Evaluating Connecting Al-Mukha New Wind Farm to Yemen Power System

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***Abstract*—This paper presents modeling and impact analysis of Al-Mukha wind farm (MWF) on Yemen power system, which is made of thermal power plants. In this paper, four kinds of major components are modeled: a 60MW wind farm, a transmission network, thermal power plants, and the Yemen power system load. To analyze the impact of the wind power generation to the Yemen power system, simulations are carried out for two case studies by using the DIgSILENT program. The first is the case of grid impact studies: impact on thermal limits, voltage variations, and system stability, in which an aggregated model of the wind farm is used. The other is the dynamic performance of the wind farm by analyzing low-voltage ride through LVRT, harmonics and flicker impact on the basis of the detailed wind farm layout with 30 wind turbines (WTs) arranged in four stands and the external grid of 2175MVA short-circuit capacity. The simulation results show that the loading of most lines and voltage variations are slightly reduced. In addition, there is no harmful effect on the system stability and also the wind farm is capable to ride through the grid fault. Finally, it is shown that the wind farm contributes voltage and current harmonics higher than the permissible limits while the flicker levels are far below any critical values.**

***Index Terms*—DIgSILENT PowerFactory, doubly fed induction generator, grid-connected wind farm, impact of wind power generation, power quality**

I. Introduction

In recent years, the wind power generation has become a very attractive utilization of renewable energy because it is now possible to improve the capability of capturing wind energy with the development of advanced power electronics technology. It has been a trend in wind power generation to build a grid-connected wind farm. The location for a wind farm is usually determined by the wind speed, and therefore the wind farms are concentrated in specific areas [1].

The doubly fed induction generator (DFIG) is used in popular wind turbine (WT) systems because of its various advantages such as high energy efficiency, variable speed, reduced mechanical stress on turbine and power electronics convertor having low rating and cost [2].

The Yemeni Government has initiated the renewable energy strategy and action plan in which different sources of renewable energy have been investigated [3]. The aim of government policy on renewable energy is to optimize the use of energy from domestic sources, increase the share of renewable energy in electricity generation to 15-20% by 2025, and promote sustainable development of the electricity sector [4].

Yemen has a long coastline and high altitudes with an estimated 4.1 hours of full-load wind per day [4]. According to an assessment of wind potential in Al-Mukha by Egyptian experts, this region alone could produce 1.8GW of power and the average annual wind speed is 7.4m/s, which is the main reason why the Yemeni government decided to construct a wind farm of 60MW capacity in this area. Total wind power potential is estimated to be 34GW. The technical potential was estimated at 14,200MW providing about 42,300GWh of electricity per year [4].

However, there are some constraints on connection of wind power stations to the Yemen power system due to the wind velocity distribution and weak power generation. First of all, total power generation capacity in Yemen including Mareb-2 power plant, which will operate in 2015, will be by only about 1740MW, and the proposed capacity of the wind farm is 60MW [5], [6]. The capacity of wind farm is assessed to be acceptable provided that any harmful effects on Yemen power system stability will not be occurred, since the increased penetration level of wind power produces negative impact on the stability of existing power system [2]. Therefore, it is recommended that the impact of wind power generation to the Yemen power grid will be carefully analyzed before connecting wind farms to the grid.

The objectives of the presented paper are to analyze the impact of the proposed Al-Mukha wind farm on the Yemen power system and to evaluate how the power quality parameters will be affected. For these purposes, simulations for both the grid and the wind farm are carried out using the trusted software DIgSILENT PowerFactory. Two types of simulations are performed. One is the case for the studies of network impact (effect on the thermal limits, voltage changes, and the stability of the system), which uses a combined model of the wind farm. The other is the dynamic performance (low voltage ride through LVRT) and power quality (harmonics and flicker) for the analysis of the wind farm integration based on a detailed model of the wind farm with 30WTs arrayed in four groups.

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This paper is organized as follows: the characteristics of Yemen power system and Al-Mukha wind farm (MWF) project are presented in Section II, modeling and simulation of Yemen system and wind turbine are given in Section III, the discussion of the results are presented in Section IV, and conclusions are finally drawn in Section V.

II. Characteristics of Yemen Power System and MWF Project

A. Power System in Yemen

The power system in Yemen has many kinds of power system components, including thermal power plants, transmission and distribution networks. The probability of electric faults is high and will be increased as the renewable energy sources are added, debasing power system stability. Electricity in Yemen depends mainly on oil power stations. The total installed capacity of Yemen in 2012 is 1288MW. The Yemeni population has the lowest access to electricity in the region, with only 54% having access. In 2009, power shortages in the country reached 250MW [4]. To address these shortages, many projects, including MWF, are planned to be implemented in the near future. The power plants generate electrical power at different voltage levels which are 10.5kV, 11kV, 13.8kV, and 15kV and then the voltage levels are boosted to the transmission voltages levels of 230kV and 400kV. The medium voltage level of 33kV is used to transmit the electricity from the substations to the demand locations. The distribution network uses the 11kV to transmit the electricity to the distribution transformers. The nominal frequency for the grid is 50Hz.

B. Al-Mukha Wind Farm Project

The assessment of wind potential in Al-Mukha has shown that this region alone could produce 1.8GW of power [4]. MWF project was initiated with the objectives of demonstrating the financial feasibility of wind power by implementing the first wind power development project in Yemen. The target capacity of 60MW will be met through introducing 30 of 2MW wind turbines generators (WTGs) that will be located according to a favorable scenario indicated in Fig. 1 [3].

III. Modeling of Yemen Power System and Wind Turbines

To verify the feasibility of integration of wind energy with the electric grid, computer simulations have been carried out with a 2MW WTGs Gamesa G-90 DFIG system, the transmission network, and thermal power plants including diesel engines, steam and gas turbine generators; and, Yemen power grid load are also modeled in the simulation.

A. Wind Turbine Modeling

DIgSILENT provides a comprehensive library of models of electrical components in power systems. The library includes models of e.g. generators, motors, controllers, dynamic loads and various passive network elements (e.g. lines, transformers, static loads and shunts). Therefore, in the present work, the grid model and the electrical components of the WT model are included as standard components in the existing library. The models of the wind speed, the mechanics, aerodynamics and the control systems of WTs are written in the dynamic simulation language (DSL) of DIgSILENT [7]. There is no wind model included in the DFIG model found in DIgSILENT library. This model was modified where a wind model was connected to the wind speed input of the original model. The implemented wind model is a measurement file (ElmFile). The measurement file is used for reading data (wind time series) from a file during calculations [8]. The wind time series is generated by the TurbSim software based on the spectral energy distribution of the wind and a superposed noise signal [9]. In a 0.05 second time step the so gained wind speed is averaged over the whole rotor area, which takes turbulence and tower shadow into account. Fig. 2 shows the modeling scheme of the WTGs in the DIgSILENT program.

