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Power Quality Analysis of Power System Involving Grid Connected Photovoltaic (PV) System

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Abstract: *Power Quality is an essential aspect for reliable operation of power grid including Photovoltaic based generation. This paper focuses on real time problem of injection of harmonics and resonance into power network having 5MW solar plant. The solar plant includes 10 inverters each of 500KW connected to 33kV bus. Power produced by plant is explored via 4km cable at 220kV, where conventional plant of 400MW running in parallel at same bus. It is observed that due to injection of harmonics and resonance at particular natural frequency after certain irradiation and hence generation, at specific time of day several inverters are tripped simultaneously. Voltage variation has also been observed. To address the said issue, this paper aims at identification of culprit order of harmonics and resonant frequency, and also the filter design to mitigate the particular issue of harmonics.*
Keywords: *photovoltaic (PV); resonance; harmonics; power quality; NEPLAN; distributed generation (DG).*

I. Introduction

Today, the world's energy supply is to a great extent based on fossil energizes and atomic force. These wellsprings of energy will not keep going forever and have demonstrated to be one of the primary driver of our ecological issues. In the long haul renewable energy such as solar energy, will essentially rule the world's energy supply framework. Energy requirement everywhere throughout the world is becoming quick. Keeping in mind the end goal to take care of the demand, ordinary way to deal with the energy requirements must be reoriented toward energy systems taking into account renewable energy and energy proficiency, which will make it conceivable to address social, monetary, and ecological concerns all the while.

In past years, with rapid development in power electronic devices and technology, the nonlinear loads such as diodes, rectifiers, electric arc furnaces, are increasing as well, these nonlinear loads inject a great amount of harmonic into power systems. These reasons cause the power quality downturn. Power Quality problems has been intended to associate with security, stability, economic and reliable operation of power system as a whole and system equipment(s). It has become an interesting motive in the research field of reactive power compensation and electrical power quality control. As specially in case of photovoltaic(s), when PV is incorporated to the conventional grid, the variable power flow because of the solar irradiance, temperature and selection of semiconductor material are a some of the parameters that influence the Power Quality of the Power System [1].

II. System Briefing

A. Problem Identification

One of the most important factor while integrating DG to grid is Harmonics. Which is generally measured at PCC. Which is mostly caused by non-linear power electronic loads connected to the grid. Connecting PV system which is already being injected by harmonics will introduce more stress on Power Quality of the grid. So, Total Harmonic Distortion Analysis is used to measure the magnitude of the harmonic distortion in any network. So that, essential steps can be taken towards mitigation of Harmonics and so does better quality of power [2].

Here, we are having 5 MW solar farm. The 5 MW Solar power plant consists of 10 inverters each of 500 KW. When run in parallel, each set of 5 inverters (under the same 2.5 MVA transformer) is able to run stably up to around 2.3 MW. Between 10:30 AM and 11:30 AM, when the irradiance reaches nearer to peak, plant reaches about 2.4 to 2.5 MW, all of sudden many inverters trip. Beyond this power level, one or more inverters trip. The error is Line Overvoltage fast. This implies that the line voltage (265V nominal) has exceeded 120% for more than 160 milliseconds. However the error clears immediately and the inverter starts to count down. Just before tripping, the inverters give out an unhealthy sound. This sound implies that there is a change in the IGBT's switching frequency. During this period there is surge in both 1.1 kV and 33 kV side. Due to this problem, the full megawatt is not getting evacuated to 220 kV Point of Interconnection substation.

B. Methodology

To have better understanding of the said problem, we have analyzed that using NEPLAN, an independently designed software by ABB Ltd. Towards the fulfilment of our ultimate goal, some steps to be followed. According to actual data and measurements, the Power System is to be modeled using NEPLAN. Through cables and overhead lines it is to be modelled to run in parallel along with conventional gas based power station. Resonance analysis and Harmonic analysis to be done in NEPLAN. Design of harmonic filter(s) in case IEEE 519-2014 harmonic distortion limit exceeds. Identifying most proper location for filter to be applied in the given Power System [3].

After the application of filter(s) identifying the THD limits according to IEEE 519-2014. If distortion level after application of filters are following IEEE 519-2014 harmonic distortion limits, the designed filter is said to be OK. Otherwise we have to re-design it, as it follows IEEE 519-2014 distortion limits.

