Dispatching Parameters, Strategies and Associated Algorithm for VSM (Virtual Synchronous Machines) and HGFC (Hybrid Grid Forming Convertors)

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***Abstract* — With the increasing drive towards renewable generation, there is no doubt that whilst the modern converter based plant is starting to replace conventional synchronous generation on a MW for MW basis, there is concern that the modern converter based plant is unable to contribute the same features as Synchronous Generation. Inertia, fault level, synchronizing torque which are for example, all fundamental pre-requisites for the design of and operation of a reliable and robust power system. There is therefore considerable interest in VSM and GFC controls which emulate the behavior of synchronous machines.**

This paper discusses various parameters, general dispatch principals in relation to VSM / GFC and proposes a possible algorithm to demonstrate a method of dispatch which aims to provide a robust level of system security whilst minimizing the plant requirements, particularly in respect of the storage, inertial and converter rating requirements which are seen as costly items as part of a plant design. In particular, the aim of this work is to develop a set of requirements which are sufficiently flexible to enable developers to meet using whatever means they wish to, yet at the same time ensuring that the Power System remains secure and robust against a background of increasing volumes of converter based plant.

The solution discussed, is not tied to commercial parameters allowing these to be selected independently. The starting point is the initial requirement from Grid Code Consultation GC0100 Option 1 [9], and this work therefore informs potential implementation of solutions and specifications.

Keywords-component; Grid Forming Convertors (GFC), Virtual Synchronous Machine (VSM), GC0100, Grid Codes, Inertia.

I. INTRODUCTION

This paper is the first of five papers describing National Grid's two VSM (Virtual Synchronous Machine) NIA (Network Innovation Allowance) projects. These two projects have been undertaken in partnership with University of Nottingham (UoN) and University of Strathclyde (UoS). They are intended to improve the understanding of the implications of the GFC proposals addressed through GC0100 Option 1 [9] and subsequently through the VSM Expert Group [15]. The purpose of the projects and/or papers are:

1. To design and test a VSM algorithm in line general GFC / VSM principals such as GC0100 option 1 [9].
2. To establish which plant, control principals, parameters and tests are particularly relevant to grid stability.
3. To understand how grid forming performance affects one of the possible convertor designs and strategies which might mitigate any negative effects.
4. To establish whether it is possible to provide grid forming performance from hybrid solutions (for example STATCOMS) where not all of the converters are grid forming.

It should be noted that whilst the authors have sought to explore a possible implementation of VSM. It is not National Grid's intention to mandate any specific design. NG ESO (National Grid Electricity System Operator) only seeks to examine some of the practical considerations surrounding the technical requirements detailed in [9] and [15]. This is not intended to prescribe a design of a physical convertor, it is intended to simply illustrate one potential approach for discussion though it is noted that some other implementations could be used some of which are also discussed in the papers.

National Grid has not sought to copyright the design or patent it, as it has been produced in support of a proposed Grid Code requirement. All work published here, is our own and has been produced from first principles without reference to existing designs. Any similarities with designs, copyrights or patents are coincidental.

Whilst manufacturers and designers are free to use and copy the ideas presented, National Grid cannot be held liable for legal action arising from their use. The ideas presented are believed to be one of many possible implementations, allowing designers further freedom in implementing differing approaches.

Table I below, shows a matrix of future anticipated GB transmission system, convertor growth inhibiters in the columns and the potential counter measures in the rows. The cells which intersect the columns and rows, show which counter measures are capable of resolving the various inhibiters.

It can be seen from table I that only three counter measures are believed to be holistic, potentially solving all/most of the anticipated inhibiters, either on their own or in combination. This does not mean that the other counter measures investigated are not useful but would need to be combined with other solutions which uniquely solve other areas, which are increasingly influencing the practical costs in the operation and planning of networks.

TABLE I. FUTURE SYSTEM INHIBITERS AND COUNTER MEASURES

Solution	Estimated Cost	RoCoF [*] [2]	Sync Torque/Power (Voltage Stability/Ref) [2] [3] [4]	Prevent Voltage Collapse [2]	Prevent Sub-Sync Osc. / SG Compitable [2] [3]	Hi Freq Stability [2]	RMS Modelling [*] [2] [3] [4]	Fault Level [*] [2]	Post Fault Over Volts [2]	Harmonic & Imbalance [5]	System Level Maturity	Key No Doesn't Resolve Issue P Potential I Improves Yes Resolves Issue Notes
Constrain Asyncronous Generation	Hgh	I	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Proven	These technologies are or have the potential to be Grid Forming / Option 1
Syncronous Compensation or More Sync. Gens at lower load	High	I	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Proven	
VSM	Medium	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	P	Modelled	
VSM0H	Low	No	Yes	Yes	No	P	P	P	Yes	P	Modelled	Has the potential to contribute but relies on the above Solutions
Synthetic Inertia	Medium	Yes	No	No	P	No	No	No	No	No	Modelled	
Other NG Projects	Low	Yes	P	Yes	No	No	No	P	P	No	Theoretical	

It is believed that only the first three options listed have the potential resolve all of them on their own, although in practice they are more likely to be used in combination as there are various pros and cons to each, which will be discussed throughout the 5 papers.

