A Review of Control Methods for providing frequency response in VSC-HVDC transmission systems

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***Abstract* – With the ultimate aim to remove/reduce constraints on the amount of non-synchronous generators that may be connected to power systems, this paper identifies potential problems associated with system dynamics under high penetrations of converter-interfaced sources, especially from the perspective of inertia and responses to disturbances. The configuration of VSC-HVDC transmission systems and their controllers is introduced and analysed. Methods that have been proposed to enable VSC-HVDC systems to provide frequency response are reviewed, and a typical VSC-HVDC system with an associated control system is built and validated in Matlab Simulink. These models will form a key part of a modelling toolkit that is being developed to investigate optimal methods for reducing (or removing) future Non-Synchronous Generation (NSG) penetration constraints in the power system in the UK, which represents further work that will be conducted in this project.**

***Index terms* - Converter control, frequency response, HVDC, low inertia, power system, synchronous generator, stability, VSC**

I. INTRODUCTION

According to [1], under the “Gone Green” scenario, 15% of energy supply in GB is expected to come from renewable sources by 2020, and an 80% reduction of Greenhouse Gas Emissions should be achieved by 2050. However, increasing penetration of renewable energy can lead to challenges to the existing power system. Firstly, there is a rapidly growing presence of the RES which are interfaced to the ac system using power electronic converters to enable connection of dc and variable frequency sources as well as to ensure the quality of power supply. This can result in a lack of system inertia (i.e. kinetic energy stored in the rotating masses of the generators and turbines) which is required to ensure adequate stability margins under N-1 maximum contingency (1800MW in UK). According to [1-3] under Gone Green scenario, it is expected that system inertia will be reduced by up to 70% between 2013/14 and 2033/34. Secondly, integration of RES into the power system will result in the reduction of fault levels, which may lead to power system protection challenges, power quality problems, etc.

Non-Synchronous Generation (NSG) are typically characterised by low (or practically non-existent) inertial responses, which can lead to system stability problems such as faster and more extreme system dynamics, higher rates of change of frequency (ROCOF), and potential problem associated with loss of synchronism. The study presented in [4] has shown that when the penetration level of NSG is above 65%, the stability limit of GB power system is reached due to a number of factors and constraints.

There have been many proposed methods and technologies to improve the power system stability problem of low system inertia, such as Energy Storage (ES) systems [5-8], demand side management [9][10] and synthetic inertia control strategy [11][12].

VSC-HVDC systems were first introduced by ABB in the late 1990s [13]. The popularity of VSC-HVDC systems has increased in recent years because of its attractive features, such as facilitation of the connection of RES to ac grids, ability to control both real and reactive power, and high quality voltage waveforms. However, because VSC decouples the systems on the opposite sides of the inverter, i.e. RES side and grid side, variations of frequency on the grid side cannot be reflected on the RES side. This means that, unless some sophisticated control scheme is used, no inertia can be contributed from the RES in proportion to the frequency variation on the grid side.

In recent years, researchers have investigated methods to overcome this problem using control strategies while still benefiting from VSC-HVDC transmission and RES-interfacing systems. Control loops can be applied on the turbine (if a turbine is indeed available – not applicable to PVs) directly or on in the converter controller system to make it possible for the VSC-HVDC to provide frequency response, often termed as “synthetic inertia” or “emulated inertia”, during a disturbance.

The remainder of the paper is organised as follows. The principles of system inertia and frequency response will be reviewed in Section II. Section III introduces the motivation for using VSC-HVDC compared to conventional ac transmission. A simulation model of a VSC-HVDC and its controller system is also described. In section IV, various methods of implementing frequency response in VSC-HVDC transmission systems are reviewed. In section V, the proposed VSC-HVDC model and its controller system are described. The model has been developed in Matlab/Simulink to investigate the power system response under various disturbances. Section VII concludes the paper.