III. Simulation Model Establishment Under Neplan

To verify the said problem, NEPLAN 5.5.4 is selected to build model for digital simulation. MATLAB or PSCAD/EMTDC can also be used for the same analysis. But as NEPLAN is freely available with ABB India Ltd, it is preferred comparing to others [4-7].

In the model, there are ten number of 0.265kV side of solar inverters. They are stepped up using 0.265/1.1 kV (500 KVA, Dy11, 5%) step up transformer and connected to 1.1kV bus via 0.08km cable. This bus is further connected to 33kV bus (PCC) via 1.1/33 kV (2.5MVA, Dyn11, 6.35%) step up transformer with the help of 0.003km cable. 33kV PCC is further stepped up using 33/220kV (7.5 MVA, YNyn0, 10%) transformer, and connected to grid.

IV. Simulation Results And Analysis

With an extensive cable system the capacitance of the cable can create a parallel system resonance in the network. If the resonance is close to the dominant harmonic current components of the system loads, the harmonic current can be amplified and result in problems.

Resonance occurs when the capacitive reactance of the cable system and the inductive reactance of the system become equal. The frequency at which this occurs is referred to as the natural frequency for the system. This natural frequency alters depending on the system short circuit level varies. The resonant frequency decreases with increasing capacitance or with decreasing system short circuit level. Here, we have considered minimum short circuit level for our analysis.

The Power Quality measurements done at Solar power plant inverter side indicate that there are significant 18th and 19th harmonics injected by the IGBT inverters. Resonance can significantly increase voltage distortion levels and result into high system voltages. To identify the natural frequency of the Solar power plant, a resonance analysis was performed by using the detailed Solar power plant model developed in previous section.

Frequency scans were made at the different buses of Solar power plant with minimum short circuit levels. Fig. 1 shows the frequency scan for the 33kV PCC. As it can be seen from figure the resonance is around 18th harmonic order (910Hz).

At several buses (33kV, 1.1kV & 0.265kV) in the network, the voltage is plotted to evaluate voltage behaviour of the network. As shown in figure 2 below the voltage is plotted against time (for one cycle) for 33kV PCC. The plot itself clears that there is a harmonic component in voltage due to Resonance effect at the frequency around 910Hz (18 times the fundamental frequency).

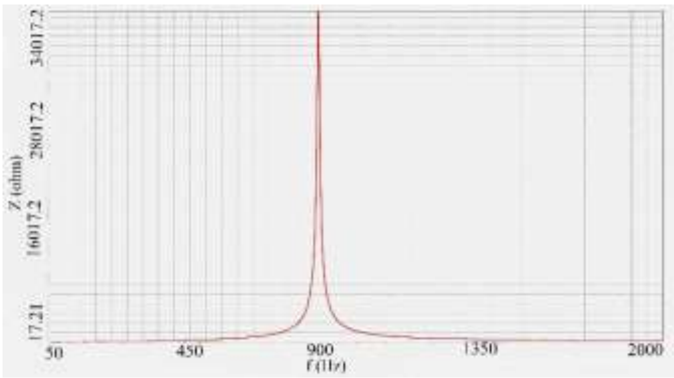

Fig.1: Impedance Plot for 33kV PCC after Resonance Analysis

Here, for 33 kV bus, the voltage is having so many ripples/distortions and the peak value has been increased up to 70 kV. Ideally it should be around 46.5 kV (33kV × √2), but due to distortion around 50%, the voltage has risen to 70 kV (33kV × √2 × 1.5) as shown in figure 2. One more thing to mention in the results below is “ripples in voltage”. As we can see, there are so many ripples in the system, that is due to the “asymmetrical switching”. As discussed earlier there is a change in IGBT’s switching frequency. The +ve and –ve half cycle of switching frequency are not having symmetry and it get concluded as additional ripples into voltage waveform.

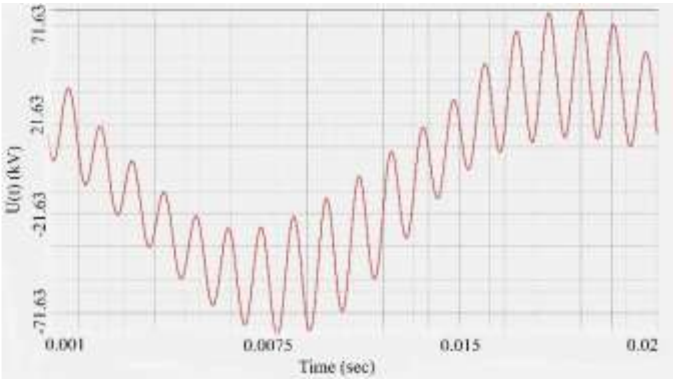

Fig.2: Voltage Plot for 33kV PCC after Resonance Analysis

Based on the Power Quality measurements done at solar power plant the harmonic levels were determined. The inverters were modelled as harmonic current sources.

