Intelligent active and reactive power control using multi-layer neural network based MPPT controller for grid tied solar PV system under fault conditions

Mehtab Fatima[1], Anwar Shahzad Siddiqui[1], Sanjay Kumar Sinha[2]
[1]Department of Electrical Engineering, Jamia Millia Islamia, New Delhi, India
[2]Department of Electrical and Electronics Engineering, Amity University, Noida, India

Article Info

Article history:

Received May 20, 2024
Revised Sep 5, 2024
Accepted Sep 29, 2024

Keywords:

Active power control
Grid-tied solar PV system
Low voltage ride through
Multi-layer neural network
Reactive power control

ABSTRACT

The integration of renewable energy sources, particularly grid-tied solar photovoltaic (PV) systems, into the modern power grid has become increasingly prevalent. However, ensuring the reliable and efficient operation of grid-tied PV systems under various grid conditions, including fault scenarios, poses a significant challenge. In the event of grid faults or disturbances, traditional control methods often fall short in maintaining stable and reliable operation. This paper introduces a multi-layer neural network (MLNN) based MPPT controller that adapts intelligently to grid fault conditions, mitigating the impact on the grid-tied PV system's performance and providing low voltage ride through (LVRT). The research employs a detailed simulation framework on MATLAB to validate the effectiveness of the proposed controller under fault conditions. The LVRT capability of the designed system was analyzed and validated according to Indian grid code. The proposed controller leverages its capacity to learn and make real-time decisions to optimize the active and reactive power outputs of the PV system as per the grid code. Simulation results demonstrate that the proposed controller not only improves the fault tolerance of grid-tied PV systems but also enhances their performance, ensuring a stable and continuous power supply in the face of grid disturbances.

Corresponding Author:

Mehtab Fatima
Department of Electrical Engineering, Jamia Millia Islamia
New Delhi, India
Email: mehtabfatima@gmail.com

1. INTRODUCTION

The accelerating transition towards sustainable energy sources and the increasing deployment of renewable energy systems have transformed the dynamics of modern power grids. Among these renewable sources, grid-tied solar photovoltaic (PV) systems have emerged as a pivotal player in reducing carbon emissions and advancing energy sustainability. Grid-tied PV systems provide a clean and efficient means of electricity generation by harnessing solar energy and injecting it directly into the utility grid. However, their seamless integration into the existing power infrastructure comes with its own set of challenges, particularly when it comes to maintaining system stability during fault conditions.

Grid fault scenarios, including voltage sags, voltage swells, and short-circuits, are inevitable in any power distribution network. Such disturbances can disrupt the smooth operation of grid-tied PV systems, affecting their performance and potentially jeopardizing grid stability. Grid-tied PV systems are required to adhere to diverse grid codes to ensure the stability of the system and strengthen its resilience in the event of disturbances [1]. One of the key grid codes is low-voltage ride through (LVRT). The LVRT capability of the PV system involves staying connected to the grid despite a decrease in grid voltage magnitude. Simultaneously, the PV system should provide regulated reactive power injection to the point of common coupling (PCC) to bolster grid voltage support [2], [3]. Prior to the introduction of the LVRT grid code, if the voltage sag exceeded the nominal value, PV systems were required to halt power generation. Consequently, the simultaneous cessation of multiple PV power generation systems due to substantial voltage sags could initiate a cumulative process, ultimately resulting in a system collapse. So, every country has LVRT requirement specified in its grid code which require PV system to remain connected and provide dynamic support in improving grid voltage in case of fault. India also has its own LVRT requirement in its grid code. There has been lot of research in LVRT for three phase grid connected PV system. Afshari *et al.* [4] proposed a control strategy for mitigating double grid frequency oscillations in the active power and dc link voltage of two stage three phase grid connected inverter during unbalanced faults. With the current reference generation method injected currents are sinusoidal and non-MPPT method contributes to current limitation method that restricts injected current to rated value. Paper by Afshari *et al.* [5] proposes LVRT strategy using current reference generation method which can eliminate the oscillations in dc link voltage and active power during unbalanced voltage sags.

Al-Shetwi *et al.* [6] DC chopper brake controller and current limiter are used to absorb excessive dc voltage and limits excessive ac current during voltage dips. The proposed strategy effectively improves the capability of ride through fault safely and provide grid support through active and reactive power control at different type of faults. A paper by Lin *et al.* [7] uses intelligent controller based on TSKPFNN-AMF which regulates the reactive power to a value that complies with the regulation of LVRT under grid faults. The proposed controller is able to eliminate the fluctuation of dc link voltage under grid faults. In work [8], the control strategy developed provide ride through fault capability during grid voltage sags and ensures grid sinusoidal current at the PCC. The active and reactive power changes as per the voltage sag level. Ismail *et al.* [9] adaptive power control is introduced by auto correction droop control to regulate P and Q in accordance with network impedance. Grid operation is thus supported under normal and voltage sag conditions by proportionally generating P and Q based on the capacity of the inverters.

Sonawane and Umarikar [10] proposes synchronverter based PV STATCOM. In partial STATCOM mode, proposed controller is able to use the remaining capacity of inverter for reactive power compensation while in full STATCOM mode it fully provides reactive power. Also the proposed controller is able to regulate the PCC voltage during LVRT by providing reactive power compensation.

Zahloul *et al.* [11] a dynamic model is developed for solar PV grid connected system with production capacity of 2 MW. The controllers one for DC-DC converter to achieve maximum power point (MPP) and other for voltage source converter (VSC) to maintain voltage quality at PCC. With the proposed controller system developed is able to regain the stability when the fault is disappeared.

Chowdhury *et al.* [12] the controller is designed for LVRT which supplies adequate reactive power in the form of quadrature axis current (I_q) to the grid as per grid code. The inverter current increase during faults is prevented by adjusting the direct axis current(I_d). The inverter current is restriced to 1.5% with the designed system during faults.

The previous research work focusses on LVRT performance of the grid connected solar PV system under different faults and how the system can remain connected and support the grid but didn’t adopt any intelligent technique for maximum power point tracking (MPPT) along with the controller. In our research work our controller is designed to work with neural network based MPPT and to support the grid during balanced faults as per the LVRT Indian grid code [13], [14]. The proposed system is able to stabilize the DC link voltage as well as the oscillations in the active and reactive power under low voltage conditions. In the event of low voltage conditions on the grid side the designed system is able to deliver required amount of reactive power to the grid so as to stabilize the voltage level.

In this research a 100 kW grid connected solar PV system is designed which has double stage configuration. In the first stage DC-DC converter is responsible for optimizing power extraction from PV panels and in the second stage inverter is there which converts DC to AC in order to fed power to the grid. Under normal conditions when power factor is unity maximum power should be fed by the solar PV system to grid. For maximum power extraction neural network based MPPT is used that ensures maximum power delivery from the solar PV system. But, under fault conditions since the solar PV system is not able to fed maximum power to the grid the DC link capacitor voltage will rise that may damage the capacitor thus in order to avoid this MPPT is to be disabled.

Conventional control techniques, which are typically designed for nominal operating conditions, often fall short when the grid disturbances occur. In this context, a pressing need exists for intelligent control strategies that can adapt dynamically to varying grid conditions, ensuring the reliable operation of grid-tied PV systems even during fault events.

This research paper addresses this critical need by introducing an innovative approach to enhance the active and reactive power control of grid-tied solar PV systems during fault conditions. The core of this approach lies in the integration of multi-layer neural network (MLNN) based MPPT with the controller, which exhibit the ability to learn and adapt in real-time, thus offering a promising solution for mitigating the impact of grid faults on PV system performance.

