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Modeling and Analysis of MIMO Controller for Grid-connected PV/FC Hybrid Energy System

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***Abstract*— Grid-connected Photovoltaic/Fuel Cell Hybrid Energy System is receiving more and more attention as it contains more than one renewable energy sources or storage techniques to provides smooth and continuous supply. But this system has the problem voltage stability, voltage regulation and exposure to multiple faults. To remove these issues in hybrid grid-connected energy system, a multi-input multi-output (MIMO) system is developed in this research work. The proposed MIMO controller is designed to monitor, control, and track the maximum power point (MPP) of FC and PV power sources, as well as manage the output power of a grid-connected DC-AC inverter to supply smooth and clean power to sensitive loads. The grid-connected PV/FC system is simulated using the MATLAB/Simulink 2020a toolbox to determine the efficiency and accuracy of the developed controllers and reduced Total Harmonic Distortion (THD) to a value lower than 5% as per IEEE Std 1159-1992, which is completely compatible with the standards of the distribution network. A comparative analysis between proposed technique and state of the art are also presented to validate the effectiveness of the proposed work.**

***Index Terms*— grid-connected system, hybrid energy system, MIMO controller, maximum power point tracking (MPPT) and PV/FC.**

I. INTRODUCTION

DUE to economic growth and population growth, there is a noticeable increase in the world's energy demand in the twenty-first century [1].

Promoting renewable energy (RE) sources, such as wind, solar, hydroelectricity, and biomass, is a practical way to fulfil the world's rising energy needs. Solar energy is receiving more and more attention as the need for renewable energy sources rises due to its simplicity and endless supply [2]. To meet the load demand, these systems either need hybridization with prime movers or substantial energy storage [3]. Hybridization of battery banks, grid-connected systems and solar systems are possible solutions for increasing the reliability of the power supply and reducing the over-dependency on storage devices [4]. For MPPT of the renewable energy source and conversion of the PV output into AC power, DC-DC and DC-AC converters are typically required in such systems [5]. Energy storage system investigates a bidirectional single-stage grid-connected inverter [6]. For the connecting of the batteries to the system DC link, many buck-boost DC-DC choppers were used [7]. In micro-grid applications, extrinsic and intrinsic resonances are investigated using a mathematical model of multi-parallel inverters [8]. The DC connection in grid-connected inverters, on the other hand, is widely known to have significant voltage ripple [9]. The number of needed converters is reduced in grid-connected PV systems to enhance total circuit efficiency, eliminating DC-DC converters from grid-connected PV systems is attempted in [10-11]. The inverter's DC-side voltage management achieves MPPT of the input power source in this situation. To boost DC-link voltage in transformer-less grid-connected PV systems, the series connection of several solar panels is required in [10,12].

A dynamic model-based controller is used to investigate low-frequency power mitigation management for grid-connected PV systems [13]. PV systems are typically integrated with additional storage systems or energy sources to rise the dependability of the renewable power plant due to the dependency of generated PV power on temperature, radiance level, shading conditions, and the absence of power output during the night hours [2, 6, 14]. In comparison to a single-source system, a hybrid

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renewable energy system with an appropriate controller can provide greater load power supply dependability [15]. Due to its adequate power efficiency and weather independence, the FC generator is an excellent choice for use with PV systems [16]. A back-stepping nonlinear controller is built for hybrid PV power supply for distant communication applications and ensures the specified controller's stability and resilience when system parameters change [17]. The linear controllers are created using the model's small signal analysis. However, the controller is only relevant to standalone renewable systems [18], there is no information related to dynamic modeling for the DC-AC inverter normally used for grid-connected systems. The DC-AC inverter and DC-DC converter are represented as distinct subsystems for the standalone mode of PV-FC battery systems [19-20]. The nonlinear robust control of PV systems is sliding mode control (SMC) which is an efficient control technique to attain maximum power. Whereas SMC has some disadvantages of the chattering effect, to remove this chattering effect some algorithms are used in literature such as super twisting SMC, integral SMC, and real twisting SMC [21-23].