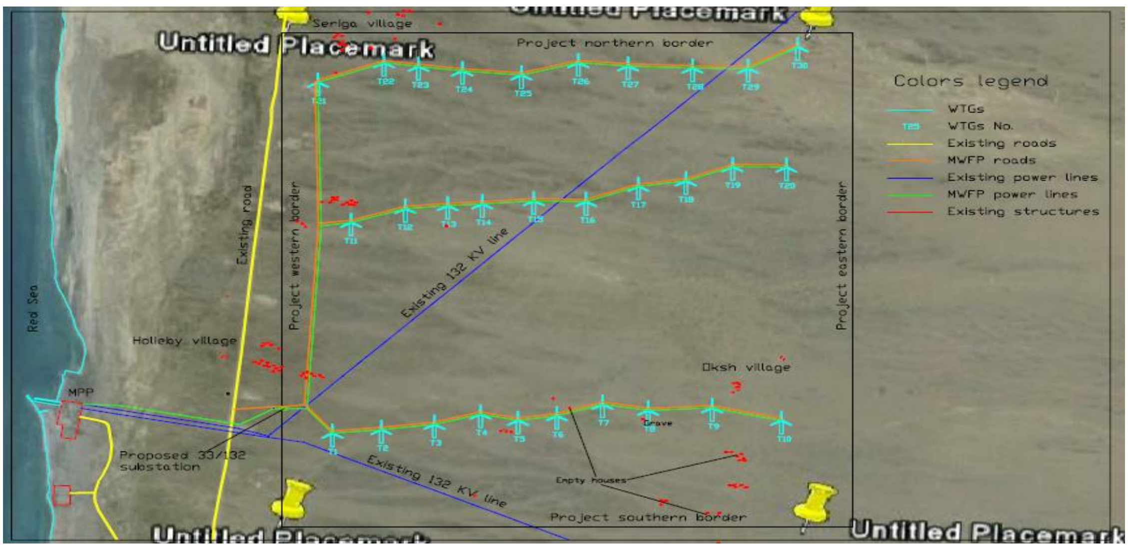

Figure 1. The proposed scenario of WTG in MWF project site [3]

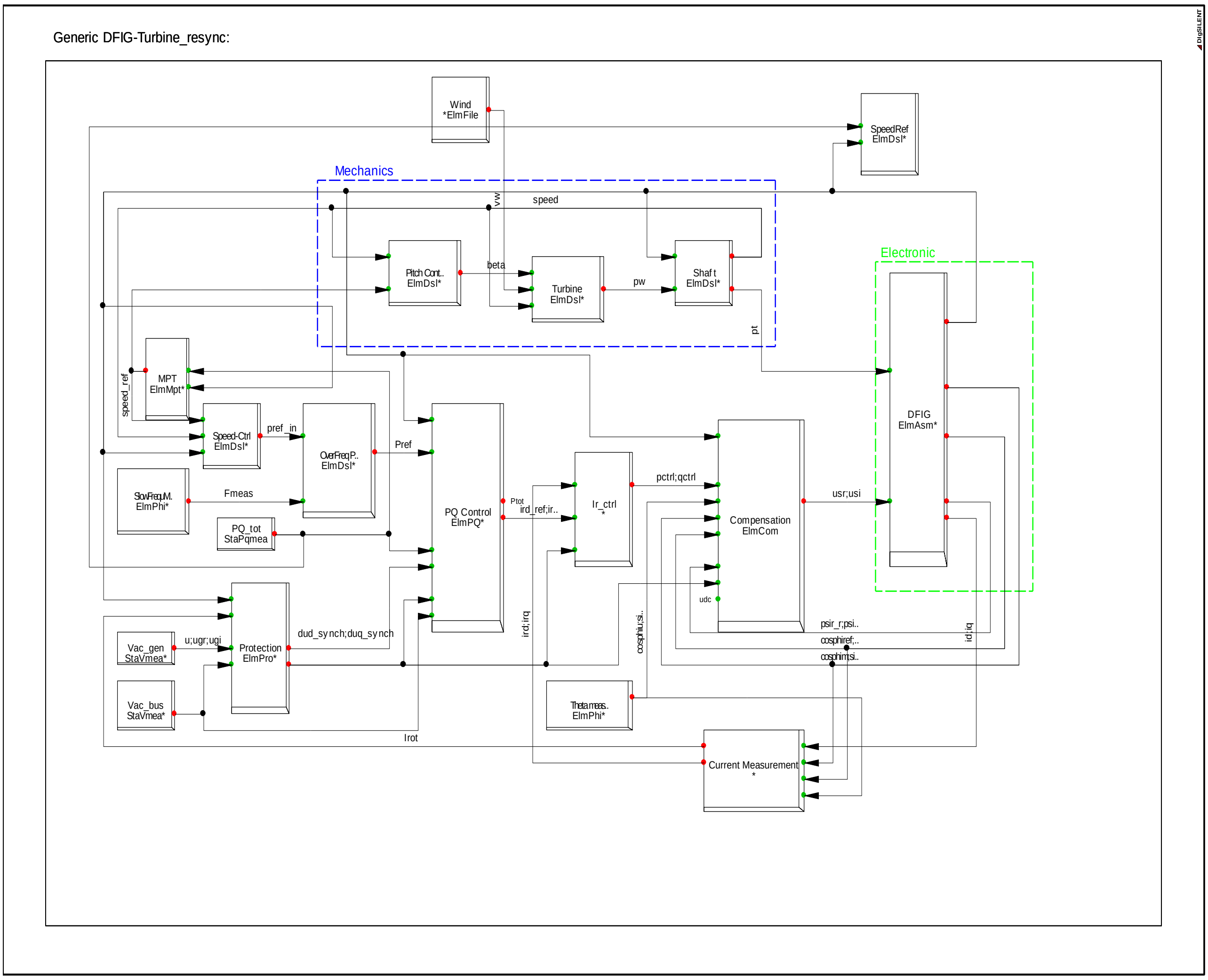

Figure 2. Complete scheme of the doubly-fed induction machine wind generator

The validation of the developed model in DIgSILENT is performed for fault free operation at different operating conditions. The rated wind speed is 11 m/s and the rated generator speed (ω_{gen}^{nom}) is 1485rpm. Fig. 3 illustrates the simulation operation at 8.5m/s mean value turbulent wind speed with turbulence intensity of 10%. This operation corresponds to the power optimization with variable generator speed reference. The speed controller has to be strong and fast in order to seek the maximum power. The speed reference corresponds to the generator speed for which the measured power is optimal. As expected for this wind speed range, the pitch angle is not active. Notice that the fast oscillations in the wind speed are completely filtered out from the electrical power. The validation is also performed when a turbulent wind speed with a mean value of 18m/s and a turbulence intensity of 10% is used. This simulation case corresponds to the power limitation strategy. The power limitation controller changes the pitch angle to keep the rated power, while the speed controller prevents the generator speed from becoming too high.

B. *Modeling of Yemen Power System*

Fig. 4 shows the DIgSILENT model of Yemen power system. There are four types of components: thermal power plants, the proposed MWF, the transmission network, and the loads. The supply of electric power is from thermal power plants composed of 439MW diesel engines, 510MW steam turbine generation systems, and 791MW gas turbine generation systems including 452MW of Mareb-2 power plant, and MWF supplying power up to the maximum of 60MW.

