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Effective Grounding of Battery Energy Storage Systems Operated in Utility Connected or Islanded Mode

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SUMMARY

When connected to the grid, Battery Energy Storage Systems (BESS) may rely on the grid connection for grounding. If the same system is intended to operate disconnected from a grid in islanded mode (as a part of microgrid), they must operate in grid forming mode and should be effectively grounded. This paper examines effective grounding during islanded or microgrid operation. It is desired that the BESS facility be capable of carrying the feeder load in islanded conditions. For this to be possible, the site needs to be adequately protected against fault conditions and over-voltages to limit insulation stress during faults involving ground. Providing fault current is only one way that a protective system might be designed to operate. Since inverters are incapable of economically providing additional fault currents, it is not a good solution. Since microgrids are new construction, designs that do not rely on high fault currents are preferred.

This paper mainly focuses on BESS systems within the islanded microgrid, and the steps involved in developing the effective grounding of such microgrid systems. The first section of the paper presents a brief background of IBRs, BESS, and the general layout of the BESS. In the second section, we discuss the introduction and importance of the methods of effective grounding to the microgrid. The third section discusses the methodology used to analyze the effective grounding where the sources are IBRs rather than the conventional generating sources. The paper also presents an example case of a BESS facility and calculation of Coefficient of Grounding (CoG) to check the validity of grounding transformer size. In the last section, we discuss the protection consideration of such microgrid followed by the conclusion.

KEYWORDS

Battery Energy Storage System (BESS), Effective Grounding, Microgrid, Grounding Transformer, Coefficient of Grounding (CoG), Protection

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INTRODUCTION

AC microgrids are increasingly popular in the energy sector due to their advantages: Increasing power quality (PQ); clean energy; increased reliability; and allowing Distributed Energy Resources (DER) to integrate into the grid. DERs could be solar photovoltaic, wind turbine, battery storage, etc. Inverters convert the power (DC to AC) from these sources and inject it into the grid. The advantages of microgrids come with challenges. One of the challenges is microgrid protection. Microgrids should be grounded to ensure that the insulation is not compromised, and protective relaying can operate for ground faults during grid-connected or grid isolated mode. In this paper, we discuss and provide examples of several aspects of effective grounding, BESS microgrid grounding bank design, and protection consideration of such microgrid.

BACKGROUND

Microgrids can operate connected to larger transmission networks or as an isolated single network; these conditions will be referred to as grid-connected and islanded operation, respectively. Typically, a microgrid contains one or more types of DERs such as wind turbines, solar panels, generators, etc. Energy storage such as battery storage is often used in islanded microgrids. Islanded microgrids may have a high percentage of IBR generation whereas conventional grids are currently dominated by synchronous generators. While operating in grid-isolated mode, the available short circuit current may be low compared to the grid-connected mode. Hence, islanded microgrids will require different protection and grounding schemes to protect the microgrid while in islanded or “grid-isolated mode. Several other challenges of microgrid protection are presented in [1].

Inverter-Based Resources

Inverter-Based Resources (IBR) insert a power electronics interface between energy sources and the utility grid. Resources such as full ac-dc-ac inverter (type 4) wind turbine generators, photovoltaic (PV) generation, and battery storage type generation are common IBRs. To minimize the rating of the power electronics, and therefore the costs, IBRs are typically designed to limit current flow. Current flow limits are accomplished by the inverter controls. The IBRs generally produce a low fault current between 1.1 to 1.4 times the rated output current of the inverter [2], [3]. Unlike synchronous generators, IBRs have negligible or fast decaying fault current envelopes, as they lack the magnetic characteristics of synchronous generators.

Battery Energy Storage System

Battery Energy Storage Systems (BESSs) are devices that store and release electrical energy. BESS are important in the development of a renewable profile due to the intermittent nature of renewables. Lithium-ion batteries are currently the dominant storage technology used for large storage. BESS mainly consist of three parts: 1) batteries, a power converter system (PCS), and a battery management system (BMS). The PCS is a three-phase converter, that couples the batteries to the grid. The PCS has a four-quadrant operation, meaning the PCS may be used as a rectifier in the charging process and as an inverter in the discharging process. Figure 1 shows the structure diagram of the BESS [4]. The BMS monitors BESS’s performance such as voltages, currents, temperatures, etc. The BMS will communicate with the PCS regarding the state of charge (SOC) and state of health (SOH) to tell the battery system to charge or discharge to prevent any damages due to excessive charging or discharging.

