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Grid Code Compliance for Integrating 50 MW Wind Farm into Dhofar Power Grid

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Abstract: *This paper addresses the impact of the first 50 MW wind farm project on the Dhofar network. The wind farm consists of 20×2.5 MW wind turbines and will be integrated into the 132 kV Dhofar network which is connected with the Maim Interconnected System through the Petroleum Oman Development grid. A model of the entire power system of Oman is developed for steady-state and dynamic studies using DIgSILENT software. Two types of generators are considered: doubly-fed induction generator and asynchronous generator with fully rated converter technology. Simulation results are presented including load flow, short-circuit, contingency and stability analyses. No adverse effects ware identified due to the wind farm connection to the Dhofar network. The currently applicable Grid Codes in most Gulf Cooperation Council (GCC) countries are focused on the connection of conventional synchronous generators but recently increasing number of non-synchronous renewable generators are being commissioned in the region. The results of this analysis can provide a basis in the future for updating existing OETC Grid Code elements and for assessing future non-synchronous connections.*

Key Words: Grid Code, Wind Farm, Oman Grid.

1. Introduction

The connection of potential renewable technologies to the power system grid in the Gulf countries is one of the most energy efficient ways of meeting future climate change targets and moving towards a sustainable future [1]. The majority of the Transmission System Operators (TSO's) in the region are currently reliant on conventional oil and gas plants for meeting their energy demands. The majority of these plants are located far from the main demand centres with growing concerns over the security of supply and the amount of fuel reserves found in the region [1, 2]. The potential of connecting renewable generation in this region is large, however the technical requirements for connecting asynchronous plants to the regional power systems have yet to be fully established in the region. Oman Electricity Transmission Company (OETC) has committed to connect a number of pilot plant renewable schemes to the main interconnected system as well as Dhofar in Oman. To date the OETC Grid Code provides a technical guidance on the connection of conventional synchronous plants, however with the introduction of non-synchronous plants, the Grid Code has to be revised to cater for the connection of non-synchronous plants i.e. solar PV plants and wind turbine. In cooperation with a number of international consultants the requirements for integrating renewable technologies to the grid has been addressed in the technical requirements defined in the Connection Conditions of Schedule 2 Draft 5 entitled "Technical Criteria for Wind Farm Power Stations Connected to the Transmission System" [3]. This will be eventually integrated into the OETC Grid Code to cater for any new future renewable projects. The aim of this paper is to assess the potential Grid Code requirements and compliancy of the first 50 MW Dhofar wind farm on the OETC Dhofar network via the technical requirements defined in the Connection Conditions of Schedule 2 draft 5. The requirements include technical elements in the form of power factor / reactive control requirements, fault ride through, power-frequency control and power quality requirements (Voltage unbalance, flicker and harmonics). The majority of these technical elements are necessary for the connection of renewable generation due to the technologies deployed being non-synchronous plants. All system studies of the paper were performed by using the DIgSILENT professional software version 15.2.

The paper is structured in the following sections: Section 2 provides a detailed overview of the Dhofar 50 MW wind farm and the basic requirements for meeting compliancy under the Connection Condition of Schedule 2, and control structure. Section 3 presents the results of power factor/reactive power/voltage control at the Point of Common Connection (POC). Section 4 describes the fault ride through performance of the wind farm while Section 5 describes the power-frequency control performance of the wind farm. Section 6 presents a high-level overview of the power quality requirements. Section 7 summarizes the main conclusions.

2. Technical Requirements and Wind Farm Layout

The Dhofar wind farm consists of 20 x 2.5 MW wind turbines consisting in total of three arrays. Each wind turbine has a 33/0.69 kV transformer which feeds the power into the 33kV wind farm cable network. The total power of the wind park is then collected at the 33kV collector substation, which then exports the power to the 132 kV network in Dhofar via a 132/33kV transformer. For all intents and purposes the point of connection is at the 132 kV busbar within the wind farm substation. For the Grid Code compliance study, an AVR has been considered on the 132/33 kV transformer and a station controller have been defined as shown in Figure 1. The AVR of the 132/33 kV OLTC transformer (tap range -19/+1) is used to control the 33 kV collector bus bar. The 33/0.69 kV transformers of the wind turbine (tap range -2/+2) have been considered as not equipped with AVR and on fixed position for the study. The station controller controls the reactive power outputs of the wind farms. It is set to control either: the power factor, reactive power or voltage at the point of common coupling. Each of the three control modes can be selected.

Two different technologies have been deployed for assessment; these are the Double Fed Induction Generator (DFIG) and Full Rated Converter (FRC) wind turbines. The requirements of the Connection Conditions of Schedule 2 Draft 5 for power factor/reactive power/voltage control are shown in the Figure 2 and Figure 3. The dotted line indicates a constant power factor of 0.95 lead and lag during the entire MW output of the wind farm (Points A-D-E). Thus for example at rated power output; the corresponding reactive power output (Q/Pmax) will be + 0.33 lag and - 0.33 lead (This corresponds to 50 MW with ± 16.5 MVAr range) which indicates a 0.95 lead/lag requirement. For reactive power control (Points A-B-C-D-E), the requirement is that of a constant MVAr output (Q/P_{max}) of - 0.33 lead and + 0.33 lag, which corresponds to ± 16.5 MVAr over the operating range of P_{max} to 0.2 P_{max}. Any MW output below 0.2 P_{max} is subject to a ± 0.606 gradient.

