DG PARK: SYSTEM AND CONTROL OPTIMIZATION FOR IMPROVING POWER QUALITY

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Abstract: the present paper introduces and investigates a particularly important topic in the field of distributed generation applications: the dc power delivery. Direct current distribution systems can represent a very interesting opportunity for connecting low voltage commercial and residential loads to distributed generators, especially if they belong to the renewable energy family. The proposed dc grid requires an optimal control strategy for obtaining the best performances of the system. The paper deals with the proposal of a dc distribution system layout and with the control logic that can achieve the best performances for ensuring a high degree of supply continuity to the customers sensitive to power quality disturbances.

Key words: power quality, distributed generation, dc distribution

1. Introduction

The complexity of the problems related to the generation, transport and utilization of energy increased with the intensification of the global problems regarding environment protection, climatic changes and the exhaust of the natural resources. These determined the large utilization of renewable resources and power generation units, known as distributed generation (DG). Moreover, small capacity DG units, comprising the storage devices units, generate dc power (like photovoltaics, fuel cells) or request an intermediate dc stage (like microturbines), [1].

The economic damages caused by power quality perturbations and the large scale utilization of power electronics and microprocessors led to the increase of the customer concerns regarding the quality of the services provided by the utilities. Many consumers, not satisfied with the power quality level supplied by the utilities are installing devices for power quality improvement many of them having an intermediate dc stage, [2]. In addition, there are customers that by their nature use the direct current (telecommunication centers etc).

Thus a dc distribution system where all these sensitive loads are interconnected, represents a viable solution in the next future. This low voltage dc distribution system will represent a high power quality network that combines the

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advantages of the equipments used for improving the voltage quality and supply continuity and uses "green" power generating units.

In this paper the feasibility study of the dc distribution system for achieving premium power quality delivered to the sensitive customers and for an easier interconnection of the distributed generators, is conducted proving the future interest for its use in the worldwide power systems.

2. System control design

The energy management of the proposed dc grid requires the choice of an optimal control strategy for obtaining the best performances of the system through:

- realization of a bidirectional ac-dc flow;
- insurance of a high degree of voltage quality and supply continuity;
- interconnection and efficient use of DG and storage systems.

In order to define the control logic of the proposed low voltage dc distribution system, in Fig. 1 the layout of the dc distribution network with distributed generators, storage energy systems and ac/dc sensitive loads is illustrated. In Fig. 1, distributed generators (renewables or non-renewables) are present. This because one of the main purposes of the dc distribution system is to allow a more easily integration of the distributed generators. Some distributed generators are interconnected with the dc network using a boost chopper and others require a rectifier, eliminating the necessity for an inverter. The distributed generators produced power is injected in the ac network during light load, and supply, in parallel with the Diesel power system, the customers during islanding operation of the dc system.

The achievement of optimal operational performance at the system level and efficient energy dispatch can be met if the interactive operation of the individual components is controlled by an intelligent energy management system. The system operation when the power generated by the distributed generators is below the load demand is illustrated in the flowchart of Fig. 2. In this case, the dc distribution system adsorbs power from the ac network in order to balance the load demand. This can be achieved only if at least one of the ac/dc interface converters is functioning. The dc voltage is controlled and maintained by the interface converter at its nominal value.

The Diesel system is turned off. Measuring sensors of the dc system sense the battery state of charge. Than the intervention of the battery converter can be commanded for charging the battery, the power flowing from the dc bus to the battery. If the battery is fully charged the battery chopper remains turned off.

If both converters are out-of-operation, the dc system operates in islanding condition. In this case the Diesel is started and if the Diesel delay time is exceeded, the Diesel engine is turned on and supplies the load. In this case the Diesel group controls and maintains the dc voltage at the assigned threshold, the power flowing towards the dc bus. Also, supplies the battery if this one is partially charged or discharged.

If the Diesel is turned off, the battery state of charge is sensed. When the battery is charged or at least partially charged, the DC voltage will be regulated by the battery converter and the storage energy system will supply the dc system. Then the process is reinitiating and the dc grid measuring sensors are reinitiating the aforesaid process by surveying the voltage value on the dc bus. If the battery is fully discharged, as there will be no energy source to supply the storage energy system, the dc system will be shut down.

