Performance Analysis of Power Quality Impact of Adama-One Wind Farm in Ethiopia

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***Abstract*—Due to the intermittent nature of wind, the power quality of the grid with wind power plants is affected. Hence, in order to assure the power quality of Adama-One wind farm, the continuous performance assessment is recommended using various performance indices. Two aspects of the wind farm performance evaluations are assessed. The first aspect is the evaluation of power and energy production performance indices. From production analysis aspect, the wind farm delivers average power of 18.43 MW to the grid with maximum of 51.09 MW and minimum of 2.08 MW. The energy delivered over one year in 2015/16 G.C has been 157.74 GWH against the design yearly harvest of 162.7 GWH per year. Hence, the Capacity Factor result of annual energy production is found to be 35.3 %. These demonstrate that based on the current status, the wind farm performance is good and within the design range. The second aspect is analysis of harmonic emission from the wind farm as the result of frequency converters and other nonlinear loads. The harmonic current data's are collected at one of the point of common coupling (PCC) which is at 33 KV bus bar systems, where 3rd and 5th current injection harmonic filters are installed. Using Matlab software, the steady state harmonic load flow analysis of the wind farm at 33KV bus-bar system is performed. It has been found that the results of mathematically analyzed Total Harmonic Distortion (THD) current and voltage values are almost similar to that of simulated THD output of current and voltage.The wind farm harmonic current emission with maximum calculated value of 5.96 % is found to be within permissible limit set by international standard at selected PCC which is 7%. The maximum calculated THD voltage is also found to be 2.75 % which is less than 5 % set by IEEE STD-519. Hence, power quality of the wind farm can be said to be good and do not have significant negative impact on the power quality of grid system at present. Finally, the grid code standard is proposed.**

Keywords: Harmonic Filters, IEEE STD-519, Performance Indices, PMSG, Point of Common Coupling, Power Quality, Total Harmonic Distortion, Wind Turbine.

I. INTRODUCTION

Now a day, wind power plants are becoming dominant in serving as source of energy. This is because of the advancement and better understanding of the technology, energy security, generation mix, and aim to decrease the greenhouse gases or global warming. The central geographical position of the wind farm is 39° 13' 48"E latitude,8°32'41"N longitude with (400-600)m wide and 5km long and the farm is 95 km far from Addis Ababa, capital city of Ethiopia.The installed capacity of Adama-One Wind farm is 51MW with 34 units each having a capacity of 1500kW. The basis of the Gold Wind 1.5MW wind turbine is its permanent magnet (PM) generator, which is gearless and directly driven by a 3 blade rotor. The converter system combined with the PMDD (Permanent Magnet Direct Drive) synchronous generator guarantees superior grid connection capabilities. But the converter-inverter system used in wind farms produces harmonic emissions; hence it may result a power quality problems within the wind farm and the grid connected to it. At the generation substation, the wind farm is connected to the grid from this substation,

- 132 kV transmission line is linked to the Adama-old grid.
- The rest is connected to Load Dispatch Center (LDC)

II. GRID CONNECTED WIND POWER PLANT

In order to fulfill the power demand needed by consumers, countries are applying various types of renewable energy sources in addition to the conventional sources. Among these renewable sources, wind energy is recently becoming dominant. But due to the intermittent nature of wind, the presence of frequency converters and nonlinear loads, Harmonics emission is resulted. This causes the power quality problem which is being observed in different countries across the world.

Wind farms have different impacts and functions on the performance of the grid than conventional power plants because of variation of wind speed in time. Doubly fed and Squirrel cage induction generators are widely used in wind energy conversion systems. These generators are usually grid-coupled via power electronic converters in order to control the voltage, frequency and power flow during the variation ofwind speed. As a consequence, wind turbines affect the dynamic behavior of the power system in a way that might be different from hydraulic or steam turbines [1].

Harmonics arise whenever non-sinusoidal currents and/or voltages are generated in the power system. These are generally referred as Harmonic Distortion. The basic conditions that give rise to harmonic-related problems in power systems are Non-linear loads, Phase imbalance, High input voltage or current and Resonance [2].

In most Swedish distribution networks, the problems related to harmonics have been until now and most often, it is not harmful. The harmonics levels have thus been acceptable. However, studies done in, for example, USA, Japan and France show that the harmonic levels have increased. The reason for the increment of harmonic level is the intensive use of power electronic devices which results high harmonics in distribution networks. The increase in harmonics level has specially been noticed in Japan where the problems related to harmonic levels also increased [3].

