MODELLING SOLAR PARKS FOR HARMONIC STUDIES

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ABSTRACT

This paper explores whether multi MW solar parks can be represented by simplified models when carrying out harmonic analysis. Solar park inverters are typically represented in harmonic models by a fault equivalent choke impedance. However, this does not reflect the internal design of the inverter, which will typically contain an LCL filter. In this paper, solar inverter models are compared for varying capacities of solar park, from 1.6 MW up to 28.8 MW. The analysis also considers whether an equivalent model of the background network can be used and, if not, to what extent this network must be modelled. The results shows that for large solar parks, the fault equivalent choke model of the inverter will produce inadequate results if the strength of the background network is low.

INTRODUCTION

In recent years there has been a significant increase in the number of large PV installations built in the UK. Power electronic inverters are inherent in the design and connection of these generators. These can introduce harmonic currents into the network and cause power quality issues. If the harmonics introduced are above a certain limit, then the solar park will need to install mitigation devices to bring them within the limits. Correctly modelling a PV park during the design stage is crucial so that any such harmonic issues can be identified at an early stage. Accurate modelling of both the PV park and the surrounding network is vital to ensure reliable and practical harmonic study results.

The aim of this paper is to investigate whether large solar parks (up to 30MW) can be represented by simplified models with comparatively less detail and complexity. The paper will also determine the extent to which a distribution/transmission network surrounding the point of compliance[1] (PoC) should be modelled and if a simplified network model can be used instead. If simplified models can be used for both the network and the solar park, this can reduce modelling time and the amount of information required to produce the model. This will make the modelling task simpler without imposing any risk on the operation of the network.

If, however, simplified models cannot be used for large solar parks, it will be determined whether they can be used for small (< 5MW) and medium size solar parks (5 to 15MW).

The PV inverter's internal components (such as the choke and filters) are normally ignored during simulations. The paper also investigates the significance of modelling these components when the solar park is connected to a 33kV node. The aim of these simulations is to explore whether the impedance of the inverter, modelled at the LV side of the solar inverter, will have an impact on the impedance as measured at the PoC. Studies have been performed in which solar parks of different sizes, ranging from small capacity to large capacity, are modelled and the impact at the PoC is analysed. All studies are carried out using the IPSA+ power system analysis tool developed by TNEI Services Ltd.

Harmonic impedance scans (between the 2nd and 50th orders) have been performed at the solar park (SP) PoC for a range of network operating cases and different modelling scenarios.

SOLAR PARK AND THE NETWORK

Solar Park Layout

Four different capacities of solar parks were modelled in this study to cover the full range between a small to a relatively large solar park. Capacities of 1.6MW (small), 4.8MW (small to medium), 14.4MW (medium to large) and 28.8MW (large) were considered. Each solar park consisted of strings of solar panels connected to a 1.6MVA inverter (at 380V) which in turn is connected to a 0.38/33kV step-up transformer. The 33kV side of the transformers are connected radially by an array cable. The distance between each solar inverter transformer in the array was assumed to be 250m. The solar park substation was assumed to be 5km away from the PoC. Figure 1 illustrates the layout for a 4.8MW SP, with transformer and cable impedances indicated.

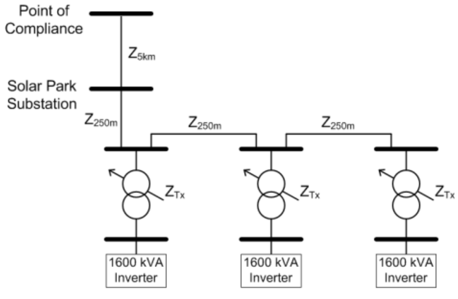

Figure 1: Configuration for a 4.8MW Solar Park

1 The point at which the solar park connects to the DNO network

A similar radial layout is assumed for a 14.4MW SP with 9 solar panels arranged radially and for a 28.8MW SP two arrays of 9 solar panels are used. In addition, a 1.6MW solar park, consisting of a single inverter, has also been investigated.

The inverter and the inverter transformer were assumed to be of the same rating, i.e. 1.6MVA, with an impedance of 7%. The 33kV array cables were sized to carry sufficient power to the solar park substations. A 5km 33kV 240mm^2 cable connected the solar park substation with the PoC. The lengths and the component ratings used in the model are typical for existing solar parks.

Inverter Representations and Solar Park Models

The solar panel inverter units can be represented and modelled as in Figure 2, where L_1 is inverter-side inductance, R_1 is L_1 parasitic resistance, L_2 is grid-side inductance, R_2 is L_2 parasitic resistance, C_F is the filter capacitance and L_G is the grid inductance [1]. In this study, R_1 and R_2 are assumed to be zero as these resistance values were not available.

