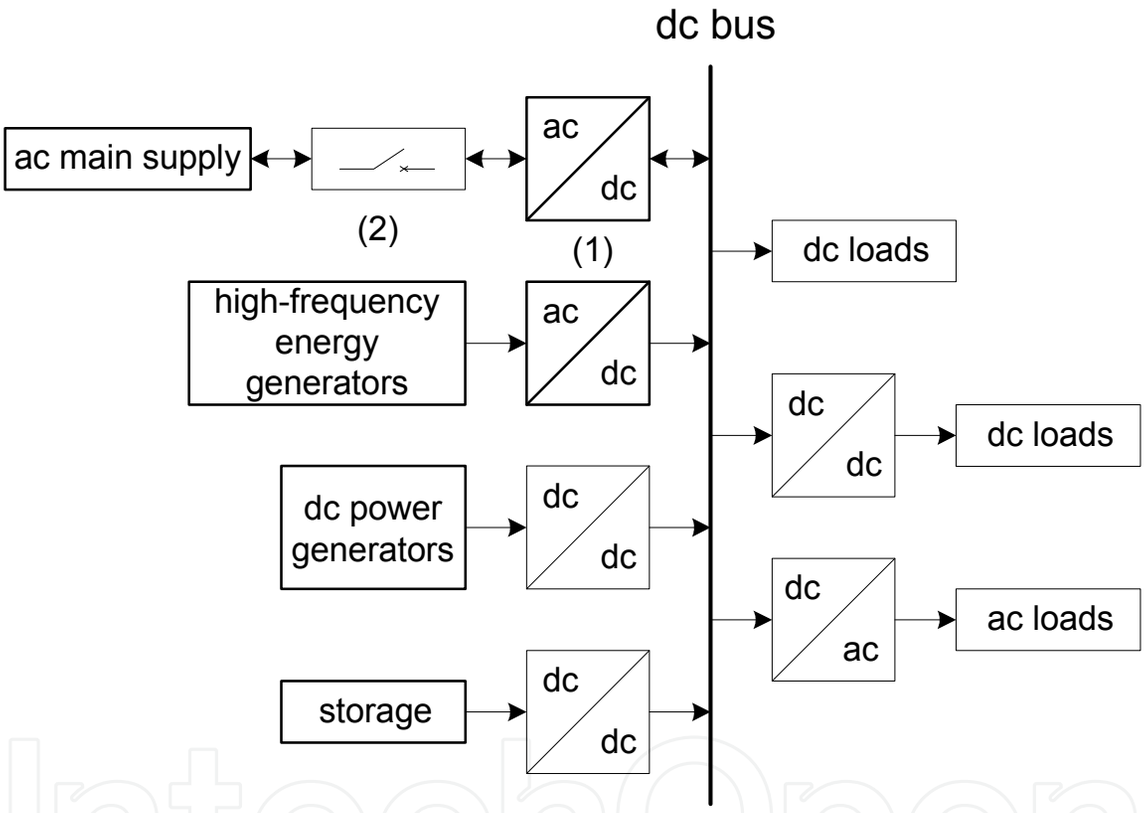


Figure 1. Layout of dc system with storage and distributed generation interfaced systems.

The design process of the low voltage dc distribution system requires the selection of the most suitable combination of energy sources, power-conditioning devices, and energy-storage systems for responding to the necessities and requirements of the dc low voltage dc distribution system, together with the implementation of an efficient energy dispatch strategy.

In Fig. 2, the layout of the dc distribution network with distributed generators, storage energy systems and sensitive loads, is illustrated.

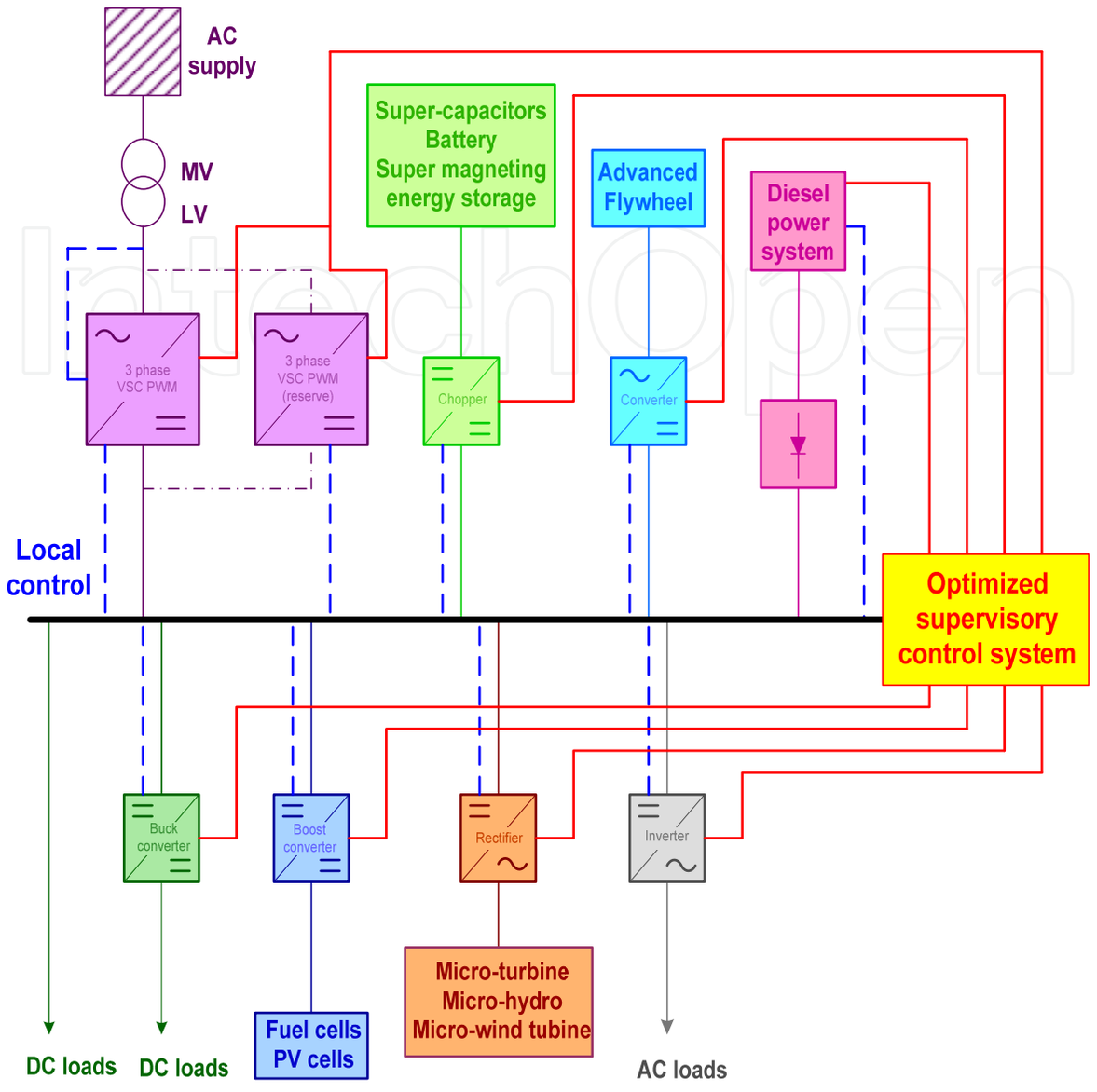


Figure 2. Layout of the dc distribution system

2.1. AC/DC interface

The voltage source converter is a PWM current-controlled one, forcing the instantaneous phase current to follow a sinusoidal current reference template; also, presents some advantages with respect to the voltage-controlled method, like major control stability and it is easier to implement [7]. Using the known PWM techniques, the ac input current drawn by the converter is controlled to become a sine wave, which is in phase with the input voltage and thus the resulting input power factor is maintained at, or very close to, unity. Since the ac input current is forced by the implementation of PWM methods to be sinusoidal, the resulting current waveform will also have a significantly lower harmonic distortion. Even if the current going through the boost inductors will be sinusoidal, there will be a high-frequency component on top of the fundamental due to the PWM switching. Therefore, a