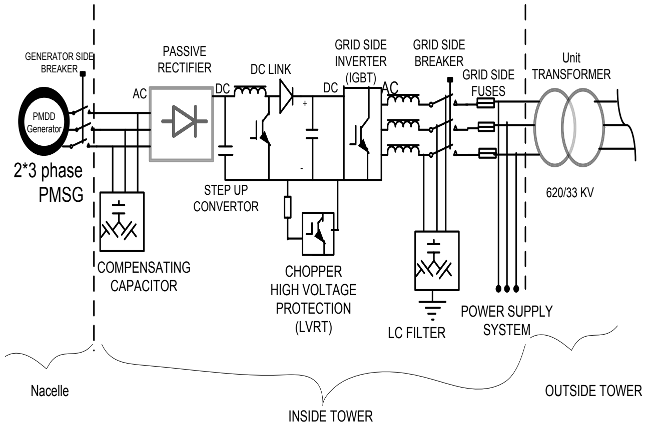

Fig. 1. Gold Wind 1.5 MW Electrical Diagram [4]

The figure above applies six phase Rectifier &frequency converter system for the sake of transferring the power produced efficiently and with good power quality. The rectifier efficiency improvement under six phase is evaluated using the DC-link output.

A. Bridge Rectifier

The DC link voltage for six pulse is given by

$$V_{dc}=\frac{\int_{30}^{90^{o}} V_{ab}\,d\omega t}{\frac{2\pi}{6}}=\frac{3}{\pi}\int_{30}^{90^{o}} V_{m}[\sin(\omega t)-\sin(\omega t-120^{o})]d\omega t \quad (1)$$

$$=\frac{3}{\pi}\sqrt{3}\,V_{m}=\frac{3}{\pi}\sqrt{3}\sqrt{2}V \qquad \text{where, } V_{m}=\sqrt{2}V$$

$$=1.35V_{LL} \quad \text{where, } V_{LL}=\sqrt{3}V$$

For six phase system, the voltage is given by,

The DC link voltage for twelve pulse is given by

$$V_{dc}=\frac{\int_{45}^{75^{o}} V_{ab}\,d\omega t}{\frac{2\pi}{12}}=\frac{6}{\pi}\int_{45}^{75^{o}} V_{m}[\sin(\omega t)-\sin(\omega t-60^{o})]d\omega t \quad (2)$$

$$=2.42V_{m}=1.398\,V_{LL}$$

From the above two results, comparison of the dc-link voltage can be seen that the six phase system is more efficient than three phase system.

B. Frequency Converter

The connection of the wind farm to the public grid is done by a frequency converter system and a transformer. The frequency converter has been specially designed for the use together with synchronous generators. It allows a complete separation of the generator operation from the grid system. So, variable speed operation of generator in a speed range of 9 to 17.3 rpm is possible.

The main circuit diagram of the converter system is as follows.

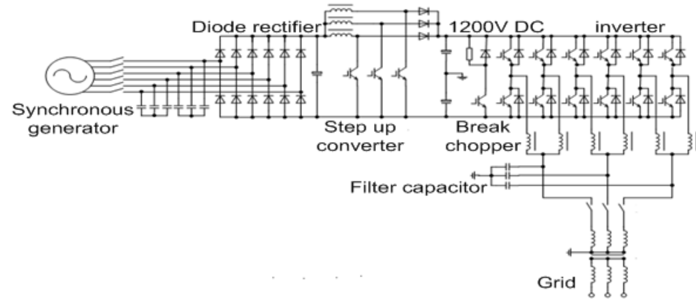

Fig. 2. Six phase converter inverter system of AWF [4]

The converter device is designed specially according to the feature of permanent magnet synchronous generator. It has an excellent flexibility with the six phase PMSG. The inductors placed as wing structure used to produce the final three phase output additionally to that of reducing the harmonics effect. The direct driven type can greatly reduce the noise of system operating and raise reliability. The applicable frequency scope of GW1500 KW set is 47.5 Hz to 51.5 Hz. In the state of power grid short circuit, there are only 1.5 to 2.5 times rated torque. It is 7 to 9 times much lower than that of IM Induction Motor (IM) or Double Fed Induction Generator (DFIG).

III. METHODOLOGY& ANALYSIS

For the analysis of the wind farm current performance, different performance indices are considered. Among this, power coefficient with respect to tip speed ratio is checked at its rated wind speed.

