

A Distributed Voltage Control Method for a Remote Microgrid Using Adaptive Fuzzy Controllers System Supported by Batteries and Solar Energy

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Abstract - To keep voltage regulation steady and power quality acceptable, intelligent and adaptive control approaches are needed as the integration of renewable energy resources in isolated microgrid systems grows. This study introduces an Adaptive Fuzzy-Artificial Neural Network (Fuzzy-ANN) based voltage control method for a standalone solar photovoltaic-battery microgrid system. Continuously optimising the controller settings to match the changing load needs, solar irradiance, and battery state-of-charge, its recommended controller combines the reasoning ability of FL with the self-learning and self-adapting capacity of ANN. In order to keep the microgrid running smoothly and adjust to different operating conditions, the system uses an adaptive control mechanism.

Results from the simulation show that the suggested Adaptive Fuzzy-ANN controller controls the system voltage, limits its variation, and minimises overall harmonic distortion at the point of common coupling. Transient response, steady state error, recovery time, and overall system reliability were measured in comparison to conventional Proportional Integral (PI) controllers and standalone fuzzy controllers. The results showed that the proposed method performed better than both of these alternatives. In standalone microgrids with distributed and intermittent renewable energy sources, the results showed that the Adaptive Fuzzy-ANN control approach is an efficient and intelligent way to improve operational performance, power quality, and voltage stability.

Key Words: Remote microgrids (R.MGs), adaptive fuzzy controller, distributed voltage control, solar energy

1.INTRODUCTION

Adaptive Fuzzy-ANN controllers are a combination of the best features of two intelligent control techniques, namely fuzzy logic and Artificial Neural Networks (ANN). The ANN component includes real-time optimization of control operations and adaptive learning capabilities while the fuzzy logic

component includes interpretability, robustness and an effective management of uncertainties. In a freestanding solar-battery microgrid, the adaptive fuzzy-ANN controller can adaptively adjust the decision parameters and control gains according to the real-time measurements of load demand, changes of solar irradiance and battery state-of-charge. It is found that the hybrid intelligent control approach can reduce voltage fluctuations and enhance the overall stability of the microgrid, compared with the traditional control methods, it can better improve the voltage regulation performance, transient response ability and stability of the microgrid. Additionally, the controller can adjust to operational, environmental, and seasonal changes in solar power production thanks to ANN's learning capabilities, guaranteeing efficient and dependable microgrid operations regardless of the circumstances.

Due to the fact that voltage variations have a direct impact on the performance, dependability, and longevity of linked electrical equipment and delicate electronic devices, voltage stability is of the utmost importance in standalone and distant microgrids. In remote places like schools, hospitals, homes, communication networks, and water pumping stations, microgrids are key sources of power to critical infrastructure. Power quality degradation or voltage instability can lead to disruption of these critical services, damage to electrical equipment, and reduced reliability of power supply services. On top of that, there are occasions that microgrids are only connected to the main utility grid for a fraction of the time, operating in island mode for much of the time. Systems of intelligent and adaptive control are extremely useful under such conditions, to maintain voltage stability in an environment with rapidly changing and uncertain load conditions. To address these challenges, the proposed Adaptive Fuzzy-ANN controller utilizes the predictive learning, adaptive parameter tuning, and robust decision-making ability to enhance the dependability of the

system in a sustainable manner while maintaining a stable voltage.

The efficacy of hybrid intelligent controllers for microgrid applications has been shown by recent advances in renewable energy research. Many studies have shown that the transient responsiveness, precision of voltage regulation, elimination of harmonics and system resilience, Adaptive Fuzzy-ANN controllers perform better than the conventional PI, PID and standalone fuzzy logic controllers. This controller has the ability to learn from how the system operates and adjust the control rules dynamically, making it suitable for microgrids heavily dependent on intermittent solar energy. In addition, by combining adaptive intelligent control with battery energy storage systems, microgrid resilience is much improved. That's because adaptive intelligent control can be used to make better use of energy, peak load managing and voltage variations mitigating. By analysing the voltage conditions in the microgrid, the controller can optimize the charging and discharging cycles to ensure efficient utilization of the stored energy and seamless operation of the microgrid.