In case of studying grid impact (impact on thermal limits, voltage variations, and system stability), an aggregated model of the wind farm is typically used. Wind speed diversity within the wind farm is initially not considered and these studies are based on the assumption that up to the registered capacity of 60MW will potentially be generated at the grid connection point. When encountering problems, such as LVRT and power quality studies, a more detailed assessment considering wind speed diversity will be carried out. In this case, the WTGs are arranged in four strands; two strands are connecting seven WTs each and the other two strands are connecting eight WTs for each one, while the power system is modeled as external grid with 2175MVA short-circuit capacity.

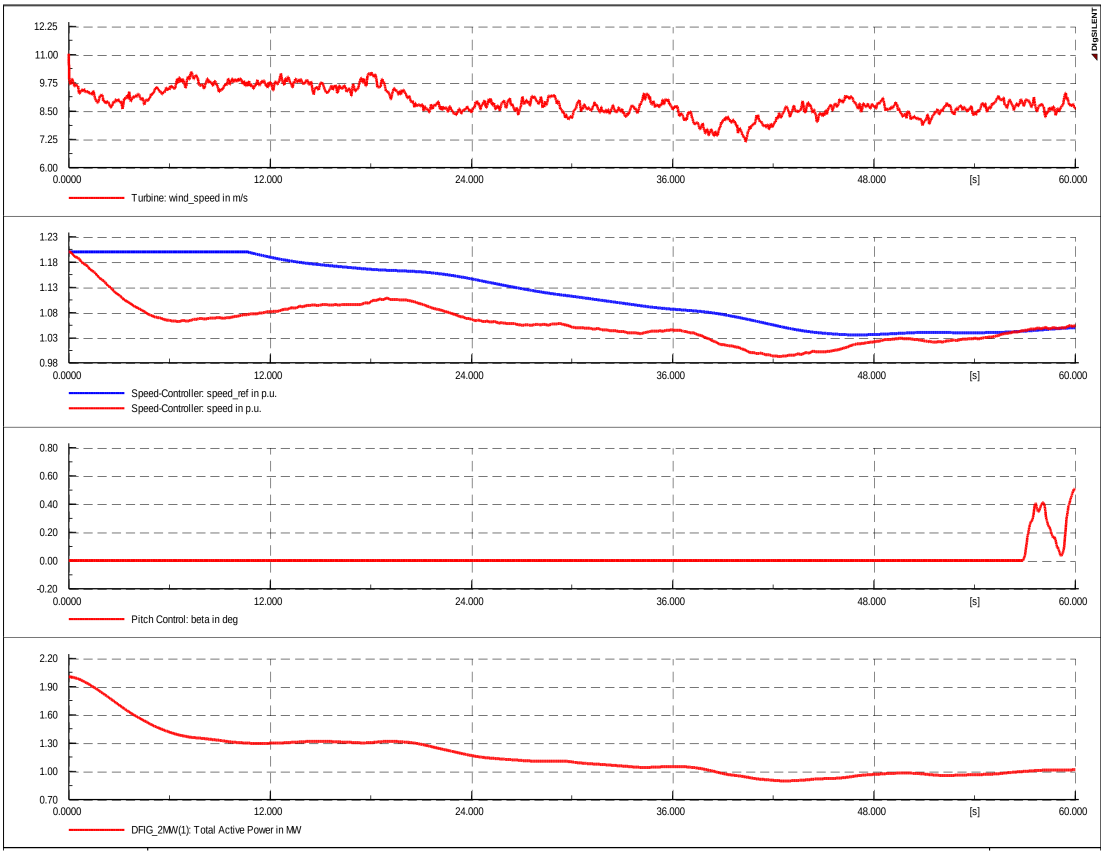

Figure 3. Simulation with turbulent wind speed of 8.5m/s mean speed and turbulence intensity of 10%

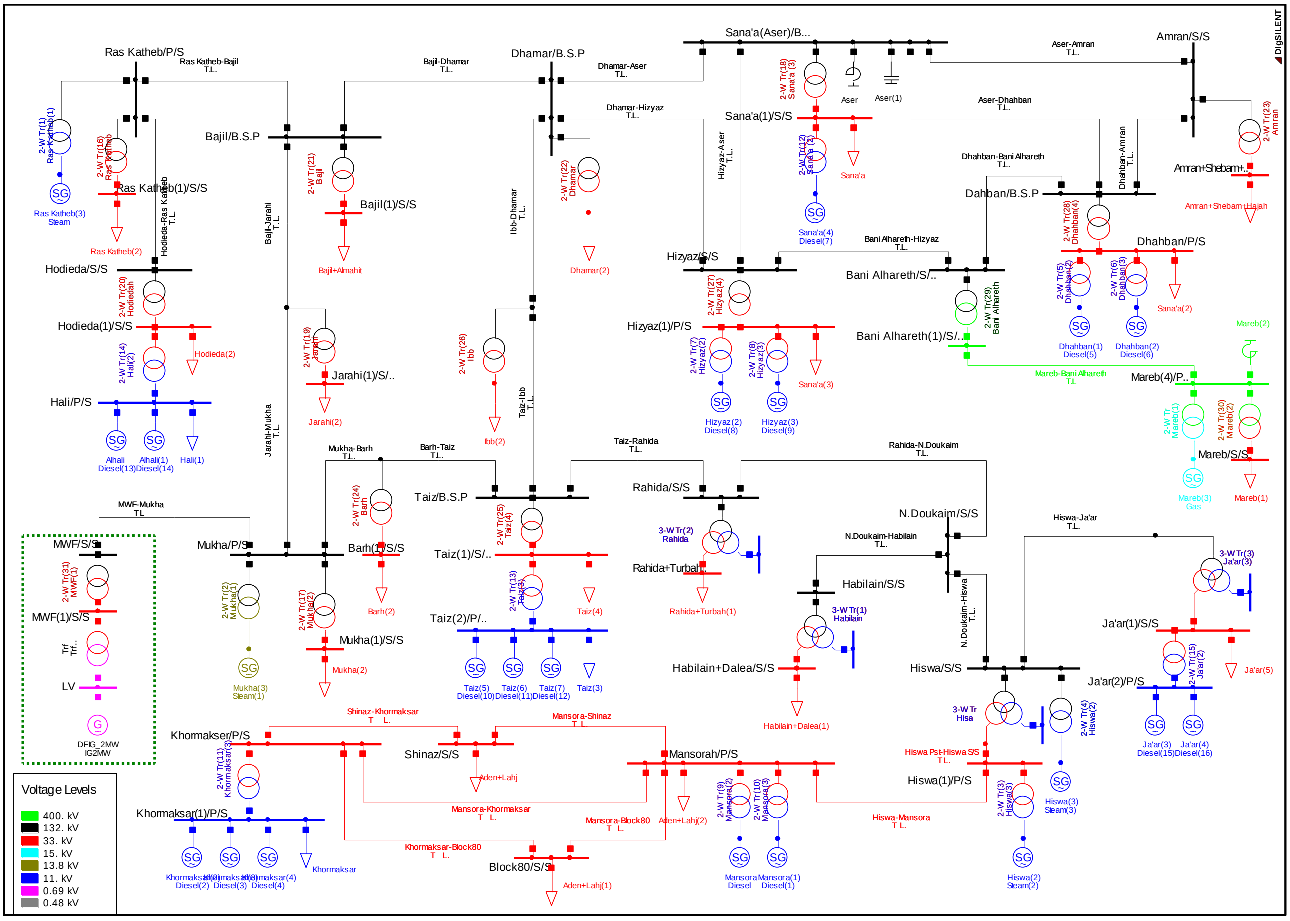

Figure 4. Yemen network scheme

IV. Simulation Results and Discussion

A. *Impact on Thermal Limits and Voltage Variations*

The load flow and contingency analysis studies allow analyzing the impact of wind generation on thermal limits and voltage variations during normal operations and during contingencies. The load flow study cases were:

- Peak load without MWF
- Peak load with MWF
- Minimum load without MWF
- Minimum load with MWF

For quick assessment, the current in transmission lines for peak load in case of without and with MWF are fully compared in Fig. 5, while Fig. 6 depicts the current comparison for minimum load case. Besides, Fig. 7 demonstrates the comparison of the voltage in the substations for peak load case without and with MWF. Fig. 8 demonstrates the comparison of the voltage in the substations for minimum load case without and with MWF respectively.