Utility fault ride-through capability of the on-grid renewable energy technique is investigated in [24] using predictive controllers. In addition to the standard capabilities of the grid-connected PV system, the controller can provide reactive power for load compensation and unity power factor operation. During voltage dips, the controller stops active power injection, and the system operates as an active power filter. In [25], the controller is intended to adjust the inverter's DC voltage, track the input power source's MPPT, and fed active power to the grid. A reactive power import capability is given for the system to safeguard it from inverter malfunctions during load shedding. Although different evolutionary techniques must be used for precise MPPT because of the non-linear I-V as well as P-V curves of the PV array on one side as well as uncertain PV generated energy due to temperature as well as climatic circumstances. In this discipline, perturbation, and observation (P&O) is a distinguished technique, although it has certain flaws when dealing with numerous maxima in the shadow condition. [21, 26].

In this research, the modeling and analysis of the MIMO controller for a grid-connected PV/FC hybrid energy system is presented, this developed control strategy consists of two parallel DC-DC boost converters that are linked to the power grid via a three-phase (3φ) universal bridge inverter to achieve the required voltage stability, voltage regulations, better efficiency, and an easily manageable hybrid energy system. This developed control strategy reduces Total Harmonic Distortion (THD) to a value lower than 5% as per IEEE Std 1159-1992 [27], which is completely compatible with the standards of the distribution network. The simulation results have been generated by using MATLAB/Simulink 2020a.

The proposed research is designed as, in section 2 methodology is described, system parameters is highlighted in section 3, in section 4 simulation results & analysis is discussed, and this research is concluded in section 5.

II. METHODOLOGY

The hybrid energy system is getting more popular due to more than one renewable energy generation, and energy storage technique in a single model, which is helpful due to high efficiency, continuous power supply, and low maintenance/management issues.

In this research, the modeling and control of the grid-connected PV/FC hybrid energy systems are studied. The circuit topology consists of DC-DC boost converters for the P/O-based MPPT of the input source of PV and boosts converter for FC. These choppers supply the DC link of the grid-connected inverter. In the proposed approach, a complete unique MIMO model of the system is employed for controller design. The amplitude modulation index of the DC-AC inverter and the duty cycles of the DC-DC boost converters serve as the system's control inputs. The electricity from the PV/ FC sources and the AC power fed into the power grid are also system control outputs. Therefore, the analyzed system is a three-input three-output circuit from the perspective of controller design.

The block diagram of the proposed controller for a grid-connected PV/FC hybrid energy system is shown in *Fig. 1*. The designed system is getting the required energy from multiple sources where the solar system is prior than others in the system then in cloudy weather or at nighttime system is getting power from the grid and in load shedding condition system depend on storage technique used here as fuel cell will fulfill required demand of energy. The system's control inputs are the inverter amplitude modulation index and the duty cycles of the DC-DC converters. The control outputs also include the injected AC current and the output power of the PV/FC sources.

The MPPT functioning of the PV module uses a P & O system. The P&O algorithm technique is represented in table I, and *Fig. 2* depicts the flowchart for P&O.

TABLE I
P&O ALGORITHM SCHEME

Delta P	Perturbation	Resulting Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

