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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 obtained for steady-state and dynamic studies using DIgSILENT software. The aim is to build confidence on the integration of the wind farm to the Oman grid and to ensure that planning criteria are met according to the Grid Code and Transmission Security Standards requirements. 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.*

## 1. Introduction

The integration of wind technology to the grid has significantly grown in the past twenty years across the world, and it is most noticeable in today's energy fuel mixes across Europe & North America. The Gulf Cooperation Council (GCC) which includes Oman, United Arab Emirates, Kuwait, Qatar, Bahrain & Saudi Arabia have embarked in committing to meet energy targets for the next coming decades. For the past decade the majority of GCC states rely on conventional synchronous generators fuelled by fossil fuels to supply its energy requirements. As the region moves towards a sustainable future, the connection of non-synchronous plant provides a solution to meet its current & future energy requirements. The connection of renewable technologies will inherently present many challenges to many transmission companies as they embark on new fuel mixes. The region is characterised by having one of the highest $CO_2$ emissions per capita in the world but the lowest in average retail electricity prices [1]. In Oman, renewable energy targets of 10% have been set by 2025. In order to meet these renewable targets Oman Electricity Transmission Company (OETC) in collaboration with the Rural Areas Electricity Company (RAECO) & Masdar have agreed to the installation of the first large-scale 50 MW wind farm in Dhofar, South-West of Oman, by 2017/18. This will save approximately 110,000 tonnes of $CO_2$ annually, as well as meet growing energy demands in Oman [2]. For OETC this will be the second renewable integration project following the 200 MW of solar photovoltaic plant and is part of their six pilot projects [3]. The paper concentrates on the impact of the wind farm on the Dhofar network, as well as compliancy with the OETC Grid Code [4] and the Transmission Security Standards [5]. Both steady state and dynamic analysis are conducted to ensure that planning standards are met with the wind farm at full capacity and at zero output.

The paper is organized as follows: Section 2 describes the Dhofar network as well as its characteristics. Section 3 displays the wind farm layout, connection and control for simulation. Section 4 gives a high level overview of the wind farm technologies deployed for the study. Section 5 discusses the planning criteria as well as the studies conducted. Section 6 presents the steady state results, while Section 7 presents the results of the dynamic studies. Section 8 summarises the main conclusion of the study investigation.

## 2. System Description

The Dhofar network is owned and operated by OETC and is located in the South-West of Oman. The Dhofar network is connected to the Petroleum Development Oman (PDO) which in turn connects to the Main Interconnected System (MIS) of Oman. The interconnections between Dhofar & PDO and PDO & MIS under normal operation are kept at zero MW exchange. The Dhofar network consists of 132 kV transmission lines which feeds numerous 33 kV Grid Supply Points (GSP) with a peak demand of about 655 MW and an off-peak demand of 274 MW [6]. The load nature of Oman is predominantly domestic & commercial load with high levels air conditioning units and large chillers which make up a large proportion of the demand during the summer peak season. Two main gas based generators feed the demand in Dhofar (i) NPS Power Plant (273 MW) and (ii) Salalah IWPP Power Plant (444 MW).


Fig. 1. Dhofar network 2018.

In 2018 Salalah-2 IPP will be connected by providing an additional 400 MW capacity [6]. By 2018 under peak conditions; 58% of the existing installed generation capacity will be committed with a spinning reserve equal to the rating of the largest generating unit connected to the transmission system. In case of combined cycle power plant, the spinning reserve equals the largest gas turbine unit plus its share in the steam turbine unit [6]. A bird's eye view of the Dhofar network is shown in Fig. 1.
DIgSILENT Power Factory version 15.2 has been used to model the entire Oman Network for steady state and dynamic analyses.