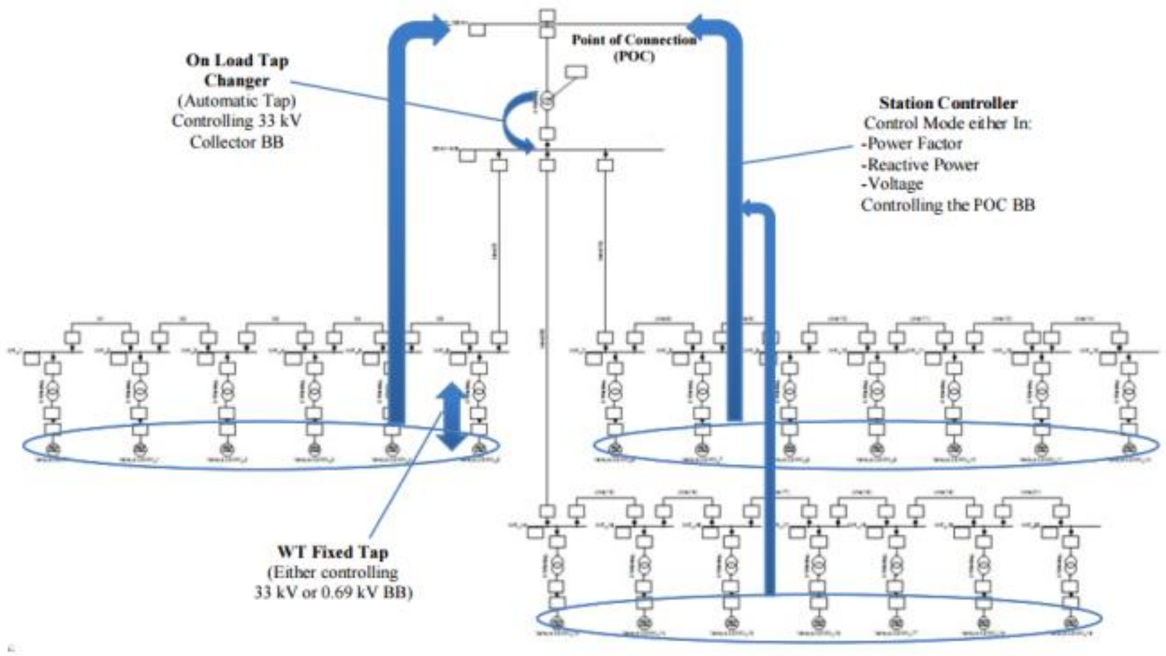

Figure 1: Dhofar Wind Farm Layout.

