Solar inverter interactions with DC side

Some Regulatory Challenges

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***Abstract*— The DC voltage on the photovoltaic (PV) array connected to an inverter plays an important role in the operation of the PV inverter system. The DC voltage is controlled by the maximum power point tracking (MPPT) controller to deliver active power based on the PV array V-P curve. This varies with solar irradiance and PV cell temperature. The DC voltage needs to be kept higher than the peak AC voltage at the inverter terminal for the inverter to operate correctly. It is also used to regulate the PV array output. The DC voltage is thus a function of both the PV array design (solar irradiance and cell temperature) and the inverter side (peak AC voltage).**

The need for a margin between the DC voltage and the peak inverter terminal voltage creates situations that may limit the active power and deliver unexpected responses. These can have regulatory compliance issues because, in Australia, the technical standards require 'continuous uninterrupted operation' (CUO). In brief, CUO has been interpreted to mean that the active power remains unchanged following power system disturbances, and that reactive power is only changed as required for voltage control for connection point voltage variations within an operating band of 90%-110%. In practice this means that additional inverters are required to meet CUO and the ratio of inverter capacity to rated active power typically exceeds 1.2. In normal operating conditions, the power plant controller must limit inverter operation to a value below the MPPT optimum at high irradiance levels, reducing both active power and yield to a level that allows active power and reactive power capability to be maintained at 90% nominal connection point voltage, without tap changer operation.

For some irradiance/ high temperature conditions, active power may reduce if the inverter ac voltage increases to within the acceptable margin of the DC voltage. Under these conditions, the DC voltage is increased to maintain the required margin between AC peak and DC voltage, consequently curtailing active power. Depending on the AC design of the generating system, the collector voltage can be significantly affected by system voltage variations. Under some feasible conditions, a decrease in inverter voltage caused by a change in the system conditions, can result in an increase in active power output when the active power is initially below maximum available level. This is not usually a power system security issue but in Australia it creates compliance issue, which has the potential to exclude otherwise high performing inverter systems or have high compliance costs.

Keywords- generator technical stanadards; solar integration; AC-DC interaction, MPPT

I. INTRODUCTION

Australia has attractive characteristics for investment in solar and wind: excellent resources, strong economy and low statutory risk. As a result, there is great interest in investment with around 7000 MW of solar in operation [1], mostly rooftop.

The National Electricity Market (NEM) supplies nearly 90% of Australian demand and is located mainly on the east and southern parts of Australia. It has a maximum demand of around 35GW and a generation fleet of around 50 GW, of which about 6GW is hydro.

At time of writing, the NEM had:

- around 960 MW of grid-scale solar in operation [2]
- 1200 MW of project about to start commissioning [3]
- 2300 MW of additional committed projects [2] and
- 22,000 MW of proposed projects [2].

There are some key issues emerging in Australia as the rate of investment in solar grows rapidly:

- There are a number of technical issues, particularly with weak grids.
- The fault ride through behavior of wind turbines contributed to a blackout event in the state of South Australia in 2016.

The market and system operator, the Australian Energy Market Operator (AEMO), has responded by more stringently interpreting certain existing clauses of the grid code, the National Electricity Rules (NER) [4] and proposing NER changes [5] that significantly tighten the technical performance standards and reduce the envelope of design options for compliance. The NER incorporates the technical issues normally in a Grid Code.

The problem arises from two key performance standards[1], which require:

- the MW and reactive output to be maintained for all voltage excursions within the continuous operating voltage band (COVB) of 90% to 110% at the connection point; and
- the delivery of reactive power (in the range 0.93 leading – lagging) under all operating conditions within the COVB.

This paper shows that that the DC design of a solar farm and the interactions between DC and AC sides may make it difficult to meet these strict requirements. An outworking of much higher performance standards might be that some plant may not be able to meet the standards. Alternatively, plant may have to be more heavily de-rated, challenging the economics of the investment.

II. The Negotiation Framework for Connection of Generation in Australia

The NER provides a framework for negotiation of generator performance standards, between minimum and automatic access standard levels. For each technical requirement, the performance of a generating system may not be below minimum access standard level and is not required to be above automatic access standard level. Negotiated performance standards can be agreed between the generator, the network service provider and the AEMO[2], at levels between minimum and automatic access standard level. Over the past few years AEMO and network service providers have been requiring increasingly high standards for connection, and their right to do so has been reinforced in the new draft technical standards Rules. Under the new Rules, any departures from the automatic access standards must be justified and negotiations for lower standards will be challenging.

