CHALLENGES FOR ACCELERATED SOLAR PV PENETRATION AND ADOPTION IN THE GRIDS

By
Sunil Chandra Das
Additional General Manager(EM)
NTPC-Farakka
e-mail: scdas01@ntpc.co.in

ABSTRACT:

Photovoltaic solar power has taken off internationally in a big way and technical challenges arising out of Solar PV integration along with other Distributed Renewable Resources in the conventional grids needs to be studied. With exponential growth in the terrestrial photovoltaic market, many issues arise regarding the integration of these systems into utility networks at high levels of penetration. Grid-Smart Inverters and Architecture (GSIA) will be a key component in the ability of all Solar Energy Grid Integration Systems (SEGIS) technologies to accelerate PV adoption.
Primary barriers to utility acceptance of large-scale grid integration of PV generation is intermittency of the renewable supply, inability to control the PV generation source in a way that fits into the existing utility control structure, including islanding control and local VAr control; and the costs of PV power.
Modern renewable energy systems containing power electronic converters can produce a spectrum of harmonics over a wide frequency range. Further, other sources of harmonics may be present, such as harmonics generated during grid side disturbances. If a harmonic generated by the renewable energy generators is close to a naturally occurring resonance point of the system, there is a potential for sustained resonance.
Integration issues and challenges for DER with a case study of 5MW Dadri Solar Plant integrated to 220KV grid is also discussed wherein field studies were done for inverters tripping on load increase, simulation studies based on modelling and implementation of solution done thus mitigating overvoltages and THD (Total Harmonic Distortion).

I. INTRODUCTION :

PV systems are composed of PV array(s) that convert incident solar energy into DC electricity, and an inverter which, as the power electronics interface between the array and utility network, performs many functions to ensure the system operates effectively and safely. These functions include performing maximum power point tracking of the array, providing DC to AC inversion, and synchronizing the AC current and voltage to that of the utility network. Inverters also act as the human-machine interface (HMI) for most PV systems, and often perform data collection duties to track and communicate the performance of the system to the owners and operators.
Typical modern grid-connected inverters that tie clean energy systems such as PV to utility grids are essentially high-bandwidth amplifiers connected to the grid, so there is no requirement that they mimic the functionality and response time of thermal or hydropower plants with large synchronous generators. These inverters are typically configured and controlled as current sources to put energy onto the grid, synchronized with the grid‘s voltage waveform. They do not, typically, supply reactive power to the grid and, in the few cases where reactive power is supplied to correct the power factor of adjacent loads on the same low voltage bus, the inverter typically only follows a fixed preset VAr supply reference.
They are also capable, if additionally powered from an energy storage device and fast grid connect device, of acting in a voltage source mode and powering local loads in a load-following manner. .

II. ISSUES AND BARRIERS OF PV INTEGRATION:

Significant efforts from private industry, academia, and governmental agencies have led to continued massive reduction in the levelized cost of energy (LCOE) from PV systems. From the point of view of the utility system operator, conventional PV systems still have many disadvantages when compared to traditional fossil-fuel generators regardless of the LCOE. Some of the key disadvantages include:

A PV system is an intermittent power source, dependent on the fluctuating sunlight local to the area in which it is installed.

Conventional PV systems operate at unity power factor, regardless of the reactive power needs of the utility network.

Due to concerns regarding unintentional islanding, current interconnection standards require distributed PV systems to cease to export power during voltage and frequency disturbances, thereby reducing generation at times when it is needed most.

Owing to relatively recent improvements in power electronics, including advances in fast semiconductor switching devices and real-time, computer-based control systems, PV inverter technology actually has the potential to overcome these barriers and provide significant added value beyond the simple kilowatt hour (kWh) production of energy. For this Solar Energy Grid Integration Systems project proposed an objective-driven method to design, develop, and demonstrate an advanced inverter with monitoring, control, and management of solar electrical energy generation. The integration of advanced power management functions provides beneficial grid support such as enhanced grid stability and reliability, voltage regulation, and reactive power (VAr) support. This approach is applicable not only to PV, but also to other renewable distributed energy resources (DER), and will help accelerate utilization of renewable energy technologies.