2. Proposed System

The distributed voltage control mechanism shown in Figure 4.1 is implemented using a test microgrid system. A DC-DC boost converter and Maximum Power Point Tracking (MPPT) link the solar photovoltaic (SPV) generating system and the battery energy storage system to a shared DC bus in this microgrid configuration, allowing for the acquisition of the necessary output voltage levels. The PWM (Pulse Width Modulation) inverter, which contains six pulses, supplies the three-phase AC network. To maintain the optimal State of Charge (SOC) for the energy storage system's batteries, load PID controllers manage the charging and discharging processes. Last but not least, these controllers keep the storage unit running smoothly by controlling the voltage and current output. A power electronic converter that uses the pulse width modulation (PWM) technology, the inverter connects the DC and AC buses. The inverter's output voltage is controlled by Adaptive Fuzzy PID (AFPID) controllers, which in turn trigger the inverter switches to maintain a stable output voltage, improve power quality, and ensure efficient power transmission throughout the micro grid system.

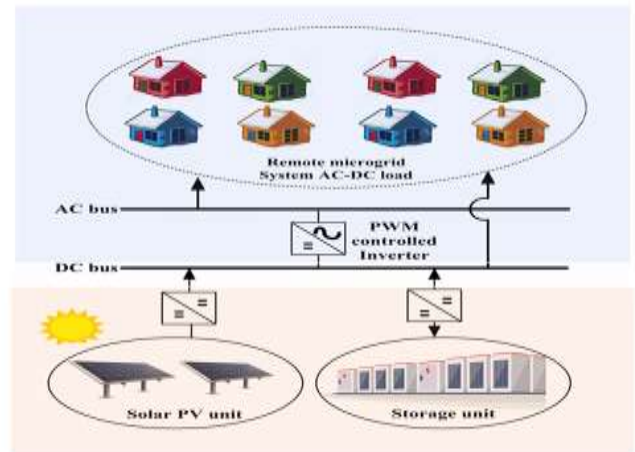


Fig.1. Typical layout of the MG system under consideration.

The circuit diagram of voltage source inverter (VSI) with closed loop feedback control for regulation of output voltage is presented in Fig.2. The suggested topology uses DC converters and local control units to interface the microgrid DC side with the battery storage and solar photovoltaic (SPV) systems. The common DC bus is connected to a three-phase AC load by a Pulse Width Modulation (PWM) based Voltage Source Inverter (VSI). The inverter output voltage in three-phase is continuously monitored and supplied back to the voltage control. The measured three phase voltage signals (V_{abc}) are transformed into synchronous rotating dq reference frame using Park's Transformation which simplifies the control technique. In this analysis, just the direct-axis voltage component (V_d) is included to simplify the controller structure and coupling effect.

The inverter voltage is smooth in dynamic settings due to low pass filter of VSI which lowers harmonics at output. Any phase-angle mismatch can be compensated using a PLL synchronisation mechanism and all the DERs connected to the microgrid are in lockstep with each other. The modulation signals are produced by comparing the voltage of the PWM inverter with the peak value of the three-phase output voltage. The voltage error signal (e_v) which is the difference between the direct axis voltage (V_d) and the voltage command (V_{ref}) is used as input to the Adaptive Fuzzy PID (AFPID) controller. The error signal is processed and then the output from the controller is fed to inverter driver and triggering circuit. The triggering circuit is used to generate pulses to the inverter switching elements and also to control the output voltage. This allows the microgrid to operate dynamically, improve the quality of voltage and operate reliably.

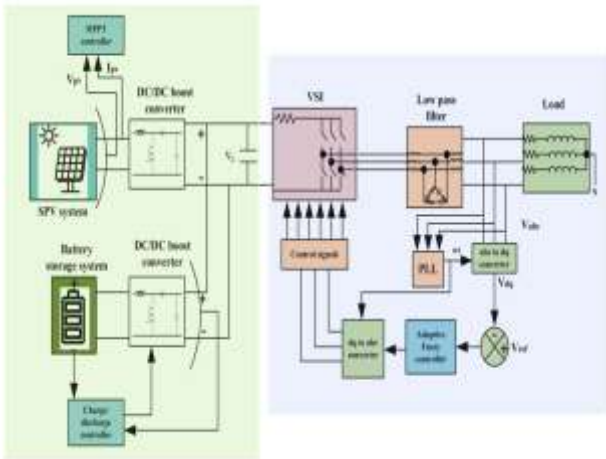


Fig. 2. Schematic diagram of VSI output voltage control scheme with closed-loop feedback.

