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Novel Control of PV-Battery Powered Standalone Power Supply System with Neuro-Fuzzy Controller

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Abstract: *Photovoltaic (PV) powered standalone electrical power supply systems are becoming more precious networks nowadays worldwide. Many challenging tasks are existed in PV based standalone systems due to random changes in solar irradiances, load and it is absent during nighttime. Innovative controllers are necessary to uphold power quality in these systems. A battery pack is required in this standalone system since solar irradiance is unpredictable and in order to provide continuous stable power to electrical loads during no irradiance. Therefore, a battery bank is connected to a standalone unit via a DC to DC bidirectional circuit. The maximum power point tracking converter, in conjunction with the perturbed and observe algorithm, is employed to optimize the operation of the PV system and enhance the overall efficiency of the system. Neuro-Fuzzy controller based novel controller is designed for both inverter as well as bidirectional circuit to supply quality power to both single and three phase loads. Comprehensive findings have been showcased and accessed via hardware-in-loop testing on the OPAL-RT platform to optimize the suggested controller for a 1MW standalone system in various scenarios.*

Keywords *PV, Neuro-Fuzzy, MPPT, HIL, Standalone System, Power Quality.*

I.INTRODUCTION

Reducing carbon emissions plays a major role in increasing human lifespan, so the whole world is investigating for ways to absorb or reducing carbon emissions [1-2]. The best way is to reduce carbon emission is the use of renewable energy sources found in nature. As long as human beings live, we can get a lot of sunlight freely through the earth. Photovoltaic (PV) device can converts this widely available sunlight into electrical power. A locally placed PV based standalone systems are more popular in some isolated places as well as where electrical supply is not possible by electric grid in world [3]. Unfortunately, there is no sunshine at night and for some time during the day also. In addition to this, solar irradiance is having intermittent changes in nature. Moreover the electrical load is also changing randomly regardless the availability of solar irradiance. Therefore an energy storage devise will play a key role in PV based standalone system since only PV cannot maintain load demand [4-5]. Battery is considered the most superior energy storage unit among the various options existed due to its rapid behavior during discharging and charging processes [4]. A DC to DC bidirectional device is utilized to integrate a battery bank into the dc-link, thereby improving power quality and reliability. Additionally, the PV system must operate at a specific voltage level in order to generate the maximum available power [4, 6]. Therefore, a boost converter is utilized in conjunction with a maximum power point tracker (MPPT) algorithm. Maximum loads in distribution system are AC, so an inverter is used to converter DC to AC.

The battery bank can able to charge from PV when load power is less than generation by PV and in the same way it can be discharge when demanded load is higher than the generation. The power mismatch between generation and load can be determined by dc-link voltage [7] at the common point of PV, battery bank and inverter connected. Hence, the dc-link voltage controller is employed with bidirectional DC to DC circuit and AC loads are connected to inverter. Mostly AC loads in distribution system are unbalanced since existing of single phase loads [7]. In order to provide power quality, the inverter should able to maintain balanced voltages at PCC where all AC loads are operating. There is a RLC filter between inverter and PCC, hence the controller of inverter needs to be generate different modulation indexes for three phases during unbalanced load because of unbalanced voltage drops existed across filter. Compared to PI controllers, a fuzzy controller can provide precious response under random changes [8]. Furthermore, the rule sets produced by the Neuro-Fuzzy based controller align perfectly with the results obtained from statistical analysis and effectively produce comprehensible and reusable knowledge. Additionally, the Takagi-Sugeno-Kang fuzzy controller offers greater flexibility in system design compared to the Mamdani fuzzy controller. As a result, the Neuro-based Takagi-Sugeno-Kang fuzzy logic controller has been utilized for both the bidirectional DC to DC circuit and inverter controllers. The system description is demonstrated in Section-II and proposed controllers are presented in Section-III. Section-IV presents the analysis of results based on Hardware in-Loop (HIL) using the OPAL-RT platform. Following the conclusion in Section-V, the parameters utilized in this study can be found in the Appendix.