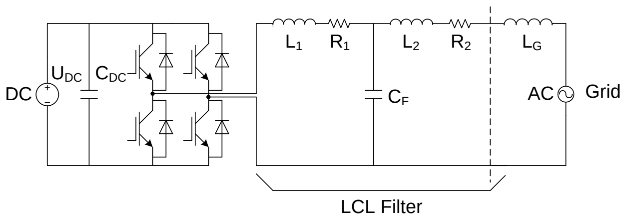

Figure 2: Single phase grid connected inverter with LCL filter [2]

The main aim of this analysis was to determine the importance of accurate LCL filter modelling. To do this, two sets of models were developed.

In the first set of models, the solar park inverters were modelled with a fault equivalent choke inductance at the 380V busbar. This is in contrast to the LCL filter representation shown in Figure 2. The impedance of this equivalent choke was set by the inverter fault current contribution, which in this case was assumed to be a typical current contribution of 1.06pu. This model was included to determine if an equivalent choke model of an inverter gives a sufficiently accurate representation of the inverter when LCL parameters are not available.

In the second set of models, the LCL filter inside the solar inverter was modelled in detail. Values for an LCL filter of a 1.6MVA inverter were provided by an inverter manufacturer, however, these cannot be published in this paper due to confidentiality issues. In the LCL filter, the reactance on the inverter-side is nearly three times greater than the reactance on the grid-side.

Furthermore, in both modelling scenarios (equivalent choke and LCL) the solar park is modelled as (1) a full model with each inverter represented explicitly, and (2) an equivalent model, with a single inverter model representing the series/parallel combination of multiple inverters.

Background Network Models

The solar park was assumed to be connected to a 33kV node in a Distribution Network Operator's (DNO) distribution network. A model of an existing distribution network was built for these simulations. The circuit parameters for this model were obtained from the relevant Long Term Development Statement (LTDS).

The DNO network was modelled to four different levels of complexity so that the impact of changing the accuracy of the DNO network model could be investigated. These four levels are as follows:

(1) Background network at the PoC modelled by a fault level equivalent generator, fault level as given in the LTDS;
(2) Network modelled up to 33kV, including 132kV/33kV transformers;
(3) Network modelled up to 132kV, including 400kV/132kV transformers;
(4) Network modelled up to 400kV (transmission level), with the model extended until the impact on the PoC impedance became negligible.

For all four DNO network models the slack busbar impedance was tuned so that the fault level at the PCC was kept the same.

For every solar park capacity (1.6MW, 4.8MW, 14.4MW and 28.8MW), each of the four solar park models was combined with each of the four DNO network models. In addition, the impedance of the background network in the absence of the solar park was also investigated. In summary, a total of 68 cases have been analysed, as described in Table 1:

- 4x Solar Park Capacities
- × 4x Background Network Models
- × 2x Inverter Models (equivalent choke/LCL)
- × 2x Representations (full/equivalent)
- + 4x Background Network Models with no solar park
- = 68 Cases.

In addition to studying the cases listed in Table 1, the impact of changing the LCL filter parameters in the absence of a background network was also explored.

The impact of the network and the solar park at the PCC is determined through impedance scans obtained for harmonic order from 1 to 50. The impedance scans were performed treating all loads as parallel R-X, treating all lines as $R(h) = R\times\sqrt{h}$, treating all transformers as constant X/R and treating all shunts as polynomial only [3,4].

Table 1: Cases Analysed

Background network/ solar park	With-out Solar park	1.6, 4.8, 14.4 and 28.8MW		1.6, 4.8, 14.4 and 28.8MW	
		SP with Equivalent Choke		SP with LCL filter	
Equivalent network	-	*Equivalent*	*Full*	*Equivalent*	*Full*
Model up to 33kV network	-	*Equivalent*	*Full*	*Equivalent*	*Full*
Model up to 132kV network	-	*Equivalent*	*Full*	*Equivalent*	*Full*
Model up to 400kV network	-	*Equivalent*	*Full*	*Equivalent*	*Full*

RESULTS

The results of the analysis have been separated into two subsections:

1. Analysis of solar park models in the absence of the background network. This determines the sensitivity of the results to variations in the LCL filter components' parameters;
2. Analysis of solar park models in the presence of a strong background network. This determines the significance to the results of the background network.

1: Impact of inverter LV impedance at PoC (self-impedance, no background network)

The sensitivity of the PoC impedance to the LCL filter components' parameters was tested by varying these parameters and performing impedance scans at the PoC. This was done with no background network present.