Three major innovations are needed. First is the design and implementation of grid-smart features for utility control and optimization through the commercially available inverters and Site Controllers. In order for PV to effectively replace fossil fuel generation, it must integrate into the existing generation mix and, at a minimum, meet the standards imposed on conventional generation. These grid-smart features are enabled via fully bidirectional SCADA communication. They include remote ability to control (on/off) or curtail generation, power factor control, and remote diagnostics and prognostics.

The second major innovation is the design and implementation of a shared inverter through the commercially available inverter. The shared inverter allows for PV arrays of different orientations, technologies, and age to share a single inverter through string-level maximum power point tracking (MPPT). This allows for a modular approach to PV system construction, and it is ideally suited for multi-plane rooftops, building-integrated PV (BIPV), and perhaps a scenario where a utility-owned central inverter is the power conditioner for a number of customer-owned rooftop PV systems on neighboring buildings.

The third major innovation is the design and implementation of inverter ride-through with a permissive signal. Many utilities continue to have concerns about localized anti-islanding solutions in a high-penetration scenario when many inverters on a feeder are running identical anti-islanding algorithms. While synchrophasors have been proposed as a potential solution, they do not address the common downed-wire hazard, when a single distribution conductor falls from a power line to an accessible location. This permissive signal architecture provides reliable anti-islanding protection with the benefit of allowing utility-enabled ride-through.

III. GRID TIED INVERTERS AND IEEE STD 1547 :

There are two main categories of grid tied inverters, Line commutated inverters derive their switching signals directly from the grid line currents while the Self commutated inverters derive their switching frequencies from internal control units as they monitor grid conditions namely voltage and frequency. PV modules behave as voltage source type inverters and they can be subdivided into voltage control and current control types. Where there is no grid reference voltage control schemes are used and inverter behaves as voltage source. Where grid connection is used current control scheme is used and the inverter behaves as current source. Modern grid tied inverters achieve efficiencies more than 95%.

IEEE Std. 1547 requires that all customer-sited DG incorporate a means to detect loss of utility power to ensure that inverters do not feed utility faults of open or downed utility lines. Also, IEEE Std. 1547 specifies that DG should trip off line if the RMS voltage at the inverter‘s terminals is 10% above or 12% below the nominal value for more than two seconds. The mandatory inverter disconnect from the grid requirement as part of IEEE Std. 1547 will likely be the source of grid instability as PV capacity grows. With higher penetrations of PV, utilities will value allowing PV and other inverter-based DG to ride through voltage sags or frequency disturbances. This is not possible with the stringent under/over voltage and under/over frequency tripping of PV inverters used today or with the present active anti-islanding requirements. These restrictive voltage or frequency trips can cause distributed PV to disconnect at a time when their continued operation would provide high value generation to the host utility. Thus, using stringent OV/UV and OF/UF settings to improve the detection of and response to line faults and loss of grid connectivity has limited the ability of PV to provide high value to the grid. Similarly, the active anti-islanding requirements are an impediment to DG based microgrids.

Mitigation Plan

Today‘s grid interconnection standards are not compatible with the voltage regulation or frequency-support functions. The modifications of the existing interconnection standards would allow PV inverters to provide grid support—voltage regulation functions, implemented through reactive power control, and would enable inverter-based DGs to be much more beneficial to the grid than is currently possible. Voltage and frequency trip settings could be widened to better accommodate utility transients and provide better ride-through, or even adjusted dynamically depending on whether the inverter was in grid-tied or isolated operational mode. It would be valuable to replace current active anti-islanding schemes with alternatives that facilitate the implementation of grid support functions in inverters.

III.POWER QUALITY AND DC INJECTION INTO AC GRID:

On one hand, large amount of photovoltaic generation integrated with grid promotes the utilization of solar resources, on the other hand, the photovoltaic generation brings new challenges on the planning and designing, power quality, operation, protection etc. Especially, after photovoltaic generation connected to distribution network, the structure of topology and the direction of flow of grid are changed, and simultaneously the power quality of users is influenced by photovoltaic power output characteristics. The impact of integration of photovoltaic generation with grid on power quality is mainly reflected in two aspects which are voltage fluctuation and harmonics.