A. Power Coefficient

Then Cp in terms of λ is given as follows

$$Cp=\frac{(1+\lambda)*(1-\gamma)}{2} \quad (3)$$

$$=\frac{(1+0.0428)*(1-0.04)}{2}$$

$$=0.5=50\%$$

Where Cp is power coefficient, λ is Tip speed ratio & γ is Ground surface coefficient.

Using the above value, Matlab simulation output of pitch controlled wind turbine power coefficient versus tip speed ratio curve at rated wind speed of 11 m/s is given below.

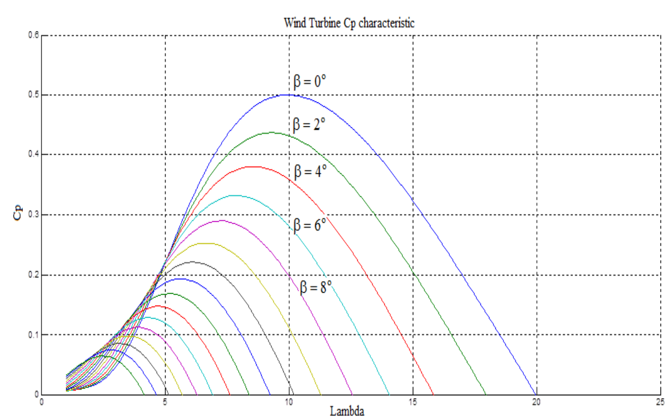

Figure 3. CpVs λ output at different pitch angle.

Among all curves, the desired one is the point where pitch angle is found to be zero because at this angle value of the required power can be produced.
Using the calculated values and the datas given from the manufacturer, available power can be determined.
Given the following data:
Blade length, l= r= 38.5 m, Wind speed, V = 11 m/sec
Air density, ρ = 0.97 kg/m3, Power Coefficient, Cp= 0.5
Inserting the value for blade length as the radius,
l= r= 38.5 m
A = πr^2, where A is the swept area
= $\pi*(38.5m)^2$
=$4654m^2$
Finally the power converted from the wind by a turbine will be,

$$P_{avail}=\frac{1}{2}\rho AV^3C_p(\lambda,\beta) \quad (4)$$

$$P_{avail}=\frac{1}{2}*0.97kg/m^3*4654m^2*(11m/s)^3*0.5$$

$$P_{avail}=1.5MW$$

The power curve analysis of a turbine system is assessed using the following diagram.

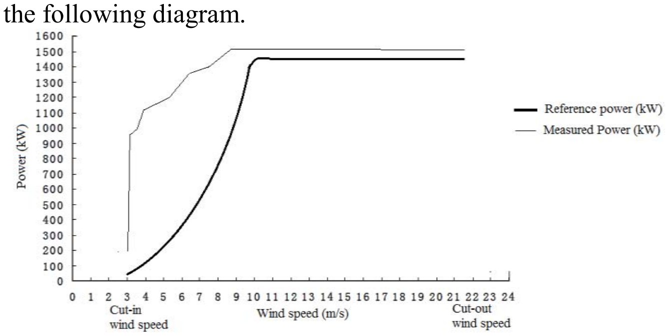

Fig. 4. Comparison between the reference and measured power curve.

From Fig. 4, the measured power curve shows almost similar characteristics with that of the reference curve that provides the maximum amount of power at rated wind speed value.

B. Permanent Magnet Synchronous Generator (PMSG) Characteristic Equations

The generator system has two sets of three-phase windings on the stator side, which are shifted by 30 electrical degrees with each other. The voltage equations for the six physical stator windings are shown below [19]

$$V_s=R_s i_s+\psi'_s \quad (5)$$

Where, V_s stator voltage, R_s stator resistance, i_s stator current and ψ_s is flux leakage.

$$V_s=[V_a \ V_b \ V_c \ V_x \ V_y \ V_z]^T,$$
$$i_s=[i_a \ i_b \ i_c \ i_x \ i_y \ i_z]^T,$$
$$R_s=r_1 I_{6*6}$$
$$\psi_s=[\psi_a \ \psi_b \ \psi_c \ \psi_x \ \psi_y \ \psi_z]^T.$$

The resulting voltage equation in d-q axis is:

$$V=Ri+\psi' \quad (6)$$

The Equivalent circuit of PMSG based on the wind energy conversion system is shown below.

