APPLICATION OF VOLTAGE SOURCE CONVERTERS TO MANAGE POWER FLOW AND ENHANCE OPERATIONAL PERFORMANCE OF A MICROGRID

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ABSTRACT

In this paper the application of Voltage Source Converters (VSCs) within a microgrid is investigated in two main areas. First, the application of VSC to manage power flow by dynamically controlling the impedance of the distribution line, to either increase or decrease the effective line impedance, allowing current to be "pushed" away from or "pulled" into a distribution line is analyzed. In this case, a desired power flow is achieved to alleviate the overload of a specified line, meanwhile increasing the transmitted power of the others. Second, by applying back-to-back converters as a connecting interface between the utility grid and the microgrid, the performance of the microgrid is enhanced especially in confronting with grid disturbances. This application mitigates the impacts of fast transients, created during faults or switching heavy loads in the grid side, on the power quality of sensitive industrial loads within the microgrid.

INTRODUCTION

A microgrid is defined as a cluster of distributed generating units (DGs) and loads, serviced by a distribution system, operating in one of the grid-connected or islanded (autonomous) modes or ride-through between these two modes. Most agree that important elements in a microgrid include co-located power generation sources, energy storage elements, and end-use loads. However, opinions differ about the aggregated generation capacity that should be contained within the power system and whether there should be a single point of common coupling with the main grid or multiple coupling points. However, microgrids are power systems in which generation elements are co-located with loads, regardless of the aggregated generation capacity or the grid interconnection. This definition covers a large application space that ranges from remote rural electrification and residential/community power networks to commercial, industrial, municipal, hospital, campus, and military base power grids. The applications also vary. Some are focused on cost of electricity (e.g., peak shaving), some are focused on local resource use (e.g., wind, solar, biomass systems), and some are focused on energy reliability and security (therefore, sophisticated generation and load controls are required). The idea supporting the formation of the microgrid is that a paradigm consisting of multiple generators and aggregated loads is far more reliable and economical than a single generator serving a single load. Within microgrids, loads and energy sources can be disconnected from and reconnected to the area or local electric power system with minimal disruption to the local loads. Any time a microgrid is implemented in an electrical distribution system, it needs to be well planned to avoid causing problems. Microgrids can also provide additional benefits to the local utility by providing dispatchable power for use during peak power conditions and alleviating or postponing distribution system upgrades [1].

Energy sources and load are connected by distribution lines within a microgrid. Power flow is determined by the impedances of these lines, i.e., the active power flow of each line is an uncontrollable parameter which depends on the microgrid configuration in addition to the line impedances. The main concern in this case is the overload of some lines and low ampacity of the others. This is important in microgrids, because the energy sources are of variable nature, so the extremes of power flows can only be foreseen at the design stage. It means a remedial system is needed to manage the active/reactive power flows of the candidate lines in order to transfer the maximum energy from geographically-scattered sources to the load centers [2].

Local resource generating units such as wind, solar, biomass systems, micro-turbines are interfaced to the microgrid by Voltage Source Converters (VSCs). In this paper two salient features of Voltage Source Converters (VSCs) are presented:

1) VSC is capable of much more than simple power conversion to ac. Exploiting its fast response in closed-loop can dynamically control the impedance of the line; allowing control of active power flow on the line. VSCs can be used to either increase or decrease the effective line impedance, allowing current to be "pushed" away from or "pulled" into a distribution line.

This paper details the principles of operation of the VSCs within a microgrid to present a desired power flow alleviating specified line overloads and increasing the transmitted power of the others.

2) VSCs can be connected back-to-back to realize VSC-based high voltage direct current transmission (VSC–HVDC), which plays a more important role in power systems. The VSC–HVDC uses pulse width modulation (PWM) with relatively high switching frequencies, which makes it possible to generate an ac output voltage with any desired phase angle or amplitude instantly. A number of

potential advantages of the VSC–HVDC for example are: facilitating the controlled power flow between the microgrid and utility which can be used in case of any contractual arrangement; reliable power quality due to the isolation of the microgrid system from utility; feeding power into passive networks with no local power generation; enabling fast control of active and reactive power independently of each other. This allows reactive power support to an area, if needed, independently of the active power transmitted, provided that the rating of the converter can handle the total apparent power; quickly reversing active power, which is a desirable feature since it enables short-term transactions in electric power markets.
The VSC-HVDC provides the much needed frequency and power quality isolation between the utility and the microgrid. In this paper the application of VSC-HVDC as a connecting interface between the grid and the microgrid is investigated to enhance the performance of the microgrid from the power quality of sensitive loads within the microgrid point of view.