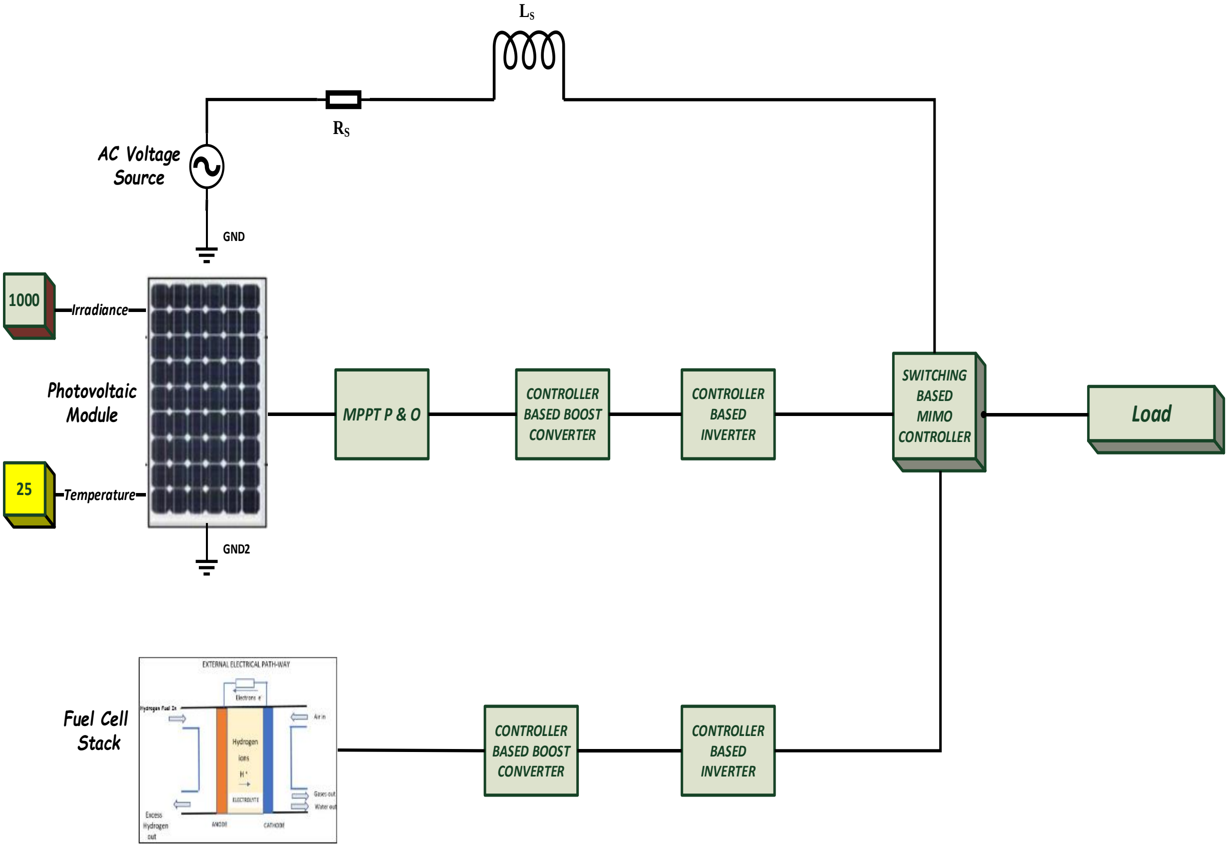

Fig. 1. Block diagram of Grid-connected PV/FC Hybrid Energy System

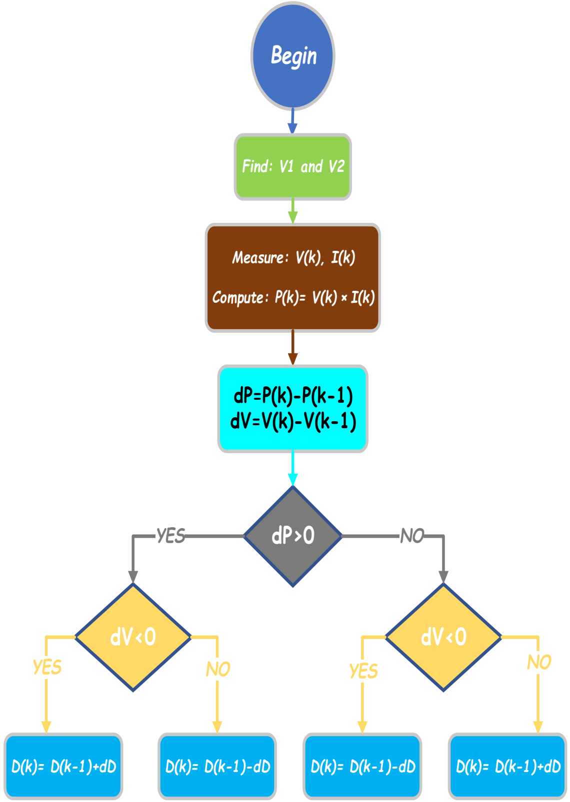

Fig. 2. Flow chart of P&O algorithm for PV System

The developed MPPT, which establishes the corresponding DC-link voltage of the PVs, is used to extract the maximum power from the PV. Like this, modern upgraded grid connected converters enable direct integration of PVs while maintaining power quality standards. The equivalent circuit shows in *Fig .3*.

