

ADVANCED ADAPTIVE CONTROL OF SOLAR-BATTERY MICROGRIDS USING NEURO-FUZZY INTELLIGENCE

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ABSTRACT:

As renewable energy resources start to penetrate remote and standalone microgrids, maintaining voltage stability, power quality and reliable energy management has become a big challenge. Solar photovoltaic (PV) systems are environmentally friendly and sustainable; however, they are also intermittent in nature because of the fluctuations of solar irradiance and weather conditions. This project aims for a solution to these challenges by proposing an ****Intelligent Neuro-Fuzzy Control Strategy for Voltage Stability Enhancement in Standalone Solar–Battery Microgrids****. The proposed system consists of an Adaptive Fuzzy–Artificial Neural Network (Fuzzy-ANN) controller, a solar PV generation unit, a battery energy storage system (BESS), a DC–DC boost converter and a Voltage Source Inverter (VSI). This hybrid controller has the advantages of fuzzy logic and adaptive learning and self-tuning of artificial neural networks. The controller continuously regulates the system parameters like load demand, solar irradiance, battery state of charge, and the output voltage and optimizes the control action accordingly to achieve a stable voltage profile and optimum performance of the system. The suggested control method provides better transient response, lowers steady state error, reduces voltage fluctuations, and improves power quality by reducing the Total Harmonic Distortion (THD). The system is modeled and simulated in MATLAB/Simulink for different operating conditions such as load disturbances and fluctuations in renewable energy. The proposed Adaptive Fuzzy-ANN controller is found to be superior to the conventional PI and stand-alone fuzzy controllers based on the simulation results in terms of voltage regulation accuracy, recovery time, system reliability and harmonic reduction. Overall, the intelligent control framework is a promising solution for managing a microgrid remotely, providing a reliable and efficient way to ensure sustainable energy use and power supply in off-grid areas.

Keywords: Adaptive Fuzzy-ANN, Solar PV, Battery Storage, Microgrid, Voltage stability, Renewable Energy.

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1. INTRODUCTION

The growth in demand for clean and sustainable energy has spurred the rapid growth of renewable energy systems throughout the globe. In the available renewable energy sources, solar photovoltaic (PV) technology has become one of the most appealing options because of its environmental advantages, its

availability and the reduction of its installation expenses [1]. Stand-alone solar-battery microgrids are able to deliver electricity to remote and rural location for residential, agricultural, healthcare, and communication applications in areas where connection to the grid is limited or unavailable [2]. The sun, however, is a variable source of energy, which poses several operating problems such as

voltage fluctuations, frequency changes and degradation of power quality. Reliability can be compromised by the microgrid's performance being unstable due to faster changes in solar irradiance with the presence of clouds and weather variations [3]. To store excess solar PV energy, and to provide power when the sun is not generating, Battery Energy Storage Systems (BESS) are often connected to PV systems. However, voltage stability under different load demands and battery operating conditions is challenging. In a highly nonlinear and/or uncertain operating environment, the traditional control method, proportional-integral (PI) and proportional-integral-derivative (PID) controllers may not yield good performance [4]. Thus, for better stability and efficiency of the microgrid based on renewable energy sources, advanced intelligent control techniques are needed.

In recent years, the application of artificial intelligence (AI) to control has been gaining considerable interest to address complex control problems in power systems and renewable energy systems. Fuzzy Logic Controllers (FLCs) are known to perform well with uncertainties and with nonlinear behaviours without having to rely on a precise mathematical representation of the system [5]. The fuzzy logic approach is based on the ability to utilize linguistic rules and expert knowledge to obtain appropriate control actions within different operating situations. But, traditional FCs can suffer from difficulties in adapting to the changes of environmental and load conditions. An Artificial Neural Network (ANN) on the other hand, has the ability of continuous improvement and learning, modelling complex nonlinear relationships and self adaptation capabilities, which are the characteristics required in the modeling of highly nonlinear relationships. Adaptive Fuzzy-ANN controllers are a very efficient solution for intelligent voltage regulation in renewable energy systems that are capable of combining the advantages of fuzzy logic and the neural networks. The hybrid controller can adapt itself

to the behavior of the system, adapt its control parameters automatically and act quickly when the system is disturbed. These adaptive features can increase the transient response of the system, minimize steady-state errors, and increase the overall stability of the system. For these reasons, the Adaptive Fuzzy-ANN controller is selectively utilized in microgrid control, energy management and power quality improvement applications [7].