II. SYSTEM INERTIA AND FREQUENCY RESPONSE

A. System inertia

In a conventional power system, electrical machines are electrically synchronised. When there is a power imbalance

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caused by disturbances or power mismatches between supply and demand, kinetic energy stored in the rotating machines will instantaneously be released or consumed to try to achieve a new steady state power balance. With higher system inertia, the system takes longer to reach a new steady state operating frequency after a disturbance, i.e. there are slower system dynamics and lower levels of ROCOF. Inertia constant (H) and ROCOF are defined by equations (1) and (2) respectively, where H is the inertia constant in seconds, ω is the machine nominal speed of rotation in rad/s, J the is moment inertia of the rotating mass in kgm^2, S_{rated} is the rated power of the machine, $\mathrm{d}f/\mathrm{d}t$ is the ROCOF. ΔP is the amount of power change in system demand (e.g. as a result of increased/decrease load, loss of generator, etc.).

$$H = \frac{\frac{1}{2}J\omega^2}{S_{Rated}} \tag{1}$$

$$\frac{df}{dt} = \frac{\Delta P}{2H} \tag{2}$$

Therefore, for a VSC-HVDC system (which inherently does not contribute to system inertia) supplying an AC system, the expected values of ROCOF under system disturbances will be much higher than that for a conventional AC power system containing mainly synchronous machines. Consequently, faster system dynamics lead to limited time for the system to react to disturbances, and an increased risk of instability or blackouts.

B. *Frequency response*

In an electrical power system, frequency is an important factor in ensuring that the whole system operates in synchronism, which is dependent on active power balance between supply and demand. Under normal conditions, where power delivered by the generation units matches the demand, the system frequency is controlled at around its nominal value within specific limits, e.g. ±1% of 50 Hz in the GB transmission systems as stated in the Electricity Supply Regulations of 1989. When the supply is not matched to the demand, frequency excursion occurs as a result. System frequency drops when there is a shortage of generation, while frequency increases when generation exceeds the demand.

Automatic corrective reaction of the system units to adjust their output under power imbalance conditions, i.e. when frequency variation occurs, is known as the frequency response. When the system frequency falls by more than 0.2Hz, generation units are contracted to provide fast-acting frequency response [11].

Frequency response can be generally classified into four categories (depending on the response time): inertial frequency response, primary frequency response (governor response), secondary frequency response (automatic generation controller response, load frequency controller response) and tertiary response. Inertial Frequency Response is usually provided instantaneously and lasts for up to a few seconds and acts to reduce any frequency deviations (or speed of generator prime mover deviations) using the kinetic energy stored in the rotating mass of synchronous generators and motors; the combined effects of this across many machines represents the total system inertia. When the system exhibits lower inertia, relatively larger frequency deviations will result from similar levels of power imbalance. Primary frequency response is provided by the turbine governor or governor-like actions to increase or decrease power output of a generating unit in proportion to system frequency variation following the inertial frequency response. Secondary frequency response employs regulating reserves to recover system frequency to its nominal value in minutes, and may involve bringing other generators on or off-line. Tertiary response is often in place to ensure current and future contingencies following the secondary frequency response.

As stated in [14], the operational limits for contracted synchronous generators are ±0.2Hz, i.e. 49.8Hz to 50.2Hz. As shown in Fig.1, within the ±0.2Hz operational limits, system will stay in continuous operation and control system will regulate the system frequency to be as close as possible to its nominal value of 50Hz. When there is a sudden loss of generation, which results in frequency excursion outside of the operational limits, inertial frequency response will automatically act during the first few seconds due to the stored system inertia in synchronous units. Then, primary frequency response and secondary frequency response will eventually restore the system frequency back to its nominal value. When frequency suddenly drops below 48.8Hz, low frequency (LF) relays will operate to disconnect certain amount of the demand in order to restore power balance, as stated in [14].

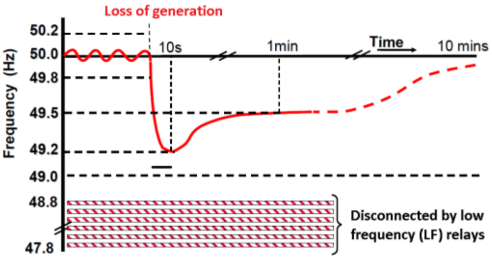

Fig 1. GB system frequency control and stability [14]

According to the characteristics of VSC-HVDC systems, where frequencies at two ends of the link are decoupled, which means generation units cannot adjust its output power according to the frequency at grid side, VSC-HVDC cannot provide frequency response under `disturbances. This can lead to severe problems in the power system, such as higher ROCOF, more easily to fall below lower frequency limitation in power system which may trip LF relays, etc. Researchers have been investigating strategies for VSC-HVDC to provide frequency response achieved by control loops, which will be introduced in section IV.

