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Power Quality Impact Analysis of Wind Farms on Utility Grid, A Case Study in Ethiopia

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Abstract:*The power quality of the grid system with wind power plants is mostly affected because of its intermittent nature. Hence, in order to assure the power quality of Adama-I wind farm and its impact on the grid, continuous assessment should be done on its operation status. Accordingly analysis of harmonic emission from the wind farm as the result of frequency converters and other nonlinear loads is studied. The harmonic current data's are collected at one of the point of common coupling (PCC) which is at 33 KV bus bar system, 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. As a result 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 which is 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.*

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

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I. Introduction

Now a days, 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-I 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,thewindfarm isconnectedtothe grid.From thissubstation,

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

II. Literature Survey

The Power quality means maintaining the voltage at its rated r.m.s value with negligible amount of harmonics and maintaining frequency with statutory limit and least amount of interruption. There are various power quality issues such as Power surges, High voltage spikes, Transients, Frequency variation, Power sag, Electrical line noise, Blackouts, Harmonic distortion etc. The major cause for a power quality distortion is the Harmonics. Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency [1].

The 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 of wind 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 [2].

Harmonics arise whenever non-sinusoidal currents and/or voltages are generated in the power system; they are generally referred to as harmonic distortion. The basic conditions that give rise to harmonic-related problems in power systems are, in brief as follows [3].

III. 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 of wind 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 [2].

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 [3].

In most Swedish distribution networks, the problems related to harmonics most often, it was 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 [4].

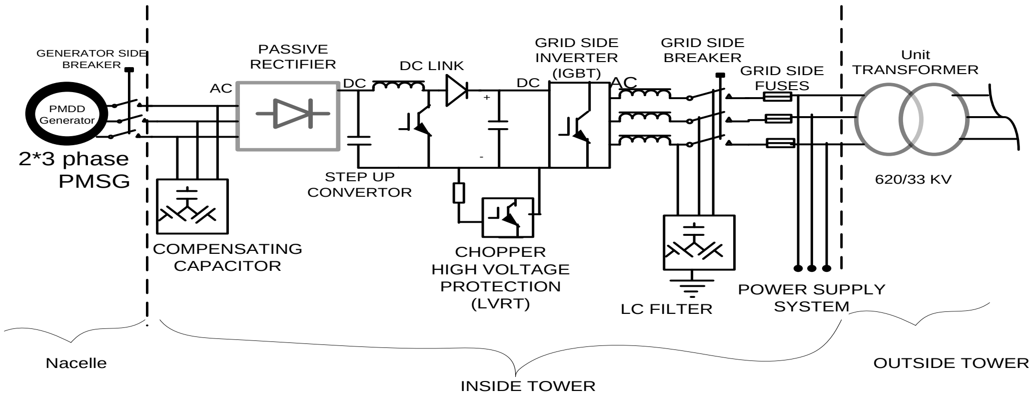

Fig. 1. Gold Wind 1.5 MW Electrical Diagram [5]

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

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

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

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

The DC link voltage for twelve pulse is given by

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

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

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.

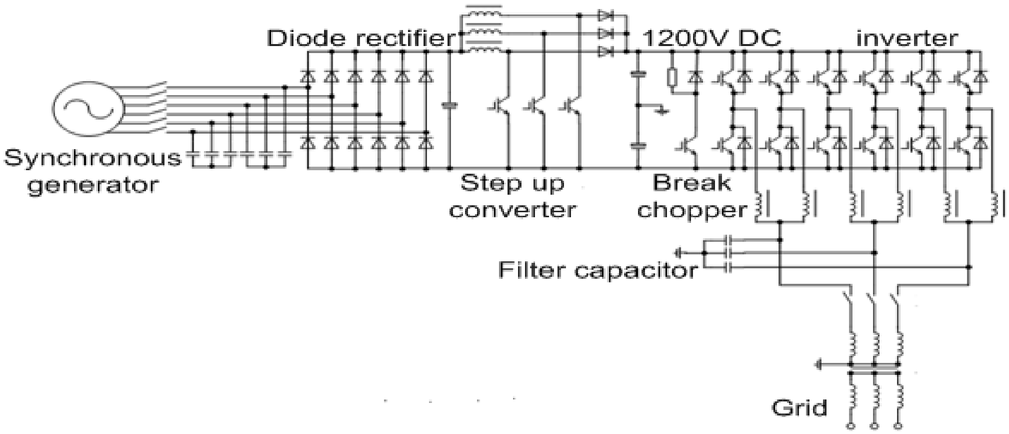

Fig.2. Six phase converter inverter system of AWF [5]

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).