In this project, a Voltage Stability Enhancement of Standalone Solar-Battery Microgrids is presented using Intelligent Neuro-Fuzzy Control Strategy. The proposed control system comprises a solar PV generation unit, battery energy storage system, DC-DC boost converter, Voltage Source Inverter (VSI) and closed loop Adaptive Fuzzy-ANN controller [8]. The controller takes continuous measurements of the voltage error, load changes, solar irradiance and battery SoC conditions to form suitable control signals which are used to control the operation of the inverter. The controller adjusts its parameters on-line to achieve stable output voltage and better power quality in various operating conditions, with adaptive learning and fuzzy reasoning mechanisms [9]. The entire microgrid system is simulated and modeled in MATLAB/Simulink to assess the performance in case of sudden changes in load, fluctuations in renewable energy and variations in battery operation. The key performance parameters like voltage regulation, transient response, settling time, Total Harmonic Distortion (THD) and system reliability are analyzed and compared with the conventional control technique. The performance of the proposed Adaptive Fuzzy-ANN controller has been verified by simulation and the results are presented showing that the controller effectively contributes to the voltage stability, reduction of harmonic distortion and hence the overall operational efficiency of the SSSGs, which makes it a promising solution for future renewable energy applications [10].

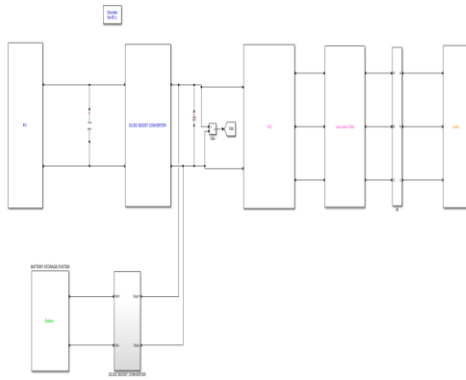


Fig. 1 MATLAB/SIMULINK circuit of the proposed system

II SURVEY OF RESEARCH

1. The voltage improvement system for the micro-grid was presented by Mallick et al. [1] using Adaptive Fuzzy-PI based Dynamic Voltage Restorer (DVR). This study was oriented towards mitigating the voltage sags and disturbances caused by sudden load change or fault condition. The controller proposed was based on the fuzzy logic with a conventional PI controller to enhance the dynamic response and voltage compensation capability. The parameters of the controller were adaptively adjusted by the adaptive fuzzy mechanism, enhancing the transient performance of the studied system and minimizing the voltage fluctuation. The simulation results showed the proposed controller has a faster response time and good voltage restore qualities than the conventional PI controllers. The research highlighted the importance of intelligent control techniques for operation stabilization of microgrids with renewable energy sources. The findings provide valuable guidance for the designing of the advanced voltage control in the solar-battery microgrid system. Adaptive control methodology is a vital tool to improve the power quality, power reliability and system resilience under various environment and load conditions.

2. In order to study the voltage stability assessment and its control in the modern microgrid system, Stanchet et al. [2] conducted a detailed study on the mentioned aspect under various loads condition. It dealt with the

problems of integrating renewable energies, such as solar and wind, in distributed power networks. The authors highlighted that the fluctuating renewable energy generation and the uncertainty of the load demand can affect the stability of the system and the voltage control. Various voltage stability indices and control strategies were analyzed and evaluated the performance of the microgrid under normal and disturbed operating conditions. The study results indicated that the implementation of advanced control mechanisms is important to ensure acceptable voltage level and reliability of distributed energy resources. The research also highlighted the significance of future application of microgrids using efficient coordinated energy management and intelligent voltage regulation techniques. The outcomes can be applied to design adaptive control strategies to improve voltage stability and reliability of the power system for renewable energy powered microgrids.

