Public-domain examples of "Grid Forming" converters used in the real world.

There are quite a lot of academic papers which talk about VSM and Grid Forming converter control techniques, although in some of the papers the terms VSM and Grid-Forming are not used explicitly. It should be noted that there are many different proposals for control structures for the VSM. Some of them do not really provide Grid-Forming functionality, and instead provide a "Synthetic Inertia" which is really a variety of fast frequency response.

In terms of Grid-Forming converter control architectures, there are two main proposed types. The first type, which is called VSM (Virtual Synchronous Machine). These devices generally contain a virtual rotor model that emulates both the inertial mass (usually defined by H), and an appropriate damping mechanism to constrain the oscillations of the virtual rotor. The damping is required in just the same way as a real SM (synchronous machine) needs to have a damped response (naturally, and/or by adding special damper windings, which look like squirrel cage sections). In these implementations, a synthetic governor and prime mover response can also (optionally) be included, that applies droop slopes and time constants which can be configure to emulate (for example) a steam turbine power station. When a dynamic event occurs, the overall VSM response is a combination of the natural virtual rotor response (dominant for the fastest dynamic), and the synthetic governor/mover/droop response (dominant for slower dynamics).

The second type is called (by Strathclyde and National Grid) VSM0H, although it is also commonly referred to in literature as "Power Synchronisation". The inertia H is zero, but the converter rotor speed responds within 20ms to a settable droop slope (f/P), and there is a similar action with V/Q interaction. Because it has no inertia, in an entirely VSM0H-powered grid, load steps result in frequency "steps" which occur over ~20ms. In a grid powered by a mix of VSM0H/VSM/SM, VSM0H can still play an important role during load steps (or generation loss), since the VSM0H will take up some of the initial power requirement within the first 10ms if it is electrically close to the event. Then, VSM0H output will drop (as it has no H), until frequency itself has fallen, at which point the VSM0H can respond quickly, with a large amount of power, as per the f/P droop slope and the device's relatively fast governor/mover response (which is ~20ms, but <50Hz bandwidth).

Several academic institutions have reported simulations and laboratory demonstration of small-scale units, although relatively few institutions (Strathclyde is one), have also demonstrated credible means to provide fault survivability and ride-through capabilities from VSM/VSM0H devices, which behave as AC positive-sequence voltage sources in series with their filter impedance X, which is normally of the order of 0.1pu.

Finding public-domain examples of VSM/VSM0H at higher power levels, supplied by industrial companies, is much harder. Notice that to be Grid-Forming requires much more than just to generate open-loop fixed-frequency and fixed-voltage AC voltages at the terminal. Existing offshore HVDC terminals used to supply wind turbines are assumed to operate in this open-loop manner, in the absence of any more public-domain information about their operation [I am happy to be corrected if I am wrong here]. By contrast, the Grid-Forming converter must be able to synchronise and share both active power and reactive power with other connected units, with controllable setpoints and droop slopes. It must be capable of connecting to weak pre-existing grids, and strengthening them, without ripping apart the existing grid and "pole-slipping" with other devices.

Below is the list of actual public-domain examples of what I believe to be Grid-Forming converters, at reasonable power scales.

GE installations, 1995-1996

The following two papers were authored by Nick Miller et. al. Essentially as I understand it, Nick and his partner (there were just 2 key people) installed this battery-powered converter to provide blackstart and grid-stiffening services to a small community in Metlakata, Alaska. The key thing was that the converter could be on first, and provide stability while a diesel was then synchronised, and grid reconnection made later (etc.). Even Nick does not know exactly what the control algorithm was (VSM, VSM0H, or something else – the software was writted by Nick's colleague), but it was definitely operated as a grid-forming voltage source "*For most operating conditions the BESS is equivalent to avoltage source behind the transformer reactance (XT)*". My guess would be VSM0H, but I cannot be sure. We also do not know what the response of the device was during major close-in faults, or if it just shut down. The 1997 paper described a second installation to Vernon, California.