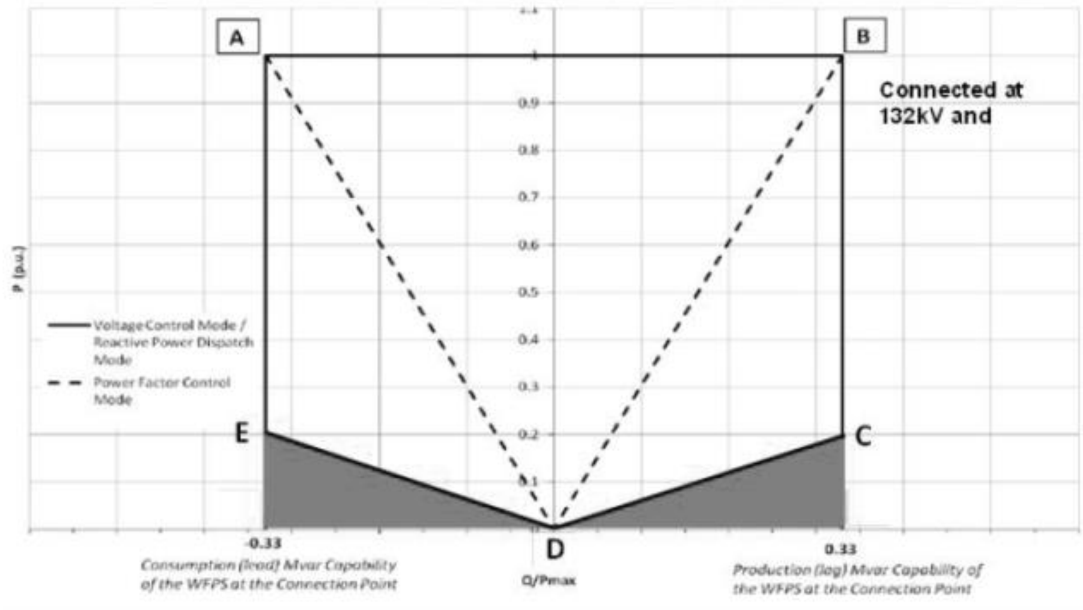

Figure 2: Power Factor Requirements at POC

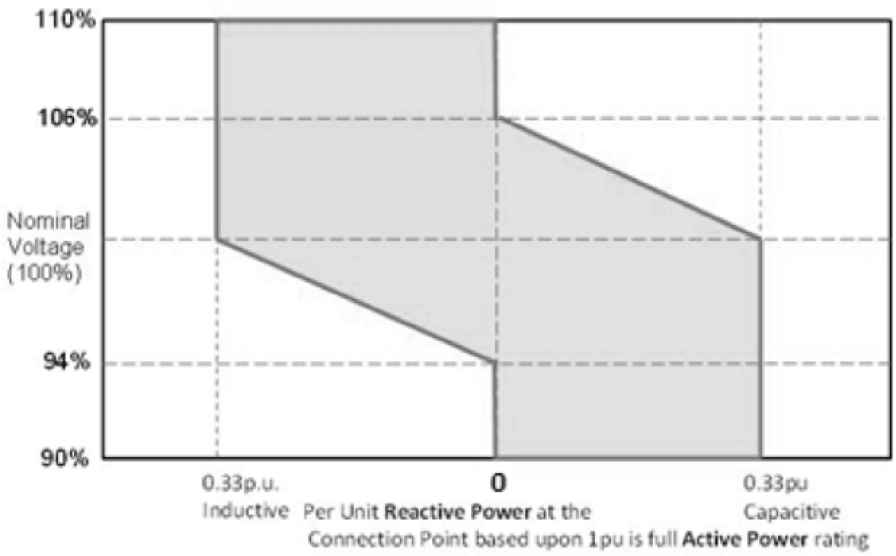

Figure 3: Reactive Power/Voltage Requirements at POC

The wind farm must be capable of providing its full reactive range for lead and lag over a voltage range of 0.9 to 1.1 pu, as shown in Figure 3. If the voltage is in the range of 0.94 to 1 pu, it must be capable of providing up to its (Q / P_{max}) limit of + 0.33 lag, but being able to control its leading capability from 0 to - 0.33 pu lead. Below a system voltage of 0.94 pu, it will only require to provide its maximum (Q / P_{max}) lag limit. If the system voltage is between the range of 1 to 1.06 pu, it must be capable of providing up to its (Q / P_{max}) limit of -0.33 lead, but being able to control is leading capability from 0 to + 0.33 pu lag. If the system voltage of is above 1.06 pu, it will only require to provide its maximum (Q / Pmax) lead limit.

For the ***Fault Ride Through*** requirements: the fault will be at the POC using a three phase to ground fault lasting for 500 ms, where the voltage recovery must reach 90% of its nominal voltage within 3 seconds and remain connected. Figure 4 shows the requirements of the fault ride through at the POC.

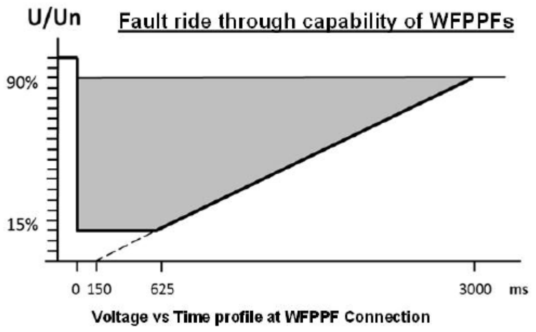

Figure 4: Fault ride through requirements at POC

Under Power-Frequency requirements; the wind farm as a whole must meet the primary frequency response. The Connection Condition Schedule 2 Draft 5 stipulates that the wind farm must provide primary response (available in 5 seconds and sustained for 30 seconds): 60% of its expected MW output based upon droop characteristics. Thus when acting to control transmission system frequency, the wind farm shall provide at least 60% of its expected additional active power response within 5 seconds, and sustained for 30 seconds from the start of the transmission system frequency excursion outside the range of nominal frequency [3].

The final technical requirements for power quality analysis are based on the OETC Grid Code [4], as summarized in Table (1).

Table (1): Power Quality Limits

Power Quality Aspect	Limits
Voltage Unbalance	1% (max 2% under abnormal conditions)
Flicker	0.8 (Short Term) 0.6 (long Term)
Harmonics	THD 2% (No individual harmonic greater than 1.5%)

3. Power Factor and Reactive/Voltage Control

The purpose of the power factor control mode is to assess the steady state power factor capability of the Dhofar Wind Farm connection; as stipulated by the Connection Condition Schedule 2 Draft 5 [3]. This will be assessed for the voltage range of 1, 1.1 and 0.9 pu respectively. Under power factor control mode, the wind turbines were dispatched via the station controller under 100%, 80%, 60%, 40%, 20% and 0% of active power dispatch over three system voltages of 1.1, 1 and 0.9 pu. This will assess whether the wind farm is capable of reaching 0.95 lead/lag over these conditions at the point of connection.

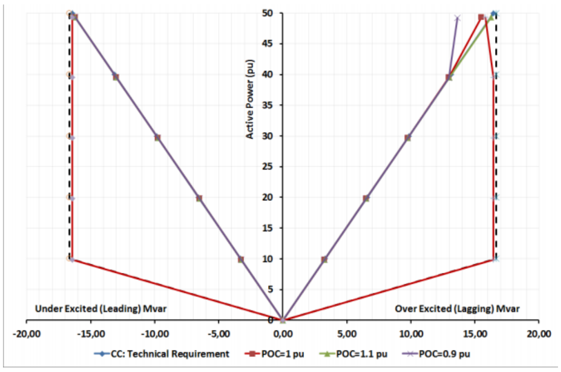

Figure 5: Power Factor capability at the POC

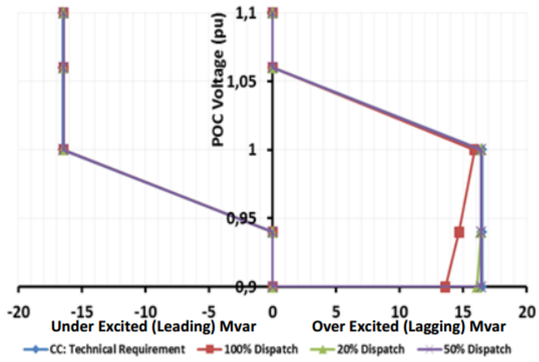

Figure 6: Reactive/Voltage capability at the POC

The results from the series of load flow simulations are shown graphically in Figure 5. It can be easily seen that the wind farm can meet the 0.95 lead/lag capability for dispatches below <100% over the voltage range of 1.1 to 0.9 pu. However at full dispatch the maximum lagging reactive power achieved is 13.7 MVAr, even though each wind turbine is producing its full MVAr output of 1.2 MVAr. This is predominantly due to the losses in the wind farm's LV network. This is evident under a point of connection voltage of 0.9 pu. Thus as a minimum a mechanically switched capacitor (MSC) of around 3-4 MVAr is required.

