

# Novel Control Technique for Power Quality Improvement in PV - Wind Operated Hybrid Stand-alone System with TSK Fuzzy Controllers

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**Abstract-** Power generation and supplying to electric loads through hybrid renewable energy sources is one of the best choices to reduce global warming as well as fulfill the needs of electric loads in many rural places. Hence establishing standalone hybrid power supply systems are becoming increasing day by day. However, due to atmospheric changes, a storage device (i.e., battery bank unit (BBU)) along with proper energy management system must be integrated into standalone system to manage power balance between load and generation. Photovoltaic-wind-battery powered standalone power supply system is considered in this work. An effective control mechanism is proposed to supply the quality power at load bus. Due to drawbacks of conventional PI controllers, a Takagi Sugeno Kang Fuzzy controller is used in proposed control methodology. Dual inverter configuration is implemented in this research work, one is operated between AC load bus and dc-link, the other one is in between BBU and AC load bus. In order to manage power balance in the system, a dc to dc bidirectional circuit is placed between batteries and inverter. In this configuration, the operation similar to inter line power flow controller is achieved by operating the inverter between BBU and AC load bus by proposed method. The Hardware-in-the-Loop is designed for analyzing various case studies in the results by connecting two OPAL-RT devices.

*Keywords: TSK-Fuzzy Controllers Renewable energy sources, Power quality, Dual inverter mode, interline power flow.*

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Nomenclature:

TSKF: TSK Fuzzy.

MPPTC: MPPT Converter.

REPS: Renewable Energy Power Sources.

HIL: Hardware – in the – Loop.

PVU: PV Unit.

WPCS: Wind Power Conversion System.

BBU: Battery Bank Unit.

IPFC: Interline Power Flow Controller.

PCC: Point of Common Coupling.

## 1. Introduction

Electricity must be required in everywhere for growth through a variety of activities, and it has now considered as one of the fundamental rights in many nations [1]. As a result, giving high-quality power to customers is essential for achieving higher output from a wide range of electrical loads. However, many locations throughout the world remain without access to the electricity grid. Furthermore, some remote locations, institutions, and hospitals, among others, are needed to have a stand-alone power supply model to meet their electrical demands [2-3]. Diesel-powered electrical power producing devices are frequently used to deliver electricity in such situations. However, diesel usage is hazardous and damaging to the environment. As a result, supplying power through independent systems based on REPS is the ideal answer to many difficulties.

Solar and wind energy are widely available in many parts of the world. As a result, photovoltaic (PV) modules and wind power generating systems based on PMSGs are studied in this research to create a hybrid standalone unit. To create a medium power range supply model, several wind and PV systems are considered at various places. All WPCS and PVUs are hybridized to provide a standard dc-link between power producing units and dc-link via their respective converters. Furthermore, with correct management algorithms, these circuits are employed as MPPTC of respective power producing modules. All of these converters contribute to the injection of current into dc-link through their respective units via current regulated controlling systems. As a result, a separate circuit with an appropriate control unit is necessary to keep the voltage of dc-link at its desired value. Simultaneously, an inverter must be placed to provide AC supply at load bus. Further, this inverter is also utilized to control voltage at the dc-link. Furthermore, this configuration may build a DC Microgrid for supplying power for any DC loads.

Establishing a shared dc-link with the assistance of several producing units helps improve system reliability. Unfortunately, the electricity provided by wind and PV units is dependent on nature, which is unpredictable as well as varies from instant to instant. This type of event can cause a power imbalance between consumed load and production of power in Microgrid. As a result, a BBU made up of many batteries is utilized to maintain power balance in the standalone system. The batteries can be linked to any location within the power supply unit through either a dc-link or an AC bus. Connecting a BBU to an AC bus via an inverter rather than a dc-link might provide additional functionality in a standalone Microgrid, especially when numerous producing units are used. In this system, two separate inverters are considered, with one inverter connecting the dc-link to the AC bus and the other connecting the BBUs to the AC bus. Moreover, a dc/dc bidirectional circuit must be

installed among the inverter and the battery unit to ensure correct discharging and charging actions. As a result, this study implements unique control techniques for two inverters and a bidirectional circuit. Control methods based on standard PI controllers are incapable of performing successfully in the face of fast changes in the Microgrid due to the standard gains of PI controllers that are set at a certain instant [4]. However, TSKF controller can outperform compared to traditional PI during sudden changes [5-7]. As a result, TSKF controllers are generally used in the suggested control techniques to obtain the highest possible performance under all operating situations.

The remaining portions of the work are organized as following sections. Section-2 compressed with an overview of the proposed system setup. Section 3 discusses the design and relevance of TSKF controllers. Section-4 describes proposed control techniques for inverters and bidirectional converter. In Section 5, the results are reviewed under various scenarios utilizing HIL. Section-6 contains the conclusions, and at the end list of references are provided.

