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Power Quality of Dhofar Network with 50 MW Wind Farm Connection

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***Abstract*—This paper investigates factors which influence the power quality performance of the Dhofar Power Grid, based upon the first 50MW wind farm project connection. The wind farm consists of 20×2.5 MW wind turbines and will be integrated into the 132kV Dhofar network which is connected with the Maim Interconnected System via the Petroleum Development of Oman grid. As this is the first wind farm project in Oman, a review of fundamental aspects which influence power quality for connecting the wind farm is presented, as well as an initial view on Grid Code performance. The power quality assessment is required as part of the license obligation for a transmission operator and is vital to a wind farm developer for their filter design and compensation sizing. The paper addresses power quality topics such as voltage unbalance, flicker and harmonic compliance, in relation to network changes and potential future non synchronous connections. Simulation studies are carried out in DIgSILENT software and are presented in the paper.**

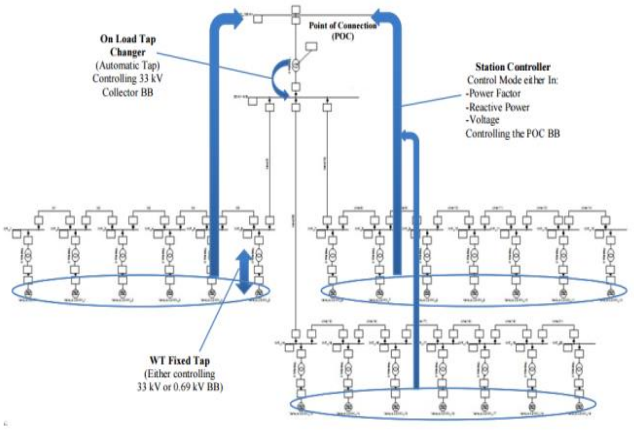
***Keywords*—Power Quality, Grid Code, Wind Farm, Oman Grid.**

I. INTRODUCTION

Many of the Gulf Cooperation Council (GCC) countries are realizing the benefit that renewable technologies can bring to their own grids with respect to sustainability, availability and cost [1]. The connection of wind farms has also been noted to increase the overall installed generation that a country has, i.e. plant margin, and power availability. The overall impact would improve security and lowers the cost of the energy supplied to consumer. Many of the GCC countries are embarking on strategies such that large volumes of renewable plant (ranging from solar to wind) can be connected in the next 10-15 years. 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 renewable schemes to the Main Interconnected System (MIS) as well as Dhofar system [2]. This presents new challenges to Transmission System Operators (TSO's) in controlling the levels of voltage unbalance, flicker and harmonic voltage distortion; not just at the Point of Common Coupling (PCC) but at sites located further away within the transmission and distribution systems. In cooperation with a number of international consultants the requirements for integrating renewable technologies to the OETC 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]. As the region is relatively new to this type of intermittent power generation and network phenomena, the paper addresses important aspects of transmission planning and connection design with respect to the first 50 MW wind farm project connection within the OETC network at Dhofar. The paper is structured with the following sections: section 2 provides a detailed overview of the Dhofar 50 MW windfarm and the basic requirements for meeting compliancy under the Connection Condition of Schedule 2. Section 3 shows the factors and results associated with voltage unbalance while section 4 shows the flicker considerations. Section 5 shows the harmonic assessment and network factors which influences the emissions, while section 6 summarizes the main conclusions. All the system studies are carried out using DIgSILENT version 15.2.

II. TECHNICAL REQUIREMENT & WIND FARM LAYOUT

The Dhofar wind farm consists of 20 x 2.5 MW wind turbines arranged in 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 via a 132/33kV transformer. The Point of Connection (POC) is at the 132 kV busbar within the wind farm substation. An Automatic Voltage Regulator (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 busbar. 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.

Fig. 1. Dhofar wind farm layout.

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 POC. Each of the three control modes can be selected. The technical requirement related to power quality analysis is based on the OETC Grid Code [4]. This is explained below:

(a) Voltage unbalance: This is a measure of unbalance on the OETC network based on unbalanced loads & 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 & harmonics: A measure of possible series & parallel resonances which can occur within the network, which can lead to voltage and current waveform distortions due to harmonic injections of the load/generator.

