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Analysis of Short Circuit Transient Behaviour of Microgrid

Debarpita Roul
College of Engineering Bhubaneswar, Odisha, India

Abstract: In order to validate the solutions put in place to lessen the undesired behavior of the power conversion systems and the gensets during transient short circuit events, this study presents the results of the medium voltage short circuit tests that were carried out on the microgrid of Graciosa island.

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1 Introduction

The Graciosa microgrid project, headed by Graciólica and overseen by ENGIE Tractebel and Inesc Tec, integrates solar and wind power generation with energy storage through the use of lithium-ion batteries from Leclanche, battery inverters from SMA, and an energy management system (EMS) from Greensmith Energy, a Wärtsilä Company. On the island of Graciosa, Graciólica emerged as a new independent power provider to supply renewable energy to the Azores' utility, EDA. The Graciosa microgrid is equipped with a sophisticated energy management system (EMS) that oversees the operation of the diesel power plant (DPP) operated by EDA in addition to the renewable plants and energy storage system.

2 Graciosa hybrid microgrid

The yearly energy consumption on the island is around 13 GWh, with a peak load of 2.3 MW and a valley load of 1.2 MW. The Graciosa hybrid microgrid consists of the following generation units connected to the 15.15 kV busbar:

- 4.6 MW DPP (3×600 kW, 1×810 kW, 2×1000 kW).
- 4.5 MW wind power plant (5×900 kW) – WPP.
- 1 MW photovoltaic (PV) power plant.
- 7425 MW battery power plant (3×2475 kW) with a capacity of 2.6 MWh in total – BPP.
- EMS autonomously controlling all above assets.

Fig. 1 represents the single line diagram of the islanded microgrid.

3 Description of the short circuit event

Event observation

On Friday on 18 January 2019 at 17:50:25 Azorean time, the EDA's load feeder Guadalupe 2 tripped due to a phase-to-phase medium voltage short circuit (SC) between phase A and B.

At the time of the fault, Genset 8, Genset 2, Genset 1, the three power conversion systems (PCS), the PV and the wind farm were connected to the grid. The PV and wind farm were fully curtailed at the time of the event.

Expected behaviour of the microgrid

During an MV SC, SC current is provided by the running gensets as well as the three PCS. The upstream breaker of the faulty line trips due to overcurrent and the fault is cleared. After fault clearance, the voltage is restored by parallel operation of the PCS and Gensets.

Observed behaviour of the microgrid

After 190 ms, the relay of feeder Guadalupe 2 tripped. After the fault clearance, the voltage and frequency did not recover to their nominal value as shown n Fig. 2. High active and reactive power swings were observed as shown in Fig. 3.

The following events occurred:

- Genset 8 tripped 1400 ms after fault occurrence due to overcurrent.
- Genset 1 and Genset 2 tripped 1850 ms after fault occurrence due to undervoltage.
- PCS 1 and PCS 3 tripped 1950 ms after fault occurrence.
- PCS 2 was then the only grid forming unit left connected to the microgrid and was able to restore the voltage and frequency to nominal values.
- PCS 1 and PCS 3 auto reconnected 30 s after tripping.
- Island load was supplied by the three PCS until the gensets were manually restarted and reconnected, a couple of minutes after fault occurrence.

4 Analysis of the SC event

The disturbance records of the event were collected and extensively analysed by Tractebel, Wärtilsä and EDA engineers. It was observed