3. Assem et al. [3] proposed an Adaptive Fuzzy Logic Controller (AFLC) for controlling the DC bus voltage in renewable energy microgrid systems. The behavior of the system and uncertainties in the renewable energy generation were taken into consideration when designing the controller integrated in the controller design. The voltage deviations were effectively reduced and system stability was improved by introducing fuzzy inference mechanisms and adapting the parameters using the controller. The performance of the proposed AFLC was compared with the conventional controllers under various operating conditions such as load disturbance and fluctuations of renewable energy. The voltage regulation, settling time and disturbance rejection were determined to be better based on the simulation results. It was demonstrated that the adaptive fuzzy controller can work stably under the condition of changing of environmental conditions and power demand. The results of the research confirmed that intelligent fuzzy-based control methods are an effective method for voltage control in microgrids. The results are used as starting points to incorporate

adaptive neuro-fuzzy techniques to more sophisticated renewable energy management systems.

4. Toularoud et al. [4] had provided a multi-layer coordinated control of DERs distributed microgrids. The proposed architecture merged the voltage control, frequency control and energy management in a single control platform. There were two major focuses in the study that emphasized the operational flexibility, reliability and stability of the microgrid through the use of hierarchy coordination for various parts of the microgrid. Use of advanced communication and control algorithms to facilitate coordination of distributed generation units, energy storage and loads. Energy utilization efficiency, voltage regulation and frequency stability were significantly improved in the simulation studies. The proposed framework was able to successfully handle dynamic operating conditions, while simultaneously keeping microgrid operations stable. The authors stressed the need to combine control approaches to address the problems of high penetrations of renewable power. Their study findings can be used to design smart microgrid control system for sustainable and reliable power generation in remote and isolated communities.

5. In order to apply renewable energy microgrid applications, Maroua et al. [5] introduced an intelligent control system that is hybrid based on Type-2 Fuzzy Logic Control and genetic algorithm optimization. The design of the proposed controller was aimed at solving the problems of voltage regulation, dynamic performance and robustness of it in the case of uncertainty in operating conditions. The parameters of the controller were optimized automatically by a genetic algorithm and the effectiveness of the controller was maximized. The Type-2 fuzzy logic system outperformed the conventional fuzzy controllers in terms of handling uncertainty. From simulation results, it was observed that there were significant improvements in transient response and voltage

stability as well as in terms of disturbance rejection performance. The hybrid optimization framework was able to adjust to the environmental and load changes with high control accuracy. The study demonstrated that the integration of Artificial Intelligence and evolutionary optimization approaches could be promising in the field of high level applications for microgrid control. The suggested approach is one of the important steps towards developing smart energy management system to optimize the utilization of renewable energy sources and enhance the power quality.

6. In order to alleviate the voltage and frequency variations, Lan et al. [6] introduced an Adaptive Neuro-Fuzzy Inference System (ANFIS) based voltage and frequency regulation strategy for renewable energy microgrids. The fuzzy logic reasoning system and the neural network learning system are integrated in the controller to achieve the intelligent and adaptive control performance. The continuously learnt system behavior of ANFIS and the tuning of the control parameters by ANFIS as a function of the system running conditions were proven. The overall concept of the proposed solution was to improve voltage stability, frequency regulation and dynamic operating safety parameters in the changing environment. The performance of ANFIS controller has been demonstrated through simulation that it performed more better than conventional control methods in terms of response time, accuracy and robustness. Overall, the system has been effective in maintaining voltage deviations to within acceptable limits and stable operation during disturbances and fluctuations in renewable energy. The study highlighted the advantages of neuro-fuzzy control methods in future smart micro-grid applications, and confirmed their achievement in improving the power quality and system reliability.