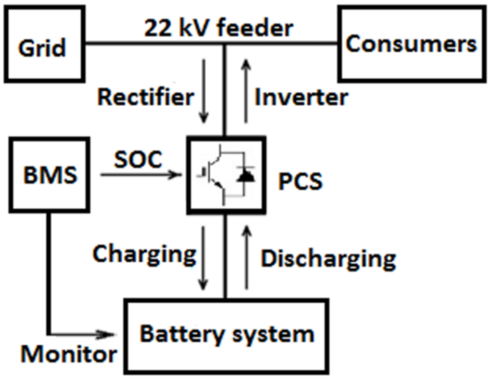

Figure 1: Structure diagram of the Battery Energy Storage System [4]

EFFECTIVE GROUNDING

There are several different forms of grounding in electrical power systems. These include solid grounding, resistive grounding, reactance grounding, resonance grounding, and floating methods. The most common method for grounding in the United States distribution and transmission system is solid grounding. These systems are usually multi-point grounded. This is not to say that other types of grounding are not utilized. For some applications, other types of grounding may be used (i.e., reactance grounding on distribution transformers to limit fault current). For further discussion on grounding methods, we encourage readers to see [6][11].

One of the main benefits of solidly grounded systems is that they limit overvoltages on unfaulted phases during ground faults. Additionally, ground faults produce high levels of ground current, making their detection simple. This system also allows for the connection of single-phase loads, which makes it well suited for US geography.

Effective grounding is slightly more complicated than simply connecting neutral points directly to ground. Consider the following example:

In a grid dominated by rotating machines, where generation is modeled as a voltage source during a fault, voltages on unfaulted phases during a line-to-ground fault can fall anywhere between 0.866 p.u. to 1.732 p.u. For the full derivation of this range, refer to [7]. What determines the voltage of a particular point is the equivalent positive-sequence impedance Z_1, and the equivalent zero-sequence impedance Z_0. IEEE C57.32 defines effective grounding as when the unfaulted phase voltage previously mentioned is at or below 80% of the maximum value. For this to be true, the ratio of X_0/X_1 must be less than 3 and the ratio $R_0/R_1 < 1$. [8-10]. This is the usual benchmark for determining effective grounding.

A special case occurs when the power system in question is no longer dominated by rotating machines. In the case of high penetration of inverter-based resources, the assumptions about fault behavior may no longer be valid. The device(s) may not act as positive sequence voltage sources behind an impedance, nor is it guaranteed that they will provide a path for negative sequence current. For this reason, IEEE guide C62.92 has a separate provision for these types of systems. Section VI states that high penetration IBR grids may be checked for effective grounding using electromagnetic transient programs (EMTPs). This type of software is useful for analyzing behavior of IBRs because it can accurately model the control systems that are used by the devices, something of which short-circuit software is not currently capable.

To determine if effective grounding is achieved, the guide states that the Coefficient of Grounding (CoG) must be less than 0.8. Essentially, this is a calculation of what percentage of the worst-case traditional overvoltage occurs for a ground fault with IBR generation. Rather than use sequence components to determine what overvoltage is expected, this method directly measures the overvoltage and expresses it as a ratio, similar to the ratio of sequence components.

An example is given in Figure 2. A 10 MVA BESS is operating as a local microgrid, providing power to a residential feeder.

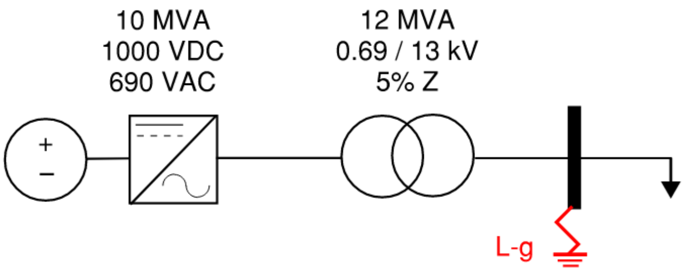

Figure 2: Single Line for BESS microgrid (simplified)

The worst-case overvoltage is likely to occur at the transformer high side, so this is the location that is used in this example. The entire feeder is modelled as a constant shunt load.