2.1. Solar Power System Model

The solar conversion system (SCS) is constituted by the PV panel connected to the DC-link through a DC-DC boost converter. The SCS mathematical model is given as below:

$$\frac{dV_{pv}}{dt} = \frac{I_{pv}}{C_{pv}} - \frac{I_{Lpv}}{C_{pv}}$$

$$\frac{V_{pv}}{L_{pv}} = \frac{dI_{pv}}{dt} + (1 - U_2) \frac{V_{dc}}{L_{pv}} - D_3$$

$$\frac{dV_{dc}}{dt} = (1 - U_2) \frac{I_{Lpv}}{C_{dc}} - \frac{I_{Opv}}{C_{dc}} + D_4$$

Inductance of the PV-side converter (L_{pv}). Current output of the PV (I_{pv}). Output voltage of the solar panel (V_{pv}). (U_2) is the control input signal to the converter switching mechanism and (I_{Lpv}) is the inductor current flowing through the converter circuit. We also show the dynamic uncertainty (D_3) and parameter fluctuation (D_4) of the energy conversion stage. The inaccuracy of this technique could be due to the change of the parameters of the photovoltaic energy conversion system, the variation of solar irradiation, switching disturbances, thermal effects and the non-linearities of the converter. To have the smooth working of the converter, better control of the voltage and reliable operation of the solar power generation system under varying load and climatic circumstances, it is important to accurately calculate these uncertainties and include them into the converter.

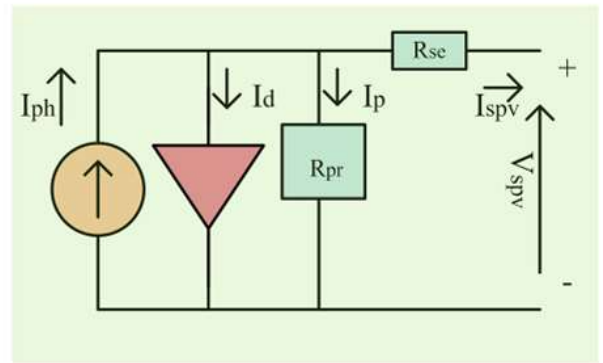


Fig.3. Practical equivalent circuit of the solar PV cell.

2.2. Fuzzy Logic Controller

An intelligent control system based on fuzzy logic and fuzzy sets is known as a fuzzy logic controller (FLC). Fuzzy logic allows partial truth values between 0 and 1, unlike traditional binary logic systems that only use true/false circumstances. When complex, nonlinear, unpredictable systems cannot be realistically simulated, FLC is the best controller to use. Microgrids, renewable energy systems, motor drives, process control, and industrial automation all make use of fuzzy logic controllers due to its versatility, robustness, and ability to handle erroneous inputs. Fuzzification, a rule foundation, an inference engine, and defuzzification are the four primary components of a fuzzy logic control system. For a visual representation, A fuzzy logic controller's fuzzification module is its starting point.

The main application of the membership functions that were previously discussed is the transformation of numerical input values into fuzzy linguistic variables. Using these membership functions, one can ascertain the extent to which an input falls into specific fuzzy sets, such Low, Medium, High, Warm, or Hot. Assume, for the benefit of argument, that the imaginary temperature is 30 degrees Celsius. As per the fuzzification method, the "Hot" set has 0.8 members while the "Warm" set has 0.2. This modification greatly improves the controller's capability to handle non-linear and unexpected data compared to conventional binary logic systems. Build an arrangement. The control mechanism is based on a set of fuzzy IF-THEN rules. The laws are based on experiments' findings or on what is known about the system's inner workings. The criteria of the message and the necessary action are linked by every rule. Assigning input conditions to control actions is the

job of every rule. A sample rule:

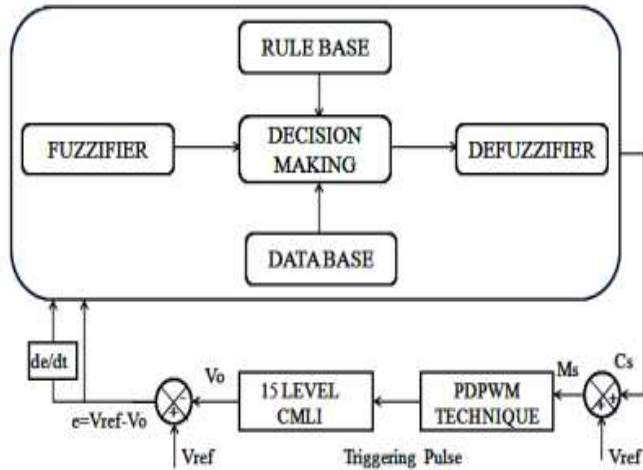


Fig. 4. Fuzzy logic Control Structure

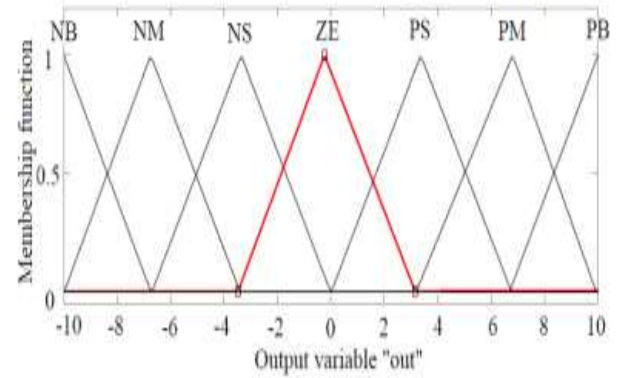


Fig.7. MF for the reference output

TABLE II

FLC RULE MATRIX

e	NB	NS	NM	ZE	PB	PS	PM
C_e							
NB	PB	PB	PB	PB	ZE	PM	PS
NS	PB	PM	PB	PS	NM	ZE	NS
NM	PB	PB	PB	PM	NS	PS	ZE
ZE	PB	PS	PM	ZE	NB	NS	NM
PB	ZE	NM	NS	NB	NB	NB	NB
PS	PM	ZE	PS	NS	NB	NM	NB
PM	PS	NS	ZE	NM	NB	NB	NB