## 2. Microgrid Configuration

As illustrated in Figure 1, numerous power producing units from PVU and WPCS establish a dc-link by connecting their unique MPPTC. As a result, this can function as a DC stand-alone system; however, there is no guaranty for maintaining constant voltage at the dc-link because of random changes in sources as well as load. Hence, an additional circuit must be included to regulate the voltage at dc-link while preserving power balance between load and power production. Once achieved a stable voltage at dc-link, all loads can be integrated directly or by using proper converter to dc-link depending on requirement. To maintain energy balance, energy storages must be included in a Microgrid [8]. Apart from this, an inverter must be operating to manage AC loads. As a result, an inverter with the appropriate control technique is linked between the dc-link and the AC-bus. By using its control mechanism, the same inverter is utilized to modulate voltage at the dc-link. Furthermore, adding a BBU at an AC bus via another inverter rather than connecting at a dc-link provides some other functionality. When operating BBU via dc-link, it is impossible to achieve balanced currents in a 3-phase alternating current system, resulting in unbalanced voltages for some loads and an increase in positive/negative sequence ratio.

Therefore, by using a second inverter which is connected between AC load bus and BBU, a balanced current can be maintained which refer similar to an IPFC. However, unbalanced flow currents will be flow in 3-phase system due to operating various single phase loads at a time at PCC. Therefore, in order to made balanced voltages in the 3-phase load bus, the second inverter must be injecting counter currents into 3-phase system to make balanced voltages. This process can be achieved by using the single phase supply to charge the batteries where less loads are operating and current will be injected into the corresponding phase(s) where more loads will be connected. For example, more battery current will be injected into Phase-A if it is operated by heavy 1-phase loads as compared with other phases and the battery will charge from the phase which draws less current. In the event of low generation, the battery can control load by injecting counter currents (unbalanced) into the alternating current bus. In a three-phase system, a balanced current flow can be accomplished by using a second inverter linked between the BBU and the AC bus and acting similarly to IPFC. If power generation is inadequate, the BBU can regulate the load by introducing unbalanced counter currents into the alternating current bus. This procedure enables a balanced distribution of currents across three phases. As a result, this procedure can compel the first inverter to function without an imbalanced effect. It is possible to manage balanced three phase voltage at the AC bus even during severe unbalanced loads connecting

in a three phase system. Imbalanced currents at the AC terminals of the initial inverter can frequently result in the introduction of a second frequency oscillating component into the voltage at the dc-link. These oscillations can be removed by operating first inverter to make balanced voltages. Consequently, the sources will be devoid of secondary frequency oscillations, thereby prolonging the lifespan of wind turbines and reducing heat at PV panel terminals. Furthermore, reducing oscillations and maintaining balanced voltages on the AC bus will enhance power quality. The power from the sources can easily be transmitted to AC bus systems through the initial inverter. As a result, additional energy balancing in the AC Microgrid can be accomplished by a second inverter comprised of a BBU. Figure 1 depicts the generalized layout of the suggested configuration for hybrid standalone power supply model. To obtain additional details, refer to Figure 2 that illustrates the operations of two inverters and the corresponding currents. Nevertheless, it is crucial to connect the BBU to the inverter using a dc to dc bidirectional circuit for efficient charging and discharging of the BBU, as suggested by [3-4]. Consequently, the input dc voltage of the second inverter is regulated by managing the bidirectional dc/dc circuit while maintaining energy equilibrium.