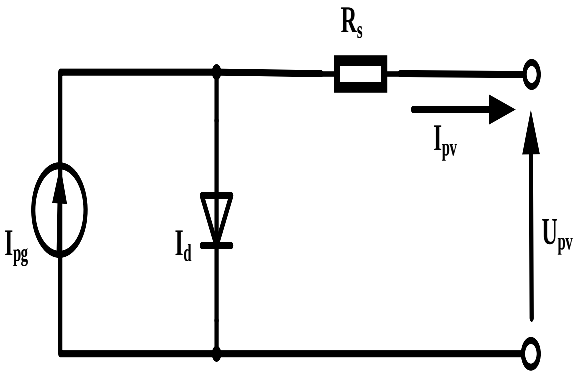

Fig. 3. Equivalent Circuit for Solar Panel input source [5]

Hence, current-voltage characteristics of the PV panel can be written as:

$$I_{pv} = I_{pg} - I_d \tag{1}$$

Where,

$$I_d = I_{rs}\left(exp\left(\frac{U_{pv}+R_s I_{pv}}{U_{tv}}\right) - 1\right) \tag{2}$$

So,

$$I_{pv} = \mathrm{I}_{pg} - I_{rs}\left(exp\left(\frac{U_{pv}+R_s I_{pv}}{U_{tv}}\right) - 1\right) \tag{3}$$

$$I_{pg} = \mathrm{I}_{sc}\frac{Ir}{Ir_o} + T_c(T_o - T_a) \tag{4}$$

Where U_{pv} and I_{pv} are the voltage as well as current of the PV panel, whereas I_{rs} and I_{pg} are reverse saturation currents and photo-generated, respectively; And R_s is known as series resistance; and thermal voltage is denoted as $U_{tv}=K_B N_S T_{PV} A/q$, where K_B, T_{PV}, q, and A are the Boltzmann constant, PV module temperature, electron charge, and diode quality factor, respectively. And short circuit is represented by I_{sc}, whereas irradiance and nominal temperature is represented by Ir_o and T_a, similarly; the temperature coefficient is represented by T_C , similarly; temperature and ambient irradiance is represented by T_o and Ir.

Furthermore, in *Fig. 4*, a controlled voltage source E with an internal resistance R_{int} can be considered for modeling the FC stack in nominal conditions.

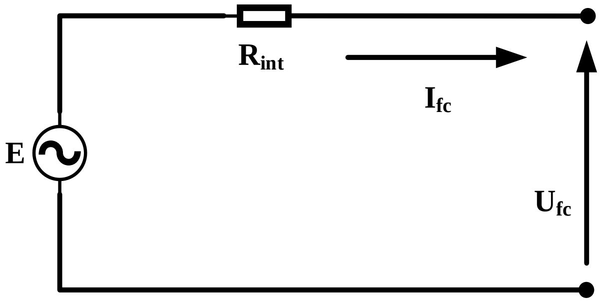

Fig. 4. Equivalent Circuit for FC Stack input source [5]

According to Kirchhoff's voltage law (KVL) and electric power formula, the value of voltage and current are feasible:

$$P = U_{fc}.I_{fc} \tag{5}$$

$$U_{fc} = E - R_{int}.I_{fc} \tag{6}$$

III. SYSTEM PARAMETERS

The parameter details are given in table II.

TABLE II.
NOMINAL PARAMETERS OF POWER CIRCUIT

Simulation Parameters	Value
Reference Temperature of Solar cell (T_{ref})	25^{o} C
Solar cell Irradiance (Ir_o)	1000 W/m^2
Number of Solar Cells (N_s)	8
Short Circuit Current (I_{sc})	7.34 A
Open Circuit voltage (V_{oc})	3.39 V
Quality Factor (N)	1.5
Frequency of System (f_o)	50 Hz
Grid Voltage (Ph-Ph)	400 V
Inductance (L)	0.297mH
Capacitance (C)	0.533µF
Impedance of Line (L_s, R_s,)	16.58 mH, 0.8929 Ω
Fuel Flow Pressure Input	1.36908036 amu
Air Flow Pressure Input	5.89420573 amu
Time of Sampling	2 µsec
Loads Rating (3φ)	Linear Load: P= 10 kW, Q = 1 kvar
Switching time for PV	0.05 sec, 0.07 sec
Switching time for Grid	0.1 sec, 0.12 sec
Switching time for FC	0.15 sec, 0.17 sec