The OETC grid code defines these power quality limits as listed in Table I.

TABLE I. OETC GRID CODE POWER QUALITY LIMITS

Power Quality	**Limit**
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%)

III. VOLTAGE UNBALANCE ASSESSMENT

Many of the grid codes define voltage unbalance as the ratio in percentage between the RMS values of the negative sequence component and the positive sequence component of the phase voltage. Voltage unbalance is an important aspect within the transmission system as the induced currents arising from the negative phase sequence components can lead to unnecessary heating of generator and motor stator windings [5]. This in turn reduces the life expectancy of the asset itself. It is generally accepted that the TSO's try to resolve the issue of imbalance by optimal phasing such that the overall net effect is minimized i.e. RYB/BYR arrangement. The issue of unbalance arises from two main sources (a) Load type and connection (b) Natural unbalance due to overhead lines and network topology/connectivity [6]. Each element is described briefly below:

A. Unbalance due to Loads

The majority of induction loads in the GCC region is connected by a single phase or phase to phase power supply. These types of connections and loads can contribute to approximately 60% of the national demand at peak conditions. These types of loads represent single phase & line–line motors, fans, traction loads, and erratic loads as in induction furnaces. These types of loads are common in the Gulf countries, and are a subject of great interest in reference to power quality and delayed voltage recovery. Many transmission operators in the region use an aggregated model to represent a proportion of the distribution network or low voltage network for transmission planning, thus the full influence of the level of unbalance on the system is not fully captured. However the impact of the level of unbalance can be approximated for single phase and phase to phase loads, which tends to be used as a first pass analysis [6]. The level of unbalance can be estimated at the supply bus by representing the system as a simple equivalent for a line to line supply. As shown in Figure 2 which represents a typical two phase load supply.

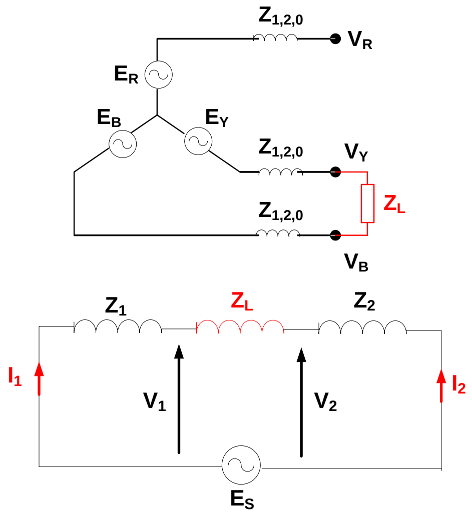


Fig. 2. Two phase load representation.

The remaining system grid and unbalanced load impedance can be determined by taking the reciprocal of the fault MVA_F and the load MVA_D respectively, where MVA_F is the 3ph short circuit level in pu. If the following assumptions are taken into consideration: (a) E_s=1pu (b) $Z_1=Z_2$ and (c) $Z_L>>Z_1$, then,

$$I_1 = -I_2 = \frac{V_{ln}}{2Z_1+Z_L} = \frac{1.0}{2Z_1+Z_L} \qquad (1)$$

The load impedance is normally much greater than the positive sequence impedance, i.e., $Z_L>>Z_1$, therefore we may assume that $Z_L \cong (2Z_1+Z_L)$; then the negative sequence voltage can be deduced as:

$$V_2 = -I_2\, Z_2 = I_1\, Z_1 \cong \left(\frac{1}{Z_L}\right) Z_1 \cong \frac{Z_1}{Z_L} \qquad (2)$$

Note that Z_1 & Z_L can be calculated as:

$$Z_1 = \frac{1.0}{MVA_F} \qquad (3)$$

$$Z_L = \frac{1.0}{S_D} \qquad (4)$$

where S_D = two phase demand in pu.

