System Operability Framework

nationalgrid

Performance of Phase-Locked Loop Based Converters

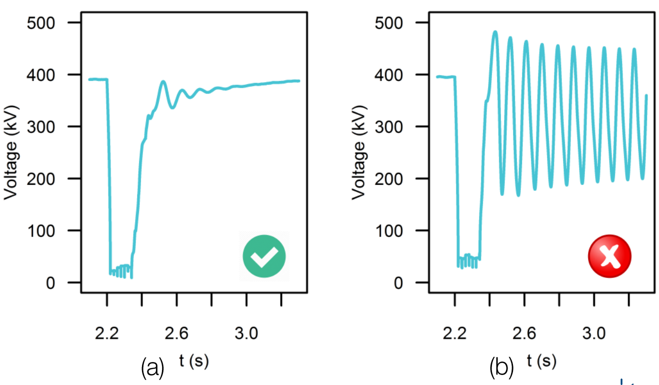
Non-synchronous generators and HVDC converters rely on phase-locked loop in converters to see and react to the electricity network status, just as motorists rely on SatNav to see the route information. We assessed the performance of phase-locked loop based converters in low system strength scenarios, as observed in our SOF, towards the end of next decade. We have found an increasing risk of converter instability. The timing and impact of this risk needs further exploration. National Grid wishes to work with manufacturers, developers and any other interested parties to further explore the risk of converter instability.

Executive Summary

The amount of renewable generation and High-Voltage Direct Current (HVDC) system in Great Britain (GB) has been increasing rapidly during the last decade. They are different to traditional electricity generators and need to be synchronised with the electricity network via power electronic converters, just as a clock needs to keep step with Greenwich Mean Time. Phase-locked loop (PLL) plays a critical role in this synchronisation. It measures the network voltage waveform, which helps the converter to control its power flow to the network.

To maintain stable operation of a converter, the PLL needs to track the voltage during a network fault, as shown in Figure 1(a). If the PLL loses track of the voltage, the converter instability could be induced as shown in Figure 1(b). This can cause damage to network equipment and loss of the generator.

Figure 1: System voltage with PLL (a) tracks (b) loses voltage



System Operability Framework (SOF) 2016 shows system strength will decrease in our transmission network over the next decade. The network voltage waveform would be more variable when disturbed and PLL is more likely to lose track of the network. In this article we assessed the performance of a generic PLL based converter when system strength is very low.

Our assessment found that there is an increasing risk of converter instability as system strength decreases. We also observed there are occasions when the PLL converter can ride through a fault occurring on the site of the converter, but can cause converter instability for remote faults. However, the Grid Code compliance test of converter only considers faults occurring at the converter. When the system strength is very low, the converter stability could be affected by the settings in PLL. The detailed impact of system strength, fault location and PLL settings on converter stability needs further exploration.

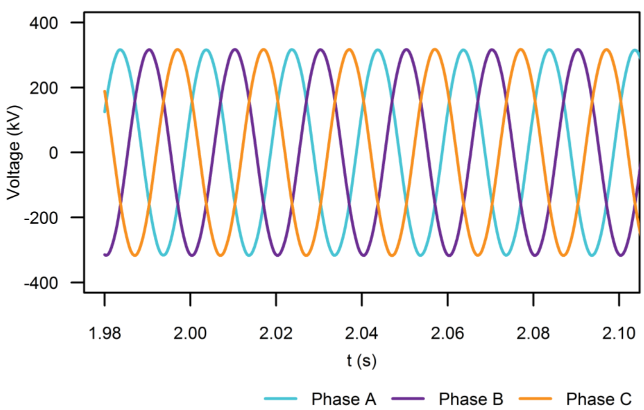
We plan to discuss the findings with manufacturers, developers and any other interested parties. A stakeholder event will be held in Spring 2018. After that, we wish to work with manufacturers, developers and any other interested parties to explore the risk of converter instability. In the future, we would like to cooperate with the industry to explore options to improve the way that converter performance is represented in the management of the network.