POWER FLOW CONTROL BY VSC

For controlling power flow on distribution lines, the series elements clearly have the highest potential and impact. The real and reactive power flow, P and Q, along a line connecting two voltage buses is governed by the two voltage magnitudes V_1, V_2 and the voltage phase angle difference, $\delta = \delta_1 - \delta_2$, as [3]:

$$P_{12} = \frac{V_1 V_2}{X_L} \sin\delta \quad (1)$$

and

$$Q_{12} = \frac{V_1^2 - V_1 V_2 \cos\delta}{X_L} \quad (2)$$

where X_L is the impedance of the line, assumed to be purely inductive. A series compensator is typically used to increase or decrease the effective reactive impedance of the line, thus allowing control of real power flow between the two buses. The impedance change can be effected by series injection of a passive capacitive or inductive element in the line. Alternatively, a static inverter can be used to realize a controllable active loss-less element such as a negative or positive inductor or a synchronous fundamental voltage that is orthogonal to the line current [2]-[3]. In the latter case, the power flow depends on the injected quadrature voltage V_q as:

$$P_{12} = \frac{V_1 V_2}{X_L} \sin\delta - \frac{V_1 V_q \cos\left(\frac{\delta}{2}\right)}{X_L} \times \left[\frac{\sin\left(\frac{\delta}{2}\right)}{\sqrt{\left(\frac{V_1 + V_2}{2V_2}\right) - \frac{V_1}{V_2}\cos^2\left(\frac{\delta}{2}\right)}} \right] \quad (3)$$

For $V_1=V_2=V$, the bracketed term is unity, so we have:

$$P_{12} = \frac{V^2}{X_L} \sin\delta - \frac{V V_q \cos\left(\frac{\delta}{2}\right)}{X_L} \quad (4)$$

Figure 1 shows the variation of power flow along a transmission line that can be achieved by injecting a series voltage in quadrature to the line current. As can be seen from this figure, for $V_q=0$, there is no compensation, but for negative values of V_q, the transferred power P_{12} is increased. Meanwhile for positive values of V_q, the power transfer is decreased, i.e., the line impedance is increased, a case suitable for fault current limiting in severe conditions.

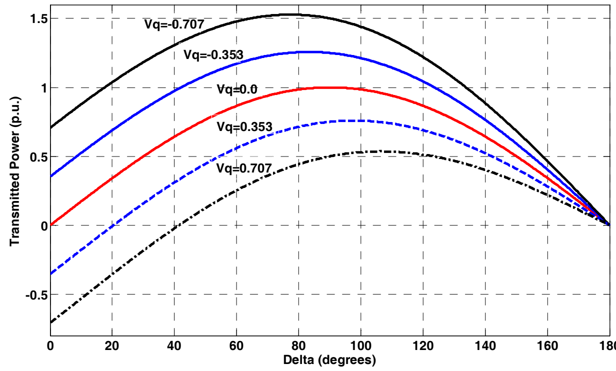

Figure 1: Transmitted power versus transmission angle δ as a parametric voltage V_q provided by the series VSC

Figure 2 shows a single line diagram of a sample microgrid presented in [4]-[5].

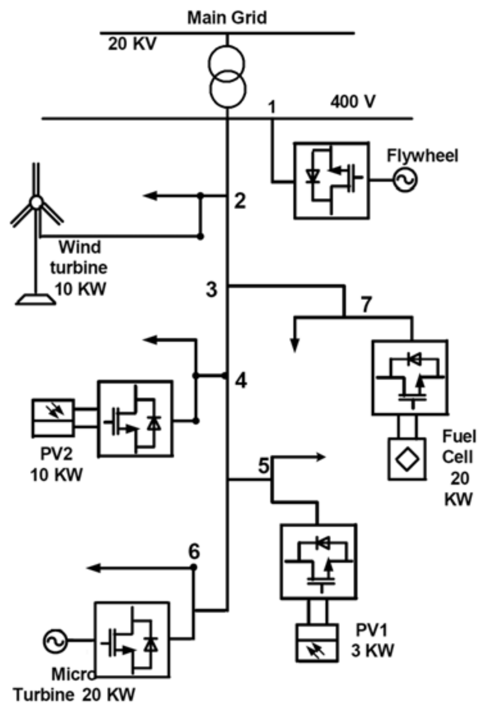

Figure 2: Single-line diagram of a sample microgrid.

