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Power Quality Performance on a Feasible Design of a Photovoltaic (PV) System for a Local Community

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***Abstract* -- This paper presents the simulation of a grid-connected photovoltaic (PV) system to supply electric power to meet the energy demand of 31 MW by a local community. The power system consists of a Generator of 250 MVA and an inverter of 2 MW. The 2 MW PV array serves a 1 MW local load and the surplus is delivered to the distribution line of 14 km which has a load of 30 MW connected to it. In the first iteration of time, PV power goes from 100% to 50 % and back up to 100 % for 60 seconds of operation (ramp rate of 100 kW per second). A three-phase line to ground fault occurs on the substation side of the 14 km feeder. The fault is cleared after 6 electrical cycles. The simulation of the distribution system is performed in MATLAB/Simulink in order to investigate if it meets the IEEE-1547 standard.**

Index terms – Power quality, photovoltaic, distributed generation, harmonic distortions, IEEE standards, IEEE-1547 standard, Low Voltage Ride Through (LVRT).

I. INTRODUCTION

Climate change is menacing the existence of the world. Worldwide, policymakers are trying to reduce the CO_2 emissions which are mainly responsible for climate change. While doing so, the energy consumption of the world is growing exponentially. To meet the energy demands, solar energy is one of the best candidates among renewable energy resources. Each kilowatt-hour (kWh) generated from renewable sources might save the environment from the burning of fossil fuels. It is known that the sun is a glint ball of gas that sends out a huge number of rays on daily basis. Photovoltaic is the most promising technology amongst the types/methods of producing electricity from solar energy. The most widely used is the solar photovoltaic base system.

Electricity generated from photovoltaic (PV) power systems is a major source of renewable energy. Scientists are developing solar resources with better technology to maximize energy production as much as possible. One of the prominent models of such a technology is the grid-connected PV system which supplies electricity directly to the power grid. They are based on semiconductor wafers that produce electricity when exposed to light. The designer of the system is responsible for selecting the value of the different parameters: number and type of PV modules, inverter type, distribution of components in the installation field, etc.

Smart grid infrastructure provides a form of technology that maintains the reliability of solar integration into the electric grid. The current electric grid has been stretched to its maximum capacity. However, updating the smart grid can help control the demand for electricity needed today.

When dealing with a photovoltaic system, power electronics play significant roles. The primary role is to interconnect solar panels in series and parallel according to requirements. For this reason, converters and inverters are used to help maintain the required current and voltage and standard voltage regulation, thus ensuring maximum efficiency.

In this work, the investigation is performed using a PV system to install 2 MW grid-connected solar PV. The various factors that are considered for performance evaluation are solar irradiation ambiance. Furthermore, a summary of the design with and the operation during the 100%-50%-100% PV transient and response to a three-phase fault condition is done by using MATLAB/Simulink. For interconnection purposes of renewable energy source (RES) to the grid, the IEEE-1547 standard is used.

From the IEEE 1547 standards, for there to be ride-through capability, the Distributed Energy Resource (DER) must provide voltage during the PV 50% output, and the fault condition. If the voltage is between 0 and 0.88 p.u., then the clearing time must be between 2 and 21 seconds for the DER to provide the ride-through capability.

II. THEORETICAL BACKGROUND

If the PV penetration is high, the photovoltaic system can be subjected to adverse effects. These include an increasing number of tap operations, overvoltage along the distribution feeder, large and frequent voltage fluctuations, PV power ramps, power quality problems, reverse power flow, increased reactive power, and islanding detection difficulties. In this paper, we consider the following impacts of connecting the proposed PV system to the grid.

A. Harmonics

Harmonic distortion is usually a result of non-linear devices in electric power systems. It poses numerous risks such as overheating of transformers and feeder lines and outages due to blown fuses and failed equipment. Solar PV systems depend extensively on power electronic converters to produce alternating current output for interconnection purposes. However, they are among the major sources of harmonics.

As such, the number of harmonics generated by the PV system depends on the type of solar inverter used. A multi-level inverter can provide desired alternating output voltage

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using multiple lower levels of DC voltages as input. Increasing the number of levels, increases the voltage steps of the output waveform, making the waveform more sinusoidal. Hence, as the number of levels increases, the harmonic distortion of the output waveform decreases [1].