Background

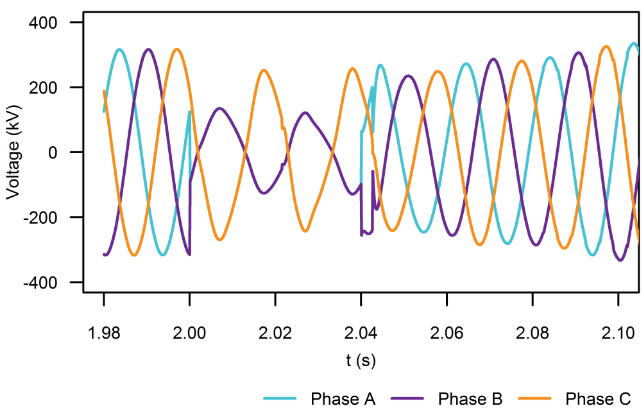
SOF 2016 demonstrated that system strength will decrease in the GB transmission network over the next decade[1]. System strength, which is generally indicated by short circuit level, reflects the robustness of network voltage to a disturbance. Network voltage normally occurs in three phases, oscillating at the system frequency (50 Hz). It is this voltage waveform which is measured on the transmission network by the PLL and the obtained network status in turn supports control and protection operation of converters in non-synchronous generators. Figure 2 shows a typical voltage waveform and how it changes over time when disturbed by a fault, such as one overhead line drops on ground due to a falling tree.

Figure 2: Three-phase voltage waveform

(a) Normal three-phase voltage

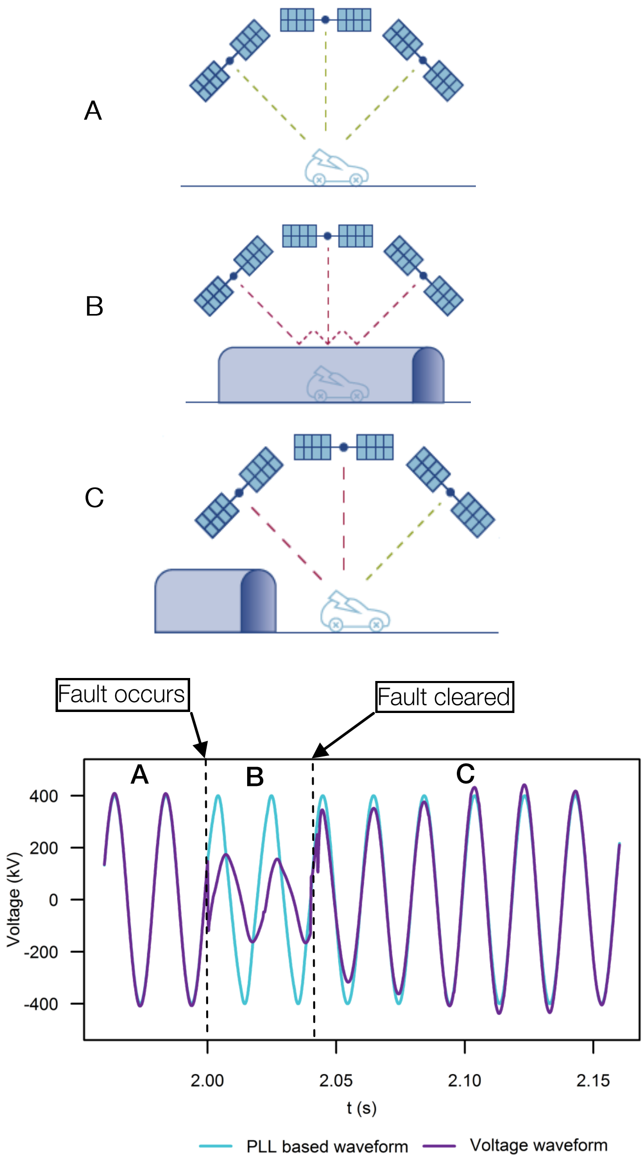


(b) Disturbed three-phase voltage



The function of PLL can be explained by an analogy with a SatNav system as shown in Figure 3. Three different case scenarios indicated by 'A', 'B', 'C' are illustrated. The waveforms at the bottom of Figure 3 show an example of network voltage waveform and the waveform based on PLL measurement. They are divided into three parts, corresponding to each of above three cases.

