Sustainable Development Microgrid Advanced Control and Protection System

Amit Sachan
Department of Electrical Engineering, IECR, India
Email: amitsachan55@gmail.com

***Abstract*—A low-voltage DC Microgrid can be used to supply sensitive electronic loads, since it combines the advantages of using a DC supply for electronic loads, and using local generation to supply sensitive loads. A commercial power system which can benefit from using a DC Microgrid is data center. The lower losses due to fewer power conversion steps results in less heat which need to be cooled, and therefore the operation costs are lowered. A protection system design for low-voltage DC Microgrid has been proposed and different protection devices and operation control methods have been presented. Moreover, different fault types and their impact on the system have been analyzed. The type of protection that can be used depends on the sensitivity of the components in the Microgrid. Detection methods for different components have been suggested in order to achieve a fast and accurate fault clearing. An experimental small-scale dc power system has been used to supply different loads, both during normal and fault conditions. A three-phase two-level voltage source converter in series with a Buck converter was used to interconnect the AC and the DC power systems.**

***Index Terms*—circuit transient analysis, DC power system, dispersed storage and generation, load modeling, power conversion, power distribution protection, power distribution fault and control, power electronics**

I. Introduction

Direct current power systems are still today used in different industrial and commercial applications, due to both historical and practical reasons: the simplicity of speed control of DC machines, and the possibility to build reliable, yet simple, power systems by use of directly connected batteries. Telecommunication systems are today supplied with 48V dc through converters connected to the ac grid. In case of a power outage the loads are supplied from batteries directly connected to the DC bus. In some telecommunication stations a standby diesel generator can also be used to support the batteries. A similar solution is also used to supply control and protection equipment in power plants and substations. However, a higher voltage level (110 or 220V DC) is used due to longer distances between sources and loads, and higher load power ratings. DC has been used in LV drive systems speed control has been required and ac in applications where it has not. In the latter case simpler and more robust Induction Machines have been used. Speed control of DC machines can be obtained by changing the supplying voltage or the magnetic flux. In the early age of DC machines this was obtained by using a variable resistor in series with the machine, or a variable resistor in the excitation circuit. This is a simple solution, but results in high losses and a poor speed-torque characteristic. By use of power electronics better, faster, and more precise control of both ac and dc machines can be obtained.

DC powered machines can be found in traction applications such as subways, trams and trains, but also in industrial drive systems. Although ac made a big breakthrough in the beginning of the 20th century dc solutions have been adopted by a number of relatively new applications such as electric vehicles, hybrid electric vehicles, electric ships and HV dc transmission. The main purpose of this paper (a) Existing residential and commercial ac loads have been tested to investigate the possibility to supply these loads with dc and within which voltage range. (b) New models of existing residential and commercial ac loads which can be used for steady-state and transient analysis of LV dc systems have been developed and compared with measurement data. (c) Different ac/dc-converter topologies suitable to use for interconnecting ac and dc power systems have been evaluated. (d) The performance of the selected converter topology during both steady-state operation and transients has been studied through simulations, and experimental tests. (e) The performance of different dc-link-voltage controllers for grid-connected voltage-source converters has been analyzed and compared. The structure of AC/DC and DC Microgrid has been analyzed, and an overview of different systems which could benefit from using such a system has been presented. (f) An analysis of a suitable control system for a data center DC Microgrid has been presented. The performance of the proposed control system has been studied through simulations. (g) Suitable protection devices and grounding methods for an LV DC Microgrid have been described. An LV DC Microgrid protection-system design has been proposed which ensures a fast and reliable fault clearance. The design has been applied on a small test system, and its behavior during faults has been studied through simulations. (h) An experimental setup has been built and used to show the feasibility of using a DC power system to supply sensitive electronic loads in order to reduce the number of converters.

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II. AC/DC MICROGRID

DC Microgrid, energy storage and a large portion of the sources and the loads are interconnected through one or more DC busses. There will still be a need for AC Microgrid since some sources and loads cannot be directly connected to DC. Moreover, as long as AC is used for distribution, the DC Microgrid will at some point be connected to the AC grid. Therefore, it is proposed that the AC and DC Microgrid should be considered as two parts of a mixed AC/DC Microgrid, which is connected to the AC grid at the point of common coupling (PCC). Power can flow between the AC Microgrid and the DC Microgrid through power converters, but also between the AC Microgrid and the AC grid. The power direction depends on the balance between load and generation.