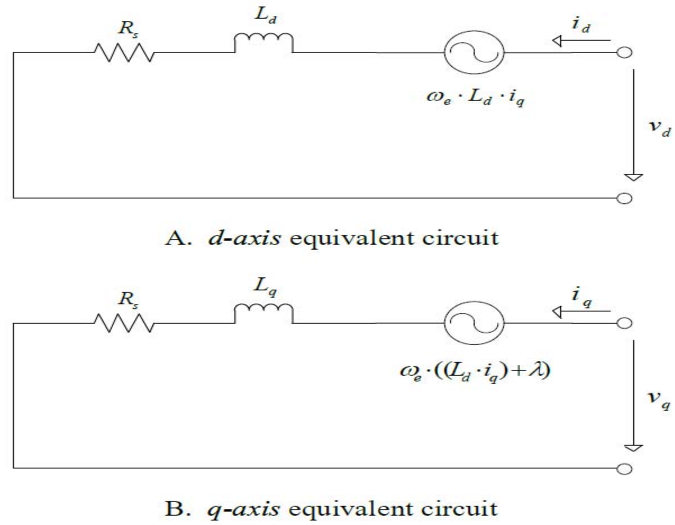

Fig. 5. Equivalent circuit of PMSG in d-q reference frame

From Fig. 5, the voltage equation can be expanded as:

$$\frac{d}{dt}i_d=\frac{1}{L_d}v_d-\frac{R}{L_d}i_d+\frac{L_q}{L_d}P\omega_r i_q \quad (7)$$

$$\frac{d}{dt}i_q=\frac{1}{L_q}v_q-\frac{R}{L_q}i_q+\frac{L_d}{L_q}P\omega_r i_d-\frac{\lambda p\omega_r}{L_q} \quad (8)$$

Where,
L_d = d axis inductance
R = resistance of the stator winding
i_q= q axis current, i_d= d axis current, V_q= q axis voltage,
V_d= d axis voltage, ω_r = Angular velocity of rotor,
λ= flux induced, P number of pole pairs.

C. Energy Production Assessment of AWF

Monthly energy production data are collected for a year and then capacity factor is calculated to check the current capacity of AWF. A capacity factor implies that the system run at full capacity the entire year. The capacity factor for a large wind farm ranges from 20% to 42%, the latter figure being close to the technology potential.

$$CF=\frac{\text{Annual energy production (MWh)}}{\text{Installed capacity * total hour in a year}} \quad (9)$$

D. Power Quality Assessment of the Farm

The following procedure has been used to analyze the THD level of the wind farm:
Step 1: Choose the point of common coupling.
Step 2: Identify the date where filters are connected to the system.
Step 3: Collect harmonic current data from filters output.
Step 4: Calculate THD of current and voltage at selected PCC.
Step 5: Verify power quality status of AWF by comparing Calculated THD of voltage and current with standard.

E. Mathematical Formulation of Harmonics

To analyze wave forms of voltage and current, the commonly used tool is Fourier series. Fourier series basics are described using the following equations.

$$f(t)=\frac{1}{2}a_0+\sum_{n=1}^{\infty}(a_n\cos n\omega t+b_n\sin n\omega t) \quad (10)$$

Where, $\omega=\frac{2\pi}{T}$

$$a_0=\frac{2}{T}\int_0^T f(t)dt$$

$$a_n=\frac{2}{T}\int_0^T f(t)\cos(n\omega t)dt$$

$$b_n=\frac{2}{T}\int_0^T f(t)\sin(n\omega t)dt$$

Where n is a whole number

The above analysis can also be expressed as follows:

$$f(t)=\frac{1}{2}a_0+\sum_{n=1}^{\infty}C_n\sin(n\omega t+\varphi_n) \quad (11)$$

where, $C_n=\sqrt{a_n^2+b_n^2}$

$\varphi_n=\arctan\frac{b_n}{a_n}$

So, a distorted voltage V (t) of period T can therefore be expressed in the following manner,

$$V(t)=V_0+\sum_{n=1}^{\infty}V_n\sqrt{2}\sin(n\omega t+j_n) \quad (12)$$

where $\omega=\frac{2\pi}{T}$

V_0: Amplitude of the DC component

j_n: The initial phase of V_n, (t=0)

Similarly, a distorted current i (t) of period T can be expressed as:

$$i(t)=I_0+\sum_{n=1}^{\infty}I_n\sqrt{2}\sin(n\omega t+\varphi_n) \quad (13)$$

where

I_0: Amplitude of the DC component

φ_n: The initial phase of I_n, (t=0)

RMS formula of harmonic voltage and current:

Related with the above basic equations, the RMS value of the signal V (t) is defined as:

$$V_{rms}=\sqrt{\frac{1}{T}\int_0^T V^2(t)dt} \quad (14)$$

Parseval's theorem tells us that:

$$\frac{1}{T}\int_0^T V^2(t)dt=V_0^2+\sum_{n=1}^{\infty}V_n^2 \quad (15)$$

This gives the following relationship of voltage and current RMS values:

$$RMS_V=\sqrt{V_2^2+V_3^2+V_4^2+\dots}=\sqrt{\sum_{n=2}^{\infty}V_n^2} \quad (16)$$

Similarly,

$$RMS_I=\sqrt{I_2^2+I_3^2+I_4^2+\dots}=\sqrt{\sum_{n=2}^{\infty}I_n^2} \quad (17)$$

Considering that DC components, V_0 and I_0=0.

