RE-ENERGIZATION OF A POWER SYSTEM WITH A DISTRIBUTION NETWORK

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ABSTRACT

The evolving energy mix increasingly integrates variable renewable energy systems into power grids, prompting the exploration of alternative black-start approaches at the distribution network. This study focuses on the use of distributed resources connected via power electronics converters to supply loads at the distribution level through transformers, following a blackout of the transmission system. Energizing transformers generates high unbalanced inrush currents with harmonics due to iron core saturation, posing a significant challenge. Unlike synchronous machines, power electronic converters cannot support large inrush currents. This paper demonstrates a grid-forming control that provides high-quality voltage while protecting the converter by limiting the inrush current. A benchmark is then implemented to illustrate the use of grid-forming to energize multiple transformers during a distributed black-start. It also demonstrates the ability of the proposed grid-forming to synchronize with an existing grid.

INTRODUCTION

In the event of a partial or total blackout, Transmission System Operators (TSOs) carry the responsibility of system restoration. Traditionally, this complex process relies on large power plants, either with black-start or islanding capabilities, to re-energize sections of the power system. This allows other large power plants to be restarted, and so forth [1]. In France, this is mainly achieved through nuclear and hydroelectric power. During this critical phase, the transmission system plays an essential role, while the distribution system typically remains passive, as it is not directly involved in these restoration measures.

With the large development of Renewable Energy Sources (RESs) within distribution networks, the traditional restoration scheme could evolve. The approach could involve local production units and Battery Energy Storage Systems (BESSs) within the distribution network to actively participate in the restoration of both distribution and, in some cases, transmission grids. In Great Britain, a world-first initiative project paved the way for the concept of distributed restart, exploring the use of distributed resources to restore power during blackout events [2].

This paper explores BESS interfaced with the grid using a Power Electronic (PE) converter. This converter is crucial for distributed restart processes as it has to regulate voltage and frequency [3]. In this context, the Grid-Forming (GFM) control has emerged in the literature as a potential strategy to generate voltage waveforms, functioning akin to a controlled voltage source [4], [5].

However, implementing this innovative concept involves numerous challenges, with transformer energization being among the top ones. Hard energization of transformers can lead to significant unbalanced inrush currents, potentially accompanied by harmonics, depending on the saturation level of the transformer's iron core [6], [7], [8]. Limiting these inrush effects is crucial in planning and designing distributed black-start strategies [9]. To address these challenges, the GFM has to switch from providing high-quality voltage and frequency in normal operation to advanced current management during the transformer re-energization phase to prevent the BESS from tripping.

In the literature, research on the capability of GFMs to energize transformers has begun. A comprehensive review highlighted the role of GFM in the energization process [10]. Controlled switching and soft energization in GFM have been assessed in [11], though challenges persist regarding an accurate knowledge of the saturation curve, residual flux, and delays of circuit breakers (CBs). [3], [12] illustrated the soft energization through a voltage ramp, yet defining an appropriate ramping time remains challenging due to varying operating conditions.

In this paper, the GFM does not require transformer data, residual flux information, or CB delays, enabling instantaneous transformer pickup. In this context, [13] illustrates the concept of implementing a Transient Virtual Resistance (TVR) to dampen inrush current. However, it does not directly address saturation in current control. [14] demonstrate an experimentally validated GFM based on droop control. It implements cascaded voltage and current control loops in the stationary frame, limiting inrush current by adjusting current or voltage references. However, defining the optimum parameters of the controllers remains challenging.

This article demonstrates the effectiveness of a proposed

GFM in achieving its objectives within the distributed black-start process. Technically, it emulates synchronous machines to control active power, while limiting current via current saturation activated at specific thresholds. Initially, the energization of a single transformer is examined. Subsequently, the study extends to re-energize a simplified distribution network comprising three types of feeders: the first type connects only generation units, the second type connects only loads, and the third type connects a mix of both generation units and loads.
The rest of this paper is organized as follows: Section two details the characteristics of the implemented transformer and defines the GFM control used for its energization. Section three presents the results of energizing a transformer using GFM. In Section four, a black-start scenario is applied to a defined distributed network benchmark. All simulations are conducted using the Electromagnetic Transients Program (EMTP) software.