Hence, issues of harmonics are one of the most important factors affecting the integration of renewable energies. To handle this, the IEEE-1547 standard focuses on the interconnection requirements of renewable sources.

B. Power Quality Problems from Harmonics

The core of the grid-connected to a PV system is the inverter. It is responsible for defining the quality of power injected into the grid. As already indicated, during the conversion of DC to AC, the inverter introduces harmonics into the system due to the presence of non-linear loads. The resulting harmonic currents introduce voltage drops, which, in turn, cause distortion in the supply voltage. Malfunctioning, reduction in a lifetime, and permanent damage are attributed to resonances in the supply system due to the presence of harmonics.

It is also well studied that the installation of capacitors in the system introduces resonant frequencies in the circuit which may be excited by harmonic currents from inverter-based PV units within the respective circuit. Current distortion can go beyond the criteria of the IEEE-1547 standard; henceforth, limiting the amount of PV penetration on the circuit [2].

To alleviate these issues, repurposing capacitors and harmonic filters can be applied. For example, an LC filter is typically installed after the inverter before connection to the grid to mitigate the harmonic levels.

C. Increased Reactive Power

Presently, the majority of the inverters used to connect the PV to the electric power grid operates at a unity power factor. For owners of small residential PV systems in an incentive-based program are levied based on their kilowatt-hour yield and not on their kilovolt-ampere hour yield. As such, it is preferred to operate PV inverters at unity power factor, maximizing the active power generation, and accordingly their returns. As a result, the reactive power demand met by the PV system is minimal. There are several points that must then be made. Because of this power factor, the portion of the distribution grid supplied by the PV system that uses the inverter will go to the lowest value as only active power would be supplied. As such, the grid is responsible for supplying the majority of reactive power, and it makes the distribution transformer operate at a low power factor. This will be achieved through a capacitor installed in the primary of the distribution grid or by the substation.

D. Islanding Detection

Islanding refers to a condition when the system continues to supply to the load even though grid power from the utility is not present. In this scenario, a circuit can still be energized which is ultimately extremely dangerous for utility workers when performing maintenance operations. As a result, the solar inverter must detect islanding and disconnect the PV system when the grid is down. This function of the PV system is known as anti-islanding. These impacts are dependent on the size and location of the PV system. According to the Solar America Board for Codes and Standards (Solar ABCs), PV systems are classified into three categories, based on the ratings of the system. Small-scale systems are rated at 10 kW or less; Medium-scale systems are rated between 10 kW and 500 kW, and large-scale systems are rated above 500 kW. This work considers a large-scale PV system of 2 MW for simulation. The Power Control Centre (PCC) is the Bus 1.

III. SYSTEM MODELING

A. The Grid Requirements for the PV System

The Grid Requirements for PV Systems due to the rapid growth of PV systems are expected to be modified in order to accommodate the increase of the PV penetration level. Low voltage ride-through (LVRT) and reactive current injection during low voltage ride-through, depicted in Fig. 1 and in Fig.2, are the main grid requirements of medium and high voltage PV systems. The principle of voltage support requirements under grid faults is depicted in Fig. 3. Those grid requirements are necessary to ensure the safety of maintenance personnel, protect the equipment, and guarantee the stability of the power grid. The voltage support of the PV system is activated when a voltage dip of over 5% of the root mean square (RMS) value of the PV inverter voltage occurs.

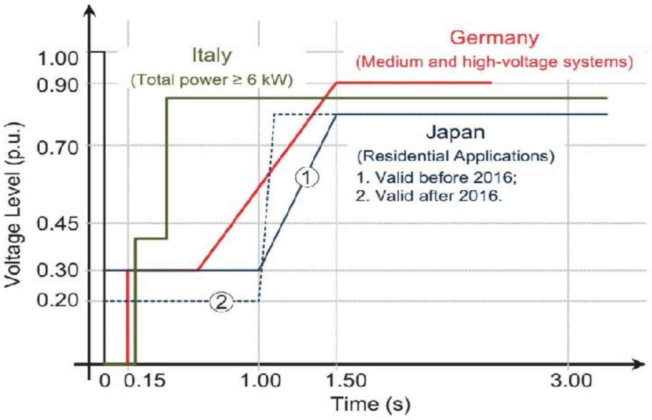

Fig. 1: LVRT requirements in different countries [3].