Figure 3: Phase-locked loop controller example



Case A: The performance of a PLL controller can be visualised as a motorist with a SatNav system. The SatNav system provides the route information to the motorist. Similarly, the PLL controller provides the information of electricity network to the converter of a non-synchronous generator or HVDC system. PLL tracks the three-phase voltage waveform shown in Figure 2 and provides the phase reference so that the non-synchronous generators or HVDC can keep synchronised with the network. The phase signal is used to control the power flow from converters. For the waveforms in Figure 3, part A represents the normal operating condition before a fault occurs. We can see the waveform obtained from PLL measurement matches the network voltage waveform. This means the converter is well informed of network information.

Case B: When going into a tunnel, the motorist loses satellite coverage. The SatNav may cease to update, respond to outdated information or act based on a fixed behaviour (such as telling the motorist to keep going straight forwards). Equivalently, the PLL close to an electrical fault could see a 'weakened reference', i.e. the retained voltage is so low that there is little or no voltage information to inform its response. Part B of the waveforms in Figure 3 indicates the condition during a fault. The network voltage reduces to a low magnitude level, the PLL measurement based waveform deviates from the network voltage waveform significantly since the PLL loses the phase reference during the fault and it just follows its pre-fault phase position in this example.

Case C: When the motorist comes out of the tunnel, the SatNav will suddenly receive new information. There could be a delay while the SatNav updates and there could be a jump in position based on the new information. This is equivalent to a PLL controller issue known as 'phase jump' which can lead to a delayed or failed response to new conditions. Part C of the waveforms in Figure 3 indicates this post-fault condition. After the fault is cleared, there is a 'phase jump' in the system voltage and its magnitude increases to the pre-fault level. However, there is a delay for the PLL controller to fully track this change.

PLL can lose track of the transmission network due to either 'weakened reference' or 'phase jump'. This can affect converter behaviour and cause converter instability. As system strength is decreasing, the voltage waveform could be more variable when disturbed. The severity of both 'weakened reference' and 'phase jump' would increase. It is essential to understand the performance of PLL based converter in a low system strength scenario and the factors that influence PLL's capability of tracking the transmission network.

However, traditional power system models used for thermal voltage and stability assessments across the full GB transmission system do not incorporate a detailed model of the PLL based control system. Also, there are numerous types of PLL identified across academic literatures. The precise design and detail of its control elements are unique to each manufacturer. In the current connection process, we normally get simplified models, which do not contain enough detail to support a full assessment of the PLL. Due to the lack of detailed models, we are not clear about the performance of PLL based converter during disturbances. This assessment aims to investigate the performance of a generic PLL based converter in a simplified network after a fault and understand the factors that influence PLL's performance.

Method

We chose to use the CIGRE developed Voltage Source Converter model. This model was created by the industry working group CIGRE B4-57[2], involving industry participants, academic and manufacturers. It contains details of PLL and its control system. By using this model, we can get clear and concise findings with relation to an industry developed and approved reference model. While individual designs and settings of plants in the GB transmission system may differ from this reference model, the discussion of the principles of performance will remain valid. The basis of this analysis will allow manufacturers or developers to replicate this analysis with their own designs. We utilised the PSCAD power simulation package, which is commonly used by manufacturers to model and assess the control design of their converters.

In this assessment, one terminal of the HVDC model is connected to a simplified scaled model of the GB transmission network. Two simple networks have been developed; Figure 4 shows the network used for voltage disturbance study and Figure 5 shows the network used for frequency disturbance study.

Figure 4: Network used in voltage disturbance study

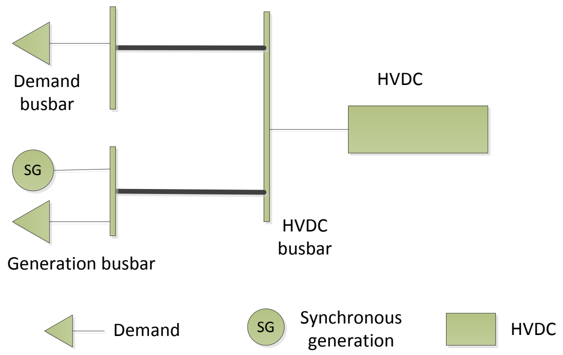
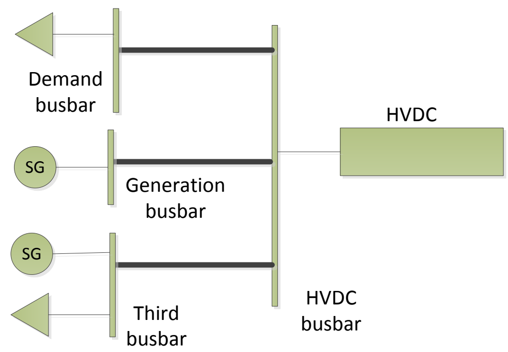