TRANSFORMER ENERGIZATION USING GRID-FORMING: SYSTEM SETUP

System implementation

Fig. 1 illustrates the setup of the studied system. A Voltage Source Converter (VSC) is implemented to energize a transformer T2. The transformer T1, located next to the VSC, represents the transformer found in converters and is not the focus of this study; it is assumed to be already energized. The nominal power of T1 and the VSC is 1 MW. The connection is made through a 1 km line with the following characteristics: $R_g = 0.72\ \Omega$; $L_g = 1.75\ mH$.
The 1 MVA transformer T2 connects a RL load to the grid during the energization process. The load is characterized by an apparent power of 1 MW and a power factor of 0.85. The system employs two breakers: CB1, which connects the line to the transformer T2, and CB2, which connects T2 to the load.

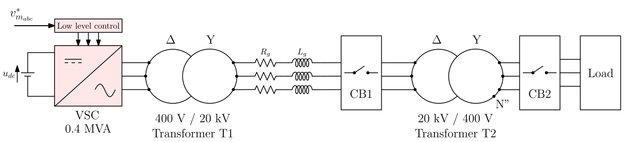

Fig. 1: System setup for transformer energization.

Transformer Specifications

To assess the effect of inrush current during transformer energization, a simplified model of transformer T2 is implemented. This model considers a 20 kV/400 V ΔY transformer based on the key specifications outlined in Table 1. The magnetization characteristics, derived from studies [11] and [16], reveal that the inrush current and generated harmonics are sensitive to the transformer's saturation curve. The transformer's parameters are provided in per-unit (pu) relative to its nominal values.

Table 1: Characteristics of the MV/LV transformer T2

Transformer's pu parameters	
Nominal Power (MW)	1
Primary voltage (V)	20000
Secondary voltage (V)	400
Winding resistance $R\ (pu)$	0.0115
Winding reactance $X\ (pu)$	0.038
Magnetization resistance $R_m\ (pu)$	500
Transformer's saturation curve	
$i_m\ (pu)$	[0, 0.001, 0.002, 0.003, 0.005, 0.01, 1]
$\Phi\ (pu)$	[0, 0.55, 1, 1.01, 1.03, 1.04, 1.05]
Initial residual flux	
$\Phi_{r_{abc}}\ (pu)$	[0.8, 0, -0.8]

Implementation of Grid-Forming Control

The VSC cannot support the high inrush currents during transformer energization, necessitating current limitation in the control. In this context, the objectives of the GFM implementation are twofold: to protect the converter by limiting the inrush current, respecting producer constraints; and to meet TSO and Distribution System Operator (DSO) requirements by ensuring a stable voltage during steady-state operation, maintaining an acceptable transient phase, and respecting grid codes [15].