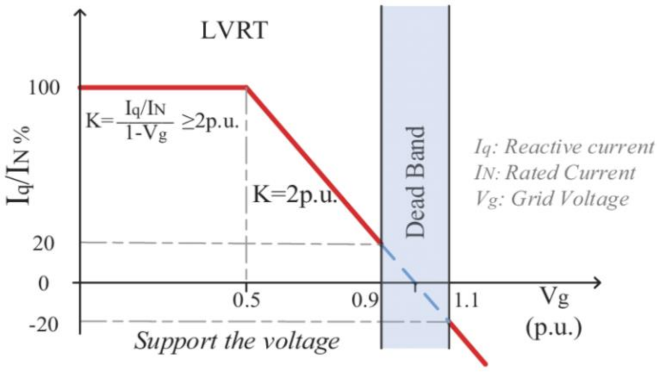

Fig. 2: Reactive current injection requirements during LVRT [3].

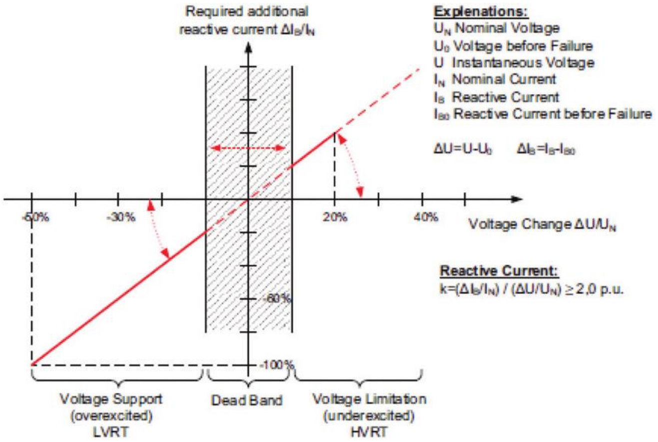

Fig. 3: The voltage support requirement during a grid failure [3].

B. *Grid-connected solar PV system*

PV grid-connected system consists of PV modules, a central inverter, and a public grid. A grid does not require a storage component as the generated energy is sold back to the main grid. The proposed model is illustrated in Fig.4 by using MATLAB/Simulink.

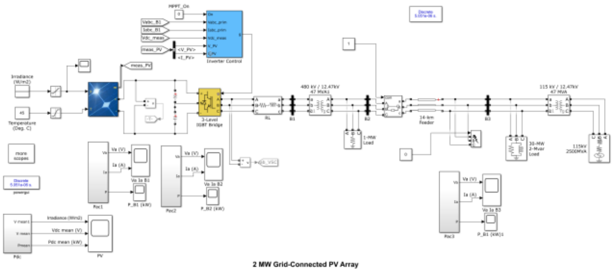

Fig. 4: Grid-Connected PV system.

The number of PV modules used to obtain the 2 MW is 6500 Modules of 310 W each. According to their technology, there are two kinds of PV modules available: Crystalline Silicon and Thin Film. In this study, we used the Monocrystalline module because it has higher efficiency than the polycrystalline module. This work uses a 3-level IGBT bridge inverter of 2 MW. The output is set to 480V at 60HZ for grid compatibility.

The PV arrays generate a peak of 2 MW in a day. A DC/DC converter, which is also used as a power optimizer, is equipped with control functions such as Maximum Power Point Tracking (MPPT). The PV system is integrated into the grid by means of a DC/AC inverter, a step-up transformer, and an evacuating line of 12.47 kV. The point of common coupling is Bus 1.