Figure 5: Network used for frequency disturbance study



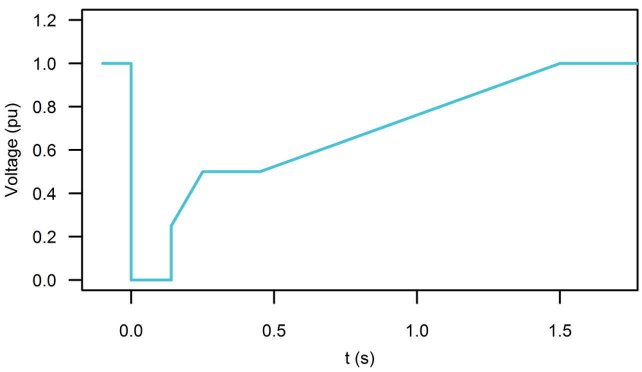
The network in Figure 4 contains a demand busbar and generation busbar, which are connected to the HVDC terminal via a HVDC busbar. The voltage disturbances are created by applying faults at the HVDC busbar, demand busbar and generation busbar respectively.

A series of case studies were carried out based on this network, which investigates the impact of short circuit level, fault location and PLL settings on the performance of PLL based converters. The case scenarios of these studies are listed in Appendix. The short circuit level considered in these cases reflect the scenarios identified within SOF 2016.

The network in Figure 5 was used to model the largest loss of generation and demand. It contains a demand busbar connected to the equivalent largest demand, a generation busbar connected to the equivalent largest generation, and a third busbar connecting the rest demand and generation.

Figure 6 shows the criteria used in our assessments, which is a profile proposed for non-synchronous generators responding fault ride through capability. It was developed as part of Grid Code 0048 working group work on implementing the ENTSO-E Requirements for Generators[3]. If the recovery of root mean square voltage profile after a fault is no worse than this criteria profile, we can confirm that generators in the transmission network would remain connected after the fault.

Figure 6: Voltage profile for fault-ride-through requirement



In our assessment if the voltage profile is above the criteria curve, we would say the converter is able to ride through the fault, which would be indicated by a tick [√] in the following result tables; if the voltage profile crosses the curve, we would say the voltage performance is not acceptable which includes oscillatory instability, this is indicated by a cross [X] in the following result tables.

When considering a frequency event, we require that the frequency does not deviate outside of the permissible range in normal operation, i.e.
49.5—50.5 Hz.

Analysis

Impact of system strength

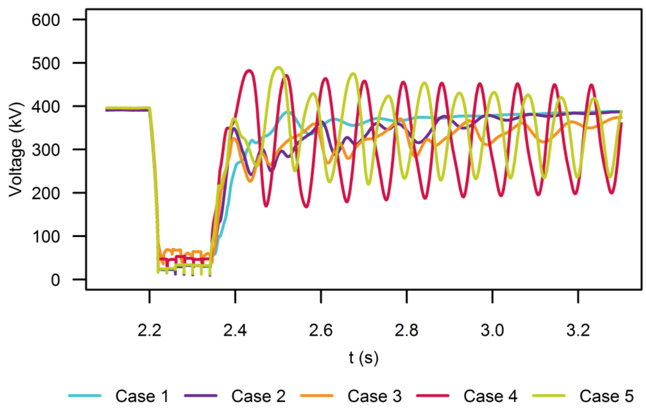
The impact of system strength has been investigated in cases 1 to 5, shown in Table 1. The declining short circuit level shows the reduction of system strength. The simulation results show the converter is able to ride through all the faults in cases 1—3. As the short circuit level is further reduced, in case 4, the converter goes into instability after a fault occurs at the demand busbar and the generation busbar. In case 5, the converter becomes unstable after all the faults. This happens because there is less reactive power to rebuild and stabilise the network voltage after the fault is cleared. It will take longer for the voltage to reach the steady state. As the voltage is approaching the steady state, its phase is dynamically changing. If this period is very long, the PLL controller might not be able to track the correct phase quickly enough, and then the converter drives the system into instability by using incorrect phase reference.