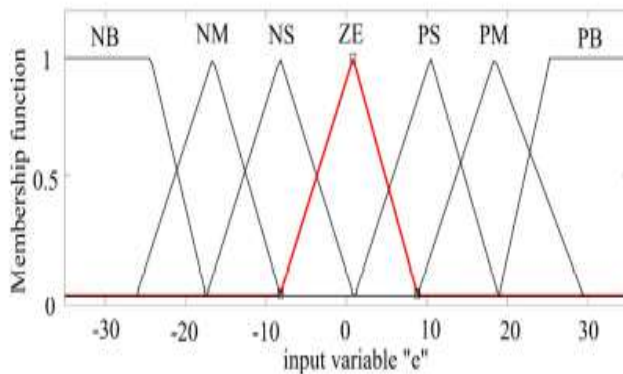


Fig.5. Membership function for error signal

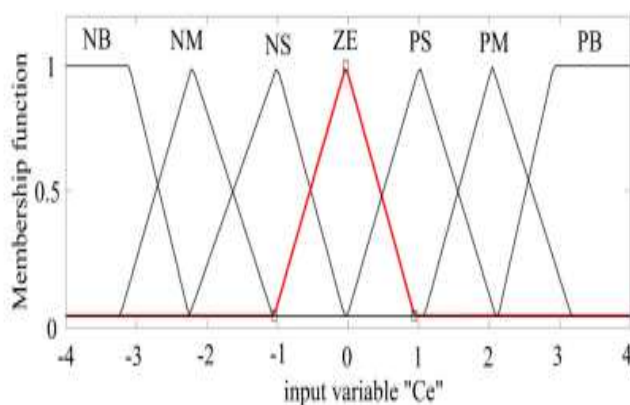


Fig.6. MF for the change in an error signal

3. Simulation Results

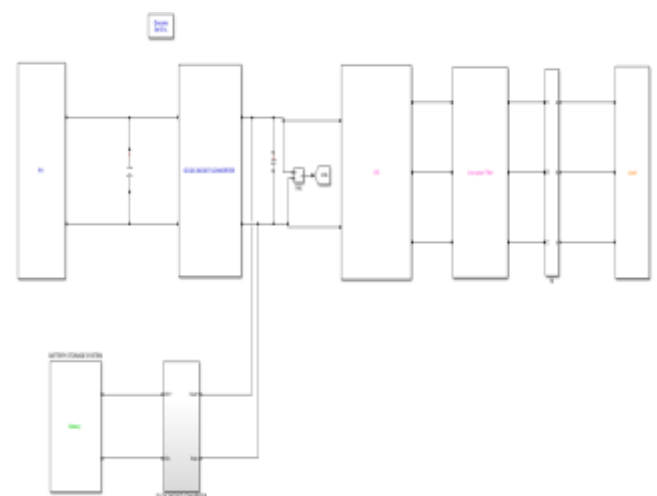


Fig.8. MATLAB/SIMULINK circuit of the proposed system

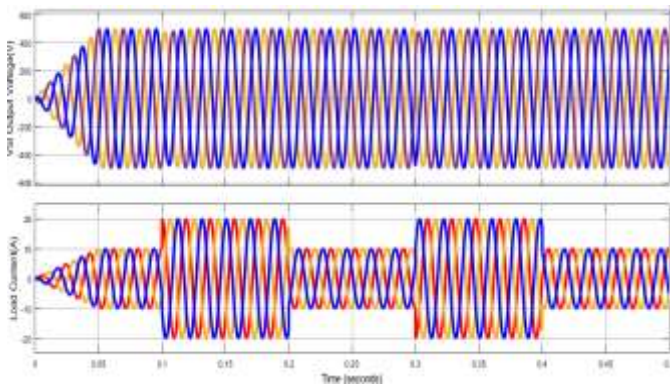


Fig. 9. VSI output voltage and load current waveforms with AFPID controller for Case1.

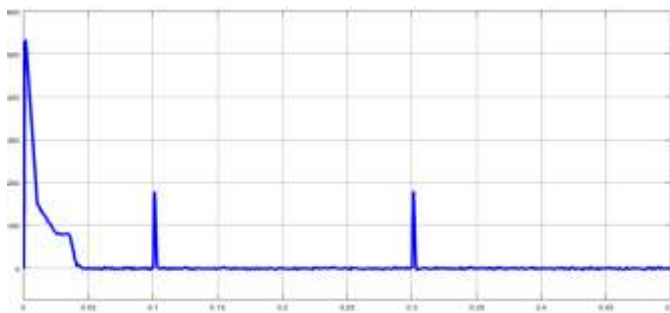


Fig.10. error profiles for Case 1.

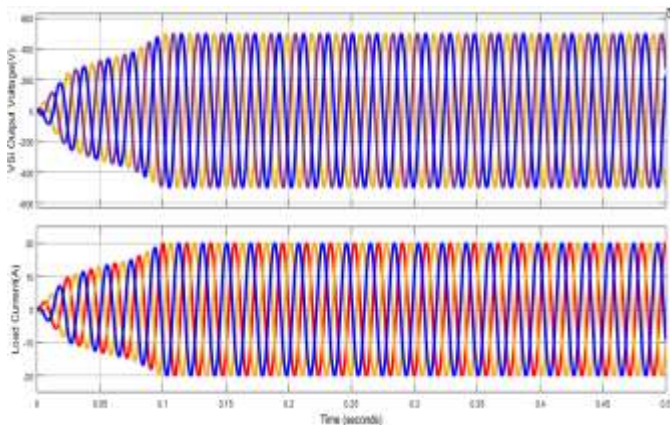


Fig.11. VSI output voltage and load current waveforms with AFPID controller for Case

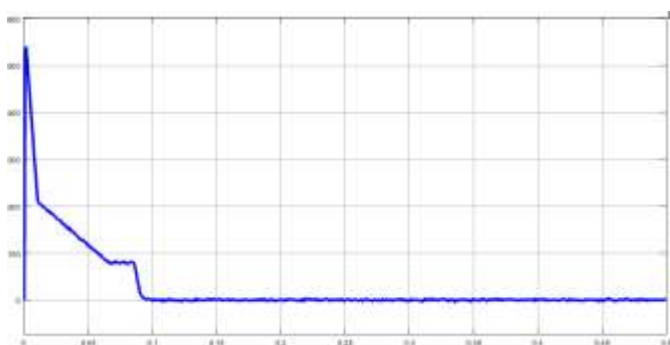


Fig. 12. error profile for Case 2.