III. VSC-HVDC TRANSMISSION SYSTEMS

A. *Motivation for development of VSC-HVDC*

The main advantage of HVDC systems is increased power transfer capacity over long distances and significantly reduced

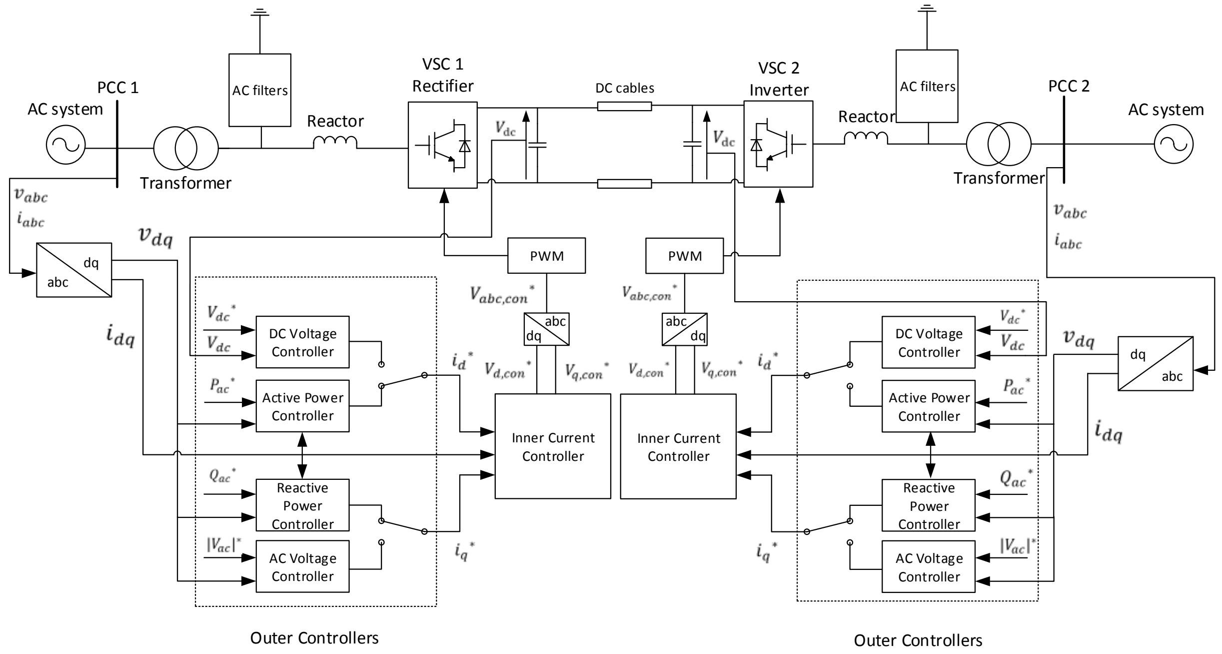

Fig 2. VSC-HVDC configuration with controller systems (* represents reference value in this paper)

power losses, which results in lower transmission costs compared to that of an HVAC system with the same capacity [15]. Furthermore, there are other advantages of HVDC,, particularly with respect to power system stability [15-18]:

- Capability to connect ac power networks with different frequencies (asynchronous connection between ac networks, e.g. 50Hz and 60Hz systems).
- Active power flow via dc link can be accurately controlled.
- Different ac networks can be separated to prevent disturbance or fault propagation from one system to another.
- Capability to improve system stability as each system maintains autonomy.

Historically, HVDC systems utilised line-commutated converter (LCC) with thyristors as main switching devices. Usually, conventional HVDC system refers to LCC-HVDC system. VSC-HVDC transmission system uses self-commutated switching devices, of insulated gate bi-polar transistor (IGBT), with high-frequency PWM. Advantages of VSC-HVDC over LCC-HVDC can be summarised as follows [16,19-21]:

- Independent control of real power and reactive power.
- Capability to generate perfect sinusoidal voltage waveforms, significantly reducing requirements for filtering devices.
- Capability to generate lagging/leading voltage phase angle to rapidly control active power at the converter bus for potentially enhancing frequency stability without extra cost.
- Possibility to feed weak ac systems and passive loads, even black-start capability.
- Better ac fault ride-through capability.
- Fast dynamic response and instantaneous power reversal without requirement to change the dc voltage polarity.
- Reduced risk of commutation failures during ac voltage dips or waveform distortion.
- No requirement for fast communications between converter stations.