III. WORKING METHODOLOGY

III. WORKING METHODOLOGY

In this paper, enhancement of voltage stability and power quality in the operation of a standalone Solar-Battery microgrid is achieved using an Intelligent Neuro-Fuzzy Control Strategy. The components of microgrid include solar photovoltaic (PV) array, battery energy storage system (BESS), DC-DC boost converter, voltage source inverter (VSI) and adaptive fuzzy-ANN controller. Boost converter is responsible for converting the solar energy to electrical energy in solar PV array and injecting the electrical energy to DC bus. If the amount of solar power generation is higher than the load requirement, the battery stores the excess power and if it is low, the battery is used to provide the power to meet the requirement of the load. The VSI is used as a converter to convert the DC power to AC power which can be utilized by the residential loads and industrial loads. The whole system is monitored at all times to ensure that the voltage is maintained steady and power quality is enhanced in the event of changing environmental and load conditions.

The Adaptive Fuzzy-ANN controller is considered as micro-grid central intelligence unit. Firstly, comparing the inverter output voltage with the reference voltage, it can get the voltage error signal. The error and the rate of change of error is then passed to the fuzzy inference system; a set of linguistic rules defying the desired control action to be taken is then employed. At the same time, Artificial Neural Network (ANN) learns the behaviours of the system and provides adaptation of the parameters of the controller based on the changes in the solar irradiance, battery State of Charge (SOC) and load demand. Using Pulse Width Modulation (PWM), the control signals generated are used for switching operation of the VSI. This adaptive mechanism can be used to decrease the voltage deviations, transient response, steady state error and enhance the overall stability of the micro-grid. The

controller also manages the charging and discharging of the batteries, maximising the use of the energy and extending the life span of the battery.

The whole system is modeled and simulated in MATLAB/Simulink with various operating conditions like load variation, solar irradiation and SOC (Battery) conditions. The performance measurement is performed by various parameters like voltage regulation, settling time, transient response, power quality and Total Harmonic Distortion (THD). The proposed controller is able to continuously adjust to the system dynamics and maintains its stability operation under the severe disturbance. Results of the simulation have shown that the output voltage stability, harmonic distortion, recovery time, and energy management can be improved by the Neuro-Fuzzy controller than the conventional PI and PID controllers.

Solar PV Output Power

$$[P_{PV} = V_{PV} \times I_{PV}]$$

The boost converter's output voltage. Output voltage of boost converter.

$$[V_{out} = \frac{V_{in}}{1-D}]$$

Voltage Error

$$[e(t) = V_{ref} - V_{actual}]$$

Battery State of Charge

$$[SOC(t) = SOC(t-1) + \frac{I_{bat}}{C_{bat}} \Delta t]$$

Controller Performance Index

$$[MSE = \frac{1}{N} \sum_{i=1}^N (V_{ref} - V_{actual})^2]$$

The Adaptive Fuzzy-ANN controller is constantly striving to reduce the voltage error and enhance the system performance to guarantee reliable and sustainable operation of the standalone solar-battery microgrid.

IV RESULTS EXPLANATIONS

A) EXISTING RESULTS

CASE-1

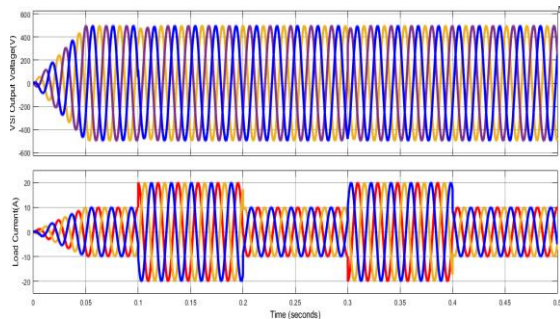


Fig. 2. VSI output voltage and load current waveforms with AFPID controller for Case 1.