II. SYSTEM DESCRIPTION

One PV module alone cannot produce sufficient voltage, hence several modules, labeled as 'N', are linked in series to create a PV string for voltage enhancement. Likewise, 'M' strings are connected in parallel to create a PV group, ensuring the rated current is maintained. The specifications of each individual module can be found in Table-1 in the Appendix section. To maximize the power output, each PV group is equipped with its own MPPT converter. The entire PV system is established by connecting parallel of 'X' number of PV groups through their respective MPPT devices. All MPPT circuits are integrated to a common dc-link along with a battery bank. Therefore, all MPPTs can work for extracting maximum power based on irradiance of corresponding PV group irrespective of dc-link voltage. Hence, the DC to DC converter of the battery may be able to adjust the dc-link voltage to its desired value. The inverter is utilized for converting DC to AC, with loads being connected to the inverter through an RLC filter. Various types of loads, including single phase, three phase, and nonlinear loads, are linked to the PCC. As a result, a four-wire system is implemented to accommodate these loads. The diagram of the entire standalone system powered by PV-Battery can be seen in Figure 1. The modeling of the PV system, battery, and RLC filters is based on references [7, 11-13]. Various scholars have proposed similar systems, with some of them being mentioned here. The authors in [3] have determined the optimal location for the energy management system. In [4], a novel MPPT algorithm was proposed for PV-based hybrid standalone systems operating under partial shading conditions. The authors also examined the control strategy for the PV-battery powered standalone system in [5]. Furthermore, in [8], the researchers presented a TS-Fuzzy based controller for a PV-Diesel-Battery hybrid system, despite the detrimental impact of the diesel generator on the environment. The authors in [13] have devised dual loop PI controllers for a DC to DC circuit in standalone systems. In [14], the authors have conducted a comparative analysis on nonlinear controllers in PV-based standalone systems. However, Neuro-Fuzzy based controllers are not presented by authors in above researches, further novel controllers are proposed for both DC to DC converter and inverter in this paper. Apart from these, more realistic configuration setup of multiple PV based system is also considered. Typically, a nonlinear load is linked to the PCC, which has the potential to introduce harmonics to other loads. To mitigate the impact of the nonlinear load, an active power filter is required [15]. Furthermore, a DSTATCOM is essential to offset the reactive power required by the load [16]. Moreover, the presence of unbalanced and nonlinear load at the PCC leads to second frequency oscillations in the dc-link voltage. These oscillations generate heat at PV modules, resulting in a decrease in power generation. Therefore, a novel controller is proposed for the DC to DC circuit to eliminate these oscillations. The inverter can work as active power filter and DSTACOM by proposed controller.