B. *Physical model of VSC-HVDC*

Fig. 2 shows a generic VSC-HVDC transmission system with its control systems, connected to a local large ac system at the receiving end. Two VSCs (VSC_1 and VSC_2) are connected at two ends of the dc transmission line, which are labelled as rectifier and inverter respectively. There are two ac systems in the diagram, which can represent, for example, a wind farm connected to PCC1 and ac grid connected to PCC2 respectively.

Typically, transformers, ac filters and/or phase reactors are connected between the VSC and the ac grid to provide satisfactory performance and to meet the transmission specifications. Transformers are to ensure the VSC output to the ac system is in the correct phase and magnitude and to act as a filter to improve power quality. Additional shunt ac filters are used to filter out high-frequency components. Phase reactors are connected for control of the active and reactive power and also for filtering of high harmonics. On the dc side, capacitors are used to reduce voltage ripple on the HVDC link [22][23].

Generally, there are two forms of representation of VSC: a detailed model and an averaged model. Detailed models [19][24] characterise all switching actions, resulting in great computation effort and are typically not suitable for use in large power system models. To enable large system studies to be conducted, the averaged VSC model is proposed in

[20][25][26] and is also applied in this paper. The averaged model represents the average response of switching devices, controls and converters by applying controllable sources and switching functions.

In the averaged model, building VSC ac and dc side power is a critical part in the VSC-HVDC modelling. In this paper, average VSC model based on synchronous *d-q* reference frame is built by using equivalent controllable voltage sources at the ac side and current sources at the dc side, as shown in Fig. 3. The voltage sources are controlled by ac voltages in *abc* reference frame. Meanwhile, the current source is controlled by dc current based on the principle of power balance between ac side and dc side, assuming the converter losses are negligible.

$$v_a i_a + v_b i_b + v_c i_c = V_{dc} I_{dc} \tag{3}$$

$$I_{dc} = \frac{v_a i_a + v_b i_b + v_c i_c}{V_{dc}} \tag{4}$$

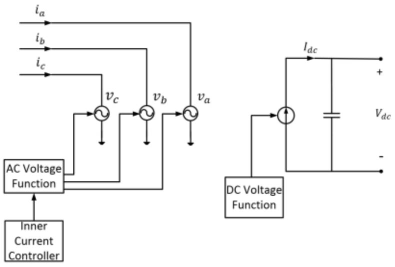

Fig 3. Average model of VSC

C. *VSC-HVDC control systems*

VSC-HVDC controllers are very important to ensure stability and satisfactory performance of the system. The papers [12][21][27][28] introduce different control strategies for VSC-HVDC transmission links. In this paper, positive-sequence *d-q* axis control system with an inner current control loop as described in [12] will be applied at both sides of VSC-HVDC model. Since intrinsic frequency response of VSC-HVDC system is of interest to be investigated, blocks of synthetic inertia in [12] have not been applied in the simulation model.

As shown in Fig. 2, the control system of the VSC-HVDC includes two main controllers, both based on positive-sequence *d-q* reference frame representations. There is an inner current controller and an outer controller on both sides of the link. Outer controllers calculate reference values of i_d^* and i_q^* with ac side voltage and currents expressed in the *d-q* reference frame. The reference current values are then used by the inner current controller to generate three-phase reference voltages v_{abc}^* to control the voltage output from the converter.

Note that negative-sequence components which can appear in measured voltages and currents under unbalanced faults in a three-phase system are not considered in this paper, but will be in future work. Therefore, for balanced transient stability studies as studies in this paper, only a positive-sequence controller is applied. However, it is worth noting that some research has already been carried out to investigate dual-sequence controllers in an VSC-HVDC system under unbalanced disturbances, such as in [29][30].