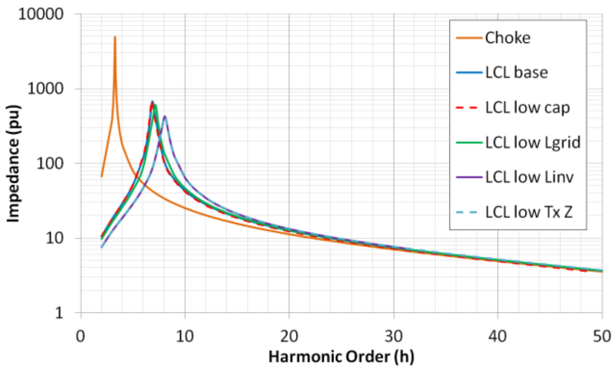

Figure 3: Impact of LCL filter components for a 4.8MW solar park at the PoC without the background network (logarithmic scale used to highlight the resonances)

Two different capacities of solar parks are investigated: 4.8 MW and 28.8 MW. The following sensitivity cases were explored:

(1) The capacitive reactance was reduced by 100 times (*LCL low cap*);
(2) The inductive reactance of the grid-side inductor was halved (*LCL low Lgrid*);
(3) The inductive reactance of the inverter-side inductor was halved (*LCL low Linv*);
(4) The reactance of the inverter transformer was reduced by 10 times (*LCL low Tx Z*).

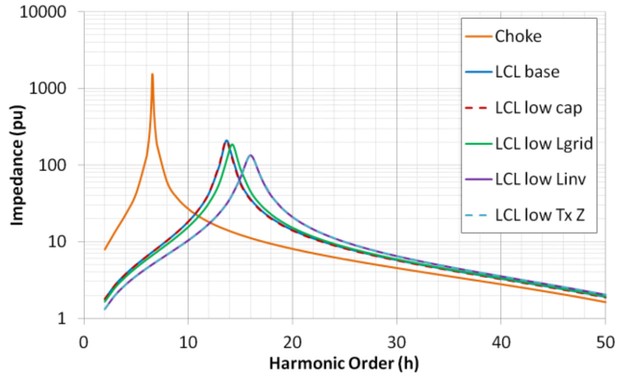

Figure 4: Impact of LCL filter components for a 28.8MW solar park at the PoC without the background network (logarithmic scale used to highlight the resonances)

Figure 3 shows that a change in the capacitive reactance of the LCL filter does not have a significant impact at the PoC between the 2nd and 50th harmonic order. This is because the capacitance is more likely to impact the impedance at higher frequencies. A reduction in the grid side reactance does not have a significant impact as the value is already quite small. However, a reduction in the inverter side reactance shifts the parallel resonance from 7th order to 8th order. Reducing the transformer impedance also shifts the parallel resonance to the 8th order. The biggest change was seen when the inverter impedance was modelled as the fault level equivalent, rather than the LCL filter. With the equivalent choke model, the resonance occurred at around 3rd rather than at the 7th order, with impedance that was approximately 7.3 times larger.

The effect of changing the LCL filter components was also determined for a large solar park capacity of 28.8 MW. These results are shown in Figure 4. The results are similar to those discussed above for a 28.8 MW solar park.

Therefore, it can be said that a change of impedance at the LV side of the inverter can be reflected at the PCC, if the background network is modelled as an open circuit. This suggests that in the absence of a strong grid, solar parks of small to large capacities should be modelled with detail LCL filters, rather than just representing them as an equivalent choke.

2: Impact of inverter LV terminal impedance at PoC (with background network)

For all the cases listed in Table 1, the impact of modelling the equivalent choke and the LCL filter when the solar park is connected to a strong background network is investigated by performing impedance scans at the PoC.

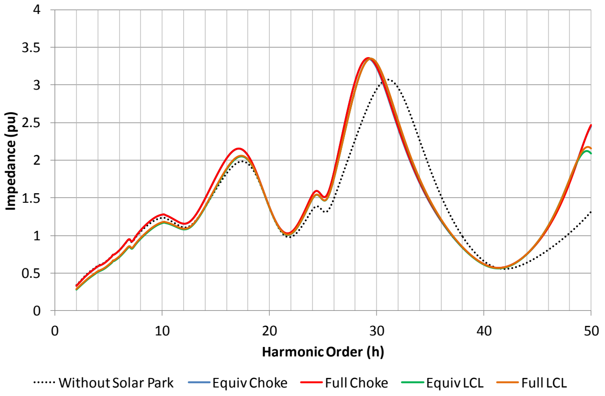

Figure 5: Impedance scan at the PoC when a 28.8MW Solar Park is modelled with a background network up to 400kV

Figure 5 shows that the connection of a large SP (28.8MW) at the PCC shifts the parallel resonances at 31st order to between 29th and 30th order. Overall, it can be seen that the addition of the solar park to the fully extended network has an impact on the impedance, even though the background network is very strong. The figure also shows that an equivalent solar park model provides a satisfactory representation of the detailed model i.e. each string can be represented by an aggregate equivalent.
Figure 5 also shows that the impedance scans are different when the equivalent choke model is used, as compared to the LCL filter, although the difference was not significant in this case study. This small difference is due to dominance of the background network strength at the PoC.