When this simulation is run in PSCAD, the following output waveforms are obtained as shown in Figure 3. The A Phase-to-Ground fault is applied at 1 second.

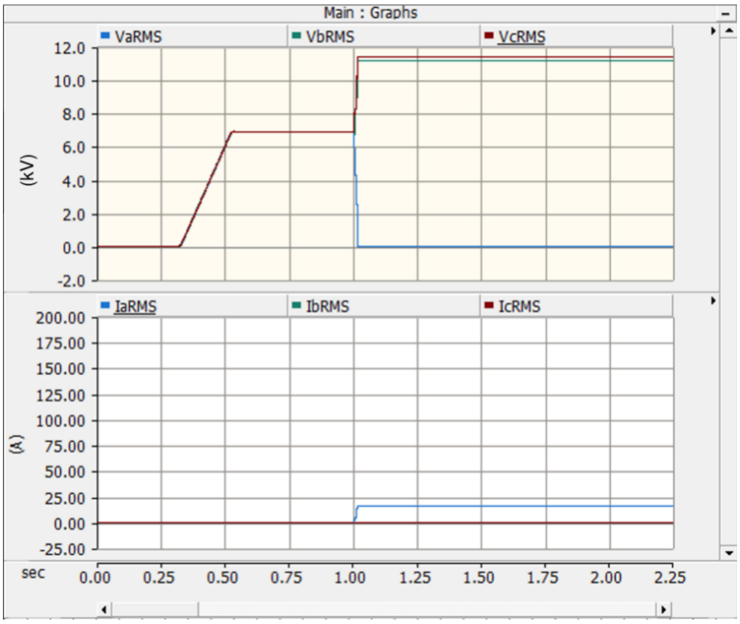

Figure 3: Line voltages and currents at high side of the transformer(Y-Yg)

Now observe the output when the step-up transformer is changed from Y-Yg to D-Yg configuration. Based on understanding of classical grounding alone, it should be expected that the overvoltages should be much lower as this transformer acts as a ground source. Results are in Figure 4.

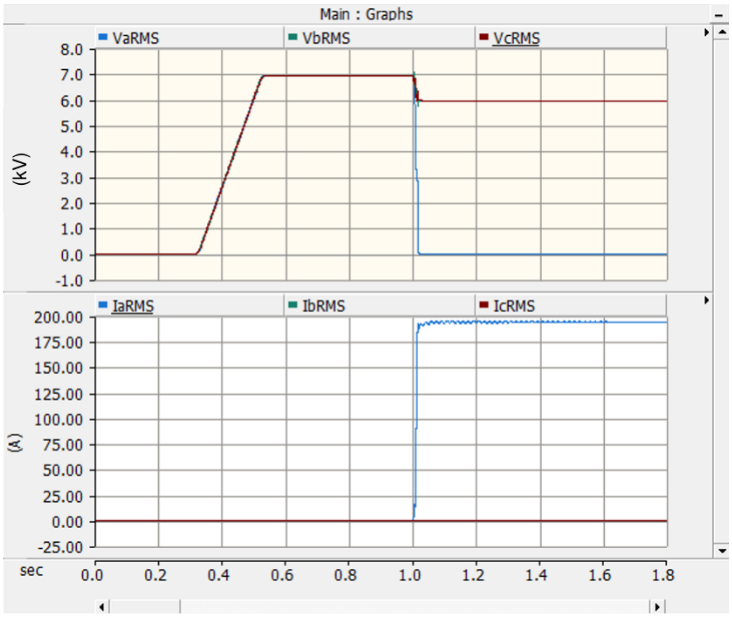

Figure 4: Line voltages and currents at high side of the transformer (D-Yg)

The traces show that the D-Yg connection has lower voltages and higher currents in the un-faulted phases.