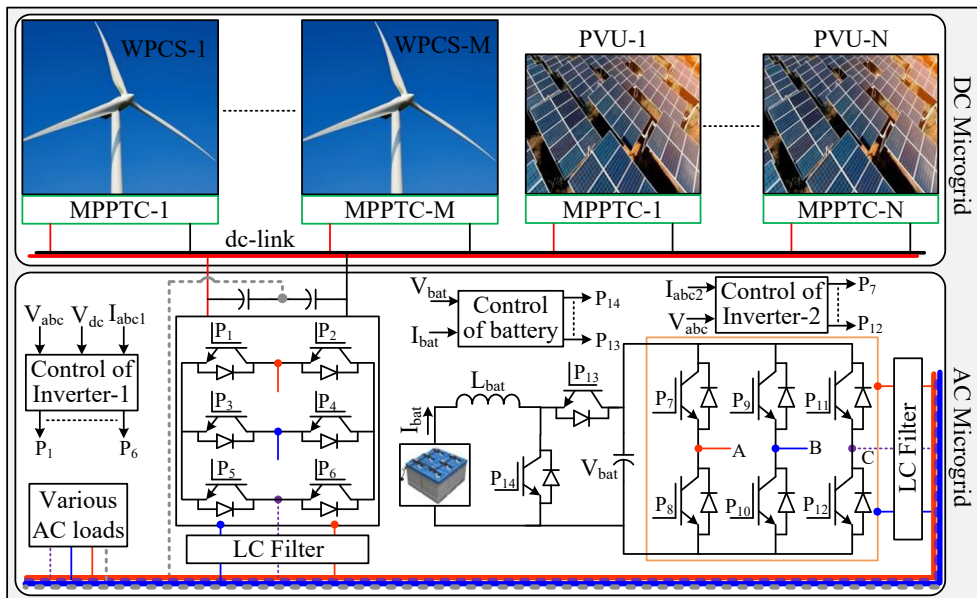


Figure 1: An AC/DC Microgrid topology with dual inverter based proposed model.

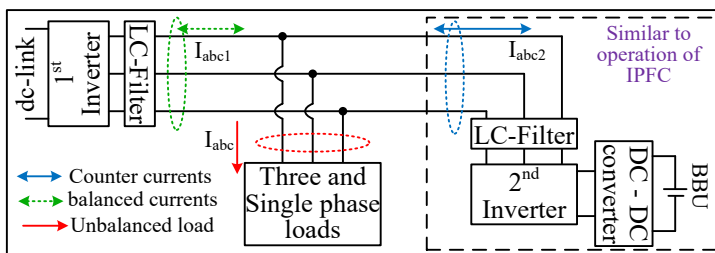


Figure 2: Current flows between loads and inverters.

Many researchers have lately proposed similar kind of systems with their features, and a few of them are included below. The authors of [9] suggest a two-level coordinated control technique for increasing power quality in a Microgrid by performing different functions via an interface converter. The authors of [10] offer a protection solution for a standalone Mi-

crogrid using a fault current control approach. The authors of [11] use an innovative modular control method to establish power sharing of several distributed generated units in a standalone model. The effective energy management system proposed by the authors of [12] is designed for a standalone system that combines a hybrid WPCS-PVU-Battery setup. The authors of [13] propose a decentralized cooperative optimum power flow for several linked Microgrids. The authors of [14] improved power quality in a standalone system consists of PV, SyRG, and battery by adopting an updated second-order generalized integrator with a frequency locked loop and an inner loop filter control algorithm. The authors of [15] use model predictive control to construct a standalone Microgrid system and developed load management for residential communities. Authors created an ideal planning to decrease costs and hazardous gas emissions in [16] for freestanding Microgrid. The authors of [17] accomplished frequency control of a stand-alone system based on several Microgrids. The authors of [18] constructed an optimal energy management system as well as a techno-economical study of a standalone Microgrid based on hybrid REPS. The authors of [19] created optimal design of hybrid standalone system powered by REPS with model predictive control technique. The authors of [9-19] examined several REPS as well as power quality concerns. However, the authors didn't include a second inverter that would function similarly to an IPFC, nor did they include TSKF controllers to obtain the quickest reaction under random variations.

The material given here is structured to achieve the following goals.

- To create acceptable TSK Fuzzy controllers for use in the suggested control approaches.
- To develop new control methods for two inverters.
- To achieve performance comparable to the IPFC using the suggested technique via the second inverter.
- To achieve the profile of a balanced voltage under unbalanced load situations while maintaining balanced current flow using the suggested technique.
- Implementing HIL by utilizing OPAL-RT devices to deliver findings for various cases.

### **3. Design of TSKF Controller**

Because normal PI controllers are tuned at certain instants, they may not deliver accurate signal quickly during sudden changes. To circumvent this problem, while creating control systems, an online tuning option for adjusting gains should be employed. The TSKF controller is the ideal controller for adjusting gains with a faster reaction. Because of the interpretable machine learning capability, the TSKF controller can update the gains/weights in response to random changes in the standalone system. In Microgrid, an Artificial Neural Network (ANN) system with well-trained mechanism will be interfaced with the TSKF model to produce a speedy reaction by swiftly modifying acceptable gains under any changes.

Figure 3 shows a common representation of a TSKF model by connecting ANN. Figure 4 depicts corresponding rules as functions of their weights. Every TSKF system control block employed in the suggested control schemes has two inputs: error and its derivative.

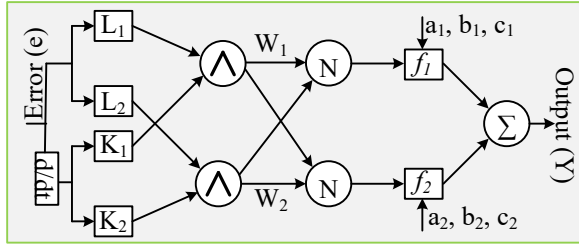


Figure 3: Illustration of a proposed TSKF model.