A. *AC/DC Interface Topologies and Their Operation Control*

The two-level Voltage Source Converter (VSC) with Buck converter is selected as the AC/DC interface to use to interconnect ac and dc power systems since it has a wide range output DC link voltage [1], can be designed to have a high transient performance during faults and disturbances, and it is suitable to be used with energy storage. Galvanic isolation can be achieved by adding a transformer with unity ratio before the VSC. The control system of the AC/DC interface consists of two independent parts: one for the VSC and one for the Buck converter [2]. Control of Three-Phase Two-Level Voltage Source Converter by using pulse width modulation (PWM) the output voltage of the VSC can be controlled, and hence the voltages across the grid filter. This means that the current through the filter can be controlled, and in turn the power flows between the grid and the VSC [3]. The power flow can be bi-directional, and active and reactive power can be individually controlled [4]. The VSC current control system adopted here uses a vector controller implemented in the synchronous DQ-coordinate system, where the positive sequence ac components appear as dc quantities [5]. From Fig. 1, the following equation for the system can be derived.

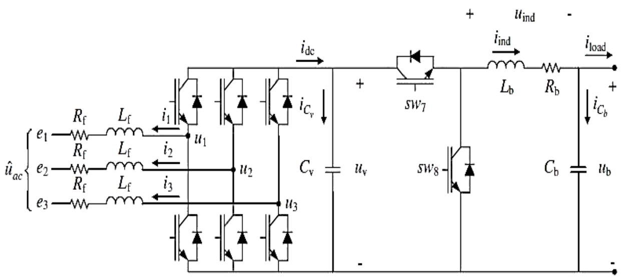

Figure 1. Topology scheme of a three-phase, two-level VSC in Series with a Buck converter

The voltage across the DC-link capacitor can be kept at a constant value by controlling the active power flow on the AC side of the VSC to equal the power required to maintain the charge of the capacitor and to supply the Buck converter connected to the DC side of the VSC. The relation between the DC-link voltage u_v and the current iC_v flowing into the capacitor C_v is

$$L_f(di_{dq})(t))/dt = u_{dq}(t) – (R_f + j\omega L_f)i_{dq}(t) - e_{dq}(t) \quad (1)$$

$$iC_v(t) = C_v(du_v)(t))/dt \quad (2)$$

This equation is used when deriving a controller for the DC-link voltage [1], [2]. The output dc-link voltage of the Buck converter, which is shown in Fig. 1, can during continuous-conduction operation be calculated as

$$u_b = u_b\, t_{on} / T_s = u_v D \quad (3)$$

where u_v is the input voltage, ton is the time during one switching period when sw_7 is on (sw8 is off), T_s is the duration of the switching period, and D is the duty ratio. However, if the output voltage of the converter should be stable in spite of load variations, a voltage controller must be designed [6]. The idea of the controller is to have one inner controller of the current through the inductor L_b, which will charge the output capacitor C_b and supply the load, and one outer loop that controls the needed inductor current to charge the capacitor C_b to the voltage reference level. A laboratory prototype of the selected interface was built and used to verify its performance during both steady-state and transients, such as load connection and grid disturbance. The interface maintains the DC-link voltage almost at its reference level, and the grid currents are sinusoidal.

A two-level three-phase voltage source converter (VSC) utilizes six switches instead of three, as in a three-phase diode rectifier with PFC. the scheme of a two-level VSC is shown in Fig. 1. The three additional switches make it possible to have bi-directional power flow. The two-level VSC operated as a rectifier has a boost output characteristic. The minimum level of the output dc-link voltage is determined by the ac voltage, and equals twice the peak value of the phase-to ground voltage. A transformer can be connected between the VSC and the ac grid to adjust the minimum output dc-link voltage. The transformer will also provide galvanic isolation between ac system and the dc system, and its leakage inductance will serve as grid filter. Finally, a two-level VSC also has controllable power factor.

III. CONTROL OF LOW-VOLTAGE MICROGIRD

DC Microgrid, energy storage and a large portion of the sources and the loads are interconnected through one or more DC busses. However, there will still be a need for ac Microgrid since some sources and loads cannot be directly connected to DC. Moreover, as long as AC is used for distribution, the DC Microgrid will at some point be connected to the ac grid. Therefore, it is proposed that the AC and DC Microgrid should be considered as two parts of a mixed AC/DC Microgrid, which is connected to the AC grid at the PCC. Power can flow between the AC Microgrid and the DC Microgrid through power converters, but also between the AC Microgrid and the AC grid.

