Capacitive Grounding for DC Distribution Grids with Two Grounding Points

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***Abstract*—Connecting large dc distribution grids on the same voltage level can allow superior utilization of infrastructure. Selective ground fault protection is necessary and can be done using low impedance grounding. Distributed energy resources would allow for higher resilience of the grid if islanding operation of dc microgrids is allowed. For safety, grounding is essential in these islanded microgrids so individual grounding points are needed. Multiple low impedance grounding points would cause dc ground currents that lead to corrosion.**

This paper introduces capacitive grounding which is high impedance in steady-state effectively eliminating ground currents but is low impedance for fault transients and thus can allow for selective ground fault protection. The sensitivity of the capacitor sizing for two grounding points is shown. Further an initial filter for ground fault discrimination is analyzed.

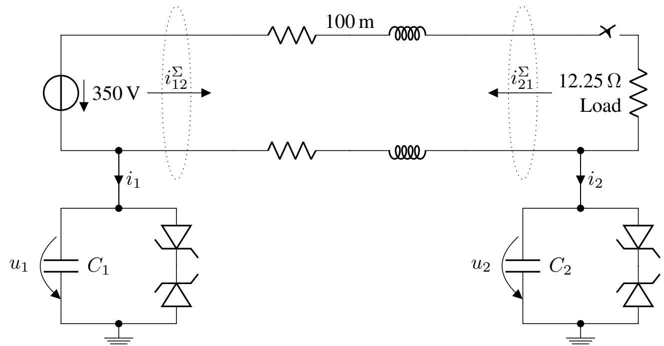

Fig. 1. Unipolar dc grid with two capacitive grounding points with voltage clamping by zener diodes. Source on the left and load on the right.

I. Introduction

The emergence of distributed energy resources suggest changes to the traditional ac power system. Most of these resources are dc inherently, or use a dc bus internally, and a majority of the loads connected to the low voltage grid nowadays directly rectify ac to dc before converting the voltage levels using dc/dc power electronic converters. DC distribution grids could remove unnecessary conversion steps and increase the utilization of the components. This can be done inside buildings, but higher benefits could be gained if the complete low voltage distribution grid would be operated on dc. In this case it would still be beneficial if dc nanogrids inside buildings could operate independently in islanding mode in case of faults in the grid [1]. These dc nanogrids may be galvanically connected and only separated by protection devices [2], [3].

Grounding is an important aspect of the protection system of a distribution grid. DC microgrids that are galvanically isolated can have various grounding schemes [4]. High impedance grounding or floating is used often for critical loads such as data centers in order to allow continuous operation in case of a single ground fault [5]. This can be done because the single ground fault current is very low. Ground faults are detected by isolation monitoring. A problem with this approach that fault localization and selectivity is difficult/not possible. Low impedance grounding allows for residual ground fault detection and selectivity using the current sum in the conductors. This is commonly applied for residual ground fault protection in ac grids.

For dc distribution grids each islanded dc nanogrid should have a low impedance grounding point to allow local selectivity. This would result in multiple grounding points in connected (non-islanding) mode and dc ground currents would flow due to difference in neutral potential. This can cause corrosion in metallic structures, e.g, reinforcement steel in concrete and has to be prevented [6].

This paper proposes capacitive grounding for dc distribution grids to prevent dc ground currents in steady state while still providing low impedance during fault transients [7]. The general properties and challenges are described. Additionally a sensitivity analysis regarding the grounding capacitor size for two grounding points is done. Initial filter design to discriminate balancing current from residual ground faults is presented.

The remainder of this paper is organized as follows: In Section II the concept of capacitive grounding is introduced and a unipolar example grid is shown. Further the properties and challenges are described. In Section III a sensitivity analysis is done on the size of the capacitors. The challenges of residual ground fault discrimination are discussed in Section IV and finally conclusions are drawn and future work is indicated in Section V.