IV. CONTROL METHODS FOR PROVIDING FREQUENCY RESPONSE IN VSC-HVDC

Conventional VSC-HVDC systems cannot provide frequency response automatically. It is necessary to design additional control loops for communicating grid frequency and generation output and thus enable frequency response in VSC-HVDC systems under ac system disturbances.

Synthetic inertia control strategies have become increasingly more popular in recent years for addressing the low-inertia issue under increasing penetrations of RES. The main aim of such methods is to adjust power output rapidly in accordance to a detected frequency variation on the grid side. Following from equation (6), which is derived directly from equation (2), the frequency response is achieved by implementing communication between RES and grid sides as well as the control loop, as shown in Fig.4. There are two approaches described in [31] for synthetic inertia control loops: continuous and “one-shot” ROCOF control. Continuous ROCOF control uses a measured value of ROCOF on the grid side which is highly adaptive but needs more complex control for filtering harmonics since instantaneous ROCOF measurement introduces a noise amplifying effect. One-shot ROCOF control is only based on initial ROCOF value, which is simpler and predictable but non-adaptive.

$$\Delta P = 2H\frac{df}{dt} \tag{6}$$

Synthetic inertia control loops can be applied directly between the generation units and the grid. For VSC-HVDC transmission systems, control loops can be applied on the converters to adjust output power from VSC-HVDC, and thus, to provide frequency response.

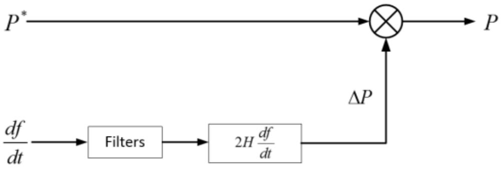

Fig.4 Generic block diagram of synthetic inertia control loop

Paper [32] introduces a control strategy to enable wind farms to provide frequency support using artificial coupling of frequencies at the wind farm side and the main grid side, connected via VSC-HVDC link. The principle of this strategy is to control dc voltage output on the inverter side of the VSC-HVDC using droop controllers in response to frequency variations on the grid side.

Two control schemes for remote offshore wind turbines connected to the main grid via VSC-HVC have been introduced in [33]. One of the schemes is to make the wind turbine adjust its output active power to the rectifier VSC according to the measured frequency on the main grid side, while maintaining constant dc voltage on the inverter VSC. This strategy requires a communication channel to transfer the value of the main grid frequency to the wind farm side,

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which has to be reliable and fast. A communication-less scheme is also proposed in this paper using frequency-voltage droop control on the VSCs to translate frequency variation on the main grid side to equivalent variation on the wind farm side.

An inertia emulation control strategy for VSC-HVDC transmission system is proposed in [12] by utilising energy stored in dc shunt capacitors of the HVDC link, which enables the system to provide inertial responses similar to that of conventional synchronous machines (SMs). The reference value of dc voltage in dc voltage controller on the inverter side is controlled in proportion to the main grid frequency, and as a result, inertial frequency response can be provided in the VSC.

Similarly, a coordinated control strategy is proposed in [34] which manipulates both the kinetic energy stored in the wind turbine rotors and the electrical energy stored in the dc shunt capacitors of the HVDC link to emulate the inertial response of a conventional SM.

According to [4], a constraint of 65% NSG penetration level has been established in simulation for the GB system due to stability limits. The authors believe that the control methods which provide VS-HVDC frequency response equivalent to the conventional inertial behaviour of synchronous generators are one of the key elements which will contribute to the resolution of this constraint.

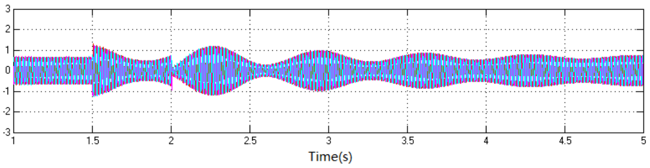
V. SIMULATION RESULTS

Some basic simulations have been carried out to show the impact of VSC-HVDC (with no inertial response) on system performance during faults – on both fault level and system frequency. An averaged model of VSC-HVDC rated at 200 MVA, as described in Section III, is modelled in SimPowerSystems Matlab based on the configuration and control system shown in Fig.2. A synchronous generator (SG) system with the same rating as the VSC-HVDC link has also been created using an independent model to enable comparison. The VSC-HVDC and the SG, connected to the same transmission grid (10,000 MVA short circuit level, X/R=10), are compared under the same 3-phase solid fault between the PCC and ac grid with a duration of 0.5s. The 3-phase fault is introduced at 1s and cleared at 1.5s.