IV. 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

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

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

$$= 0.5 = 50\%$$

WhereCp 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.

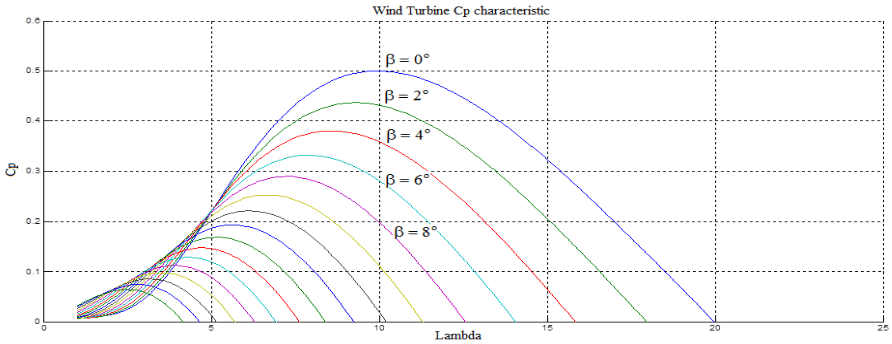

Fig.3. Cp Vs λ output at different pitch angle.

From the above figure it is demonestrated that, 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 powercan 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,

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

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

$$P_{avail} = 1.5MW$$

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

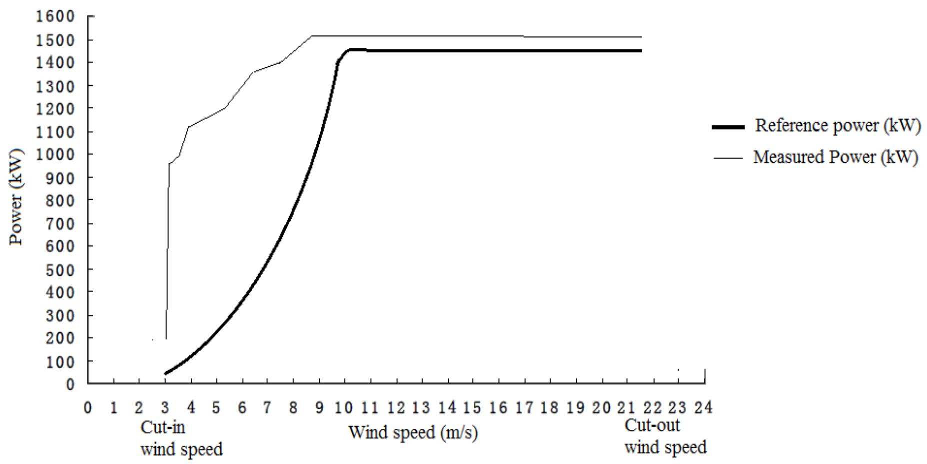

Fig.4. Comparison between the reference and measured power curve.

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.

$$V_s = R_s i_s + \psi'_s \tag{5}$$

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

$$\mathbf{V}_s = [\mathbf{V}_a \;\; \mathbf{V}_b \;\; \mathbf{V}_c \;\; \mathbf{V}_x \;\; \mathbf{V}_y \;\; \mathbf{V}_z]^T,$$
$$\mathbf{i}_s = [\mathbf{i}_a \;\; \mathbf{i}_b \;\; \mathbf{i}_c \;\; \mathbf{i}_x \;\; \mathbf{i}_y \;\; \mathbf{i}_z]^T,$$
$$\mathbf{R}_s = r_1 \mathbf{I}_{6*6}$$
$$\boldsymbol{\psi}_s = [\boldsymbol{\psi}_a \;\; \boldsymbol{\psi}_b \;\; \boldsymbol{\psi}_c \;\; \boldsymbol{\psi}_x \;\; \boldsymbol{\psi}_y \;\; \boldsymbol{\psi}_z]^T.$$