Mathematical representations of a TSK Fuzzy system are given by eqs. (1-3).

$$f_1 = b_1 X_2 + c_1 + a_1 X_1 \tag{1}$$

$$f_2 = b_2 X_2 + c_2 + a_2 X_1 \tag{2}$$

$$W_2^n f_2 + c_3 + W_1^n f_1 = Y \tag{3}$$

The rules were created by

If  $X_1$  &  $X_2$  are both less, then  $Y = X_2 - X_1 + 3$ .

$Y = -X_2 + 5$  if  $X_1$  is less &  $X_2$  is more.

If  $X_1$  is more and  $X_2$  is less, the equation is  $Y = -X_1 + 4$ .

If  $X_1$  &  $X_2$  are both large, then  $Y = X_1 + X_2 + 1$ .

The TSKF controller, which operates based on rules, is intricate, although the outer layer remains discernible and comprises four planes. The TSKF model is widely preferred for sample data-based modeling of a fuzzy block due to its ability to eliminate the need for the time-consuming and theoretically challenging defuzzification procedure. A trained ANN system can update the appropriate weights to provide a quick response. Once a good TSKF model is created, it may simply be substituted for the PI controller in the suggested control approach. As a result, the suggested control has a high priority while generating the quickest output response under extreme variations in the Microgrid.

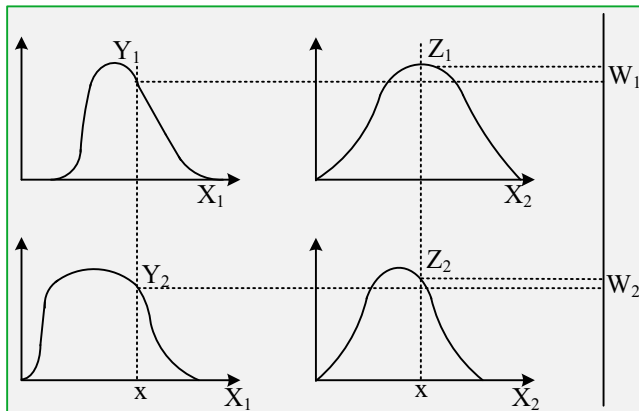


Figure 4: rule-weight of a TSKF model.

### 4. Proposed Methodology

The suggested standalone Microgrid architecture includes one dc to dc bidirectional circuit, two inverters, and appropriate MPPTC for renewable energy-based power generation units. In this work, various MPPTC and controllers from [1-7] are used. The control method for dc to dc bidirectional circuit is developed based on [1]. TSKF controllers are used to offer strategies for both inverters in this article. The main objective of inverter-1 is to transfer active power from the DC Microgrid to the AC bus while simultaneously controlling the RMS voltage. As a result, even if no power is available from sources, this can function as reactive power compensation. When constructing the control mechanism, correct dq components are employed to eliminate the decoupling impact. Figure 5 depicts the proposed control technique for the first inverter that is operated between the AC load bus and DC Microgrid. The presence of power generation within a DC Microgrid may impact the voltage levels at the dc-link. Consequently, the exchange of active power between the DC Microgrid and the AC bus is achieved by comparing the voltage at the dc-link with its designated value. TSKF controller generates the targeted real current component of direct axis ( $I_{d1}^*$ ) from dc-link voltage error. Similarly, the targeted reactive current component of quadrature axis ( $I_{q1}^*$ ) is created from the RMS voltage error at the AC bus using the TSKF controllers. As a result, by regulating RMS voltage at its reference, the inverter may compensate for reactive power requested at the AC bus. However, pulses generated from reference currents ( $I_{dr}$  and  $I_{qr}$ ) via a hysteresis loop will aid in injecting needed balanced current into the AC bus. Keeping balanced 3-phase current can assist in reducing voltage swings at the dc-link. As a result, power quality in DC Microgrids will be enhanced, as will wind generator wear life and heat at PV panels.

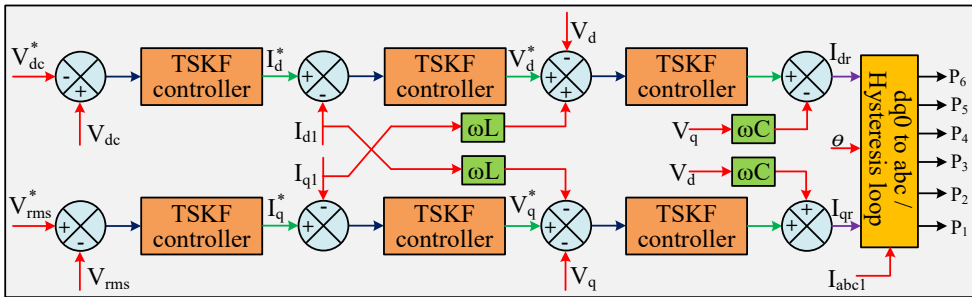


Figure 5: Inverter control mechanism linked between AC bus and DC Microgrid.