small passive filter is required on the source-side of the boost inductors to eliminate this harmonic.

In order to obtain the benefits mentioned above, proper control of the power converter semiconductor switches is required. The operation of the different topologies becomes even more complicated when perturbations in ac supply system occur. The use of the forced commutated converter imposes the constraint that the output dc voltage must have a higher level than the peak value of the maximum ac input voltage. This implies a step-up or boost type of ac-to-dc power conversion, with the converter more commonly known as a boost converter.

2.2. DC network devices

2.2.1. Battery system

The high power quality degree of the low voltage dc distribution system is ensured with the help of storage energy systems. The storage energy systems must operate each time the ac/dc interface converter is not able to cover the difference between the load requested and the power generated by the distributed generators, case that can appear during voltage sags or short interruptions of the ac network. The storage energy system sizing is determined in correlation with the operations that has to fulfill. An over sizing of the storage energy system allows to realize the peak shaving function, storing the energy produced by the distributed generators during light load and using it during peak load, avoiding in this way to take it from the ac network. Still, considering the high costs associated with the storage energy systems, it is not considered the peak shaving function and is avoided the over sizing of the storage system.

The existing technologies for the storage energy systems are:

a. lead-acid batteries;
b. super-capacitors;
c. compressed air;
d. flywheels.

The lead-acid batteries are most spread and offer the best ratio cost/performances. By connecting more cells in series or parallel, the capacity desired at the required values of voltage, respectively current are obtained.

Super-capacitors, from a constructive point of view, are similar to electrochemical batteries in that each of the two electrodes is immersed in an electrolyte and they are separated by an ion permeable membrane. The main difference, compared to electrochemical batteries, is that no electrochemical reactions or phase changes take place and all energy is stored in an electrostatic field; for this reason the process is highly reversible and the charge discharge cycle can be repeated frequently and virtually without limit. The charge separation process, which requires a voltage difference across the electrodes, takes places on the two interfaces electrode electrolyte; thus, super-capacitors are usually known as double layer capacitors.

Each electrode electrolyte interface represents a capacitor; therefore, the complete cell comprises two capacitors in series. The thickness of the double layer depends on the concentration of the electrolyte and on the size of the ions.

The voltage regulation function is strictly dependent of the storage system capacity and availability. The bidirectional chopper allows the recharge of the storage system, if it is necessary, when the power is flowing from the ac network to the dc system or when in the dc network an excess energy is available. During the discharge process of the storage system, the control system maintains and stabilizes the dc voltage during islanding operation of the dc network. The chopper is behaving as a boost chopper during the discharge process of the storage system and as a buck chopper during the recharge cycle. The dynamic behavior of super-capacitors is strongly related to the ion mobility of the electrolyte used and to the porosity effects of the porous electrodes; the storage process in the double layer is a superficial effect, consequently the electrode surface behaviors play an important role. The most common super-capacitors for industrial application are based on carbon for the electrode materials and an organic solution for the electrolyte.

2.2.2. Diesel power system

The Diesel power system is designated to supply the dc loads during sustained interruptions in the ac network. The Diesel power system is constituted from a Diesel engine with a synchronous generator and a three phase diode bridge. The diode bridge, of high reliability, has to prevent the power flow through the Diesel power system during the islanding operation of the dc system. In this case, the Diesel power system regulates the voltage of the dc distribution system by acting on the synchronous generator excitation system, while the load demand is achieved regulating the output of the Diesel engine. When the dc power system is grid connected with the ac main supply, the Diesel group is not turned on and has to step in during the loss of the ac grid.

2.2.3. Distributed generators

The diffusion of the distributed energy sources and the storage systems will increase in the power systems all over the world. Most of the small power distributed energy resources and storage energy systems located close to the point of consumption of the customer are generating dc power or require a dc intermediate stage. Hence many of these sources can be connected to a dc distribution system. These energy sources, in correlation with the type of the technology implied and depending on their operating characteristics, are generating powers at different voltage levels. In order to connect them to the same dc bus, these sources are interfaced with the help of power electronic converters, like inverters or choppers.

The wind turbine is interconnected with the help of an ac/dc converter. In order to control the wind speed, within the laboratory implementation, the wind speed is generated by an ac motor drive connected to the wind turbine. The wind turbine is a permanent magnet brushless generator.

The photovoltaic generators allow to directly convert the solar radiations into electrical energy without producing pollutants [8]. The photovoltaic cells are simple in design and require reduced maintenance operations. A key advantage of the photovoltaic cells is the fact that can operate interconnected with the public network or in remote areas. Another important characteristic is their modularity that allows reaching new panels with the purpose to increase the power generated. The diffusion of the photovoltaic plants and the utilization of this energy are limited by the costs of the power generated. Even if this cost is independent on the type of used photovoltaic plant, is directly related to the efficiency of the plant. In the last years it can be noted a progress of the photovoltaic cells, both from the point of view of cost reduction and the improvement of the efficiencies obtained with the technology multilayer. Nowadays, the cost of the electrical energy produced by the photovoltaic plants cannot compete with the energy produced by other technology of distributed generators. The photovoltaic plants are sized with respect to the local loads, where the energy excess is sold to the network or is stored with the help of storage systems. During the design of the photovoltaic plants, the aspects related to electrical safety have to be considered. The photovoltaic panels are ideal for remote applications that require power between watts to hundreds of kilowatts of electrical power. Also in the areas where there is a public network, some applications that require non-interruptible power or standby power can use the photovoltaic power. The photovoltaic plants, as consequence of the incentives proposed by various governments, are the most diffused form of distributed generation in the low voltage distribution systems. To this contributed also the possibility to integrate the photovoltaic panels within the existing buildings. The photovoltaic panel consists of 72 series connected mono-crystal silica cells interconnected to the dc system with the help of a dc chopper.

The fuel cell is a proton exchange membrane fuel cell supplied with pressurized hydrogen and ambient air. The fuel cell is interconnected to the dc system with the help of a dc chopper.

The distributed generators contribution is to allow the injection in the ac network of the power excess, during light load, and to supply, in parallel with the storage system, the dc power system during islanding operation.