Control Strategy

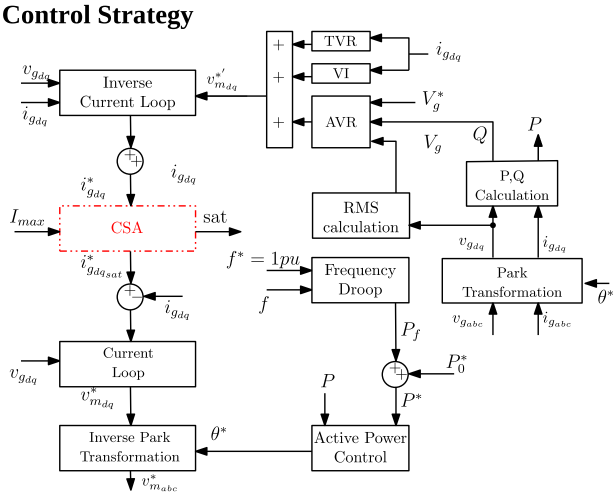

Fig. 2: Overall structure of the implemented Grid-Forming

The used GFM control is derived from the Voltage Control Grid-Forming (VCGFM) defined in [16] (See Fig. 2). It incorporates a current control exclusively for current limitation, ensuring the current follows the references provided by the "Current Saturation Algorithm (CSA)" block. In this study, the maximum threshold of the RMS current is 1.2 pu. The CSA generates current references that ensure $\left|i^*_{gdq_{sat}}\right| = 1.2\ pu$ while maintaining the original directions for the dq axis. To preserve the "voltage source" characteristic, a reverse function is added to the control setup. During normal operation, the dynamics of the PI controller of the current control are eliminated by the "Inverse Current Loop". The system also includes a TVR of 0.09 pu for quick damping, a virtual inductance of 0.3 pu, and Automatic Voltage Regulation (AVR) at the Point of Common Coupling (PCC) to stabilize voltage levels. For the active power control, a GFM embedding an inertial effect with frequency droop control of 4 % is employed [5]. For DC voltage, the DC voltage controls are not modeled, and the DC bus voltage is considered fixed. In addition, the model takes into account the converter's voltage limitation. Further details are provided in [16].

TRANSFORMER ENERGIZATION: RESULTS INTERPRETATION

Energization using an ideal voltage source

First, the VSC is replaced by an ideal three-phase source. Fig. 3 illustrates the three-phase current provided when T2 is energized at t = 0.1 s. The results are presented in pu with the base linked to the converter. The results demonstrate that hard energization can lead to a high unbalanced inrush current, potentially exceeding 4 pu, depending on the saturation level. Consequently, when the VSC is implemented, the inrush current must be limited to prevent potential damage to the system components.

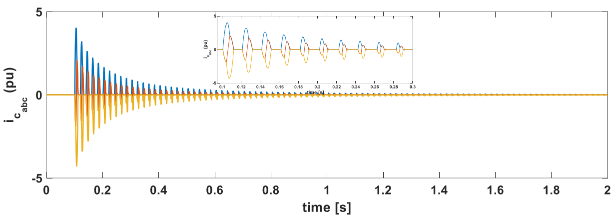

Fig. 3: Inrush current waveform during hard energization.

Energization using the proposed Grid-Forming

The transformer energization is now performed using the GFM. The results are presented in Fig. 4 and Fig. 5. The GFM successfully saturates the first peak of the inrush current due to the automatic activation of the current control, which overrides the references from the "Inverse Current Control" block during this period. This current control mechanism effectively limits the magnitude of the inrush current, followed by an exponential decay. This decay is further damped due to the implementation of the TVR. Conversely, the impact of limiting the inrush current during the initial moments of transformer energization can be seen on the voltage side (See Fig. 5). Specifically, the voltage at the PCC becomes distorted to align with the saturated current references set by the "current loop". Nevertheless, after the initial peaks are saturated and the transformer becomes energized, the voltage gradually returns to its sinusoidal waveform, maintaining its good quality in steady state. Fig. 6 illustrates the connection of the load. It demonstrates that the load is effectively supplied with the required active and reactive power.

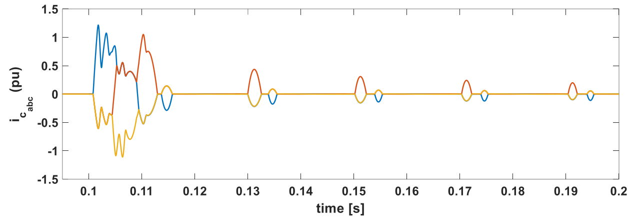

Fig. 4: Inrush current waveform after GFM implementation

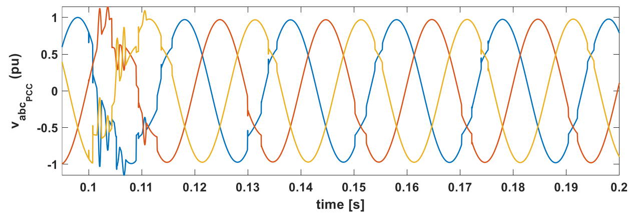

Fig. 5: PCC Voltage following GFM implementation.