The resulting voltage equation in d-q axis is:

$$V = Ri + \psi' \tag{6}$$

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

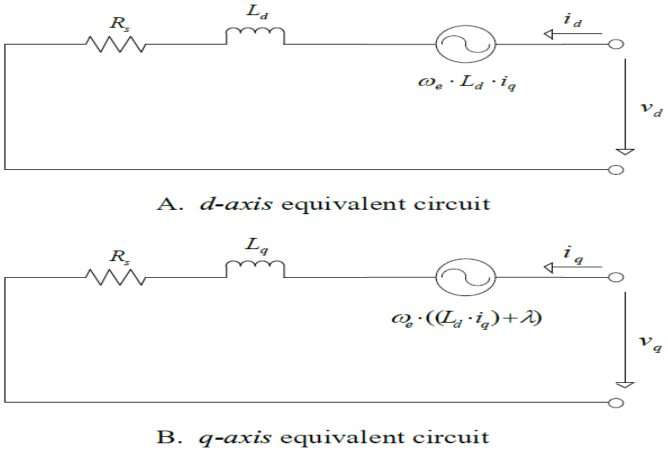

Fig.5. Equivalent circuit of PMSG in d-q reference frame

From Figure 5 above, the voltage equation can be expanded as:

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

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

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, $\omega_r =$ Angular velocity of rotor, λ= flux induced, P number of pole pairs.

C. **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 the Calculated THD of voltage and current with standard.

D. **Mathematical Formulation of Harmonics**

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

$$f(t) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t) \tag{9}$$

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:

$$f(t)=\frac{1}{2}a_0+\sum_{n=1}^{\infty}C_n\sin(n\omega t+\varphi_n) \tag{10}$$

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

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

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

$$V(t)=V_0+\sum_{n=1}^{\infty}V_n\sqrt{2}\sin(n\omega t+j_n) \tag{11}$$

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

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:

$$i(t)=I_0+\sum_{n=1}^{\infty}I_n\sqrt{2}\sin(n\omega t+\varphi_n) \tag{12}$$

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:

$$V_{rms}=\sqrt{\frac{1}{T}\int_0^T V^2(t)dt} \tag{13}$$

Parseval's theorem tells us that:

$$\frac{1}{T}\int_0^T V^2(t)dt=V_0^2+\sum_{n=1}^{\infty}V_n^2 \tag{14}$$

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

$$RMS_V=\sqrt{V_2^2+V_3^2+V_4^2+\ldots}=\sqrt{\sum_{n=2}^{\infty}V_n^2} \tag{15}$$

Similarly,

$$RMS_I=\sqrt{I_2^2+I_3^2+I_4^2+\ldots}=\sqrt{\sum_{n=2}^{\infty}I_n^2} \tag{16}$$

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

$$THD_I=\frac{\sqrt{\sum_{n=2}^{\infty}(I_{n,\ rms})^2}}{I_1} \tag{17}$$

$$THD_V=\frac{\sqrt{\sum_{n=2}^{\infty}(V_{n,\ rms})^2}}{V_1} \tag{18}$$

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

$$I_{fund}=\frac{kV_{actual}/\sqrt{3}}{X_{fund}} \tag{19}$$

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.

$$SCR = \frac{\text{short circuit MVA}}{\text{load MW}} = \frac{I_{sc}}{I_L} \quad (20)$$

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 33kVshort circuit point;
Taking short circuit current from Nazareth substation I_R = 10 KA, Short circuit capacity,

$$MVA_{sc} = \sqrt{3} * U_n * I_R = \sqrt{3} * 132 * 10 = 2286.24\,MVA \quad (21)$$

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:

$$I_z = I_z^{'} * I_j = 4.279 * 1.75\,KA = 7.49\,KA \quad (22)$$

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:

$$\sum I_z = 7.49 + 4.324 = 11.814\,kA$$

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

$$I_{SC} = \sqrt{2} * K_{ch} * \sum I_z = \sqrt{2} * 1.9 * 11.814 = 31.5\,kA \quad (23)$$

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

Load current calculation:

$$I_L = \frac{\text{Load MW}}{V_{Load}} = \frac{51MW}{33kV} \quad (24)$$

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.