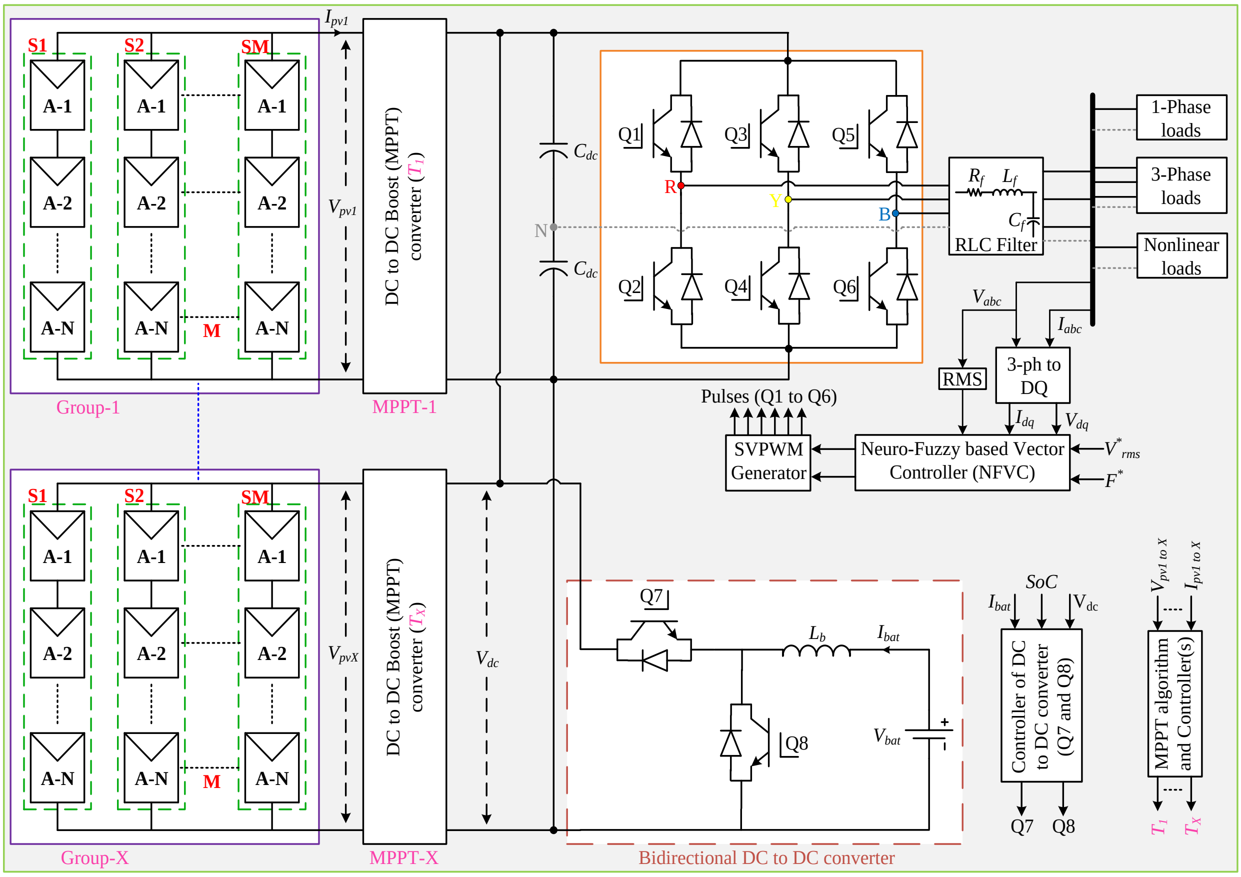

Fig. 1: A standalone model.

III. DC-LINK VOLTAGE AND INVERTER CONTROLLER

Each MPPT converter will operate at different voltage ratings, since all PV groups cannot receive same irradiance. Despite variations in output voltage among MPPT converters, boost converters employed for MPPT will adjust the current according to the power availability from the corresponding PV group to the dc-link. Nevertheless, the dc-link voltage can be controlled by a DC to DC circuit through the regulation of battery bank charging and discharging. Details of battery bank are listed in appendix. Perturbed and observe method is implemented to generate duty cycles for all MPPT converters. The bidirectional circuit controller is implemented to regulate battery current corresponding to power mismatch between generation and load. Generally fuzzy controllers are having superior performance than PI controllers during random changes in either generation or load side. Neuro-Fuzzy has the advantage of being able to adjust gains rapidly compared to a fuzzy controller. The Takagi-Sugeno-Kang fuzzy controller is designed as a replacement for PI controllers. Figure 2 illustrates the block diagram of the Neuro-Fuzzy system based on Takagi-Sugeno-Kang. The inputs to the system are the error and the rate of change of error. The developed Neuro-Fuzzy controller is then utilized in both the DC to DC controller and the inverter controller to improve the response significantly when faced with unpredictable variations.

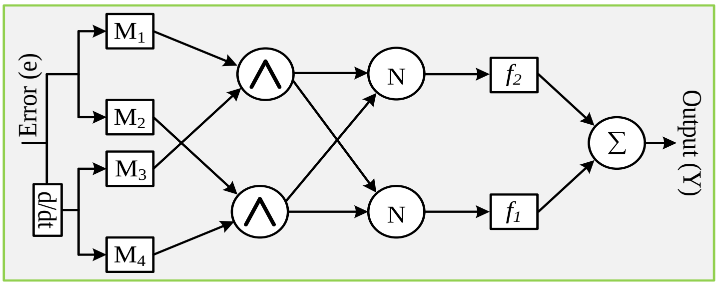

Fig. 2: Neuro-Fuzzy system model.