## 3. Wind Farm Connection & Layout

Fig. 2 shows the layout of Dhofar wind farm which consists of 20 × 2.5 MW wind turbines. The wind farm will be connected to a new 132/33 kV substation located between Thumrait (Dhofar) and Harweel (PDO). This will require the existing circuit to be line-in/line-out connected to the new substation and will act as the point of common coupling or Point of Connection (POC) as shown in Fig. 2.
A 33 kV AIS substation will be connected to the new 132 kV substation and via a 63 MVA 132/33 kV transformer with an on load tap changer. The 33 kV AIS substation has three feeders: two of them having seven wind turbines connected in series and one of them connecting six. There are twenty separate 33 kV switchgear, each with its own 2.8 MVA 33/0.69 kV transformer connecting to each of the wind turbine. The cable lengths have been provided by Masdar based upon their feasibility study. The inter 33 kV cabling have been based upon generic 33 kV cable characteristics which are common in the region.
A station controller has been assigned to the 20 × 2.5 MW wind turbines. There is a facility in DIgSILENT that coordinates the control of the wind farm generators to regulate either (i) the voltage of a specific bus bar, (ii) reactive power control and (iii) power factor operation. Only one control mode can be used at a time.

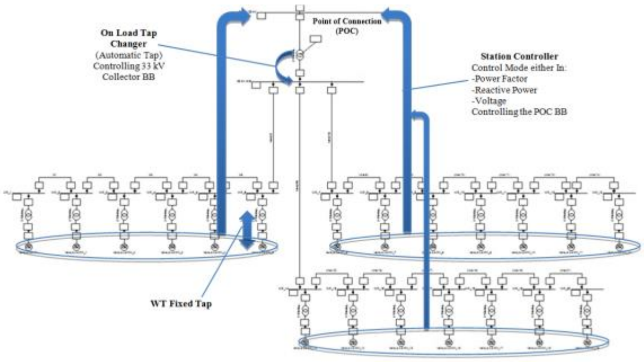


Fig. 2. Dhofar wind farm layout.

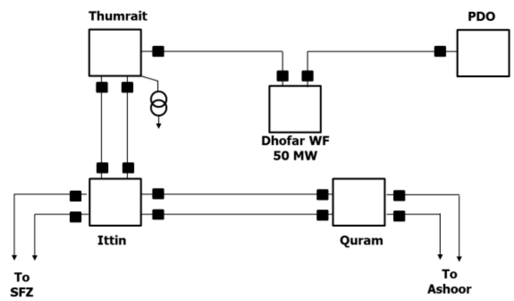


Fig. 3. Dhofar wind farm substation.

## 4. Wind Farm Technology

Two wind farm technologies will be used to assess the grid impact study on the Dhofar network for dynamic analysis. The two technologies used are the Doubly Fed Induction Generator (DFIG) and the fully rated converter technology. A typical configuration of a DFIG wind turbine is shown in Fig. 4.
The application of the slip rings on the wound induction generator allows current to be transmitted between the converter and rotor windings. Variable speed operation is obtained by controlling the reactive power (voltage) into the rotor at the desired slip frequency [7]. The power converter decouples the electrical and mechanical frequencies for variable speed operation. Thus depending on the mode power can be transmitted from the stator or from the rotor and converter.

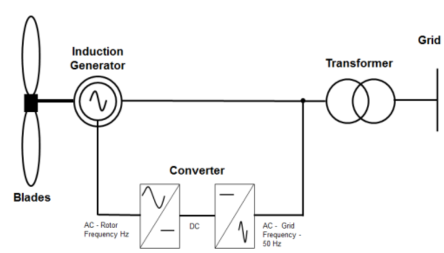


Fig. 4. DFIG 2.5 MW turbine.

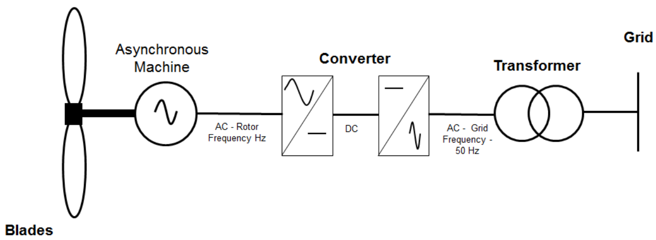


Fig. 5. Full converted 2.5 MW Turbine.