A power quality concern of DER converters is that it injects direct current into the grid either due to offsets in internal control loops or a component failure increasing saturation of magnetic components such as distribution transformers which cause increased power distortion. DC current within the low voltage AC network could cause significant disturbances within distribution and measurement transformers. The most significant being “half cycle saturation”, where a transformer, which normally operates with a very small exciting current, starts to draw as much as a hundred times the normal current. This results in the transformer operating beyond the design limits. Other effects within transformers include excessive losses (i.e. overheating) , generation of harmonics, acoustic noise emission, and residual magnetism In addition, there is evidence for the seriousness of corrosion risks associated with DC currents in the grid. PV inverters can cause a DC bias due to the following mechanisms: imbalance in state impedances of switches, different switching times for switches, and imperfection in implementing the timing of drivers .

Special K-rated transformers need to be used which are designed to have lower eddy current losses.

$$\text{Mathematically, } K = \sum_{h=1}^{h=\infty} Ih\,(pu)^2 . h^2$$

where Ih(pu) is harmonic current in per unit value and h is the harmonic order

K factor rating applied to transformer is an index of transformers ability to supply harmonics (% THDi which is total harmonic distortion in current) at its load current while operating within its temperature limits. K rated transformers are only intended to survive in harmonic rich environment and do not mitigate harmonic voltage and current. IEEE C57-110-1986 is prescribed procedure used to derate the transformer loading based on specific harmonic content.

DER interconnection standard limit dc current injection to a low level, typically 0.5% of the DER rated current. The simplest and the most certain method to avoid dc injection is to insert a line frequency isolation transformer at the output of the DER converter so there is no path for dc current into the grid. However the transformer adds significant cost, size and weight. Hence techniques have been developed to precisely regulate dc offset in the converter to minimize dc injection during normal operation and to detect dc injection and de-energise the converter if a failure occurs.

USA has a permissible level of DC injection which should not exceed 0.5% of the full rated output at the interconnection point, according to IEEE 1547 62.

In India, the CEA regulated current DC injection limit is in line with the IEEE 1547 standard.

IV. RESONANCE:

Network resonance can be classified into two types: series resonance, and parallel resonance.

In the case of series resonance the impedance becomes low at resonant frequency, which causes the flow of large current in the network. At times this can also cause a high distortion in the voltage at the distant buses. However, parallel resonance is associated with high impedance at resonant frequencies that causes large distortion in the voltage and produces a large harmonics current.

A PV system is a source of harmonics current. If for any network condition(s), the network resonance frequency becomes aligned with the harmonics injected by the PV system, excessive voltage and current harmonics distortions may occur, and can cause damage to the customer and utility equipments.

Network resonance frequency varies with the short circuit ratio (SCR) of the system. For a network, if the SCR increases, the resonance frequency shifts towards higher order frequencies and as SCR decreases, resonant frequency shifts toward lower order frequencies .

The combination of harmonic linearization and sequence impedance decomposition provides an effective and systematic method to model inverter output impedance for system harmonic resonance analysis. Under balanced or mildly unbalanced grid conditions, a three-phase inverter-grid system can be decomposed into a positive-sequence and a negative sequence subsystem, and Nyquist stability criterion can be applied to each subsystem separately to determine system stability as well as possible resonant modes. The analytical impedance models provide a means to shape the inverter output impedance through control and circuit design of grid-connected inverters to avoid undamped resonances. Adaptive control such as gain scheduling can be used in conjunction with online grid impedance identification techniques to guarantee stable and harmonic-free operation under variable grid conditions.

The resonance between power-factor-correction capacitors and the line reactance is a common cause for harmonic capacitors and the line reactance is a common cause for harmonic problems in traditional power systems. Grid-connected inverters integrating renewable energy sources into the grid exhibit capacitive output impedance at harmonic frequencies and may also resonate with the grid impedance. In addition to possible amplification of current and voltage harmonics, such resonances may lead to inverter control instability and other dynamic problems.

A new method to detect potential resonances between the inverter output impedance and the grid impedance is based on the Nyquist stability criterion. These measurements demonstrate the importance of both inverter control and grid impedance in harmonic performance of grid-connected inverters. To reduce the risk for resonance, the inverter output impedance should be as high as possible, ideally above the grid impedance at all frequencies. Since this is impractical due to the inductive nature of grid impedance, it is important to identify the frequencies at which the inverter and the grid impedance intersect, and to ensure sufficient phase margin through proper inverter control design. The analytical impedance models provide a means for such design. Additionally, since the grid impedance changes from site to site and may vary over time, adaptive control based on real time grid impedance measurement may be considered .