Thus by substituting for Z_1 & Z_L in equation (2), we obtain:

For phase-phase load: $V_2(\%) = \frac{MVA_{D(ph-ph)}}{MVA_F} \times 100$ (5)

For single-phase load: $V_2(\%) = \frac{MVA_{D(ph)}}{MVA_F} \times 100$ (6)

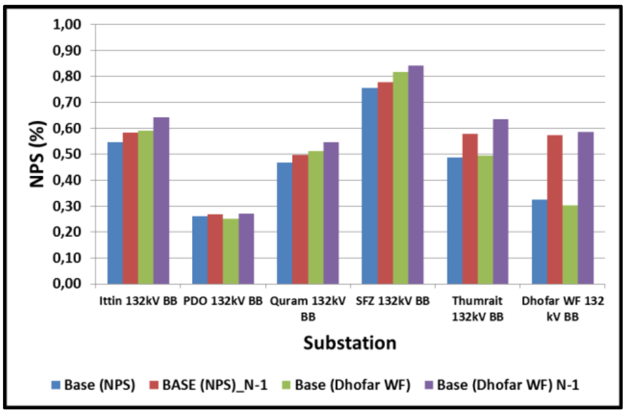


Fig. 3. Voltage unbalance based upon Dhofar network.

A similar approach can be demonstrated for single phase unbalanced loads. Thus the level of unbalance at the supply bus is proportional to the unbalanced load and inversely proportional to the three-phase fault level. Based upon these expressions it can be easily seen that the fault level plays an important role in determining the level of unbalance (NPS %). Based on the Oman Dhofar system, different unbalanced magnitudes against faults levels have been plotted and summarized in Table II and actual results from DIgSILENT are shown in Fig. 3. It can be clearly seen that the results are in good approximation i.e. in the peak conditions the average fault level in the Dhofar network is approximately 4500 MVA. The deciding factor associated with unbalanced is the fault level. If more renewable technologies are connected, the level of synchronous generation can decrease which inherently reduces the fault infeed's and hence the overall fault level.

TABLE II. APPROXIMATED NPS% BASED ON FAULT LEVEL & LOAD LEVEL.

	Demand Connection Size (MVA)						
MVA Fault	100	80	60	40	30	20	10
3000	3.33	2.67	2.00	1.33	1.00	0.67	0.33
3500	2.86	2.29	1.71	1.14	0.86	0.57	0.29
4000	2.50	2.00	1.50	1.00	0.75	0.50	0.25
4500	2.22	1.78	1.33	0.89	0.67	0.44	0.22
5000	2.00	1.60	1.20	0.80	0.60	0.40	0.20

It is important to state that level of unbalance which already existing in the system plays a vital role in whether compliancy is met or not. Thus it is crucial to conduct voltage unbalance studies in assessing whether new connections give rise to higher levels of negative sequence voltages within the system.

B. Unbalance due to Overhead lines & Topology

On double circuit overhead lines, the tower geometry and conductor positioning can give rise to asymmetry across a given tower route. This is predominately due to mutual couplings and the interaction of the magnetic field of the opposite circuit in question. The interaction of the conductors to earth which is described in Carson's equation as the self and mutual impedances are characterized due to the magnetic field interaction of the tower.

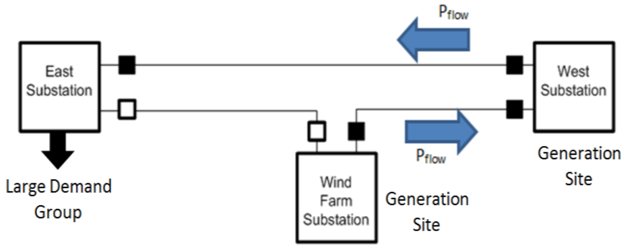


Fig. 4. Impact of counter current flow on voltage unbalance.

These impedance terms will be a function of tower geometry, conductor positioning & spacing, permeability, phase arrangement, polarity, number of strands, etc. and will inherently lead to a 7x7 impedance matrix in where the matrix can be reduced to a 6x6 if the earth wire is negated [7]. Thus the sequence voltages can be determined for both circuits as:

$$\begin{bmatrix} V_{1-PPS} \\ V_{1-NPS} \\ V_{1-ZPS} \\ V_{2-PPS} \\ V_{2-NPS} \\ V_{2-ZPS} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} & Z_{15} & Z_{16} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} & Z_{25} & Z_{26} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} & Z_{35} & Z_{36} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} & Z_{45} & Z_{46} \\ Z_{51} & Z_{52} & Z_{53} & Z_{54} & Z_{55} & Z_{56} \\ Z_{61} & Z_{62} & Z_{63} & Z_{64} & Z_{65} & Z_{66} \end{bmatrix} \times \begin{bmatrix} I_{1-PPS} \\ I_{1-NPS} \\ I_{1-ZPS} \\ I_{2-PPS} \\ I_{2-NPS} \\ I_{2-ZPS} \end{bmatrix} \quad (7)$$