It can be concluded that when connecting MWF, the current flows are redistributed in the lines and reduced in most of the lines, where the maximum current is reduced by 6.32% in the peak load case and 7.17% in the minimum load case while the voltage in substation buses slightly rises enhancing the lowest value (in Dhamar) from 0.910 to 0.923pu in the peak load case.

From the results shown, it can be deduced that MWF integration does not significantly affect the voltages and currents performance along the network.

This section also contains the analysis of the power system performance (in the peak load with MWF) in the following contingencies:

- Losing one of the lines of Mareb – Bani Alhareth.
- Losing one of the lines of Al-Mukha – Barh.

The n-1 analysis based on load flow calculations of the considered lines leads to the conclusion that there is a thermal overload problem in the case that one of the parallel circuits between Mareb and Bani Alhareth is out of service.

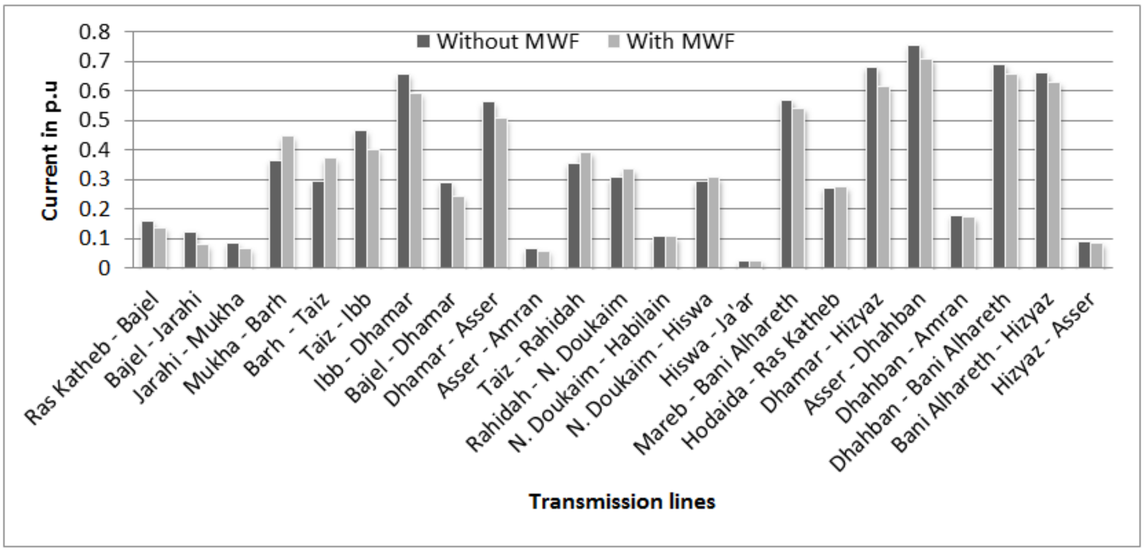

Figure 5. Comparison of the current in transmission lines (peak load without and with MWF)

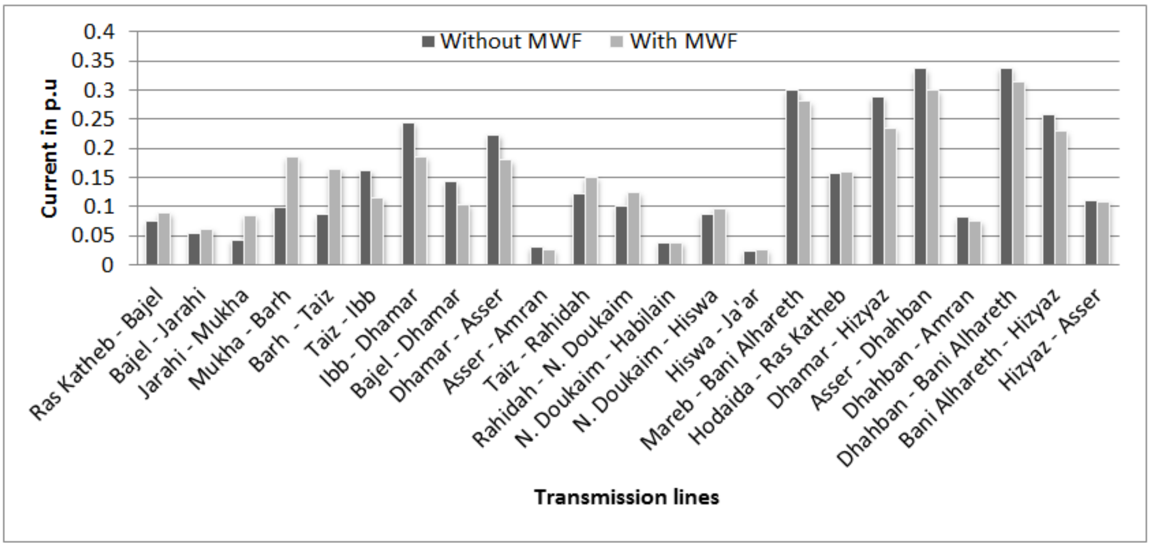

Figure 6. Comparison of the current in transmission lines (minimum load without and with MWF)