Fig. 1 below shows the overall block diagrams of the controllers implemented by NG ESOs partners UoN and UoS. The implementation of the controllers and associated hardware differ slightly as each partner focused on different aspects of the design but both are similar implementations and are discussed in the relevant papers. In addition to the physical implementation and realization of the convertors both partners and NGESO have built models in MATLAB, RTDS and RMS models in PF (PowerFactory).

The numbers [2] [4] etc. in Fig. 1 indicate where specific topics are covered by specific papers and [*] refers to this paper.

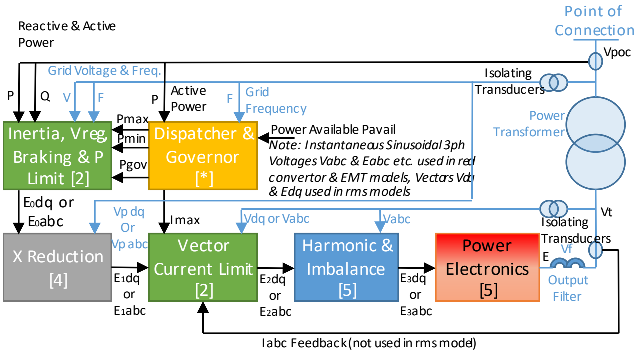

Fig. 1. Simplified Block Diagram of a potential VSM Implementation

The implementation within the RMS models differs in some respects as the primary variables are AC vectors i.e. real and imaginary RMS quantities which are essentially constant for a steady state operating condition at 50Hz. Conversely, continuously varying sinusoidal AC signals are used in the MATLAB and RTDS models and the real convertors, which capture the full detail and complexity of all the interactions. In addition, not all models represent all aspects. For example, the RMS model does not have the harmonic and imbalance components represented and some aspects are modelled differently and it is not necessary to have current feedback in the RMS vector current limiter (this is explained in the second paper [2]).

Both the RMS and physical implementations of the controllers are discussed throughout the papers. The accuracy of RMS simulations is critical to NG ESO as this is currently the main tool used for dynamic analysis in planning and operational timescales.

Whilst the tools are evolving quickly and it is possible that, in the future, other techniques may find favor such as mixed EMT/RMS analysis or full EMT analysis, these have not been widely used to date. Consequently, the ability to model using RMS techniques is of very high importance, not least as this is one of the primary methods used by System Operators for undertaking dynamic studies in a timely manner.

From Fig. 1 we can see the converter design largely consists of 6 major blocks:

- Dispatcher and Governor
- VSM (Inertia simulation and stabilizing, Dynamic braking, Voltage Control and Power Limiter.
- Impedance Reducer
- Current Limiter
- Harmonic and Imbalance Management
- Convertor Output Stage and Power Electronics

This paper focuses on the dispatcher and governor algorithms.

II. INTRODUCTION – DISPATCHER AND GOVERNOR

The governor is essentially a closed loop controller which operates on a continuous basis regulating its output power and frequency in response to feedback signals. However, the initial response of a grid forming convertor is almost instantaneous and takes place without feedback measurement. GFC's are designed to operate as a voltage source behind an impedance whose frequency phase and magnitude are modulated slowly, provided the device remains within rating. Consequently, the current is the only quantity which can change quickly and this is determined by the load and network. The second phase of any response from the VSM design presented, is determined by the inertia simulation and damping, with the governor continuously modulating the final phase of the response at lower bandwidth / update rate to produce the final steady state value.

The dispatcher either performs its operation once on start up or at a lower bandwidth than the governor. Its various functions are related to managing the inertia, stored energy resources and fault level.

The dispatcher determines if there is enough stored energy to ensure worst case network conditions can be supplied with the correct inertial response. The dispatcher also contains an additional algorithm to automate the management of fault level in Distribution Systems and this will be explained in section IX.