The objectives of this research are two-fold. First, we seek to develop and implement a MLNN-MPPT based controller using a simulation framework that intelligently manages the active and reactive power outputs of grid-tied PV systems, effectively responding to different fault conditions. Second, we aim to assess the performance of the controller in fault scenario, with a focus on rapid response, fault tolerance, and overall system stability.

This paper is structured as follows: section 2 provides overview of LVRT as described in Indian grid code and its importance. Section 3 offers detailed design of the proposed system. Section 4 presents the proposed control approach. Section 5 details the neural network based MPPT algorithm and simulation results of it. Section 6 gives the controller designed for the proposed system. Section 7 provides simulation framework and the detailed results of analysis. It delves into the implications of our findings and potential practical applications. Finally, the paper concludes by summarizing the key contributions and pointing to future research directions. In a world committed to sustainable energy production and resilient power grids, this research strives to make a significant contribution by enhancing the adaptability of grid-tied PV systems during both normal and fault conditions.

2. LOW VOLTAGE RIDE THROUGH (LVRT) IN INDIAN GRID CODE

As per the Indian grid code [13] the PV System should remain connected to the grid whenever there is voltage sag and should supply reactive power to the grid till the voltage recovers or maximum of 300 ms whichever is lower. Figure 1 shows the LVRT requirement in Indian code. As it can be seen inverter must remain connected to the grid above red line area while below the red line area it should stop and disconnect itself from the grid.

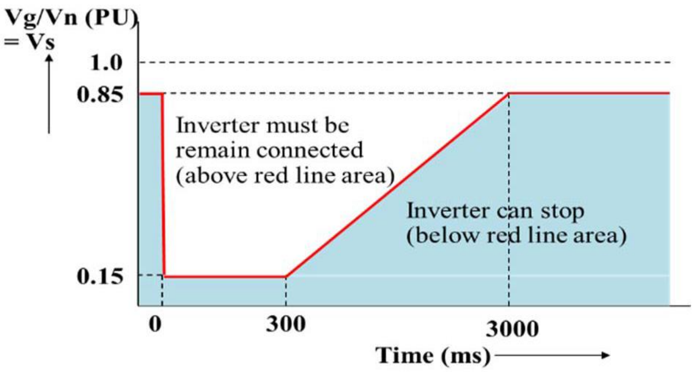


Figure 1. LVRT requirement in Indian grid code [3]

During LVRT operation the solar PV system should supply active power in proportion to the amplitude of grid voltage. The reactive power injection requirement under different voltage sag level according to the Indian grid code is shown in Figure 2. During fault the injection of active and reactive current is governed by (1) and (2) respectively [13], [14].

– Inject reactive current during LVRT Indian grid code [9]:

$$Iq = \left\{ \begin{matrix} 0(deadband) & 0.85p.u \leq Vg \leq 1.1p.u \\ K \times (1 - Vg) \times In & 0.50p.u \leq Vg < 0.85p.u \\ In & Vg < 0.50 \end{matrix} \right\} \quad (1)$$

– Reference active current during LVRT [9]:

$$Id = \begin{Bmatrix} In & 0.85 \le Vg \le 1.1p.u \\ \sqrt{(I_n^2 - I_q^2} & 0.85 \le Vg \le 1.1pu \\ 0 & Vg < 0.50 \end{Bmatrix} \tag{2}$$

In above equations K is adjustment factor and it is given by:

$$K = \frac{\frac{Iq}{In}}{Vg} \ge 2 \tag{3}$$

K should be greater than or equal to 2 in order to provide voltage support under grid failures and V_g=grid voltage level in p.u, I_n= rated grid current or rated inverter current.

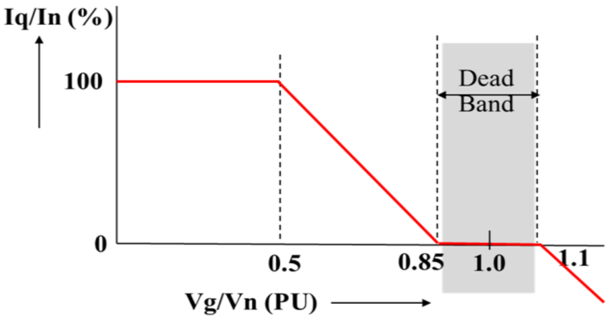


Figure 2. Reactive current vs voltage dip [3]

3. DESIGN OF THE SYSTEM

The system consists of two stages. First stage comprises of DC-DC boost converter which basically controls the power coming from PV source i.e., it ensures maximum power is drawn from solar PV system under normal condition and to provide proper control under voltage sag conditions during fault. The second stage comprises of a three-phase VSC. The boost converter output is connected to the VSC through a DC link capacitor. The VSC output is then connected to the grid at PCC through an LCL Filter. The block diagram of the complete system is as shown in Figure 3. For extracting maximum solar power from PV, we have used ANN based algorithm because of its robustness and improved accuracy. The grid current has harmonics so in order to reduce the same LCL filter is used in the design [15]-[20]. The other parameters that are used in the complete design are specified in Tables 1 and 2. The complete schematic of the designed system is as shown in Figure 4.

The design parameters for Boost converter are obtained using by (4) and (5) [11]:

$$L = \frac{Vin(Vo-Vin)}{\Delta I \times fs \times Vo} \tag{4}$$

and,

$$C = \frac{Io(Vo-Vin)}{\Delta V \times fs \times Vo} \tag{5}$$

Table 1. Boost converter parameters

Parameter	Value
Voltage Input V_{in}	250-350 V
Voltage Output V_o	600 V
Rated Power (P_{MPP})	100 kW
Switching Frequency f_B	5 kHz
Voltage Ripple(ΔV)	1%
Current Ripple(ΔI)	5%
Boost Converter Inductance L_b	1.25 mH
Boost Converter Capacitance C_b	4000 uF

Table 2. Inverter data

Parameter	Value
Grid nominal RMS voltage line to line (V_{gL-L})	415 V
Grid Nominal Frequency	50 Hz
Inverter Side Inductance for LCL filter(L_1)	500 uH
Grid Side Inductance for LCL filter(L_2)	500 uH
Capacitance of the LCL Filter (C)	100 uF
Switching Frequency of Inverter (f_{SW})	10 kHz
DC Link Capacitor C_{dc}	3227 uF
DC Link Voltage V_{dc}	600 V