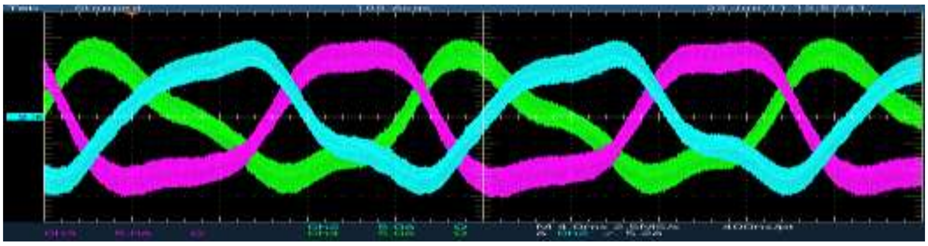


Fig 1: Distortion due to Harmonic resonance between inverter and grid

V. CASE STUDY:

a) INTEGRATING 5MW SOLAR PLANT AT NTPC DADRI TO 220KV POWER BUS

NTPC, has recently commissioned 5MW solar power plant at Dadri, The 5MW Solar power plant consists of 10 inverters each of 500KW. During peak hours some of the inverters were tripping once the power level reached to 2.5MW.

ABB has performed the system resonance analysis and harmonic analysis of the Solar power plant. The inverters are connected to 265V/1100V, 500kVA transformers. 5 set of inverters connected to one 2.5MVA, 1100/33kV transformer another 5 set of inverter are connected to 2.5MVA, 1100/33kV transformer. These two transformers are connected to 33kV Solar Power Plant Bus. From 33kV bus, 4kM cable is connected between solar power plant and 220kV NTPC generator bus via one 33/220kV, 7.5MVAR power transformer.

Problem statement and observations at field:

1. When run in parallel, each set of 5 inverters (under the same 2.5MVA transformer) is able to run stably up to around 2.3MW. (AND)
2. Between 10:30am and 11:30 am, when the plant reaches about 2.4 to 2.5 MW, all of a sudden many inverters trip.
3. Beyond this power level, one or more inverters trip. The error is “Line Overvoltage fast.” This implies that line voltage (265V nominal) has exceeded 120% for more than 160 milliseconds. However the error clears immediately and the inverter starts to count down.
4. Just before tripping, the inverters give out an “unhealthy” sound. This sound implies that there is a change in the IGBT’s switching frequency.
5. During this period there is surge in both 1.1kV and 33kV side.

Due to this problem, the full megawatt was not getting evacuated to 220 kV Point of Interconnection substation at NTPC, Dadri.

b) HARMONIC STUDY AND RESULTS

Based on the power quality measurements done at Solar Power Plant the harmonic levels were determined. The harmonics were modeled as harmonic current sources.