II. Capacitive Grounding

For capacitive grounding the neutral wire connected with a capacitor to ground. This is done in each place where otherwise solid grounding would be used, i.e., in each dc nanogrid that should be able to operate in islanding mode. Fig. 1 shows an unipolar example of such a configuration with two grounding points with capacitors C_1 and C_2 connected

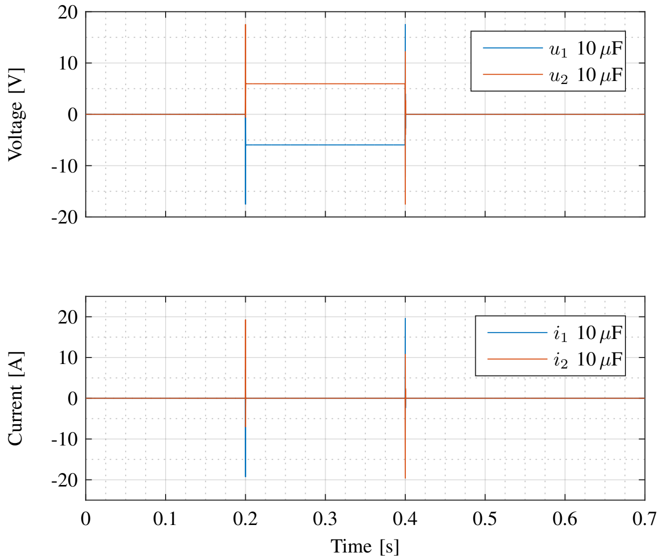

Fig. 2. Unipolar dc grid with load connect (0.2 s) and disconnect (0.4 s). The capacitors are charged to the new voltage of the neutral line when connecting and discharged at disconnect. The voltages are clamped at 17.5 V and the balancing currents are in the magnitude of 20 A.

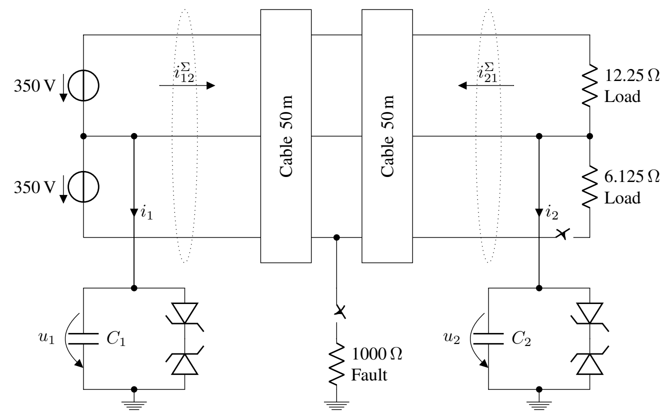

Fig. 3. Bipolar dc grid with two capacitive grounding points with voltage clamping by zener diodes. Sources on the left and asymmetrical loads on the right. The 20 kW load on the negative pole is disconnected to change the load balance. Further a human ground fault can be generated in the middle of the cable of 100 m length.

to the negative conductor. The impedance of a capacitor in Laplace domain is

$$Z_C(s) = \frac{1}{sC}. \tag{1}$$

The main advantage of this grounding configuration is that the impedance to ground is infinite in steady state ($s = 0$). This means that no dc ground currents can flow. In this way corrosion can be avoided. For high frequencies the capacitor impedance $Z_C(s)$ decreases. Thereby it behaves similar to low impedance grounding for fast fault transients. Due to this fact selectivity and short circuit protection can be done similarly as with low impedance grounding.

A. Load Change – Balancing Currents

One challenge that occurs is that the capacitors always need to be charged to the voltage potential of the neutral, respectively grounded wire. This voltage changes depending on the load in unipolar grids, likewise load balance in bipolar grids. In order to charge the capacitors, ground currents will flow at load changes. The charge is depending on the size of the capacitors and relates to voltage and current as

$$u_C(t) = \frac{q_C(t)}{C} = \frac{1}{C}\int_{t_0}^{t} i_C(\tau)\mathrm{d}\tau + u_C(t_0) \tag{2}$$

where $q_C(t)$ is the charge of the capacitor at time t. The current is further dependent on the impedance of the ground loop. In Fig. 2 the simulation of the unipolar grid of Fig. 1 is shown. The load is connected at 0.2 s and disconnected at 0.4 s. The capacitors charge and discharge to the respective neutral voltage potentials. There is a significant overshoot which is caused by the cable inductance. It can be seen that the currents reach values of almost 20 A.

B. Voltage Clamping

Capacitors are rated for a maximum voltage. A maximum neutral voltage should be specified, in order to limit the cost and size of the grounding capacitors. It is important that capacitors used do not have polarity. This is because the potential of the neutral conductor can go negative. Due to isolation leakage, or other means, the capacitors could charge over time to either their maximum or minimum voltage. Therefore, the voltage across them has to be clamped. A possible implementation are two Zener diodes in anti-series configuration as shown in Fig. 1. For this paper a value of $\pm 5\,\%$ of 350 V is chosen, which results in a clamping voltage of ± 17.5 V as can be seen in Fig. 2 on the top.