As a sample system it consists of 7 buses. Flywheel with rating 20 kW is connected to bus 1. Wind generation system (10 kW) is connected to bus 2. Two photovoltaic panels with rating 10 kW and 3 kW are connected to buses 4 and 5 respectively. A single shaft micro turbine (SSMT) with rating 20 kW is connected to bus 6. A solid oxide fuel cell (SOFC) with rating 20 kW is connected to bus 7. It is worth noting that the power generation of the microgrid sources is not constant and depends on the availability of the environmental sources. So the maximum transfer of power does not exist most of the times. Meanwhile, the main feeder that connects the generating sources and loads to the grid needs to be designed for a capacity which is used only a small fraction of time during a day. The series compensating VSC helps to use a moderate feeder which its transmission capacity is increased according to (4) in peak demand and its impedance would be increased in case of a severe fault to protect the feeder. This strategy is not only valuable from economic point of view, but also establishes an enhanced flexibility in power flow management. A sophisticatedly designed VSC can be used to manage the power transfer of the feeder based on the outputs of the sources, the transmission capability of the feeder and the requirements of exporting/importing power to the grid. Figure 3 shows the location of the compensating VSC to increase/decrease the line impedance based on the operational requirements.

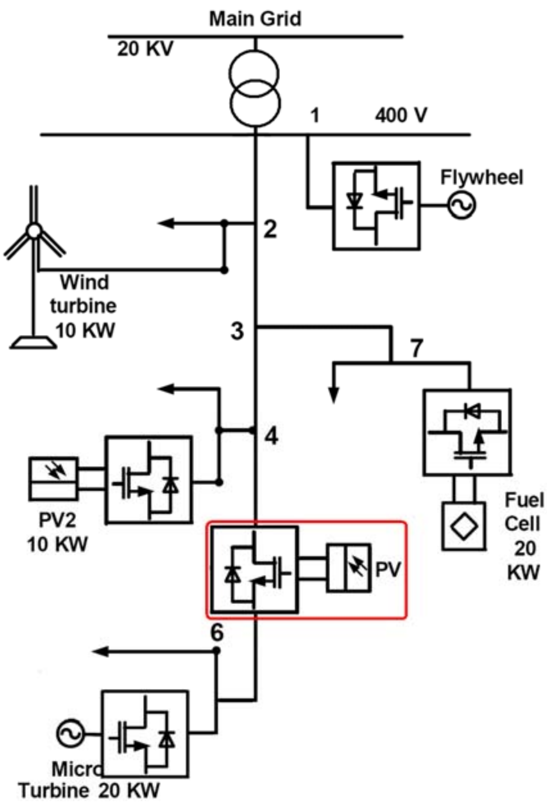

Figure 3: VSC application within a microgrid to increase/decrease the power transfer capability of the main feeder.

BACK-TO-BACK CONNECTED VSCS

Figure 1 shows the single-line diagram of the sample system when it is connected to the grid by two back-to-back VSCs.

Both the converters are supplied by a common dc bus capacitor. The system can run in two different modes depending on the power requirement in the microgrid. In mode-1, a specified amount of real and reactive power can be supplied from the utility to the microgrid through the back-to-back converters. Rest of the load demand is supplied by the DGs. The power requirements are shared proportionally among the DGs based on their ratings. When the total power generation by the DGs is more than the load requirement, the excess power is fed back to the utility. This mode provides a smooth operation in a contractual arrangement, where the amount of power consumed from or delivered to the utility is pre-specified. When the power requirement in the microgrid is more than the combined maximum available generation capacity of the DGs (e.g., when cloud reduces generation from PV), a pre-specified power flow from the utility to the microgrid may not be viable. The utility will then supply the remaining power requirement in the microgrid under mode-2 control, while the DGs are operated at maximum power mode. Once all the DGs reach their available power limits, the operation of the microgrid is changed from mode-1 to mode-2. While mode-1 provides a safe contractual agreement with the utility, mode-2 provides more reliable power supply and can handle large load and generation uncertainty [6].

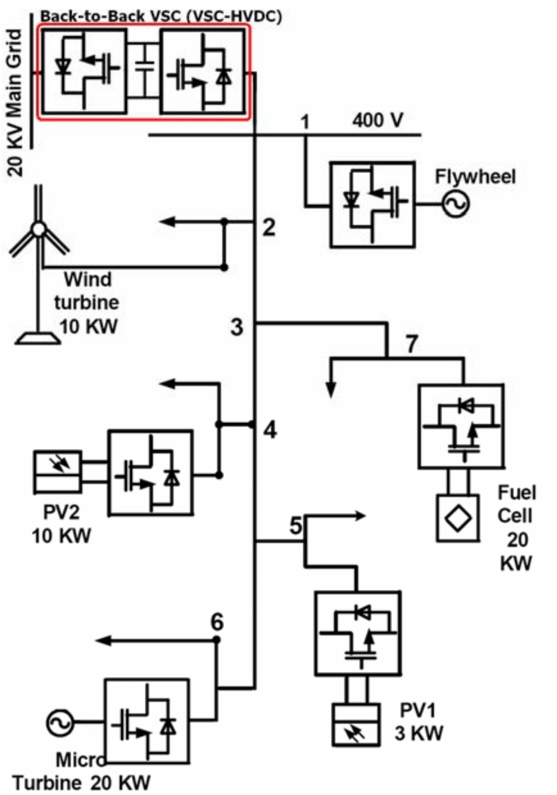

Figure 4: Sample system with two back-to-back VSCs.