Typically, the final negotiating position is close to or at the automatic access standard level, to the extent that this is technically and economically feasible. In any case the standard needs to be set at a level that would not adversely affect power system security or quality of supply to other users. For this paper we shall focus on the automatic access standards.

A. *Reactive power capability*

The automatic access standard for reactive power capability (s5.2.5.1 of the NER) is that at:

(1) any level of *active power* output; and

(2) any *voltage* at the *connection point* within the range 90 to 110% of *normal voltage*[3]*,*

the *generating system* must be capable of supplying and absorbing continuously at its *connection point* an amount of *reactive power* of at least the amount equal to the product of the *rated active power* of the *generating system* and 0.395.

The automatic access reactive capability requirement can be conceptualized as symmetrical vertical lines on the capability curves, as shown in Figure 1.

The normal voltage is usually the nominal voltage, and the 0.395 multiplier equates to a power factor of 0.93 at maximum active power. The requirement applies to all operating temperatures. For solar farms, performance standards are usually written with capability described at 25/30 and 50ºC reflecting the temperature dependent capability of inverters. The reactive power requirement can then be defined to apply to the active power capability derated for temperature. Temperature-dependent active and reactive power limits are generally implemented in the solar farm, in either the power plant controller (PPC) or through SCADA, to reflect these capability curves.

The capability is also described for 90%, 100% and 110% of normal voltage at the connection point. Inverters are typically current limited and therefore have capability that change in proportion to the voltage of the inverter. At 90% inverter voltage the MVA capability is 0.9 x the value at nominal voltage.

The reactive power capability clause has historically been interpreted to mean the steady state capability, so that the capability can be expressed considering transformer tapping to manage collector system voltages, but this is not explicitly stated in the wording, and might be open to different interpretation. In addition, some connection points have historically been on the medium voltage (MV) side of a grid step-up transformer, rather than the high voltage (HV) side. This reflects the ownership of the transformer – the connection point being the ownership boundary. The connection point, while determined from commercial considerations, has ramifications for the performance defined for the plant. Extension of overvoltage duration requirements in the draft technical standards[4] mean that

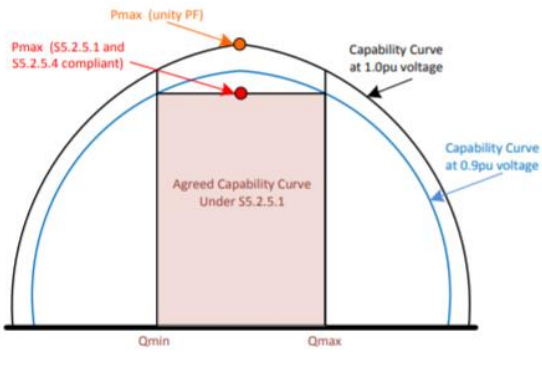

Figure 1 PQ capability curve, to meet continuous uninterrupted operation under S5.2.5.4 [6]

[1] S5.2.5.1 Reactive Power Capability and S5.2.5.4 Response to voltage disturbances

[2] AEMO is involved in the negotiation for certain technical standards related to power system security.

[3] Paraphrased from the actual clause, which references clause S5.1a.4.

[4] 120% overvoltage for 20 minutes

future connection points will likely be defined on the HV side of the transformer.

B. *Maintaining active power constant for voltage disturbances*

The relevant part of the technical standard for the response to voltage disturbances (s5.2.5.4 of the NER), for the COVB, is:

"a *generating system* and each of its *generating units* must be capable of *continuous uninterrupted operation* where a power system disturbance causes the *voltage* at the *connection point* to vary within the following ranges:

…

(2) 90% to 110% of *normal voltage* continuously;

…"

where *continuous uninterrupted operation* has the definition:

"In respect of a *generating system* or operating *generating unit* operating immediately prior to a *power system* disturbance, not disconnecting from the *power system* except under its *performance standards* established under clauses [protection clauses] and, after clearance of any electrical fault that caused the disturbance, only substantially varying its *active power* and *reactive power* required by its *performance standards* established under [clauses for voltage control, frequency control and active power control], with all essential auxiliary and reactive *plant* remaining in service, and responding so as to not exacerbate or prolong the disturbance or cause a subsequent disturbance for other connected plant."