Total Harmonic Distortion (THD):

It is the measure of power quality of the wind farm by analyzing the non-sinusoidal wave forms of voltage and current. Assuming no DC component in the output, THD can be determined as follows

$$THD_I=\frac{\sqrt{\sum_{n=2}^{\infty}(I_{n,\ rms})^2}}{I_1} \quad (18)$$

$$THD_V=\frac{\sqrt{\sum_{n=2}^{\infty}(V_{n,\ rms})^2}}{V_1} \quad (19)$$

The fundamental current (I_{fund}) which is used for total harmonic current distortion estimation has been selected using the equation shown below [24].

$$I_{fund}=\frac{kV_{actual}/\sqrt{3}}{X_{fund}} \quad (20)$$

Where, K is the k factor of the step up transformer in the substation (PCC). V_{actual} is the actual voltage measured at selected bus bar (PCC) [V].$X_{fund}$is the per phase fundamental reactance [Ω]. After computing the current and voltage THD from the collected harmonic currents, IEEE standard harmonic current limit is selected using the following formula to know that the estimated values are within the limit or not.

$$SCR=\frac{\text{short circuit MVA}}{\text{load MW}}=\frac{I_{sc}}{I_L} \quad (21)$$

Where,

$I_{SC}$is the maximum short circuit current at the PCC.

$I_L$is the maximum demand load current at PCC.

Short circuit current calculation:

Assuming S_j = 100MVA, Select short circuit point, that is 33kV short circuit point;

Taking short circuit current from Nazareth substation I_R = 10 KA, Short circuit capacity,

$$MVA_{sc}=\sqrt{3}*U_n*I_R=\sqrt{3}*132*10=2286.24\,MVA \quad (22)$$

Short circuit reactance unit value,

$$X_x=\frac{S_j}{S_{MVA}}=\frac{100}{2286.24}=0.0437$$

Main transformer reactance unit value:

$$X_T=\frac{U_Z\%}{100}*\frac{S_j}{S_n}=0.105*\frac{100}{55}=0.19$$

1. Reactance unit value calculation of 34 WTGs:
   $X=X_x+X_T=0.0437+0.19=0.2337$
2. Considering infinite bus system
   $I_z^{'}=\frac{1}{X}=\frac{1}{0.2337}=4.279$
3. Reference current:
   $I_j=\frac{S_j}{\sqrt{3}*U_j}=\frac{100MVA}{\sqrt{3}*33}=1.75\,KA$
4. Short circuit current from infinite bus system:

$$I_z=I_z^{'}*I_j=4.279*1.75KA=7.49KA \quad (23)$$

Short circuit current from 34 WTGs

1. Reactance unit value of total 34 WTGs:
   $X=0.51$
2. Effective reactance of 34 WTGs:
   $X_{js}=X*\frac{S_n}{S_j}=0.51*\frac{51/0.95}{100}=0.274$
3. Then, $I_z^{'}=4.6$
4. Reference current
   $I_j=\frac{Sn}{\sqrt{3}*U_j}=\frac{51/0.95}{\sqrt{3}*33}=0.94\,kA$

Then, $I_z=I_z^{'}*I_j=4.6*0.94=4.324\,kA$

Short circuit current:

$$\sum I_z = 7.49 + 4.324 = 11.814\,\text{kA}$$

Maximum short circuit current, considering circuit breaker sizing factor is computed as:

$$I_{SC}=\sqrt{2}*K_{ch}*\sum I_z=\sqrt{2}*1.9*11.814=31.5\,\text{kA} \quad (24)$$

Where K_{ch} is sizing factor of circuit breaker [5].

Load current calculation:

$$I_L=\frac{\text{Load MW}}{V_{Load}}=\frac{51\text{MW}}{33\text{kV}} \quad (25)$$

I_L= 1.54 kA.

The load current (I_L) is computed by taking the ratio of maximum Load power in MW and the voltage at 33 kV bus bar systems. Short circuit ratio is determined from I_{sc} and I_L and then the limit for current and voltage are found.

