Modeling and Steady State Response Analysis of Interconnected Hybrid Renewable Energy Network with Embedded VSC - MTDC Transmission System for Secure and Efficient Power Delivery

Ritu Raj Soni[1], Radhey Shyam Meena[2], Shivani Johari[3], Mukesh Lodha[4], Jitendra Singh Rathore[5]

[1,3,4,5] Shri Balaji College of Engineering & Technology, Jaipur (Rajasthan)

[2]Ministry of New & Renewable Energy, New Delhi (India)

Corresponding Author: Radhey Shyam Meena

Abstract: **This paper deals with one of the major challenge in the field of Indian Power Sector with a objective of to provide a framework for promotion of large grid connected and interconnected Renewable Energy (RE) networks for optimal and efficient utilization of transmission infrastructure and land, reducing the variability in renewable power generation and thus achieving secure and better grid stability with improved power quality at delivery end. The proposed studies are going to encourage new technologies, methods and way-outs involving combined operation of wind and solar PV power generation systems with embedded Voltage Source Converter (VSC)-MTDC transmission system, to transmit bulk power, to control power, to modulate power and to improvement in system stability. The paper focused on a case study of two separate-interconnected systems through a DC transmission network of the capacity of 24 kW wind power generation system and 24 kW solar power generation system has been used for analysis of steady state response of the system. Performance of the system and steady state response analyze using MATLAB techniques and is better then non-RE network and also found in acceptable range for secure operation and better grid stability.**

Key words: **Integrated Solar Wind System, Interconnected Renewable Energy Network (IREN), Multi Terminal Direct Current (MTDC) Transmission System, Voltage Source Converters (VSC), Power Quality (PQ) of India Power Sector (IPS), Grid Stability (GS).**

I. INTRODUCTION

India has set an ambitious target of reaching 175 GW of installed capacity from renewable energy sources including 100 GW from solar and 60 GW from wind and plan for 10 GW solar wind hybrid capacity by the year 2022 for which the Government of India has launched several schemes for promotion of solar and wind energy in the country to achieve the target. The Government is promoting renewable energy through fiscal and promotional incentives such as capital subsidy, tax holiday on the earnings for 10 years, generation based incentive, accelerated depreciation, viability gap funding (VGF), financing solar rooftop systems as part of home loan, concessional excise and custom duties, preferential tariff for power generation from renewables, and foreign direct investment up to 100 per cent under the automatic route etc. The country has already crossed a mark of 32 GW of wind and 12.28 GW of solar power installed capacity up to March 2017[1].

Solar and wind power being infirm in nature impose certain challenges on grid security and stability. Studies revealed that solar and winds are almost complementary to each other and hybdridation of two technologies would help in minimizing the variability apart from optimally utilizing the infrastructure including land and transmission system. Superimposition of wind and solar resource maps shows that there are large areas where both wind and solar have high to moderate potential. The existing wind farms have scope of adding solar PV capacity and similarly there may be wind potential in the vicinity of existing solar PV plant. Suitable policy interventions are required not only for new wind-solar hybrid plants but also for encouraging hybridization of existing wind and solar plants [2-3]. Performance and feasibility explained in [4] for an integrated hybrid system in which a solar cell, wind turbine, fuel cell and ultra capacitor system is developed using a novel technique to complement each other. Hybrid renewable energy systems in [5] help to increase system reliability and improve power quality. This paper explained the way to integrate the power output from solar photo voltaic array, fuel cell stack and battery with a provision for on site hydrogen generation by means of an electrolyzer and H_2 tank. The control strategy handles the source power effectively by considering the limited life cycle of storage devices. In [6] one such novel initiative wherein electricity requirement is fulfilled by renewable energy presented. In this study, an integrated hybrid system is used to generate electricity from the combination of solar and wind energy. Fuel cell and electrolyzer also used for storage and better performance on remote applications. A combination of a solar cell, fuel cell, and ultra capacitor system for power generation was presented in [7]. In this work the available power from the renewable energy sources is highly dependent on environmental conditions such as wind speed, radiation, and ambient temperature. Fuel cell and ultra capacitor system were used to overcome the deficiency of the solar cell and wind system. This system is used for off-grid power generation in non-interconnected or remote areas. High Voltage DC Transmission system is used to transmit bulk power, to control power, to modulate power for improvement in system stability. Mostly voltage source converters used as insulated gate turn of thyristor in dc network. In [8] it was described the basic modeling and simulation of voltage source converter in HVDC are explained. In [9] it was proposed to integrate large capcity renewable energy into the existing power grid, provide remote islands with reliable power supply, and regulate the frequencies. Though, to expand an existing traditional point to point line controlled converter HVDC line into hybrid MTDC system achived [10]. One of the most suitable applications of VSC-based MTDC transmission systems is in the field of wind farms interconnection. Of course there are many publications which investigated the possibility of utilizing CSC converters for aggregation of offshore wind farms [11-13]. However, CSCs need for reactive power support at the point of connection which consequently leading the connected AC system to have a high enough short circuit ratio [14-15]. Some literature has proposed that installation of Static Compensators (STATCOM) at the point of connection CSC terminal to offshore station can solve this problem [16]. However, the proposed solution brings about other issues such as a wider footprint, more losses, and more complexity in the wind power system. Contrarily, based on VSC HVDC link characteristics such as rapidly and independently control of active and reactive powers and black-start capability, these VSC links are superior to CSC links for wind farm grid interconnection [17-19]. That is why VSC links have been proposed as a more rational and efficient solution to be used for interconnection of wind farms. Therefore, due to these especial characteristics of VSC links, such systems are mostly used for wind farms interconnections. Reference [20] proposed the construction of a low voltage DC grid using VSCs to aggregate the power of several wind turbine units. It has also been proposed using hybrid MTDC systems based on VSCs and CSCs for subtransmission and distribution systems in urban areas of large cities [21].

II. AN APPROACH TOWARDS INTEGRATION

Under the integration category of wind-solar hybrid power plants, Wind Turbine Generators (WTGs) and Solar PV systems have been configured to operate at the same point of grid connection. There can be two different approaches towards integrating wind and solar depending upon the size of each of the source integrated and the technology type. Here we concluded two approaches i.e. (a) Technology front (b) Size of the source

On the technology front, in case of fixed speed wind turbines connected to grid using an induction generator, the integration can be on the HT side at the AC output bus. However, in case of variable speed wind turbines deploying inverters for connecting with the grid, the integration can even be on the LT side before the inverter i.e. at the intermediate D.C bus. The second important aspect would be related to the sizing – which would depend on the resource characteristics.

In order to achieve the benefits of hybrid plant in terms of optimal and efficient utilization of transmission infrastructure and better grid stability by reducing the variability in renewable power generation, in the locations where the wind power density is quite good, the size of the solar PVs capacity to be added as the solar-hybrid component could be relatively smaller. On the other hand, in case of the sites where the wind power density is relatively lower or moderate, the component of the solar PV capacity could be relatively on a higher side. However, a wind-solar plant will be recognized as hybrid plant if the minimum ratio of total rated capacity of WTGs and solar PV plant is 1: 0.25.

The implementation of wind solar hybrid system has depends on different configurations and use of technology detailed below:

(a) Wind-Solar Hybrid- AC integration:

In this configuration the AC output of the both the wind and solar systems is integrated either at LT side or at HT side. In the later case both system uses separate step-up transformer and HT output of both the system is connected to common AC Bus-bar. Suitable control equipment is deployed for controlling the power output of hybrid system.

(b) Wind-Solar Hybrid- DC integration:

DC integration is possible in case of variable speed drive wind turbines using converter-inverter. In this configuration the DC output of the both the wind and solar PV plant is connected to a common DC bus and a common invertors suitable for combined output AC capacity is used to convert this DC power in to AC power.

III. MODELING OF INTERCONNECTED HYBRID NETWORK

In this section an interconnected hybrid network of the wind and solar based configuration is presented. With their advantages of being abundant in nature and nearly non-pollutant, renewable energy sources have attracted wide attention. Wind power is one of the most promising clean energy sources since it can easily be captured by wind generators with high power capacity. Photovoltaic (PV) power is another promising clean energy source since it is global and can be harnessed without using rotational generators. In fact, wind power and PV power are complementary to some extent since strong winds mostly occur during the night time and cloudy days whereas sunny days are often calm with weak winds. Hence, a wind–PV hybrid generation system can offer higher reliability to maintain continuous power output than any other individual power generation system.

This kind of hybrid generation system can be divided into two main types—the stand-alone off-grid system and the grid-connected system. For the grid-connected system, the interface between the hybrid generation system and the power grid has to be specially designed. For the stand-alone off-grid system, the hybrid generation system can easily be set up in remote and isolated areas where a connection to the utility network is either impossible or unduly expensive. Over the years, there has been only few research work on the standalone wind–PV hybrid generation system in which the wind generators are focused on induction machines. The purpose of this thesis is to present a new way of grid connected and interconnected wind–PV hybrid generation system with embedded VSC-DC transmission system for secure and efficient power delivery to the end users.