III. KEY PARAMETERS AND DIFFERENCES BETWEEN GFC AND ROTATING SYNCHRONOUS MACHINES

GFC differs from conventional rotating SM (Synchronous Machines) in the following key areas:

1. The current in SM's is largely limited by the impedance of the circuits and from a design perspective, thermal constraints which typically allow for considerably longer time constants than GFC. Conversely, convertors would, we anticipate, implement fast acting current limiters to prevent damage to the semiconductors and other components.
2. The inertia is an inherent property of SM's whereas, it is a simulated / calculated quantity and response in GFC. In the latter, additional energy is required to support the inertial response and this is typically achieved by either reducing steady state output (i.e. de-loading or pre-curtailment), adding storage e.g. battery or super capacitor or extracting inherent stored energy e.g. inertia from the blades of a wind turbine or a combination of these.
3. Because the inertia is simulated, the storage is decoupled from the response and appropriate calculations must be performed to ensure it is adequately sized such that there is enough capability to maintain the level and duration of power output to ensure system security during critical events. This is not the case for SM's where the inertia is an inherent property of the plant and there is no possibility of running out of energy before 47Hz is reached.
4. The combination of the above (1, 2 & 3), results in the need to implement a power and current limiter which caps the maximum output power and current of the convertor.
5. The steady state physical impedance of convertor based connections is typically much lower than that of SM's. Consequently, a convertor operating as a GFC is typically capable of being stiffer and provides greater response to vector shift / electrical angle change. Additionally, low impedance typically results in no requirement for the SM equivalent of a UEL (Under Excitation Limiter).

NB in relation to 3: It should be noted that both the GB Stability Pathfinder [13] [16] and the GC0100 option 1 [9] draft require the VSM specification to be provided across not just one, but multiple potential events, providing NGESO with details as to how this may be achieved, which may permissibly involve more limited subsequent energy delivery where the fall-off impact may be defined and agreed with NGESO. The VSM minimum specification also includes consideration of the time duration of this response- as clarified within its stability pathfinder [13] [16] as an initial 0.5s inertial energy deployment period, followed by meeting or exceeding a 12secs time constant of residual inertial energy, providing a suitable handshake between the inertia the Power System requires and the range of frequency services that would subsequently follow it.

The GC0100 option 1, proposed specification [9] published in 2017, suggested:

1. An overrating capability on real and reactive power of 33%
2. An overrating capability on current of 50% which roughly equates to the current required for the additional power rating.
3. VSM convertors should have a minimum impedance of 10% (this is the apparent internal filter impedance of the convertor).
4. The H (equivalent inertia) should be adjustable between 2 and 7p.u. secs. NB stability pathfinder allows a minimum 1.5p.u. secs specification.
5. Convertors must be capable of providing additional energy (up to 33%) for a period that may permit up to 20seconds (noting the stability pathfinder clarifications, the full 33% would not be provided beyond the first 0.5s, attenuating to the 12secs time constant thereafter.
6. The convertor (when not in current limit) should look like a voltage source behind a reactance over the 5Hz to 1kHz bandwidth.

During wider consultation with stake holders of GC0100 option 1 [9], questions were asked about the above and these are largely answered in this and the associated papers [2, 3, 4 & 5]. This paper will discuss the overrating of real power and the storage requirements. The current limiter and inertia is discussed in [2] and the impedance in [3] and [4]. The bandwidth is discussed in [2, 3, 4 & 5].

IV. GC0100 STORAGE AND ENERGY OVERRATING REQUIREMENTS

In 2016 a system split study was performed [6] where the low frequency island was left with approximately 4.4GW of lost generation. To allow time for LFDD (Low Frequency Demand Disconnection) to operate, the remaining generation had to provide this deficit whilst the frequency dropped.

The study was performed at 93% convertor penetration, with only 7% of the generators being SM's. 70% (i.e. 75% x 93%) were grid following convertors and not expected to provide any additional energy. Based on the studies it was identified that only 23% (i.e. 25% x 93%) of the generation of convertors were GFC and along with the 7% of synchronous plant were required to deliver the additional energy required. The GFC went from approximately 40% of the continuous power rating to 60-70% for approximately 6 seconds.

Breaker stuck studies performed in 2014-15 for GC0062 [10] demonstrated the potential for similar losses of generation which exceeded normal frequency reserves. In this case the system being studied was dispatched with high quantities of conventional synchronous generation. Whilst both scenarios studied are highly unlikely, the core power system should have the be capability to withstand such events, without total collapse for high losses which exceed the maximum single power loss that may occur (a level which may be up to 1800MW in GB). The inherent and simulated inertia provided by the SM's and GFC respectively, which "catches" the system, making this possible by supplying the load while the frequency drops and allowing LFDD time to operate. If this capability did not exist, there is a risk the frequency could collapse so quickly that the Low Frequency

Demand Disconnection Scheme has little benefit (i.e. frequency falls so quickly it is in effective).