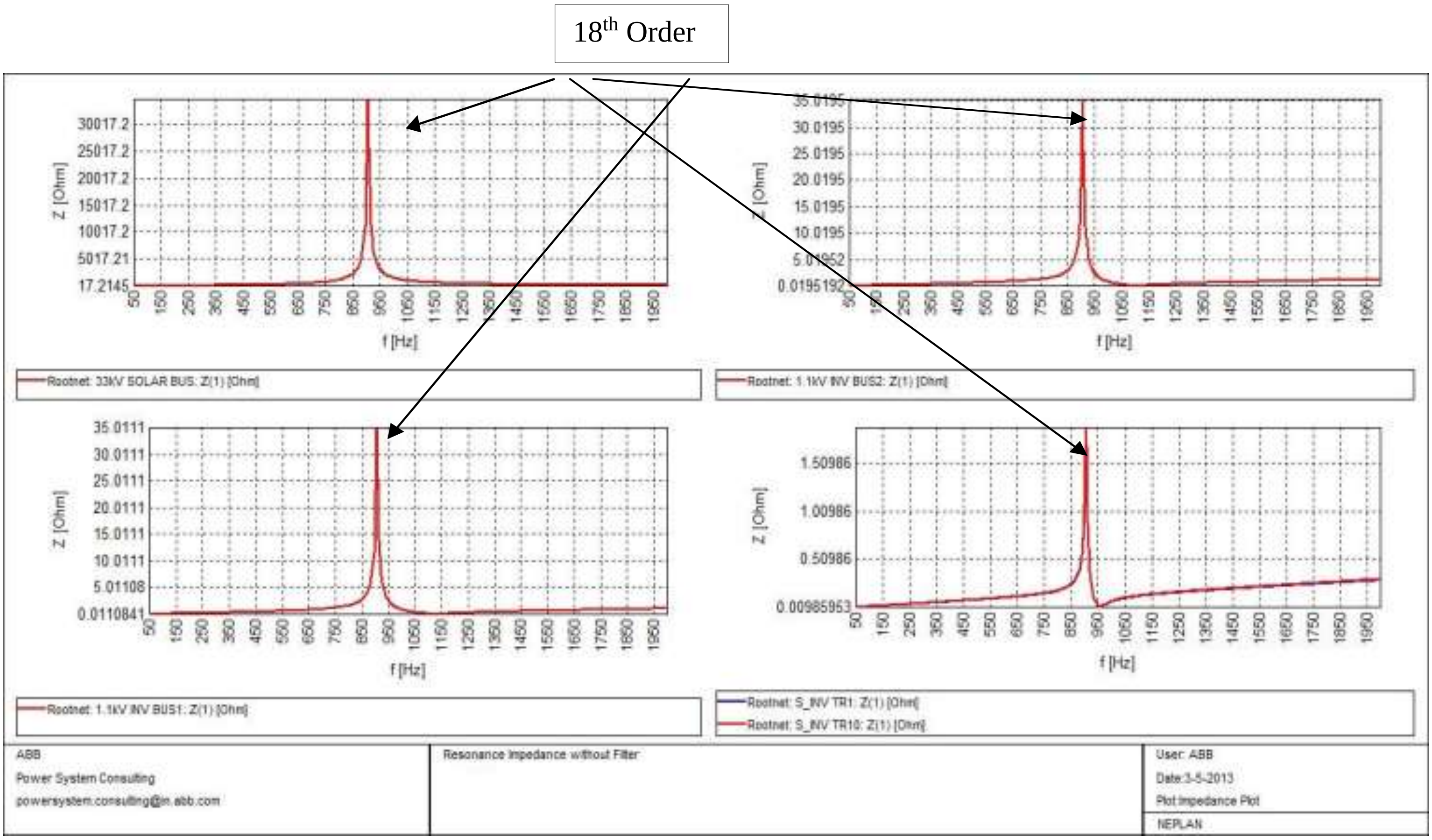


Figure 2: Frequency Scan – Normal System Configuration without Filter

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.

The power quality measurements done at Solar power plant inverter side indicated that there are significant 18^{th} and 19^{th} 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.

Figure 2 shows the frequency scans for the 33kV, 1.1kV & 0.265kV buses of Solar power plant. As it can be seen from Figure 3 the resonance is around 18^{th} harmonic (890Hz).

Simulation studies after modelling of system parameters were done and proposed solution was filter at 1.1KV side of 2.5MVA Transformer.

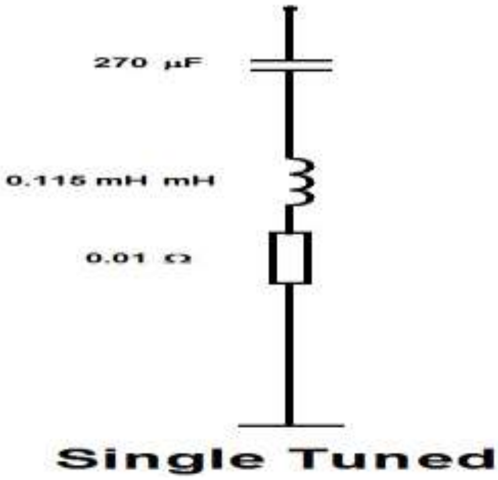


Figure 3: 18th Single-Tuned Filter at 1100V

Table below show that the voltage distortion levels at different solar power plant buses with filter at 1100V plant bus.