F. Harmonic Power Loss Evaluation of the Farm

Power loss of Adama-One wind farm due to the harmonics emission effect is assessed at a PCC of 33 KV, 2000A bus bar system. The power loss calculation is done using harmonic voltage, current and true power factor.

$$P_{loss}=V_H*I_H*pf \quad (26)$$

Evaluation of Harmonic Filters and Their Impact:

The impact of 3rd and 5th harmonic filters installed in AWF is evaluated based on their contribution of power factor improvement of the wind farm. The active and reactive power datas are collected for a sample of one month. To calculate the power factor, first apparent power (S) is calculated from collected power datas using equation shown below.

$$S=\sqrt{P^2+Q^2} \quad (27)$$

And,

$$\cos\varphi=\frac{P}{S}$$

Where S apparent power and $\cos\varphi$ is power factor.

For estimation of the power factor, the maximum values of active and reactive power are used to find the power factor value at worst case.

IV. RESULT AND ANALYSIS

A. Energy Production Analysis of Adama-One Wind Farm (AWF)

The Fig. 6 below summarizes the annual energy production of AWF based on the collected data from Data Logger and SCADA system.

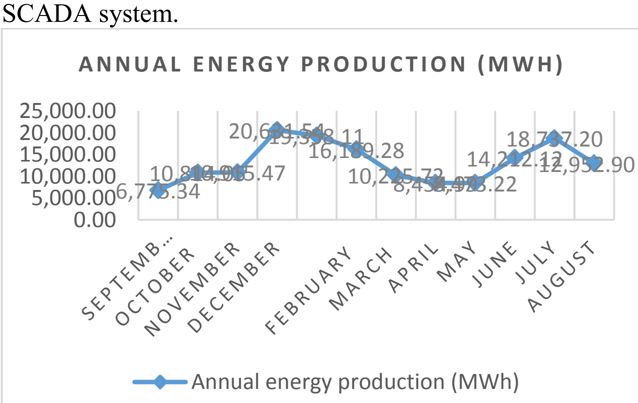

Fig. 6. Result summary of AWF Annual energy production

As per the above production analysis, there is 3% difference between the currently calculated annual energy production of 157,739.93GWhand that of the reference value of firm energy production of 162.7GWh per year which was held during the contract agreement with Ethiopian Electric Power Corporation (EEPCo). So, it is found that the farm is providing the desired power.

Capacity Factor (CF) of AWF:

The Capacity Factor (CF) of AWF based on the above summarized data can be estimated as follows.

$$CF = \frac{157{,}739.93\,(\text{MWh})}{51\,\text{MW}*8760\,\text{h}}$$

$$= 0.353,$$

$$CF = 35.3\%$$

Based on the above value of CF, it can be concluded that the wind farm is operating well since the value fulfills the international standard limit which is between 20 to 42 %. But the maximum CF value of the farm set during feasibility study was 38%. Hence, only a difference of 2.7 % is found.

Capacity Factor versus Average Load:

The wind farm production contribution to the grid system is analyzed by using the relationship between monthly capacity factor and average load. The farm average load data is collected from three turbine groups and capacity factor is calculated for each month from the respective energy production of the wind farm.

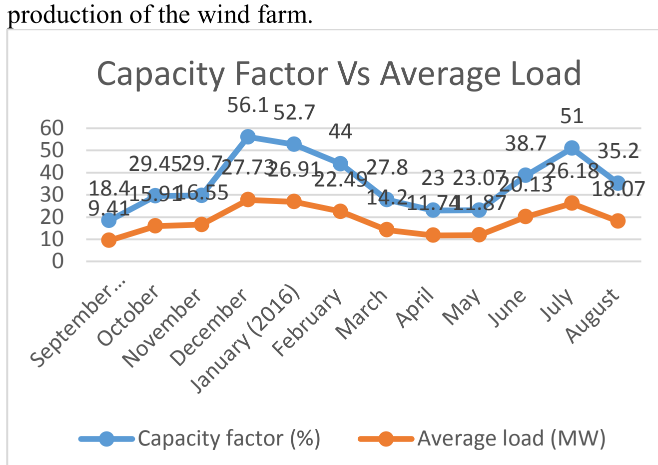

Fig. 7. Capacity Factor vs. Average Load of AWF

From Fig.7 above, it can be seen that the wind farm capacity is high which can handle the respective load (MW) effectively, so it can be said that the farm contributes its part for avoiding the energy shortage currently.