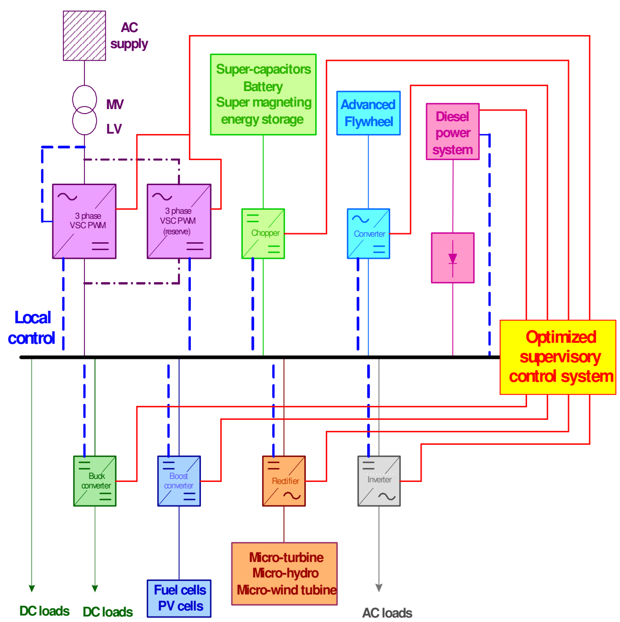

Figure 1. Layout of the analyzed low voltage dc distribution system.

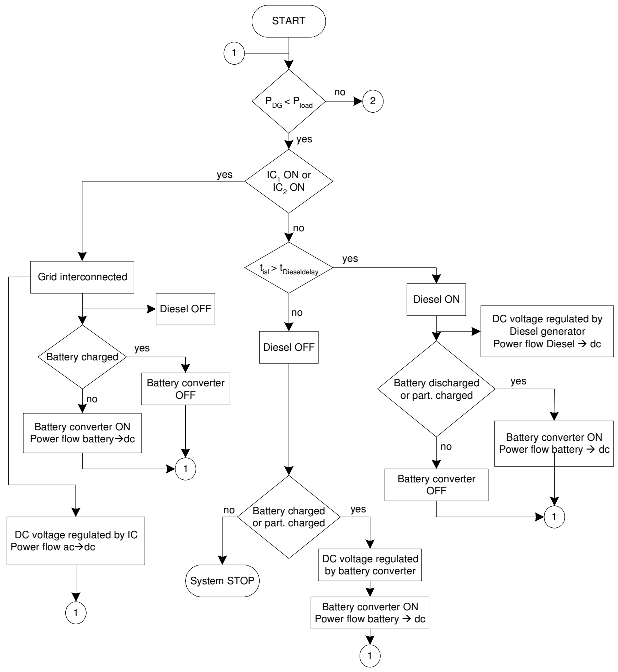

Figure 2. States of operation of the dc distribution system (PDG < Pload).

3. Bidirectionl AC/DC VSC

In Fig. 3 the bidirectional ac/dc interface converter, highlighting the internal resistances R of the converter inductors L, the three legs of the voltage source converter and the dc link smoothing capacitors, is illustrated, [3]. The dc capacitors have the middle point connected with the neutral of MV/LV transformer secondary and grounded for safety and protection operation reasons. The VSC can achieve the IGBTs commutation using the hysteresis band technique, due to the accuracy and good dynamics of this method.

For the ac/dc interface converter, two control methods have been analyzed:

- voltage source converter controlled using Fryze method;
- VSC controlled using synchronous Park transformation

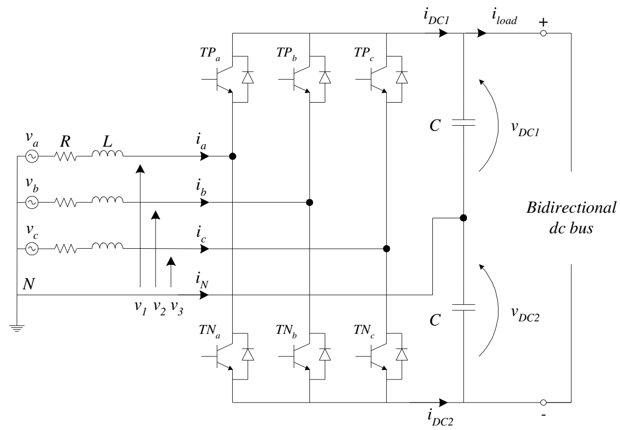

Figure 3. States of operation of the dc distribution system (PDG < Pload).

A. Voltage source converter controlled using Fryze method

The control strategy imposes the template of the reference current i_{ref1} obtained multiplying the ac voltages *v* for a gain *G*. This one results from the dc voltage control loop using a proportional integral (PI) regulator for obtaining null steady state error (Fig. 4).