Based on this matrix alone, the negative sequence voltages for both circuits can be deduced. It is common practice for many TSO's to connect generators/demand at a given site, and over the years the networks topology changes surrounding the substation. Various network configurations may lead to system unbalance in either pre or post fault conditions especially if counter current flows are deduced under an N-1 condition [8]. An example is shown below in Fig. 4 of a loop-in of a generation point which creates counter current flows. It can be seen from that the pre-fault network topology varies under post fault conditions if an N-1 condition occurs. This leads to a resultant power flow which inherently causes a current mismatch on each circuit within the same tower route. This will lead to a higher voltage unbalance at the East substation. This has been demonstrated in DIgSILENT in Fig. 5 where it can be seen that the loss of the circuit results in higher power flows on the West-East substation leading to a counter flow on the West-Wind Farm substation.

The positive sequence voltage inherently drops due to a higher impedance pathway, while the negative sequence voltage increases. Thus the overall impact would lead the level of negative phase sequence voltage (%) to increase from 0.1% to 0.2% at the East substation which is below the 1% planning limit. If higher flows are seen on the network, the NPS voltage would considerably increases [8]. Thus in order to consider the connection design of the first wind farm project in Oman, the site was selected to ensure that the NPS levels are kept as low as possible.

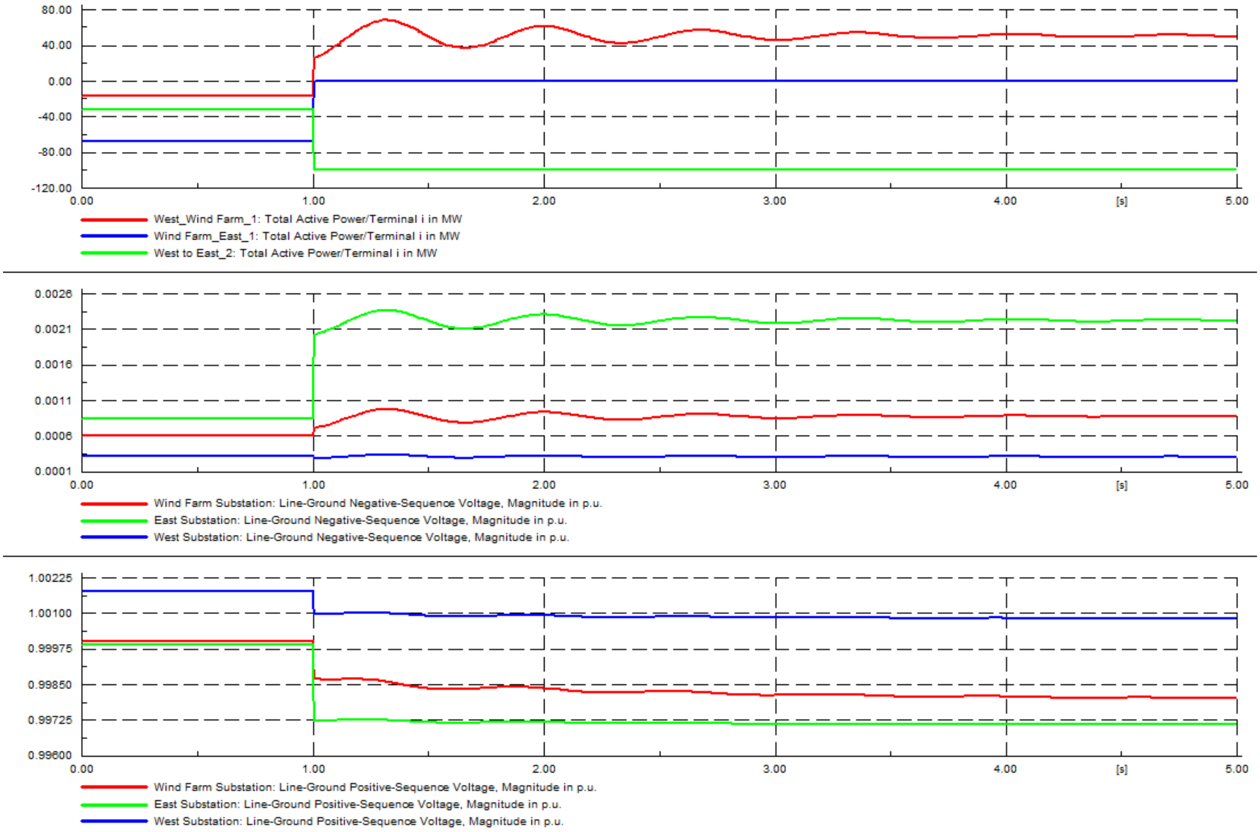


Fig. 5. Impact of counter flow on voltage unbalance due to counter flow.

The selected site utilized the single circuit which ran from Thumrait to Harweel, such that the wind farm substation was turned in with respect to the circuit. Thus as only one circuit is used for the connection of the windfarm, NPS levels were kept to a minimal.

IV. FLICKER ASSESSMENT

Flicker assessment is associated with the rapid change in fluctuating loads which results in a visual sensation (unsteadiness) as induced by a light stimulus whose luminance or spectral distribution fluctuates with time. As larger non-synchronous plants connect to the grid, which could possibly supplant the conventional synchronous plants; flicker levels would be more visible. Flicker emissions from wind turbines are produced during start-up, but also during the continuous operation of the wind turbine which is caused by variation of power output due to variation in wind speed, gradients and shadow [9].