A typical configuration of a fully-rated converter-based wind turbine is shown in Fig. 5.

In this type of technology an asynchronous generator coupled with a fully rated voltage source power electronic converter is used. The converter consists of an active rectifier and a grid side inverter. Once again the power converter allows for variable speed operation by decoupling the mechanical and electrical frequencies. The advantage of having a fully rated connected converter is that it is able to withstand the large amount of reactive power [7] that the DFIG is incapable of. Classical DIgSILENT models and typical manufacturer control systems have been used to capture the dynamics of the wind farm model as well as the protection settings.

## 5. Planning Standards and Compliancy

The grid impact study was assessed against the Planning Code and Connection Conditions Code of the OETC Grid Code [4] in addition to Transmission Security Standards [5]. The voltage performance margin will then be assessed in where the voltage does not exceed the pre-defined voltage limit of ±10% of nominal, where only transmission level voltages are assessed. The contingency analysis will study the two system states to assess the consequences of the loss of transmission equipment (line, cable, transformer, load, generation unit) in the vicinity of the wind farm as per the requirement of the (N-1) security criteria. Three-phase and single-phase short circuits are then compared to circuit breaker ratings and are in accordance to IEC 60909. For dynamic stability, no pole slipping or improper damping should occur.

## 6. Steady Sate Analysis

A balanced AC load flow study was used to assess the thermal loading and voltage performance of the network under pre and post fault conditions for all assets modelled.

### *Voltage Profile*

The voltage profile of the Dhofar network was set such that sufficient reactive reserves existed in the region meanwhile respecting the pre and post fault voltage limits. This was carried out be conducting a reactive balance in the Dhofar network and optimising the voltage of the region. The main objective function in voltage optimisation is to minimise the committed pre-fault reactive requirements of the system, mean while ensuring that the maximum the level of reactive reserves are held. A further constraint was also considered in such that the transformer taps are close to the neutral position as possible. Fig. 6 displays the voltage optimisation of the region for all transmission and distribution voltage levels within Dhofar. It can be seen that the voltage is within 0.95-1.05 pu limit.

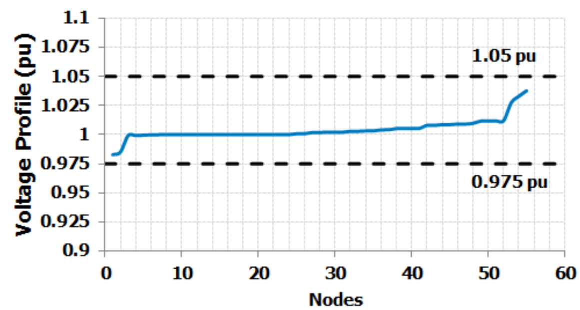


Fig. 6. Voltage profile of the Dhofar network.

### *PTDF*

Power Transmission Distribution Factors (PTDF) relates the sensitivity due a change in flow relative to a reference injection location. It is expressed mathematically as:

$$PTDF_i = \frac{f_{io} - f_{i1}}{P_{inj}} \tag{1}$$

$f_{io}$ is the original flow on a given circuit I, while $f_{i1}$ is the new circuit flow due to an injection ($P_{inj}$) at a given node. Under a balanced dispatch in the Dhofar network (including the wind farm in operation), the *PTDF* values for each circuit is shown in Fig. 7.

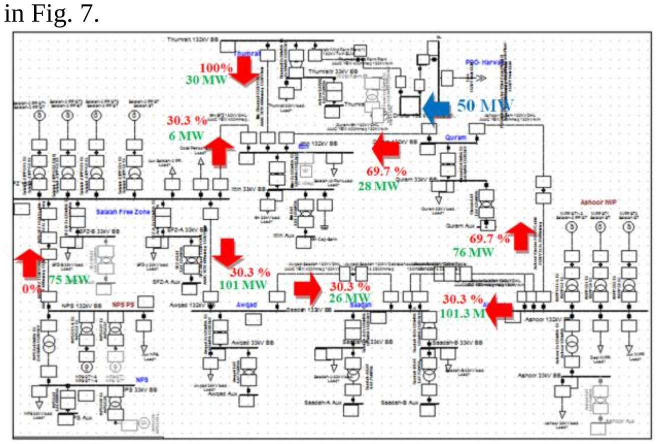


Fig. 7. PTDF of Dhofar network.