A. AC/DC Microgrid Statistics Centers

Data center power system with sensitive computer loads (together with their internal Switch mode power supply (SMPS) with power factor correction (PFC)) and HVAC equipment [7], [8]. The power system has a connection to the ac grid, which normally supplies the loads. If an outage occurs in the AC grid, the loads can be supplied from a standby diesel generator. During the time it takes to detect the outage, disconnect the AC grid and start the diesel generator, the sensitive loads are supplied from an AC un-interruptible power supplies (UPS) one way for data centers to combine the need for high reliability and the possibility to reduce the losses is to use a DC Microgrid [9]. Fig. 2 shows a scheme of a proposed DC Microgrid for data centers connected to the AC grid, which is one special case of the LV AC/DC Microgrid. The DC Microgrid is indicated as Zone 1. Zone 2 is prioritized ac loads which are located close to the data center DC Microgrid. Finally, Zone 3 is the ac grid and the loads connected to it.

B. Control of DC Microgrid for Data Centers

The data center DC Microgrid has a number of components which can be controlled as show Fig. 2 converter C1, the energy storage unit, converter C2 (together with the diesel generator), switches SW2 and SW3. An adaptive control system is therefore required to coordinate the control of these components. Converter C1 can be operated in three different modes: controllable dc source (cdcs), controllable ac source (cacs) or controllable power source (cps). When it is operated as a cdcs it is regulating the DC-link voltage in the DC Microgrid. When it is operated as a cacs it can be used to generate AC voltage and supply the loads in Zone 2 (switch SW2 must then be open). Finally, when it is operated as a cps it can inject a controllable amount of active power to the AC grid. Converter C2 can only be operated as a cdcs. Switch SW2 is used to disconnect the DC Microgrid and the prioritized AC loads from the AC grid, and switch SW3 to disconnect Zone 1 from Zone 2. The adaptive control system changes the control variables based on the input variables and the current operation mode. If any of the input variables change state, the adaptive control system will change the control variables and these results in a transition from one operation mode to another.

The DC Microgrid for data centers has eight different operation modes which can be used. It can only change from one operation mode to another operation mode which is relevant from an operational and control perspective. Each transition from one operation mode to another operation mode is due to an event (planned or unplanned). Fig. 3 the proposed adaptive controller was implemented and tested in the simulation software package EMTDC/PSCAD. The most critical transitions 1 and 22 are due to an outage in Zone 3.When it occurs it is important to quickly detect the outage and change the operation mode in order to keep the sensitive loads in Zone 2 online.

Fig. 2 shows a typical scheme of a data center power system with sensitive computer loads (together with their internal SMPS with PFC) and HVAC equipment. The power system has a connection to the ac grid, which normally supplies the loads. If an outage occurs in the ac grid, the loads can be supplied from a standby diesel generator. During the time it takes to detect the outage, disconnect the ac grid and start the diesel generator, the sensitive loads are supplied from an ac UPS. One way for data centers to combine the need for high reliability and the possibility to reduce the losses is to use a dc microgrid.