The PCC is connected to a majority of loads that display characteristics of both unbalance and nonlinearity. As a result, there are frequency oscillations at twice the fundamental frequency ('2ω') in the dc-link voltage. These oscillations can generate heat at the PV modules, thereby reducing their power generation capacity. To mitigate the impact of these oscillations on the PV modules, a battery controller is designed to allow the oscillations to circulate through the battery and the DC to DC circuit. This configuration also enables the battery to be charged by these oscillations. The proposed controller for the DC to DC circuit, as depicted in Figure 3, utilizes a Neuro-Fuzzy controller.

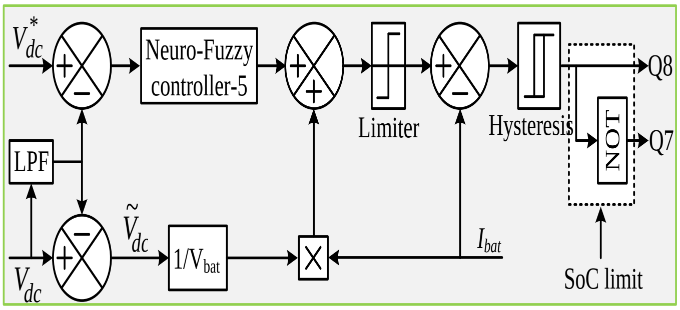

Fig. 3: Proposed control method of dc circuit.

The imbalance in power can result in fluctuations in the dc-link voltage. For instance, an increase in generation compared to the load will cause the dc-link voltage to rise, while a power deficiency will lead to a decrease in the dc-link voltage compared to the reference value. As a result, a circuit is required to allow charging current to enter the battery once the voltage at dc-link surpasses its reference signal. On the other side, the battery must discharge when the dc-link voltage drops below its reference value. Figure 3 uses the error signal between the battery voltage and its reference to calculate the reference battery current via the Neuro-Fuzzy controller. To eliminate '2ω' oscillations, the existing oscillations are obtained from the dc-link with the assistance of a LPF and then converted into the necessary oscillating component of the battery current. Required oscillating component of battery current is added to reference battery current and resultant is limited through a limiter to prevent battery from over discharging and charging currents. The limiter produces a battery reference current, which is then compared to the actual battery current. The hysteresis loop generates the necessary pulses for the DC to DC circuit by utilizing the error between the actual battery current and its reference. Consequently, the controller enables the flow of '2ω' oscillations in both the battery and the DC to DC circuit. Additionally, the SOC is integrated to produce pulses that regulate the battery charging and discharging levels within acceptable boundaries, as illustrated in Figure 3.