The above studies demonstrate the need for inertial volumes which exceed normal frequency response reserves, for short durations. They provide a simple method of calculating how much additional rating is required for uncommon severe events (beyond secured events). The overrating capability is therefore a question of the balance of cost and risk.

Following the closure of the GC0100 option 1 consultation [9] and further feedback received through the VSM Expert Group [15], it became clear that:

1. There were significant cost implications for storage requirements (initially quoted as an additional 33% Power for 20 seconds)
2. Overrating of HVDC and other convertors can only be achieved at the cost of uprating the convertor
3. There is sometimes head room available in the convertor because the generator or HVDC System is not operating at full power.

Consequently, in this paper we discuss the possibility of algorithms that calculate the amount of energy required for a specific response and value of H and determines whether the storage available can meet the requirement and de-rate the output accordingly.

V. GFC RESPONSE OVER THE FREQUENCY RANGE 52-47HZ

During GC0100 option 1 [9] and through the VSM Expert Group [15], there has been considerable debate as to how VSM provides inertial response over the full frequency range of 52-47Hz. Equally, there is concern on System Performance of an over frequency event followed by a low frequency event and the support required.

Studies performed by ENTSO-E for Continental Europe [11] demonstrate the potential for high frequency events followed by low frequency events and the desirability of inertial response over the wider frequency range.

The authors of this paper consider such a response might also be achievable with the majority of storage fitted for the 50 to 47Hz frequency drop and only a relatively small amount of storage for the 52 to 50Hz drop (see Fig. 2). This possibility results from the GBGC (Great Britain, Grid Code) and RfG requirements to reduce power output at or above 50.4Hz even in LFSM mode, leaving headroom for an inertial response all be it at a lower power level above 50.4Hz (see Fig. 2).

In order to achieve such a response, the LFSM-O (Limited Frequency Sensitive Mode – Over Frequency) governor must operate quickly, both to avert an over frequency event which might lead to loss of generation and to ensure that should such an event occur, the necessary active power headroom is available for an inertial response.

This paper only considers LFSM-O operation, as this is worst case for the dispatcher using limited storage such as super capacitors, which are scaled for delivery of inertial services only. Limited storage of this nature is unlikely to be able to provide additional energy for LFSM-U as the inertial operation must be guaranteed on a repetitive basis first.

Battery systems, capable of sustained additional output would be required to provide the inertial response and if its physically possible, LFSM-U. Additionally the reduction in active power output at 50.4Hz and above, shown in Fig. 2, is not necessary where extended operation at the higher power limit is possible from 52Hz down. This extend Pmax capability is shown by the bold dashed purple line.

As previously stated, fast action of the LFSM-O governor is also desirable as it helps reduce the over frequency nadir reducing the risk of generation tripping due to high frequency. In the design presented here, the LFSM-O governor is separated from the FSM governor and the two operate independently.

Fig. 2 shows a typical LFSM-O governor response, the green line indicates where power is anticipated to drop off at 50.4Hz with a maximum droop, of 10% (the droop can be less providing a steeper line but under RfG [8] must be greater than 2%).

In the example shown in Fig. 2, Pset (continuous active output power) is set below the Pavail (continuous active power available) e.g. the output is restricted. This could for example, be the result of constraints on transmission capacity or because the dispatcher has determined the installed capacity of storage is not large enough to supply the worst-case system event i.e. the storage is adequate for the inertia being simulated. To avoid the latter constraint condition, more storage would need to be fitted, the economics of which would need to be determined by the generator and developer.

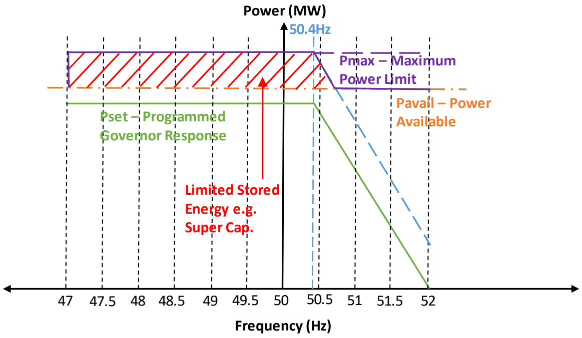

Fig. 2. Storage requirement vs frequency

Assume it is agreed the device is required provide an inertial response up to Pmax, the purple line. To do this it must have an energy store which covers the difference between Pmax and Pavail. The store must be large enough to ensure that the device will deliver energy for all frequency events for the agreed H (Inertia) value programmed into the device.