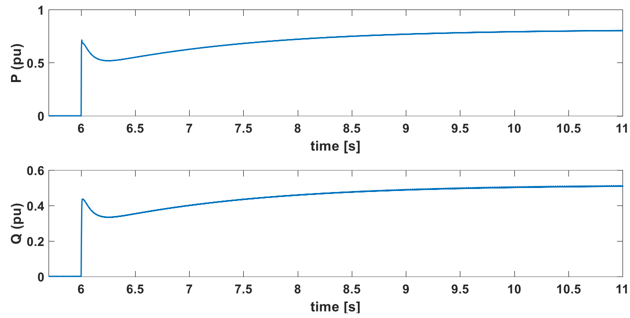

Fig. 6: Active and reactive power waveforms after the connection of the RL load at t = 6 s.

APPLICATION OF GRID-FORMING TO A BENCHMARK SCENARIO

Benchmark Definition

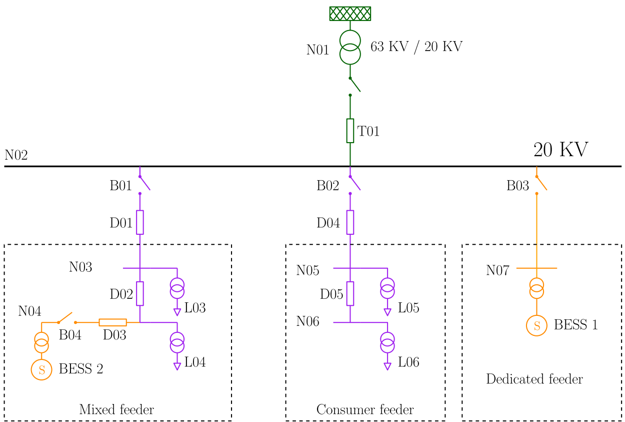

Fig. 7: Presentation of the proposed MV benchmark constituted with three feeders.

The benchmark for this study is designed to establish a framework for restoring power in a distributed black-start scenario, ensuring the re-energization of critical loads. It comprises three types of feeders, as illustrated in Fig. 7:

1. **Production Feeder:** It is connected to a BESS GFM with a nominal power of 11 MVA. It plays a crucial role in the initial stages by energizing

other transformers within the distribution level.

2. **Consumer Feeder:** It consists of two loads.
3. **Mixed Feeder:** It includes another BESS GFM with a nominal power of 4 MVA, along with two loads. The BESS 2, although initially inactive, is integrated into the re-energization process to supplement the power provided by the BESS 1.

All loads are interconnected via a MV/LV transformer with the same magnetic characteristics as listed in Table 1, and the corresponding transformer has a nominal power equal to the apparent power of the load. The characteristics of the distribution lines are found in Table 2. The four considered RL loads are described in Table 3.

Table 2: Distribution lines characteristics.

Line	D01	D02	D03	D04	D05
L (mH)	0.66	0.56	0.2	1.75	0.19
R (Ω)	0.41	0.35	0.18	0.72	0.11

Table 3: Loads characteristics.

Load	L03	L04	L05	L06
S (MW)	3	1	6	4
Cos Φ	0.85	0.95	0.8	0.9

Scenario description

The proposed re-energization scenario is divided into several key phases, detailed as follows:

1. **Initial Activation:** The dedicated feeder (BESS 1) is activated by closing B03, establishing the initial voltage source.
2. **Loads Connection (t = 3 s):** B01 is closed while maintaining B04 open. Consequently, L03 and L04 are directly connected.
3. **Connection of BESS 2 (t = 6 s):** BESS 2, also operating as a GFM, is connected to the grid by closing B04 to assist BESS 1 in the power supply. Initially, before connecting BESS 2, The two BESSs are not synchronized. This setup evaluates the ability of the proposed GFM of BESS 2 to synchronize with the grid during a blackout.
4. **Connection of the Consumer Feeder (t = 9 s):** B02 is closed to supply L05 and L06.