Table 1: List of scenarios with decreasing system strength

Case NO.	Short circuit current (Peak/ @100ms kA)	Fault at HVDC busbar	Fault at demand busbar	Fault at gen. busbar
1	2.41/0.839	√	√	√
2	2.378/0.813	√	√	√
3	2.355/0.787	√	√	√
4	2.25/0.772	√	X	X
5	1.959/0.472	X	X	X

This effect may be seen more clearly in Figure 7 which shows the voltage profile with the fault at the demand busbar in cases 1—5. Compared to case 1, the post-fault voltage in case 2 becomes more variable during the first second of voltage recovery. In case 3, the variability further increases. In cases 4 and 5, the voltage does not stay at the previous level but goes into oscillation with a frequency of around 12.8 Hz.

Figure 7: Voltage RMS profile in case 1 to case 5

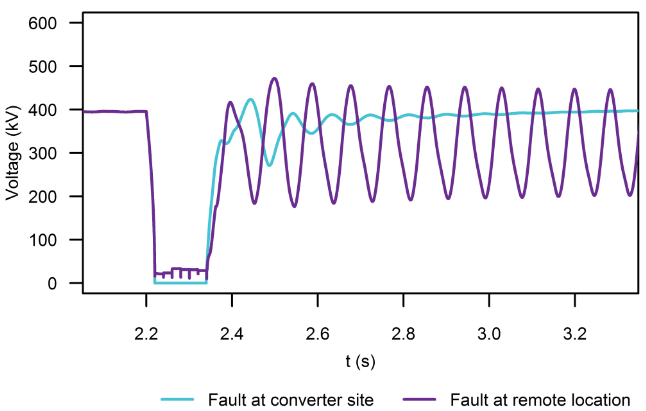


The above results indicate a minimum short circuit level is required for the normal operation of fully converted non-synchronous generators and HVDC. Our SOF 2016 shows that the short circuit level of the GB transmission system declines in future years and extremely low short circuit level could occur in some regions. It is not possible to tell what is the exact minimum short circuit level required for our GB system in this assessment. This minimum level depends on the specific network characteristics at transmission and distribution level, the number and variety of non-synchronous sources, their operating conditions and capacities, and the converter design.

Impact of fault location

The impact of fault location on converter behaviour was studied in case 4 and case 6 by use of the network shown in Figure 4. In these two cases, three-phase-ground fault is applied at the converter site (HVDC busbar) and a remote location (demand busbar) respectively. Figure 8 shows the results in case 4. We can see the converter is able to ride through the fault at the converter site; in this case the retained voltage level during the fault is zero. However it goes into instability after a fault happens at a remote location which has a short distance to the converter, in this case, the retained voltage level is non-zero. In case 6, we can observe the same result.

Figure 8: Voltage profile in case 4



This happens because the converter model, in this case, responds differently to these two faults. During the fault at converter site, there is no reference voltage for the PLL, therefore the PLL just follows its previous phase position and remain stable, ignoring the phase changes in the network. During the fault at remote location, there is a small retained voltage for PLL to reference. The PLL fails to track the network phase across the phase jump occurring when the fault is cleared, and the converter goes into instability.

The fault-ride-though capability of PLL based converter is not only affected by the magnitude of the retained voltage level during the fault but also the range of phase change required to recover the voltage. However the Grid Code compliance test of converters is designed based on the principle of voltage magnitude and only faults at the converter are tested. We find that a remote fault might cause a large phase change at the converter, this could lead to a lower margin of stability of the PLL converter as compared to a fault occurring at the converter itself.