Note however, not much stored energy is required for an inertial response above 50.5Hz because the LFSM-O rapidly reduces the output power at 50.4Hz in GB (50.2Hz in Continental Europe), leaving headroom for an inertial response between Pavail and the LFSM reduced Pset. However, there is a trade off as Pmax is reduced above 50.4Hz.

Fig. 2 shows inertial response is provided down to 47Hz, below which generators may trip but this is yet to be confirmed as LFDD starts to operate at much higher frequencies (48.8Hz and below within the GB Grid Code [7]). Further operation periods for which a generator may operate down to 47Hz become progressively more time limited within the Grid Code [7]. Energy storage for a long low frequency duration event to 47Hz may therefore not be necessary, lessening the requirement further. Further work is are needed to determine this.

VI. DISPATCHER

Fig. 3 below shows the overall block diagram for the dispatcher and governor algorithms. There are two dispatchers and two governors.

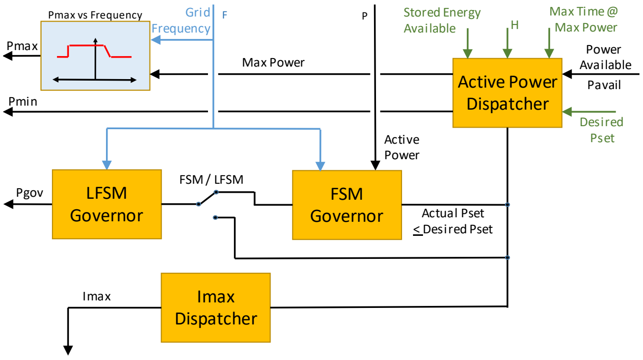

Fig. 3. Block Diagram for Dispatchers and Governors

The power dispatcher calculates if there is enough storage capacity to ensure the convertor can provide the agreed amount of energy for the worst-case duration of any event on the system required with network survival. If it hasn't got the storage capacity required one option is to reduce the pset (the steady state active power output) prior to the event to provide the appropriate headroom, to deliver the necessary response. Alternatively, if more economically desirable, appropriate storage can be fitted.

Assuming adequate storage is not fitted, the above worst-case calculation takes into account the longest high energy output scenario which could occur. It uses the H programmed into the inertia simulation, the RoCoF rate which gives the highest energy output in MW, the duration of the event from 50.5Hz to 47 or 47.5Hz and then determines if the energy store (e.g. super capacitors are big enough) and if not de-rates the output of the generator.

These are dynamic considerations- for example as the frequency falls below 48.8Hz, the RoCoF cannot expect to remain the same as it would be positively impacted by the actions of LFDD.

GC0100 option 1 [9] is a functional specification intended to be relevant to a range of technologies being deployed, accordingly it was concluded that this could be left to generators and developers, as different generators might determine solutions which are most economically appropriate.

For example, if it were anticipated that GFC operating modes are required in GB at low load with high solar penetration e.g. at summer minimum load. It's conceivable that solar might fit storage to ensure it maximises the yield but this may not be the case for other renewables or HVDC. Depending on commercial and other factors, HVDC may choose to constrain output instead and wind generators may determine some storage is desirable in combination with constraining output. As such the general principles of the dispatcher needs to be flexible to a wide range of options for achieving necessary headroom.

The dispatcher algorithm calculates how much energy must be delivered for the worst case low frequency event for the H setting of inertia simulation. It determines the Pset and modifies the Pmax value sent to the Active Power Limiter in line with Fig. 2 (the active power limiter is described in [2]). The Pset value is sent to the Governors and Fault Level Dispatcher which are described in the following sections.

VII. FSM GOVERNOR

Fig. 4 below shows the block diagram of the Frequency Sensitive Mode (FSM) governor. All signals in the diagram are p.u. (per unit) values. The FSM governor has three input signals, frequency and power feedback measurements and power reference. In addition, there is an internal frequency reference which is always set to 1pu in this design (this can be made adjustable if desired, e.g. to cover an occasional system frequency target of 50.05Hz). The FSM governor also has a power output signal which feeds the LFSM governor, the LFSM governor then feeds the inertia simulation which is covered separately by paper 2 [2].

The FSM governor is a basic power droop governor with a droop setting which is adjustable between 2-5%. The gain in Fdroop of the multiplier block specifies the droop setting. The model shown above has facilities to model dead bands e.g. $\underline{+}$0.015Hz as allowed by the GBGC [7] and is implemented by the blocks in the dotted line.