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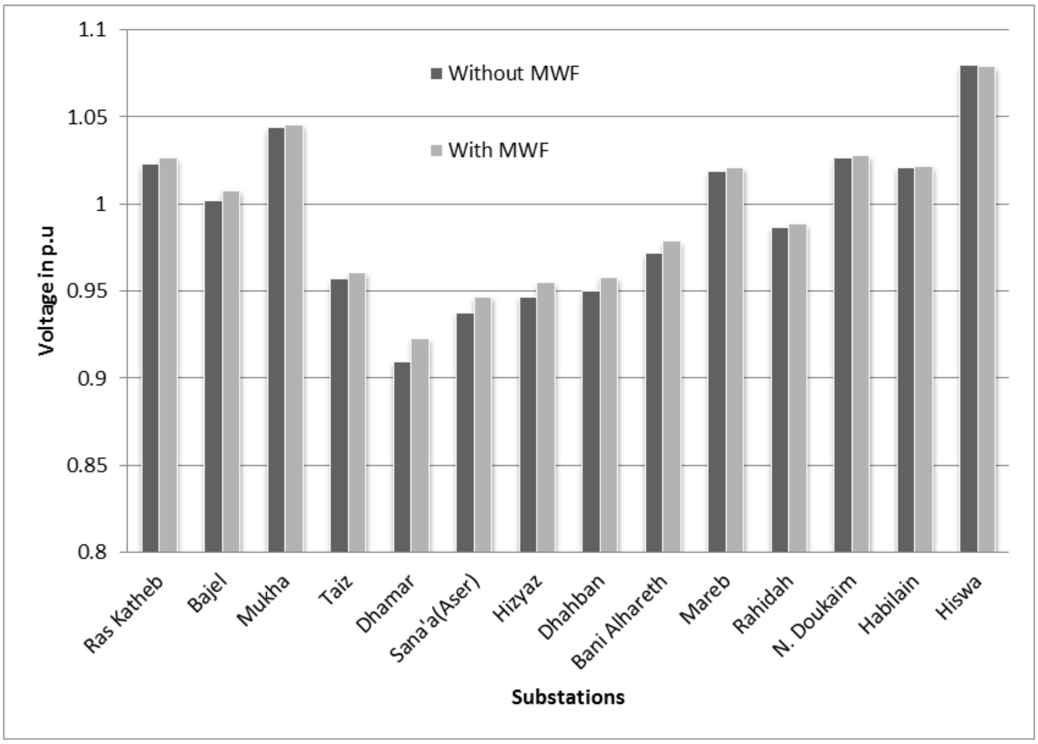

Figure 7. Comparison of the voltage in the substations (peak load without and with MWF)

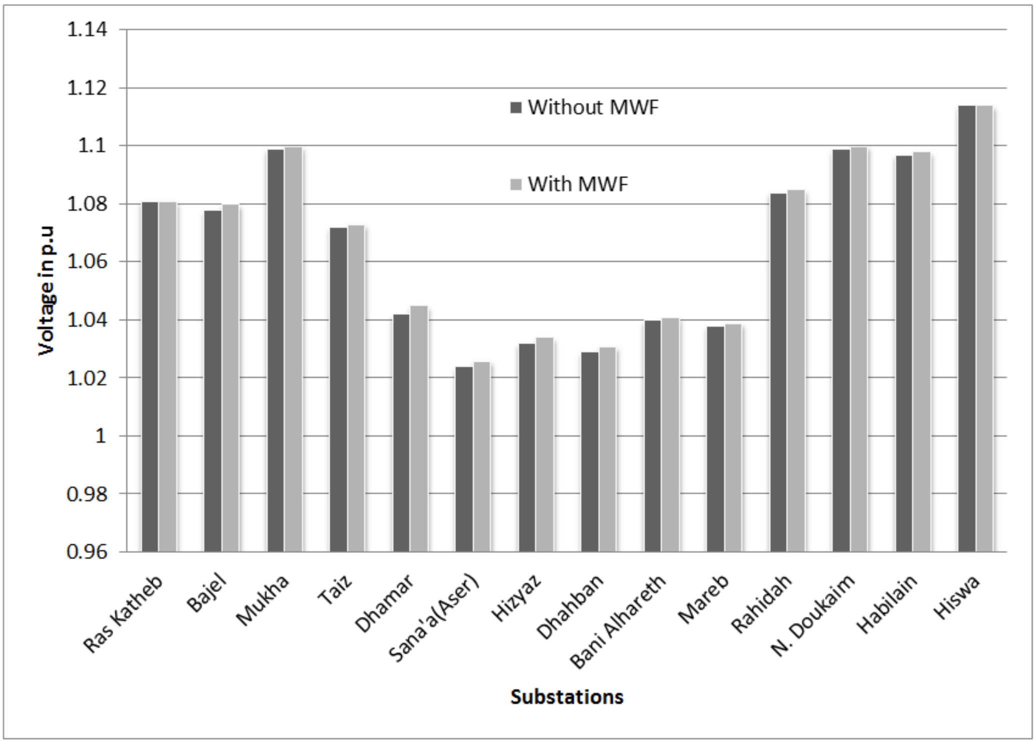

Figure 8. Comparison of the voltage in the substations (minimum load without and with MWF)

B. *Impact on the System Stability*

The following cases were considered as transient events:

- Sudden fall of MWF (stop producing energy).
- 3-Phase short circuit in Al-Mukha substation (the point of common coupling (PCC)).

For these cases, the stability of voltage and frequency were verified by the angles obtained for the power plants' generators. These angles are represented below in Fig. 9 and Fig. 10. As shown, a stability status was reached after clearing the fault, which is assumed at 100ms.

According to these achieved results, the system is capable to return to a stable state and MWF will not weaken the transient stability of the system.

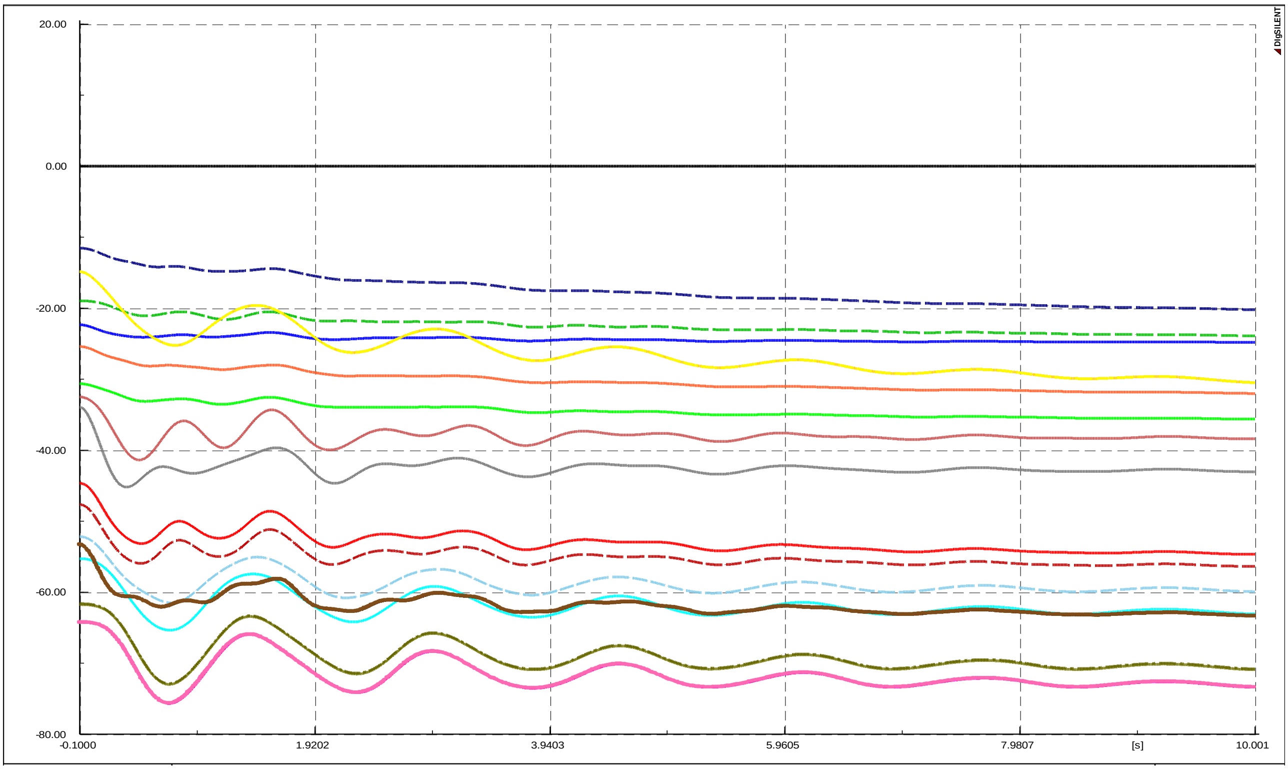

Figure 9. Generators relative power angle in degrees (sudden fall of MWF)