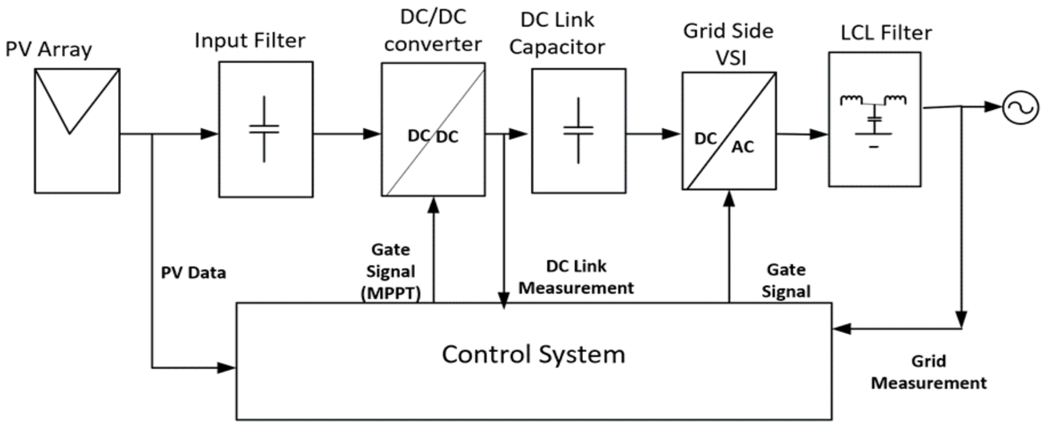


Figure 3. Block diagram of the proposed system

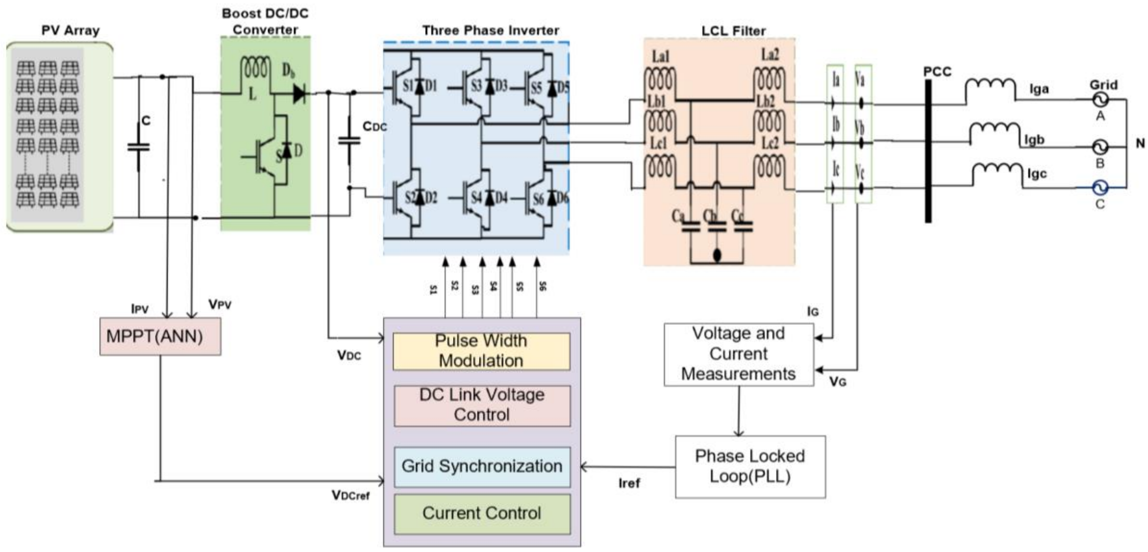


Figure 4. Three-phase grid-connected PV system (GCPS)

4. CONTROL APPROACH

Under low voltage conditions during faults there is mismatch between generated power and delivered power from PV system. This difference in generated power and delivered power will cause rise in DC link voltage which may damage the capacitor [21]-[23]. Thus, during LVRT condition in our proposed control approach MPPT operation is disabled and system will work under non-MPPT mode so as to reduce the power generation. Thus, under normal conditions solar PV system will work under MPPT mode and thus delivers maximum power but when there is drop in voltage at PCC due to fault then system should switch to non-MPPT mode and required reactive and active power should be supplied from the inverter till the voltage at PCC recovers. Once the voltage recovers and fault is cleared system should be switched back to MPPT mode. The flowchart in Figure 5 shows the switching of system from MPPT to non-MPPT mode depending the grid voltage level. Thus, if grid voltage V_g<0.85 then faulty mode of operation is activated and depending on the sag in grid voltage power reduction is done by switching to non-MPPT mode and delivering active and reactive power as prescribed by the grid code. This faulty mode of operation is deactivated once the fault is cleared and system is switched back to normal mode.

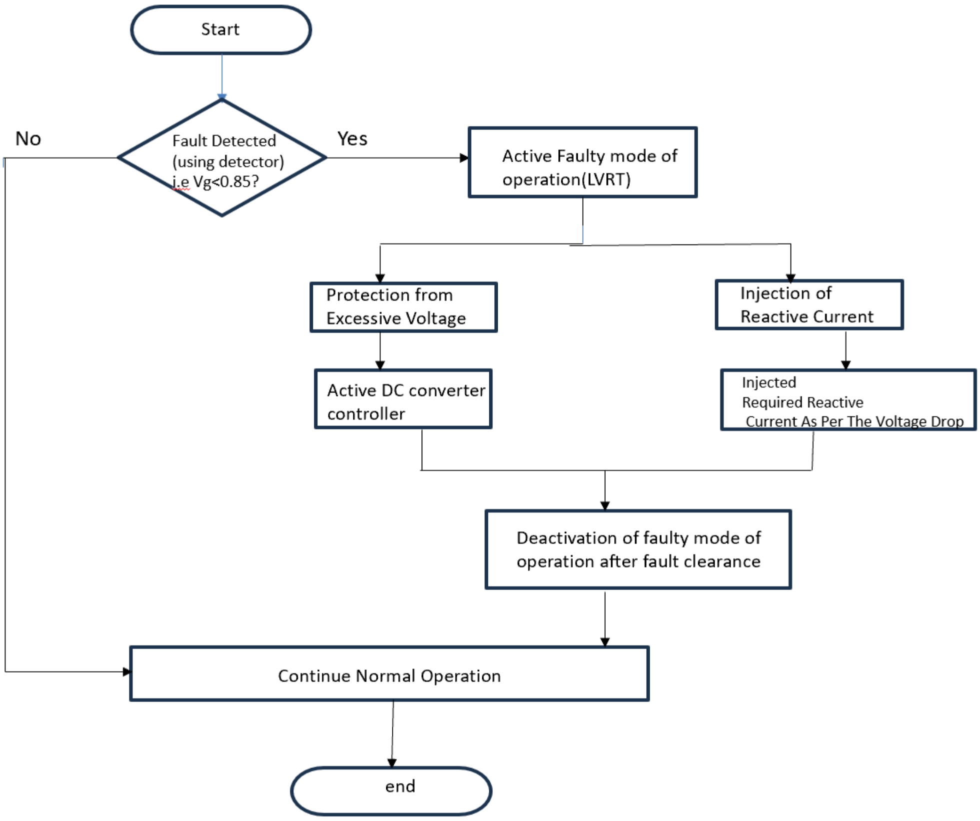


Figure 5. Flow chart of the proposed strategy

5. ANN BASED MPPT

The proposed method utilizes the adaptive learning capabilities of ANNs to accurately track the MPP of the PV array under varying environmental conditions. The performance of the ANN-based MPPT is assessed via simulation studies [24] and contrasted with conventional MPPT methods like perturb and observe (P&O) and incremental conductance (Inc Cond), demonstrating superior efficacy in terms of tracking accuracy, response time, and resilience to fluctuating solar irradiance and temperature [25]. In recent years, artificial neural networks (ANNs) have garnered significant interest due to their capacity to comprehend intricate patterns and provide precise forecasts [26]. Within the domain of MPPT, ANNs present a compelling substitute for conventional algorithms, harnessing their adaptive learning prowess to consistently fine-tune the operating parameters of the PV system. The architecture of the ANN comprises an input layer, one or more hidden layers, and an output layer. The input layer receives environmental parameters such as solar irradiance and temperature, while the output layer provides the duty cycle for the DC-DC converter to maintain the PV system at its maximum power point.

5.1. Training of the ANN

The training data for the neural network is solar temperature and irradiance for which 1000 data one for each irradiation and temperature is generated for one set of samples. Output is MPP voltage which is used further to generate the duty ratio for the boost converter control. Thus, to train the neural network 1000 data is taken i.e temperature range is from (15 °C to 35 °C) and for irradiance range is from (0 W/m^2 to 1,000 W/m^2). The activation function of input and output layer is tansig and purelin respectively. The trained ANN learns the nonlinear relationship between the environmental variables and the optimal operating point of the PV system, enabling it to adapt to varying conditions and track the MPP accurately. Figure 6 shows the different layers for neural network training of MPPT. The training of the neural network is performed after determining the Vmpp (Vpv*) value at various irradiance and temperature levels. This Vpv* is compared with the instantaneous Vpv, generating an error signal that is fed to the PI controller. The output of the PI controller is then supplied to the PWM signal generator to produce the necessary duty cycle. Optimal tuning of the PI controller is essential for enhanced performance.