2.2.4. Loads

The loads interconnected to the dc distribution system can be dc loads or ac loads. In the first case, the supply can be realized directly, if the loads operation permits, or by using a buck converter, when the loads operating voltage is lower than the dc voltage level. In the second case, an inverter is the interface device.

3. Logic of control

The use of the optimized control is based on the supervision of the sources and converters states that has to determine the power requests such that to realize the load sharing [9]. The optimized control strategy needs to ensure high reliability of the system.

The supervisory control allows avoiding the interaction between the electric devices controllers and obviating the occurring high or sudden transients (Fig. 3). The input commands and the limiting values to these controllers come from the supervisory control that produces the required references for the system devices. The supervisory control system determines the behavior of each component: only one device is operating as a voltage source (when the component is directly responsible for the regulation of the dc voltage) while others are operating as current sources (when the component is injecting or absorbing its power available at that instant of time) [10].

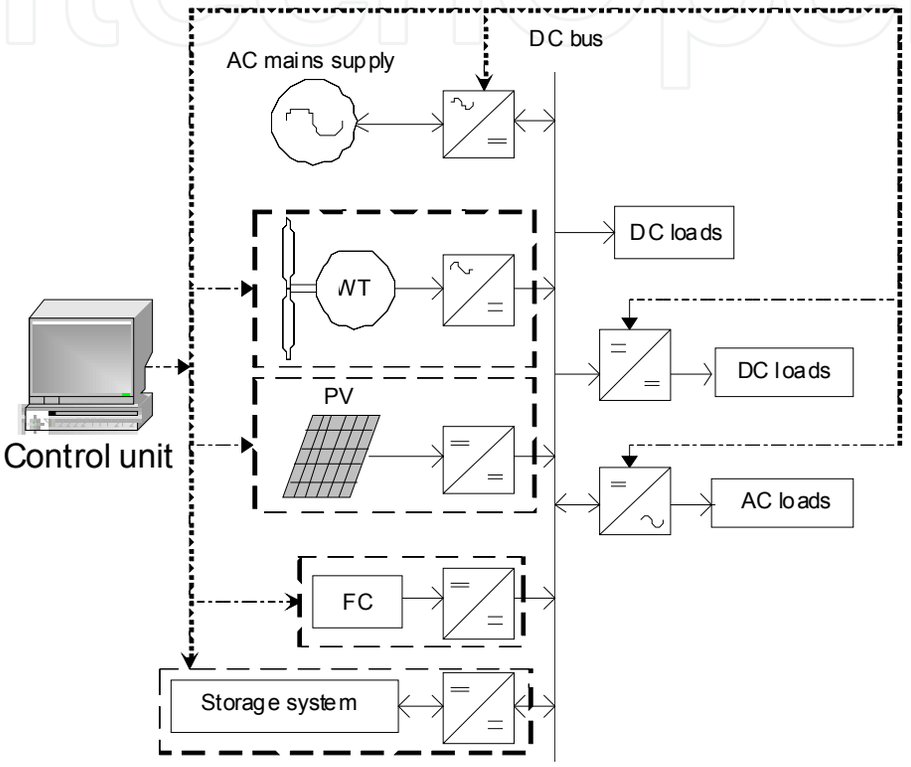


Figure 3. Layout of control implementation

The supervisory control is based on the fact the power systems are current-controlled devices, even when these are behaving as voltage sources. Hence, the optimized control strategy imposes the current of the various power systems, and in this way also the power injected by these devices, for maintaining the dc voltage at the desired value. The philosophy of supervisory controlling the sources and loads is important to be correctly established such that the interaction between the various devices, operating in parallel, must not lead to the instability of the system. The supervisory control has to manage the sources present in the dc distribution system in order to be guaranteed the load sharing.

4. Network components modelling and simulation

The energy sources, the dc loads and the power electronic devices interconnected to the dc bus are modeled within the ATP/EMTP software package. The control strategies are implemented using the Models subroutine.

4.1. Storage system

The charge and discharge states are commanded by a control loop that compares the measured dc voltage V_{DC} with the thresholds V_{stc} (voltage state of charge) and V_{std} (voltage state of discharge). The control strategy of the chopper is realized taking into consideration the various charge states of the storage system, respectively:

- state of charge: absorbed current (I_{bat}<0) and increasing voltage (V_{bat}). This state occurs if the dc voltage exceeds the threshold V_{stc};
- state of discharge: injected current (I_{bat}>0) and decreasing voltage (V_{bat}). This state occurs if the dc voltage is below the threshold V_{std};
- inert state: no power flow between the storage and the dc power system. This state occurs if the dc voltage is between the thresholds V_{stc} and V_{std}.

During the charge state, the current absorbed by the battery is imposed in conformity with the characteristics of the storage system and must not be influenced by the value of the dc voltage. The threshold V_{stc} is a reference for the charge state and does not represent a value at which the dc voltage has to be maintained. On the contrary, the reference V_{std} is the dc voltage value that the storage energy system imposes during the discharge state, caused by sags or short interruptions of the ac network. In this case the injected current is the result of the control strategy, such that the dc voltage is stabilized and maintained by the storage energy system at the reference value V_{std}.

If the voltage at storage system terminals is between the maximum and minimum limits is realized the second part of the control strategy, bordered in Fig. 4. Otherwise, the chopper is shut down and the storage system is maintained in its state of charge (fully charged or fully discharged). The dc voltage is filtered with a low pass filter for reducing the high frequency ripple of the dc voltage. The output of the low pass filter, represented by V_{mis}, is then compared in the upper and lower loops with the thresholds V_{stc}, respectively V_{std}. In the upper control loop of Fig. 4 the recharge process of the storage system is conditioned by the constraint that the dc network voltage has to exceed the threshold V_{stc} for a certain duration Δt, e.g. 1 s. It must be noted that during storage system recharge process, the reference current value is negative as the storage system is absorbing current.

During the discharge process, lower control loop in Fig. 4 the voltage V_{mis} is compared with the threshold value V_{std} and the resulting error is the input of a proportional-integral (PI) regulator that stabilizes the dc network voltage at the reference V_{std}. The output signal is limited (IF condition) such that the requested current does not exceed the maximum injecting current of the battery I_{dmax}.

In order to verify the control strategy of the interface bidirectional chopper, the voltage values of the two thresholds were chosen V_{stc} = 1.06 p.u. and V_{std} = 1 p.u.; the reference value has to be maintained by the voltage control loop even in the case of sags and short interruptions of the ac network. The current references associated to the charge and discharge processes are strictly dependent of the maximum current that the storage system can inject.