The inverter is modelled with fundamental current and the corresponding harmonic currents were injected at the inverter output voltage i.e. at 265V. The plots for voltage harmonics are shown in figure 3. As seen in figure, the 18th and 19th order harmonic is dominant. Hence, the voltage distortions were observed when the resonance was close to 18th harmonic (910Hz). Note that, here total distortion in voltage is around 50%, which exceeds IEEE 519-2014 distortion limits. So, the present harmonics in the system should be mitigated by means of additional filtering circuits.

A harmonic filter analysis was performed to investigate the potential filter configurations for reducing harmonic distortions. At different locations the harmonic filter has been considered.

As, it is already concluded from the Harmonic Analysis Results, that the current distortion at individual bus is not exceeding but the voltage distortion at 0.265kV, 1.1kV & 33kV bus is exceeding the limits as per IEEE 519-2014. So, mitigation of Harmonics to have the distortion limits within the allowable range is necessary.

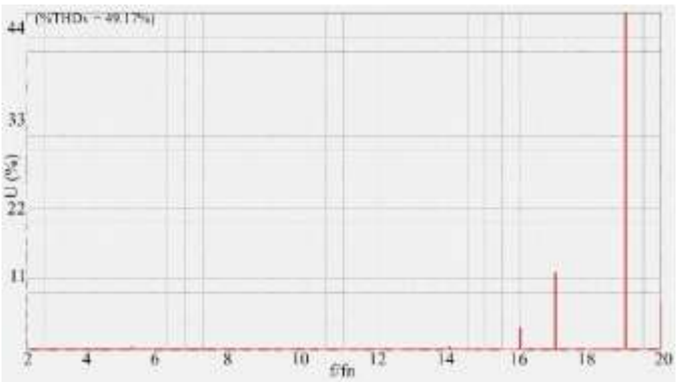

Fig.3:. Voltage Spectrum Plot for 33kV PCC after Resonance Analysis

This can be achieved using some additional “filtering circuits". To design the “Harmonic Filter", we have to follow certain steps. The very first from that is determining the Reactive Power injection requirement for that particular bus. For that Load Flow Analysis is a basic necessity. After having multiple load flow results, we have concluded the filter ratings for 0.

265kV, 1.1kV and 33kV voltage bus. Here, after placing the multiple filters at different buses, we have got different level of %(THD)v at all buses. From that, the 1.1kV bus, 100KVAr passive harmonic filter was found to be most significant according to the system conditions. Several steps are followed to design the 1.1kV passive harmonic filter, as we have V=1.1kV, Q=100 KVAr, f_n=901.6 Hz [8-11].

Firstly, we have to have the Inductive Reactance ($\%X_L$) for given bus. It can be obtained using harmonic order (n),

$$n = {}^{100}/_{\%X_L}$$

After Having Inductive Reactance, we've to find Filter Impedance (Z_{filter}), which is calculated from,

$$Z_{filter} = {}^{kV^2}/_{MVAr}$$

Once we have Filter Impedance, we can easily calculate the Filter Capacitance (C) and afterwards Filter Inductance (L) from,

$$I_{filter} = {}^{V_{ph}}/_{Z_{filter}}$$

here, please note that we have to have 10% of safety margin in current.

$$V_C = V_{BUS} + V_{reactor}$$

Now, the capacitor bank voltage (V_C) has to be calculated from, $V_C = V_{BUS} + V_{reactor}$
And the concluding step towards the design of passive filter is to determine the capacitor bank MVA rating from,

$$MVA_C = \frac{kV^2}{X}$$

So, after having the 18th order Single Tuned L-C Filter at 1.1kV bus, the impedance, voltage and voltage spectrums are plotted again. To have the graphical understanding of filtering effect. Below are the plots of the system after filtering.