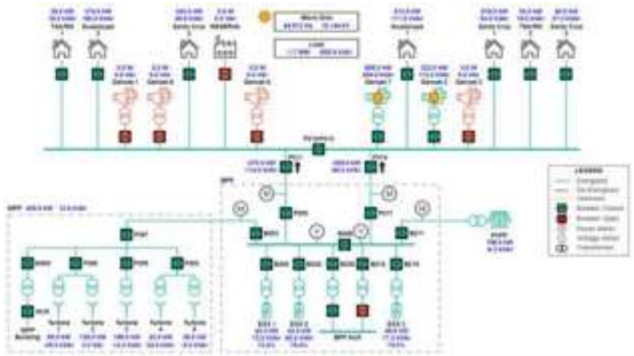

Fig. 1 *SLD of the Graciosa microgrid (Source: Graciolica)*

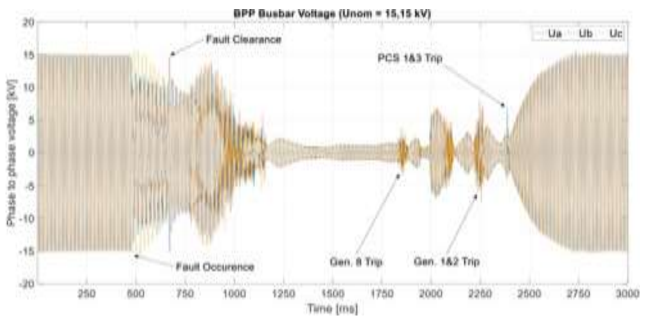

Fig. 2 *Ph–Ph three-phase voltages at the medium voltage busbar during and after the event (Source: Graciolica)*

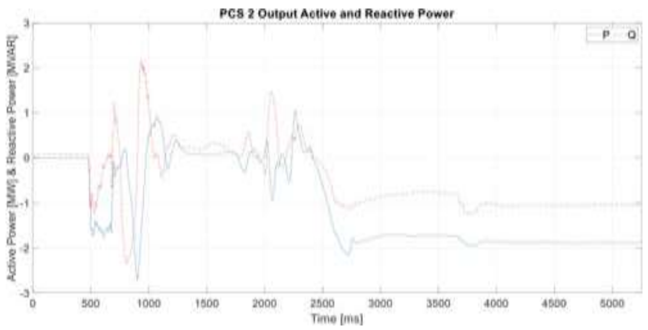

Fig. 3 *PCS 2 active and reactive power output during and after the event until stabilisation (Source: Graciolica)*

that the unexpected behaviour occurred due to two different causes interfering with each other.

Cause 1: Desynchronisation of the PCS

After the clearance of the fault, the three PCS try to restore the voltage to the nominal value. A couple 100 ms after fault clearance, the three PCS start interfering which each other as shown in Fig. 4.

The PCS active and reactive power output is managed in droop mode through a control loop that operates thousands of times per second. The EMS operates a control loop that sends active and reactive power setpoints to each PCS a few times per second. These setpoints are processed with a small time difference between each PCS. During normal operation, this small-time difference has no impact on the parallel operation of the PCS. However, during and after the SC, the system is in a transient state and the setpoints sent at different times to the three PCS will affect the voltage control loop. This results in the three PCS starting to counteract each other's operation causing large differences in the phase angles between current and voltage and causing high active and reactive power flows between each PCS. This leads to desynchronisation and eventually to a trip.

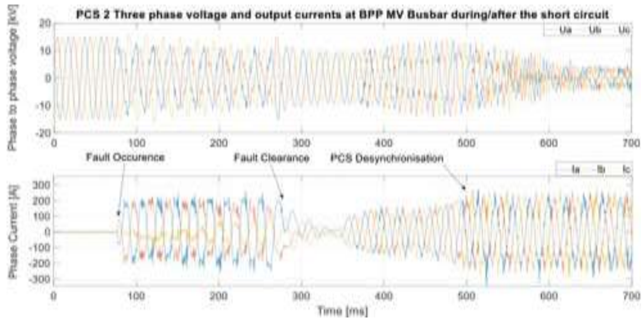

Fig. 4 *PCS 2 measurements during and after fault (top) PCS 2 AC output voltage, (bottom) PCS 2 AC output current*

Cause 2: genset voltage collapse

After fault clearance, the excitation system of the gensets reacts quickly to limit the voltage and current while trying to stabilise the voltage around 1 pu. However, as shown in Fig. 5, the voltage did not rise back to 1 pu and collapsed until the genset tripped.