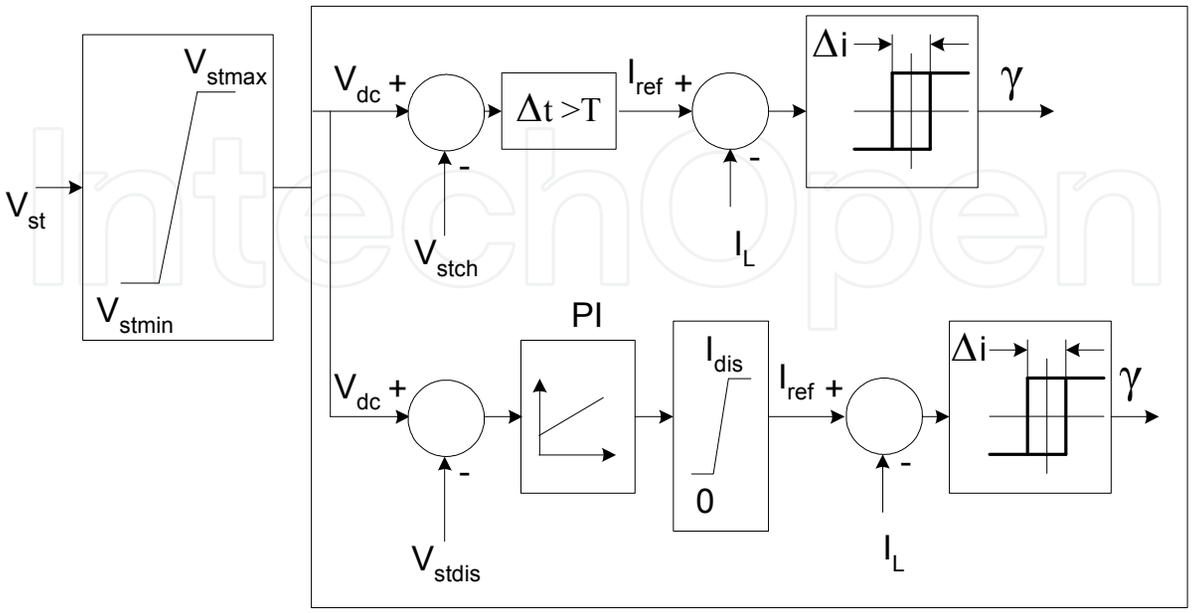


Figure 4. Control loop of the storage energy system

In a first simulation a 50% load reduction is considered, occurred at the time instant 0.07 s. Fig. 5 shows the dc voltage waveform and the two thresholds V_{stc} and V_{std}. Fig. 6 illustrates the storage system current waveform and the reference values I_{stc} and I_{std}. It can be seen that, after the load diminution, the storage system current is null as long as the dc voltage is below the threshold V_{stc}.

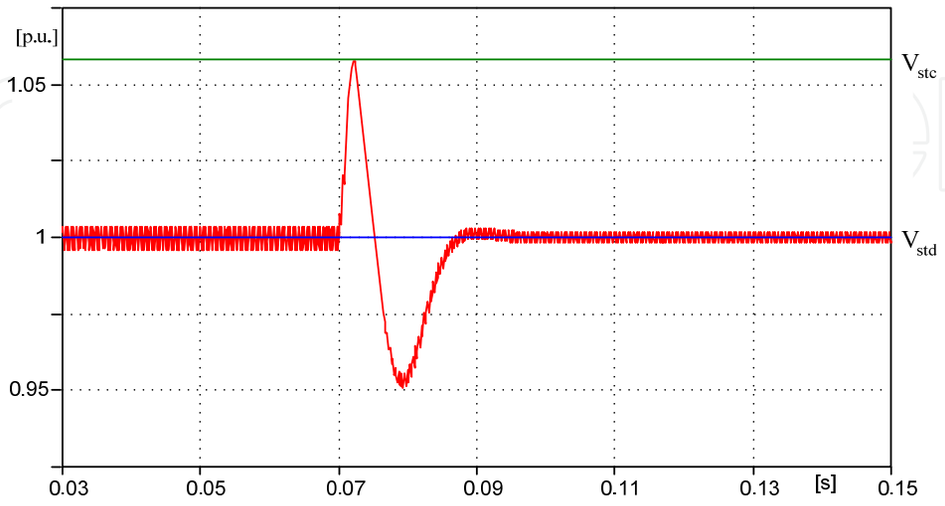


Figure 5. Dc voltage waveform and the reference thresholds V_{stc} and V_{std}.

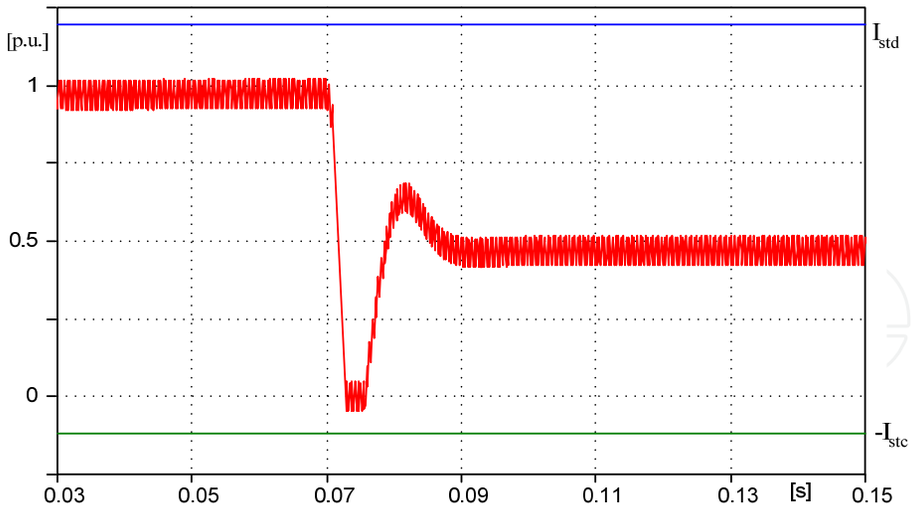


Figure 6. Waveform of the current flowing through the inductor and thresholds I_{std} and $-I_{stc}$.

4.2. AC/DC converter

The ac/dc interface converter is realizing the bidirectional power transfer between the ac and the dc network in correspondence with the dc voltage behavior. As the control strategy is based on the dc voltage feedback, a reference value V_{DCref} has been assigned; this value is maintained and stabilized by the interface converters in any operating condition. This is achieved using the control strategy of Fig. 7; the effective dc voltage, ripple filtered, is compared with V_{DCref}. The VSC converter is absorbing from the ac network three sinusoidal currents and in phase with the ac voltage, avoiding in this way the reactive power flow. The control strategy illustrated in Fig. 7 shows the hysteresis current controller for phase *a*, forcing the phase currents to follow the reference template. Identical controllers are used in phase *b* and *c*. The control strategy imposes the template of the reference current i_{ref1} that is obtained multiplying the ac voltages v_a for a gain *G*. This one results from a PI controller that guarantees null steady state error of the dc voltage. The gain *G* imposes that the currents taken from the ac network are always in phase with the voltage (positive gain) or in opposition (negative gain), if the phase shift introduced by the *LC* filter is not considered. The phase shift is determined by the reactive power absorbed by the *LC* filter that at fundamental frequency is behaving as a capacitance. The phase shift can be significant, even if the *LC* filter is correctly sized.