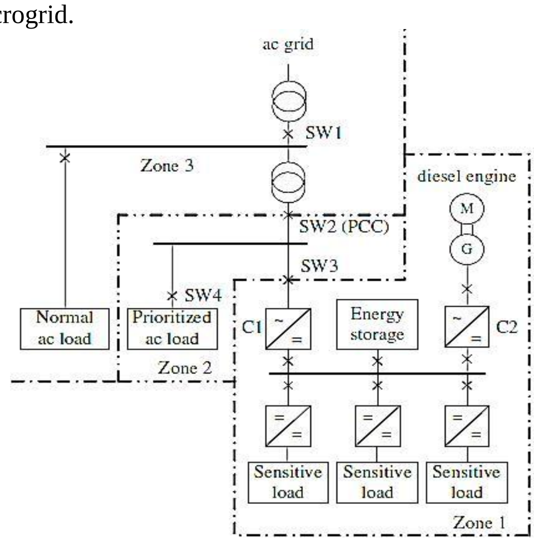

Figure 2. Control data center

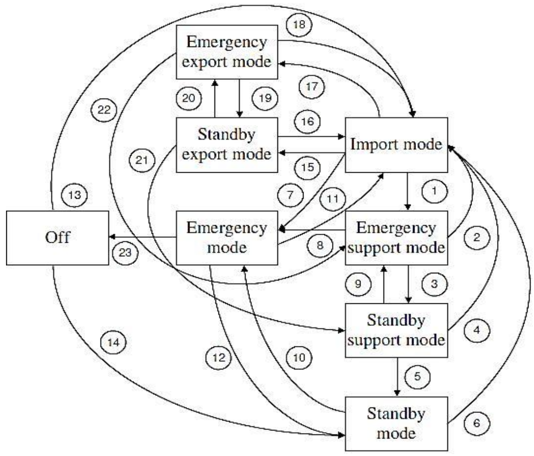

Figure 3. Operation modes and transitions of the data center

IV. DC MICROGRID PROTECTION

These systems utilize grid-connected rectifiers with current-limiting capability during DC faults. In contrast, an LV DC Microgrid must be connected to an AC grid through converters with bi-directional power flow, and therefore a different protection-system design is needed [10]-[12] Short-circuit current calculations for LV DC systems have been treated, and fault detection. However, the protection devices have not been considered. So far the influence of protection devices on the system performance has only been considered in studies of HV DC applications such as electric ships and HV DC transmission systems [13], [14].

A fuse consists of a fuse link and heat-absorbing material inside a ceramic cartridge. When the current exceeds the limit of the fuse, the fuse link melts and an arc is formed. In order to quench the arc, the arc voltage must exceed the system voltage. This can be done by stretching and cooling the arc. There is no natural current zero in a DC system which helps to interrupt the fault current. Voltage and current ratings of fuses are given in RMS values, and are therefore valid for both AC and DC. A molded-case circuit breaker consists of a contractor, a quenching chamber and a tripping device. When a molded case circuit breakers (MCCB) is tripped the contacts begin to separate, and an arc is formed between them. The arc is forced into the quenching chamber by air pressure and Lorentz magnetic forces. The quenching chamber consists of multiple metal plates which are designed to divide the arc into multiple smaller arcs. This will increase the total arc voltage and decrease the arc temperature, and the arc will in most cases extinguish. To improve the voltage withstands capability multiple poles can be connected in series. Molded-case circuit breakers are usually equipped with a thermal-magnetic tripping device and the voltage and current ratings are given in RMS values. The magnetic tripping senses the instantaneous value of the current, which means that the rated current for DC is $\sqrt{2}$ times higher than for AC. However, for the thermal tripping the values are the same. There are some problems associated with fuses and circuit breakers in LV DC systems such as large time constants and long breaker operation time. By utilizing power-electronic switches such as gate-turn-off thyristors (GTOs) the operation speed decreases and the inductive current interruption capability can be increased however, the losses of such a solution are much higher compared with a mechanical switch. Therefore a combination of one mechanical switch and one power-electronic switch.

A. Protective Relays and Measurement Equipment

High-speed DC circuit breakers are equipped with mechanical instantaneous overcurrent tripping devices, which can be set to trip the breaker if the current exceeds 1-4p.u. The electromagnetic force generated by the current is used to trip the circuit breaker. However, if the circuit breaker shall be tripped due to other events, a protective relay is required [12]. Protective relays use information from measured voltages and currents, and in some cases also information based on communication with other units. It is important to note that the measurement equipment must be able to handle dc quantities in order to work properly [15].

Besides overcurrent, protective relays can calculate time derivatives and step changes of currents to determine if the system is in normal operation or if a fault has occurred. More sophisticated numerical methods to detect faults and identify them from normal operation in traction applications, for example by using neural networks.

B. Protection System Design

The overall function of the LV DC Microgrid protection system is to detect and isolate faults fast and accurately, in order to minimize the effects of disturbances. The design of the protection system depends on a number of issues: the type of faults which can occur, their consequences, the type of protection devices required, the need for backup protection, detection methods, and measures to prevent faults, and finally, measures to prevent incorrect operation of the protection system. Possible fault types in a DC Microgrid are pole-to-pole and pole-to-ground faults. Pole-to-pole faults often have low fault impedance, while pole-to-ground faults can be characterized as either low-impedance or high-impedance faults. The location of the faults can be on the bus or one of the feeders, inside the sources or the loads. The main difference between an LV DC Microgrid and other existing LV DC power system is the type of converter that is used to interconnect the DC system with the ac grid. Converters used for example in dc auxiliary power systems for generating stations and substations, and traction applications are designed to have a power flow only from the AC side to the DC side. Therefore, it is also possible to design the converters to be able to handle faults on the DC side by limiting the current through them. However, the power flow between an LV DC Microgrid and an AC grid must be bi-directional. A different type of converter is then required, and it may not be possible to limit the current through the converter during a fault in the LV DC Microgrid.