A similar result to that of the power factor mode is presented in Figure 6, where a maximum MVAr output of 13.6 is achieved at the POC even though the wind turbines are at full reactive capability.

4. Fault Ride Through

In order to evaluate the full effect of the fault ride through performance as specified in the technical requirements for the Connection Conditions of Schedule 2 Draft 5 "Technical Criteria for Wind Farm Power Stations connected to the Transmission System" [3]. Voltage performance was controlled in such a way (at POC), that it follows exactly the requirement as shown in Fig 7.

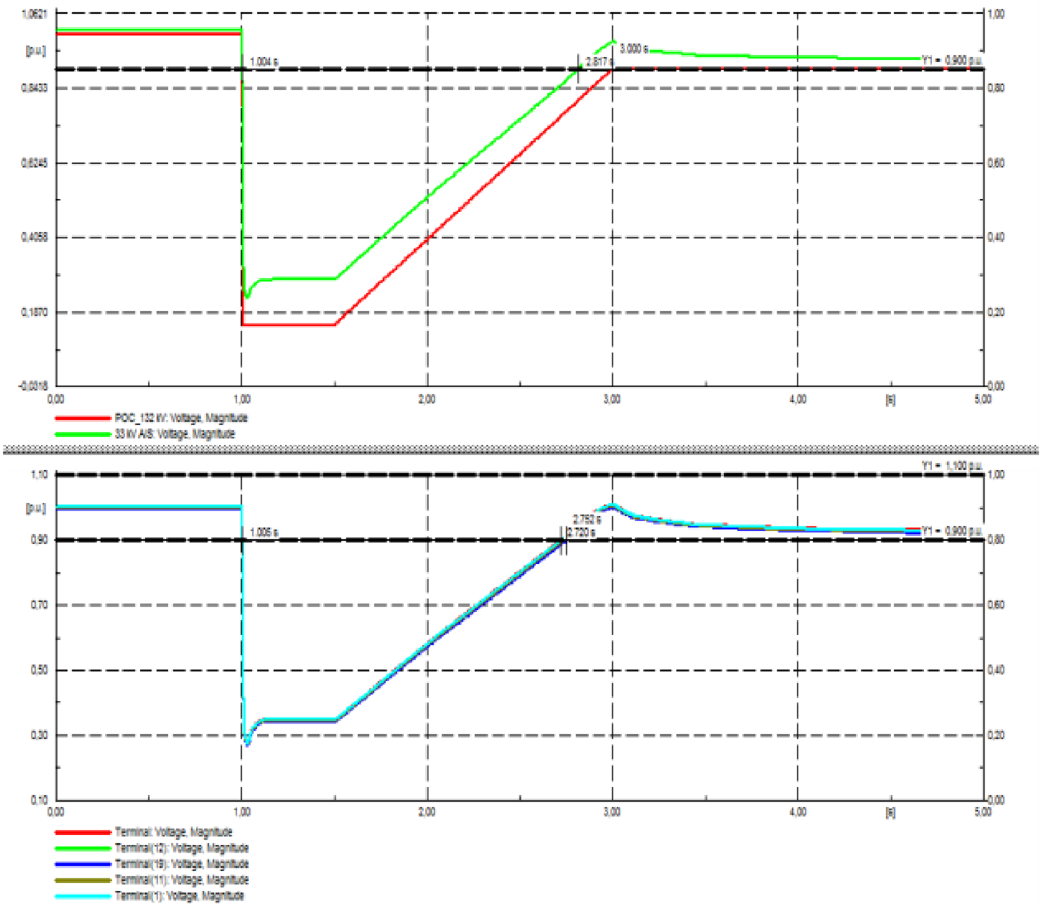

Figure 7: Fault Ride Through capability at the POC

It can be seen that in both cases all wind turbines remain connected even if the voltage at the point of connection responds to the voltage profile of the connection condition. This was carried out for different grid strengths and all gave rise to similar results. This suggests that both wind farm technologies (via their specified control system) are compliant against the technical criteria for fault ride through.

5. Power Frequency Control

Primary response analysis was carried out against the equivalent grid and the Dhofar network model. Under the Dhofar network model, every generator on the system will respond to a step response to both voltage and frequency: based upon their control characteristics. Thus an equivalent model ensures that the wind farm is tested to its full capability under a frequency deviation. The results of the DFIG & FRC models are shown in Figure 8 and Figure 9 to a frequency step change using the equivalent grid.

Both wind farm technologies are capable of meeting the technical connection requirement of Connection Condition Schedule 2 Draft 5 [3]. The 60% power reduction/increase based on the droop setting is 19.5 MW and 9 MW respectively. This is based on the assumption that there is sufficient wind speed for this operation. Both technologies technically meet the requirements within 5 seconds and it is sustained for 30 seconds.

It should be noted that the FRC meets the response faster due to the control system being deployed, while the DFIG has a slower response to reach its default full MW output steady state value. This is predominately due the control system deployed, its response and ramp rates being used, but in theory can be set to meet a faster steady state value.