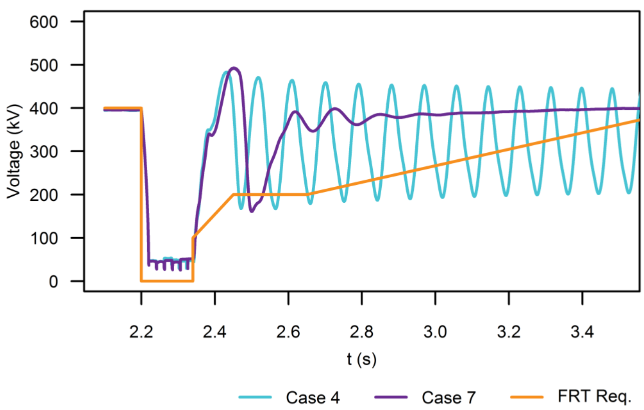
Impact of PLL setting change

The rate of response of PLL to the changes in network voltage waveform is affected by the PLL proportional/ integral gains. The case scenarios listed in Table 2 are used to study the impact of PLL proportional/integral gains on converter behaviour. Based on case 4, the PLL proportional/integral gains are reduced from 300/200 to 75/50 in case 7, making the converter response slower. The results show this change improves the voltage performance for all the faults; the converter goes through the fault occurring at demand busbar in case 7, while it previously did not. For the fault at generation busbar, although the voltage in case 7 crosses the fault -ride through required curve, it is able to recover to the nominal level as shown in Figure 9. This is improved compared with the oscillations in case 4.

Table 2: List of scenarios with different PLL proportional/integral gains

Case No.	Proportion-al/Integral Gains	Fault at HVDC busbar	Fault at demand busbar	Fault at gen. bus-bar
4 (Weak system)	300/200	√	×	×
7 (Weak system)	75/50	√	√	×
2 (Strong system)	300/200	√	√	√
8 (Strong system)	75/50	×	×	×

Figure 9: Voltage profile for fault at generation busbar in case 4 and 7



The gain pair of 75/50 is further tested in a relatively stronger network in case 8, which is created based on the scenario in case 2. The result shows the system goes into instability for all the faults. This shows no single set of PLL gains is suitable for all the scenarios. In low system strength scenario, lower PLL proportional/ integral gains would slow down the response of PLL to the volatile system voltage, this would help to maintain the stability by ignoring some rapid disturbances. While in strong network, a high set of PLL gains would help to rapidly capture the system voltage during a disturbance, improving converter stability. The optimal proportional/ integral gains is dependant on the system strength, the values of the gains need to be calibrated according to the network change.

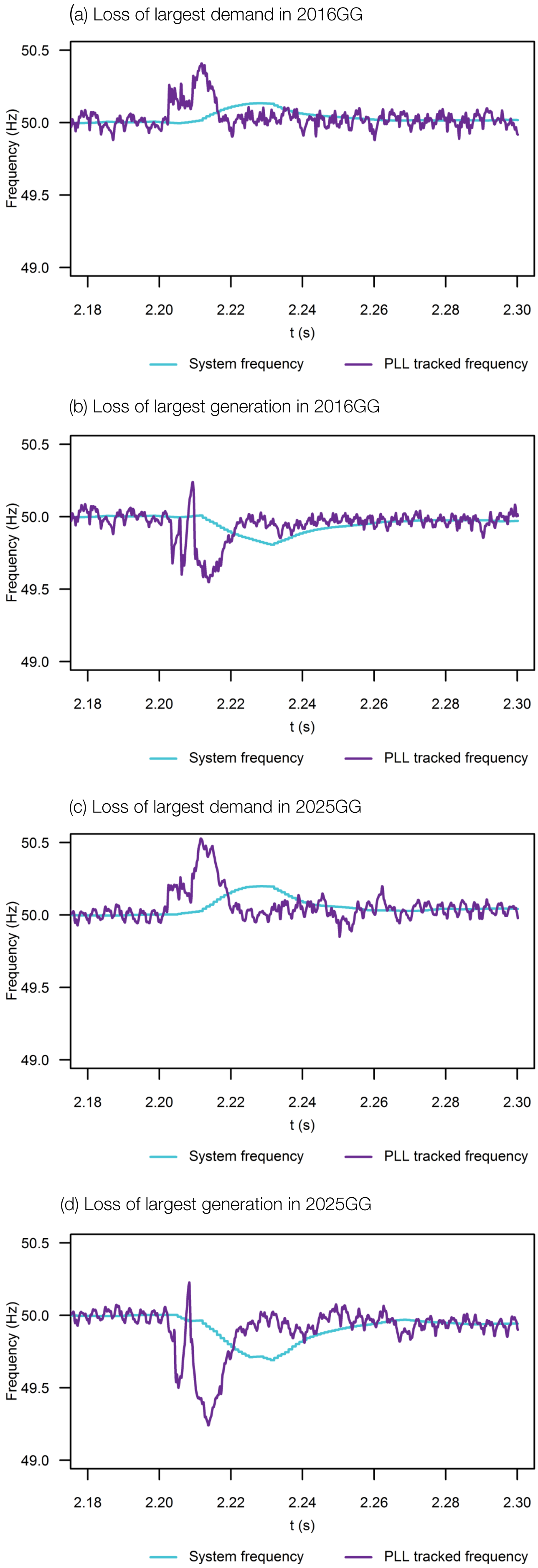
Performance of converter in frequency disturbances