IV. SOLAR SYSTEM

The solar radiation resource is fundamentally determined by the location on the earth´s surface, the date, and the time of day. These factors determine the maximum level of radiation. Other factors such as height above sea level, water vapor or pollutants in the atmosphere and cloud cover decrease the radiation level below the maximum possible. Solar radiation does not experience the same type of turbulence that wind does but there can be variations over the short term. Most often, these are related to the passage of clouds.

Simulink blocks of the different components in the experimental model are shown in Figure. In the figure, these are the PV array system block, inverter block, three-phase source block, controller block and the load block respectively. This model also includes the MPPT model, in the next chapter, these blocks will be discussed individually will look into how the models are implemented as shown in figure 1 and figure 2.

This model based on 24 kW system which design internally in figure1 and full diagram as shown in figure 2.

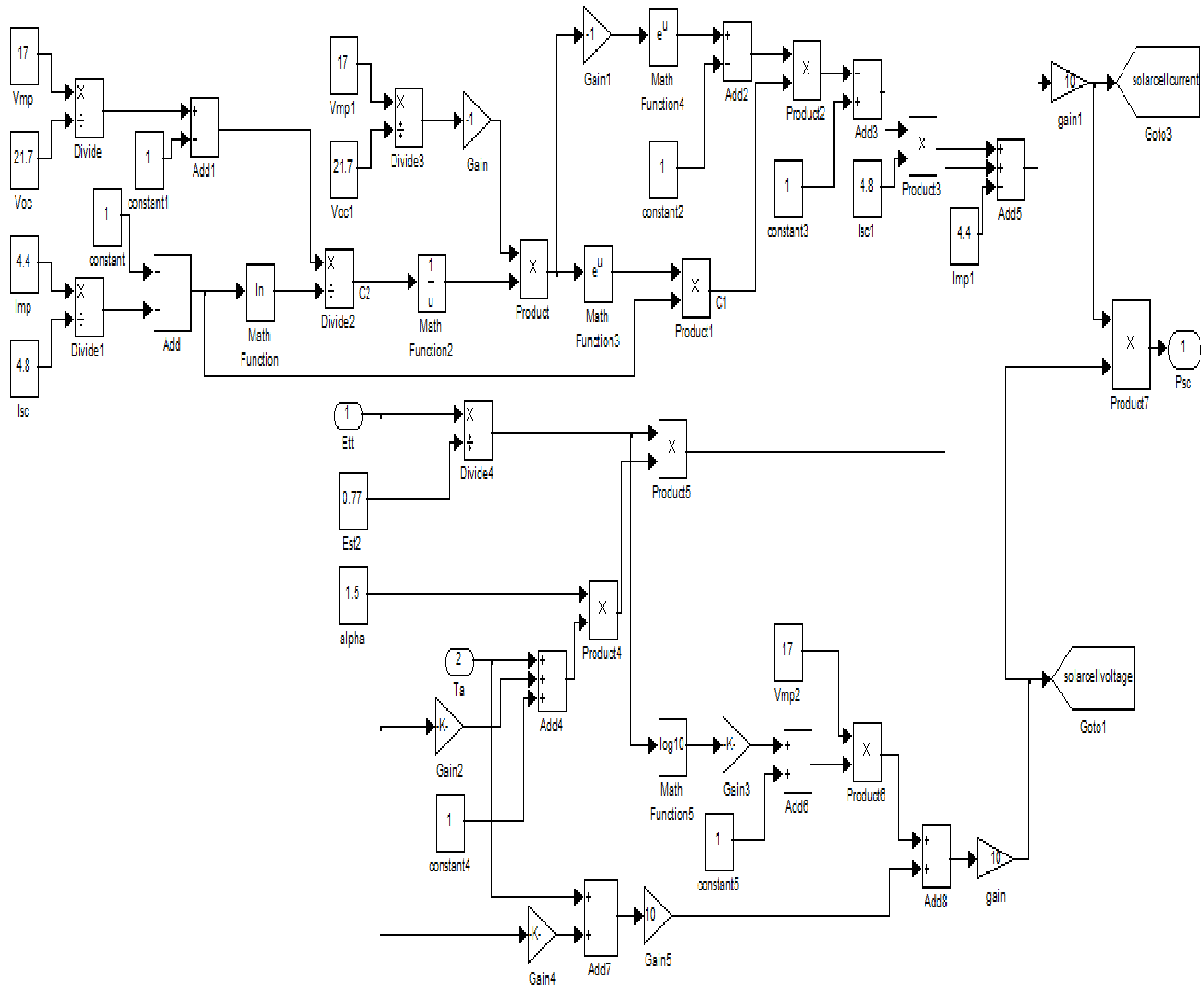

Figure 1: Internal model of solar system based on the equations

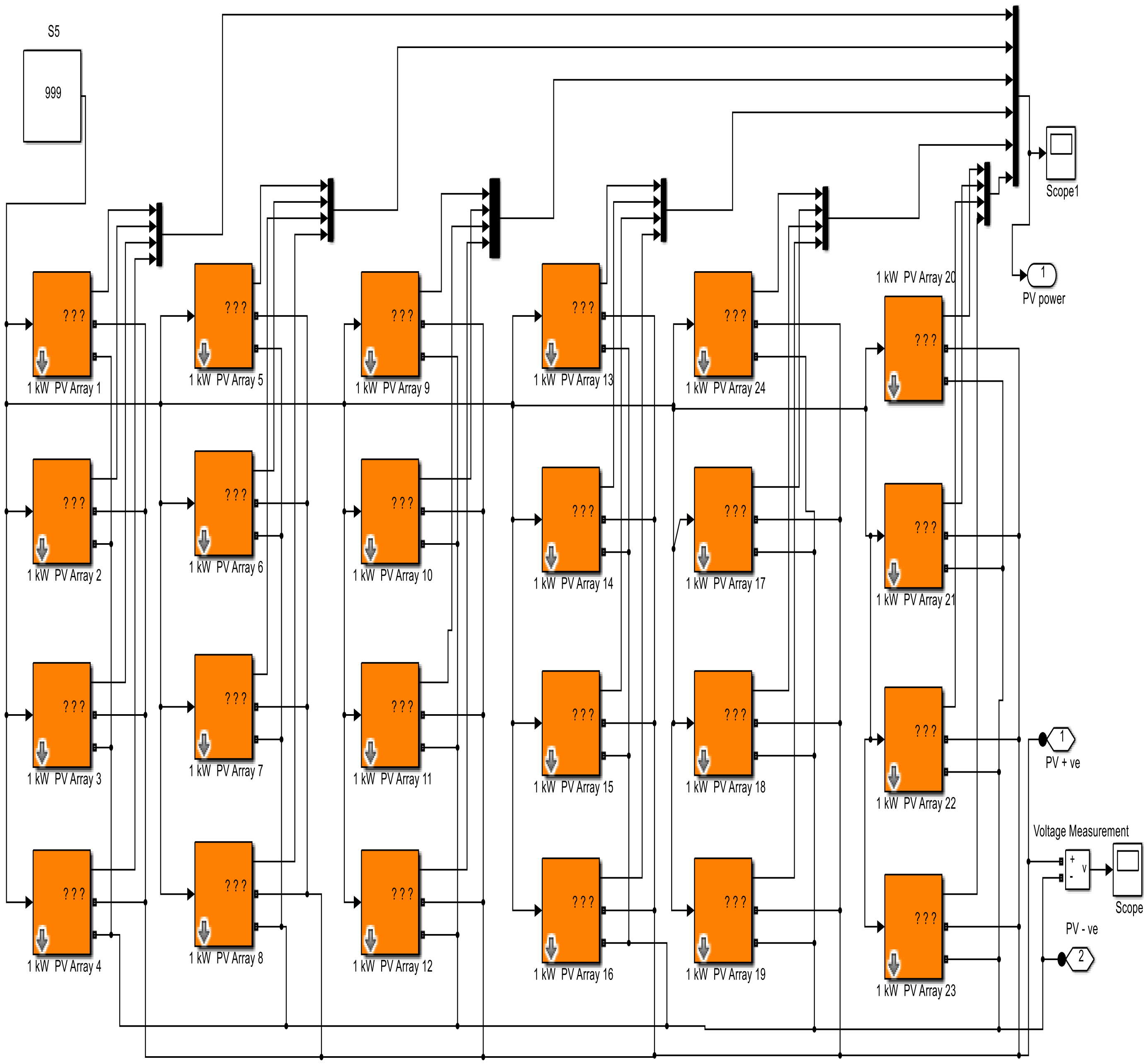

Figure 2: 24 kW PV system

V. WIND SYSTEM

Ultimately wind resources are driven almost entirely by the sun's energy, causing differential surface heating, but they tend to be very dependent on location. Over most of the earth, the average wind speed varies from one season to another. It is also likely to be affected by general weather patterns and the time of day. It is not uncommon for a site to experience a number of days of relatively high winds and these days to be followed by others of lower winds, strongly interfering with the operation planning of a hybrid system comprehending wind turbines. The wind also exhibits short term (seconds to minutes) variations in speed and direction, known as turbulence.