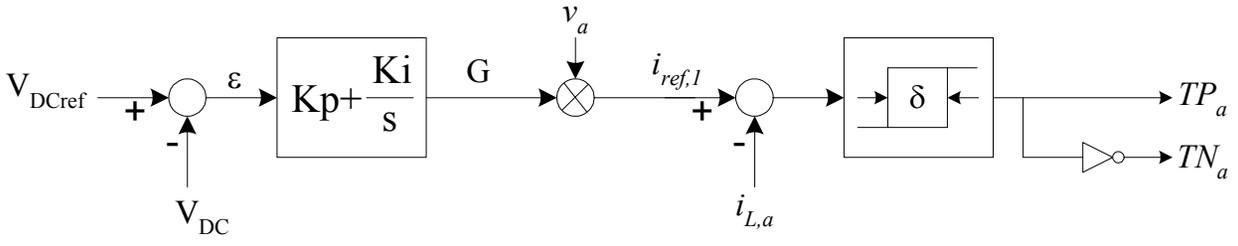


Figure 7. Control strategy of the voltage source converter.

4.2.1. PV system

The PV generator is interfaced with the dc network with the help of a boost chopper. The control system is shown in Fig. 8. The reference current is obtained using the signal I_{MPP} resulting from the MPPT system of the PV generator. This system is not implemented as its dynamics is much slower with respect to the one of the boost converter.

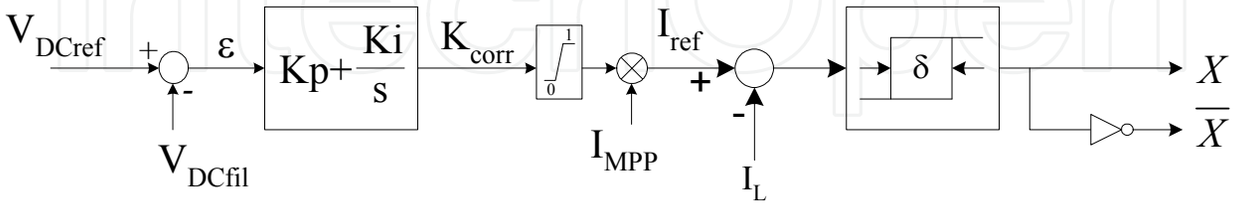


Figure 8. Control system of the boost chopper.

Thus, I_{MPP} is considered constant and corresponding to the MPP in standard environmental conditions of solar radiation and temperature. The control system produces null reference current in case the dc voltage V_{DCfil} exceeds the V_{DCref}. In this case the boost chopper limits the power produced by the PV generator such that to maintain the dc voltage at the reference value assigned.

4.2.2. DC loads

The dc loads are interfaced through a buck converter. The load control strategy requires a feedback loop. The current reference template is generated using a PI regulator. A hysteresis band modulation method is used to produce the PWM pattern for the power valves.

5. Case studies

5.1. Fault the mains supply

Initially, the system has been tested both for showing the transition between the voltage source converter and the battery. A three phase fault occurs at time instant t=0.4 s and it lasts for 250 ms. The ac voltages in this case study are illustrated in Fig. 9.

The dc voltage, maintained before the fault by the interface converter at the nominal value, will decrease until it reaches the threshold value V_{BS} = 0.96 p.u. of the storage energy system reference voltage (Fig. 10). This will determine the intervention of battery that comes in and supplies the load demand. In correspondence, the battery current will decrease until becomes zero, as in Fig. 11. After a first transient when the battery is injecting the maximum power for compensating the dc voltage drop, the control regulator of the battery system is stabilizing the dc bus voltage at the reference value V_{BS} and the current injected by the battery will reach the regime value.

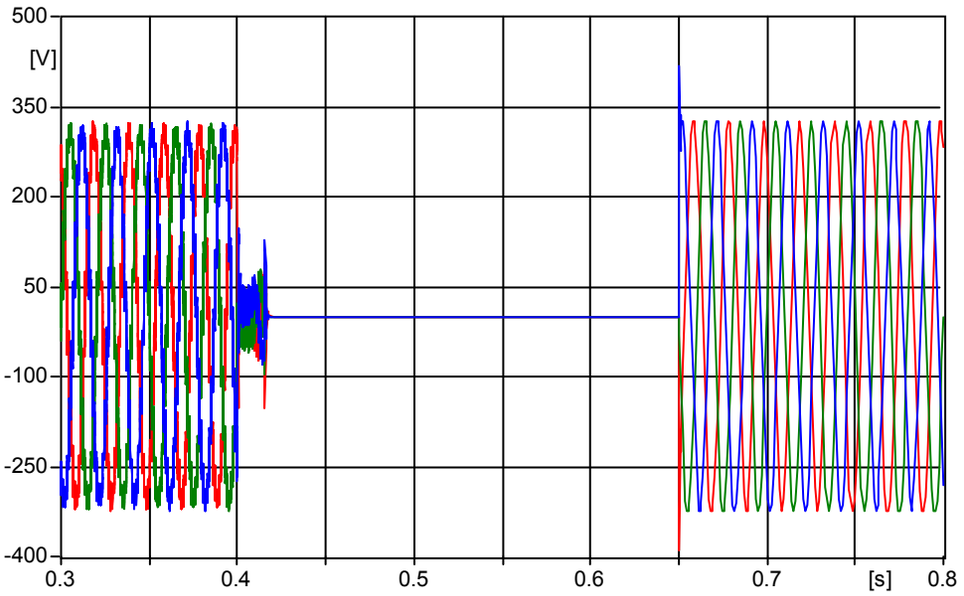


Figure 9. Voltages upstream the ac/dc interface converters during a three phase fault in the ac system.

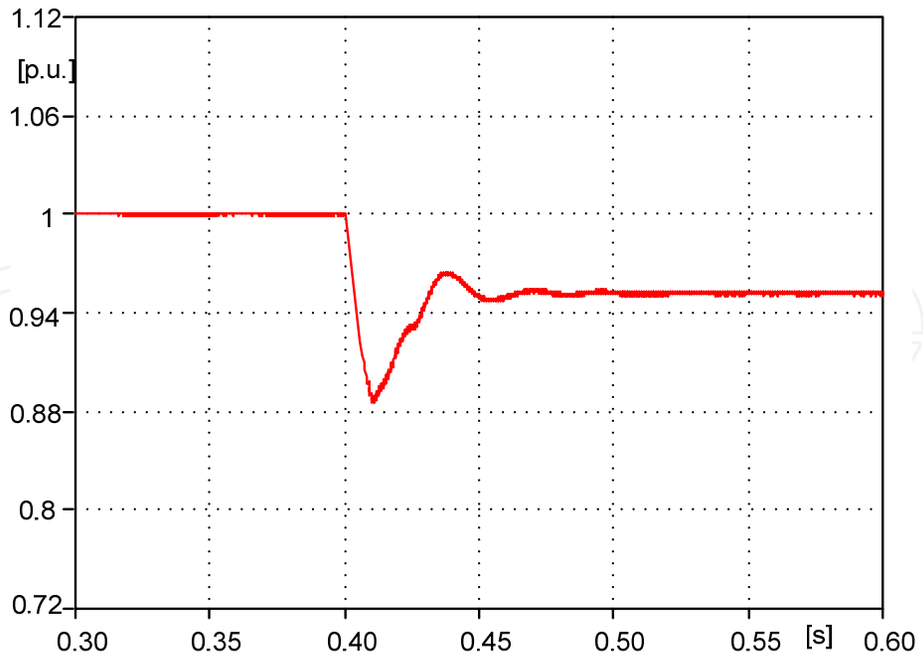


Figure 10. DC voltage waveform during a three phase fault in the ac grid.