After fault clearance, the genset excitation system tried to stabilise the voltage around 1 pu. However, this failed due to the behaviour of the PCS. When an SC occurs, the PCS will provide the maximum current according to its capabilities. At first, the current is limited by hardware (HW) protection means to ensure that the PCS provides the highest currents possible while protecting the semiconductors from damage. With the current version of firmware on the PCS, the duration of HW protection operation is limited and after a defined time the software (SW) protection will kick in and reduce the voltage setpoints to provide high current without triggering the HW protection. After fault clearance, the PCS will gradually restore the voltage to nominal operation (voltage recovery) as shown in Fig. 6 (in accordance with the

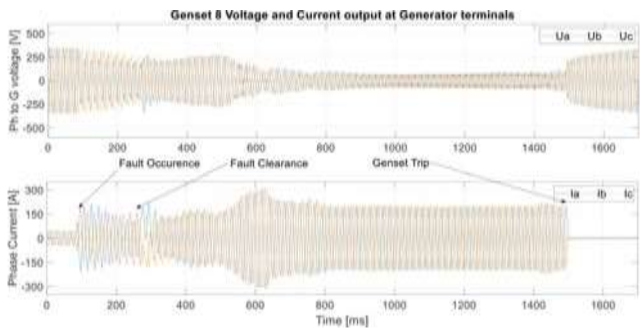

Fig. 5 *Genset 8 output measurements after fault occurrence (top) Genset 8 output voltage, (bottom) Genset 8 output current (Source: Graciolica)*

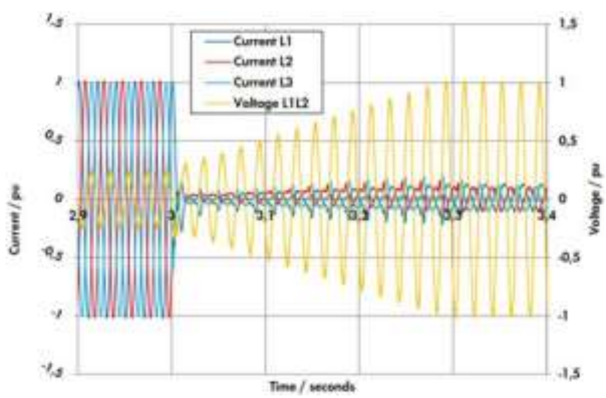

Fig. 6 *Voltage recovery due to the SW protection after clearance of the SC, per the firmware installed currently at this site (Source: PCS Manufacturer, SMA)*

current version of the firmware at this site). The time required for this voltage recovery depends on how long the SW protection was active. The difference in voltage recovery behaviour of the PCS units and the gensets caused high active and reactive power swings between the units as shown in Fig. 3. The excitation systems of the gensets cannot operate as intended and get pushed beyond their limit and ultimately collapse.

5 Implemented solutions

Cause 1: PCS desynchronisation

To solve the desynchronisation of the PCS, adjustments needed to be made to the EMS settings in accordance with the inverter vendor's recommendation that was provided after the observance of this event. In order to detect an SC, the EMS monitors the voltage and frequency closely and handles the event in close coordination with the PCS units.

Cause 2: genset voltage collapse

The PCS HW protection limit was increased so that the SW protection limit and thus the voltage recovery is not required after fault clearance. By doing this, the voltage setpoint of the PCS after fault clearance is 1 pu, equal to the engines voltage setpoint after fault clearance. To ensure that the HW protection limit is active for the entire fault clearance duration, the setting was increased to 600 ms which is longer than the maximum time a fault can exist in the microgrid (510 ms: 450 ms for main and backup protection fault clearance +60 ms breaker opening time).

Implementation

A dynamic study was performed by Wärtsilä to validate the proposed solutions above. After approval by ENGIE Tractebel, and EDA, the solutions were implemented and tested by performing live SC tests to verify the correct operation of the microgrid during SC events.

6 Medium-voltage SC tests

Test overview

A total of six SC tests were performed, three per scenario as described below.

- *Scenario 1*: BPP disconnected from the DPP (two PCS in voltage source mode and one PCS in current source mode as a load):
    - Phase to phase SC test.
    - Phase to earth SC test (bolted).
    - Phase to earth SC test (resistive).
- *Scenario 2*: BPP connected to the DPP (two PCS in voltage source mode and one PCS in current source mode as a load, Genset 1 connected):
    - Phase to phase SC test.
    - Phase to earth SC test (bolted).
    - Phase to earth SC test (resistive).