The Dhofar network model was used to study the wind farm response with other generators on the system. The loss of approximately 30 MW was considered sufficient for demand disconnection during the winter period, while the largest unit loss was considered adequate for generation loss.

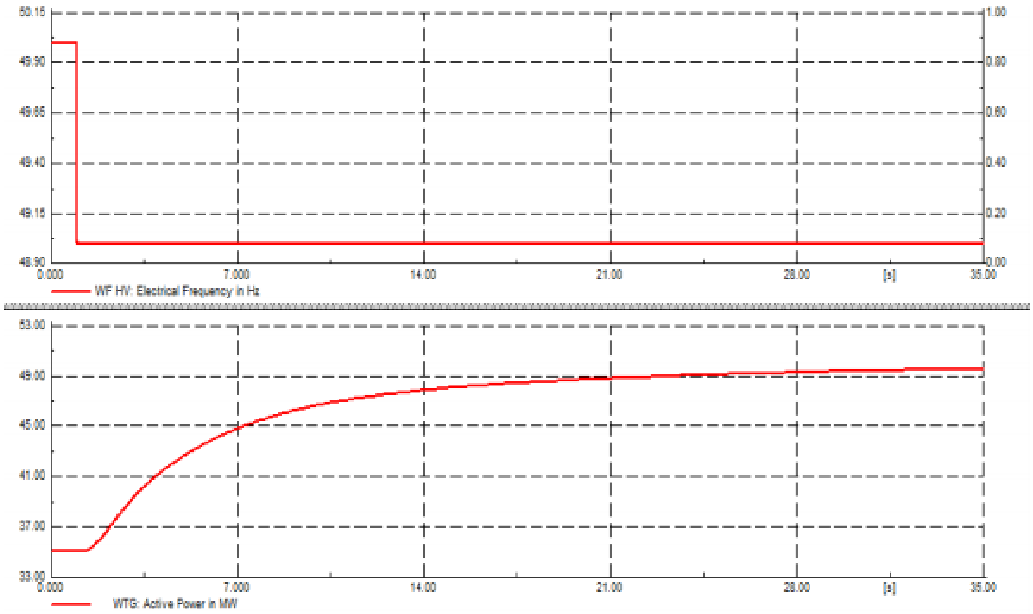

Figure 8: DFIG Primary Frequency (Under frequency) capability at the POC

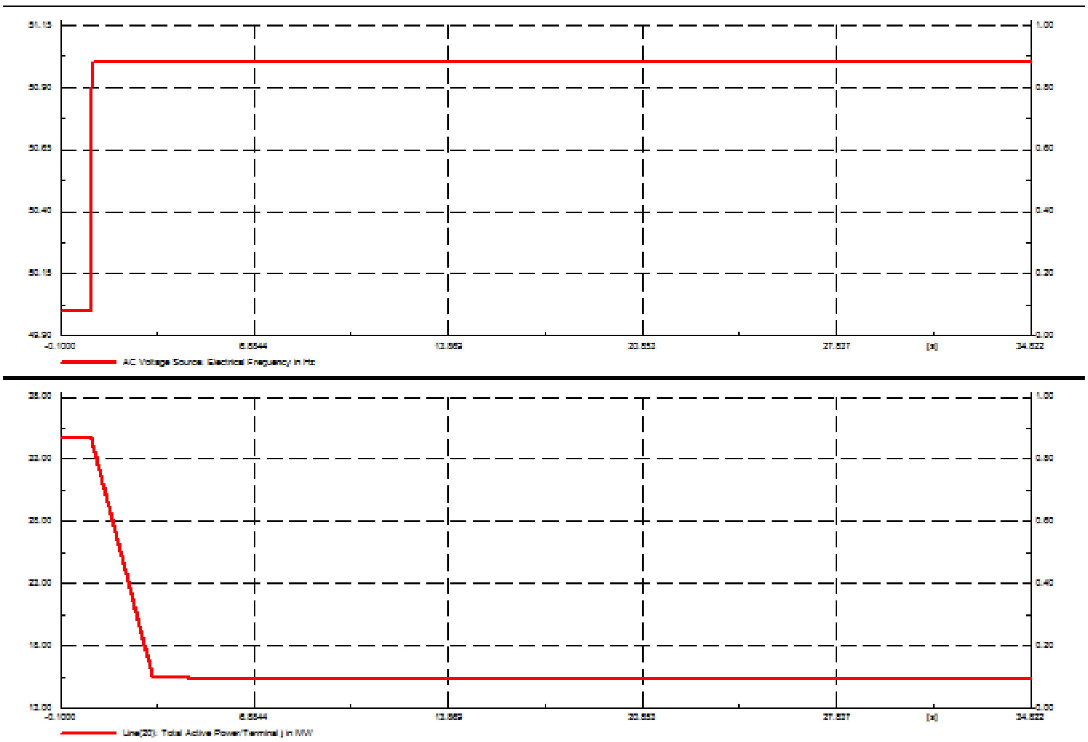

Figure 9: FRC Primary Frequency (Over frequency) capability at the POC

The results for the loss of generation and demand are studied. Figure 10 shows the system response to a loss in demand. The top graph shows the system frequency, the middle shows the active power of the wind farm and the bottom graph shows the response of the other generators in the Dhofar network. Similar responses were recognised by both wind farm technologies (DFIG and FRC). From the results it can be seen that the wind farm responds well to the Dhofar network model accompanied by other generators.