E. **Harmonic Power Loss Evaluation of the Farm**

Power loss of Adama-I 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.

$$P_{loss} = V_H * I_H * pf \quad (25)$$

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.

$$S = \sqrt{P^2 + Q^2} \quad (26)$$

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.

V. Result And Discussion

F. **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.

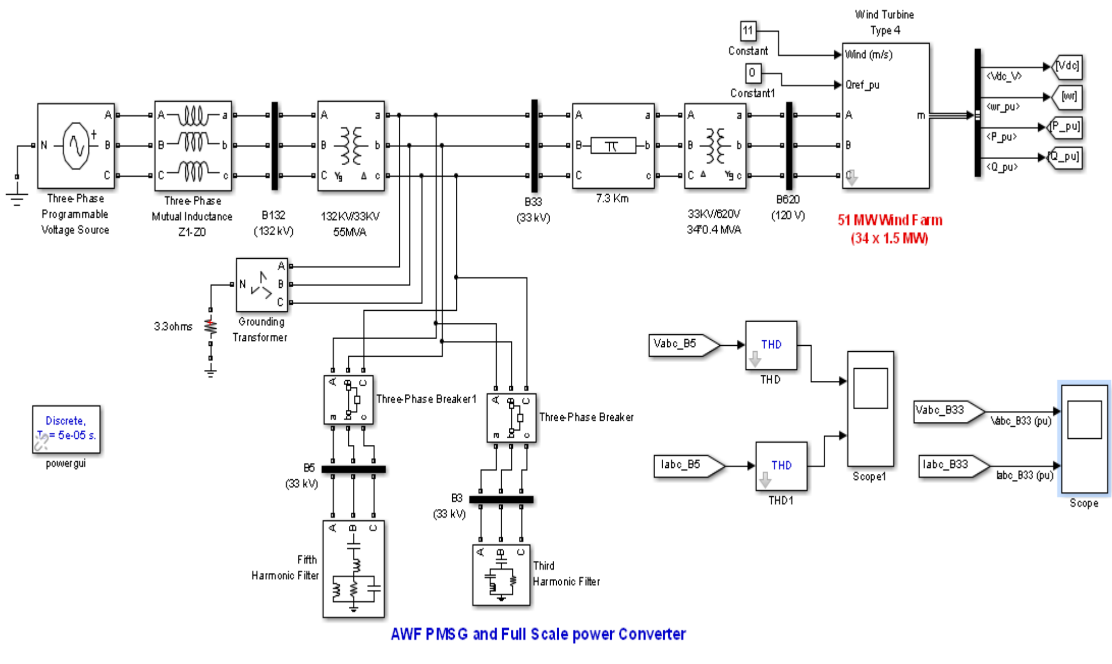

Fig.6. Simulink Block diagram of AWF

Using Fig.6 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.