The MV SCs were performed on the overhead transmission line to the WPP, just before the closest pole to the WPP. A shorting link was installed across two phases for the phase to phase test, from one phase to the earth conductor of the overhead line for the bolted phase to earth test and from one phase to a steel pole placed 1 m deep into the ground for the resistive phase to earth fault. The WPP circuit breaker BPP203 was then remotely closed to initiate the SC. The protection settings of the microgrid were analysed and changed where necessary in order to double protect the equipment.

In all of the SCs described in the following sections, the three PCS and the Genset remained connected and stabilised the microgrid of Graciosa immediately after fault clearance. No further tripping was encountered.

Test results – phase to phase SC test – DPP connected

The phase to phase SC with DPP and BPP connected was initiated on 8 July 2019 at 14:09:08 h and it was observed that the fault was cleared in 300 ms.

Fig. 7 shows the RMS Ph–G voltage and frequency at the BPP Busbar. The vertical line in RED reflects the EMS coordination. The figure shows the following events:

- 14:09:08.995: A SC is detected by the EMS on Phase A. Shortly after Phases B and C also indicate an SC.
- 14:09:09.036: First EMS setpoint coordination.
- 14:09:09.470: All three voltages and frequency have returned to normal levels and normal operation is resumed.

From the above it can be concluded that the voltage and frequency are recovered after 475 ms.

Test results – bolted phase to earth SC test – DPP connected

The bolted phase to earth SC test with BPP and DPP connected was performed on 10 July 2019 at 13:49:41. Fig. 8 shows the RMS Ph–G voltage and frequency at the BPP Busbar. The figure shows the following events:

- 13:49:41.780: A SC is detected by the EMS on Phase A. Shortly after Phases B and C also indicate an SC.
- 13:49:41.992: First EMS setpoint coordination.
- 13:49:42.150: All three voltages and frequency have returned to normal levels and normal operation is resumed.

From the above, it can be concluded that the voltage and frequency are recovered after 370 ms.

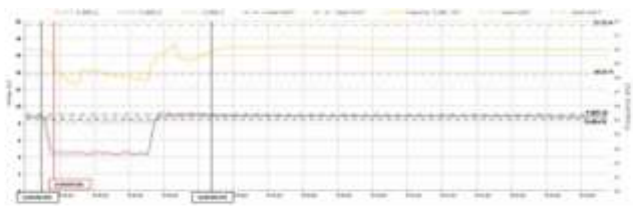

Fig. 7 *BPP busbar frequency and Ph–G voltage measured at BPP busbar during Ph–Ph SC test (Source: Graciolica)*

Fig. 8 *BPP busbar frequency and Ph–G voltage measured at BPP busbar during bolted Ph–G SC test (Source: Graciolica)*

Fig. 9 *BPP busbar frequency and Ph–G voltage measured at BPP busbar during resistive Ph–G SC test (Source: Graciolica)*

Test results – resistive phase to earth SC test – DPP connected

The resistive phase to earth fault was initiated on 10 July 2019 at 13:35:00 hours and it was observed that the fault was cleared in 320 ms. Fig. 9 shows that during the resistive earth to ground fault neither the frequency nor the voltage deviated enough to require any EMS coordination.

7 Conclusion

In this paper, the origin of the event that occurred after a medium voltage SC on the microgrid of Graciosa was investigated. The two root causes of the unwanted behaviour were determined and a solution was implemented and tested by performing live SCs on the microgrid. When designing these hybrid microgrid systems, extra attention should be put on the transient stability of the system as the generation units in these microgrids have very different responses to these transient events (rotating machines versus IGBT-based components) and the parallel operation of these units can cause unexpected and dangerous events if not designed and configured correctly. It is also shown that it is necessary to assess the operation of the EMS during these transient events to ensure that any potential interference of these automatic systems with the operation of the PCS units has been carefully and intentionally coordinated.