It can be seen that the 50 MW injected feeds Thumrait 33 kV load (approx. 20 MW). The remaining 30 MW travels via Thumrait and into the Dhofar system. This suggests that the Dhofar wind farm feeds the local demand, and if the wind is low, it will only feed the Thumrait load. Due to the wind farm connection, the power flow dynamic change beyond Thumrait, but are all the new circuit flows are within its current carrying capability.

***Thermal Loading***

The impact of thermal loading due to the wind farm connection is displayed in Table 1. It can be seen that the wind farm reduces loading on a number of circuits. The greatest impact is seen on the NPS-SFZ 132 kV circuit in where the wind farm (once connected) reduces the generation output of NPS to meet the Thumrait load. The change in transformer loadings are negligible and are not shown here.

Table 1. Circuit loadings.

| Branch ID (2 x Circuit) | Voltage (kV) | No Wind Farm | With Wind Farm |
|---|---|---|---|
| | | % Loading | |
| Ashoor-Quram Cable | 132 | 15.4 | 13.9 |
| Ashoor-Quram OHL | 132 | 12.0 | 10.9 |
| Ashoor-Saadah Cable | 132 | 18.0 | 19.3 |
| Ashoor-Saadah OHL | 132 | 13.3 | 14.4 |
| Awqad-Saadah Cable | 132 | 6.6 | 5.3 |
| Awqad-Saadah OHL | 132 | 4.9 | 3.8 |
| Ittin-SFZ OHL | 132 | 6.9 | 1.3 |
| Ittin-Thumrait OHL | 132 | 3.6 | 4.4 |
| NPS-SFZ OHL | 132 | 17.8 | 10.9 |
| NPS-SFZ cable | 132 | 22.8 | 14.1 |
| PDO –WF OHL | 132 | 0.0 | 0.0 |
| Quram-Ittin OHL | 132 | 5.0 | 3.8 |
| SFZ-Awqad OHL | 132 | 15.6 | 14.5 |
| Thumrait- WF OHL | 132 | 4.2 | 14.1 |

The Thumrait-WF OHL has a thermal rating of 358 MVA. Prior to the connection of the wind farm a flow of approximately 15 MVA flows on the circuit. This is predominantly due to feeding of the losses associated with overhead lines and transformers in the area. When the wind farm connects the flows becomes approximately 51 MVA. Thus the percentage loading moves from 4.2% to 14.1%. The PDO-WF circuit is maintained at zero loading stating a zero exchange between the two networks.

***Fault Level***

Tables 2 and 3 show the impact of three-phase and single-phase faults on the Dhofar network. In order to obtain the maximum fault current possible, all generator breakers were closed with all compensation in service. The voltage profile was also elevated to ensure that the worst case RMS current is obtained. It is assumed that each wind farm a sub-transient (peak making) short circuit level of 1.8 pu, a transient (peak breaking) short circuit level of 1.25 pu, and a “R to X ratio” of 0.1 pu. It can be seen from Table 2 that the fault levels decrease slightly. This is due to the fact that the wind farm has little inertia which will result in minimal fault contribution which is then coupled with the number of generators being in operation at NPS, as the wind farm connects. This effect has been reported by other TSO’s [8-10]. It is important to state that the fault contribution is based on the size and type of the wind generator [11]. For single-phase faults no major difference can be noticed. It can also be stated that the fault currents are within their breaker capabilities.