The Impedance which was earlier having peak around 900Hz (18th order) is shifted to the frequency around 1200Hz (24th order) as shown in figure 4. As, there is less impedance (around 3.4 KΩ) comparing to which we have before filtering, it will affect the voltage as shown in figure 5.

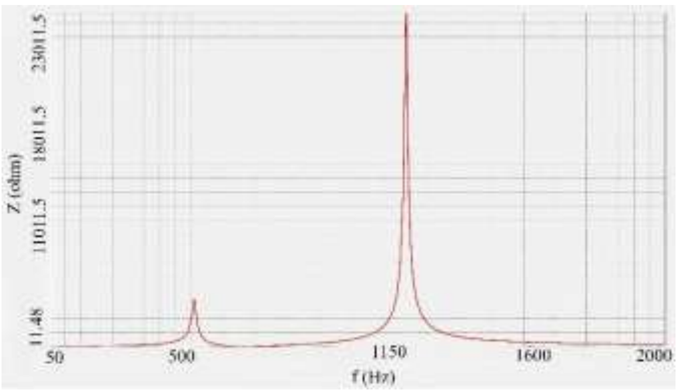

Fig 4: Impedance Plot for 33kV PCC after Filtering

According to our measurements done at solar power plant, as there is no harmonic current for 24th order of harmonics, this resonant impedance will not get interacted with any harmonic currents further. As a result, we will not have any additional voltage at 33kV PCC.

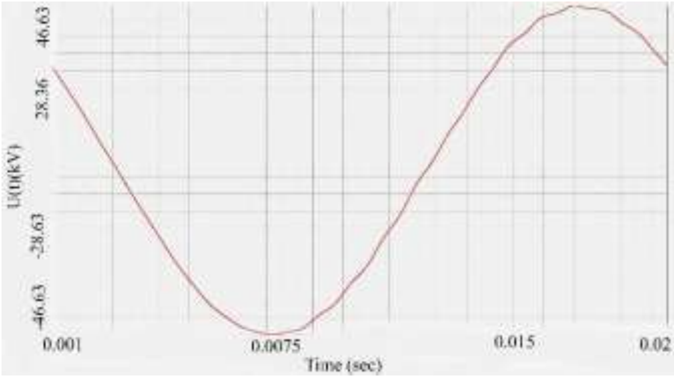

Fig 5: Voltage Plot for 33kV PCC after Filtering

As, there is no additional voltage, we will have voltage plot as shown below in figure 5. As we can see that, the peak voltage here is, around 46.5 kV (33kV × √2), which should be the normal RMS value of voltage at 33kV PCC. Here note that, the additional harmonic component is mitigated.

The Voltage spectrum can also be seen as a scattered one, and shifted towards the lower current side, with comparison to the earlier one as shown in figure 6. Now after filtering, it is not dominant to any one order of frequency, and get scattered to all order of frequency. Note that, here total distortion in voltage is dropped down from 50% to around 1%, which follows IEEE 519-2014 distortion limits.

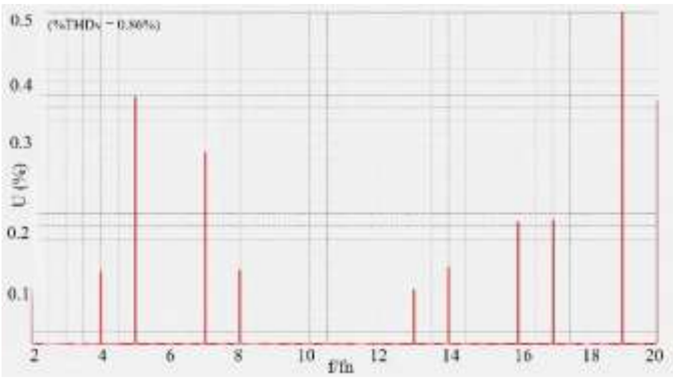

Fig 6: Voltage Spectrum Plot for 33kV PCC after Filtering

V. Conclusions

In this paper, the harmonic analysis of grid connected PV system is done. A passive filter was designed accordingly the requirements of harmonic mitigation. Through the simulation of Power System involving grid connected PV system, simulation results for impedance, voltage and voltage spectrum are presented, before and after application of harmonic filters. Simulation results show that the voltage distortions are mitigated successfully with application of two 100 KVAr passive harmonic filters at 1.1kV bus and the low THD is achieved, which follows IEEE 519-2014 THD limits.

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