IV. SIMULATION RESULTS AND ANALYSIS

Different tests have been carried out on MATLAB/Simulink 2020a to check the efficiency of the proposed MIMO Controller for grid-connected PV/FC hybrid Energy Systems. *Fig. 5*, describes the test system for modeling and analysis of the MIMO controller for a grid-connected PV/FC Hybrid Energy System. PV source, three-phase (3φ) voltage source, and fuel cell when all three of these are in the same system, will generate some issues such as voltage regulation, stability, efficiency.
After mitigation these issues, the improvement in the following assessment happens:

- Voltage Regulation and Stability.
- Better Controller Management and Switching of devices.
- More efficient System with less THD than 5%.

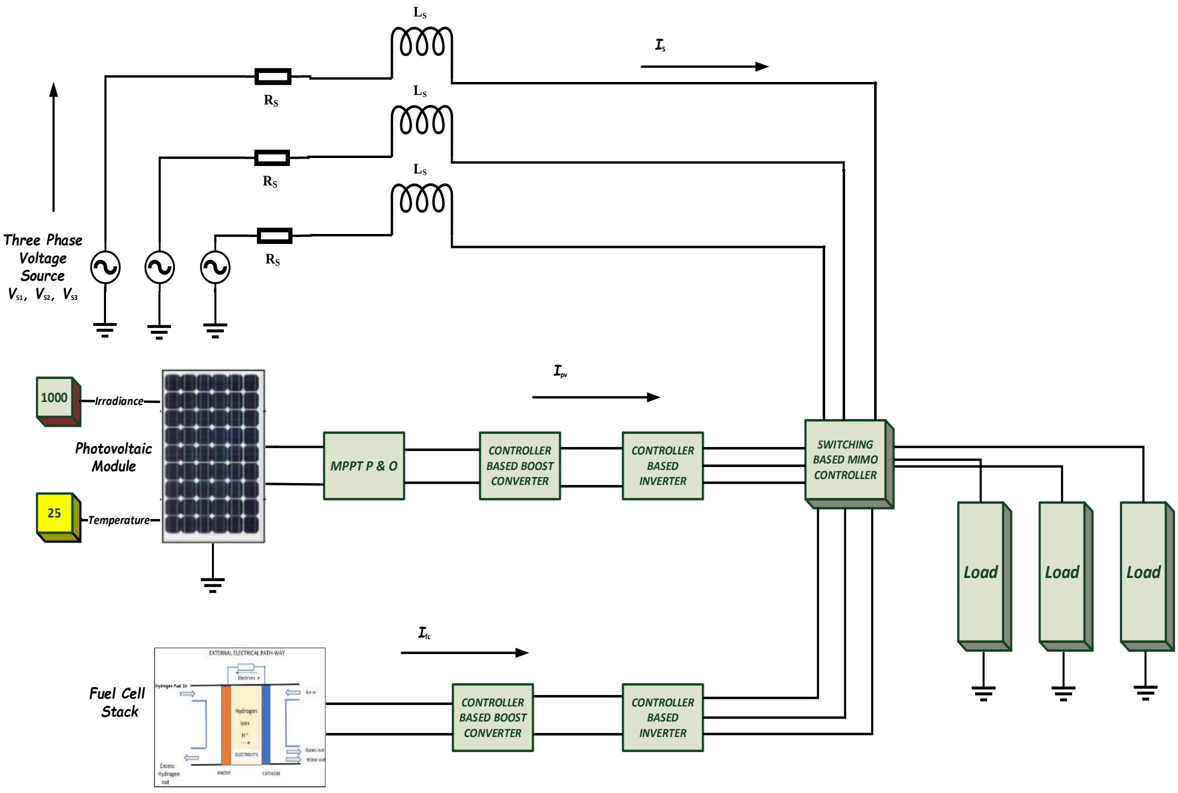

Fig. 5. Three phase Grid-connected PV/FC Hybrid Energy System

A. *Case 1: PV Fault*

Due to cloudy weather, at night, or under fault, the voltage supply coming from PV Source is not entirely consistent with the requirements of a distribution network. When the fault occurs at the PV source, the system will automatically connect to the second preferred power supply after the PV source which is the grid source in the proposed hybrid model. This PV fault starts from 0.05 sec and ends at 0.07 sec as shown in *Fig. 6*. PV source fault is mitigated in a very small period of 0.02 sec. Where system will start getting its required voltage supply from the grid source until the fault occurs at the grid source.