Table 2. Peak three-phase fault currents.

| Site | Rating (kA) | No Wind Farm Ik” (kA) | With Wind Farm Ik’’ (kA) |
|---|---|---|---|
| Ashoor 132 kV BB | 31.5 | 21.4 | 21 |
| Awqad 132 kV BB | 31.5 | 16.6 | 16 |
| Dhofar WF 132 kV BB | 31.5 | N/A | 4.2 |
| Ittin 132 kV BB | 31.5 | 16.9 | 16.4 |
| NPS 132 kV BB | 31.5 | 24 | 22.4 |
| Quram 132 kV BB | 31.5 | 16 | 15.7 |
| SFZ 132 kV BB | 31.5 | 24.2 | 22.6 |
| Saadah 132 kV BB | 31.5 | 14.5 | 14.1 |
| Thumrait 132 kV BB | 31.5 | 6.9 | 7.1 |

Table 3. Peak single-phase fault currents.

| Site | Rating (kA) | No Wind Farm Ik’’ (kA) | With Wind Farm Ik’’ (kA) |
|---|---|---|---|
| Ashoor 132 kV BB | 31.5 | 25.5 | 25.6 |
| Awqad 132 kV BB | 31.5 | 17.2 | 17.2 |
| Dhofar WF 132 kV BB | 31.5 | N/A | 2.3 |
| Ittin 132 kV BB | 31.5 | 16.8 | 16.9 |
| NPS 132 kV BB | 31.5 | 28.3 | 28.3 |
| Quram 132 kV BB | 31.5 | 15.0 | 15.0 |
| SFZ 132 kV BB | 31.5 | 28.8 | 28.9 |
| Saadah 132 kV BB | 31.5 | 16.3 | 16.4 |
| Thumrait 132 kV BB | 31.5 | 6.2 | 6.2 |

***Contingency Analysis***

(N-1) contingency analysis was conducted for the Dhofar network at peak conditions. The analysis showed that the system is compliant for both voltage and thermal conditions prior and after connecting the windfarm as in accordance to the OETC Transmission Security Standards [5]. However it was noticed that if the Dhofar wind farm to Thumrait circuit is lost under (N-1) conditions, the Dhofar network would result in an islanded state from the rest of the Oman grid. The wind farm in this case will supply its power to the PDO region resulting in a maximum of a 50 MW loss to Dhofar, which is then catered for by the spinning reserve within Dhofar. This is shown in Fig. 8. The additional 50 MW transfer to PDO/MIS would result in system frequency in this part of the network to slightly increase, but would be controlled by the generator governors (under frequency control mode) to restore the system the active power balance.

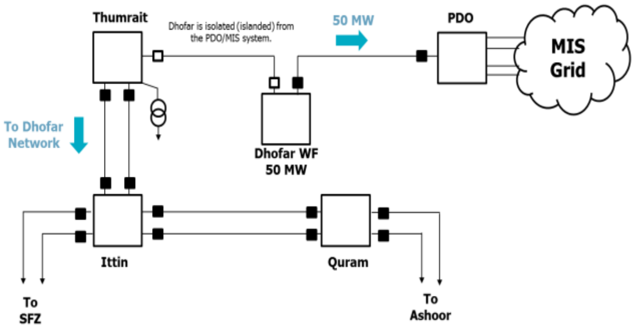


Fig. 8. N-1 Dhofar islanded.

Even though the steady state analysis indicated that this condition is compliant and does not violate the planning standards, it has been considered for dynamic analysis as presented in section 7.

## 7. Dynamic Analysis

Rotor angle, voltage and frequency dynamic stability analysis was conducted for: (i) three-and single-phase bus faults, (ii) three-phase line fault followed by the loss of the circuit (N-1) and (iii) the loss of the largest generating unit for the Dhofar region. This was conducted for both wind farm technologies. In accordance to the OETC Transmission Security Standards [5], no pole slipping or poor damping should occur under the appropriate clearance time. The clearance time for 132 kV is 120 ms following the fault.