In conjunction with the definition of continuous uninterrupted operation, AEMO has interpreted part of S5.2.5.4 to mean that a generating system is not permitted to vary its active power or reactive power in the range 90% to 110% in a way that would exacerbate a disturbance [6]. Effectively this means that the solar farm is substantially derated, so as to contain the P-Q capability curve at 90% connection point voltage, as illustrated in Figure 1.

AEMO also does not allow any switching of reactive plant or tapping of transformers to be considered to meet the requirements of this clause.

C. *Implications for solar farm sizing*

For a connection point on the high voltage (HV) side of a grid transformer, operation at 105% normal voltage at the connection point would not be uncommon. This means that the solar farm must maintain its active power constant for an instantaneous 15% dip (105% to 90%) in grid voltage. With full reactive power capability also required, the solar farm must be further over-sized. For 100 MW output at power factor of 0.93, this would be more than:

$$100/0.93/(1-0.15)= 126.5 \text{ MVA} \quad (1)$$

taking account of transformer reactive and active power losses, that is, oversized by more than 27%.

AEMO's position has been reflected in the draft technical standards and seems likely to be encapsulated in the new technical standards Rules.

III. INVERTER AC AND DC INTERACTIONS

The performance standards for voltage response and reactive power capability have until recently considered the AC characteristics of inverters – current rating, MVAr limits, thermal derating, and continuous voltage capability. Until recently, it has been industry practice to ignore the characteristics of the DC side of the inverter in assessment of the performance standards. The DC to AC ratio is usually around 1.2:1, so the expectation was that DC capability would exceed the AC capability, and that the DC side could be treated as an ideal source for transient phenomena such as faults and for calculating the reactive power capability. Many of the solar farms under construction at present have performance standards based on this assumption. However, recent experience has shown that this is not necessarily true, and that there can be AC-DC voltage interactions that affect compliance with performance standards.

The key relationship that links the AC and DC capability is that the DC voltage must always exceed the AC voltage peak, for the inverter to be able to operate correctly. Conditions that increase inverter AC voltage or decrease DC voltage will decrease the margin between them.

If, when operating at a low DC voltage condition, the inverter AC voltage is increased, the margin between DC voltage and the new AC voltage may become inadequate. The operating point must then be adjusted to a higher DC voltage, which decreases the active power output from the PV array. The power curve in Figure 2 shows initial operating point and how it moves *down* the power curve as the DC voltage is increased. The reduction in active power does not satisfy an interpretation of CUO that requires constant active power.

Depending on inverter design, the reverse can also occur: when an inverter output, initially constrained by an AC- DC margin, experiences a reduction in AC voltage, the active power can increase. An increase in active power for a voltage reduction may also be considered unacceptable under the Rule.

A. *Factors that affect inverter DC voltage*

DC voltages on the inverter are influenced by several factors. The DC voltage of the PV system is affected by the V-I characteristics of the panels, and the design of the array, particularly the number of strings in series. The DC open circuit voltage of the panels is temperature dependent, and

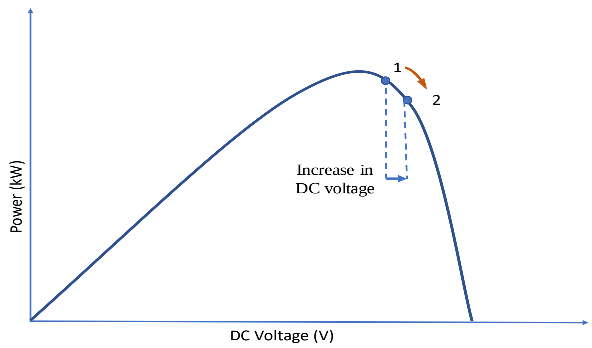

Figure 2 PV array power output versus Vdc

the design must consider the range of temperatures for operation. At lower temperature the open circuit voltage is higher, so the lowest expected temperature will dictate the maximum number of panels in series, so as not to exceed the maximum design voltage. Many solar farms sites in Australia experience wide daytime temperature ranges, particularly in inland areas. As the panel temperature rises both the maximum active power output for a particular insolation level and DC voltage at which the maximum power point (MPP) occurs reduce.