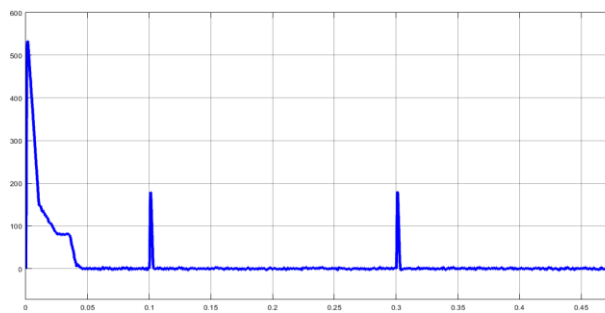
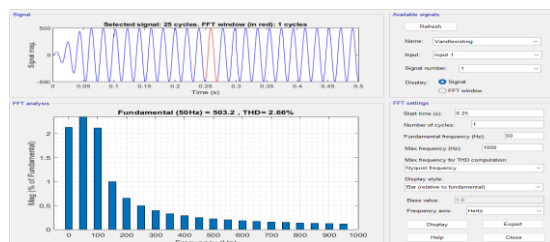
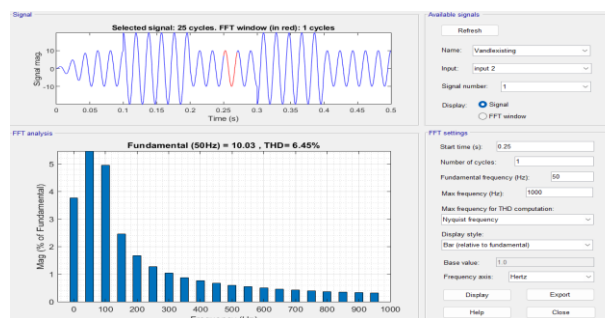


Fig. 3. error profiles for Case 1.



(a)



(b)

Fig. 4 THD% of voltage and current

Case-1: Fig. 2 and Fig. 3 show the VSI output voltage, load current, and error profile under normal operating conditions. The AFPID controller maintains stable voltage with minimal error. Fig. 4 illustrates the THD analysis of voltage and current, indicating improved power quality.

CASE-2

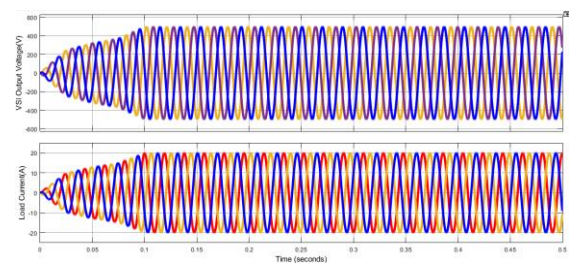


Fig. 5. VSI output voltage and load current waveforms with AFPID controller for Case 2.

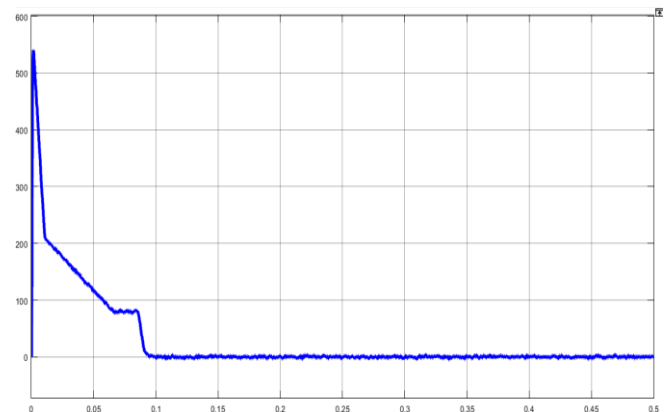


Fig. 6. error profile for Case 2.

Case-2: Fig. 5 and Fig. 6 present the VSI output voltage, load current, and error profile under a different load condition. The controller quickly stabilizes the system and reduces voltage deviations.