Option: Filter at 1.1kV Main Bus - (Total Filters 2)					
Filter Value	**Resonant Frequency**	**VTHD_33kV (%)**	**VTHD_1.1kV (%)**	**VTHD_0.265kV (%)**	**Voltage at Solar Bus**
(kVAR)	**(Hz)**				33.15KV
100	1220 (24th)	1	1.69	4.7	

The 18th order Single Tuned L-C Filter at 1100V was found to be significantly reduce the resonance impedance and provide the most damping for the 18 th as well as other lower and higher harmonics compared to 265V & 33kV locations.
100kVAR filter at each 1100V Bus (i.e. on 2.5MVA transformer 1100V side) shall be required to reduce the overvoltages and voltage THD levels appearing in Solar power plant bus. The total harmonic distortion (THD) was reduced to less than 5% and meets IEEE 519 guidelines with this filter.

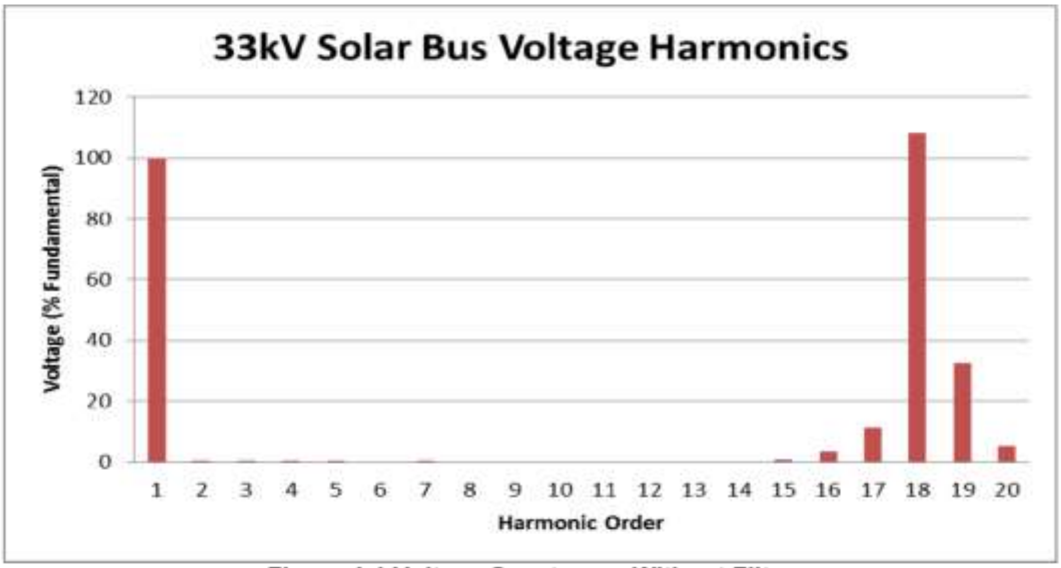


Figure 4-1 Voltage Spectrum – Without Filter

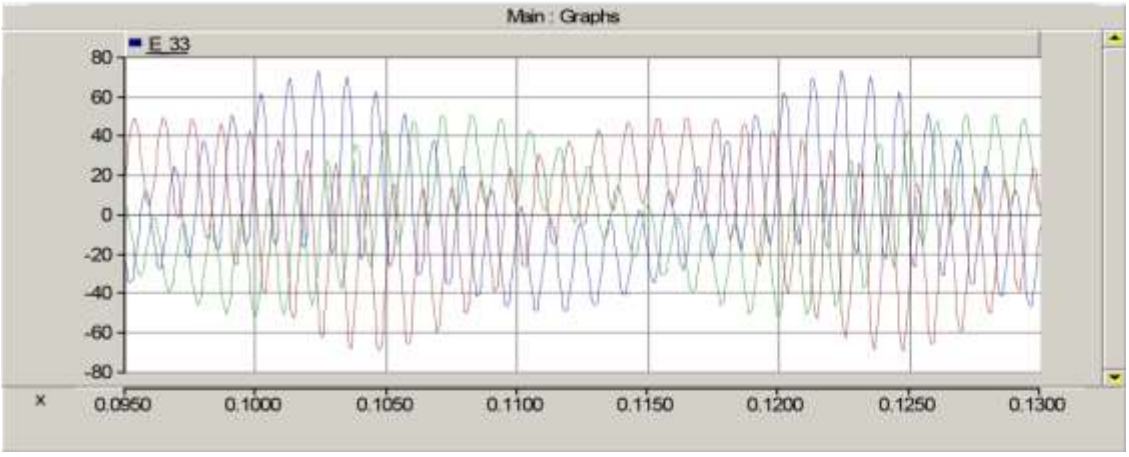
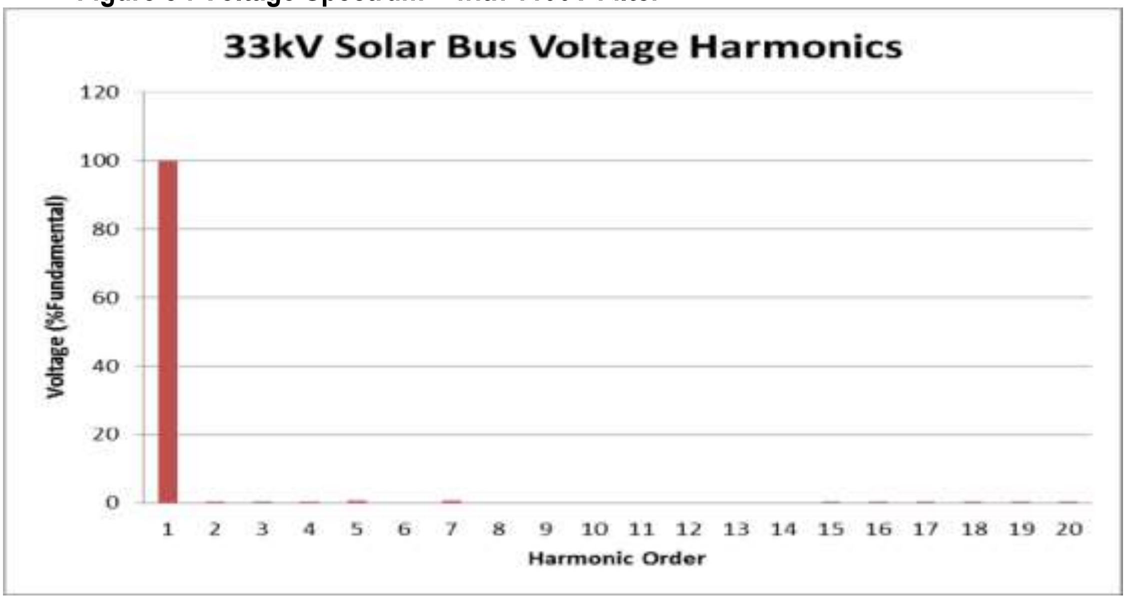


Figure 5 : Voltage Spectrum – with 1100V Filter



VI. CONCLUSION:

Concerted efforts are required to develop, validate and commercialize Grid-Smart Inverters for wider photovoltaic utilization, particularly in the utility sector. Advanced power electronics of the advanced inverters will go far beyond conventional power plants, making high penetrations of PV not just acceptable, but desirable. PV power generating plants will not achieve their full potential until they cease to be