Summer temperatures in the range 30 – 40°C are common in Australia, and many locations with high insolation also experience temperatures up to the mid-forties. At these high temperatures, DC voltages for MPP are reduced. Figure 4 provides an example of how solar panel I-V characteristics vary with temperature. The PV array characteristics are also affected by the technology employed for the cells. For example, in [7] measurements for mono-crystalline silicon solar cells show approximately 11% reduction of Vdc for MPP from 25°C to 50°C, at irradiance of 550W/m^2 and in [8] measurements show a 14.7% and 13.8% reduction for mono- and poly-crystalline solar cells from 10°C to 50°C at 1000 W/m^2. The Vdc for MPP increases with irradiance in both technologies, around 9% for mono-crystalline solar cells, and around 3% for poly-crystalline solar cells between 200 and 1000 W/m^2 [8]. Considering the approximate relationship between ambient and cell temperatures (for wind speed of 1m/s) [9] for Australian conditions, cell temperatures in the range 40°C – 80°C can occur.

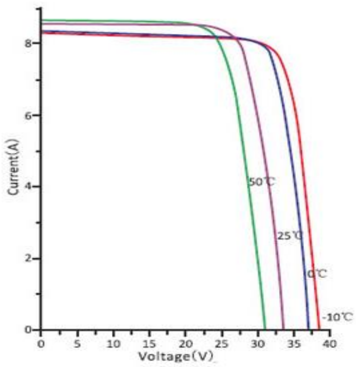

Figure 4 Example of solar panel I-V variation with temperature **[10]**

Inverters maximize the output of solar arrays by tracking the MPP. They have, according to their design a range of DC voltages over which they can track MPP. At high Vdc, IGBT switching losses increase [11] and depending on the cooling design of the inverter, this can substantially affect the inverter current capability, particularly when combined with high ambient temperatures.

When the solar farm's output is required to be restricted, as is the case for the Australian NEM requirement to maintain active power for voltage drop to 90% nominal voltage, the inverter does this by increasing operating point of the DC voltage, to move the active power away from the MPP. On the power curves shown in Figure 2, this is moving down the steep right side of the curve.

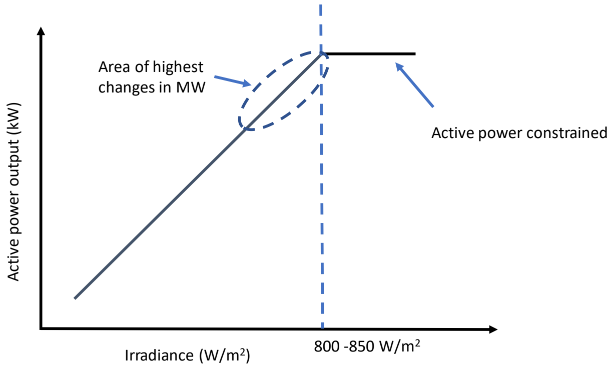

Figure 3 Active power versus irradiance showing region of highest MW change with Vdc change

The highest operating DC voltages will arise when the inverter is operating:

- at low temperatures,
- with high irradiance, and
- where the inverter is limiting the active power output from the panels.

The lowest DC voltages occur for:

- lower irradiance (when the inverter not limiting output), and
- high temperatures,
- where the inverter is tracking MPP.

B. Irradiance levels for highest active power changes

The typical irradiance levels where the largest changes in active power can occur is illustrated Figure 3. Smaller changes in active power can also occur for lower irradiance levels.

To avoid a condition where active power reductions occur for any output, the Vdc required from the PV array to support the highest case inverter AC voltage, must be lower than the MPP voltage at the lowest irradiance and highest temperature of operation. The authors are not convinced this condition can be satisfied for all conditions under which solar farms operate in Australia, considering the limitation on open circuit Vdc.

C. Conditions where inverter ac voltage is high

There are several causes of high inverter ac voltages:

1. The inverter has a high nominal ac voltage (relative to the DC voltage)
2. The inverter AC operating voltage for normal operating conditions is above nominal
3. The collector MV voltage is operated in a way that leads to high voltages without power system disturbances or
4. There is a power system disturbance that elevates the voltage on the power system generally, which causes a rise in voltage at the inverter terminal.