C. Ground Faults

There are two types of faults that have to be considered. The first case is the residual ground fault which would occur when a subject touches a live wire. In this case currents are limited to values lower than 1 A by the relatively large fault impedance (more than 500 Ω). The fault will be cleared by residual ground fault protection within a reasonable time and should not pose a problem for the power limit of the Zener diodes.

In case of a low impedance fault currents would be naturally higher and could easily destroy both Zener diodes and grounding capacitors. Therefore, this grounding scheme is only applicable with a low short-circuit current protection philosophy [8]. Ground faults with potentially high currents would be cleared in the μs range by solid state breakers, such that the energy dissipation in the Zener diodes does not pose a problem.

III. Capacitor Sizing Sensitivity

One of the challenges when using capacitive grounding is the proper sizing of the capacitors. The capacitance will determine the current behaviour during load changes. Therefore,

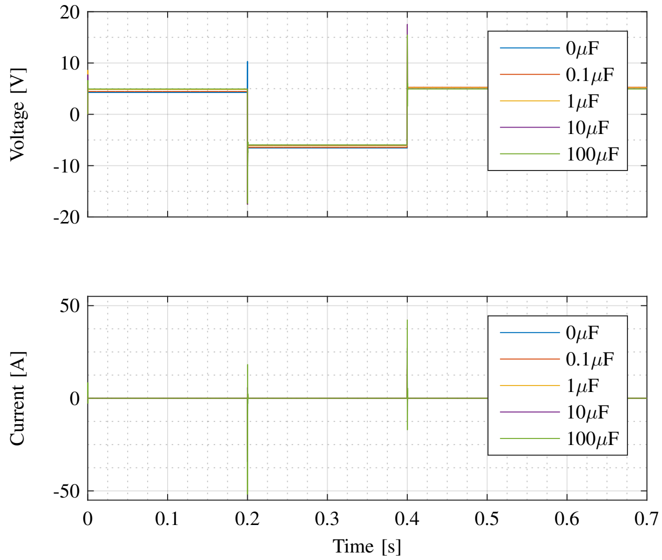

Fig. 4. Sensitivity simulation results for different capacitance values. Top plot shows the voltage of C_1 shown on Figure 3. Bottom plot shows the current flowing through C_2 to ground as shown on Figure 3. Load is initially connected. At 0.2 s load is disconnected and reconnected at 0.4 s, human fault is omitted for this simulation.

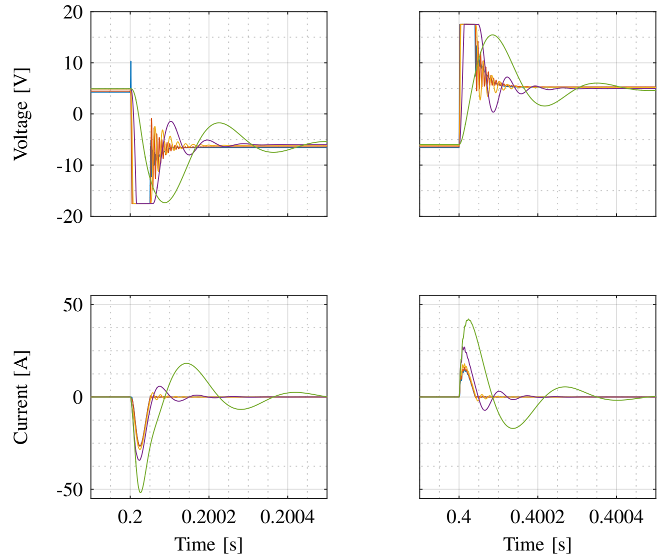

Fig. 5. Zoom for connection and disconnection points of Fig. 4for both voltage and current. From top to bottom and left to right: zoom of voltage peak at 0.2 s (Disconnection), zoom of voltage peak at 0.4 s (Connection),zoom of current peak at 0.2 s (Disconnection), zoom of current peak at 0.4 s (Connection).