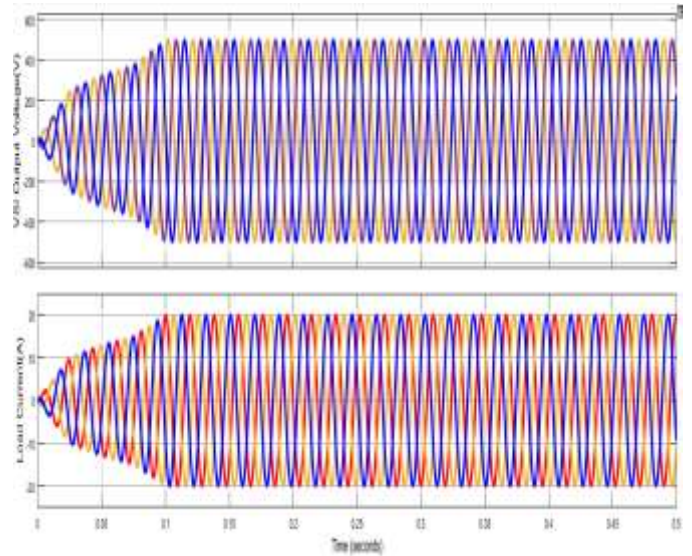


Fig.13. VSI output voltage and load current waveforms with AFPID controller for Case 3

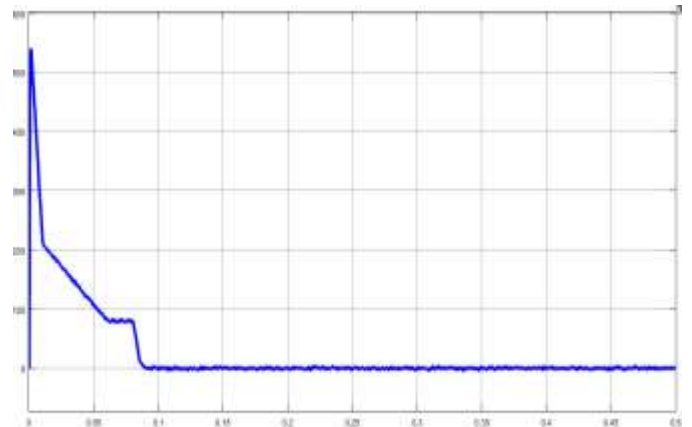


Fig.14. error profile for Case 3.

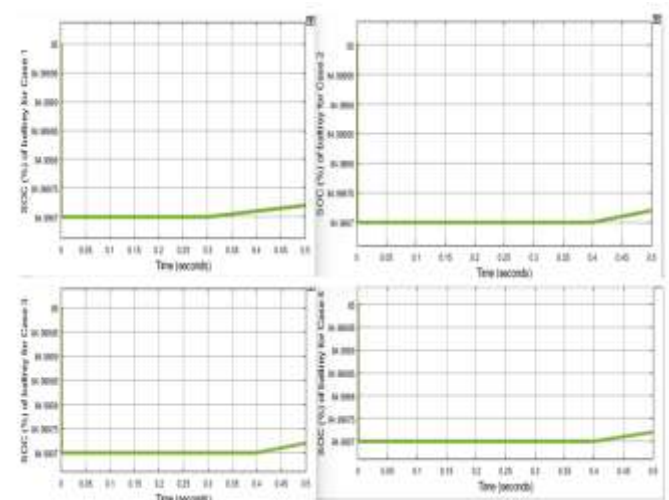


Fig.15. Storage system profile under various cases. (a) SOC profile for case 1. (b) SOC profile for case 2. (c) SOC profile for case 3. (d) SOC profile for case 4.

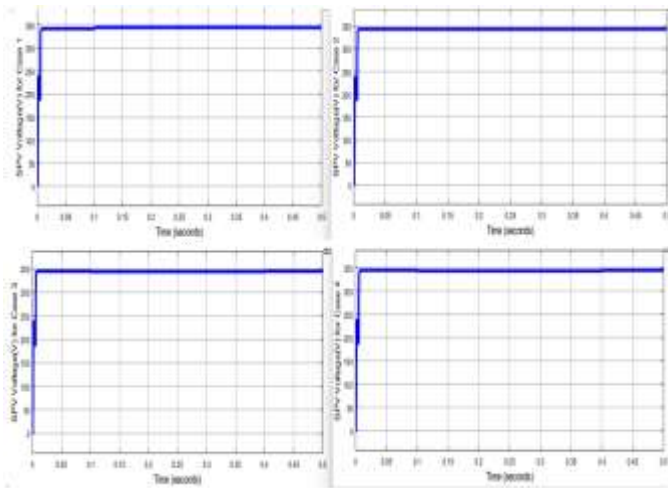


Fig. 17. Solar PV output voltage profile for. (a) Case 1. (b) Case 2. (c) Case 3. (d) Case 4.