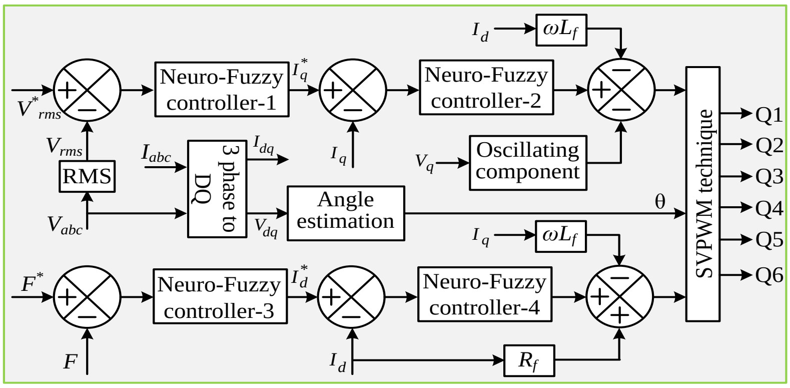

Fig. 4: Neuro-Fuzzy controller based proposed inverter controller

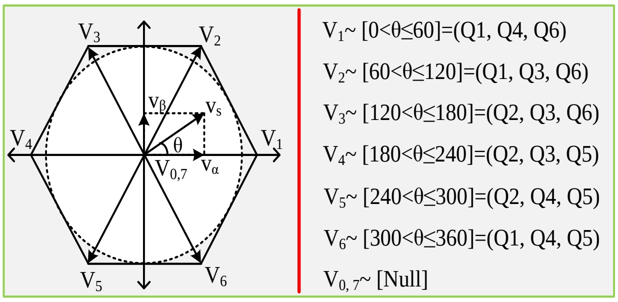

Fig. 5: SVPWM Technique

The inverter with proper controller needs to be developed for converting DC to AC [17-18]. The inverter can able to produce required AC voltages with the help of modulation index once stabilized dc-link voltage. The inverter controller proposed in detail can be seen in Figure 4. Since it operates as an independent system, the frequency will play a crucial role. Changes in active power will reflect in changing in frequency. Therefore, the direct axis current's reference component is produced by the Neuro-Fuzzy controller, which compares the frequency with its reference value. Similarly, the responsive element of the electric current is achieved by contrasting the root mean square (RMS) voltage with its designated benchmark. Additionally, the decoupling components are incorporated by taking into account the filter parameters. Furthermore, the reduction caused by resistance in the filter is also taken into consideration and incorporated into the reference voltage signal solely for the direct axis component. This can helps to overcome voltage drop across filter resistance irrespective of load current at PCC. The required pulses are generated through SVPWM technique as shown in Fig. 5.

IV. RESULTS

The real-time simulator (RTS) is a digital simulator that can operate in real-time by solving power system equations quickly to continuously generate output conditions that accurately reflect conditions in the actual network. The use of RTS technology is widely acknowledged as a highly efficient method for designing, developing, and evaluating power system control strategies. In order to establish the HIL configuration, researchers have employed two RTS modules developed by OPAL-RT technologies. The plant model is fully operational on unit-1, while the controllers are located in unit-2. Each unit is furnished with analog and digital cards to facilitate connections and create a closed loop system. Analog signals are transmitted from the plant to the control, while digital signals are sent from the control to the plant. Extensive results are obtained through another computer for analysis. The HIL model setup, using two OPAL RT-4510 modules, is shown in Figure 6. The proposed model, depicted in Figure 1, is divided into the plant and controller. The block representation of a HIL process for the proposed system, with appropriate color coding, is presented in Figure 7. Additionally, the results are showcased in the subsequent case studies.

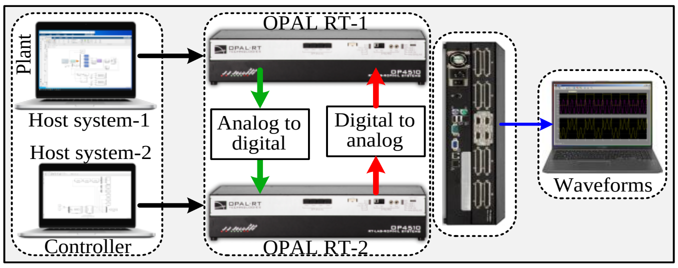

Fig. 6: HIL configuration.

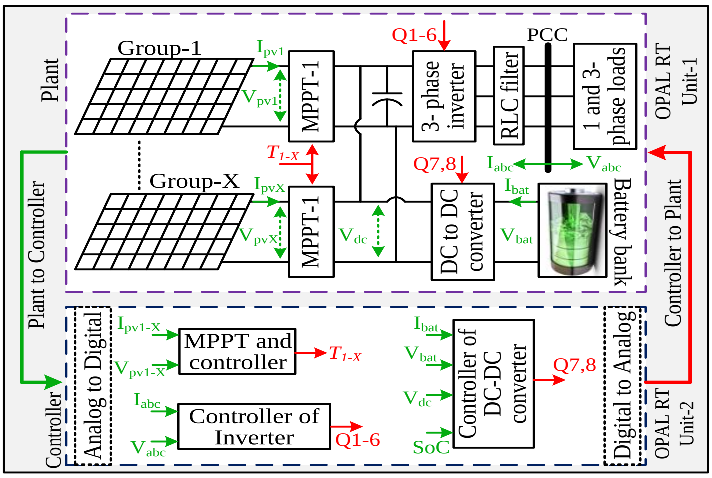

Fig. 7: Model HIL block of proposed system.