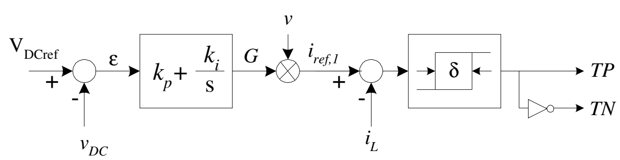

Figure 4. Fryze control strategy applied to the voltage source converter

The commutation of the converter IGBTs is realized with the help of the hysteresis band technique, easy to implement and offering high precision for the ac current to follow the reference pattern. The equations that govern the operation of the VSC neglecting the internal resistances of the inductors and under normal conditions ($v_{DC1}=v_{DC2}=v_{DC}/2$) are:

$$
\begin{aligned}
& v - L\cdot\frac{d}{dt}i - \frac{v_{DC}}{2} = 0 \quad when\,TP\,is\,ON\,and\,TN\,is\,OFF \\
& v - L\cdot\frac{d}{dt}i + \frac{v_{DC}}{2} = 0 \quad when\,TP\,is\,OFF\,and\,TN\,is\,ON \\
& i_{DC} = \frac{C}{2}\cdot\frac{d}{dt}v_{DC} + i_{load}
\end{aligned}
\tag{1}
$$

Each leg of the VSC is independently PWM commutated, such that considering δ_P the duty cycle of the positive IGBTs and $\delta_N = 1 - \delta_P$ the duty cycle of the negative IGBTs, by combining the first two equations in (1) results:

$$
L\cdot\frac{d}{dt}i = v + \left(-\frac{v_{DC}}{2}\right)\cdot\delta_P + \left(\frac{v_{DC}}{2}\right)\cdot(1-\delta_P) \tag{2}
$$

and simplifying is obtained

$$L \cdot \frac{d}{dt} i = v - \delta_P \cdot V_{DC} + \frac{v_{DC}}{2} \tag{3}$$

The third equation of (1) and (3) govern the operation of the VSC:

$$\begin{aligned} \frac{d}{dt} i &= \frac{v}{L} - \delta_P \cdot \frac{v_{DC}}{L} + \frac{1}{L} \cdot \frac{v_{DC}}{2} \\ \frac{d}{dt} v_{DC} &= \frac{1}{C/2} \cdot i_{DC} - \frac{1}{C/2} \cdot i_{load} \end{aligned} \tag{4}$$

1) Sizing of the passive components

As the IGBTs commutation is achieved using the hysteresis band technique, the value of the VSC inductor Is given by:

$$L = \frac{\left(\frac{v_{DC}}{2}\right)^2 - v^2}{f_s \cdot \Delta I_L \cdot v_{DC}} \tag{5}$$

where f_s is the switching frequency [Hz], ΔI_L is the amplitude of the hysteresis band [A], v_{DC} is the dc voltage [V] and v is the line-to-ground voltage [V].

The sizing of the dc link capacitors is achieved using the hold-up time method. Large dc link capacitors offer a major support during transients in the dc distribution system. Still, the investment cost increases and the response of the control strategies is slower, as the constant times are bigger. The total capacity connected on the dc bus is given by

$$C_{tot} = \frac{C}{2} = \frac{2 \cdot P_{load} \cdot t_h}{V_{DC}^2 - V_{DCmin}^2} \tag{6}$$

where V_{DCmin} is the imposed minimum value of the dc voltage, P_{load} is the load rated power and t_h is the hold-up time.

The Fryze control method presents high stability during the interface converter functioning as rectifier. On the contrary, when in the dc distribution system an excess of generated power occurs, this surplus is transferred to the mains and the gain G becomes negative highlighting the ac grid disturbances and possible leading to the instability of the power flow.

B. Voltage source converter controlled using Park transformations

For avoiding the drawbacks associated with the Fryze control method, another method for generating the sinusoidal reference current template is advisable to use. For obtaining null reactive power transfer, the reference currents will have to be in phase with the ac voltages. Hence, will be adopted a control strategy that generates three sinusoidal and balanced currents starting from the three phase ac voltages. These ac voltages will be generated by applying a Park transformation to the effective measured phase voltages in order to free them of perturbations.

For obtaining the reference voltages with which the reference currents i_{ref} are computed and for eliminating the various perturbations present in the mains, the Park transformation is applied (Fig. 6).

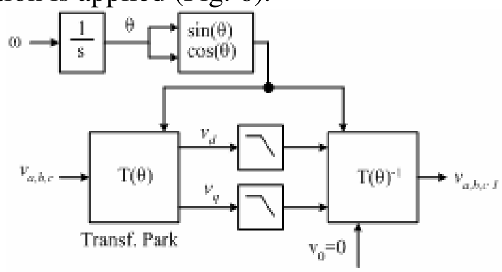

Figure 6. Application of Park transformation in the control system.

In this way, a variable transformation from *a*, *b*, *c* reference frame to the *d*, *q* coordinates is realized, using a synchronous reference frame transformation. The two voltages v_d, v_q are filtered with a low pass filter for selecting only the dc component to which corresponds the positive sequence component of the ac voltages. For this, the angular frequency ω it has to be determined. By applying the inverse Park transformation, using the same phase θ as for the Park transformation, the three phase voltages v_1 corresponding to the positive sequence are obtained.

4. Case studied

The rated power of the low voltage dc system is 800kW, with a dc voltage equal to 800V. The characteristic data of the current-controlled interface converter are reported in Table 1.