Miller, N.W., Zrebiec, R.S., Delmerico, R.W., Hunt, G., and Achenbach, H.A.: 'A VRLA battery energy storage system for Metlakatla, Alaska', Battery Conference on Applications and Advances, Eleventh Annual, 9-12 Jan 1996

DOI: https://doi.org/10.1109/BCAA.1996.485002

Miller, N.W., Zrebiec, R.S., Delmerico, R.W., and Hunt, G.: 'Design and commissioning of a 2.5 MWh battery energy storage system', CIRED. 14th International Conference and Exhibition on Electricity Distribution., 2-5 June 1997 1997

DOI: https://doi.org/10.1049/cp:19970479

The system in Metlakatla was still working in 2009 and I am not aware it has been decommissioned.

https://www.omb.alaska.gov/ombfiles/09_budget/CapBackup/proj48869.pdf

There is also an earlier report on performance and battery conditions

http://www.sandia.gov/ess/EESAT/2000_papers/00023.pdf

"The BESS is used to provide instantaneous power to the utility system to satisfy the random instantaneous load demands of a log chipper at the mill without causing brownouts or overvoltage conditions to the remainder of the utility.s customers."
"The study indicated that a 1-MW, 1.4MWh battery energy storage system (BESS) could provide the spinning reserve, frequency control, and power quality improvements that Metlakatla needed. The study concluded that the cost of the BESS could be recovered within three years based on operational cost savings alone."

Marine power systems (Vacon / Rolls-Royce)

It is not obvious from literature, but for about 10 years, Danfoss' Vacon drives have had a VSM0H (Power Synchronisation) form of Grid-Forming converter control algorithm as an option. It is called "*micro-grid mode*". Rolls-Royce is one customer, who fit the drives into marine power system solutions.

http://drives.danfoss.co.uk/industries/marine-and-offshore/hybrid-propulsion-solutions/#/

It is really hard to confirm my statements from that (or any) public domain information. However, there is a clue sentence on that page: "*with proper software able to create and control AC-grid (Micro Grid) behavior.*". Also:

http://drives.danfoss.co.uk/products/vacon/low-voltage-drives/vacon-nxp-grid-converter/#/

http://danfoss.ipapercms.dk/Drives/DD/Global/SalesPromotion/Brochures/ProductBrochures/UK/NXPGridConverter/?page=8

I was not allowed to carry out close-in-fault testing when I was investigating my Vacon unit's performance for Rolls-Royce, so I do not know how well it performed (or performs now) during faults in its "micro-grid" model.

The Caprivi Link

The Caprivi link is a 350kV HVDC scheme (built by ABB), *"that stabilizes weak power networks in Namibia"*.

http://new.abb.com/systems/hvdc/references/caprivi-link

Reading between the lines (this is my interpretation of the available public-domain literature, but since there are only words, and not equations or actual control diagrams, there is a possibility that my interpretation is not quite correct):

In standard (normal) mode, the link terminals are controlled with a standard vector-current control (DQCI) algorithm, augmented with some Q/V droop slopes to regulate voltage by changing reactive power setpoints to the standard DQCI inner current loops. However, either one of the terminals can drop out into an inertialess VSM mode (VSM0H-like, I assume), working on an f/P (and presumably V/Q) set of droop slopes. Its possible the control is more "open loop" fixed V & f, but it seems unlikely to me that this simple mode would work in all the Caprivi scenarios described in the words of the articles.

http://search-ext.abb.com/library/Download.aspx?DocumentID=9AKK105713A0755&LanguageCode=en&DocumentPartId=&Action=Launch

"The scheme connects two presently very weak AC networks where the fault levels are in the order of the rated power of the converters."

Caprivi Link HVDC Interconnector: Comparison between energized system testing and real-time simulator testing (CIGRE Paper, 2012)

http://search-ext.abb.com/library/Download.aspx?DocumentID=9AKK105713A1110&LanguageCode=en&DocumentPartId=&Action=Launch

"Passive or islanded network operation

Passive or islanded ac network conditions are detected by frequency deviation criteria and the converter station connected to the passive/islanded network will be transferred from power control/dc voltage control to passive/islanded network operation with frequency control. The other converter station will control the dc voltage and needs to be connected to a normal, healthy ac network."

The New Black Start: System Restoration with Help from Voltage-Sourced Converters, IEEE Power and Energy Magazine (Volume: 12, Issue: 1, Jan.-Feb. 2014)

DOI: https://doi.org/10.1109/MPE.2013.2285592

This paper also refers to a number of other HVDC schemes in difficult weak-grid scenarios, which may have similar controls.

"Others

There must be other examples, but is hard to find them. I would be astonished if some of the bigger companies like GE, Alstom, Vestas, Siemens etc. do not have at least prototypes or simulations of VSM/VSMOH Grid-Forming devices. Clearly, GE had the capability in 1995, but it may have been limited to one or two key engineer's knowledge and not well documented, even internal within that company.

Andrew Roscoe. 18th may 2018