The objective is to demonstrate that the proposed re-energization strategy with the GFM can effectively manage the distribution network, maintaining voltage quality, and limiting current to acceptable levels, thereby ensuring a reliable and efficient power restoration process.

Simulation and Results

Fig. 8 and Fig. 9 illustrate the current provided by BESS 1 and BESS 2, respectively. The pu values in each figure correspond to the base of each converter. As shown, the current is limited in all cases where transformers are energized. At t = 3 s, BESS 1 provides the required current to supply the loads of the mixed feeders. At t = 6 s, when BESS 2, operating as a GFM, is connected, the power is shared between the two converters according to their nominal power ratings. At t = 9 s, the consumer feeder is connected and it is supplied the required power shared between BESS 1 and BESS 2. Fig. 10 compares the voltage at BESS 2 between the grid side and the converter side to evaluate the GFM's capability to resynchronize with an existing grid. The results demonstrate that the voltage successfully resynchronizes with the grid phase. This connection could be considered a 'pessimistic' approach, as the VSC can measure and align the phase before connecting, thereby avoiding transients.

In conclusion, the proposed control effectively energized the transformers, supplied the loads, and demonstrated its efficiency in synchronizing with an existing grid.

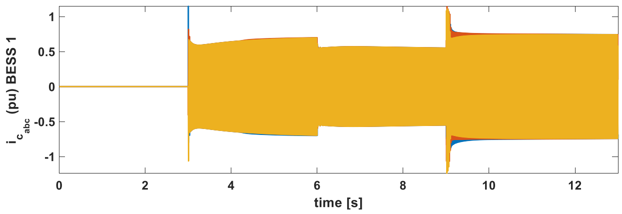

Fig. 8: Current waveform provided by BESS 1.

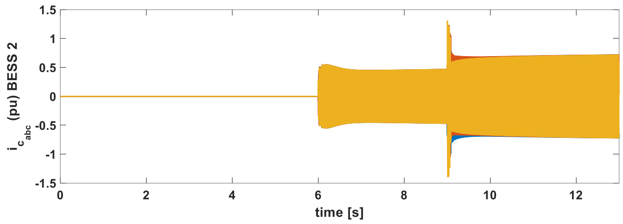

Fig. 9: Current waveform provided by BESS 2.

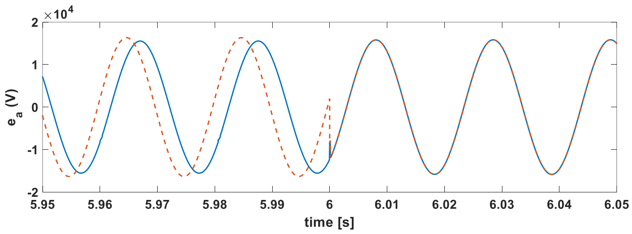

Fig. 10: Comparison of Phase A Voltage at BESS 2 level: Converter Side (red) and Grid Side (blue).

CONCLUSION

As the integration of BESSs into the distribution network increases, the need for innovative black-start strategies at the distribution level becomes critical. This paper provides an examination of the challenges associated with the distributed restart process, with a focus on energizing the distribution grid using a converter operating as a GFM, a role traditionally filled by synchronous machines.

A GFM control was described, designed to limit inrush currents, thereby protecting components and ensuring the recovery of a sinusoidal voltage waveform. The study was extended to the simultaneous energization of multiple loads within a benchmark scenario, as well as the integration of an additional GFM control to help in power

supply. Furthermore, the results demonstrated the control's effectiveness in re-synchronizing with an existing grid.
It is noteworthy that energizing a larger HV/MV transformer in the transmission network can lead to wider constraints due to the potential for stronger inrush currents. Additionally, rapid changes in voltage to limit currents might pose challenges for the protection systems. Consequently, future work will focus on testing the energization of the HV/MV transformer using the GFM converter to better mitigate these challenges.

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