Figure 7 shows the neural network training in MATLAB. MATLAB provides several training algorithms for neural networks, each with its advantages and limitations. Levenberg-Marquardt is chosen for neural network training due to its advantages in terms of convergence speed, stability, and generalization performance. Once the network architecture and training algorithm are selected, the training process begins. During training, the neural network iteratively adjusts its weights and biases to minimize the difference between its predicted output and the actual output in the training dataset. The performance is tested using mean squared error (MSE). The neural network block generated after training is as shown in Figure 8. The trained neural network block is shown in Figure 8(a) with its hidden layers shown in Figure 8(b).

Figure 9 shows performance of trained neural network, Figure 9(a) shows the regression data and it can be clearly seen that all samples are aligned in same line indicating high accuracy in data acquisition and confirming their validity. Figure 9(b) shows the admissible MSE is approximately which is 4.3451e-11 obtained at epoch 1000. The results obtained from trained neural network based MPPT is as shown in Figure 10. The response curves of PV output power is shown in Figure 10(a), MPPT output power in Figure 10(b) and the varying radiations are shown in Figure 10(c) where it can be clearly seen that the MPPT method is working properly and is able to track maximum power from the system under all varying weather conditions with maximum of 100 kW at 1000 W/m^2 radiations. ANN-based MPPT offers significant advantages over conventional methods by providing improved accuracy and efficiency in tracking the MPP under varying environmental conditions. It features faster response times, reduced oscillations, and robust performance even with noise and disturbances.

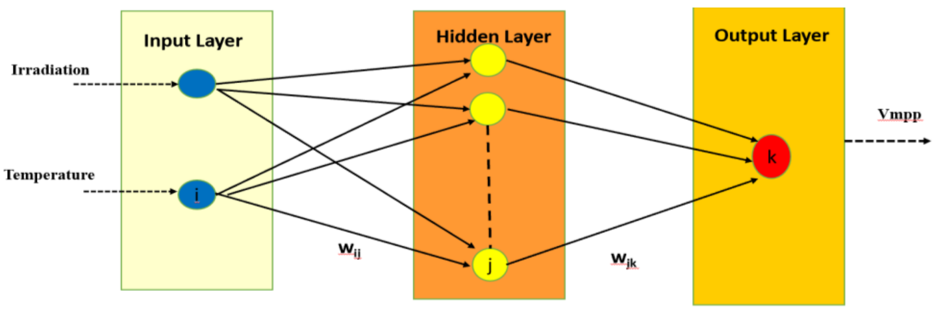


Figure 6. ANN Structure for MPPT

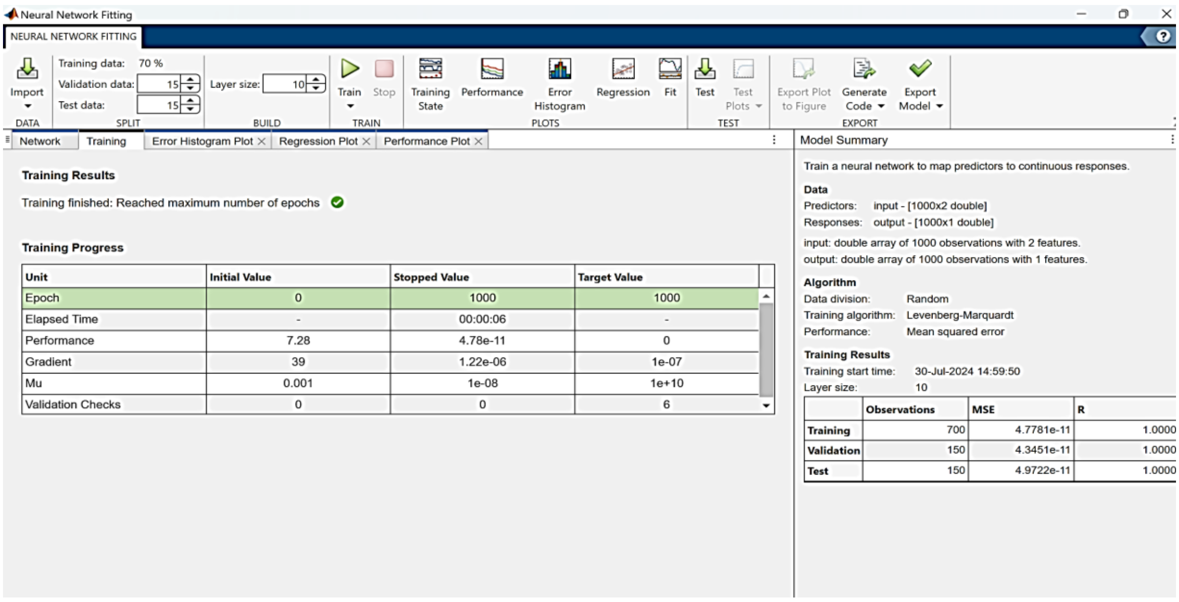
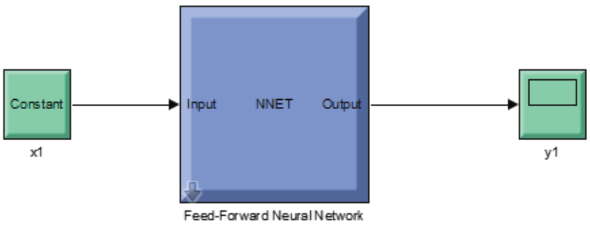
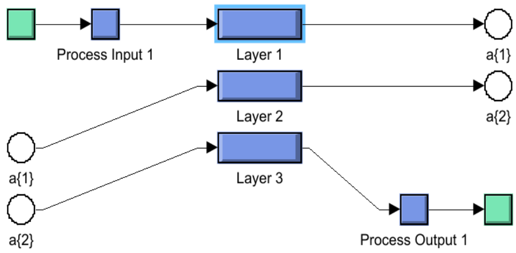


Figure 7. Neural network training in MATLAB

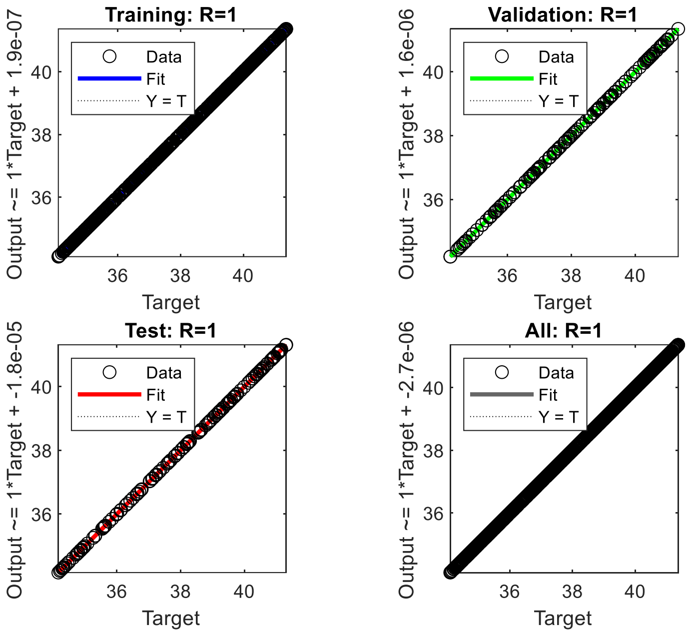


(a)