The output response of the governor is reduced in bandwidth by the 1/(1+sT) which softens the response. This low pass filter blocks signals above 5Hz, avoiding the convertor interactions with other electromechanical plant on the system. It is set in excess of that in this example to provide a response similar to conventional plant, although this is not strictly necessary.

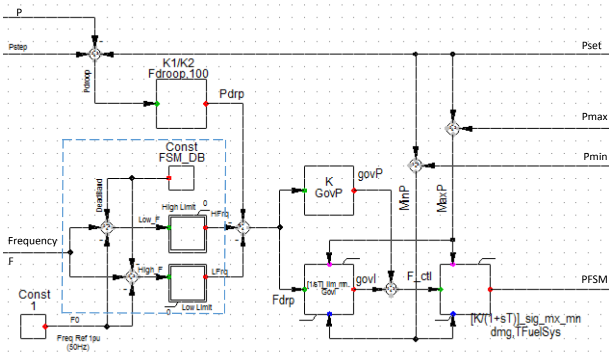

Fig. 4. FSM Governor

The PI (Proportional Integral) controller which feeds the output filter is tuned to provide the appropriate dynamic response. Finally, there is a min/max limiter algorithm which prevents the integrator term and output filter from exceeding the minimum and maximum power deviation set by the dispatcher (see following text). Additionally, the minimum power set point should be set such that the FSM governor cannot override the LFSM governor when it is in operation, however this is not shown in the above diagram.

To be GB GC compliant the LFSM-O governor could be bypassed when in FSM mode, however there are some important differences between the LFSM-O and FSM governors, hence better results are obtained with FSM governor output connected in series with the LFSM-O governor.

VIII. LFSM-O GOVERNOR

Fig. 5 below shows the LFSM-O governor. The LFSM-O governor which has two input signals, frequency feedback and power reference signal and one output signal which is the power set point for the stage which simulates the inertia and is described in paper 2 [2].

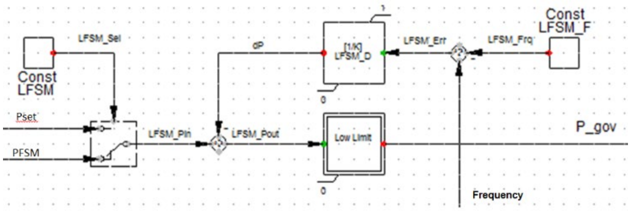

Fig. 5. LFSM-O Governor

As mentioned earlier only the LFSM-O governor is considered in the RMS models presented which relate to a worst low or partial storage case (e.g. super capacitor sized for inertia and not frequency response). However, for battery installations a LFSM-U governor would also be required.

For LFSM-O the power reference signal is either derived directly from the power reference when the governor is in LFSM mode or the output of the FSM governor when in FSM mode.

The GBGC [7] specifies that the generator should reduce power at a rate of at least 2%/0.1Hz when above 50.4Hz for LFSM and 50.5Hz for FSM. For FSM, the governor should have a droop setting of between 3 and 5%. Provided the governors droop setting is the same above 50.5Hz, a separate LFSM governor is not required, however it's been included here to identify some distinguishing features, most notably:

1. The LFSM governor has a droop setting which is independent of the FSM droop which must be set in accordance with the "Bilateral Agreement" between National Grid and the connecting party (e.g. Generator or HVDC System). This arrangement allows the droop to be set independently above 50.4Hz.
2. The LFSM governor is fast acting, ensuring power is reduced quickly above 50.4 and 50.5Hz, leaving power headroom to provide the inertial response shown in Fig. 2.

In many applications, the FSM governor could be made to operate quickly but there may be mechanical or other constraints, which under normal circumstances make this less desirable. For the LFSM governor operation above 50.4Hz or 50.5Hz in FSM mode should only occur infrequently and the cost benefit of less storage may override other disadvantages of implementing a fast, infrequently used response.

IX. FAULT LEVEL DISPATCHER

Some Distribution Network Owners (DNO's) have indicated concerns associated with increased embedded generation, related to higher fault levels.

The fault level dispatcher shown in Fig. 6 overcomes the fault level issues associated with ever increasing amounts of embedded generation, by setting the fault level produced by specific generators in proportion to their dispatched output and is defined in GC0100 option 1 [9].