The power output of wind turbine relates to wind speed with a cubic ratio. Both the first order moment of inertia (J) and a friction based dynamic model for the wind turbine rotor and a first order model for the permanent magnet generator are adopted. The dynamics of the wind turbine due to its rotor inertia and generator are added by considering the wind turbine response as a second order slightly under-damped system. Using this simple approach, small wind turbine dynamic is modeled as shown in figure 3 and figure 4.-

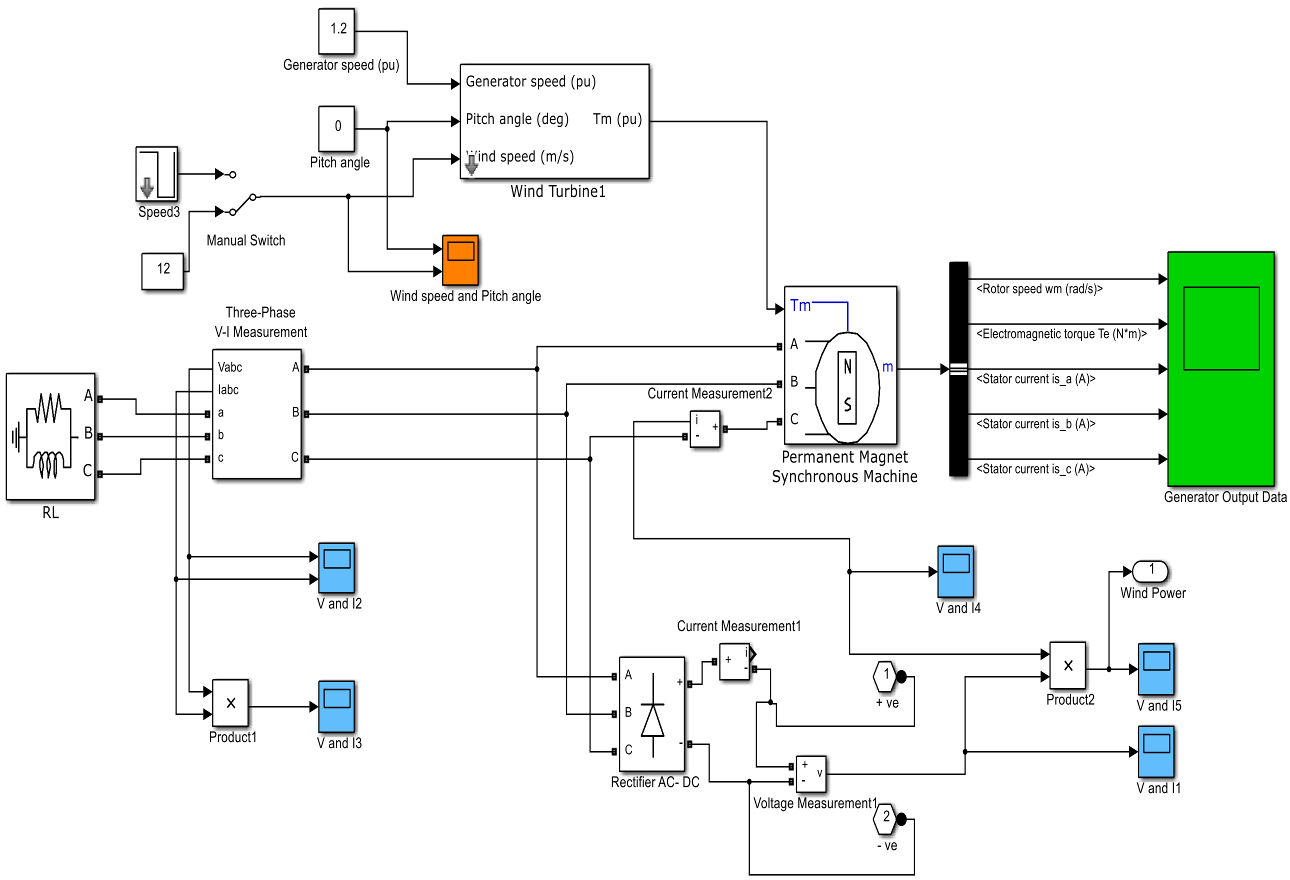

Figure 3: Internal Model of 3 kW wind system

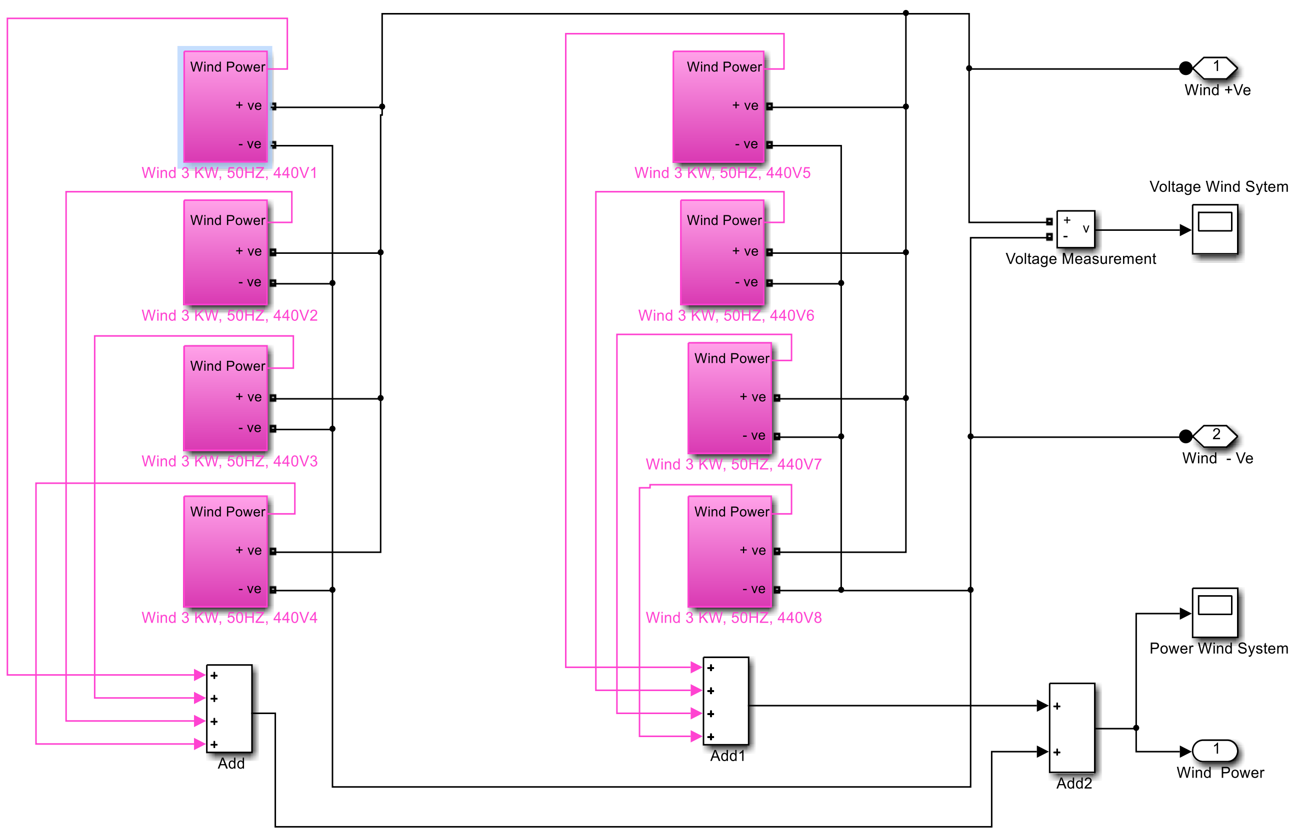

Figure 4: 24 kW Wind System

VI. VOLTAGE SOURCE CONVERTER (VSC) BASED MULTI TERMINAL DC (MTDC) SYSTEM

Two basic converter technologies are used in modern HVDC transmission systems. These are conventional line commutated, current source converters (CSC) and self commutated, voltage-sourced converters (VSC). Two types of configuration can be adopted in Multi Terminal DC (MTDC) systems. The parallel connection which allows DC terminals to operate around a common rated voltage VDC. The second configuration is the series connection where one of the converters controls the current around a common rated current and the power is controlled by the rest of converters. This configuration is well suited for Current Source Converter (CSC) MTDC systems since CSCs in the DC side are functioning as a voltage source which can be connected in series without need for special switching.