As the GCC loads are heavily dependent on motors, arc furnaces and now intermediate energy sources, the emission sources and their coordination becomes increasingly important. The IEC 61000-3-7 Standard provides total flicker levels for system planning at a high voltage level in which individual installation must not exceed taking into account the existing system disturbance level. The IEC limits for HV are 0.6 and 0.8 short term (P_{st}) and long term (P_{lt}) respectively based on the compatibility levels [10]. A flicker study was conducted for the Dhofar wind farm in where the purpose of this study is to ensure that the wind farm is compliant with IEC 61400-21 based on the information available for continuous operation. To do so the following IEC 61400-21 flicker emission and coefficient equations are used:

$$P_{st\Sigma} = P_{lt\Sigma} = \frac{1}{S_k} \times \sqrt{\sum_{i=1}^{N_{wt}} (ci(\psi_k, v_a) \times S_{n,i})^2} \qquad (8)$$

$$ci(\psi_k, v_a) = P_{st} \frac{S_k}{S_n} \qquad (9)$$

where: $C(\Psi_k, v_a)$ is the flicker coefficient of the wind turbine for the given network impedance per phase, Ψ_k at the POC, and for the given annual average wind speed, v_a at hub-height of the wind turbine at the site. S_n is the rated apparent power of the wind turbine, while S_k is the short circuit apparent power at the POC. In the analysis, it has been assumed that each wind turbines is identical in design, size, and possesses the same flicker coefficient. To calculate the flicker levels at Dhofar 132 kV & 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.

Based on these formulas it can be seen that the short circuit ratio's and the X/R ratio's play an important role in flicker compliance. In essence the short circuit power level at a given point in the electrical network represents the system strength. If the voltage at a remote point can be taken as constant, the short circuit power level in MVA is defined as V^2/Z_k where Z_k is the equivalent impedance as seen from the point of fault. In essence a lower fault level would lead to a lower Short Term (P_{st}) & Long Term (P_{lt}) values for a given flicker coefficient. The X/R ratio of the windfarm was calculated at the 33 kV collector site and was in the region of 9-12 for off-peak & 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 III.

The flicker study demonstrates that Dhofar 132 kV would be within limits set out in IEC 61400-21. It should be noted that possible measures against flicker includes fast acting Static Var Compensation systems, higher voltage connections at the POC, and coordination of system topology.

TABLE III. FLICKER AT DHOFAR WF SUBSTATION DUE TO WIND FARM.