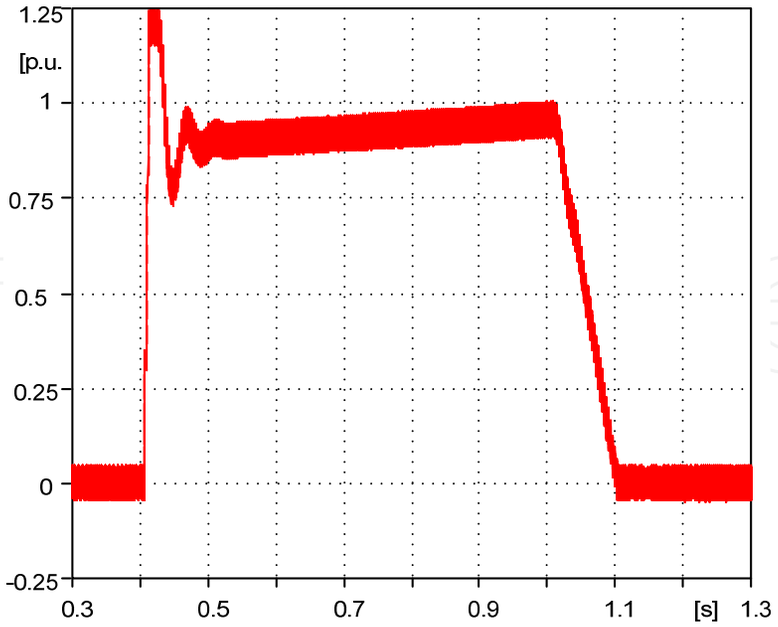


Figure 11. Waveform of the battery current.

After the fault clearance, the synchronization of the ac/dc interface converter with the ac network is required for having a proper operation of the power system.

5.2. Sustained inperruption in the mains supply

The interruption of the ac main supply is occurring at time instant t=0.4 s and lasts for 600 ms. Initially the dc voltage is maintained by the interface converters at the rated value, but after the interruption occurrence the storage system controls the dc voltage at the reference value. At instant t=0.5 s, the Diesel power system is started and the output voltage follows a ramp increase until it reaches the reference value of 0.97 p.u.. The transition between the two devices is illustrated in Fig. 10, where the interaction instant is highlighted.

The currents injected by the Diesel group and the output voltages of the generator of Diesel power system are illustrated in Fig. 14. As it can be observed, when the Diesel output voltage intersects the dc bus voltage, the Diesel group starts injecting power in the dc grid.

When the Diesel group starts injecting power into the dc power system, the voltage regulator of the storage energy system initiates decreasing the current flowing through the battery chopper inductor until it becomes null.

The ac grid is restored at time instant t=0.95 s but the ac/dc interface converter cannot start supplying the load until the synchronization with the ac grid is achieved. The currents flowing through the ac/dc interface inductors increase and the dc voltage, maintained by the Diesel generator at the reference value assigned, is brought by the interface converter to the initial state, respectively 1 p.u., as depicted in Fig. 14.

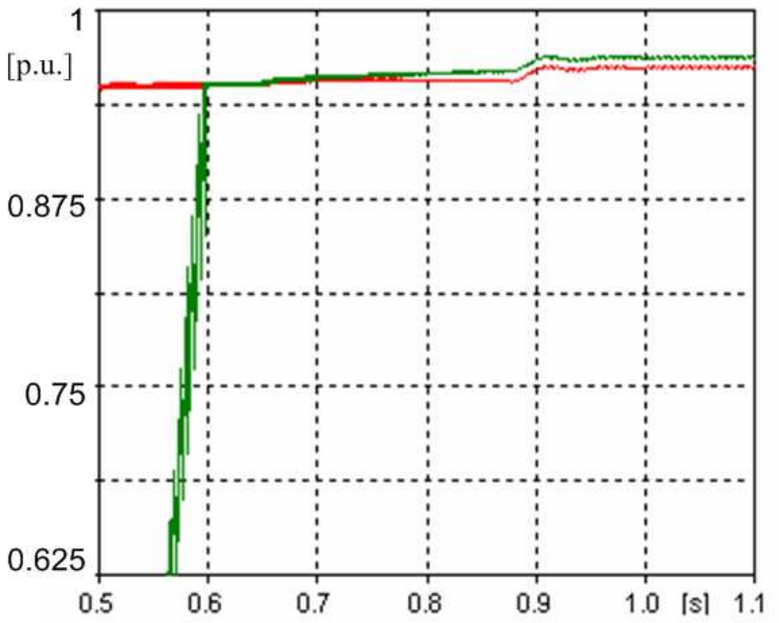


Figure 12. The transition between storage system (red) and Diesel system (green).

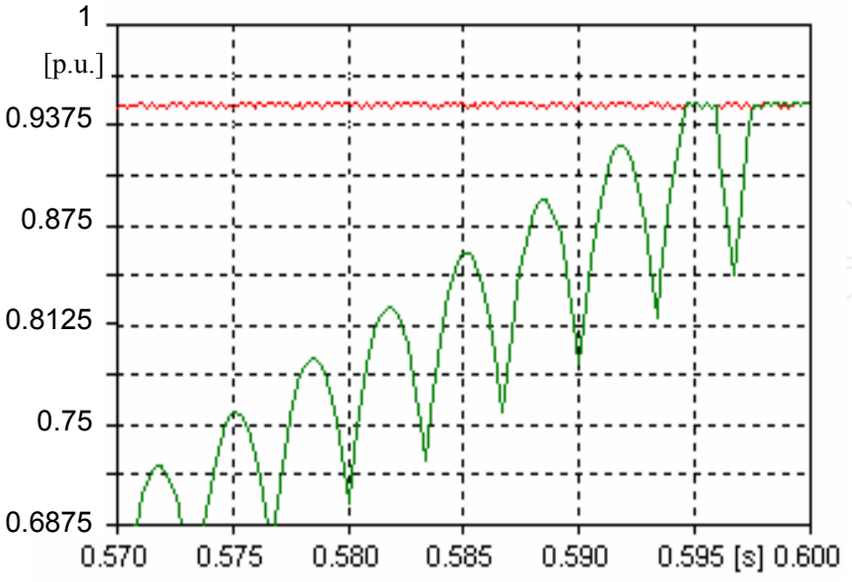


Figure 13. Magnified representation of the transition between storage system (red) and Diesel system (green).