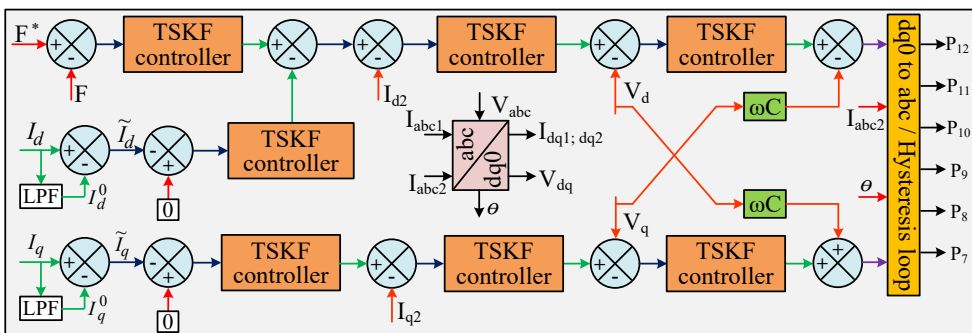


Figure 6: Inverter method proposed between AC bus and BBU.

In most freestanding Microgrids, frequency control is a critical component. Differences in frequency can be utilized to ascertain the actual power difference between the DC Microgrid and the load on the AC bus. Furthermore, the inverter that links the BBU and the AC

bus must not only control the frequency but also ensure a uniform distribution of current in the AC bus by providing opposing current. Unbalanced currents will often cause oscillation in both dq components of currents. As a result, these oscillations derived from current generated by 1<sup>st</sup> inverter, and these  $I_{d1,2}$  are compared to a zero. A LPF: low pass filter is used to acquire oscillating components. In unbalanced load scenarios, hysteresis loop-generated pulses can be utilized to introduce counter currents into inverter-1, thereby achieving balanced currents. In case of uneven loads, the battery possesses the ability to balance the currents on the AC bus by either charging or discharging and introducing counter currents until equilibrium is achieved. Consequently, this inverter-2 can also perform interline power flow operations. This specific task involves extracting currents from the lower phases and injecting them into the phase or phases that are linked to heavier loads. Furthermore, in situations where there is a light load (when the load is not evenly distributed), the batteries possess the capability to recharge from the AC bus by transforming opposing unbalanced currents in order to uphold a balanced flow of current. However, the process of discharging or charging the BBU is controlled by utilizing a bidirectional DC to DC circuit that is connected between the battery and inverter-2. As a result, the combination of two inverters, a BBU, and an AC bus can create an AC Microgrid that allows for the easy operation of any type of AC load. The entire block diagram of the proposed control approach using TSKF controllers is illustrated in Figure 6.

## 5. HIL based Results

By creating an HIL with the use of OPAL-RT devices [1, 20, 21], responses similar to genuine performances may be produced. The OPAL-RT module is capable of solving complicated power system equations in real time. As a result, an HIL is created by connecting back to back configuration of two OPAL-RT devices in a loop. The Simulation model created in Figure 1 is separated into two models: control unit and plant of the system. Except for the suggested control mechanisms in Figure 1, the plant is compacted with all of its components. The control model is made up of the suggested control techniques for the converters shown in Figure 1. The plant configuration is loaded into OPAL-RT unit-1, while the control model is in OPAL-RT unit-2. The OPAL-RT unit-1 sensing signals (voltages, currents, etc.) are now regarded input signals to the OPAL-RT unit-2. The pulses generated by OPAL-RT unit-2 are considered as inputs for the converters of OPAL-RT unit-1. Proper digital-analog and analog-digital cards are interfaced to achieve an optimal communication between two modules. A second computer is utilized to examine the answers, which is supported by MATLAB. Figure 7 depicts a simplified laboratory setup for the HIL. Various replies of the suggested technique are offered to analyze the system's performance in the case studies below.

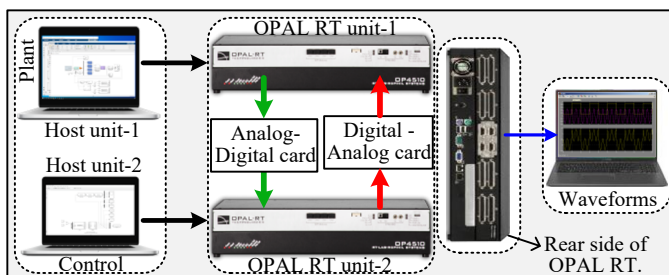


Figure 7: HIL implementation.