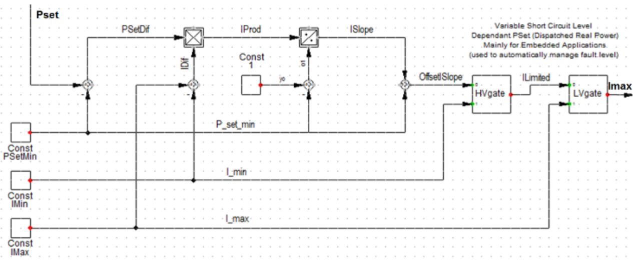

Fig. 6. Fault Level Dispatcher

For example, solar operating early in the morning at reduced output would produce a reduced fault level, were as a battery system operating at higher or full output would produce higher or its full fault level capability. Consequently, the fault level can be programmed to be roughly proportional to the embedded generation output, as opposed to the total MVA of the embedded generators connected which is anticipated to rise dramatically. This approach has also been permitted under the stability pathfinder work at transmission level.

Using this algorithm, the fault level could be better managed as it becomes semi-automated. GC0100 option 1 [9] proposed three parameters for the fault level dispatcher:

1. Max Fault Level – The fault level produced at 100% continuously rated output (typically 1.5pu rated current)
2. Min Fault Level – The fault level produced at or below the min fault dispatch
3. Min Fault Dispatch – The output value at or below which the fault level stops reducing (e.g. if set to 50% the fault current would be Min Fault level at for active power dispatch of 50% and below).

For operating points between maximum dispatch / rated power and the Min Fault Dispatch the fault level is between Max and Min Fault Levels and is proportional to the continuous or target output value of the convertor. Fig. 7 below provides an example of the fault level vs dispatched output power explaining the meaning of the parameters.

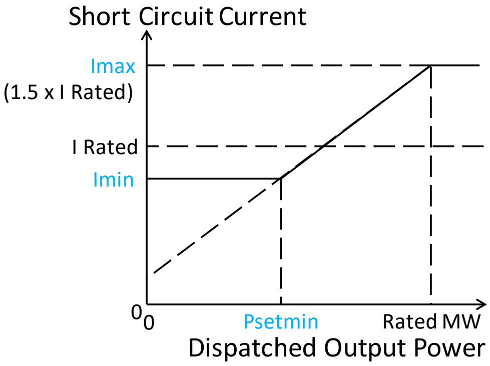

Fig. 7. Fault Level vs Pset for differing parameters

X. FURTHER CONSIDERATIONS RELATING TO GRID CODES

The work presented in the five papers has increased the understanding of the technical aspects of this relatively new technology, potentially allowing further refinement to the definition of a Grid Code or testing requirements, that facilitate GFC solutions. The objectives of such codes should be functional, in defining requirements against system need and less focused on the implementation aspects.

In respect of clarifications requested by stakeholders, relating to GC0100 option 1 [9], namely:

1. How much storage (i.e. stored energy) is required?
2. What does the 10% impedance relate to?
3. The voltage source bandwidth requirement of 5Hz to 1 kHz
4. The equivalent inertia of 2 to 7 seconds
5. 1.5x Rated Current Fault Level
6. Up to 1.33x Rated Power Injection
7. Dynamic braking during faults

It may be appropriate to consider the many ways such functional requirements inform further tests and/or guidance associated with delivering the GFC effect. For example, it may be helpful to define performance during and immediately following faults by stating that "the reference for the voltage waveform of the AC voltage source should be prevented from changing phase angle, frequency and voltage magnitude during the period of the fault as alternative or in addition to discussing dynamic braking.

Events with different RoCoF could result in a proportional response in real power and this could be specified in preference to H the mechanical equivalent inertia. Alternatively, it may be more meaningful to specify the amount of power required for a 1Hz/sec or 0.1Hz/sec change. This relates to the instantaneous behaviour of the voltage source rather than some measurement operating below the 1kHz bandwidth, which would not be compliant.

In relation to the impedance, a requirement for a proportional change in power for vector shifts i.e. electrical angle change, at the POC may be specified, rather than specifying an impedance its self. This increase would be expected in the first cycle or half cycle.

Flexibility in the demonstration of GFC performance is potentially of importance for OFTO networks, where for radially connected Offshore wind farms the requirement might be specified at the interface between the Onshore transmission system and the OFTO network and not the generator (see papers 3 and 4 [3] [4]). Avoiding the need to discuss impedances in this situation are particularly beneficial, as there are a number of components in the OFTO network which that are interconnected and complicate any definitions of impedance. This might represent a useful approach to supporting guidance or compliance testing. surrounding any code or specification.

The authors, welcome many of the ideas in the draft ENTSO-E TG HP technical report [12], in particular the contributions on damping and more generic terminology such as GFC (Grid Forming Convertors).