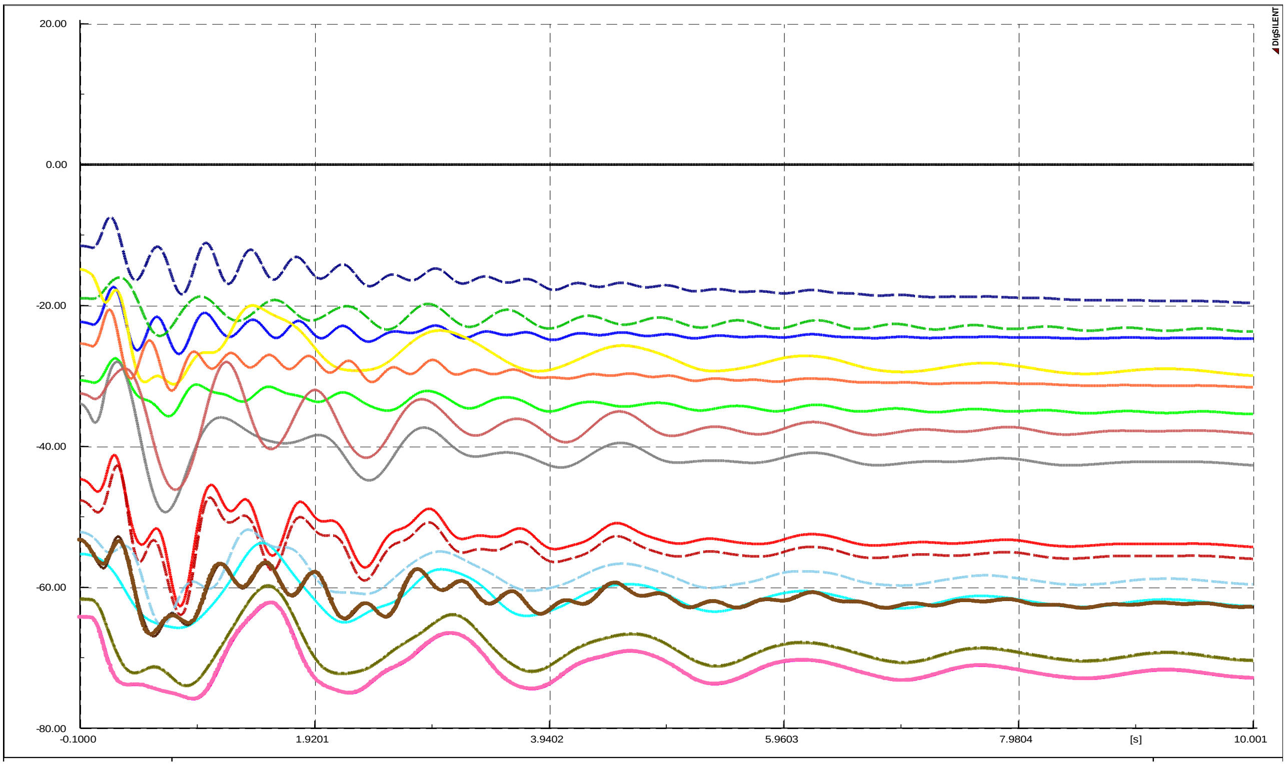

Figure 10. Generators relative power angle in degrees (3-phase short circuit in the PCC)

C. *LVRT Capability of DFIG Based WTG*

LVRT capability of the WTG is defined as the capability of the generator to remain connected to the grid under grid disturbances. In this study, three different wind scenarios were used for the investigation of the wind generator behavior as follows:

- Strong wind conditions
- Medium wind conditions
- Low wind conditions

For different wind conditions, various faults are applied to the grid. The following fault scenarios are simulated at the PCC:

- Solid 3-phase short circuit with 150ms clearing time (0% remaining voltage).
- 3-Phase short circuit with 150ms clearing time, 20% remaining voltage.
- 3-Phase short circuit with 150ms clearing time, 80% remaining voltage.
- Solid 2-phase short circuit with 150ms clearing time.

Fig. 11 shows the simulation results of a solid three-phase fault in the PCC at high wind conditions. When the fault was created at the HV bus at zero second, a voltage dip of zero p.u occurs at HV bus and occurs at MV bus with 0.1p.u. The rotor speed is increased from 1.2p.u. to about 1.27p.u. With respect to the change in speed, there is a variation in pitch angle between zero degree to 6.5 degrees. The current in the rotor is suddenly raised to about 1.9 times the rated capacity of the rotor. The fault is cleared at 150ms, at this moment; the voltage is rising to its pre-fault level. The speed and also pitch angle are also reduced after the clearance of fault. The value of rotor current is also reduced after the fault. In post fault conditions, the rotor current reached the value of about 0.8p.u.

As shown in Fig. 12, the active power generated by DFIG before fault occurrence is about 2MW. When the fault occurred, there is a reduction of power to zero value. After the fault clearance, there is a slight increase in power to 0.65MW there after it reached to zero value at 180ms then it gradually regained to its original value at 1.35s then there is a slight increase in power till 3.5s there after it regained to its original value. The phase current of the generator is also raised to about 3.5kA when the fault was occurred; it came gradually, after decreasing to 0.63kA, to its original value after the clearance of the fault.

The results show that the generators do not face instability. Besides, at low or medium wind conditions, i.e. at a low loading of the generators, no unstable behavior was shown.

During the fault, the DFIG supports the voltage stability by reactive current (reactive power) as shown in Fig. 12. The voltage supporting properties allow the wind farm to better ride-through network faults.

The results of the tested cases for the transient stability are summarized in Table I.