B. Power quality evaluation of the wind farm

Simulation output of voltage and current at PCC:

The steady state output of voltage and current THD values are analyzed using FFT analysis from Matlab and detailed model of AWF is shown below.

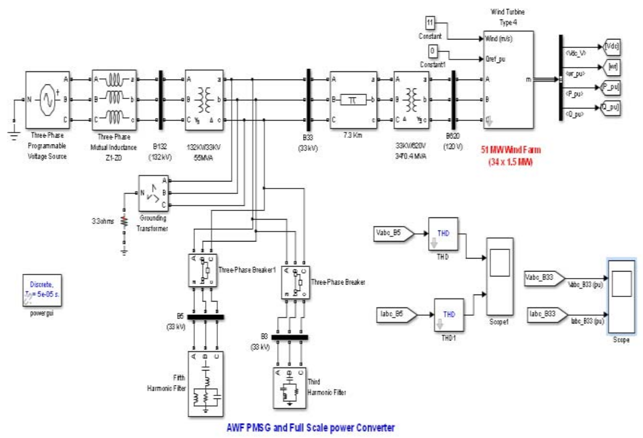

Fig. 8. Simulink Block diagram of AWF

Using Fig.8 above, the simulation is done at the selected PCC of 33 KV bus bar system. The simulation result of current and voltage THDs are having similar values with the mathematically computed THD values of the actually collected harmonic current datas. Three phases waveform output of current and voltage in per unit at 33KV bus bar system is shown below.

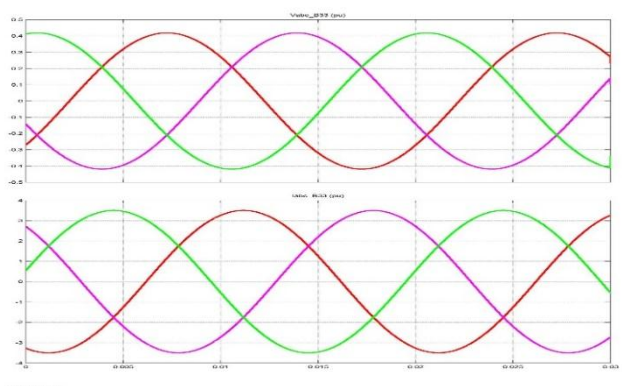

Fig. 9. V and I three phase wave form output at 33 KV busbar

FFT analysis of Current THD:

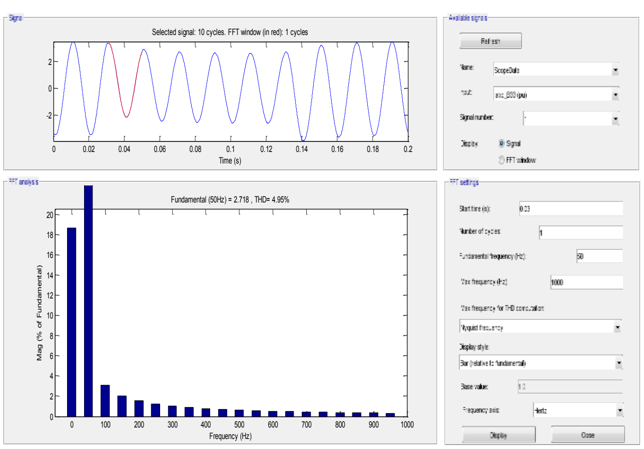

Fig. 10. FFT output of total harmonic current distortion

FFT analysis of Voltage THD:

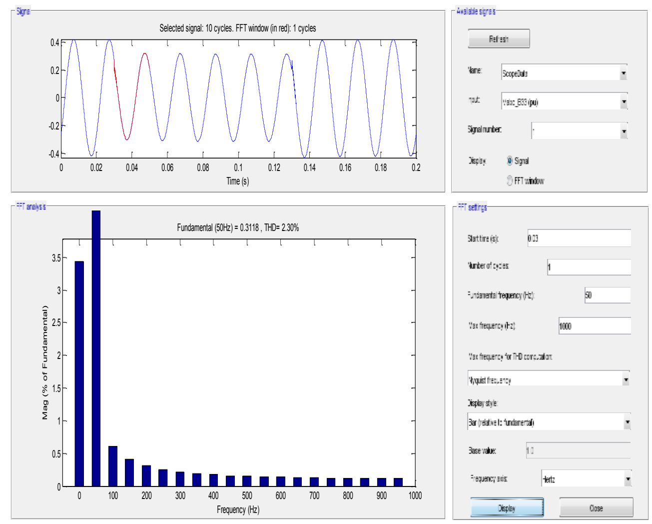

Fig. 11. FFT output of total harmonic voltage distortion

C. Summary of total harmonic current distortion

After analysis of two months harmonic current data, the result is summarized as follows.