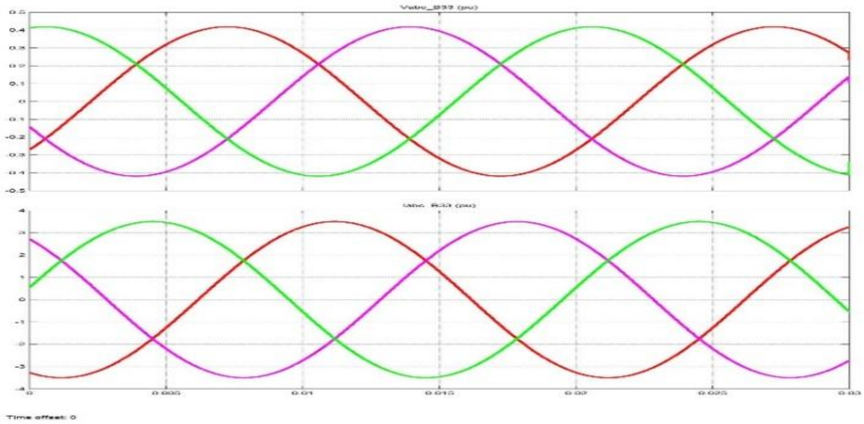

Fig. 7. V and I three phase wave form output at 33 KV busbar

FFT analysis of Current THD:

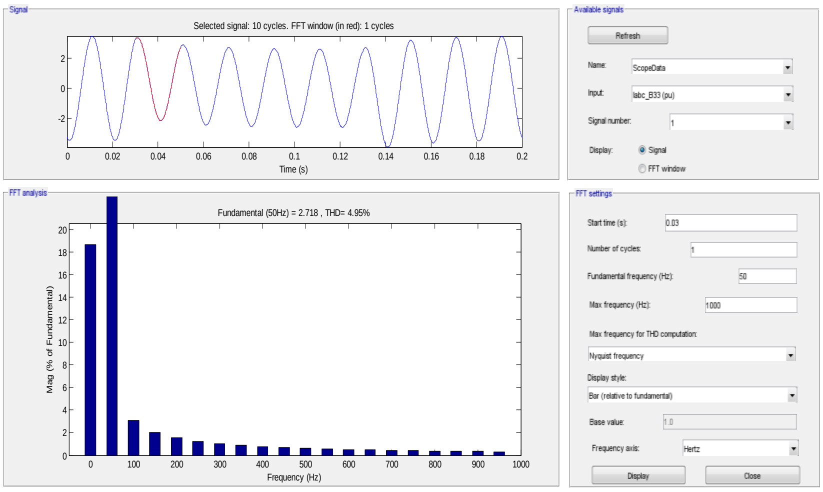

Fig. 8.FFT output of total harmonic current distortion

The THD value found from the simulation is almost similar to the mathematically estimated result. As compared to the IEEE power quality standard and guideline, this result is found to be within permissible limit. As indicated in the FFT analysis the fundamental frequency is found to be optimal and hence the Impact of the farm is almost negligible. In addition the THD value of 4.95 %, which is less than 5% is also validated with respect to IEEE standard.

FFT analysis of Voltage THD:

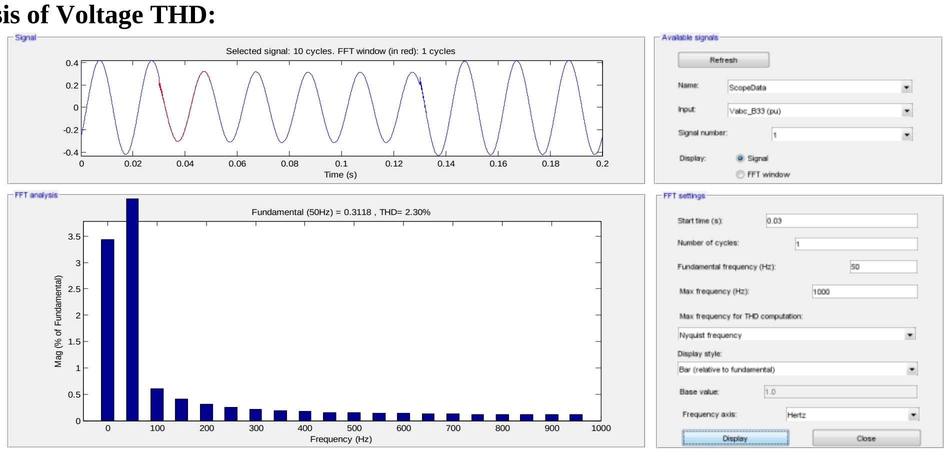

Fig. 9.FFT output of total harmonic voltage distortion

As indicated from Fig. 8 & Fig. 9, it can be seen that the harmonic filters used in the farm have the capability to cancell the amount of harmonic current values displayed. The figures found using matlab simulation outputs have almost similar magnitudes as compared to that of the actual harmonic current outputs of filters in the wind farm SCADA system.