TABLE I. TRANSIENT STABILITY RESULTS

Fault conditions	Strong wind	Medium wind	Low wind
3ph short-circuit, 0%	Stable	stable	stable
3ph short-circuit, 20%	Stable	stable	stable
3ph short-circuit, 80%	Stable	stable	stable
2ph short-circuit	Stable	stable	stable

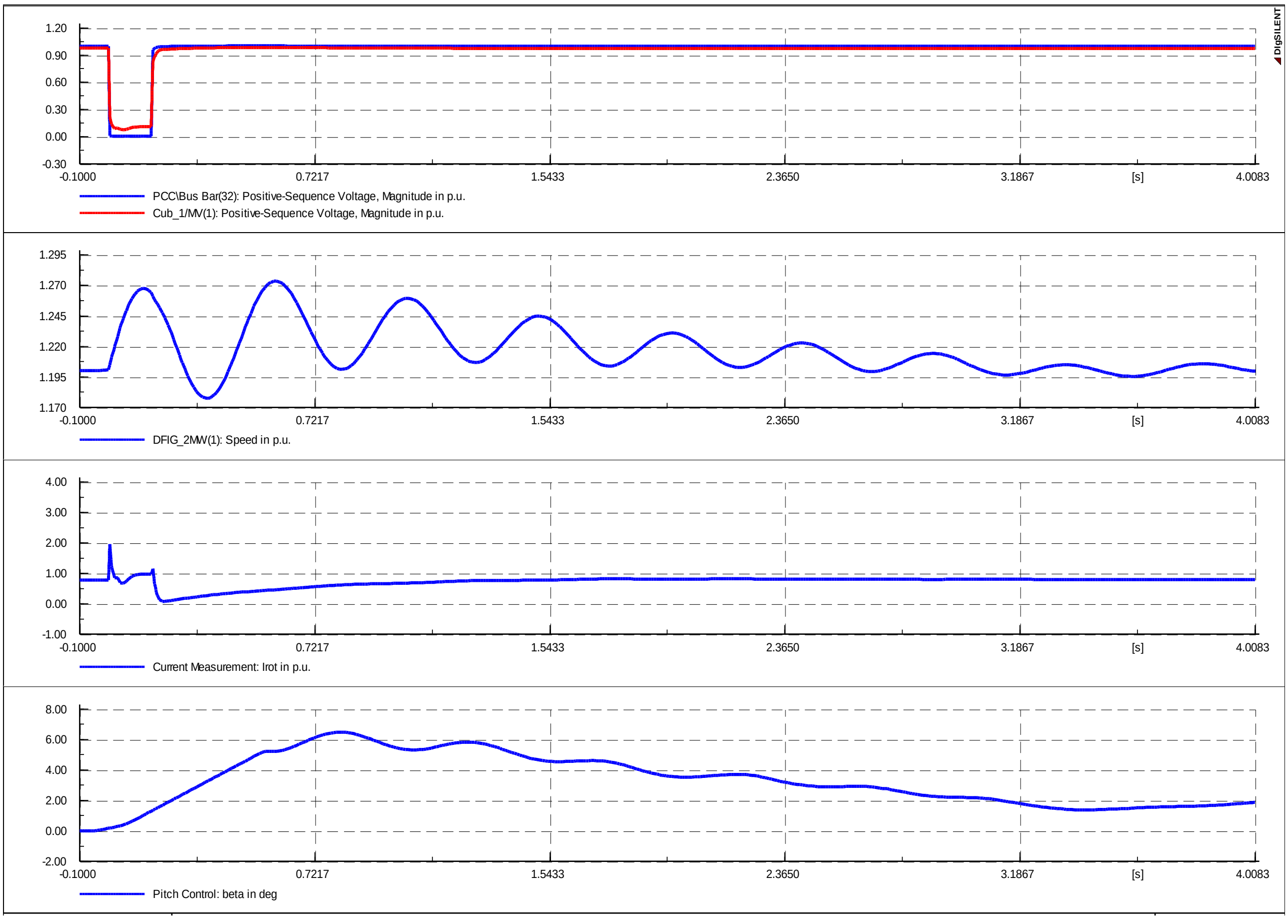

Figure 11. Voltages (at the PCC and at the MV bus), the generator speed, the rotor current, and the pitch angle during a solid three-phase fault for 150ms at high wind conditions

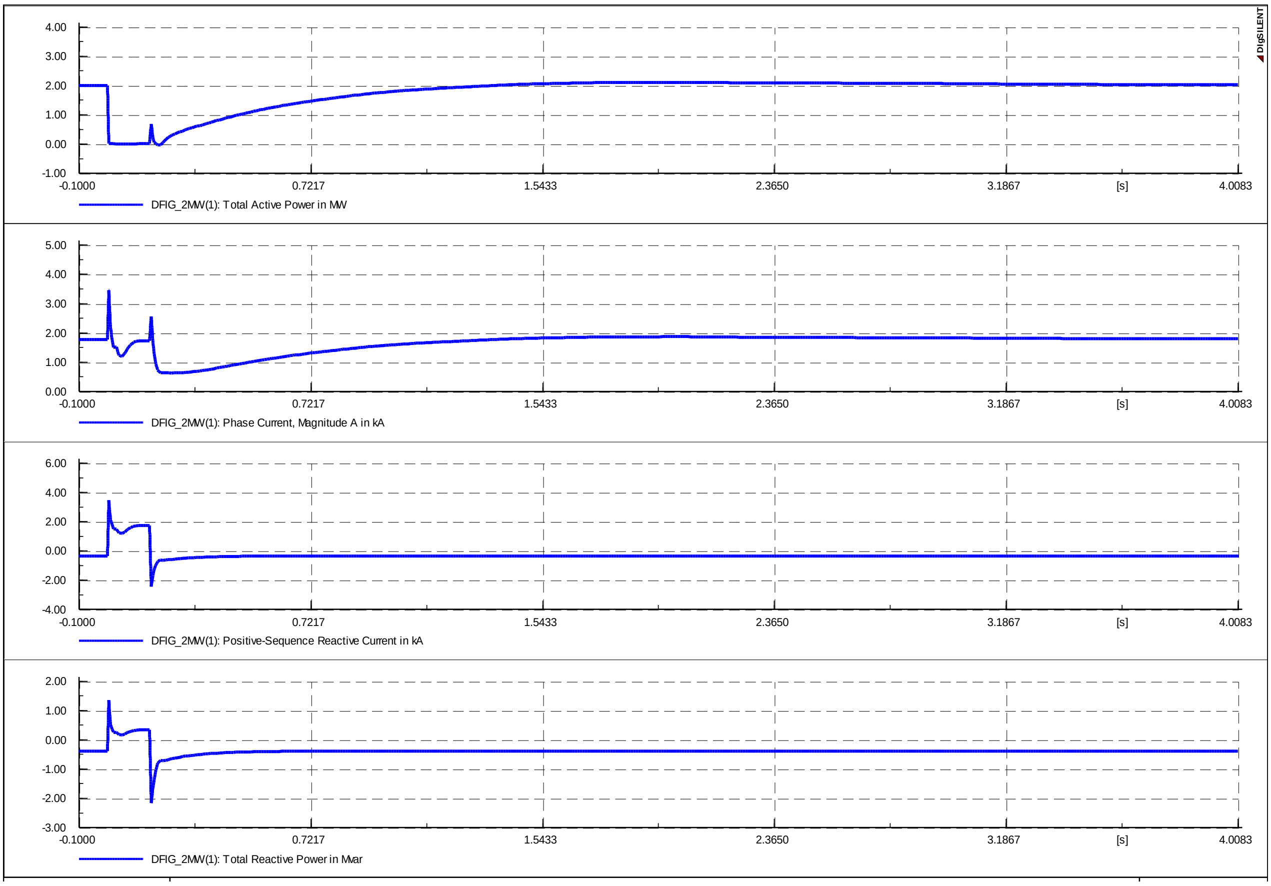

Figure 12. Generator active power, phase current, reactive current, and reactive power during a solid three-phase fault for 150 ms at high wind conditions

D. Analysis of Power Quality Aspects:

1) Analysis of harmonic impact of wind turbines on the grid:

According to DIgSILENT technical reference manual [10], harmonic load-flows allow the calculation of harmonic voltages or current based on the pre-defined harmonic sources and grid characteristics. Also, the software allows for the user-defined harmonic current sources to be located at any bus-bar on the grid. In this investigation the PMW converter has been defined as the harmonic source, its harmonic current spectrum has also been assumed to resemble that of the ideal (generic) model given in DIgSILENT.