Compared to CSCs, VSCs are functioning as an ideal current source in its DC sides allowing the parallel connection of several DC terminals without posing any technical difficulties. As perviously mentioned, in a VSC link the direction of power can be changed through the reversal of current direction and the voltage polarity at the DC side can remain unchanged. These capabilities are perfectly suited for constructing an MTDC system. VSC MTDC systems with parallel connected converters have a great potential to be used in the future bulk power systems. Possibility of such connections has led to the proposition of a DC 'Super Grid' that could connect several renewable energy sources to a common MTDC network. Utilizing VSC-based MTDC systems can give the following possibilities to the power systems- (a) Control of the MTDC system, (b) increasing the flexibility of power flow controllability, (c) enhancing transmission capacity, (d) improving the voltage profile in the network, and integrating large scale of renewable or new energy sources positioning at different locations.

VSC based multi terminal DC system contains number of VSC's either offshore or onshore connected to same DC link. VSC connected to generating station can be offshore or onshore depending upon renewable energy nature i.e. tidal energy, offshore wind farms, solar panels etc. But throughout this paper we will consider offshore wind farms as it have more capacity to generate electricity and can meet the needs. Each offshore wind farm requires an offshore substation used to install VSC converter and number of connections to DC link depends upon MTDC application, same in the case of PV system. Before designing MTDC system, design engineer must consider techno-economic factors imposed by utility. Economic factors include geographical location, number of offshore substations, onshore platforms, DC link, DC Circuit Breaker, ultra-fast mechanically actuated disconnector, and cost. Technical aspects can be: effective utilization of MTDC lines, rating of DC link, protection of MTDC under abnormal conditions and support to connected AC network.

MTDC system must satisfy the security and Quality of Supply Standard as well as DC voltage of MTDC system must be constant during abnormal conditions on AC sides of VSC DC. Each terminal of VSC based MTDC system must be able to control active and reactive power, support AC network voltage and frequency independently. VSC based MTDC system behavior strongly depends upon the control nature which mainly rely on system topology and kind of AC grid connection.

Figure shows the VSC station model with its elements. The model at the DC side is depicted as single line representation. The model consists of AC buses, coupling transformer, series reactance, AC filter, converter block on the AC side and on the DC side, DC Bus, DC filter and DC line. As it can be seen each VSC station is connected to the AC grid at the so called point of the common connection (PCC). PCC is connected to AC side of VSC through a converter transformer, shunt filter and finally phase reactor. On the other side i.e. DC side, DC bus, at which a shunt DC capacitor is connected to the ground, is connected to the VSC from one side and to DC line from other side as shown in figure 5.

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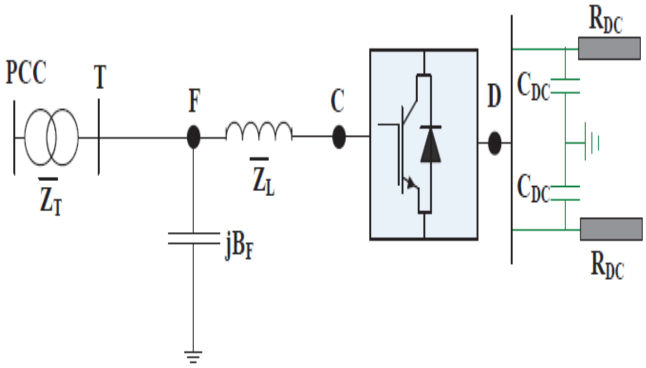


Figure 5: VSC Station Model

VII. INTERCONNECTED NETWORK

In this work, a detailed dynamic model and simulation of an interconnected hybrid power system are developed using the VSC topology. Modeling and simulations are conducted using MATLAB/Simulink software packages to verify the effectiveness of the proposed system. The results show that the proposed hybrid power system can tolerate the rapid changes in natural conditions and suppress the effects of these fluctuations on the voltage within the acceptable range and supply power at end user with better quality.

This system has 48 kW PV generation System, a 48 kW wind energy system, a 500 kM DC transmission line and VSC universal bridge for conversion purpose used. It is used to step up voltage to DC 440 V and invert to Vrms, 50 Hz AC.

The renewable energy based hybrid system model made in Simulink is shown in Figure 6, 7 and 8.