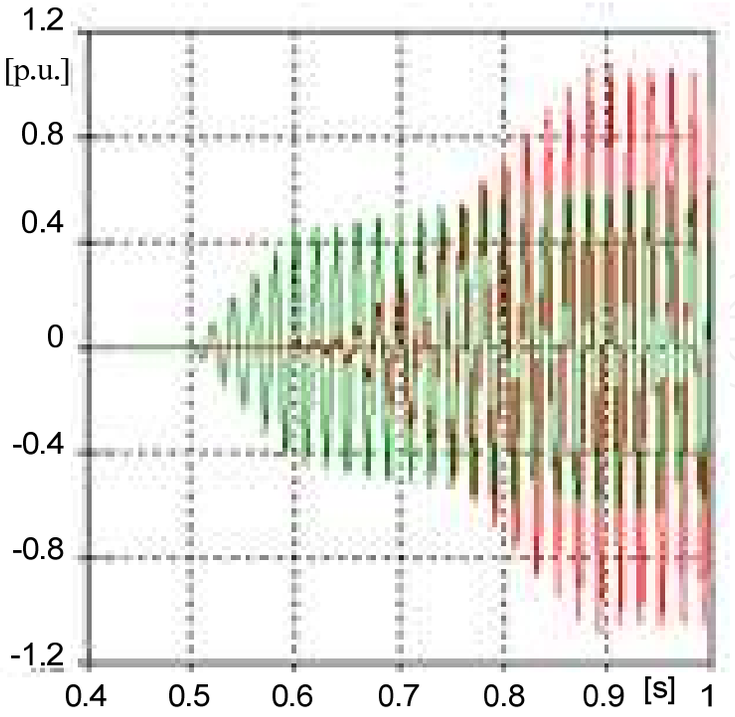


Figure 14. Characteristic current (red) and voltages (green) of the Diesel group.

5.3. DC faults

A short-circuit on the dc busbar leads to the interruption of the supply and each device interconnected to the dc busbar (load, generator, interface converter) is affected. An IGBT electronically breaking system is used for the interruption of the dc circuit. Two electronically interrupters were used, one for each pole, controlled by an over-current relay. The choice for two interrupters is justified by the necessity to interrupt the pole-earth fault. The relay measures the currents of the two poles and commands their disconnection even when one current exceeds the established threshold. This choice protects the ac/dc converter in case of unsymmetrical dc pole-earth faults. The layout of the dc system, in case of a pole-pole fault, used for the protection system investigation is illustrated in Fig. 15.

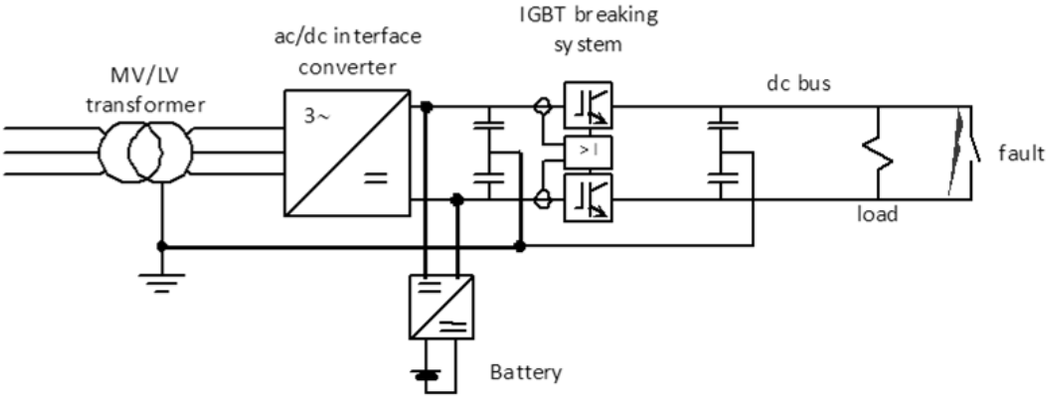


Figure 15. Layout of the dc system protection investigation

The voltage of the bus where the dc fault occurs is shown in Fig. 16. The voltage quickly drops to zero in a time period depending on the system time constants, allowing the complete discharge of the dc capacitors installed across the dc bus of the voltage source converter. In the first instants, the voltage quickly decreases in a time period shorten than the clearing time of the IGBT breaking system.

The waveform of the dc voltages upstream the IGBT breaking system are illustrated in Fig. 17. Initially, the dc voltages drop due to the dc fault, but slowly and much less with respect to the one of the dc bus due to the effect of the decoupling inductance present within the IGBT breaking system. Afterwards the breaking system intervention, the voltages grow as in the first instances after the fault occurrence, the converter control system maintains unchanged the power exchanged with the ac system which is entirely stored in the dc capacitors installed across the dc bus of the VSC.

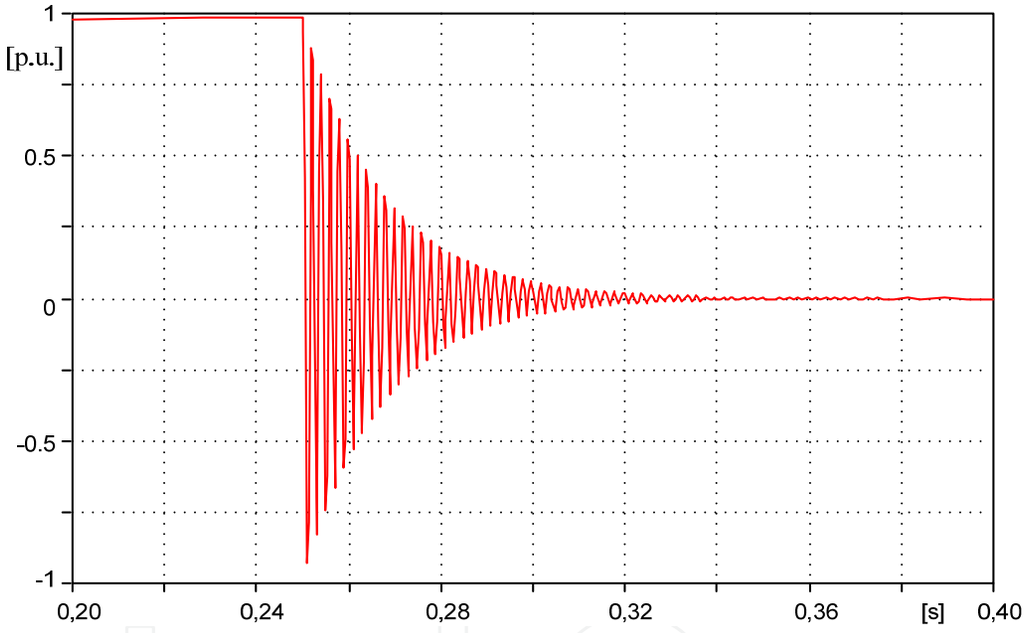


Figure 16. DC voltage of the low voltage distribution system

Then, the converter control system maintains the dc voltages at the rated value. The overvoltages depend on the value of the dc capacitors installed across the dc bus of the VSC and on the fastness of the controller intervention. The current flowing through the IGBT breaking system is illustrated in Fig. 18. When the current reaches the 2 p.u. threshold, the relay commands the breaking system opening, within milliseconds. The IGBT breaking system has the advantage to immediately limit the current, which is very important for the VSCs, which are difficultly supporting current spikes even of short duration. The protection of the interface converter is guaranteed both in case of overvoltages and overcurrents, due to the dc faults occurrence. The dc fault occurrence does not lead to overcurrents in the ac system, due to the decoupling between the ac and dc networks, as seen in Fig. 19.