Table 1.

Interface converter characteristic data

P rated power	800kW
V_n nominal voltage	800 V
L_s VSC input inductance	0.061mH
f_{sw} switching frequency	5kHz
C_{dc} dc bus capacitance	0.2F

The simulations were conducted using the software package ATP-EMTP that allows a detailed modeling of the power converters, but also the implementation, through the MODELS subroutine, of the adequate control strategies, [4].

A. Control robustness

For showing the control robustness, a 50% load reduction at time instant t=0.4s is depicted in Fig. 7. As it can be seen, the control is fast and after the first transients the current is suddenly reported to the steady state value. The line current is always maintained within the hysteresis band of amplitude 20 % of the nominal ac current.

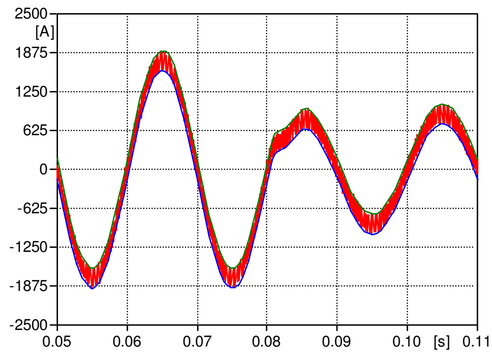

Figure 7. Line current flowing through converter inductor and the hysteresis band, during a 50% load reduction.

B. Anti-islanding behavior

The islanding detection of the power network with distributed generators is of high importance, in order to protect the utility personnel and to prevent the damage of the various equipments. Also, it has negative impacts on the protection and operation of the various devices. Thus is required the fast detection of the islanding occurrence and the isolation or tripping of the DGs for ceasing to energize the power system, [1].

Both control methods have been tested when the dc power system injects in the ac grid a real power of 200 kW, absorbed by a resistive load interconnected to the ac low voltage grid. The three line-to-ground voltages, when an interruption occurs at instant t=0.1 s, are illustrated in Fig. 9. It can be noted that even in load demand equilibrium, the converter loses the control and is causing the suddenly intervention of the interface device commanded by the frequency relays.

In case of the voltage source converter controlled using Fryze method, the detection of the islanding condition is achieved, the interface converter becoming unstable. Still, this control method is by its nature not always stable, particularly when the voltage source converter is functioning as inverter. Thus, this control method can not be considered trustable and is disregarded.

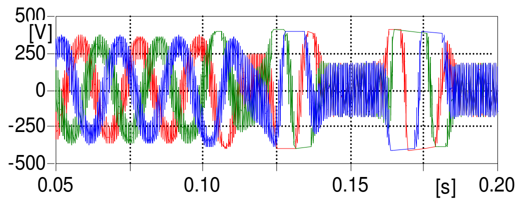

Figure 9. Ac voltages during an ac grid interruption, using Fryze control method and in condition of equilibrium of the load demand.

In Fig. 10, the three line to-ground voltages when the frequency detection algorithm is used together with the control method based on Park transformation, are depicted. An interruption of the ac main supply is occurring at instant t=0.5 s. The frequency relays will suddenly determine the cease of converter operation and the dc power system will be decoupled from the ac grid. The loads will be supplied by the other power sources connected to the dc bus [5].

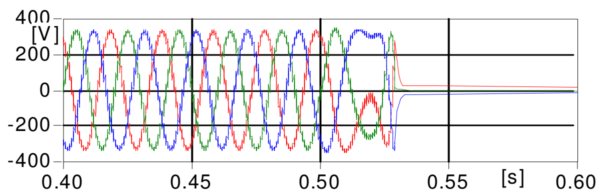

Figure 10. Ac voltages during an ac grid interruption, using Park control method and frequency detection algorithm, in condition of equilibrium of the load demand.

5. Conclusions

The paper proposes a low voltage dc distribution system that represents a solution for solving the problems related to ensuring an adequate power quality degree.

The design of a dc distribution grid, where distributed generation sources, storing energy devices and Diesel group 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.

A possible control strategy could be the use of a supervisory control that allows to avoid the interaction between the electric devices controllers, which can lead to transients in the dc distribution system. Still, this method can diminish the reliability of the entire network and leads to high investment costs.

The main device of the dc grid is the ac/dc interface converter. Two control methods have been analyzed in order to achieve the robustness of the dc network operation. The study of the unintended island is of high importance in the systems with DGs. In case of the voltage source converter controlled using Fryze method the detection of the islanding condition is achieved, the interface converter becoming unstable. For the protection of the devices and for the utility personnel safety a possible solution could be the use of a frequency detection algorithm that is behaving very well when the dc power system is ac-grid connected. Also is responding promptly in case of ac interruptions occurrence when is suddenly varying and determines the intervention of the frequency relays.

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