SIMULATION RESULTS

VSC-HVDC and Power Quality of Microgrid Loads

In order to show the inherent potential of back-to-back VSCs to isolate the disturbances from one area (utility grid) to the other area (microgrid), a sample system (Figure 5) is set up with two strong networks. The two networks are connected by two VSCs with a dc link between them. This could be an extreme case of a powerful microgrid. A 200 MVA (+/- 100 kV DC) forced-commutated VSC interconnection is used to transmit power from a 230 kV, 2000 MVA, 50 Hz system to another identical AC system. The rectifier and the inverter are three-level Neutral Point Clamped (NPC) VSC converters using close IGBT/Diodes. The discrete control system generates the three sinusoidal modulating signals that are the reference value of the bridge phase voltages. The amplitude and phase of the modulating signals can be calculated to control either: the reactive and real AC power flow at the PCC, or the reactive power flow at the PCC and the pole to pole DC voltage [7].

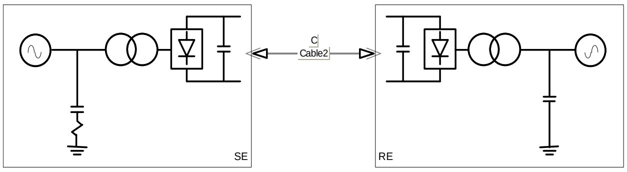

Figure 5: Sample system for simulation of VSC-HVDC

At first, the VSC-HVDC is replaced by a common ac transmission line, so the two systems are connected without any VSCs between them. A three-phase fault is simulated at t=2.1s at the utility grid side and removed after 0.15s. The active and reactive powers of the microgrid are shown in Figure 6 for microgrid receiving power. Before the fault the microgrid was delivering 1p.u. active power to the grid,i.e., -1p.u. power is receiving. During the fault the power transfer is zero, but after the fault, the system recovers with remarkable oscillations, harmful to industrial sensitive loads in its network. Figure 7 shows the same case, but with VSC-HVDC between the two networks. The oscillations are damped efficiently, i.e., acceptable power quality.

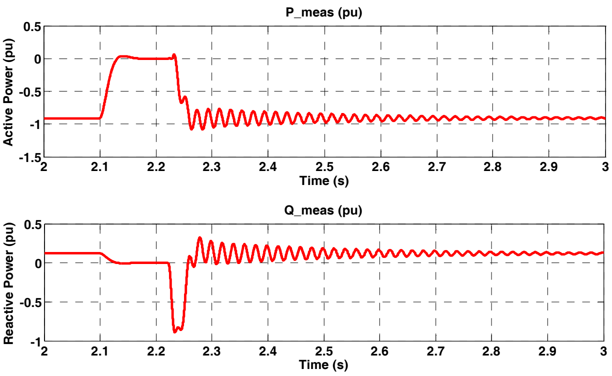

Figure 6: Sample system without VSC-HVDC

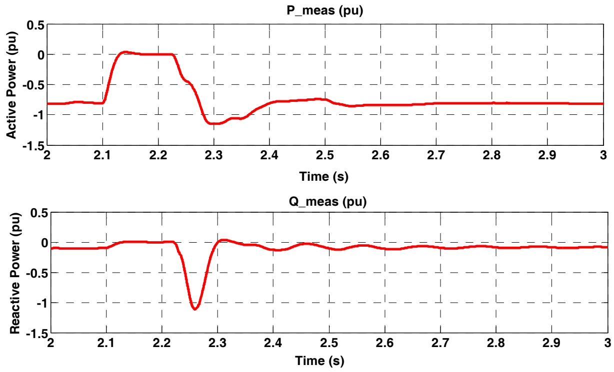

Figure 7: Sample system with VSC-HVDC

CONCLUSION

In this paper the application of VSCs to manage power flow of a feeder in a microgrid is presented. Transmission capacity is increased by decreasing the effective impedance of the feeder; allowing to using an optimum size for the main feeder of the microgrid. Fault current limiting can also be achieved by increasing the impedance of the feeder using VSC. Back-to-back converters as a connecting interface between the utility grid and the microgrid is another application that is presented in this paper. By using back-to-back VSCs for interconnection, the impacts of fast transients of the utility grid side on the power quality of the sensitive industrial loads in the microgrid are mitigated. This application enhances the performance of the microgrid, especially in confronting with grid disturbances.

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