IV. RESULTS & DISCUSSION

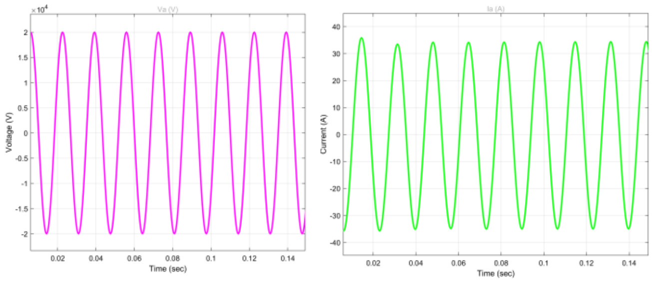

Fig. 5: Voltage and Current at the PCC Bus 1 in the steady-state condition

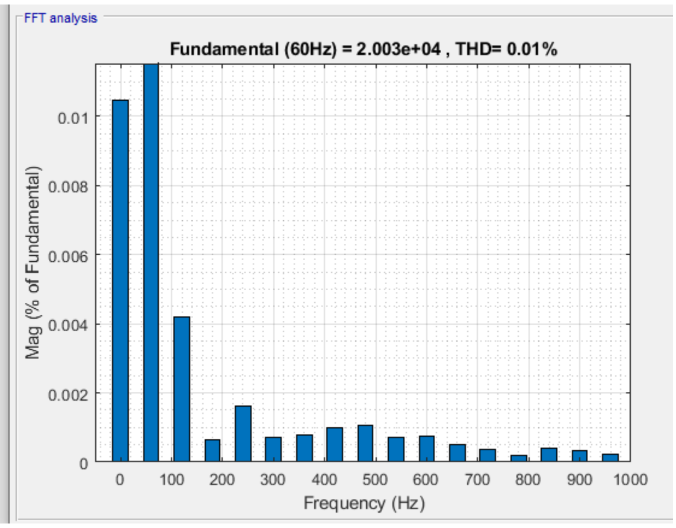

Fig. 6: THD calculations for voltage at bus B1.

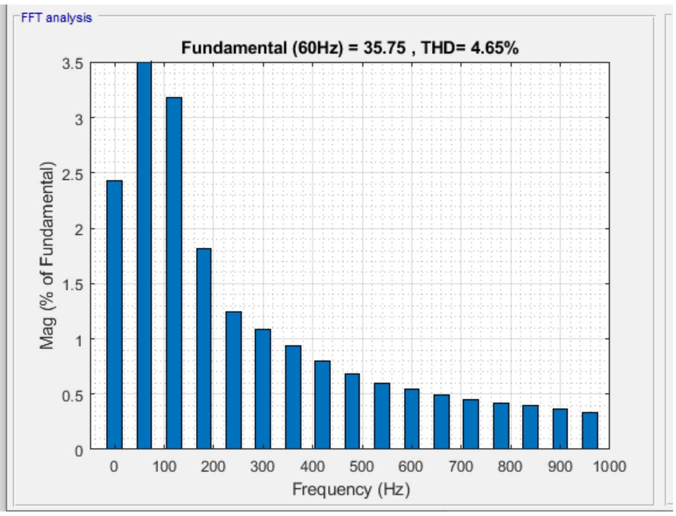

Fig. 7: THD calculations for current at bus B1.

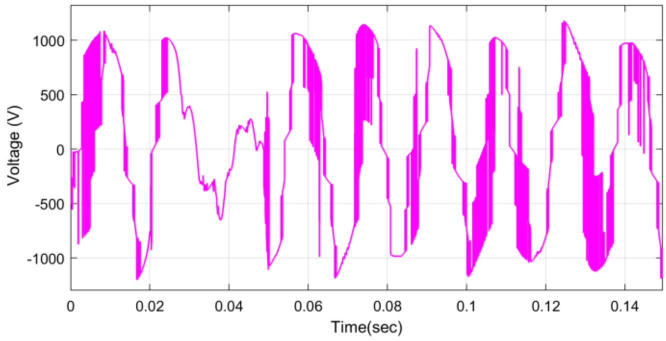

Fig. 8: Output Voltage of the Inverter before Filter.

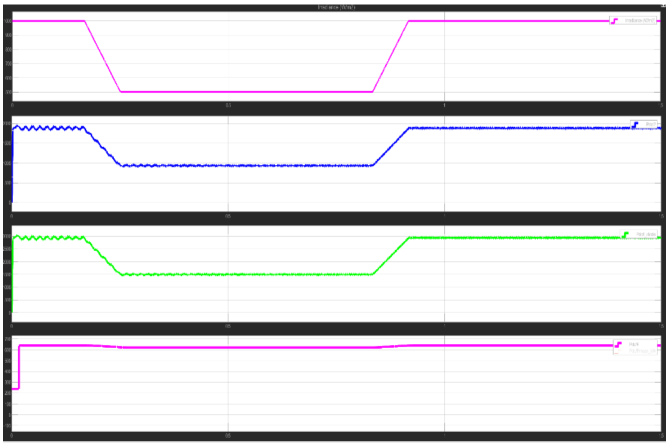

Fig. 9: Power variation with irradiance variation 100%, 50%, 100%.