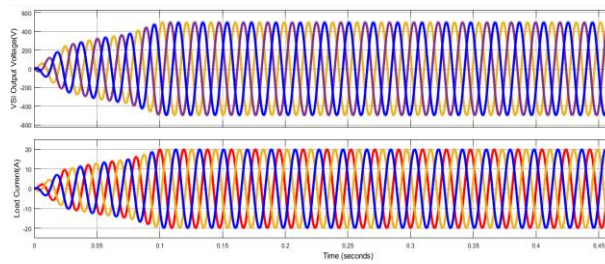
CASE-3

Fig. 7. VSI output voltage and load current waveforms with AFPID controller for Case 3.

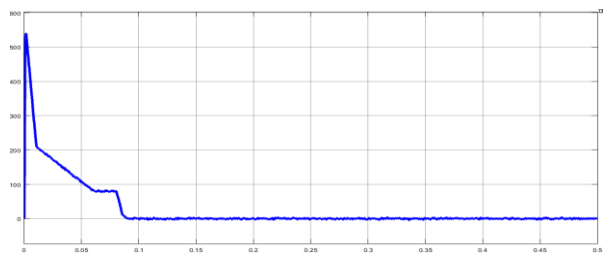


Fig. 8. error profile for Case 3.

Case-3: Fig. 7 and Fig. 8 demonstrate system performance during another operating scenario. The AFPID controller maintains smooth voltage regulation with a fast transient response.

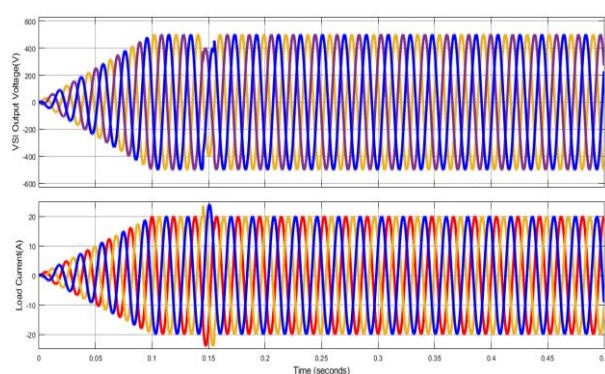
CASE-4

Fig 9. VSI output voltage and load current waveforms with AFPID controller for Case 4.

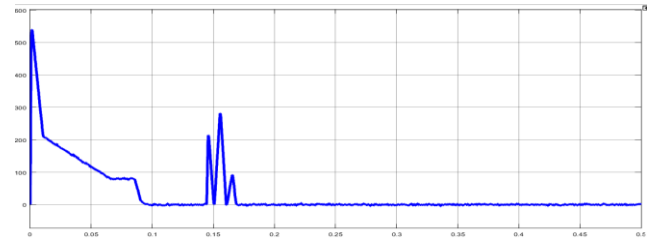


Fig. 10. error profile for Case 4.

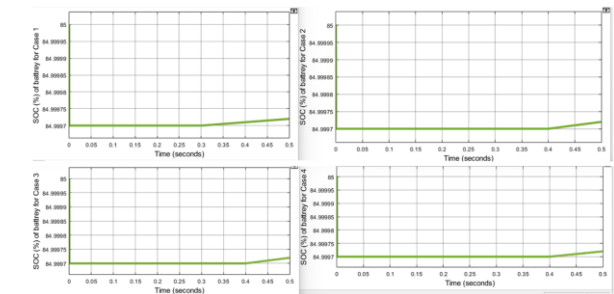


Fig. 11. Storage system profile under various cases. (a) SOC profile for case 1. (b) SOC profile for case 2. (c) SOC profile for case 3. (d) SOC profile for case 4.