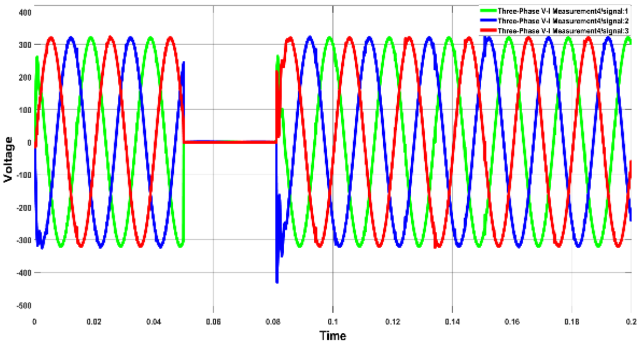

Fig. 6. PV System under three phase faults

B. *Case 2: Grid Fault*

When the fault occurs at the grid source, the system will automatically connect to the third preferred power supply after the grid source which is the Fuel cell used for the energy storage in the proposed strategy. This fault starts from 0.1 sec and ends at 0.12 sec as shown in *Fig. 7*. Grid source fault is mitigated in a very small period of 0.02 sec. Where system will start getting its required voltage supply from the FC source until the fault occurs at the FC source.

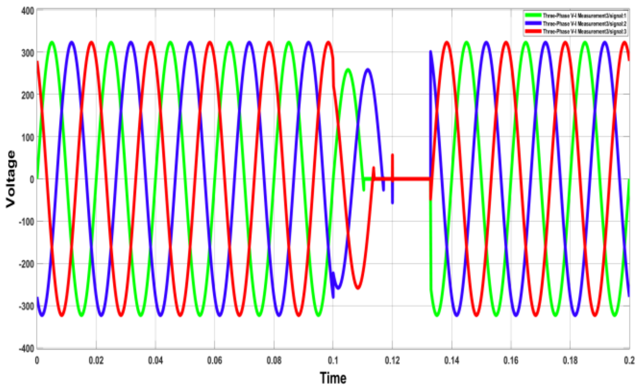

Fig. 7. Utility Grid Under three phase faults

C. *Case 3: FC Fault*

When the fault occurs at the FC source, then a switching-based controller named MIMO controller will be used to reduce the chance of a fault in the proposed model. This fault starts from 0.15 sec and ends at 0.17 sec as shown in *Fig. 8*. FC source fault is mitigated in a very small period of 0.02 sec.

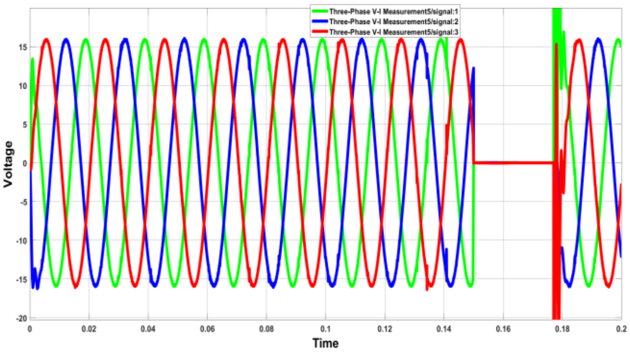

Fig. 8. FC System Under Three phase faults

D. *Case 4: When Fault is Resolved*

The system will start getting its required voltage supply from the hybrid energy systems if a fault occurs at any part of the system, then due to the hybrid system the proposed model will get a consistent voltage supply according to the requirements of a distribution network. A small transient may occur due to a sudden change in switching time and then with the help of a MIMO controller-based hybrid energy system will provide a stable injection of voltage as shown in the *Fig. 9*.