Damping has been included in the Stability Path Finder [13] [16] but would not normally be defined in detail until the detailed design stage of a given project. The ENTSO-E TG HP draft technical report [12] has provided further insight and indicates that GFC might provide high degrees of system damping over and above those traditionally seen from SM's. These findings have been echoed in recent research and development on wind (WIPOD [14]).

It is noted some stakeholder prefer the more generic term GFC to VSM as suggested and used by the ENTSO-E. The ENTSO-E specification provides a greater degree of flexibility allowing TSO's (Transmission System Operators) and SO's to choose certain requirements. Whilst the desire of stakeholder is understood and the efforts of the ENTSO-E are appreciated, the focus in GB has resulted in an extended specification in areas of angle, reactive support and bandwidth etc. it may therefore be necessary to differentiate either continuing with VSM or an alternative e.g. GFC-GB.

In these papers, we have explained the benefit of specifying the bandwidth over which the device should operate as a voltage source (currently 5Hz to 1kHz). Further feedback and thoughts on this would be welcomed. 1kHz potentially omits some older technologies (Gate Turn Off Transistors) and switching / update rates that might require some equipment to be modified. There are potentially a variety of ways this might be handled but feedback is needed to understand any concerns.

In the second paper 2 [2] the need for further consideration is pointed out as to whether the operating angle of convertors should be limited. This would prevent convertors from continuously slipping the angle to reject power and further feedback on this subject would be welcome.

GC0100 option 1 [9], specified a fault level capability of 1.5pu on rated current and 1.33pu on rated active power. These figures are correlated, provided the convertor has a 1.1pu over rating for fault current. This is based on the following calculation of operation at 1.33pu Active Power with a power factor of 0.95 (which corresponds to 0.31pu reactive power:

$$S = \sqrt{P^2 + Q^2}$$
$$I = S/V$$
$$I_{sc} = 1.1 \cdot I$$

Where: S = MVA Rating in p.u.
P = Active power in p.u.
Q = Reactive Power in p.u.
V = Nominal Voltage in p.u. (i.e. V = 1)
I = Current at extend 1.33pu power rating
I_{sc} = maximum short circuit current

Therefore:

$$I_{sc} = 1.1 \cdot \sqrt{1.33^2 + 0.31^2}$$
$$I_{sc} = 1.1 \cdot 1.365 \text{ pu}$$
$$I_{sc} = 1.502 \text{ pu}$$

The additional rating can be achieved either by fitting higher powered semiconductors to allow for the additional 1.33pu extended power and 1.5pu extended current range or by derating the convertor to 75% of its original rating when it is operating in GFC mode.

Paper 2 [2] indicates, as specified in GC0100 option 1 [9], that the phase angle of any fault current should attempt to restore the correct phase of the voltage rather than inject reactive current relative to the measured voltage phase during the fault as currently specified in many Grid Codes. Hence convertors are required to attempt to restore the voltage angle during the fault.

Paper 5 [5] considers how the extended 33% power rating can be utilised to supply harmonic and unbalanced load current when not supplying active power or fault current.

National Grid is currently engaged in a VSM Expert Working Group [15] and Stability Path Finder [13] [16] work engaging with the market and across various developments with academia manufacturers and developers, supporting implementation of these new technologies where appropriate and relevant.

XI. CONCLUSIONS

Previous [6] work has highlighted the need for inertial energy stores associated with converter connected power sources. These stores should be capable of: resisting vector shifts, maintaining energy output, reducing the Rate of Change of Frequency and remaining connected and contributing until LFDD has operated.

This paper discusses calculations made within the convertor, to ensure that adequate reserves exist. Any given set of programmed parameters should work under all circumstances ensuring that the system does not run out of energy before 47Hz or 47.5Hz. In the event that stored energy in the convertor is inadequate e.g. the super capacitor is too small or convertor power rating headroom cannot provide the agreed energy increase, the convertor should reduce output power to provide the appropriate headroom between the output power and power available. Alternatively, the convertor rating can be increased and/or more energy storage installed. Further considerations on these concepts can be found within the GB stability path finder technical webinar slides and associated Q&A responses published [13] [16].

It has been suggested that the storage requirements for inertial response between could be further reduced if the LFSM operating frequency were lowered to 50.2Hz. However, this could lead to different requirements for different generators and this and technical factors need further consideration.

The solutions presented provide one practical approach to a GFC control which meets the VSM requirement of the GB GC0100 option 1 solution [9], but others may equally be possible. The work hopefully further informs the reader as to the considerations in any such control.

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