Case-A: response with PI and TSKF controllers.

In this study, emphasizes the significance of employing TSKF controllers in suggested control approaches for shifting a 250% load on an AC bus. Figure 8 depicts the frequency response of the system utilizing PI and TSKF controllers in the suggested techniques during a load change at  $t=1.0$ sec. TSKF controllers provide a superior responsiveness in terms of frequency dip and settling time. As a consequence, further outcomes are produced by employing TSKF controllers in the suggested inverter control approaches.

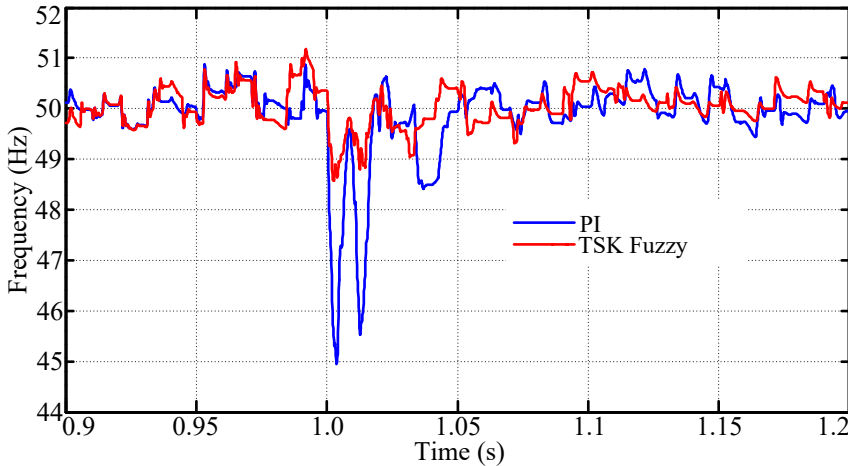


Figure 8: Frequency responses with TSKF & PI when load changes.

Case-B: Voltage responses at a dc-link using suggested and traditional techniques.

Minimizing voltage oscillations at the dc-link in a DC Microgrid can be achieved by implementing the recommended control strategy for the second inverter, as opposed to connecting batteries. At  $t=1.0$ sec, an imbalanced load is connected. The voltage response at the dc-link is shown in Figure 9 for the suggested technique (battery linked to AC bus with a separate inverter) and the existing way (battery interfaced with DC Microgrid). It is obvious that the suggested approach maintains the same type of voltage profile as the standard way even after attaching the imbalanced load. Conventional systems have a severe response during imbalanced load scenarios owing to oscillating component interference into voltage at the dc-link, which would hurt the generator shaft and cause heat at the PV panels. As a result, the suggested design has improved the power quality.

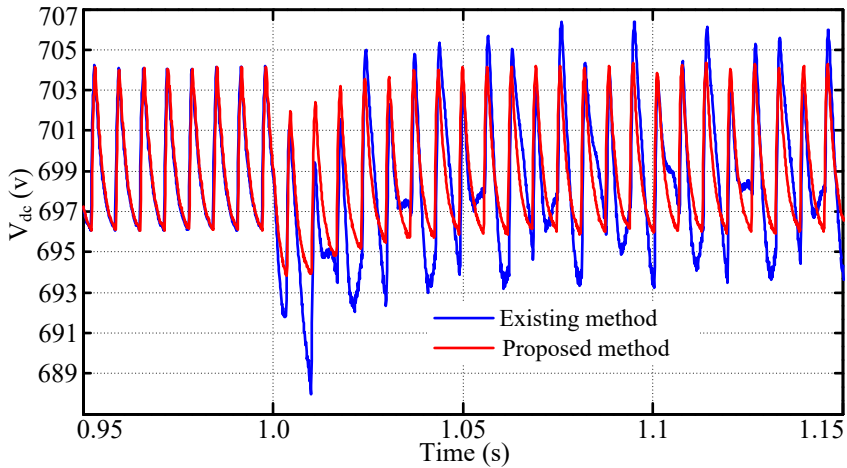


Figure 9: DC-link voltage response.

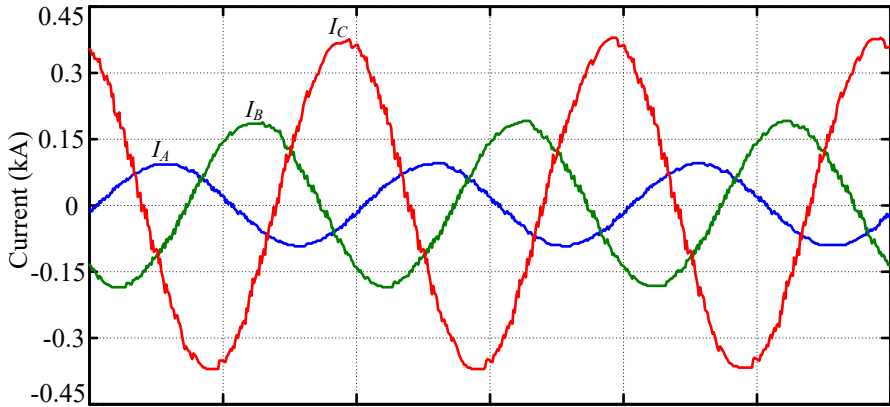
#### Case-C: Responses during unbalanced conditions in AC Microgrid.