The results showed that in all cases considered no pole slipping or undamped oscillations existed during a secured event. This was conducted with and without the connection of Dhofar 50 MW windfarm. Fig. 9, Fig. 10 and Fig. 11 show the rotor angle, voltage and frequency dynamic simulation, respectively for a three-phase bus fault at the Dhofar wind farm substation. It can be stated that dynamic simulation is stable and the Dhofar network is capable of withstanding these sever conditions.

Fig. 12 illustrates the impact of the Thumrait-Dhofar windfarm (N-1) under peak conditions (worst case) which results in Dhofar being in island. This results in a dip in frequency of approximately 0.12 Hz. The loss of a possible 50 MW equates to a 7% loss at summer maximum conditions. It can be easily seen the frequency remains above the statuary limits of 49.5 Hz and is stable. It can be easily seen that the connection of the windfarm does not impact the rotor angle or voltage performance of the network, as the dynamic state moves towards a stable operating point. This is clearly seen in all the figures as the oscillations are quickly dampened after 15 seconds. This is predominately due to the strength of the network, the demand/generation levels at peak and the interconnection to the wider PDO/MIS system. As the wind farm is remotely connected from the wider Dhofar transmission system and feeds the local demand at Thumrait, the net flows on the wider system is minimal. Thus the impact on dynamic analysis is minimal.

## 8. Conclusion

The grid impact study showed that no adverse effect was identified due to the wind farm connection to Dhofar network. No thermal requirements or voltage violations were identified and the connection of the windfarm meets the requirements of the OETC Grid Code and the Transmission Security Standards. The fault currents are below the standard breaker rating capability. Rotor angle, voltage and frequency studies were conducted for various credible conditions. No pole slipping or inadequate damping was identified during these studies. Voltage recovery was also responsive and remained within the specified limits of 0.9-1.1 pu post fault. Thus the grid impact of the first wind farm in Dhofar is minimal for both technologies assessed.

## Acknowledgement

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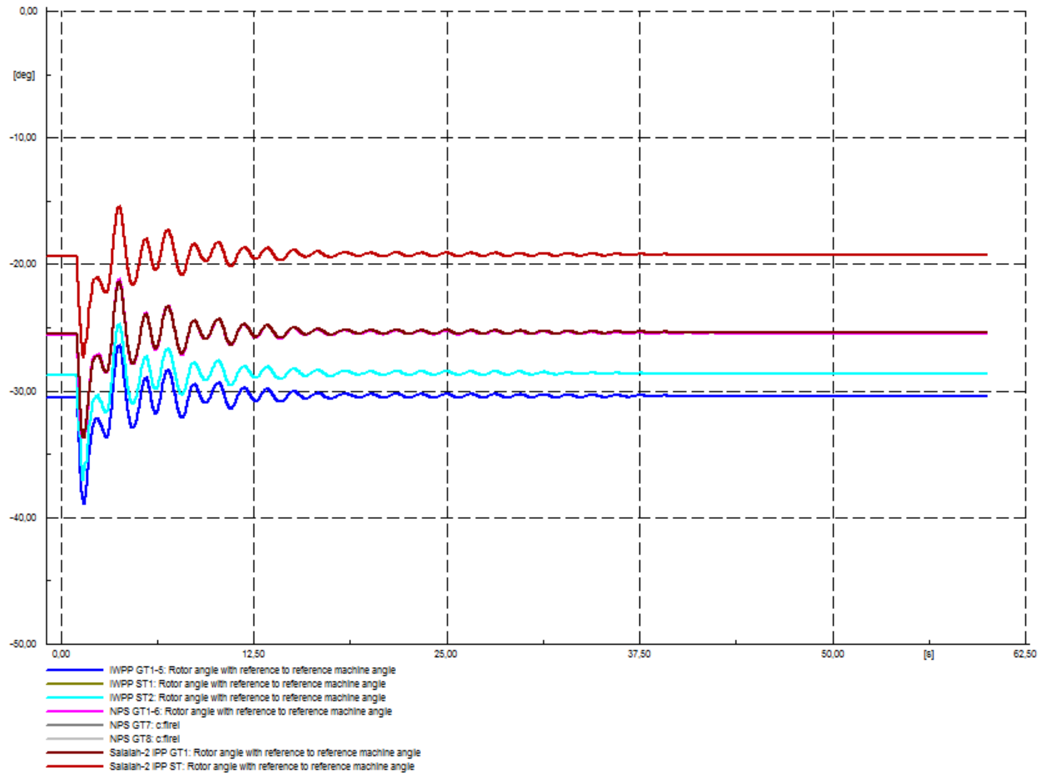


Fig. 9. Rotor angle response to a three-phase bus fault at the Dhofar wind farm substation.