As can be observed, the TDH is less than 5 % at the PCC. Thus, it means the IEEE 1547 standard for interconnection has been met. Additionally, the output power of the PV generator the pink curve in the figure above following the irradiance variation from 2000 kW to 1000 kW again to 2000 kW as the irradiance varies from 100%, 50%, 100%. In the figure above, the irradiance curve is a function of time as shown by the brown curve (Fig. 8).

A. Analysis and Discussions for Inverter 50% of its Outputs

The voltage of the inverter before the filter is around 800V. However, when the PV drops to 50% of its rated output power, the voltage drops to 780V Peak. The PV current goes from 3kA to 1.5kA, power drops to 1MW, and the DC voltage drops to 780V. However, the inverter voltage and current with the filter at Bus 1 remain constant. The filter consists of an RL filter, that allows for the THD to be lower than 1% a. During the drop in voltage, the inverter works very well in the ride through capability enough to maintain the system stable.

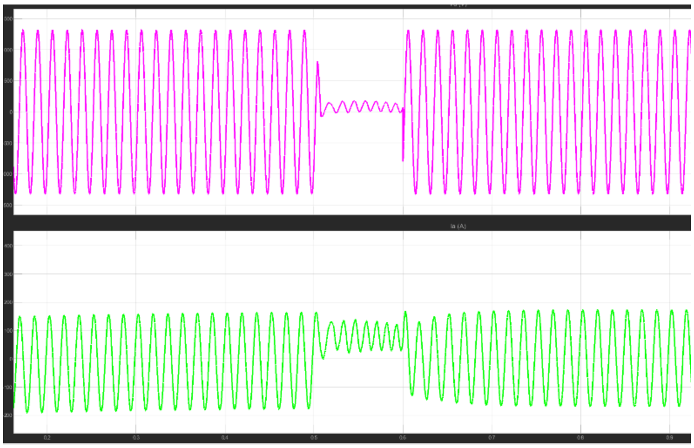

Fig. 10: Voltage and current at bus B1 during the three-phase fault.

As can be seen, during a short period of time like 6 cycles bus B1 is subjected to an under-voltage situation. The output of the inverter witnessed some transient in his current. This drop demonstrates that the inverter would not provide voltage to the rest of the system when the voltage output is filtered during the fault condition. However, once the fault condition ends, the Inverter is able to recover the voltage at every point in the system quickly.

B. Low Voltage Ride-Through Analysis

In electrical power engineering, the low voltage ride through (LVRT) is the capability of electric generators to stay connected in short periods of voltage dips. According to the IEEE 1547 standards, the DER must be capable to maintain voltage during with PV 50% of its output, and with the presence of the fault condition. If the voltage is between 0 and 0.88 p.u., then the clearing time must be between 2 and 21 seconds for the DER to provide the ride-through capability. From the Inverter output voltage seen in Figures above, the voltage drop is insignificant, which reaches 0.97 p.u., if the nominal voltage is around 565V L-L RMS.

The standards state that this value is inside the permitted range for continuous operation in all three categories since it states that the voltage must be between 0.88 to 1.1. By looking closely at Bus1 voltage during the fault condition, the voltage drops to nearly 0 volts, which means the p.u value is not in the 0.88 p.u. to 1.1 p.u. range. In fact, the voltage in Bus1 is less than 0.1 p.u. during the fault condition. This voltage dip shows that the inverter would not able to maintain voltage for the rest of the system when the system is subjected to a three-phase fault. However, once the fault is cleared, the inverter voltage returns to the steady-state condition in the distribution systems.

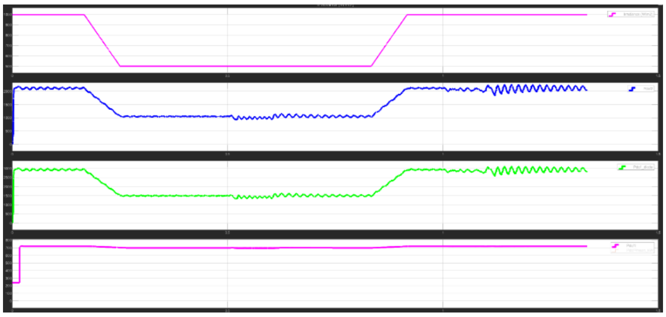

Fig. 11: Inverter output power during the three-phase fault.