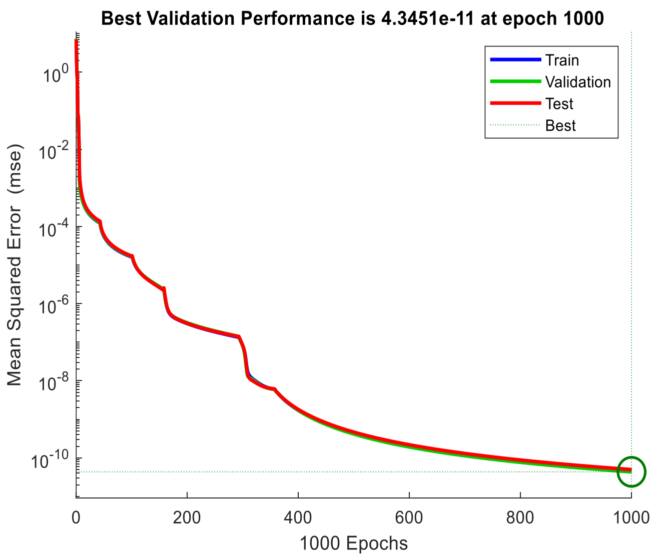


(b)

Figure 8. Neural network block and hidden layers (a) trained neural network block and (b) hidden layers inside block

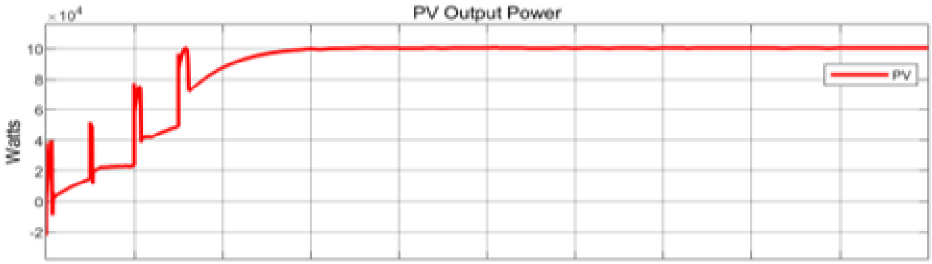


(a)

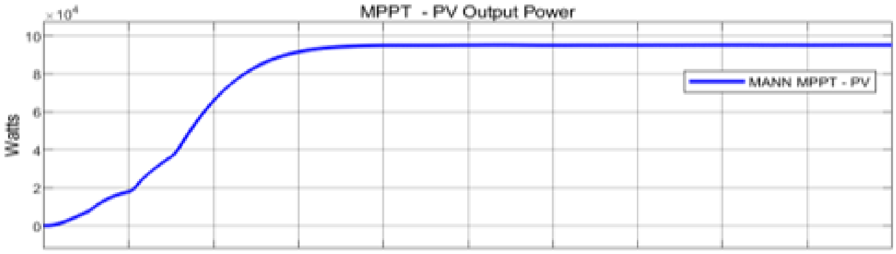


(b)

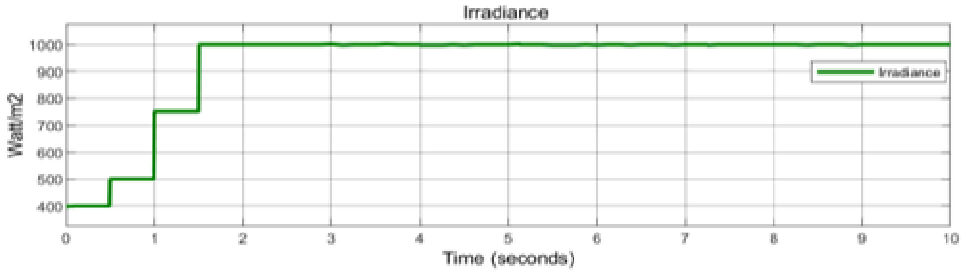
Figure 9. Performance of trained neural network (a) targets convergence and (b) best validation performance



(a)



(b)



(c)

Figure 10. Neural network based MPPT results: (a) PV output power (W), (b) MPPT-PV output power (W), and (c) irradiance (W/m^2) on PV panel

6. CONTROL DESIGN

The control Logic Diagram is as shown in Figure 11. Depending on the grid voltage system switches from one mode to the other that is from MPPT to non-MPPT mode. For the DC link voltage control PI controller is being used. The values of K_p and K_i is as given in Table 3 [15]. In MPPT mode only the active current will be fed to the grid by the inverter while reactive current will be zero. The active current from the inverter is its rated current i.e I_d=I_n. In non-MPPT mode the active current and reactive current will be as per the level of drop in grid voltage. In case the grid voltage falls and is below 0.85 but greater than 0.5 both active current and reactive current will be fed from inverter as per the equations defined in LVRT code. And if the grid voltage drop is below 0.5 p.u then only the reactive current will be fed from the inverter i.e I_q=I_n where I_n is rated current of the inverter. In the current control loop PI controller is used with K_p and K_i as defined in Table 4 [15]. The voltage references for the feedforward control are given by (6) and (7).

$$v_d^* = v_d + Ri_d + L\frac{di_d}{dt} - \omega Li_q \qquad (6)$$

$$v_q^* = v_q + Ri_q + L\frac{di_q}{dt} - \omega Li_d \qquad (7)$$

Table 3. Voltage controller parameters for the simulations

Parameter	Symbol	Value
Outer voltage PI controller	K_p	0.25
	K_i	300

Table 4. Current controller parameters for the simulations

Parameter	Symbol	Value
Inner Current PI controller	K_p	10
	K_i	20

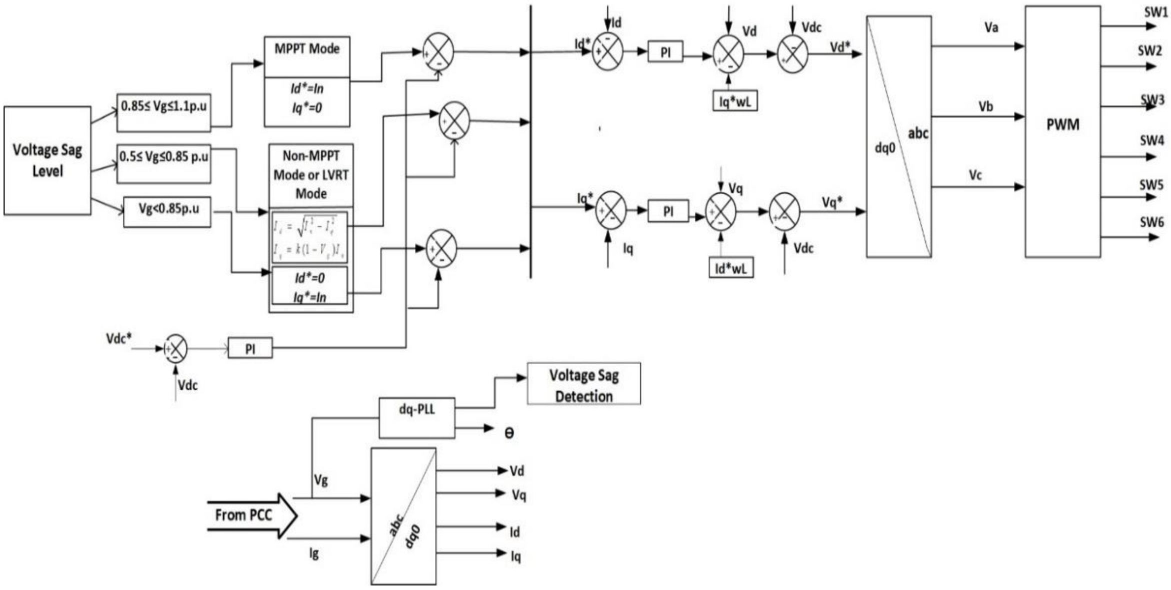


Figure 11. Controller design

7. SIMULATION RESULTS AND DISCUSSION

The three-phase system with controller as shown in Figure 11 is implemented in MATLAB Simulink. There are two modes of operation for the implemented system depending on the grid voltage measured at PCC. First mode is normal mode which is also MPPT mode and the other is faulty mode in which the system will be in non-MPPT mode. The two modes are described with their simulation results in details in the below sections.