GROUNDING IN THE ISLANDED BESS

It is important to maintain effective grounding in microgrids for two reasons. One is to limit the excessive overvoltage during line-to-ground fault and the second is to facilitate good ground protection. If the DERs at microgrids are interconnected to the grid through a transformer with a solidly grounded Y connection at the PCC side (high side) and delta connected at the DER side (low voltage), the microgrid is solidly grounded. If the microgrid's DERs are connected with the delta at the PCC side or an ungrounded wye on the low side, the microgrid system is not solidly grounded. Therefore, while operating in grid isolated mode, a grounding transformer may be required to maintain effective grounding. The main concerns for sizing a grounding bank transformer in a microgrid are as follows:

1. The transformer bank should be able to withstand the neutral current from short time duration faults in the system under microgrid conditions (thermal current rating).
2. Assuring that effective grounding for the system, that is a coefficient of grounding (CoG) less than 80% is achieved at different locations in the system during faults. This will also help lower the temporary overvoltages (TOV) in the system. Preferable (CoG) is below 72%, which means that the TOV is limited below 1.25 pu of the pre-fault voltage.
3. The transformer should be able to handle the neutral current created by voltage unbalance. In this report, 5% voltage unbalance (line to ground) has been assumed.
4. Continuous current carrying capability of the transformer should be greater than 15% of the peak load.

The example below will show the steps involved to validate the size of the grounding transformer. Figure 5 below of a microgrid with battery energy storage shows the locations of the faults applied to check the validity of the size of the grounding transformer.

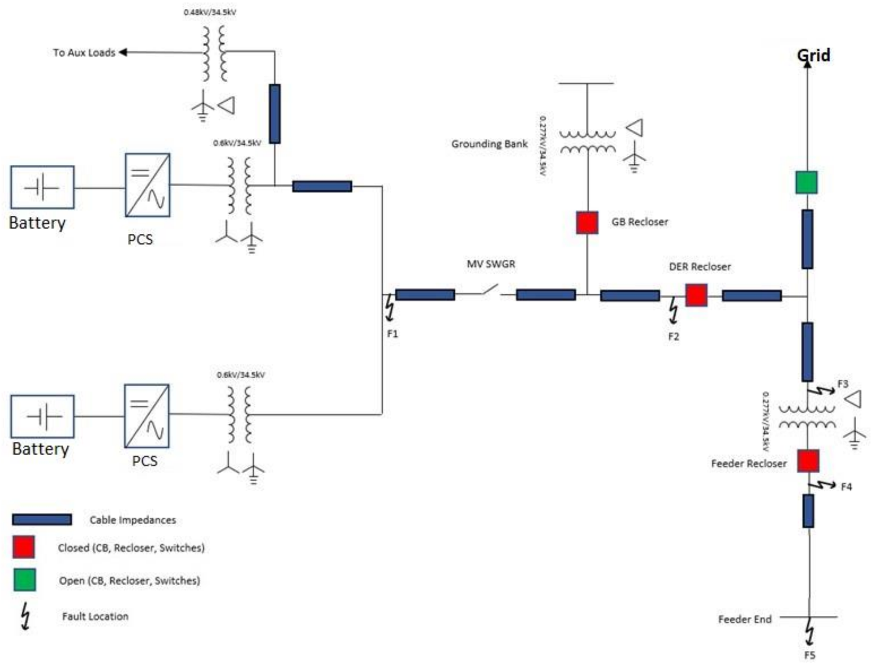

Figure 5: One Line Diagram showing Fault Location

Consider the single line-to-ground (SLG) fault F1 at BESS MV bus. If the Grounding transformer (GT) is not in-service, a fault on the 34.5 kV network will result in a very high TOV of around 35 kV L-G on the un-faulted phases as shown in Figure 6. From the plot, the CoG is approximated to 1.73 (=$\frac{V_{l-g,fault}}{V_{l-l,pre-fault}}$).