During a fault, all sources and energy storage units connected to the DC Microgrid will contribute to the total fault current. The converters used in the LV DC Microgrid have a limited steady state fault current capability due to their semiconductor switches. However, they can provide a fault current with a high amplitude and a short duration from their DC-link capacitors. Energy storage, for example lead-acid batteries, can provide a large steady-state fault current. In contrast to converters, they have a long rise time [16]. The components within the DC Microgrid must be protected from both overloads and short circuits. Depending on the sensitivity of the component different solutions exist. Power-electronic converters are very sensitive to overcurrent's, and if they do not have internal current limiting capability, they require very fast protection. Examples of such devices are fuses, hybrid circuit breakers, and power-electronic switches. Batteries and loads do not require such fast protection, and therefore simpler and cheaper devices can be used. To achieve selectivity in the DC Microgrid, it is necessary to coordinate the different protection devices. Feeders and loads are preferably protected by fuses since they are simple and cheap, and it is easy to obtain selectivity. However, it is common to use MCCBs closest to the loads due to their two-pole interruption. The protection devices protecting sources and energy storage devices must be able to separate a bus fault from a feeder or a load fault, in order to achieve selectivity. The DC-link-voltage level and the derivative of the current is the best fault-detection method for converter protection, due to the converter fault current characteristic. Batteries have a different fault-current characteristic so it is possible to use the instantaneous value of the current to detect a fault.

V. Result

The steady-state performance of the loads is studied, where the main focus lies on the contents of the current harmonics. The result shows that using DC to supply electric loads is better when compared with AC. In a DC system there will not be any problems associated with current harmonics. In the second case different arrangements of protecting sensitive loads from transient disturbances are studied. The experimental test shows that a computer and a fluorescent lamp used in the test are affected by voltage dips in the ac grid; the computer restarted and the fluorescent lamp shut off.

It is demonstrated that supplying the loads with the DC system connected to the ac grid through the interface can prevent disturbances to affect the loads. This solution has lower losses compared with a conventional AC un-interruptible power supplies (UPS), which is otherwise required to provide a disturbance-free power supply.

VI. Conclusion

The main aim is to investigate the existing LV AC loads that could operate with DC without any modifications and within which voltage ranges. The second aim is to develop simple models of the loads which can operate with DC. The measurement result shows that resistive loads operate equally well with DC as with AC as long as the RMS voltages are equal. However, problems may arise with load switches, which are not designed to interrupt DC current. Depending on the rated power, a resistive load is modeled either as a pure resistance or as a current-depending resistance. Rotating loads with a universal machine and electronic loads could also operate with DC without any modifications. The voltage range within the loads may vary among the different designs. A universal machine is modeled as a voltage-dependent current source, and electronic loads as a diode rectifier with a filter and the steady-state load characteristic.

An interface is required in order to interconnect an AC and a DC power system. The design of the interface highly affects its performance with respect to controllability, power quality and safety. A VSC in series with a Buck converter is selected to be used, since these converters together have bi-directional power flow, generate no low-frequency harmonics, and can preferably be used together with an energy storage device. Galvanic isolation can be obtained by connecting them to the ac grid through a transformer with unity ratio. Different designs of the VSC DC-link voltage controller have been analyzed and compared with respect to stability, voltage control, and load-disturbance rejection. An LV DC Microgrid can be preferable to an AC Microgrid, where most of the sources are interconnected through a power-electronic interface and most loads are sensitive electronic equipment. The advantage of an LV DC Microgrid is that loads, sources and energy storage then can be connected through simpler and more efficient power electronic interfaces. A paper on four different commercial power systems with sensitive loads showed a data center has a possibility to greatly improve its operation performance by using a LV DC Microgrid. An adaptive controller was designed for the data center DC Microgrid which coordinates the operation of the sources based on local information system studies showed that the data center DC Microgrid can be used to support loads in its close vicinity.

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Mr. Amit Sachan has completed M.Tech degree in department of Energy & Power Engineering. He is continuing profession as Assistant Professor in Educational Institution and doing research work in the field of Electrical power Engineering.