G. **Summary of total harmonic current distortion**

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

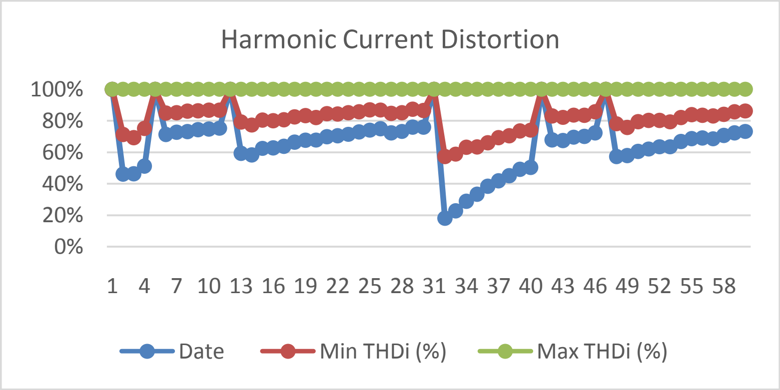

Fig. 10. Summary of current THD at 33 KV bus bar system

The simulated harmonic current value compared to estimated current THD, is found to be almost similar and also met with the standard.Hence, it is found to be within the permissible limit. Therefore, can be said that the wind farm power quality is good enough.

H. **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.

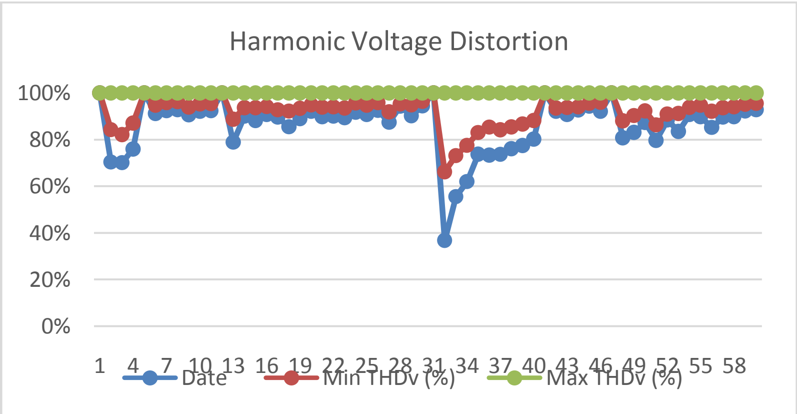

Fig. 11. Summary of current THD at 33 KV bus bar system

From the above 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.

I. **Harmonic filters and their impact**

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

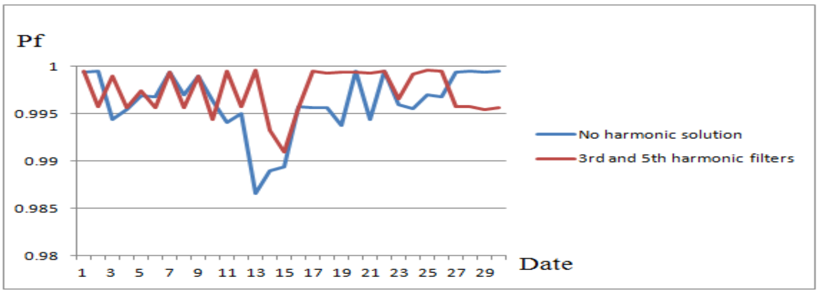

Fig. 12. Harmonic Filters impact on power factor improvement

As it is observed from the above analysis the power factor values are found to have no significant difference when harmonic filters are connected and disconnected. But the harmonic filter connection does not have negative impact as observed from the above result.

VI. Conclusion

Based on the collected data from data loggers and SCADA system of the plant, the current performance status and its power quality impact of Adama-I 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 harmonic data at standard PCC is 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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