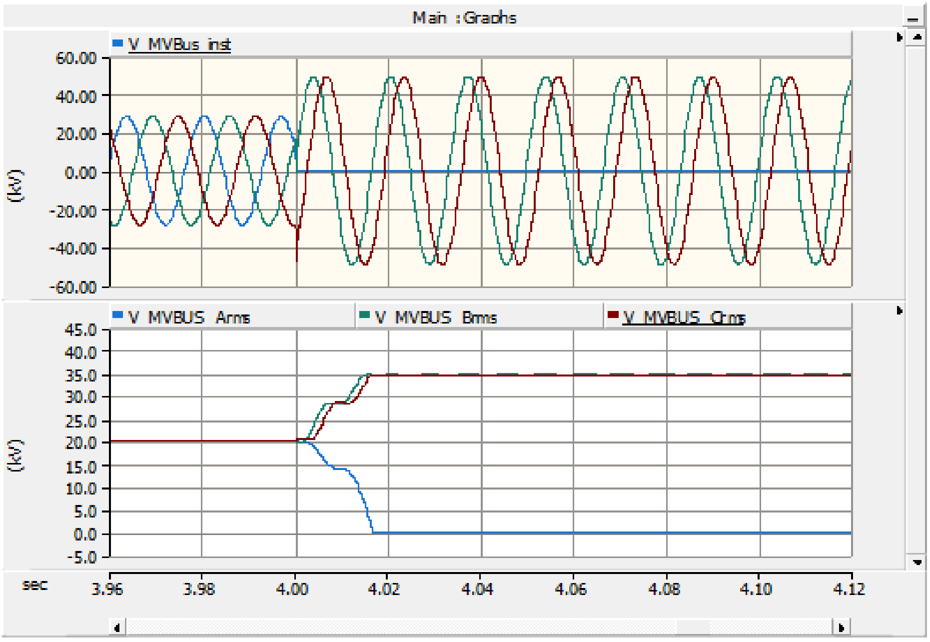

Figure 6:Temporary Overvoltage on MV Network without the Grounding Bank

Figure 7 shows the plot of voltages at faulted and unfaulted phases with the grounding bank in-service.

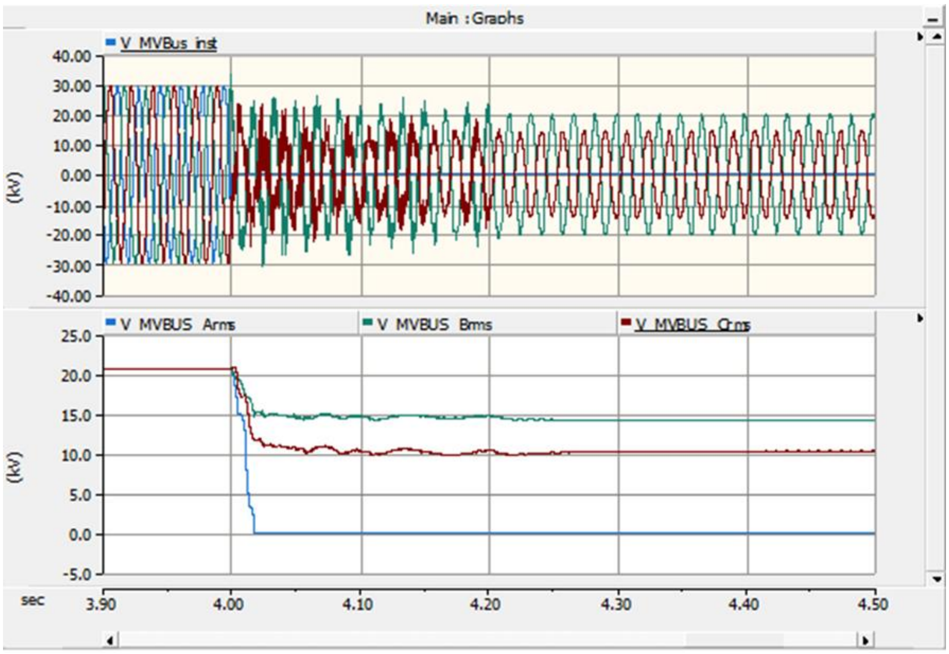

Figure 7: Instantaneous and RMS voltage at BESS MV location (F1)

The CoG is approximated to 0.4 which is significantly less than the preferred threshold. The CoG values for the SLG faults at the fault locations shown in Figure 5 are given below in Table 1.

Fault Location	Coefficient of Grounding (CoG)
F1	0.397
F2	0.397
F3	0.324
F4	0.300
F5	0.493

This table demonstrates that the CoG at several possible fault locations is less than the preferred threshold. Hence the size of the GT is adequate to effectively ground the system.

PROTECTION CONSIDERATION

The design of the grounding system will have several impacts on the protection system that is used for the microgrid.

One of the first considerations is the difference in fault conditions when a system is operating in a grid-tied mode versus when it is operating in a grid isolated local microgrid mode. In most cases, the available fault current from the grid is going to be significantly higher than the available fault current of a microgrid.