Flicker	$C(\Psi_k, v_a)$	**Dhofar WF**	**IEC Limit**
33 kV Short Term P_{st}	1.11	0.085	0.6/0.8
132 kV Short Term P_{st}	1.11	0.1087	0.6/0.8

The wind developers may also mitigate the level of flicker by taking into consideration design aspects such as the individual size of the wind turbines or splitting the wind farm into two coherent connection points or feeders to improve the overall fault level. The developer may also employ a fast acting voltage control loop can be employed to both regulate the voltage and flicker level within tolerable bounds. It is also important to state that depending on the type of wind technology deployed the level of flicker emissions may vary i.e. fixed speed may be more advantageous than variable speed in reference to flicker at a given connection point [11].

V. HARMONIC ASSESSMENT

Power system harmonics are associated with the voltage distortion of the voltage supply sinusoidal waveform. The term harmonic implies that a term of the waveform occurs at an integer multiple of the fundamental frequency of 50Hz. For example a harmonic number of three corresponds to a sinusoidal wave form at a frequency of 150 Hz. Historically the root cause of harmonics in a power system is due to the nature of non-linear load as well as erratic loads [12]. This is further exacerbated by series and parallel resonance at a particular frequency. Parallel resonance (peaks in the frequency impedance scan) usually occurs in the network when the inductive reactance is equal to the capacitive components under the self-impedance of the network itself [13]. At this particular frequency the self-impedance is only limited by the network resistance. Series resonance occurs with respect to the network transfer impedance (troughs in the frequency impedance scan). The wind farm connection is assessed against a THD limit on the transmission and/or distribution system [4]. Wind farms are a source of harmonic pollution which effects power supplies of neighboring customers and this is predominately due to the harmonic currents that it injections into the network. The wind farm layout design as well as the low voltage cable network can cause resonances affecting the existing background level of harmonic voltages within the network. The introduction of the capacitive cabling due to the wind farm interconnection on a predominately inductive network will inherently shift the peak resonance to higher harmonic values as seen from the POC which can amplify the levels of harmonic distortion and may lead to non-compliance [14]. Figure 6 shows that parallel resonance peak shifts from harmonic number 14 to 18. Thus the importance of network design and load modelling plays an important role in harmonic evaluation. Another important consideration which should be considered in harmonic evaluation is the detailed modelling of all power system components in the region of interest.

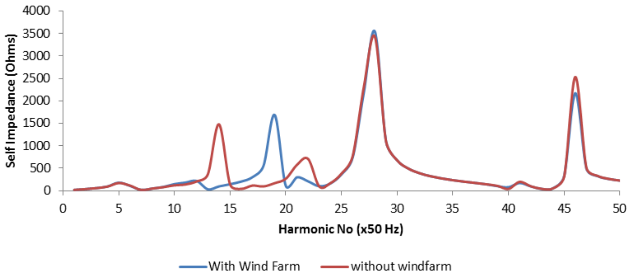


Fig. 6. Impact of wind farm connection on self-impedances.

Fig. 7 shows the impact of modelling overhead lines as a simple lumped model, distributed model and a frequency dependent model. The distributed model captures all the series and parallel resonance at higher harmonic numbers. In essence lumped parameter overhead line is considered accurate for short lines or medium length lines. For harmonic analysis, the frequency increase is due to the line being longer, and so to model using distributed parameters is appropriate [15]. The same is particular true for harmonic load models such that a realistic representation of the system impedance downstream in the distribution network is captured, to account for harmonic phenomena in the low voltage network.

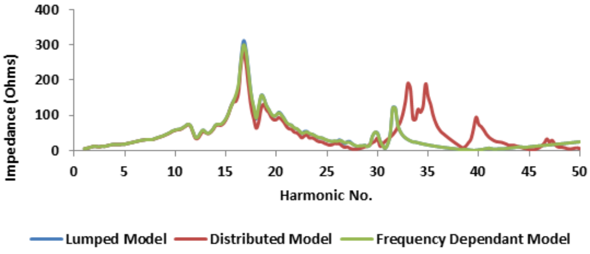


Fig. 7. Impact of overhead line modelling on harmonic analysis.