regarded by utilities as a problem or potential hazard, but instead as a resource that can be monitored and dispatched to contribute to the efficiency and stability of the grid. Proper filters are to be installed in system to take care of harmonics arising. In Dadri Solar Plant case study it was found that capacitances of extensive cables caused harmonic resonances causing inadvertent trips which was mitigated after proper study and solution. Technological innovations and advancements can transform the way PV is utilized in today's energy generation, transmission, and distribution (T&D), and transform the use paradigm in the scenario of present power systems.

REFERENCES:

[1] Sandia National Laboratories , USA on " Solar Energy Grid Integration Systems"
[2] ABB-Power System division report on "Root cause analysis for Solar Power Plant-Dadri"
[3] IEEE Std. 519-2014, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.
[4] M. Pielahn, K. Mudunkotuwa, A. Ranaweera, D. Muthumuni on "Efficient EMT modeling approach to studying resonance phenomenon in PV and wind energy systems"
[5] S.C.Das on "Harmonics and Resonance Issues in Solar Plants integrated to the Grid"
[5] Kleber Facchini on " How To Manage Grid Impact As Solar Deployment Increases"
[6] Byomakesh Das on "Novel Control and Harmonics Impact of PV Solar Farms"
[7] Anna Grishina on "A New Quasi Resonant DC-Link for Photovoltaic micro-inverters"