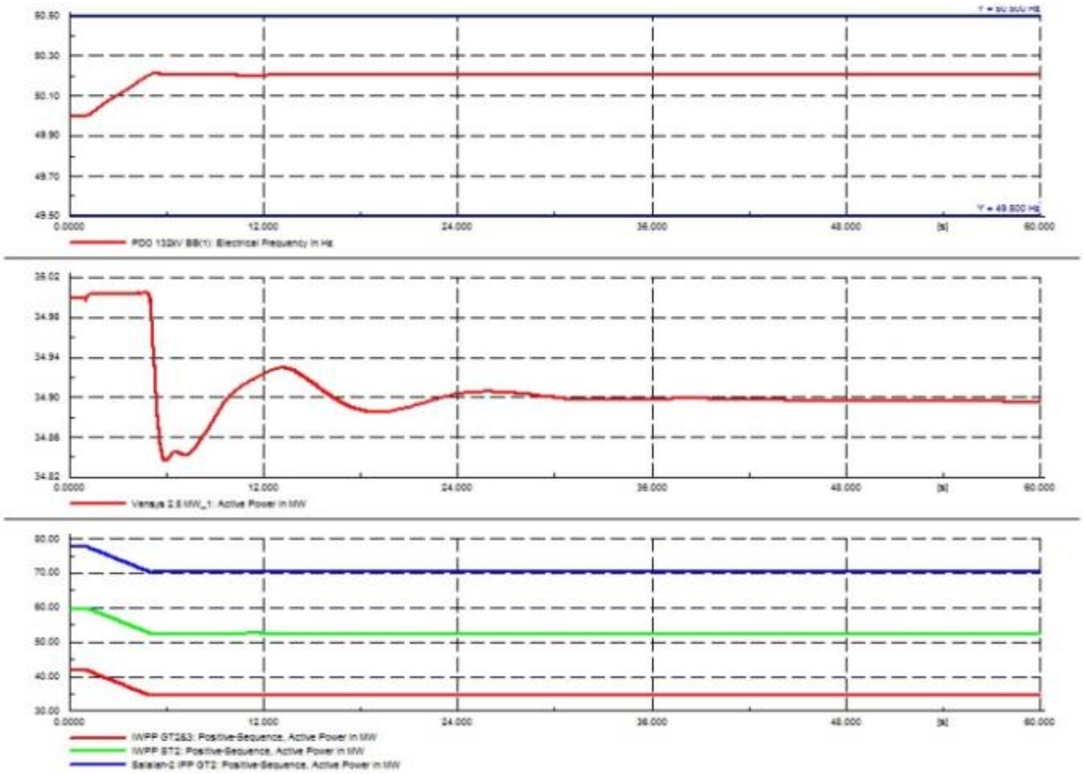

Figure 10: Primary Frequency (Under frequency) capability with respect to the Dhofar network

6. Power Quality Assessment

The following studies are required for power quality assessment in accordance to the OETC Grid Code [4]:

(a) Voltage Unbalance (Negative Phase Sequence): This is a measure of unbalance on the OETC network based on unbalanced loads and tower asymmetry.
(b) Flicker: A measure of visible change in brightness of a lamp due to rapid fluctuations in the voltage of the power supply.
(c) Impedance Frequency Scan and Harmonics: A measure of possible series and parallel resonances which can occur within the network, which can lead to the voltage and current waveform distortion.

A high level group of studies were conducted to obtain a view on the possible issues for the Dhofar wind farm connection prior to the detailed design stage.

Modelling Requirements:
A generic 132 kV tower has been used to improve the accuracy of the power system model for the power quality assessment. This enables the lumped overhead line parameters to be converted to an Impedance matrix based on phases, height and tower type. The modelling is essential for all the studies listed, to capture the level of asymmetry found in overhead lines. The tower dimensions are shown in Figure 11, and have been applied to all overhead lines in the Dhofar region.

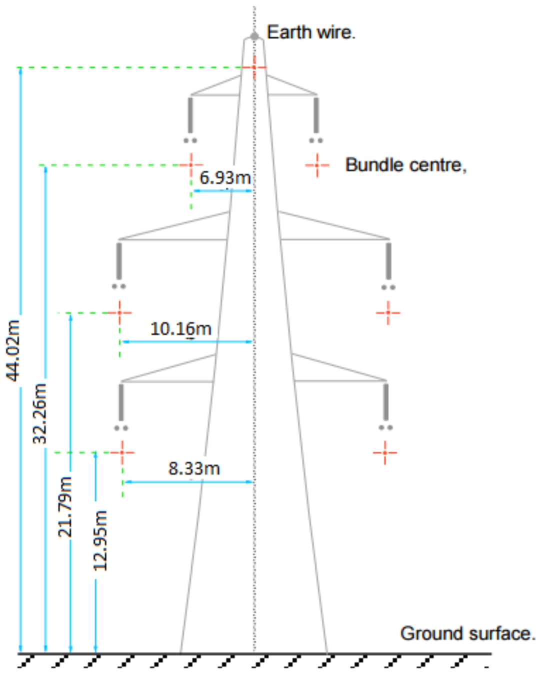

Figure 11: Generic 132 kV Tower dimension

DIgSILENT software is used to calculate the natural impedance matrix in ohm/km leading for a double circuit three phase line construction with a one earth wire [6]. Twin YEW 400 mm^2 conductor 132 kV line, has the following characteristics and has been used as reference. The sequence phasors (PPS-Positive phase sequence, NPS-Negative phase sequence and ZPS-Zero phase sequence) per circuit per tower can be determined as:

$$\begin{bmatrix} V_{1\,PPS} \\ V_{1\,NPS} \\ V_{1\,ZPS} \\ V_{2\,PPS} \\ V_{2\,NPS} \\ V_{2\,ZPS} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} & Z_{15} & Z_{16} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} & Z_{25} & Z_{26} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} & Z_{35} & Z_{36} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} & Z_{45} & Z_{46} \\ Z_{51} & Z_{52} & Z_{53} & Z_{54} & Z_{55} & Z_{56} \\ Z_{61} & Z_{62} & Z_{63} & Z_{64} & Z_{65} & Z_{66} \end{bmatrix} \begin{bmatrix} I_{1\,PPS} \\ I_{1\,NPS} \\ I_{1\,ZPS} \\ I_{2\,PPS} \\ I_{2\,NPS} \\ I_{2\,ZPS} \end{bmatrix}$$

V, Z, I are the voltage, impedance and current phasors, while the numerical subscripts relates the self and mutual impedance between each phase of each circuit.

The complete overhead line model is based upon a frequency dependant distributed model, as this gives rise to the highest accuracy for the impedance matrix which is ideal for all studies listed [6]. The frequency dependant model is based on the Bergeron´s method in where the characteristic impedance and propagation constant has to be determined.

A simple harmonic load model shown in Figure 12 is applied to all loads within the Dhofar region which in essence captures an element of the series and parallel resonances within the network [7, 8]. At each substation the harmonic load model consists of a step-down transformer-usually to 11 kV, cables and OHL coupled with a shunt capacitor. At the LV bus a lumped equivalent of the downstream system has been inserted.

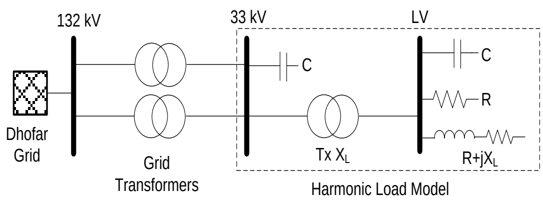

Figure 11- Harmonic Load Modelling

The equivalent model consists of:

(a) Harmonic Capacitance: This represents the total capacitance of the DNO's circuits.
(b) Harmonic Inductance: This represents the impedance of the DNO's transformers to 400V.
(c) Power Factor Correction: This is the total power factor correction of the demand and of the low voltage network.
(d) Resistive MW is the total amount of resistive damping applicable at harmonic frequencies.

Voltage Unbalance: Figure 12 shows the negative phase sequence voltages calculated for an intact network, under a planned outage condition with and without Dhofar wind farm at maximum conditions. It can be seen that under all conditions specified that under a planned outage, the level of voltage unbalance increases for all sites from its intact pre-fault values. The SFZ substation tends to have the highest reading, predominately due to high power flows as well as being the connection point of Octal Petrochemicals. However in all conditions the level of voltage unbalance is below 1%, making it compliant against the Grid Code. The worst condition for the Dhofar WF Substation is when the PDO interconnector is out of service, as this leads to a 0.25% increase in NPS voltage at Dhofar WF Substation.

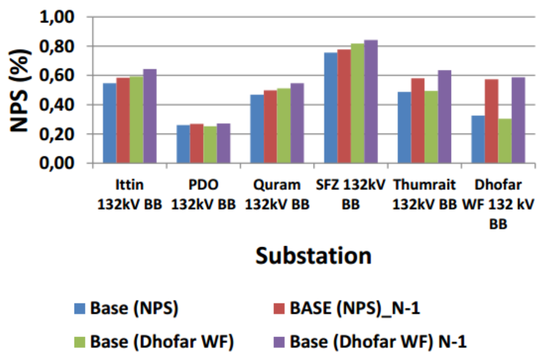

Figure 12- Voltage Unbalance Results

Flicker:

A flicker study was conducted for the wind farm. The purpose of this study is to ensure that the wind farm it is compliant with IEC 61400-21 Standard [5]. To calculate the flicker levels at Dhofar 132 kV and at the 33 kV collector substation transfer gains were used based on the 33 kV collector substations. The study was based on the minimum fault level at these sites as this leads to maximum flicker level which could be possibly encountered. The X/R ratio at the 33 kV collector site was in the region of 9 to 12 for off-peak and peak respectively. This leads to a network impedance phase of 79 degrees; thus the standard value of 85 degrees has been used as in accordance to the IEC Standard. Generic wind farm compliance test data were used to obtain an appreciation of the flicker emissions. The results are presented in Table (2). The flicker study demonstrated that Dhofar 132 kV would be within limits set out in IEC 61400-21Standard [5].

Table (2): Flicker Severity Results.

Flicker	C(ΨK,va)	Wind Farm	IEC Limit	Compliant
Pst: 33kV	1.11	0.085	0.6/0.8	YES
Pst: 132kV	1.11	0.1087	0.6/0.8	YES

Impedance Scan and Harmonics:

The first step in conducting a harmonics study is to conduct a frequency scan for the point of connection over a range of frequencies in the Dhofar region. This is referred to as the self-impedance and it has the advantage that it can calculate the impedance at any number of given frequencies, including 50 Hz. This is then repeated with all mutually coupled impedances (known as the transfer impedance). The transfer impedance is the voltage at a point in the network induced by current injected at a remote point, with no other sources present. This has been done for maximum (peak) as well as the winter (off-peak) backgrounds as well as a number of network configurations under N-1 conditions.

It can be easily seen that a number of series and parallel resonances occurs. Once the self and transfer impedances are determined the transfer gain can be determined.