Highest inverter AC voltages are most likely to arise for a condition that causes the inverter to inject reactive power in conjunction with high voltages on the collector system MV bus. The worst-case conditions are solar farm design-specific and are also affected by connection point operating voltage under normal conditions. The worst-case conditions for compliance will also be affected by whether the connection point is on the MV or HV side of a grid transformer.

1) High inverter nominal AC voltage

There is a trend to using high inverter nominal voltages, because the MVA rating increases with the voltage. In the past two years there has been a change from panels and inverters rated at 1000 V DC to 1500 V DC, which has facilitated the increase in rating of inverters, and lower overall solar farm installation prices. Examination of inverter manufacturers' brochures will also show that they offer a range of inverter sizes for the same DC voltage rating, and as the rating is increased, the nominal AC inverter voltage is increased. As nominal inverter AC voltage increases, the margin between the DC and AC voltages is reduced. With higher inverter AC nominal voltages there is an increased risk of CUO non-compliance, all other factors being equal.

2) Inverter operating conditions above nominal

As described in section II, the continuous uninterrupted operation requirement, associated with S5.2.5.4, has led to a need to substantially oversize the solar farm AC capacity, in the order of 15-30%, (depending on whether highest reactive power capability is also required). One way of increasing the active power capability at 90% connection point voltage is to change the tap position of the inverter transformers (MV/LV) so that the LV operating voltage is increased above nominal. Unfortunately, this solution also reduces the AC/DC margin, and increases the risk of CUO non-compliance for high inverter AC voltages and high temperatures, other factors being equal.

3) High operating voltages on the MV system without power system disturbances

Another way that designers have sought to mitigate the over-design of solar farms arising from the CUO requirement at 90% connection point voltage, is by increasing the MV operating AC voltage above nominal. This has only been an option where the connection point is on the HV side of a grid transformer, since the CUO requirement applies for *connection point* voltages in the COVB. This solution also increases the CUO non-compliance risk.

Depending on the design of the MV system, there may be other factors that cause elevated voltages to occur. For example, consider a HV connection point, with a transformer controlling the MV voltage, but with a wide deadband. The upper range of the deadband will give the highest voltage. Similarly, if the transformer does not have enough tap range to maintain nominal voltage on the collector system, for all connection point operating conditions in the COVB, then elevated MV conditions can occur under steady-state conditions.

If the design has an MV connection point, then the full range of COVB (90-110%) needs to be considered for compliance, regardless of the transformer arrangements. From a compliance perspective, having the connection point at MV level is advantageous for voltage drops, if the MV voltage is normally around nominal, as the solar farm rating for voltage dips only needs to consider a 10% drop. For voltage increases, this is a much more arduous condition under which to test compliance, as a change from normal operation to 110% is a voltage 10% rise. The voltage control strategy can also affect the voltages at the inverter terminals. This is discussed in the next section.

4) Power system disturbance elevates inverter voltage

The impact on inverter AC voltage from a power system disturbance that raises the connection point voltage is very design-dependent.

Consider the following case study, for a solar farm with voltage controlled on the 33kV with droop, and connection point on the HV side of the grid transformer. Statistical investigations using load flow and a DC design software, and historical meteorological data, found that:

- irradiance of around 750-800W/m^2
- high temperatures, and
- MV voltage step from the lowest voltage for full reactive power absorption to the highest voltage for full reactive power injection,

gave the worst-case change in active power. Figure 5 illustrates results from an electromagnetic study with irradiance of 750 W/m^2, and panel temperature of 60°C, equivalent of approximately 37°C ambient temperature, and worst-case voltage step. The resulting active power change was 3.7 MW for a solar farm of approximately 40 MW.