Case-1: performance under changes in generation and load

Generally all PV groups are unable to receive same level of irradiance. The generation from total PV power is obtained by adding power of all PV units. The changes in total PV power and load are considered as per depicted in Fig. 8(a). The battery is responding accordingly to maintain power balance between PV and load. Negative power of battery represents charging and positive refers to discharge. Corresponding dc-link voltage which is regulated by battery is shown in Fig. 8(b). Due to individual MPPT converters, the dc-link voltage won't affect much during changing in PV power. Fluctuations in the dc-link voltage occur due to changes in the load, but these fluctuations are relatively small in comparison to the reference dc-link voltage of 720V. The 3-phase RMS voltages can be observed in Fig. 8(c). The precise outcomes were made possible by the Nuero-Fuzzy controllers, known for their rapid response to system changes. To evaluate the controllers' performance, one can analyze the instantaneous waveform, as illustrated in Fig. 9, showing the respective 3-phase currents under varying load conditions.

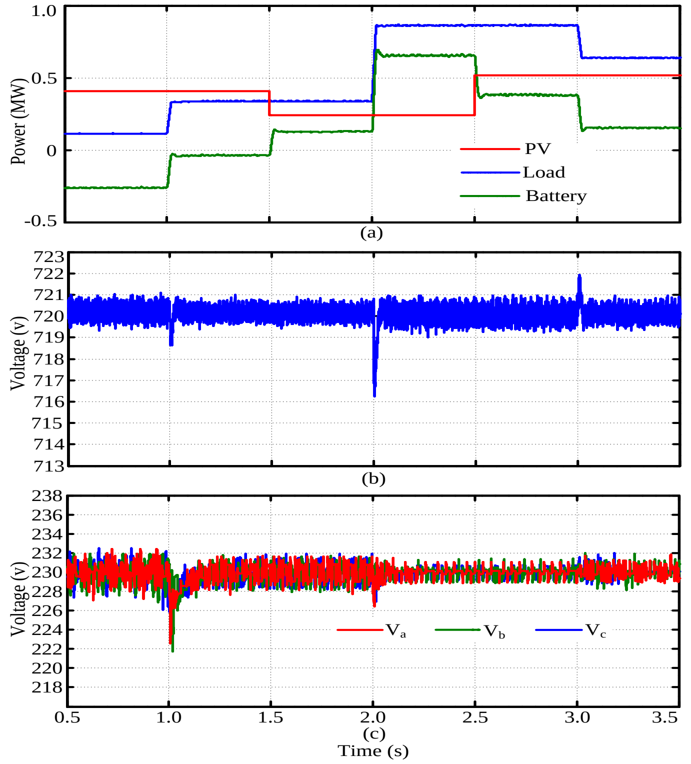

Fig. 8: (a) Powers, (b) dc-link, (c) RMS voltage

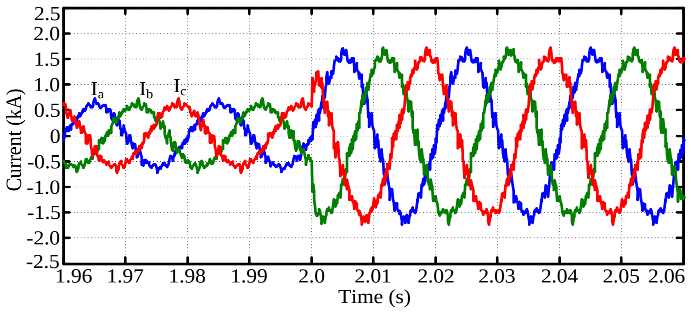

Fig. 9: Instantaneous currents at PCC.

Case-2: Operation during unbalanced load

The distribution system typically experiences unbalanced loads. The unbalanced load profile depicted in Figure 10, with one phase current remaining unchanged, is deemed the most critical scenario. The filter's uneven drop results in inconsistent voltages at the PCC. To ensure balanced voltages at the PCC, the controller must generate different modulation indexes for the inverter. The 3-phase RMS voltages are depicted in Figure 10 (b). These voltages show minor fluctuations during abrupt load current changes, but stabilize at the reference voltage (230V) in a steady state. However, due to the unbalanced load, second frequency oscillations will be present in the voltage across the PV group. These oscillations should be eliminated to reduce generated heat across PV modules. The battery's proposed controller is efficiently functioning to circulate these oscillations via the DC to DC circuit. Consequently, the voltage across the PV group will be devoid of these oscillations. The PV group-1 is operated at voltage corresponding to MPPT (i.e., 636.3V) and corresponding voltage is depicted in Fig. 11 with normal and proposed controller. It is evident from Figure 11 that the controller of the DC to DC circuit effectively eliminates second frequency oscillations from the PV voltage.