V. CONCLUSION

This work presented a study on three-phase grid-connected PV systems under grid faults. PV array, PV inverter, and PCC of the grid-connected PV system are perturbed by grid fault events. The impact of grid faults on PV systems depends on the fault type and less on the fault distance. Symmetrical faults have a higher impact on PV systems performance than asymmetrical faults, both at the PCC and inside the grid-connected PV array.

The output voltage of the inverter before the filter was around 800V Peek, but when the PV drops to 50% output power, the inverter output voltage drops to 780V Peek. The PV current goes from 3kA to 1.5kA, power drops to 1MW, and the DC voltage drops to 780V. However, the measurements of the inverter voltage and current with the filter, measured from Bus 1, show no change in amplitude. The filter consisted of an RL filter, that allows for the THD to be lower than 1%. During the drop in voltage, the Inverter provides sufficient ride-through capability to maintain the system stable.

During the PV output power 50% drop, the voltages at all of the busses do not change at all, which means that the DER is able to provide enough voltage and current to the system even when operating at 50%. Therefore, the DER does provide ride-through during the PV output drop, but it is not clear if it can provide enough ride-through capability during the fault condition.

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APPENDIX

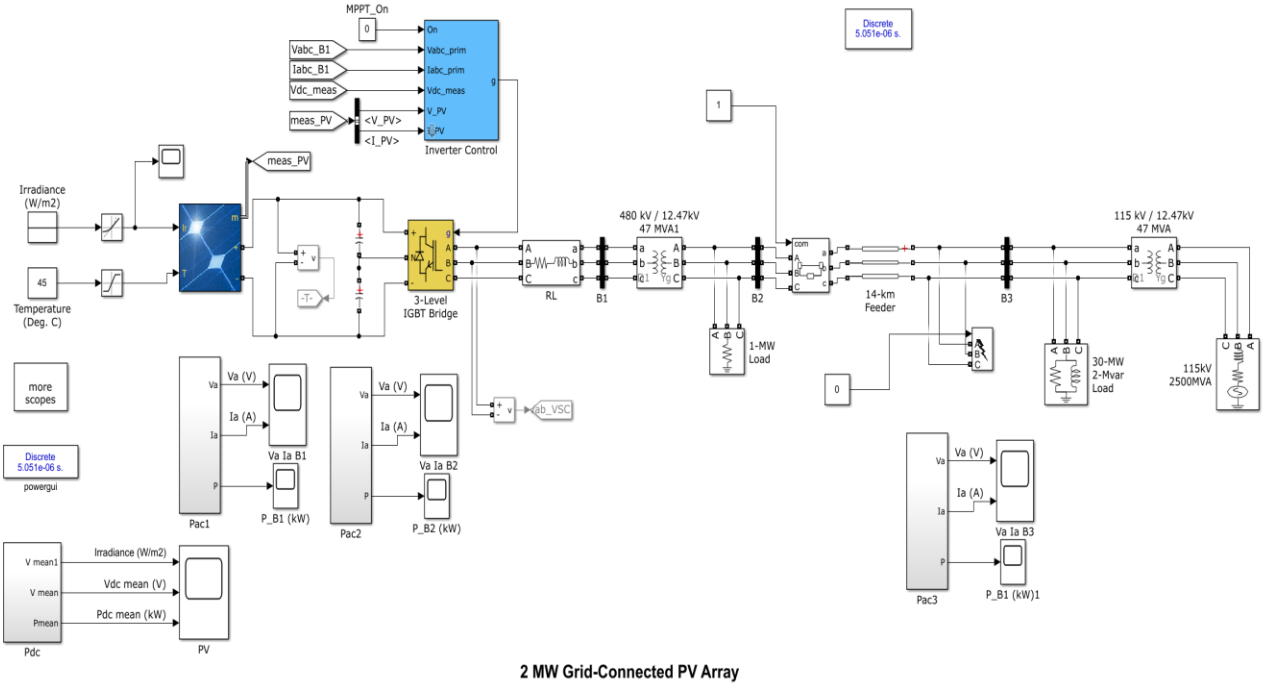

Fig. 12: The Proposed System from Fig. 4 is shown here larger for viewing.