Because of the functioning of single phase loads, the majority of the loads in a 3 phase power supply system are imbalanced. As a result, oscillations in a DC Microgrid will be presented and makes unbalanced voltages in a 3-phase supply system. The suggested arrangement, on the other hand, may maintain balanced flow of currents by injecting counter imbalanced current into the AC supply system via the second inverter. Hence, the suggested approach may balance the providing currents from the first inverter (connected between the DC Microgrid and the AC bus). This can assist in mitigating voltage fluctuations at the dc-link and ensuring a balanced 3-phase RMS voltage at the AC bus. The imbalanced load profile depicted in Figure 10(a) is considered in this scenario. Figure 10(b) displays the counter currents generated by the second inverter, which aid in balancing the currents of the first inverter as illustrated in Figure 10(c).

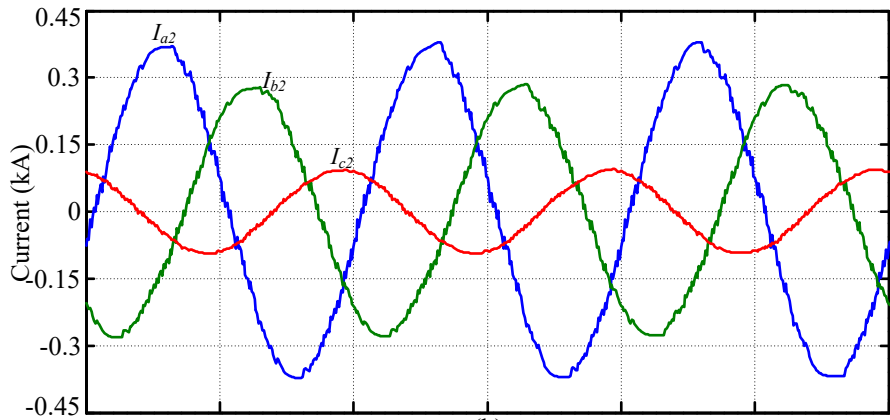
The balance of currents is essential for preserving the balance of the three-phase line-to-line voltages shown in Figure 10(d). Although the 3-phase RMS voltage of the AC bus is depicted in Figure 10(e), it should be noted that instantaneous line-to-line voltages may not offer a comprehensive representation. As shown in Figure 10(e), under severe unbalanced load conditions, the 3-phase voltage remains nearly constant at its reference value of 231.0V.

#### Case-D: THD analysis.

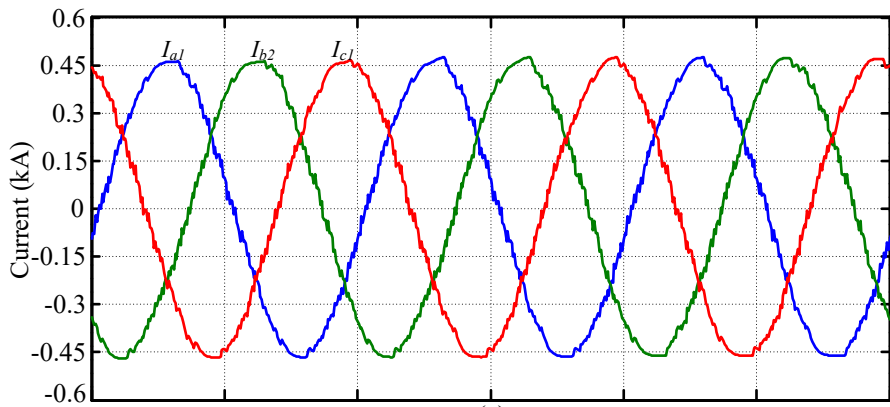
The total harmonic distortion (THD) of the Microgrid will grow when nonlinear loads are operated at the AC bus. The suggested approach can assist in lowering THD to a tolerable level. The THD of the Microgrid is nearly 4% at line to line voltage during nonlinear load operation, as shown in Figure 11.