TABLE I
CABLE PARAMETERS

Parameter	Value
Cable Resistance	4.61 Ω/km
Cable Inductance	360 μH/km
Cable Capacitance	260 μF/km
Capacitance ESR	10 Ω/km

a simulation is made in order to test the system sensitivity to different capacitance values. Fig. 3 shows the schematic used which consists of a bipolar dc grid system with a 350 V voltage source on each pole and two unbalanced loads of 10 kW on the positive and 20 kW on the negative pole. Two grounding points are included with a connection distance of 20 m both to source and load. A shielded cable with a length of 100 m is assumed and modeled with a Π model, in order to consider the effect of the cable capacitance in the simulation. The cable parameters used are listed in Table I. The cable chosen is relatively thin, which is meant to show in principle a considerable voltage drop in order to make the load change more significant.

Additionally a ground fault on the negative pole is included to emulate a human ground fault. Human impedance is by no means a constant value and depends on many factors. Nevertheless, a reasonable value of 1000 Ω is chosen according to the IEC Standard 60479-5 [9]. The human ground fault is only used in the next section.

Five simulations are made individually, each of them with a different capacitance value. The capacitance values are 0, 0.1, 1, 10 and 100 μF. The 20 kW load at the negative pole is disconnected and connected again at 0.2 and 0.4 s respectively. Fig. 4 shows the voltage and current values of C_1 shown on the schematic of Fig. 3 for the different capacitance values with a total simulation time of 0.7 s.

A zoom on each peak for each plot (voltage and current) is shown on Fig. 5. The color coding of the lines is the same as before. Looking at the 0 μF capacitance case the behaviour is similar to the capacitances of 0.1 and 1 μF, which is a consequence of the parasitic/snubber capacitance of the zener diodes which are modeled on the capacitive grounding points. Moreover, the voltage for the capacitance values of 1 and 10 μF shown on Fig. 5 clamp at 17.5 V which corresponds to the breakdown voltage of the zener diodes.

Furthermore, the system becomes more stiff with increasing capacitance as it is shown for 1, 10 and 100 μF capacitance values. At the moment of connection/disconnection currents around 25 and 50 A corresponding to 1 and 10 μF flow through the capacitors to ground. It is important to note that low capacitance lower to 1 μF are in the order of the cable capacitance value shown on Table I which for further system sensitivity simulations maybe omitted. The time it takes for the transients to be no longer relevant to the analysis is less than 0.5 ms which is a relatively fast compared to the time it takes current flowing through the human body to cause irreversible damage [9].

IV. RESIDUAL GROUND FAULT DETECTION FILTER DESIGN

As shown in Section III, relatively high currents occur at the moment of load change. Nevertheless, load changes are a normal behaviour in dc distribution grids and from the protection scheme point of view this needs to be taken into account. This current behavior poses a challenge for

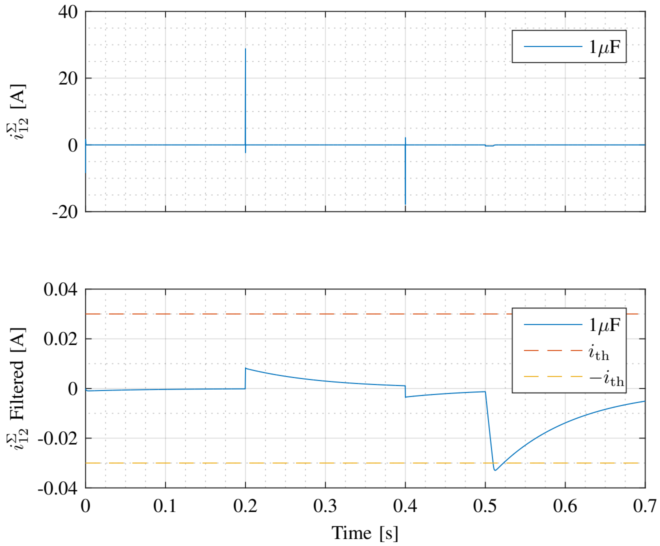

Fig. 6. Current sum measurement and low pass filtered current sum with time constant $\tau = 100\,\mathrm{ms}$. The negative load is disconnected at 0.2 s and reconnected at 0.4 s. A $1000\,\Omega$ residual ground fault of 10 ms duration occurs at 0.5 s. It can be seen that the threshold is only reached for the residual ground fault and not for the balance changes, even though the raw magnitudes (on top) have the opposite relation.