It can be easily seen that number of series and parallel resonance occurs. Once the self and transfer impedances are determined the transfer gain can be determined. This transfer gain exists as a function of frequency and can be calculated for any number of harmonic orders/frequencies. A transfer gain is the ratio of transfer impedance to self-impedance. Thus the transfer gain in our case is the ratio of the harmonic voltage distortion at the point of common coupling to the harmonic voltage distortion causes at a remote node. This is then used to calculate the voltage (%) distortion at each harmonic level. The results for the FRC are shown below based on standard harmonic injections for this type of technology.

Figure 14 shows the Voltage Harmonic distortion due to the FRC wind farm throughout the Dhofar network. The FRC is based on VSC HVDC technology in where the rotor is directly connected to the converter. This in essence lowers the number of harmonics produced. It can be seen that this type of wind farm has high harmonic voltage distortion at the 5th, 7th, 11th and 23rd harmonic frequency.

7. Conclusion

The paper has presented Grid Code compliance studies of the first Dhofar 50 MW wind farm in accordance to the technical requirements of the Connection Condition Schedule 2 Draft 5 as well as the OETC Grid Code. The results have shown that about 4 MVAr capacitor should be installed at the 33kV collector to meet the 0.95 lead/lag capability at the POC at full export conditions. Both wind farm technologies (DFIG and FRC) were found to be capable of meeting the primary frequency response requirements as well as the fault ride through requirements based on the dynamic models used. Power quality analyses have shown that both voltage unbalance and flicker are compliant at peak conditions whilst the 5th, 7th, 11th and 23rd harmonic frequency are being predominate for FRC.

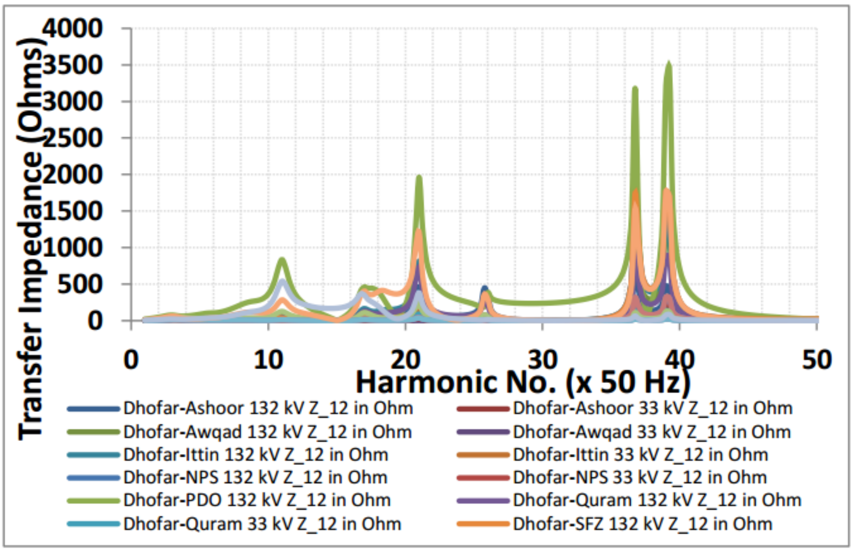

Figure 13: Transfer Impedance Results

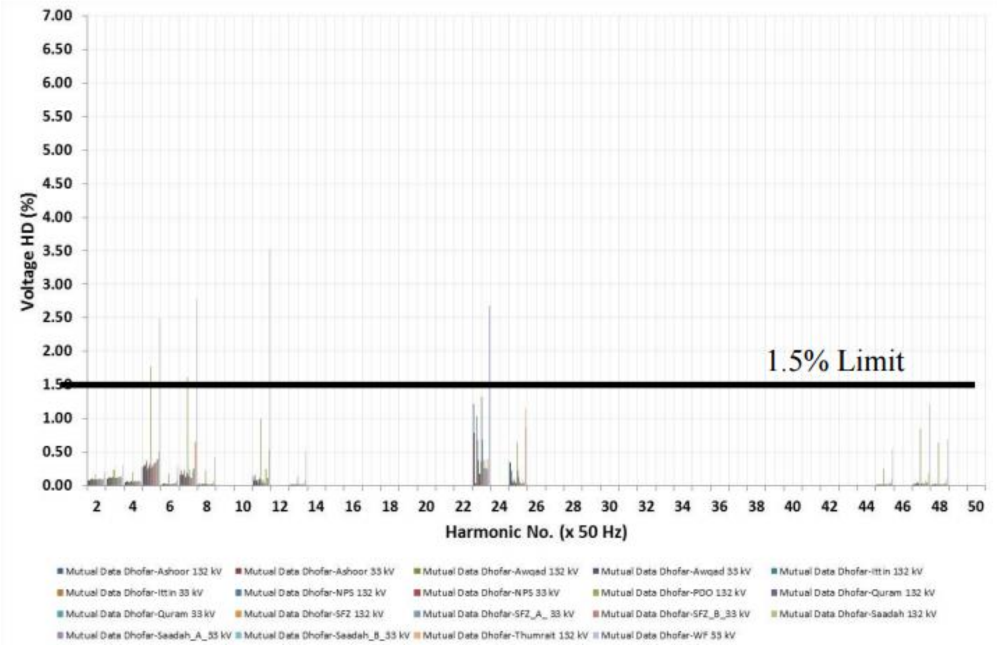

Figure 14: Voltage Harmonic Distortion Results

8. Acknowledgement

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