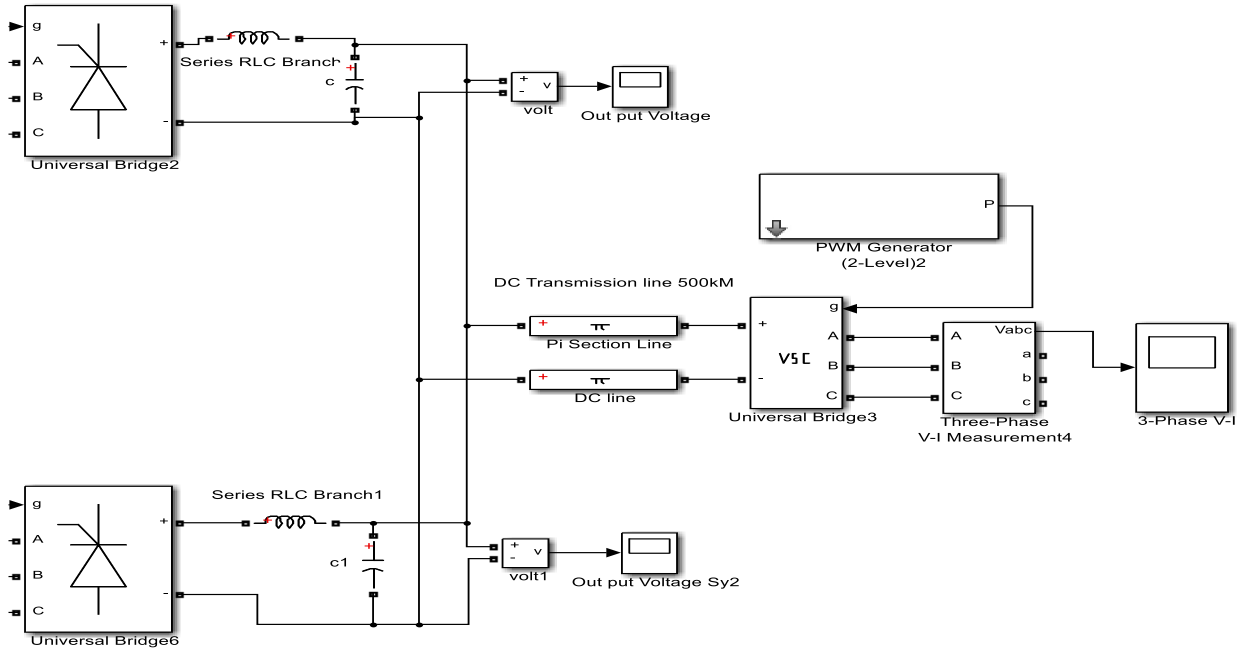


Figure 6: Interconnected through a DC Transmission Network and VSC system

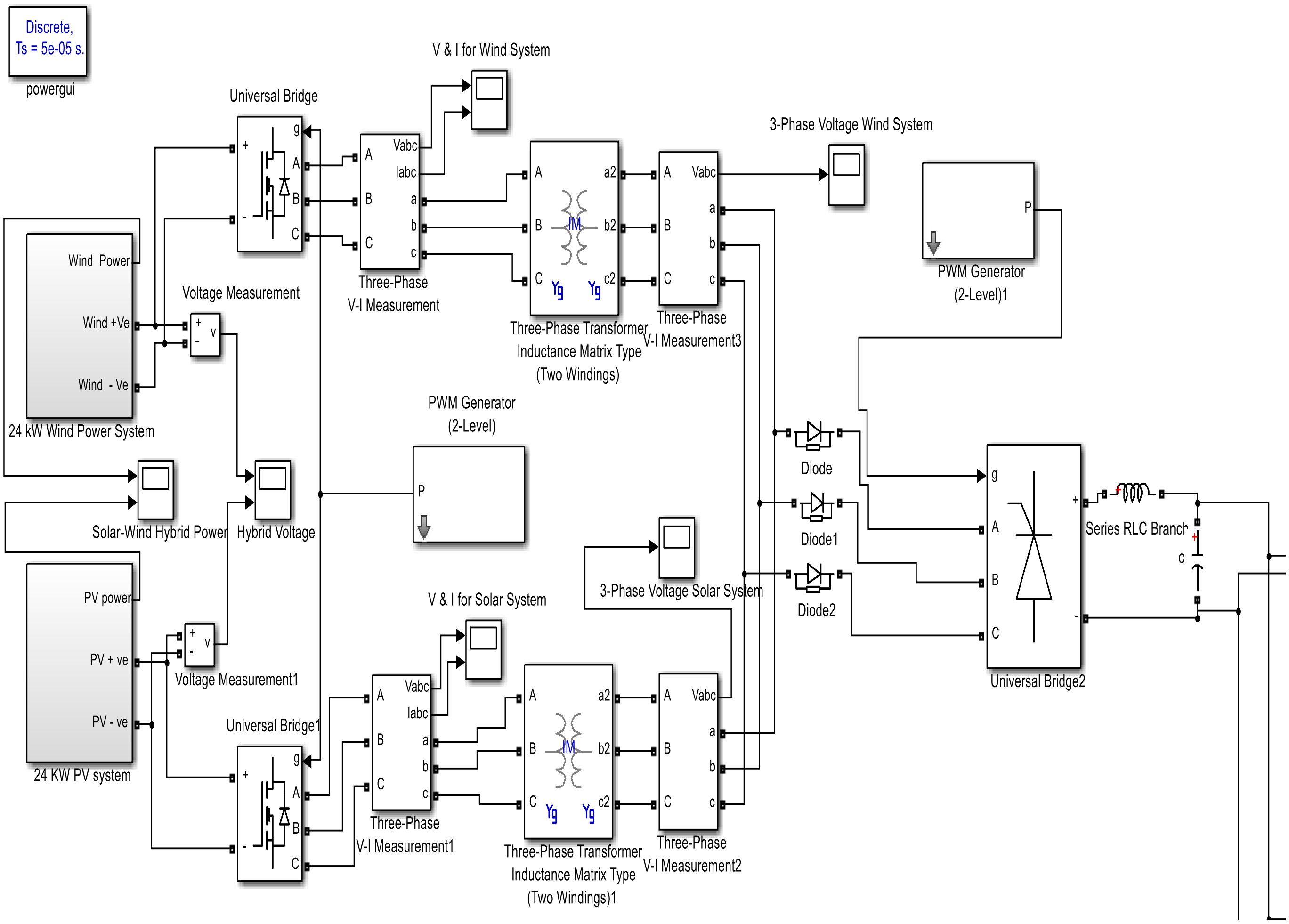


Figure 7: System-I of Capacity 24 kW wind and 24 kW PV system

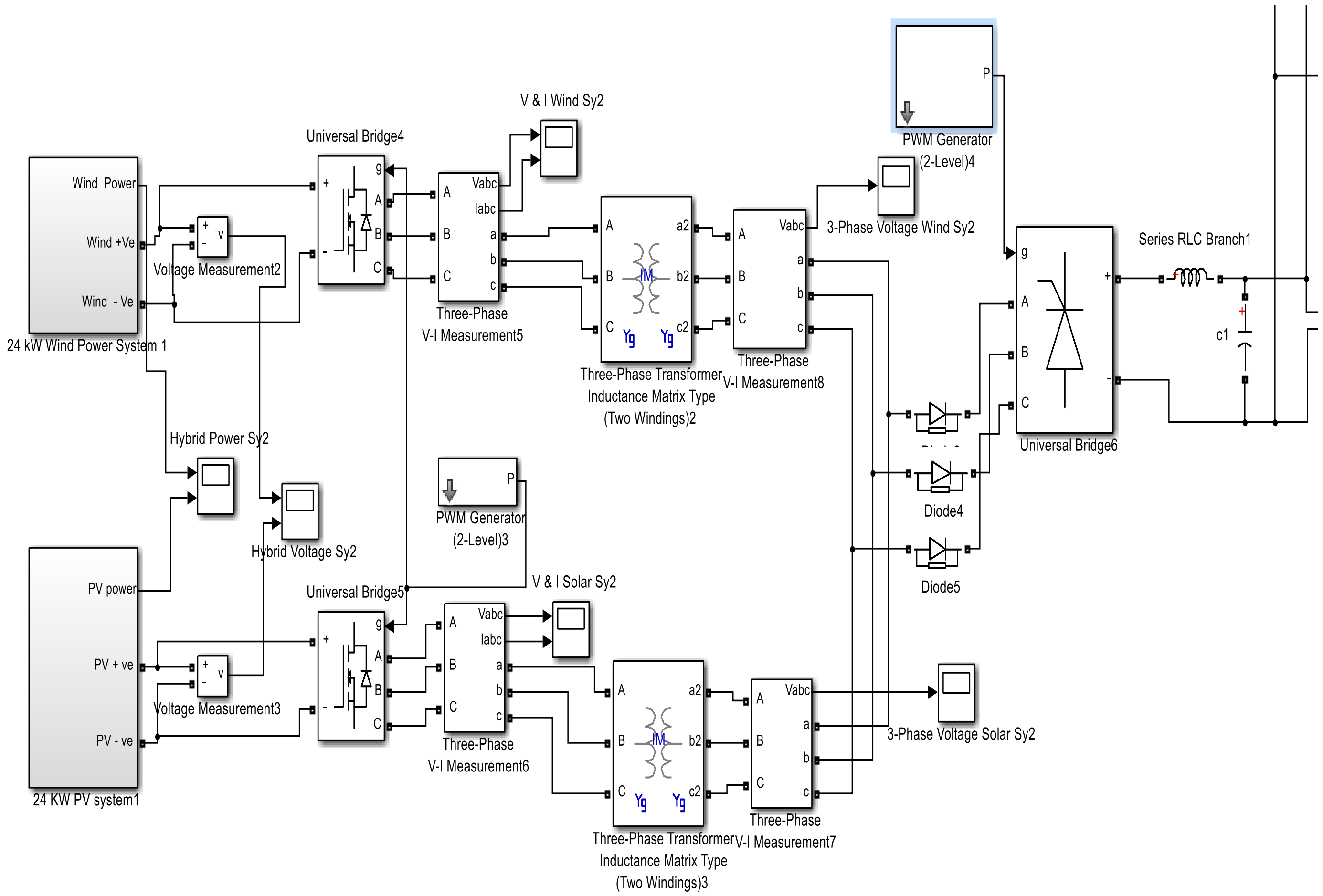


Figure 8: System-II of 24 kW wind and 24 kW PV system

VIII. SIMULATION RESULTS OF THE INTERCONNECTED NETWORK

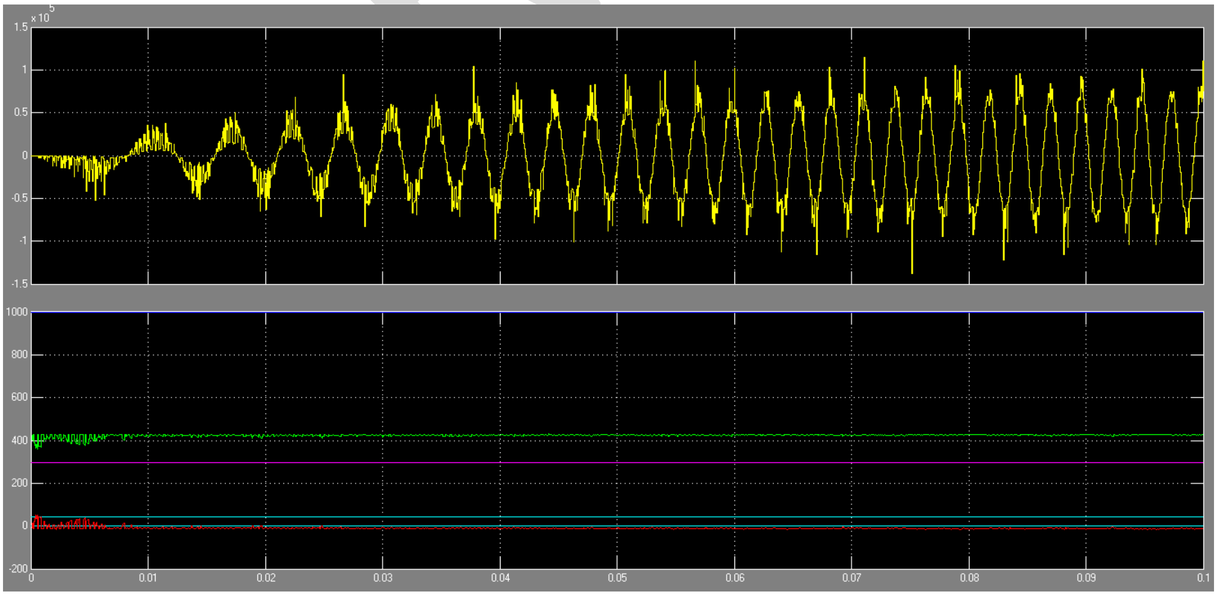


Figure 9: Wind Solar Power

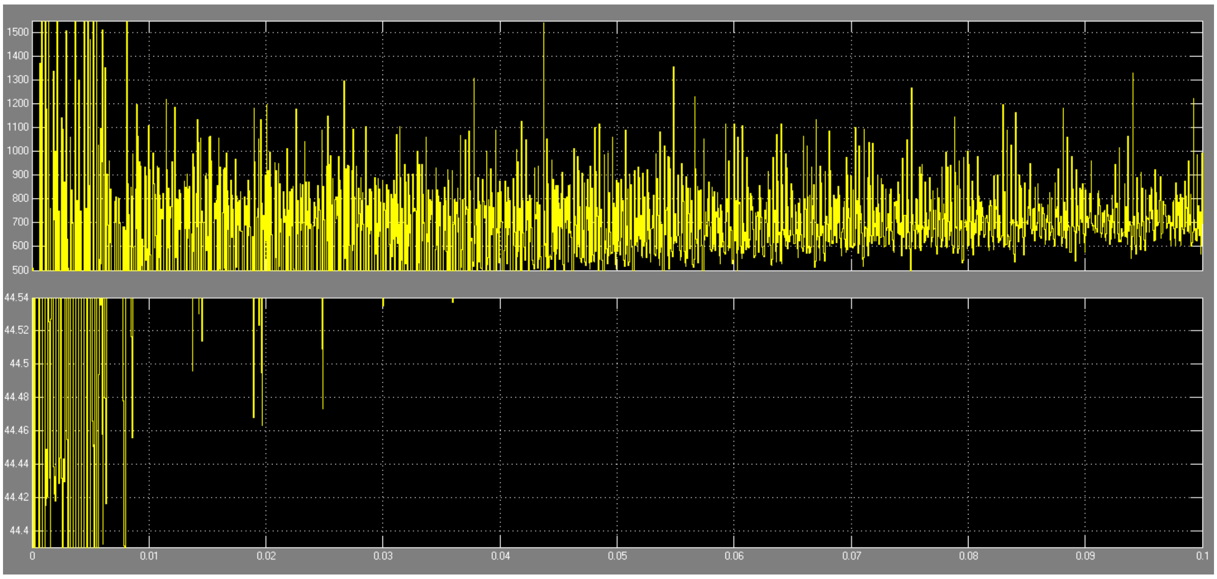


Figure 10: Hybrid Voltage

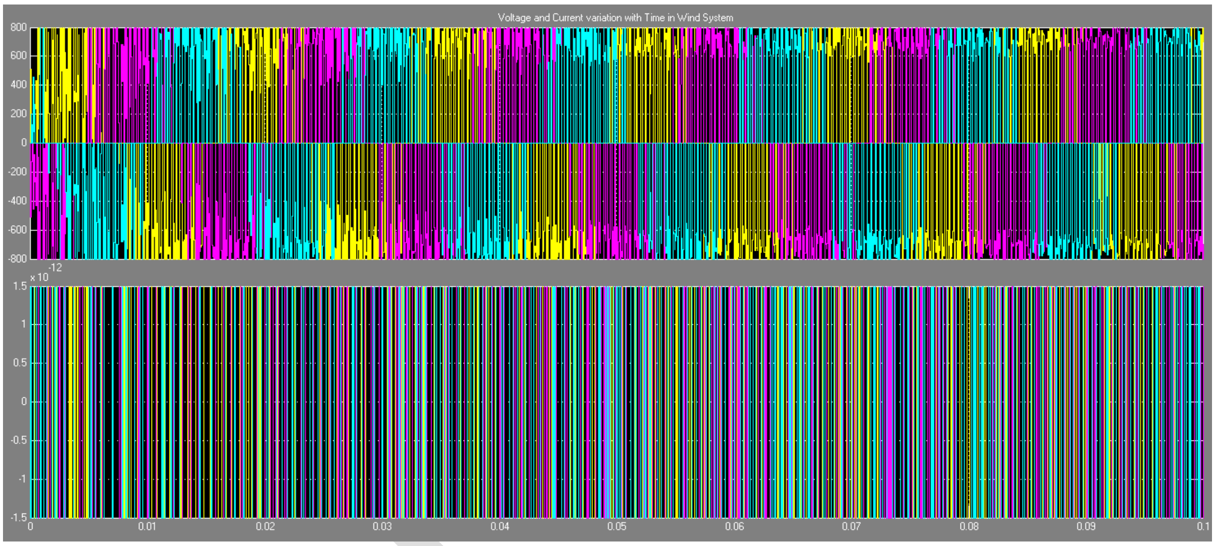


Figure: 11 Voltage and Current of Wind System

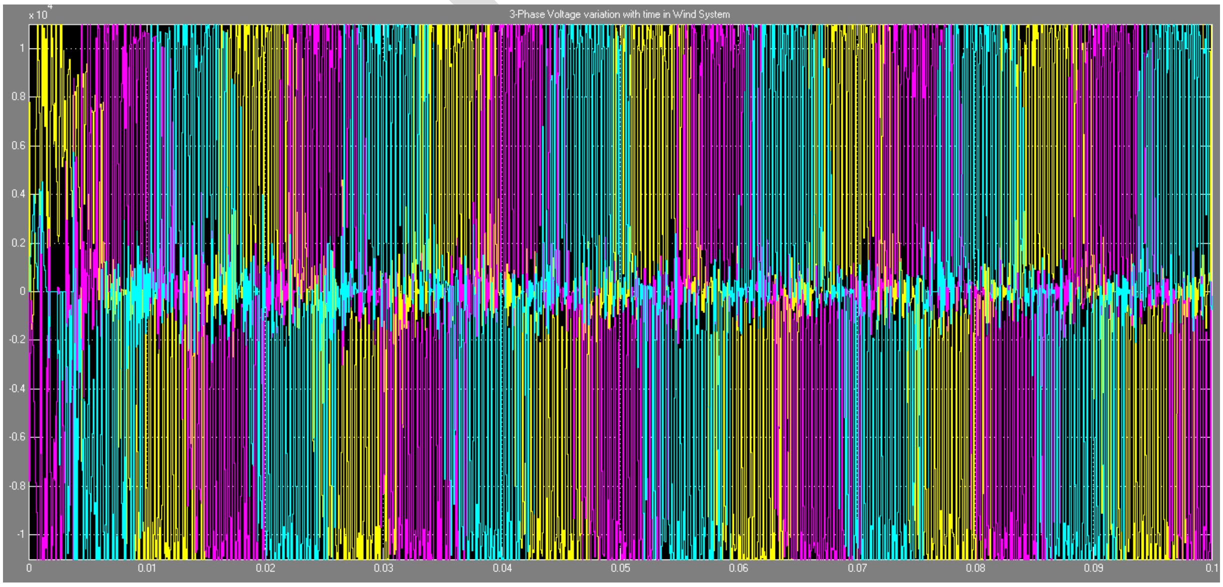


Figure 12: 3-Phase Volatage of wind

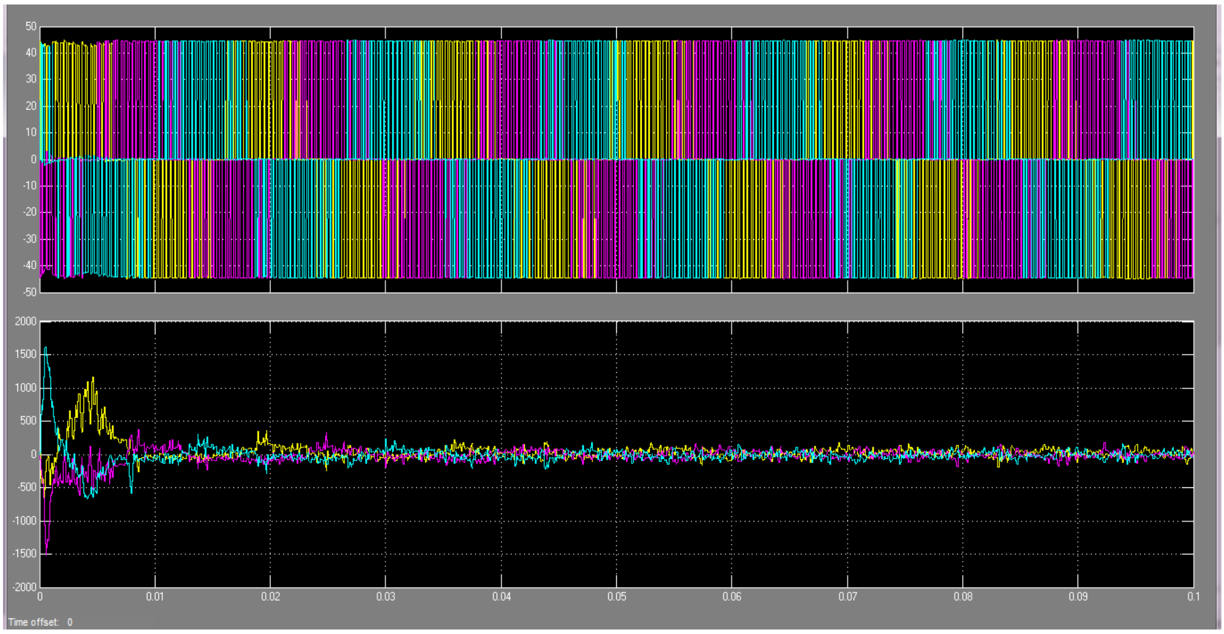


Figure 13: Voltage and Current for Solar System

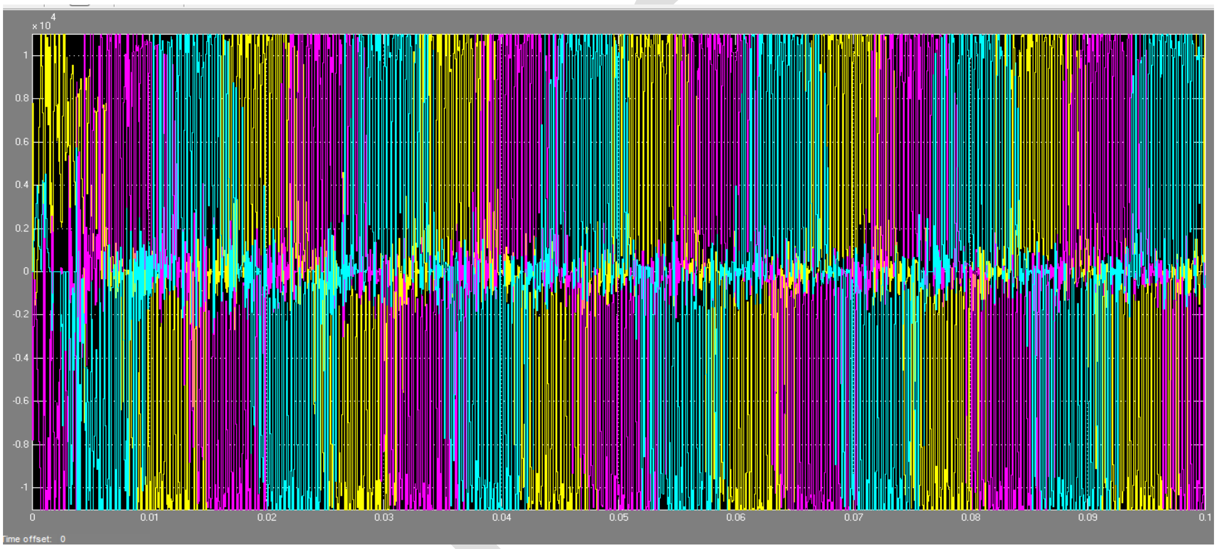


Figure 14: 3 Phase Volatage for PV System

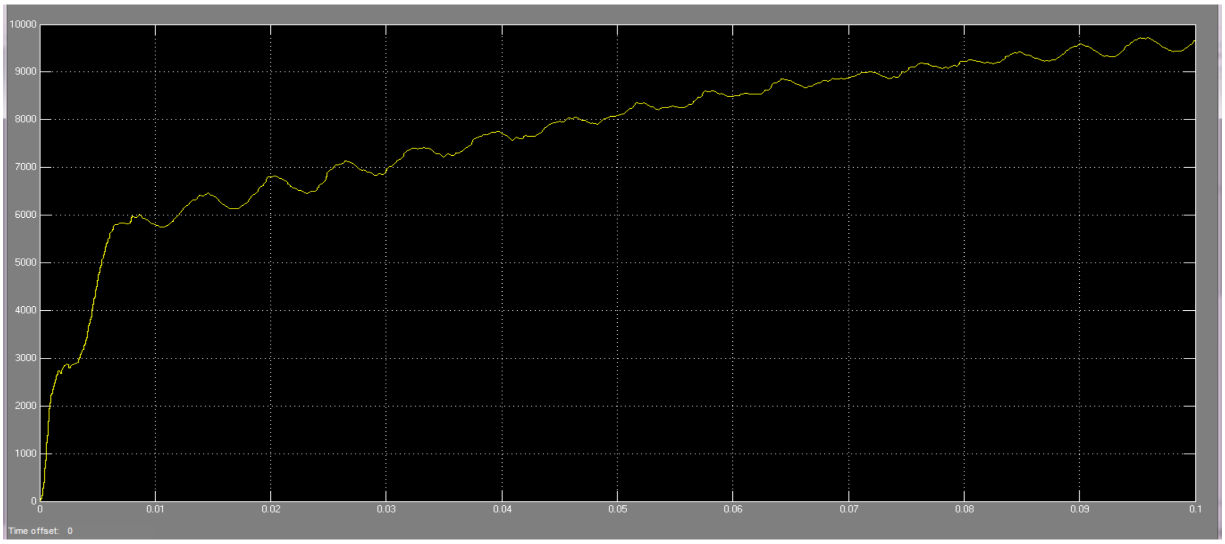


Figure 15: Out put Voltage of System 1

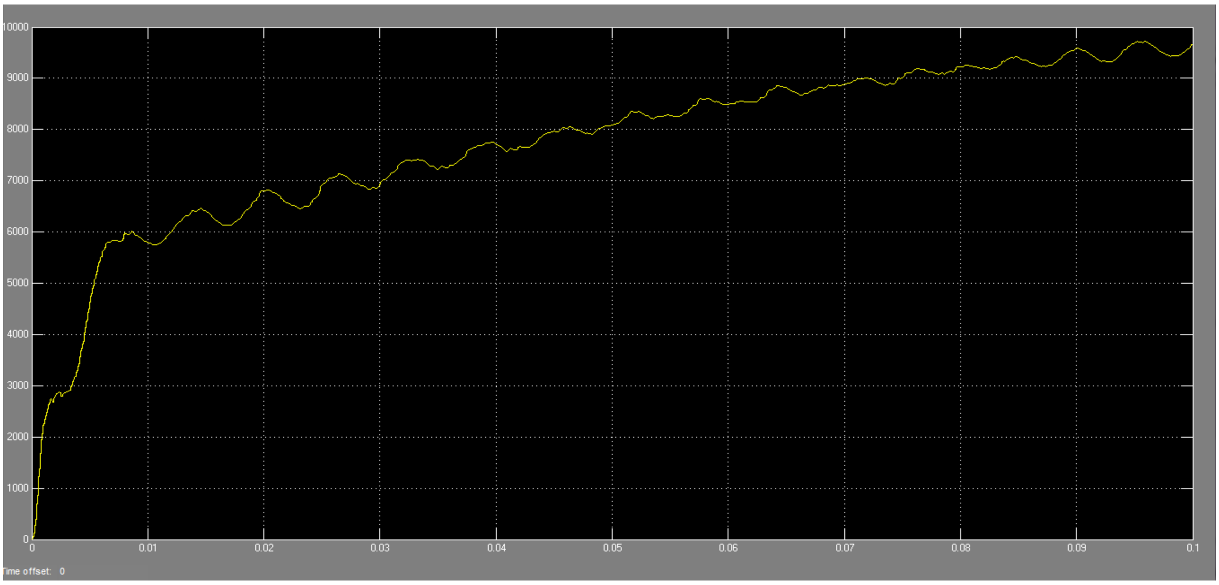


Figure 16: Out put voltage of System 2

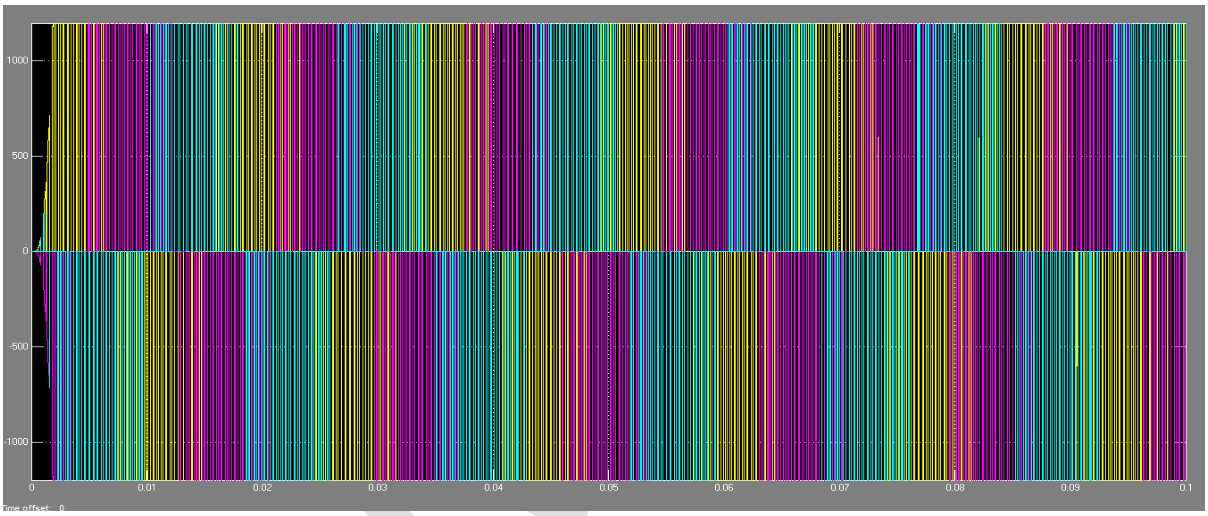


Figure 17: Combined 3-Phase Volatge after Transmission

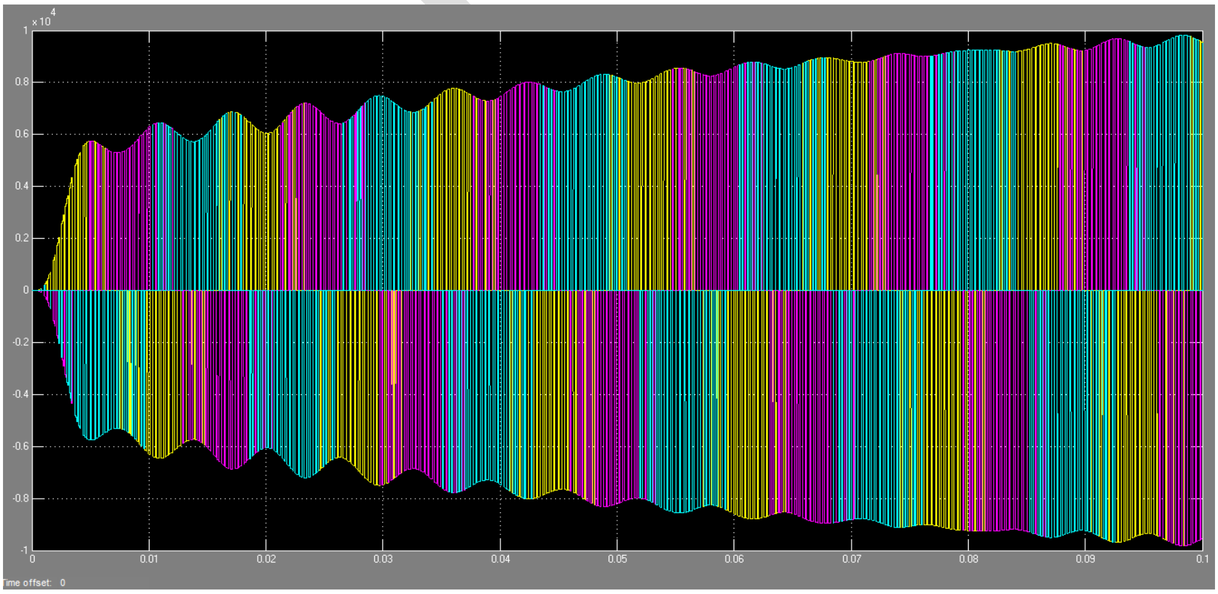


Figure 18: Interconnected 3-Phase Voltage

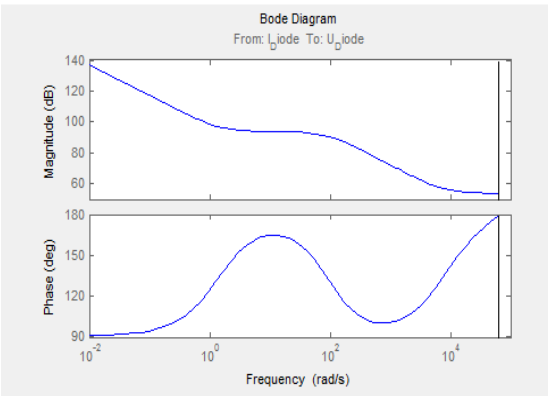