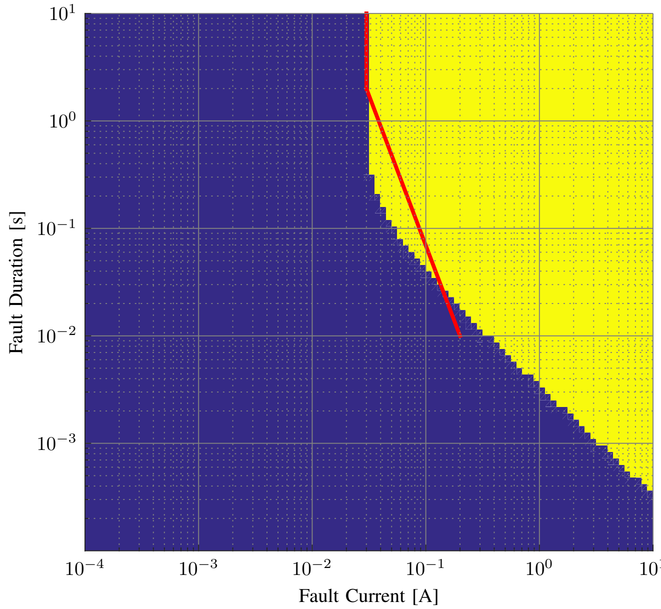

Fig. 7. Detection map for first order low pass filter. Blue color implies no detection from the filter whilst yellow color means favorable detection. Red line shows the limits for currents that may cause permanent damage to human body according to [9].

discrimitating load change currents from human fault currents, as the magnitude of the load change is much bigger than that of the fault. A simulation for a grounding capacitance value of $1\,\mu\mathrm{F}$ is modeled using the schematic in Fig. 3 and including the human ground fault at 0.5 s with a duration of 10 ms. The balancing current peaks can be seen in Fig. 6 on top. The human ground fault can barely be seen at 0.5 s.

For discrimination these measurements are filtered. A first order lowpass filter with transfer function

$$H(s) = \frac{1}{1 + \tau s} \tag{3}$$

is used for the sum of currents i_{12}^{Σ} shown in Fig. 3. A time constant $\tau = 100\,\mathrm{ms}$ is choosen for this simulation. A fault is detected when the filtered value reaches the selected current threshold of 30 mA in both the positive and negative direction. Looking at the simulation results shown on Fig. 6 it is easy to see that the duration for both the load change currents and the human fault current serves as discriminating variable for the protection scheme. The high peaks of the balancing currents are very short and thus have only a small effect on the filter output. The small magnitude of the human ground fault is compensated by the duration of 10 ms that is needed to cause considerable harm. In this simulation only the human ground fault filtered current peak the value is higher than the selected threshold value of 30 mA.

If a protection scheme for capacitive grounding were to be implemented using the aforementioned scheme, the filter should follow the IEC standard [9] in order to guarantee safety for all users. Therefore the residual ground fault protection filter is analized for different current magnitudes and fault durations. Thereby a detection map is derived that is shown in Fig. 7. The map consists of currents between $100\,\mu\mathrm{A}$ and 10 A with durations ranging from $100\,\mu\mathrm{s}$ to 10 s. The first order low pass filter has a time constant $\tau = 100\,\mathrm{ms}$ with a detection threshold of 30 mA. For each value of current and time the filter is tested to compare allowed limits according to standard [9]. On Fig. 7 the detection map for the given filter is shown. The IEC standard [9] limits are included on Fig. 7 (red line) to make a proper comparison. The standard only defines te behaviour above 10 ms as traditional ac circuitbreakers can not protect faster anyway. The filter follows approximately the sectors that the standard states for dangerous currents through the human body corresponding to values at the right of the red line. It can be seen that even though the filter detects most of the area located at the right side of the standard, it also has a considerable amount of detection to the left of it.

V. Conclusion

In this paper capacitive grounding was introduced as a possible grounding scheme for dc distribution grids with multiple grounding points. Its advantages are the prevention of dc ground currents in steady state, while still showing low impedance behavior for fault transients. The challenging magnitudes of load change and balancing currents were shown in a sensitivity analysis on the capacitor size for two grounding points. A filter was shown which can discriminate between residual fault currents and balancing currents.

Future work comprises the extension to a multitude of grounding points in order to generalize the system. Further filter synthesis should be done in order to prevent false positives. The boundaries of the applicability have to be identified and guidelines for capacitor size and line lenghts have to be derived.

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