The network shown in Figure 5 was configured to have the equivalent system inertia, largest generation loss and demand loss to the GB transmission system for the Gone Green scenarios in 2016/17 and 2025/26. The frequency events are created by disconnecting either the largest generation or the largest demand at 2.2 s in the simulation. In Figure 10, the system frequency and the PLL tracked frequency during these events are illustrated. After the frequency disturbance, there is deviation between the PLL tracked frequency and system frequency for a short time of around 40 ms, after which the PLL could always recover to track the system frequency quickly. This indicated the PLL could capture the system phase reference quickly after the frequency disturbance.

Comparison with synchronous generation

The performance of PLL based converter was compared with a traditional synchronous generator. We find that by replacing the HVDC converter with synchronous generators, the system is able to ride through all the faults in all the cases studied above, which is quite different to a PLL-informed HVDC converter. This is because the synchronous generator provides a strong capability of rebuilding and stabilizing the voltages; it is able to inject around 5—7 p.u. reactive current in the network to rebuild the system voltage rapidly during fault and maintain a stable voltage level. This comparison shows we created fair case scenarios for the PLL based converters in this assessment.

Figure 10: Results in frequency event simulation



Conclusions

The performance of PLL based converters in low system strength scenario have been studied. We find that there is an increasing risk of converter instability as system strength is decreasing. When the system strength is very low, the converter stability could be affected by fault location and the settings in PLL.

The variability of system voltage waveform makes it difficult for the PLL controller to measure the system phase reference rapidly across a voltage disturbance. This mainly relates to the decrease of the short circuit level. Our study shows a remote fault could lead to a lower margin of stability of the PLL based converter as compared to a fault occurring at the converter itself. The fault-ride-though capability of PLL based converter is not only affected by the magnitude of the retained voltage level during the fault but also the range of phase change required to recover the voltage. In Grid Code, the fault ride-through capability test of converters only considers fault happening at the converter and several specific levels of voltage step change. In addition, the impact of modifying the setting of control quantities within the PLL have an influence in the performance. A single set of settings could not always provide stability across the variation of system strength conditions to which the convertor operates.

We currently receive limited information of actual PLL controllers through Grid Code arrangements. All these findings above are obtained by use of the CIGRE developed model. We would like to keep discussing the findings with manufacturers, developers and any other interested parties and explore the risk of converter instability in the GB transmission network. A stakeholder event will also be held in Spring 2018. In the future, we wish to cooperate with industry to explore options to improve the way that converter performance is represented in the management of the network.

While the PLL approach is currently used to inform non-synchronous generator control, National Grid together with the wider industry have been active in investigating alternative control approach with less or no inherent reliance upon the monitoring and referencing of the voltage waveform. One example is the concept of a Virtual Synchronous Machine formulation of control[4]. In addition, National Grid is working with others to fully define the range of instabilities and control options relative to voltage based disturbances under innovation research[5]. The combination of new levels of modelling, new options for control and increased levels of cross-industry dialogue offer the potential to develop further levels of insight in this area across future years.

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Appendix

Table 3: List of case scenarios in voltage disturbance study

Case NO.	Demand (MW)	HVDC Import (MW)	Line length to Demand Busbar (km)	Line Length to Gen Busbar (km)	SG Unit NO.	Inertia H (GVA.s)	PLL Proportional/ Integral Gains
1	800	760	33.4	50	2	80	300/200
2	800	760	33.4	200	2	80	300/200
3	800	760	200	200	2	80	300/200
4	600	576	33.4	200	2	80	300/200
5	600	576	33.4	200	1	80	300/200
6	600	576	33.4	100	2	80	300/200
7	600	576	33.4	200	2	80	75/50
8	800	760	33.4	200	2	80	75/50

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You can write to us:
System Performance
National Grid House
Warwick Technology Park
Gallows Hill
Warwick
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