7.1. Mode 1: MPPT mode

This is the normal mode of operation i.e when grid voltage is greater than 0.85 p.u i.e V_g>0.85 p.u. In this mode system is generating maximum power as per the MPPT algorithm under varying radiations. Figure 12 shows the PV power in varying Irradiations. For 1000 W/m^2 irradiation power is 100 kW i.e from 0 to 0.4 sec. Then from 0.4 to 0.8 sec as the irradiations falls to 600 W/m^2 power from solar PV panel is 60 kW and from 0.8 sec power output is 30 kW for 300 W/m^2 irradiations. Figures 13 and 14 shows the active and reactive power from the solar PV inverter in the varying radiation conditions. As it can be seen from the Figures 13 and 14 only active power is generated while reactive power is zero in normal operation. Figure 15 shows the variation of DC Link voltage with the varying radiations and it can be clearly seen that DC link voltage is maintained constant by the voltage controller. Thus, system under normal mode of operation has unity power factor and is able to deliver maximum power to the grid under all varying irradiations.

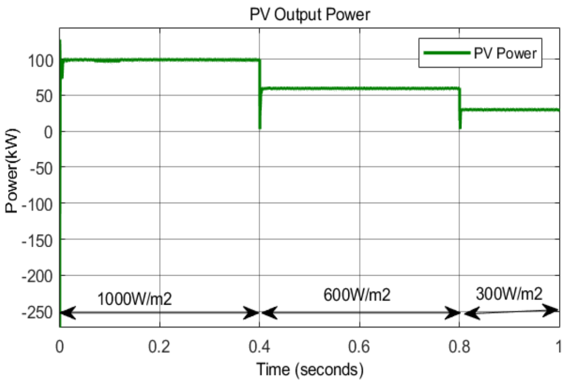


Figure 12. PV power in varying radiations in normal operation

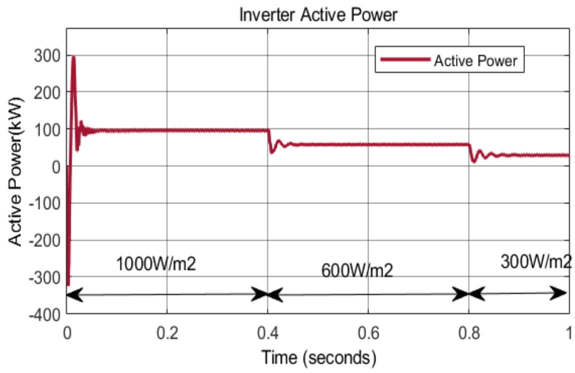


Figure 13. Active power from the proposed system in normal operation

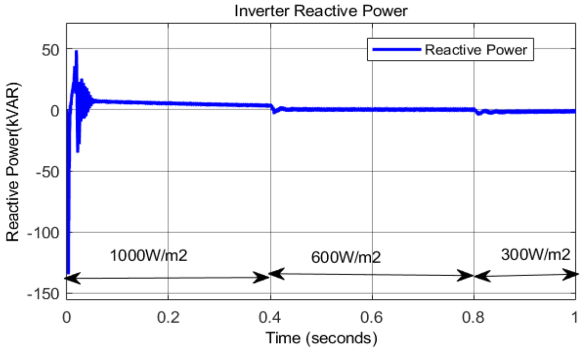


Figure 14. Reactive power from the proposed system in normal operation

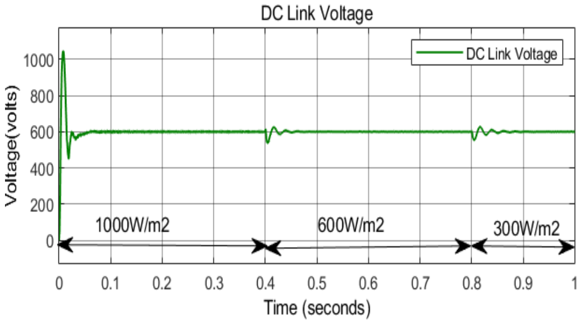


Figure 15. DC Link voltage in normal operation

7.2. Mode 2: non-MPPT mode

The second mode of operation is non-MPPT mode. As per the proposed control logic when the grid voltage falls below 0.85 p.u i.e when fault occurs at PCC then system should switch to non-MPPT mode. MPPT should be disabled in this case so as to avoid overvoltage across DC link capacitor. In this mode system should operate as per the grid code and should supply active and reactive power depending on the drop in voltage level on grid side and as per the equations defined in grid code.

To test the system performance under faulty mode of operation a symmetrical fault is simulated at 0.2 sec and at 0.7 sec to create voltage sag. The irradiations are kept same as 1000 W/m^2.Initially system works in normal mode of operation and delivers maximum power as per the irradiations and reactive power is zero. When fault occurs at 0.2 sec the grid voltage drops to 180V (line to line) which is less than 0.5 p.u. In this case, the system promptly switches from MPPT mode to non-MPPT mode to decrease power generation.

The drop in power generation depends on the level of voltage sag. More the voltage sag more will be the reduction in power generation. As per the grid code defined in (1) and (2) system should inject only reactive power. Figure 16 shows the PV Power output during MPPT Mode and non-MPPT mode of operation. Figure 16 clearly illustrates the transition from MPPT to non-MPPT mode, with the simulation results indicating that the switching is both rapid and stable.

Thus when grid voltage is found to be less than 0.5 p.u then the system immediately switches to non-MPPT mode. The active power should be zero and reactive power as per the defined equation in grid code i.e in (1). The simulation results in Figure 17 clearly shows that active power is zero and only reactive power from inverter is generated from 0.2 sec. This fault persists for 196 ms. When the fault is cleared then system will switch to MPPT mode and only active power will come from inverter. The simulation result of Figure 17 clearly shows that when fault is cleared at 0.4 sec system switches back to MPPT mode and only active power is coming from the inverter. Since the voltage sag detection unit takes few msec to assess the grid conditions, the MPPT and other control units continue to operate in their normal mode instead of taking immediate action. As a result, there is slight fluctuation in the grid current during this interval and hence in active and reactive power too. Similarly, this behavior is observed when the grid fault is cleared and system restores back to normal condition.