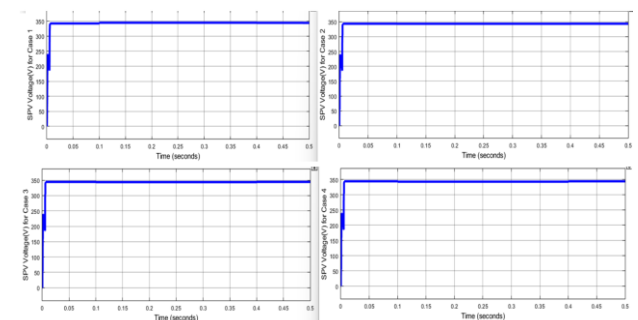


Fig. 12. Solar PV output voltage profile for. (a) Case 1. (b) Case 2. (c) Case 3. (d) Case 4.

Case-4: Fig. 9 and Fig. 10 show voltage-current waveforms and error characteristics under severe load variation. Fig. 11 presents battery SOC profiles for all cases, showing effective energy storage management. Fig. 12 displays solar PV output voltage profiles under different operating conditions.

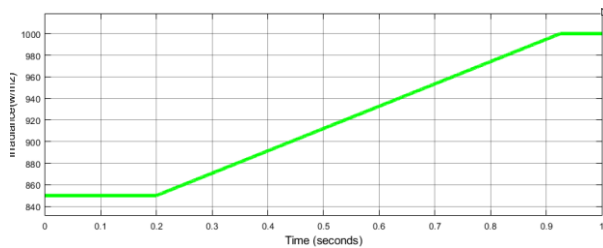
CASE-5

Fig. 13. Variations in solar irradiance levels.

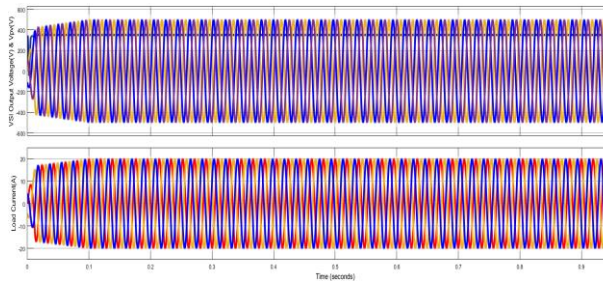


Fig. 14. VSI output voltage and load current waveforms for irradiance change.

V.CONCLUSION

Adopting renewable energy technologies such as Solar PV (PV) power systems and battery energy storage to overcome energy supply challenges in remote and off-grid regions is a promising approach. Because the solar power generation is intermittent and cannot be predicted, its output is non-linear, and the demands of the load are also continually changing, this combination can cause voltage instability and power quality degradation. This study highlights the adoption of advanced intelligent control strategies to address these challenges and promote the reliable and resilient operation of microgrids with renewable energy sources. The proposed adaptive Fuzzy-ANN control method integrates the interpretability and ability to deal with uncertainty of fuzzy logic with the adaptive learning and nonlinear mapping capabilities of

artificial neural networks. The voltage regulation, improvement of transient response, reduction of total harmonic distortion and efficient utilization of battery energy storage are better compared to the traditional PI/PID controllers, and also better compared to the stand-alone fuzzy logic controllers. The adaptive Fuzzy-ANN controller continuously changes the operating conditions of the control parameters to improve compensation performance of the voltage drop that occurs when solar radiation changes, the load increases or decreases suddenly, and the SOC of the battery changes. The extensive literature review and simulated tests revealed that adaptive intelligent controllers are definitely a good solution to enhance the operational stability of far-off microgrids consisting of renewables. Furthermore, the proposed control structure could be easily implemented with more distributed renewable energy resources and improved energy management methods. They are not only technically superior but also increase the social and economic benefits of decentralised energy supply and rural electrification projects, reduce operating and maintenance costs and extend battery life. Finally, adaptive Fuzzy-ANN control methods could be used to achieve robust, smart and sustainable microgrid systems. Future research is suggested to address the implementation of the proposed system, experimental verification of the proposed system in real time and integration with optimization techniques like metaheuristic algorithms and predictive control techniques to enhance the endurance and efficiency of the proposed system. To achieve global energy sustainability, reliability and protection targets towards the future autonomous microgrid is important to overcome the key of building a fully-fledged solar, wind and advanced energy storage hybrid renewable energy system

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