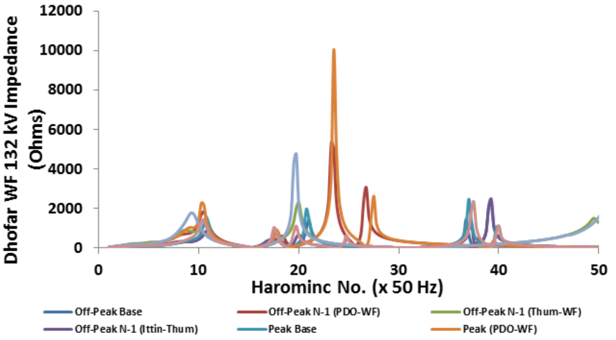


Fig. 8. Self-impedance of Dhofar wind farm substation.

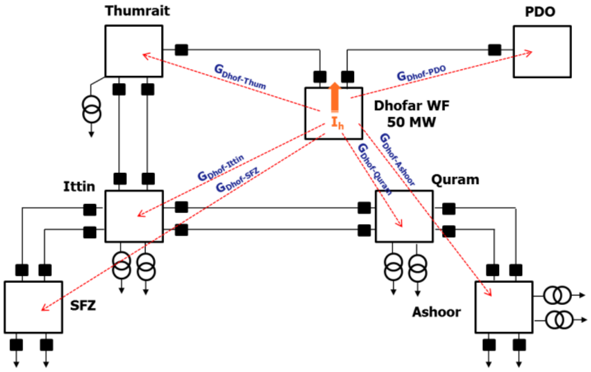


Fig. 9. Transfer impedance & gains of Dhofar wind farm.

In harmonic distortion studies; a realistic representation of the system impedance must include the system downstream, with load impedances. This path is commonly neglected in theoretical studies because the data is not readily available, and this can cause large error in calculations. For simplicity, to obtain a view of the level of requirements, a simple equivalent model is used with characteristics which are pessimistic but seen to be credible. This should only be used as a view and no design should be conducted with this type of model. It is necessary to develop a detailed model of the study region which includes the distribution network, to accurately represent the harmonic phenomena and allow a frequency scan on system impedance. This model should then be used to assess any harmonic load/connection against transmission and/or distribution voltage quality limits. A simple harmonic load model is applied to all loads within the Dhofar region which in essence captures an element of the series and parallel resonances within the network. At each substation secondary busbar a lumped circuit capacitance and an equivalent impedance of the downstream system have been inserted.

Figure 8 shows the self-impedance at the 132 kV Dhofar Wind Farm (WF) substation. The peak of the parallel resonances occurs at different frequencies under different network conditions. There is a high self-impedance at around the 1200 Hz at the POC under a PDO-Dhofar WF line outage. The second large peak is at around 1000 Hz under a Thumrait–Dhofar WF outage. The self-impedance values were grouped over every single harmonic for each condition state, and the maximum value was used to determine the transfer gains.

An important aspect in determining frequency scans is the impact of transfer impedance and inherently the gains. A transfer gain is defined as the ratio of transfer impedance to self-impedance at the point of connection. The windfarm itself can inject harmonic currents and this current can propagate to other substations due to the transfer impedance and gains at different frequencies. A high transfer gain would indicate that the current injection has a considerable impact on the remote substation, and would amplify the harmonics seen at that particular substation [13]. Thus the evaluation of the impact of the harmonic injection should be considered not only at the point of connection but to neighboring substations in order to assess the compliance of the wind farm.

Figure 9 diagrammatically shows the impact of harmonic current injection from the Dhofar WF substation due to the transfer gains and impedances. Figure 10 shows the transfer impedance for the Dhofar region. A number of series and parallel resonance occurs. As previously stated 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.

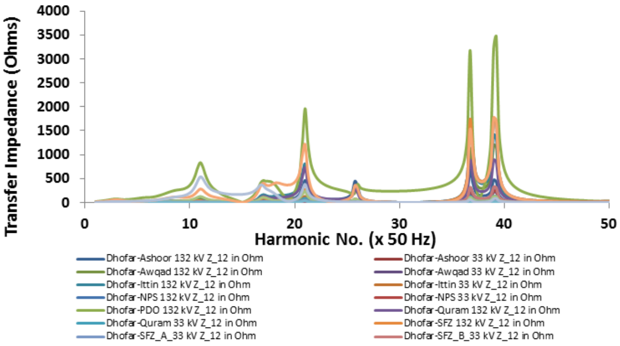


Fig. 10. Transfer impedance of Dhofar region (winter off-peak).