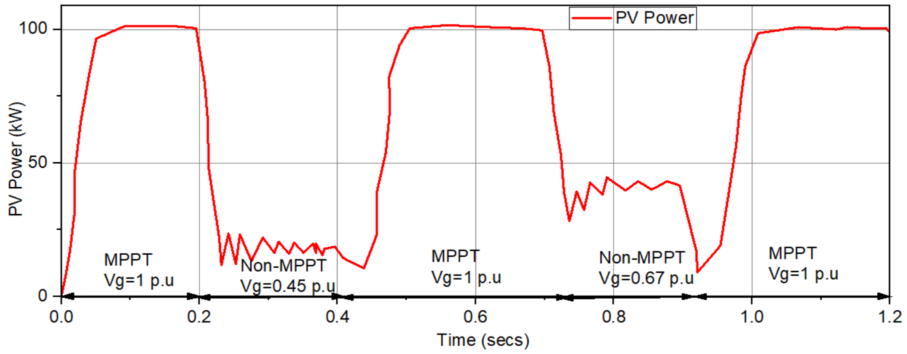


Figure 16. PV power

Then another voltage sag occurs at 0.7 sec again due to simulated symmetrical fault. During this fault grid voltage drops to 270V which is 0.67 p.u i.e greater than 0.5 p.u thus as per grid code inverter should supply both active and reactive power in this case as per (1) and (2). From the simulation results of Figure 17 it is clearly observed that proposed system switches immediately to non-MPPT mode as desired and it is delivering active and reactive power both in this case as per the LVRT grid code. This continues till the fault is cleared and system voltage regains back to previous value.

Once the fault is cleared and voltage sag disappears then system comes back to normal operation with MPPT on. Figure 18 shows the DC link voltage variation with faults at different duration. From simulation result DC link voltage is found to be stable during fault and also when fault is cleared. Figure 19 shows the inverter voltage and current are in phase during MPPT operation as system operates at unity power factor and there is a phase difference between voltage and current wave during non-MPPT operation due to reactive power from solar PV inverter. During fault duration from 0.2 sec to 0.4 sec voltage and current wave have 90-degree phase difference while from 0.7 sec to 0.9 sec phase difference is less than 90 degrees.

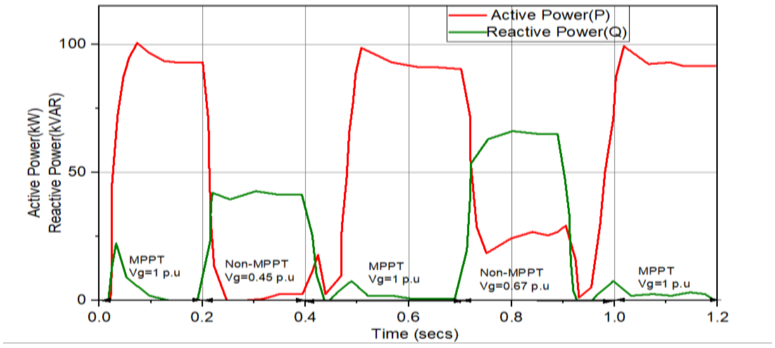


Figure 17. Active and reactive power from inverter

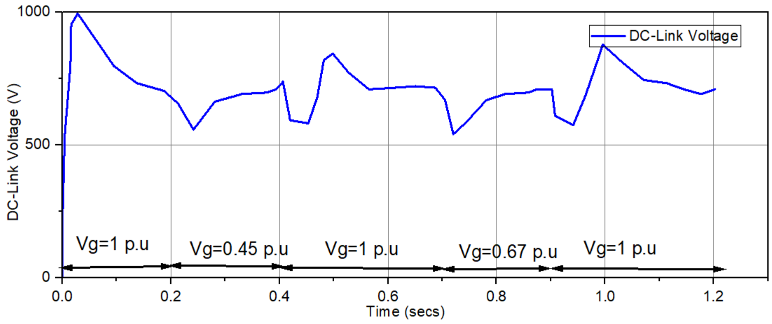


Figure 18. DC link voltage

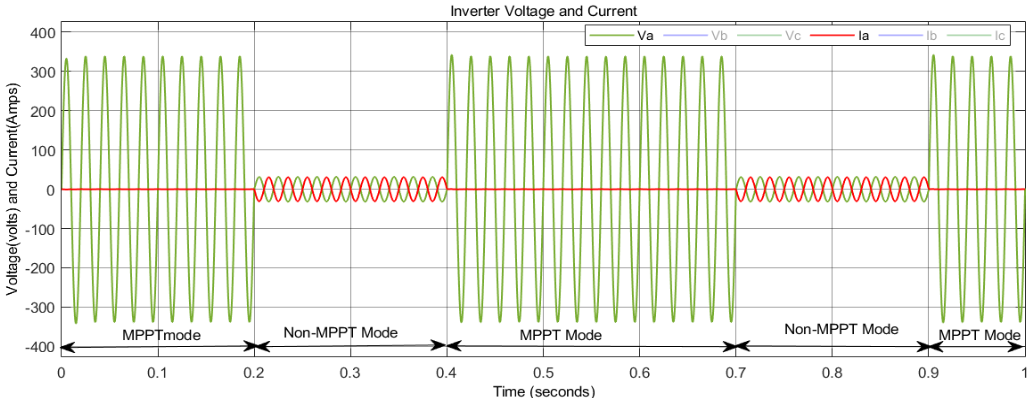


Figure 19. Voltage and current waveforms

8. CONCLUSION

The proposed system is able to effectively perform under faulty conditions as per the Indian grid code for LVRT. The simulation results clearly show that the PV system operates at unity power factor and injects only active power under normal operating conditions. The implemented ANN based MPPT works effectively in delivering maximum power under all varying irradiations in the normal mode of operation. During faulty condition system switches to non-MPPT mode and injects controlled reactive power as per Indian grid code for LVRT. The suggested control approach maintains a consistent and efficient DC Link voltage throughout operation. The proposed controller design for solar PV grid integrated system is thus effective under symmetrical voltage sags and enhancing the fault ride through capability of system. In the future work system can be tested for other type of faults.

REFERENCES

[1] P. Patel, Y. Patel, and K. Shimada, "Indian grid code based low voltage ride through control development for large scale solar PCS," in *2020 IEEE Texas Power and Energy Conference, TPEC 2020*, Feb. 2020, vol. 50, pp. 1–6, doi: 10.1109/TPEC48276.2020.9042515.

[2] M. Sufyan, N. A. Rahim, B. Eid, and S. R. S. Raihan, "A comprehensive review of reactive power control strategies for three phase grid connected photovoltaic systems with low voltage ride through capability," *Journal of Renewable and Sustainable Energy*, vol. 11, no. 4, Jul. 2019, doi: 10.1063/1.5095185.

[3] C. Nithya and J. Preetha Roselyn, "Multimode inverter control strategy for LVRT and HVRT capability enhancement in grid connected solar PV system," *IEEE Access*, vol. 10, pp. 54899–54911, 2022, doi: 10.1109/ACCESS.2022.3175872.

[4] E. Afshari *et al.*, "Control strategy for three-phase grid-connected PV inverters enabling current limitation under unbalanced faults," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 11, pp. 8908–8918, Nov. 2017, doi: 10.1109/TIE.2017.2733481.

[5] E. Afshari, B. Farhangi, Y. Yang, and S. Farhangi, "A low-voltage ride-through control strategy for three-phase grid-connected PV systems," in *2017 IEEE Power and Energy Conference at Illinois, PECI 2017*, Feb. 2017, vol. pp, pp. 1–6, doi: 10.1109/PECI.2017.7935767.

[6] A. Q. Al-Shetwi, M. Z. Sujod, and F. Blaabjerg, "Low voltage ride-through capability control for single-stage inverter-based grid-connected photovoltaic power plant," *Solar Energy*, vol. 159, pp. 665–681, Jan. 2018, doi: 10.1016/j.solener.2017.11.027.

[7] F. J. Lin, K. C. Lu, T. H. Ke, B. H. Yang, and Y. R. Chang, "Reactive power control of three-phase grid-connected PV system during grid faults using takagi-sugeno-kang probabilistic fuzzy neural network control," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 9, pp. 5516–5528, Sep. 2015, doi: 10.1109/TIE.2015.2407851.