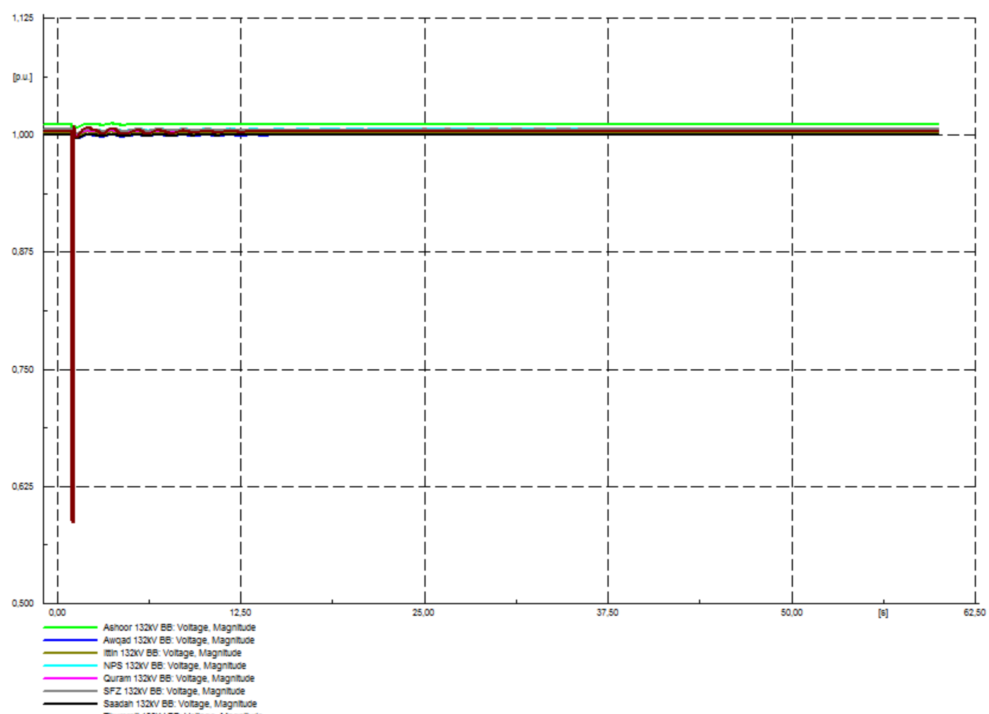


Fig. 10. Voltage response to a three phase bus fault at the Dhofar wind farm substation.