Another consideration is the effect of the microgrid ground source when the system is grid-tied. When this equipment is connected to the electrical system, it provides a shunt zero-sequence path that will affect ground current values during ground faults. They are intentionally designed to be low impedance paths to provide ground current during local microgrid operation, but the path will still exist during grid tied operation unless it is disconnected. Consider the system below in Figure 8.

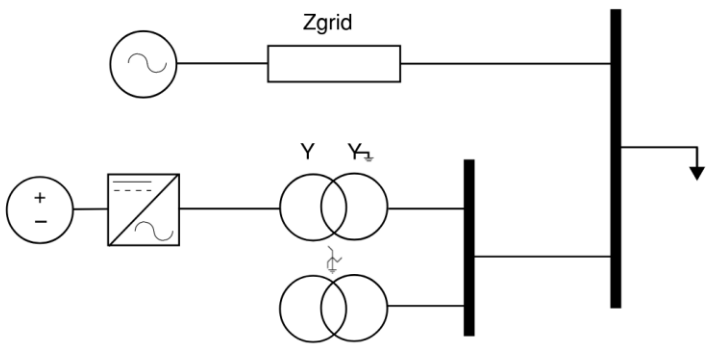

Figure 8. Example one-line for BESS operating in grid-connected mode.

In this scenario, there are two parallel paths in the zero-sequence network. This is shown in Figure 9.

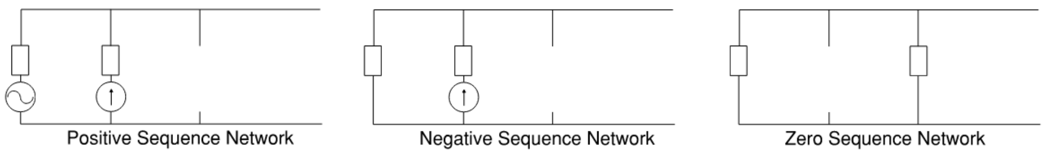

Figure 9. Sequence networks for the system in Figure 8.

A challenge is posed for relaying that operates on zero-sequence quantities. If the setpoints for ground overcurrent protection at the upstream substation are not adjusted after the introduction of this new ground source, the scheme may no longer be sensitive enough to detect downstream ground faults. Even if the protection is not defeated entirely, coordination could be skewed due to longer operating time for this device.

There are a few ways to rectify this situation. First, a switch could be installed before the ground source at the microgrid. During grid-tied operation, the switch would remain open, and during grid-forming operation, the switch would remain closed. This scheme requires provision for closing the grounding transformer in when the feeder breaker opens. This will be a challenge if the microgrid is intended to pick up the load without interrupting the customers.

A second option is to adjust the relay settings for upstream devices to account for the change in fault current, provided a setting that accommodates operations in both grid connected, and isolated modes can be found. This is likely the most inexpensive solution.

A third option could be to set the microgrid ground overcurrent element to trip in a short time. After the microgrid is removed from the network, the ground current through the substation ground path will increase, and the 51G protection would be able to trip in its expected time. Care needs to be taken to ensure that the BESS will meet applicable ride through requirements.

Finally, more significant changes to the protection system can be considered. These might include using ground impedance relaying, adding a communication-based scheme, or differential protection.

CONCLUSION

This paper demonstrates that grounding design is an important aspect when creating a microgrid. Proper grounding ensures that overvoltages due to ground faults are limited to safe levels and that the proposed protection system will operate as needed. To ensure that proper grounding is achieved, a design engineer can follow the guidelines presented in C62.92-series to obtain an appropriate coefficient of grounding, either by using sequence components for rotating machinery based microgrids, or with EMTP simulations for IBR microgrids. If necessary, site design may be modified for proper grounding. This could include changing the GSU winding configuration or with the addition of grounding transformers. With each method, proper design calculations must be followed to ensure appropriate sizing of equipment. Once the microgrid is determined to be properly grounded, protection must be re-examined. Elements operating on ground current may be impacted by the change in the grounding design and may no longer operate as intended. Correctly studying coordination of all devices in the area will ensure that the protection is adequate both for the system when connected to the grid and when operating as a microgrid.

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