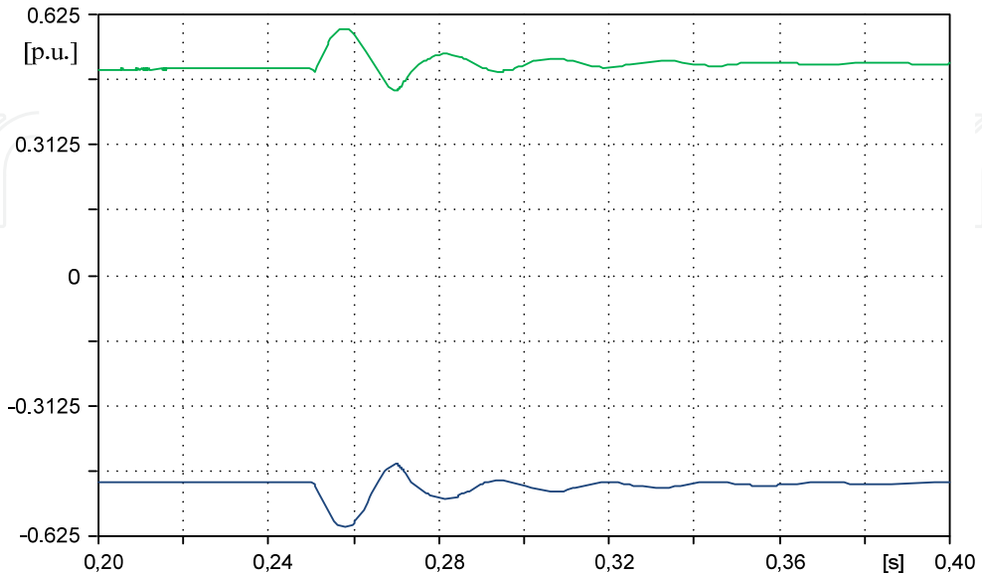


Figure 17. DC voltages upstream the IGBT breaking systems

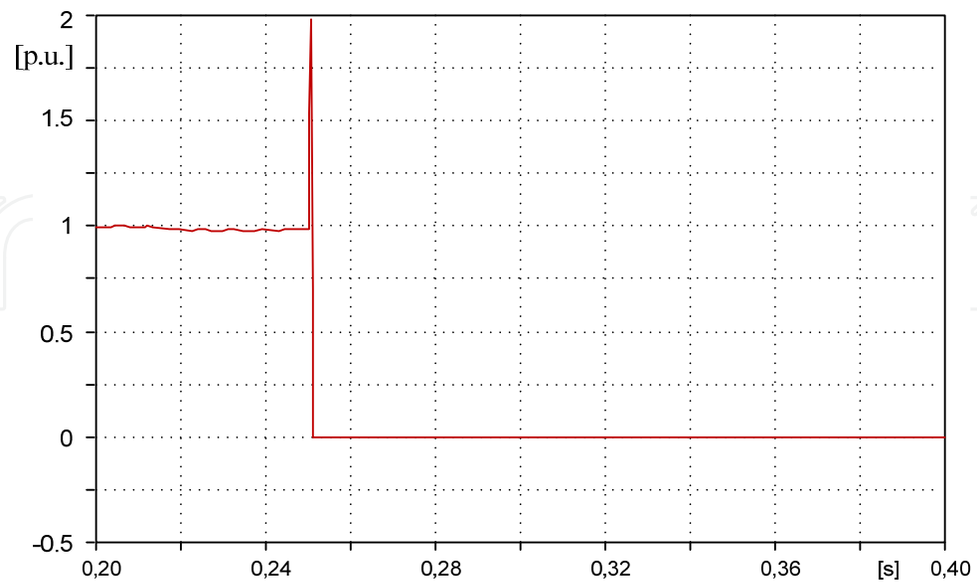


Figure 18. Current flowing within the IGBT breaking system

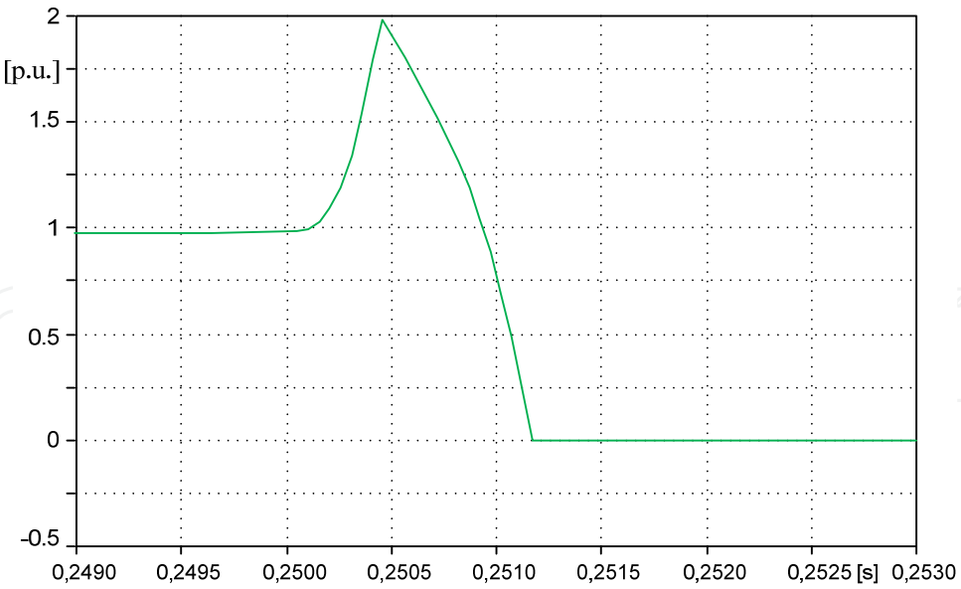


Figure 19. Interruption moment of the dc fault current in the IGBT breaking system

The ac phase voltages are not highly influenced by the dc fault transients. A small increase of the ac voltage, due to the small voltage drop, is occurring.

6. Conclusions

The integration of renewable sources and storage systems within the existing power system affects its traditional principles of operation, the utilization of these alternative sources presenting advantages and disadvantages. The existing trend of installing more and more small capacity sources implies the establishment as accurate as possible of their impact on power system operation. The realization of a low voltage dc distribution grid is technologically feasible and the use of direct current may lead to less power losses and more transmissible power with respect to the ac one. The design of a dc distribution grid, where distributed generation sources and storing energy devices are interconnected, is a difficult task. The choice of the most suitable equipments, which respond to the requirements of an optimum operation of the entire system, is necessary. For guaranteeing the correct and robust operation of the system is essential to adopt adequate control logic for obtaining the best system performances. As the ac fault protection system does not represent such a difficult task, the dc circuit breaking has been covered. A protection strategy using an IGBT breaking system is used. The fast and safe isolation of the dc fault, such that the dc distribution system equipments are not damages, is the most challenging task.

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