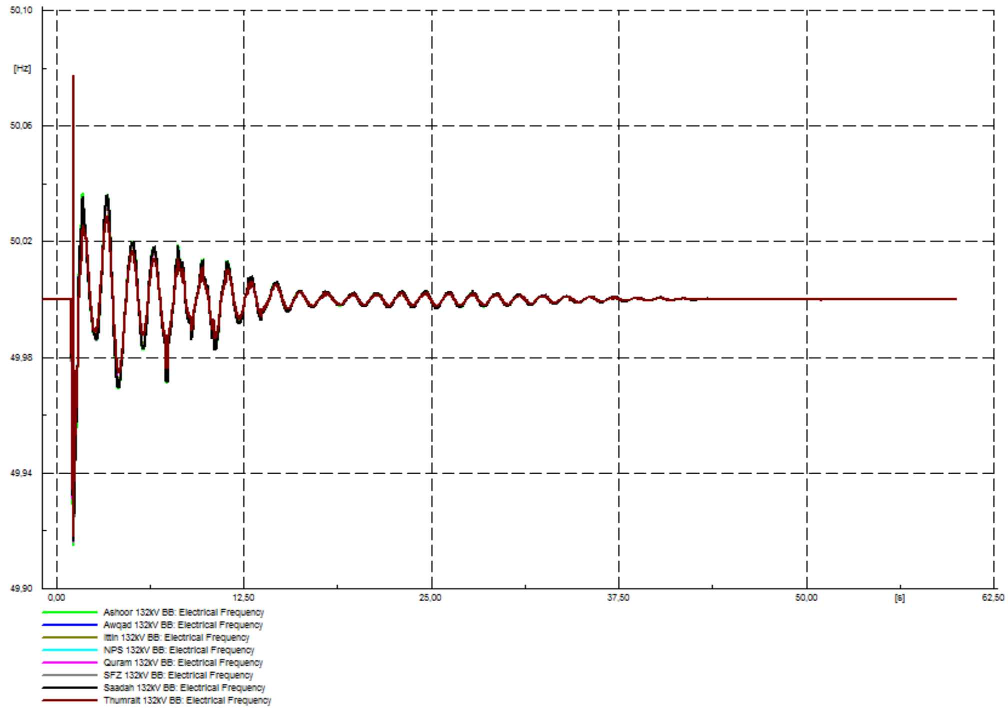


Fig. 11. Frequency response to a three-phase bus fault at the Dhofar wind farm substation.

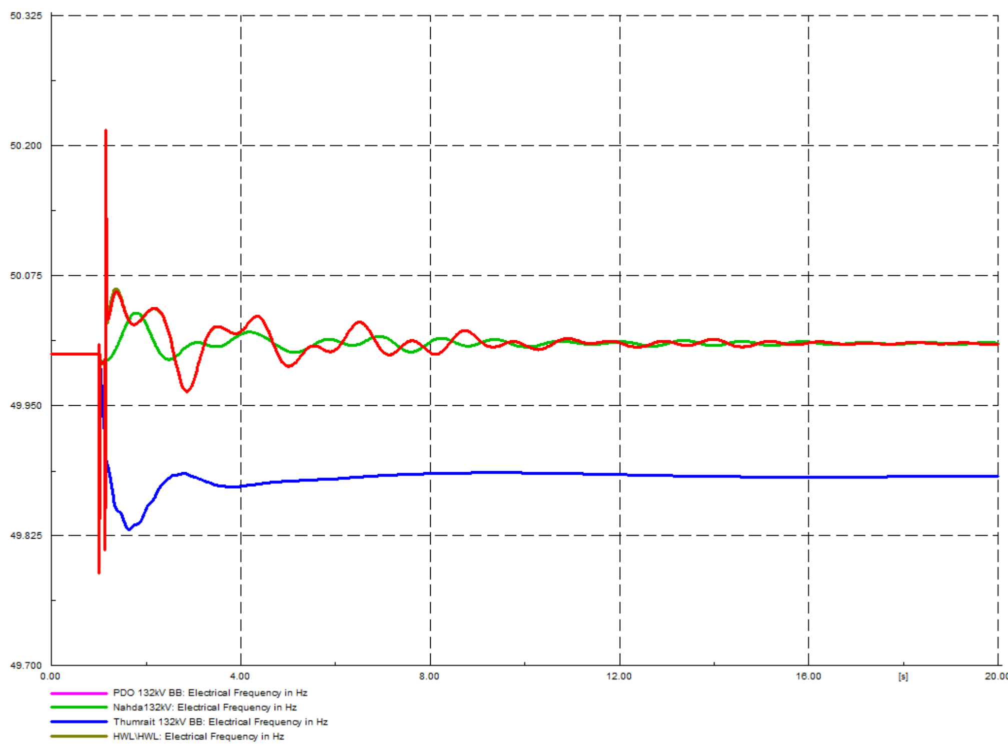


Fig. 12. (N-1) Dhofar islanded.