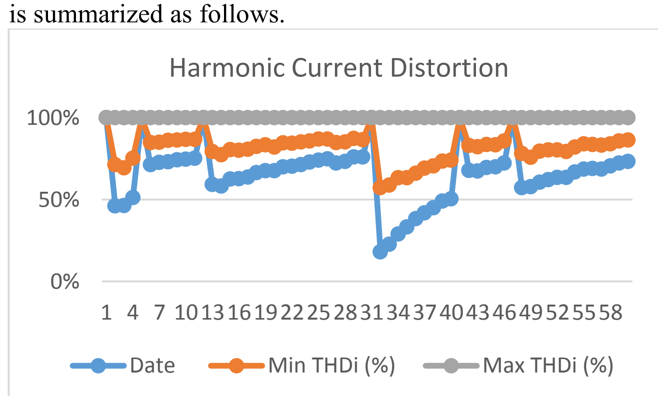

Fig. 12. Summary of current THD at 33 KV bus bar system

D. Summary of total harmonic voltage distortion

After analysis of two months harmonic voltage data, the result is summarized as follows. The harmonic voltage distortion is computed from harmonic current and harmonic power filters out put with the corresponding power factor values.

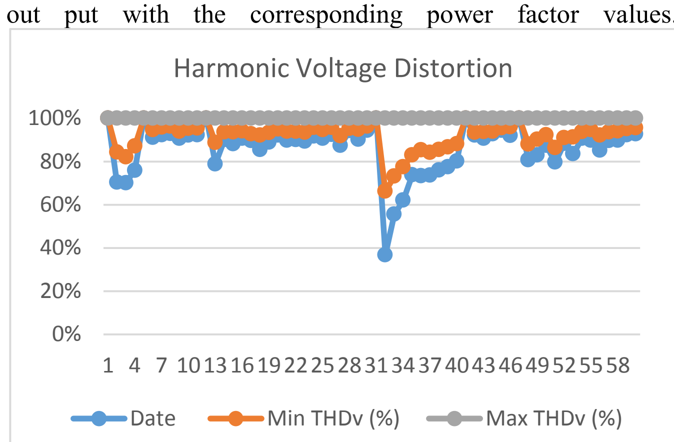

Fig. 13. Summary of current THD at 33 KV bus bar system

From the two graphs, the result summary of harmonic voltage and currents are within permissible limits as compared to IEEE standard values. And therefore, it can be said that the wind farm power quality is good and did not affect the grid system power quality.

E. Harmonic filters and their impact

Using maximum active (P) and reactive power (Q) datas from SCADA system, the power factor of the farm has been analyzed in order to assess the impact of filters in the wind farm.

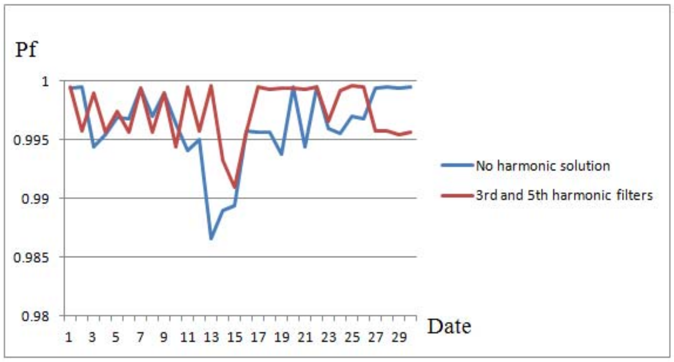

Fig. 14. Harmonic Filters impact on power factor improvement

It is found that there is no significant difference observed when harmonic filters are connected and disconnected.

V. CONCLUSION

Based on the collected data from data loggers and SCADA (Supervisory control and data acquisition) system of the plant, the current performance status and its power quality impact of Adama-One Wind Farm is analyzed. The results obtained from the assessment of this wind farm can be used as an input for the other wind farms to be connected with grid system in the future. The energy delivered over one year in 2015/16 has been 157.74 GWH against the design yearly harvest of 162.7 GWH per year.

The harmonic data at standard PCCis collected and analyzed for its current THD level and found to be 5.96 % and less, against the IEEE standard level of 7 % for the case of selected PCC. Hence, comparing the above results with IEEE standards, it is deduced that currently the wind farm performance is good and has no significant negative impact on grid system power quality.

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