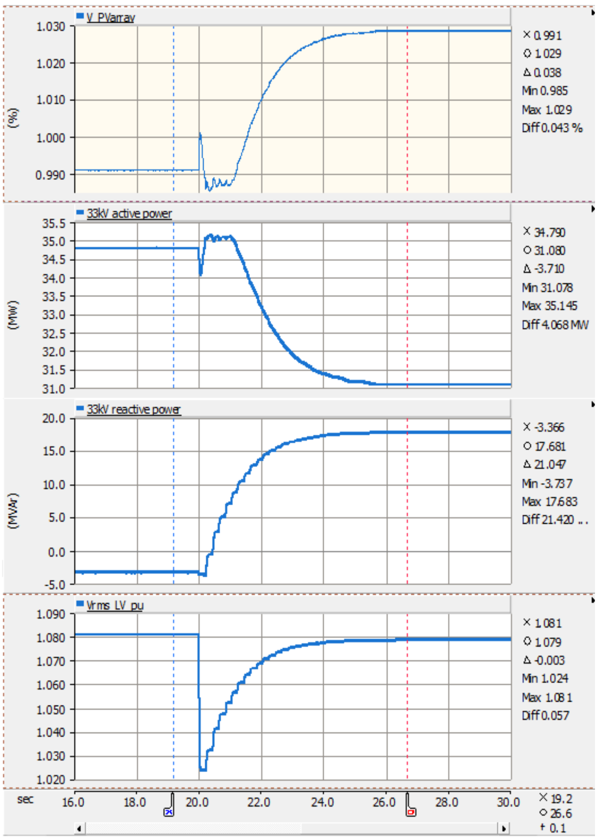

Figure 5 Illustration of active power change for a voltage step. From top to bottom, the graphs are Vdc, MV active power, MV reactive power and Inverter AC voltage

Investigations suggest that the active power changes for voltage steps that changes connection point voltage from 103% to 110% and 103% to 90% would produce smaller active power changes of around 0.3 MW.

For a solar farm with an HV connection, the difference between normal to 110% connection point voltage affects the voltage changes for which active power must be maintained. A solar farm that has a HV connection point operating at 101% of nominal would need to maintain constant active power for a 9% step up of voltage, and at 107% operation the voltage rise would only be 3%. These examples, along with the previous one, illustrate the site-specificity of the issue.

If the plant was in power factor (PF) control, instead of voltage control, the inverter voltage would be higher, and the effect of injecting reactive power (assuming lagging PF) would instead add to the effect from the voltage step. The risk of non-compliance according to the CUO requirement is higher in this operation mode. In the current NER, and in the proposed NER changes, PF is still a permitted mode of operation, at least for distribution-connected solar farms.

An extreme case occurs if the connection point is the MV side of the grid transformer, and the grid transformer is controlling the MV side. If the solar farm's PPC controls the HV side voltage (which the network service provider can and does request), one can envisage a 'quasi-steady state' situation in which full reactive power is required from the solar farm, while the MV side voltage is 110%. For example, consider a solar farm controlling the HV voltage to 105%, the usual operating voltage of this connection point. The power system voltage drops to 90% at the connection point, for long enough for the grid transformer to operate, and then restores to some intermediate position such as 95%. In this period the MV is at110% but the solar farm is injecting maximum reactive power, then slowly the transformer will adjust the MV voltage back to nominal. Our analysis so far suggests solar farm designers will struggle to achieve simultaneously the highest level of reactive power required under S5.2.5.1, in combination with high voltages and high temperatures, with zero change in active power for large voltage steps.

IV. A NOTE ABOUT THE MAGNITUDE OF CHANGES

Our investigations of AC-DC interactions as they relate to maintaining active power constant for CUO are ongoing. We have not yet come to an understanding of the magnitude of the problem. So far, we have investigated one solar farm, for which a change in active power of 2% or more could occur for about 6 hours in a year for an increased inverter voltage. At another site, with more extreme temperatures, the design leads to potential for much higher inverter ac voltages. This site would have more significant compliance issues.

V. CONCLUSIONS

In this paper we have investigated the interaction between the AC and DC sides of inverter operation, in the context of NER technical standards for reactive power and response to voltage disturbances. The paper has focused on a definition of continuous uninterrupted operation (CUO), and the interpretation that this clause requires active power to be maintained constant for changes in connection point voltage in the range of 90% to 110%. The CUO requirement forces inverter-based generation to constrain generation so that they can maintain active power for voltages at the connection point down to 90% of nominal.

This paper demonstrates that inverter AC-DC interactions at low DC voltage for high inverter AC voltages may make compliance with a strict interpretation of CUO extremely difficult. It will further require restrictions on solar farm design and increase the cost of meeting CUO. Many solar farms currently under construction could experience compliance issues with CUO during commissioning or over the life of the plant, because of these inverter AC-DC interactions. A key question is whether the materiality of the issue warrants such an impact on costs.

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