Various wind turbines may emit variable harmonic spectra and their shapes (magnitudes) are dependent on the characteristics and control of the wind turbine converters used. In this case, the ideal spectrum which is provided in the DIgSILENT manual was used and modified to be IEC 61000 harmonic source with only integer harmonics.

The harmonic load-flow was performed for a 60MW DFIG wind farm. The monitoring was done at the PCC and, Fig. 13 illustrates the harmonic distortion (HD). The resultant total harmonic distortions (THD) are 18.8% and 6.61% of Irated for current and voltage total harmonic distortion respectively.

The limits for HD and THD are IEC 61800-3 [11] and IEEE 519 standards are used in DIgSILENT for current and voltage harmonics respectively.

The current and voltage THD for the proposed wind farm is much higher than the limits imposed by the standards. Also the current and voltage HD of the 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonics were above the permissible limits with a maximum current HD of 9.89% in the 11^{th} harmonic and a maximum voltage individual harmonic content of 3.71% in the 7^{th} harmonic. In such a case, it is needed to install filters to mitigate the distortions.

2) Analysis of flicker:

Flicker assessment for the wind farm is typically carried out according to IEC 61000-3-7 [12], and IEC 61400-21 [13]. The method requires the calculation of the minimum short circuit level and impedance angle (ψ_k) at the PCC.

Based on the impedance angle ψ_k, the maximum values for $C(\psi_k)$, $k_f(\psi_k)$, $k_u(\psi_k)$, N_{10}, and N_{120} for the relevant impedance angle at the PCC must be taken from a wind turbine measurement sheet according to IEC 61400-21, where:

- $C(\psi_k)$: Flicker coefficient as a function of the network impedance angle.
- $k_f(\psi_k)$: Flicker step-factor as a function of the network impedance angle.
- $k_u(\psi_k)$: Voltage change factor as a function of the network impedance angle.
- N_{10} , N_{120} Maximum number of switching operations in a 10-minutes, and 120-minutes period respectively.

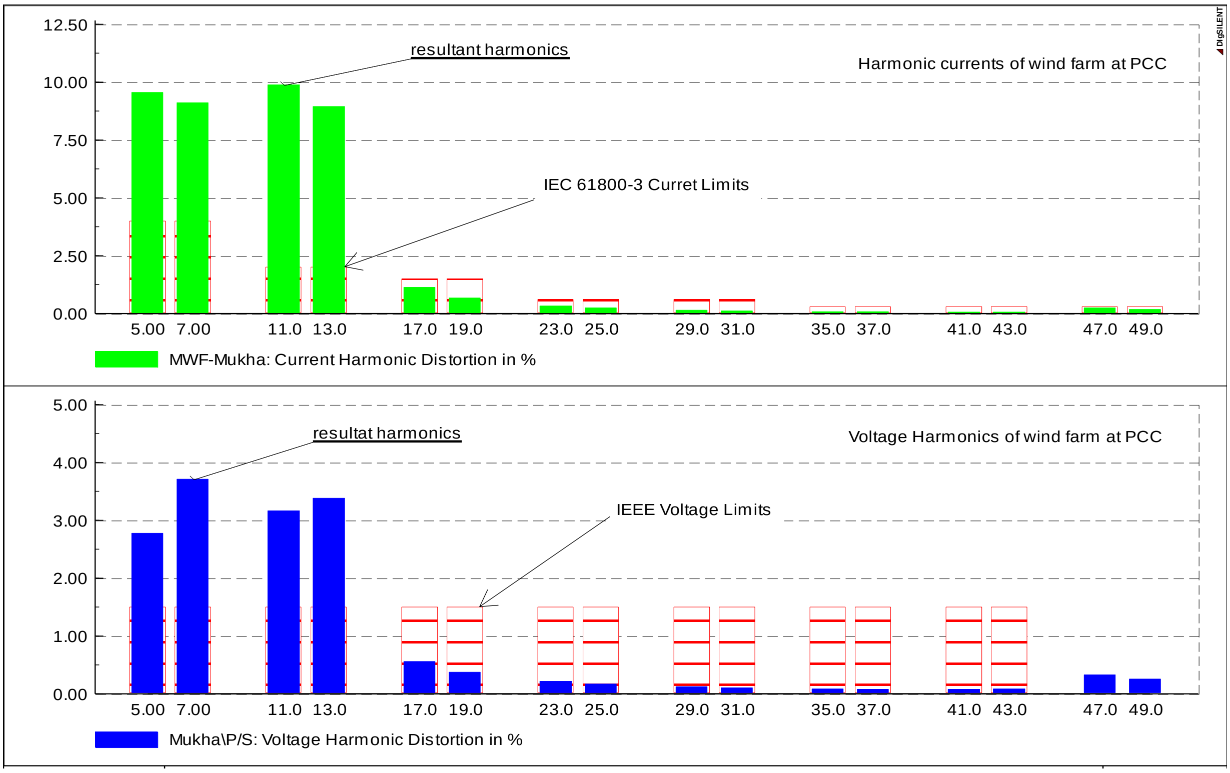

Figure 13. Current and voltage HD at the PCC

These values together with the minimum fault level at the PCC allow calculating:

- Short-Term and long term flicker disturbance factors (P_{st_cont} / P_{lt_cont}) during continuous operation.
- Short-Term and long term flicker disturbance factors (P_{st_sw}/P_{lt_sw}) due to switching actions.

The resulting flicker levels are as follows:

- $P_{st\_cont} = P_{st\_sw} = 0.01$,
- $P_{lt\_cont} = 0.04$, and $P_{lt\_sw} = 0.01$.

The significance of the actual results is very limited because the actual results will depend on the actual type of turbines that will be installed. However, since the calculated numbers are far below any critical values (found in [12]), it can be assumed that flicker will not cause any problem in the case of a 60MW at MWF project.

V. Conclusion

Modeling and impact analysis of integrating Al-Mukha wind farm to the Yemen power system, have been performed using the DIgSILENT program.

The studies of load flow showed that the loading of most lines and voltage variations are slightly changed. Under the contingency situations, there is a thermal overload issue of the overhead lines. Additional findings from the transient stability studies indicate that MWF will not weaken the system transient stability. The LVRT study showed that after the fault is cleared, the wind turbine generators recovered their voltage level almost to its pre-fault voltage value. It is found that the proposed wind farm contributed voltage and current THDs higher than the permissible limits specified in the standards. This would require a harmonic filter to be installed in order to mitigate the harmonics. As for the flicker, the resulting levels are far below any critical values so it can be assumed that flicker will not cause any problem in the studied case.

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