(a)



(b)



(c)

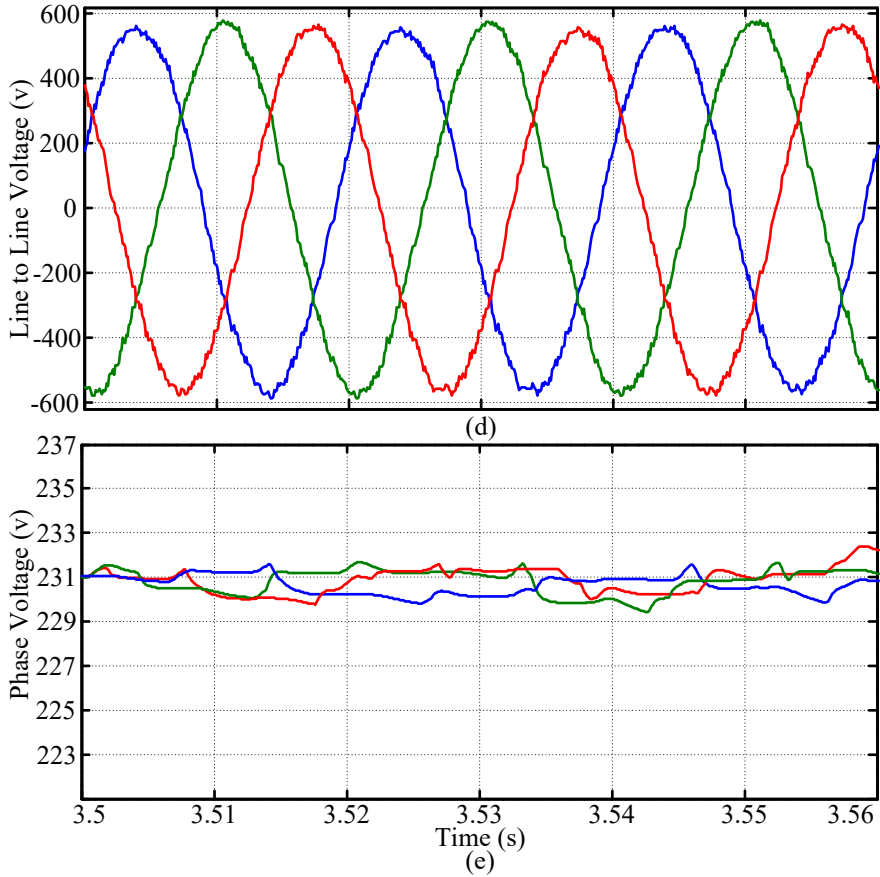


Figure 10: currents of {(a) unbalanced load, (b) injected by second inverter, (c) supplied into the AC bus by the first inverter}, Voltage of (d) L-L instantaneous, (e) 3-phase RMS}.

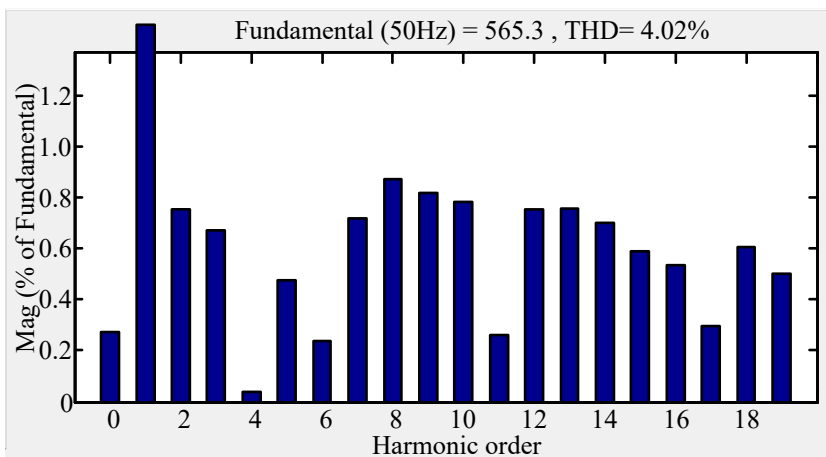


Figure 11: THD of L-L voltage during nonlinear load.

## 6. Conclusions

This research presents a standalone Microgrid based on multiple PV and wind generators to improve power quality using the proposed strategy. The Microgrid architecture incorporates two inverters to enhance power quality when dealing with unbalanced loads. These inverters function similarly to an IPFC and are equipped with TSK Fuzzy controllers to ensure swift and accurate responses. The first inverter, connected between the AC bus and the BBU, generates counter currents to compel the second inverter, linked between the DC Microgrid and the AC bus, to provide balanced currents during unbalanced load operation. Consequently, the second inverter consistently delivers balanced currents to the three-phase AC bus, thereby improving power quality in both DC and AC Microgrid systems. Additionally, one inverter compensates for reactive power demands of the loads, while the other regulates the frequency at the AC bus. To obtain real-time feedback, various case studies are conducted using HIL and OPAL-RT modules.

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