It can be seen that high magnitudes of harmonic transfer impedances can occur during the off-peak conditions. Key magnitudes include the 11th, 18th, 20th 37th and 40th harmonic frequency. As the self-impedance and transfer impedance have been calculated for the network, the system transfer gains can be calculated. Thus the worst case transfer gains lead to a list of sites to be measured for the existing background harmonic distortion. As no background measurements are available; only the Harmonic Distortion (HD) due to the wind farm injection can be calculated (This is not the Total Harmonic Distortion THD) based on standard harmonic current injections for different wind farm technologies.

Figure 11 shows the voltage harmonic distortion for a typical Fully Rated Converter (FRC) wind farm technology throughout the Dhofar network. As FRC wind farms are based on Voltage Source Converter (VSC) HVDC technology the number of harmonics produced would be limited compared to other technologies.

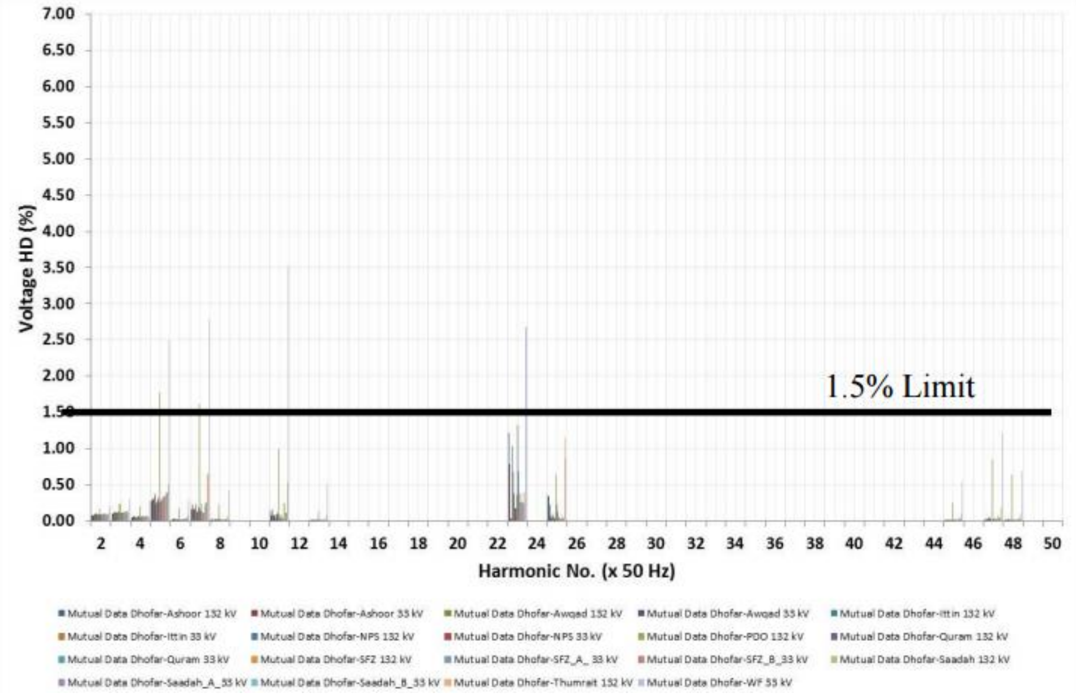


Fig. 11. Voltage harmonic distortion results.

This type of wind farm has high harmonic voltage distortion at the 5th, 7th, 11th and 23rd harmonic frequency which is slightly higher than the 1.5% harmonic limit as imposed by the OETC grid code.

VI. CONCLUSION

The paper presents an overview of important consideration for assessing power quality in reference to the Dhofar wind farm grid connection. Special emphasis has been placed in this paper on voltage unbalance, flicker and harmonic evaluation in reference to methodology and considerations. However all issues related to wind farm connections and their impact on the power system grids need further detailed studies, but the main factors have been accounted for here. These studies require a careful balance between modelling and power system design in evaluating power quality requirements for the wind farms. The results of these types of studies can have an impact on the design and network topology of the power system itself to ensure compliance and minimal effects when a wind farm is connected to the power grid.

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