[8] E. M. Khawla, D. E. Chariag, and L. Sbita, "A control strategy for a three-phase grid connected pv system under grid faults," *Electronics (Switzerland)*, vol. 8, no. 8, p. 906, Aug. 2019, doi: 10.3390/electronics8080906.

[9] F. Ismail, J. Jamaludin, and N. A. Rahim, "Enhanced energy delivery for solar PV distributed generators at voltage sags," *IEEE Access*, vol. 11, pp. 139688–139705, 2023, doi: 10.1109/ACCESS.2023.3338361.

[10] A. J. Sonawane and A. C. Umarikar, "Voltage and reactive power regulation with synchronverter-based control of PV-STATCOM," *IEEE Access*, vol. 11, pp. 52129–52140, 2023, doi: 10.1109/ACCESS.2023.3276787.

[11] H. Zahloul, A. Khaliq, H. Hamzehbahmani, S. Veremieiev, and S. Salous, "Evaluation of LVRT capability and stability analysis of VSC based advanced control approach for grid connected PV system under grid fault conditions," *Heliyon*, vol. 10, no. 5, p. e26935, Mar. 2024, doi: 10.1016/j.heliyon.2024.e26935.

[12] S. B. R. Chowdhury, S. Roy, A. Maji, and P. K. Gayen, "Enhancing LVRT capability of single stage grid connected PV system in accordance with Indian grid code using proportional direct axis current control technique," *Electrical Engineering*, Jul. 2024, doi: 10.1007/s00202-024-02568-5.

[13] "Central electricity authority (technical standards for connectivity to the grid) regulations," *Central Electricity Authority*, 2007. https://cea.nic.in/regulations/technical-standards-for-connectivity-to-the-grid-2007/?lang=en.

[14] "IEC standard: IEC TS 62910-Edition 1.0." 2015. [Online]. Available: https://webstore.iec.ch/en/publication/23566.

[15] M. Fatima, A. S. Siddiqui, and S. K. Sinha, "Implementation of three-phase two stage solar PV inverter for grid connection," in *8th International Conference on Advanced Computing and Communication Systems, ICACCS 2022*, Mar. 2022, pp. 1325–1329, doi: 10.1109/ICACCS54159.2022.9785351.

[16] A. Reznik, M. G. Simoes, A. Al-Durra, and S. M. Muyeen, "LCL Filter design and performance analysis for grid-interconnected systems," *IEEE Transactions on Industry Applications*, vol. 50, no. 2, pp. 1225–1232, Mar. 2014, doi: 10.1109/TIA.2013.2274612.

[17] A. O. Zué and A. Chandra, "Simulation and stability analysis of a 100 kW grid connected LCL photovoltaic inverter for industry," 2006, doi: 10.1109/pes.2006.1709455.

[18] R. A. G. Teran, J. R. Perez, J. A. J. Beristain, I. T. Sosa, and J. H. L. Hernandez, "Comparison of three-phase grid-connected inverters topologies for reactive power compensation and PV power injection," in *2018 IEEE International Autumn Meeting on Power, Electronics and Computing, ROPEC 2018*, Nov. 2018, vol. 13, pp. 1–7, doi: 10.1109/ROPEC.2018.8661353.

[19] G. Mehta and S. P. Singh, "Design of single-stage three-phase grid-connected photovoltaic system with MPPT and reactive power compensation control," *International Journal of Power and Energy Conversion*, vol. 5, no. 3, pp. 211–227, 2014, doi: 10.1504/IJPEC.2014.063199.

[20] L. Liu, H. Li, Y. Xue, and W. Liu, "Reactive power compensation and optimization strategy for grid-interactive cascaded photovoltaic systems," *IEEE Transactions on Power Electronics*, vol. 30, no. 1, pp. 188–202, Jan. 2015, doi: 10.1109/TPEL.2014.2333004.

[21] Z. Liu, Y. Ding, J. Zheng, and Y. Gou, "Research on LVRT control combination strategy of PV station," in *2023 IEEE Sustainable Power and Energy Conference, iSPEC 2023*, Nov. 2023, vol. 47, pp. 1–6, doi: 10.1109/iSPEC58282.2023.10402939.

[22] M. N. I. Sarkar, L. G. Meegahapola, and M. Datta, "Reactive power management in renewable rich power grids: A review of grid-codes, renewable generators, support devices, control strategies and optimization Algorithms," *IEEE Access*, vol. 6, pp. 41458–41489, 2018, doi: 10.1109/ACCESS.2018.2838563.

[23] R. Rai and B. Singh, "Converter control during low voltage ride through operation for grid-interfaced solar PV battery assisted system," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 9, pp. 9181–9191, Sep. 2023, doi: 10.1109/TIE.2022.3213900.

[24] D. Beriber and A. Talha, "MPPT techniques for PV systems," in *International Conference on Power Engineering, Energy and Electrical Drives*, May 2013, pp. 1437–1442, doi: 10.1109/PowerEng.2013.6635826.

[25] L. P. N. Jyothy and M. R. Sindhu, "An artificial neural network based MPPT algorithm for solar PV system," in *Proceedings of the 4th International Conference on Electrical Energy Systems, ICEES 2018*, Feb. 2018, pp. 375–380, doi: 10.1109/ICEES.2018.8443277.
[26] M. Nour Ali, "Improved design of artificial neural network for MPPT of grid-connected PV systems," in *2018 20th International Middle East Power Systems Conference, MEPCON 2018 - Proceedings*, Dec. 2018, pp. 97–102, doi: 10.1109/MEPCON.2018.8635202.

BIOGRAPHIES OF AUTHORS

Ms. Mehtab Fatima received the B.Tech degree in Electrical Engineering and M.Tech in Electrical Power System Management from Jamia Millia Islamia. She is currently pursuing Ph.D degree from Department of Electrical Engineering, Faculty of Engineering and Technology, Jamia Millia Islamia, New Delhi, India. Her research areas of interest are grid integration of solar photovoltaic systems, design and control of solar PV inverters, reactive power management in grid connected solar PV system. She can be contacted at mehtabfatima@gmail.com.

Anwar Shahzad Siddiqui is a Professor in the Department of Electrical Engineering, Faculty of Engineering and Technology, Jamia Millia Islamia (JMI), New Delhi, India, and has 24 years of teaching and research experience in the field of Power systems Control and Management. Dr. Anwar has done extensive research work in the broad area of Power System Control and Management, specifically on Congestion management in Deregulated Power System, FACTS Devices and Applications of Artificial Intelligence Techniques in the field of Power System. He has more than 100 research papers published in refereed international and national journals of repute having more than 1550 citations with h-index 21 and i10-index 41. He is serving as an expert in many Govt. of India constituted Boards and Committees beside being member of BOS/COS of many institutes of repute. He can be contacted at assiddiqui@jmi.ac.in.

Sanjay Kumar Sinha is a Professor in the Electrical and Electronics Engineering Department at Amity University, Noida. He obtained his Ph.D. from IIT Roorkee, MTech from NIT Jamshedpur and B.E from M.I.T Muzaffarpur, Bihar. He has 28 years of teaching, research and industrial experience. During his academic and industrial career, he held various key administrative positions. His research interests include AGC, Power System Stability, Power System Transients, and Renewable Energy. He has published around 75 research papers in reputed international journals and conferences and has filed few patents. A number of research scholars are working with him towards their Ph.D. and five of them have completed their Ph.D. As a convener he has organized several conferences, workshops and lectures. He is the reviewer of several reputed journals from the likes of publishing houses of Wiley and Springer. He is an active researcher and has delivered several talks related to his research area. He can be contacted at sksinha6@amity.edu.