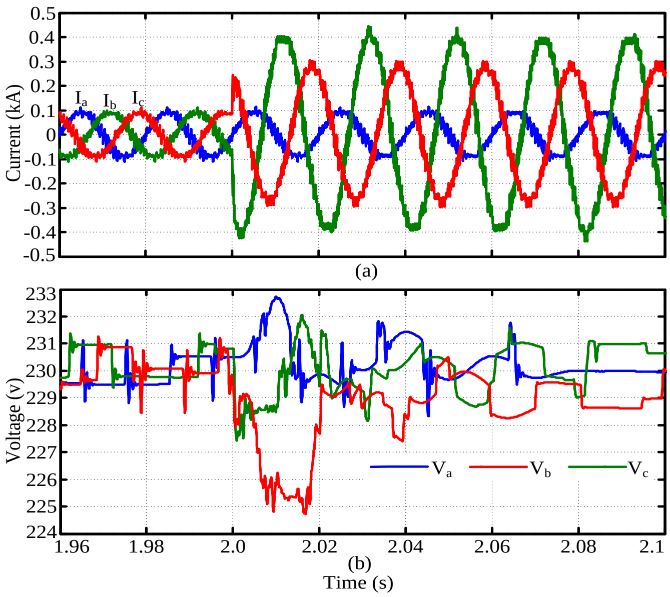

Fig. 10: (a) Load current, (b) voltages.

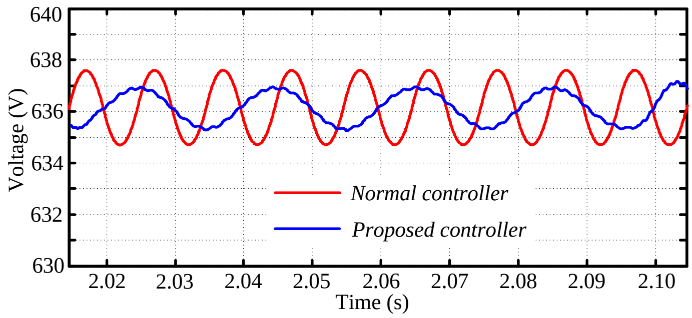

Fig. 11: second frequency oscillations in dc-link

V. CONCLUSION

The Neuro-Takagi-Sugeno-Kang fuzzy logic is utilized to develop novel controllers for a bidirectional DC to DC converter and inverter in a 1MW PV-Battery operated standalone system. To present the results in a more realistic manner, a HIL setup with OPAL-RT technology is employed. The inverter controller proposed in this study effectively maintains balanced voltages at the PCC even under unbalanced loads. Additionally, the power quality is significantly enhanced by the implementation of the proposed inverter controller. Furthermore, the proposed controller successfully eliminates second frequency oscillations from the PV system voltage.

Appendix:

Parameters of 1MW PV system are listed in Table-1.

Single module (215.2W)		
S.No	Parameters	Values
1	Current of Short-circuit.	8.011A
2	Open-circuit voltage.	36.89V
3	Voltage at MPPT.	30.29V
4	Current at MPPT.	7.1A
Combinations of Series and parallel to make an 1.0MW		
5	‘N’ in String (number of modules)	21
6	‘M’ in Group (number of strings)	9
7	‘X’ in PV System (number of groups)	25

Parameters of battery bank.

The battery bank rating is determined by the voltage of the battery bank and the number of hours needed to supply power to loads when there is no power available from the PV system. This study considers a 480V battery bank and a backup designed to last for 72 hours for an average load of 0.5 MW. The necessary current rating (Ah) is calculated using the equation provided below at SoC of 60%.

$$I_{bat} = \frac{5{,}00{,}000 \times 72}{480 \times 0.6} = 125kAh$$

480V, 125 kAh rating battery bank		
S.No	Parameters	Values
1	Voltage rating of Single battery.	48.0V
2	Current rating.	125A
3	Series batteries in a string.	10
4	Parallel strings.	1000

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