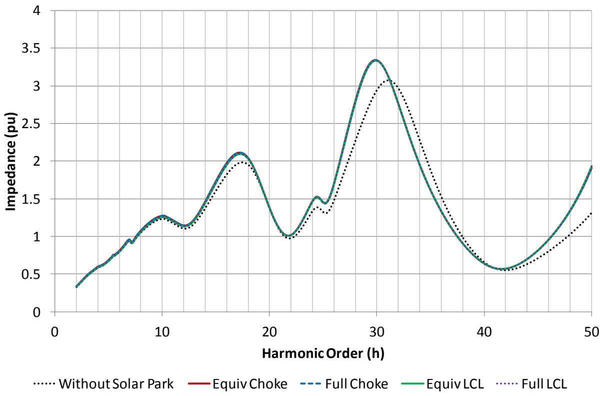

Figure 6: Impedance scan at the PoC when a 4.8MW Solar Park is modelled with a background network up to 400kV

The impedance scans with a small to medium size solar park (4.8MW) with full background network up to 400kV is shown in Figure 6. It can be seen from this figure that modelling the solar with an equivalent choke rather than a full LCL filter does not have a significant impact on the impedance scan at the PoC. Again, in this case the background network strength dominated at the PoC and the impact of modelling the solar inverters with either the equivalent choke or the LCL filter did not make any significant impact.

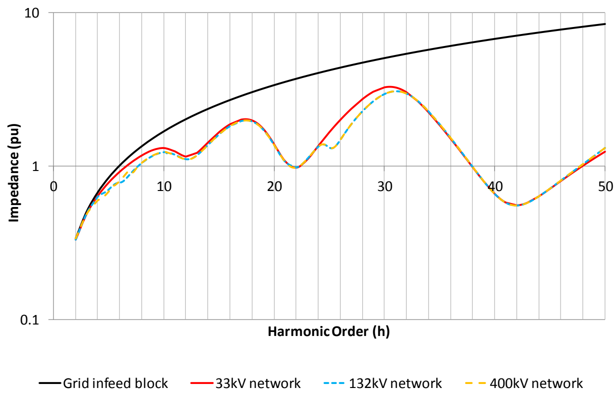

Figure 7: Impedance Scans at the PoC without the solar park modelled for background network modelled up to 33kV, 132kV and 400kV and by an equivalent grid infeed (y-axis on logarithmic scale to clearly show the resonances)

Figure 7 shows that there is a significant difference in impedance scans when modelling the background network through a grid infeed block, as compared to a detail model with all components in, which is justified since the grid infeed does not take into account the impact of reactive power devices, lines, transformers and reactive power devices on the impedance at different frequencies.
Figure 7 also shows that, for this case study, modelling the network up to 132kV refines impedance scans as compared to when modelled up to 33kV. In other words, the impact of the 132kV network components is observed at the 33kV PoC. However, there is no discernible difference when the network is extended to 400kV. This is because the 132/400kV transformers have very high impedance. Therefore, the network should only be extended until there is no further impact on the impedance scans at the PoC. These results suggest that if high accuracy is desired, then the network should be modelled in detail at the PoC voltage level, and one voltage level above. If less accurate results are required, it may be sufficient to model the network at the PoC voltage level only.

CONCLUSIONS

The following conclusions can be drawn from the results presented here:

- If no background network is modelled, or if the background network is not strong (low impedance), then the fault equivalent impedance model results in an inadequate representation at the PoC of the solar park inverters. Therefore, the full LCL model should be used in cases where the grid fault level is low.
- When the solar park is connected to a strong background network, the impact of the inverter LV side impedance at the PoC was negligible for a solar park of 4.8 MW. A noticeable difference was observed when a large solar park of 28.8 MW was modelled. This suggests that use of the LCL filter model will not be necessary for small solar parks with small numbers of inverters.
- The level of detail to which the surrounding background network impedance is represented can influence the harmonic impedance scans at the PoC. The network should be 'grown', upstream and downstream, until adding further network components do not change the impedance scans at the PoC. In most cases, a fault level equivalent grid infeed block is not an adequate representation of the background network, as most series and parallel resonances seen on the background network are not observed with the equivalent grid infeed. In addition the equivalent resistive 'damping' provided by the background network is underestimated.

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