The system presented in this study is simulated under several conditions like different input voltages and different load sharing ratios. Some of the simulation results are given in this section. As mentioned previously, the system is controlled by the PI control blocks. If the converters operate uncontrolled, some serious problems may occur like overshooting and instability.

Figure 9 illustrates waveforms of wind and solar power in the case of hybrid system. Figure 10 illustrates waveforms of wind and solar voltage. Figure 11 illustrates waveforms of Voltage and Current of Wind System. Figure 12 illustrates waveforms of 3 phase voltage of wind system. Figure 13 illustrates waveforms of Voltage and Current of PV System. Figure 14 illustrates waveforms of 3 phase voltage of PV system. Figure 15 illustrates waveforms of voltage in the case of hybrid system for system 1. Figure 16 illustrates waveforms of voltage in the case of hybrid system for system 2. Figure 17 illustrates waveforms of voltage in the case of interconnected system. Figure 18 illustrates waveforms of 3 phase voltage in the case of interconnected system.

Voltage and current signals when the converters operate uncontrolled. Also, parallel connection operation is achieved in a very short time, around 0.3 s, which means that the system has a fast response time. In the study, another test is carried out to observe the system response against the load variations after the system is passed to steady state conditions. The system response against the load variations is illustrated in Fig. 18 when the load is shared equally. As depicted on the figure, the load value is 100 ohm between 0 s and 1 s.

The presented load sharing system has been also tested for different sharing ratios. This situation can be observed in Fig. 10, where the wind system feeds the load with 70 % load ratio, and the PV system feeds it with 30 % load ratio. Figure 10 also illustrates that parallel operation of the system continues without any interruption, even input voltages of the converters have different values. The ripple on the output voltage of the system is given in Fig. 17. It has been obviously seen that the ripple is quite less (1.2 V), around 0.385 %, which is highly considerable value. Moreover, this ripple has been minimized by controlling the converters with high switching frequencies without using an external filter.

IX. STEADY STATE RESPONSE



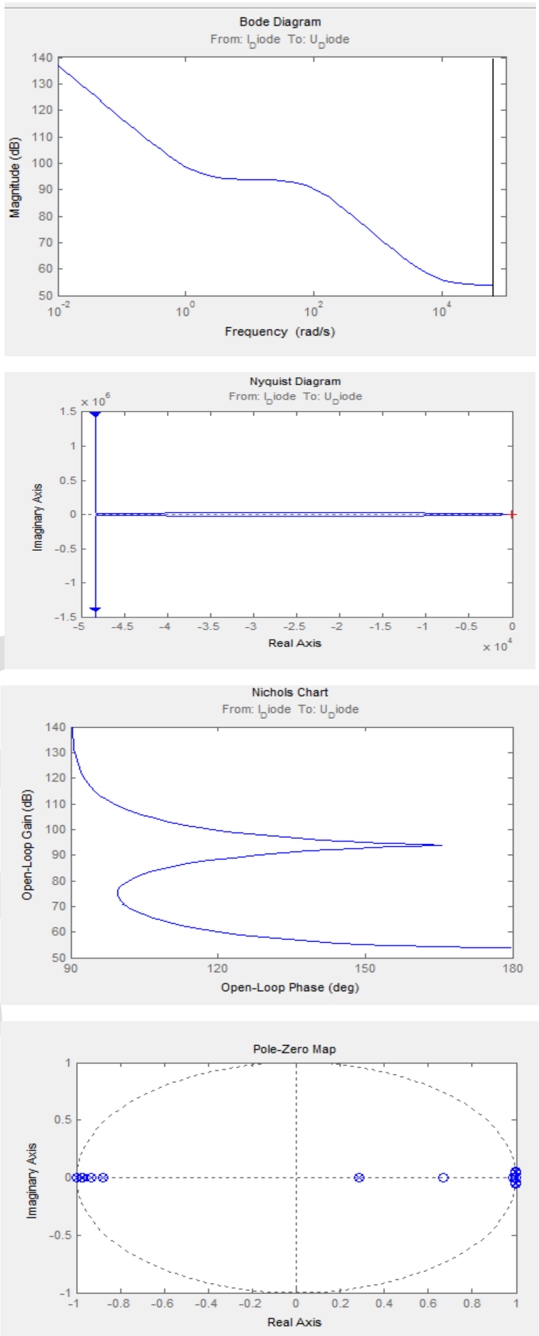


Figure 19: Bode Nichols and Pole Zero Charstrstics for the System

Figure 19 explain the Bode Nichols and Pole Zero Charstrstics for the System

X. CONCLUSION

In this study, an effective parallel connection model for interconnected hybrid network has been developed to use it in multi-input energy systems. Firstly, the system is modelled and mathematically analysed. Once the converter is mathematically modelled, it is then simulated in MATLAB/Simulink in order to test the mathematical model and to define the required circuit parameters. Then, a model for parallel connection operation is also developed and simulated in MATLAB/Simulink. According to simulation results, it has been observed that ripples on the output voltage of the converters are considerably minimized.

Furthermore, parallel operation of the system has been maintained without any interruption, even though the energy sources have different input voltages. Transient state analysis of the system is also realized and it is observed that the system reaches to steady state conditions in a very short time. In the system presented, load sharing operation among the converters is carried out by realizing the active current sharing techniques in order to ensure power flow control among the energy sources. The system presented is also tested against the instant load variations on the output side. Negative effects of the load variations are eliminated in a very short time and load sharing operation is maintained successfully under new load conditions. The system performance can satisfy the user in all perspectives. It could regulate the output power properly while its transients were damped very quickly.

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