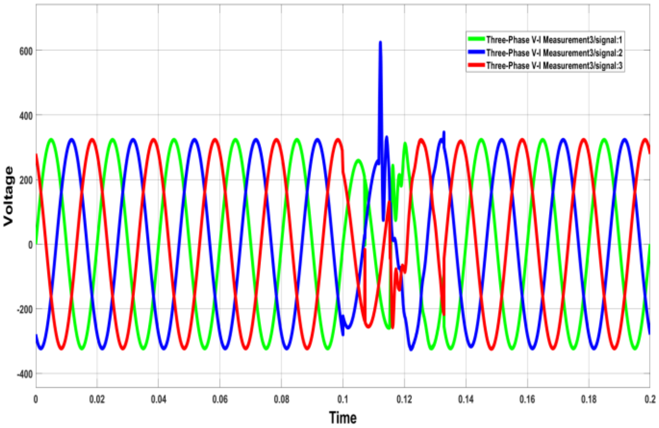

Fig. 9. Voltage Waveform after Fault is Resolve

When fault resolved, the THD of system is 0.66%, 0.13% and 0.27 % for phases A, B and C respectively. The THD graph for Phase A as shown in *Fig. 10*. All three of these values are according to IEEE Standard 1159-1995 which recommends that the harmonic content in load voltage should be less than 5%. The THD value after fault is resolved for Phase A is shown in *Fig. 10*. THD analysis for all cases are shown in table III.

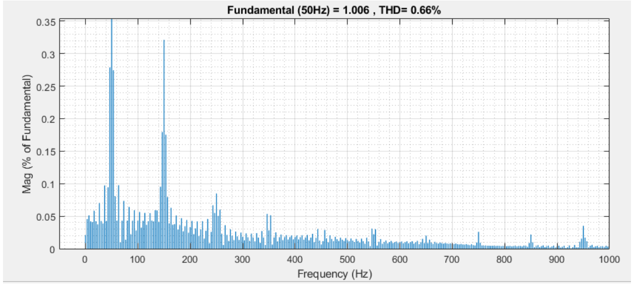

Fig. 10. THD value after fault resolve for phase A

Table III
THD Analysis

Cases	Load end THD (%) in all Cases
Case 1	0.6, 0.13, 0.27
Case 2	0.8, 0.55, 0.43
Case 3	0.5, 0.59, 0.67
Case 4	0.7, 0.3, 0.2

E. *Case 5: Comparative analysis*

In this case, a comparative analysis of SISO controller and proposed MIMO controller is presented based on the Voltage regulation (VR) and Voltage stability (VS) under three phase faults. Initially, the VR and Vs of the SISO controller is faster than the Proposed controller. But after 250 msec, the response of Proposed MIMO controller improves, and the VR is approaching nearly 100% as shown in *Fig. 11*.

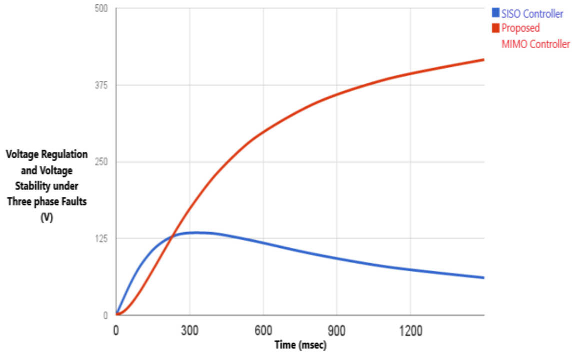

Fig. 11. Comparative analysis of SISO Controller and Proposed MIMO Controller

V. CONCLUSION

In this research work, an innovative technique for modeling and analysis of MIMO controllers for grid-connected PV/FC hybrid energy systems is presented. The proposed control technique will provide voltage stability, voltage regulation, and efficient switching of devices as well as give smooth power to loads. By using a MIMO controller with a hybrid energy model, the system can export generated power to the grid and providing MPPT for PV/FC sources. The effectiveness and accuracy of the suggested MIMO controller are evaluated by using simulation results in MATLAB/Simulink 2020a. Considering the outcomes of the simulation, the designed MIMO controller efficiently removes fault in 0.02 sec in each case. The THD value is less than 5% in all three phases after the fault is resolved and that complies with distribution network requirements. The simulation outcomes show that the suggested MIMO controller is accurate and stable with the least disturbance at various operating points. The recommended MIMO-based hybrid energy system overtakes traditional renewable techniques because of its continuous supply of energy for a long span of time. But the high cost and compatible size are still challenges of the system that needs to mitigate.

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