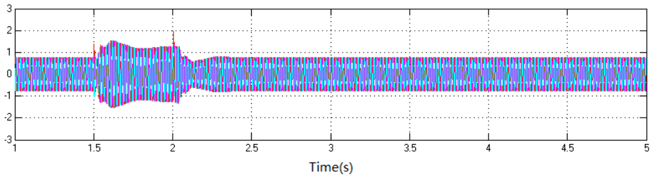
The phase currents at the main grid side in both systems are shown in Fig.5. It can be observed that, as shown in Fig.5(a), the SG's output current/power oscillate for a few cycles before settling down after the fault, whereas the VSC-HVDC outputs steady current/power immediately after the fault clearance. The oscillatory behaviour of the SG is because the inertia of the synchronous machine inherently requires oscillating adjustments of energy before re-alignment with the synchronous electrical frequency of the grid is achieved. For a large-scale power system, this inertial behaviour enhances the overall system angular stability. In contrast, as observed from Fig. 5 (b), no inertial behaviour is provided by the VSC-HVDC. This can also be observed in frequency variation of both systems, as shown in Fig.6, where frequency variation in the VSC-HVDC-supplied system after the fault is much greater than that of the SG system with no inertial frequency response. Also, due to the lack of frequency response in VSC-HVDC system, the system frequency returns to its nominal value of 50Hz faster, where in SG system, small variation of frequency can still be seen after 2.5s.

It can also be observed in Fig.5, during the fault, VSC-HVDC outputs current waveform with a well-controlled and limited magnitude, whereas the SG outputs current waveform with significant high magnitude and the over-current graduate decays to the nominal value. This is due to the limited overcurrent capability in semiconductors, which explains why VSCs contribute no or limited fault current and therefore reduce overall system strength.

Therefore, when there is a considerable amount NSG interfaced to the ac system using VSCs, the system inertia can be reduced and system strength can be reduced correspondingly.

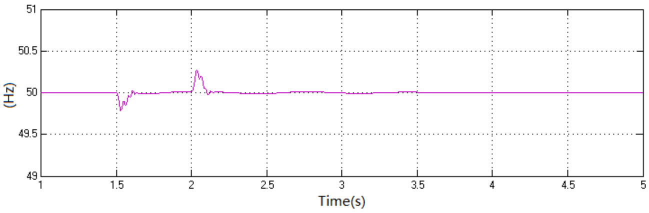


(a) Main grid three-phase current in SG system

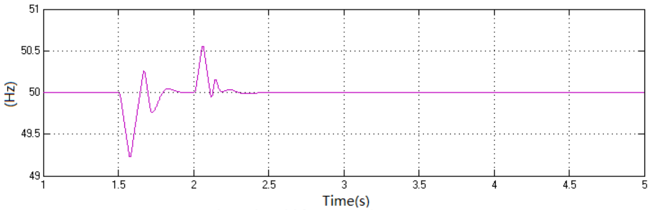


(b) Main grid three-phase current in VSC-HVDC system

Fig 5. Three-phase currents at the main grid side



(a) Main grid frequency in SG system



(b) Main grid frequency in VSC-HVDC system

Fig 6. System frequency at the main grid side

It must be noted that the results represent an idealised situation, since an ac voltage source and impedance are used to form the ac system. Therefore, the results represent a somewhat small penetration of VSC-HVDC. Further work will be carried out to build the power system in a more realistic way in order to explore impacts of increased penetration levels of VSC-HVDC in practical power systems.

VI. CONCLUSIONS

This paper has introduced the future energy development trends in the GB power system and highlighted some of the

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challenges that may be introduced by high penetration of RES in the future. Problems associated with reduced or no frequency response support being provided from converter-interfaced RES under disturbance scenarios have been described. VSC-HVDC transmission technology, which may be capable of improving power system stability, has been described, along with an overview of various control methods, which may enable the VSC-HVDC system to provide frequency response. In the future, a more sophisticated control methodology is required to be designed and test to increase or remove the constraint of 65% NSG penetration level that is presently estimated for GB stability limits.

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