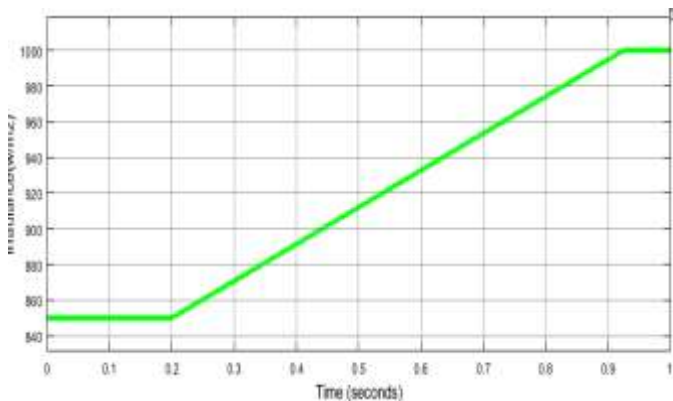


Fig.18. Variations in solar irradiance levels.

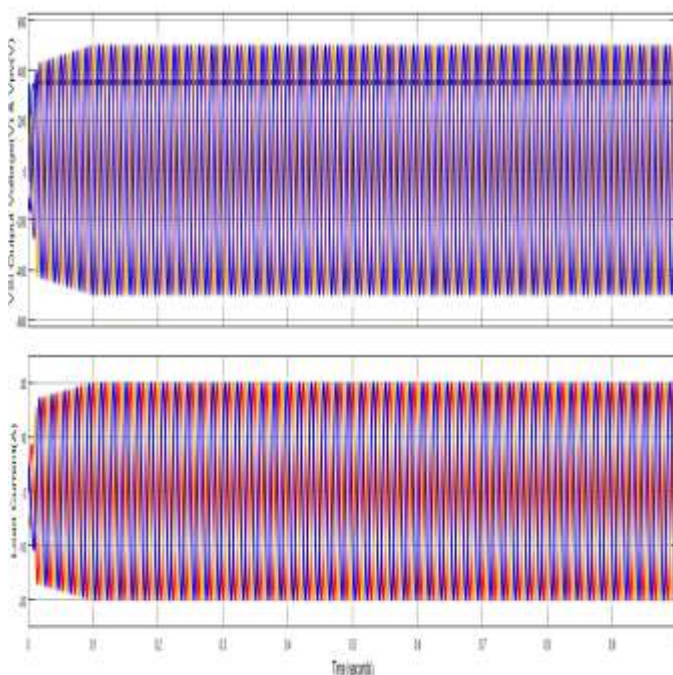


Fig.20. VSI output voltage and load current waveforms for irradiance change.

3. CONCLUSIONS

The integration of renewable energy sources, particularly solar PV (PV) power systems and battery energy storage is an effective solution to address energy supply challenges in remote and off-grid areas. However, the intermittent nature and non-linearity of solar power generation, along with the ever-evolving demands of loads and the capabilities of conventional control systems, can lead to voltage instability and power quality deterioration. In order to overcome these problems and ensure the dependable, stable, and sustainable functioning of microgrids powered by renewable energy, this research emphasizes the use of sophisticated intelligent control approaches.

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. Hybrid intelligent controllers are better than the traditional PI/PID controllers and also better than the stand-alone fuzzy logic controllers in the voltage regulation, transient response improvement, reduction of total harmonic distortion and efficient utilization of the battery energy storage. The adaptive Fuzzy-ANN controller continuously adjusts the operating conditions of the control parameters to enhance the compensating effect of the voltage drop due to the change of solar radiation, sudden load increase or decrease, and battery SOC.

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. In conclusion, robust, smart and sustainable microgrid systems could be obtained by adaptive Fuzzy-ANN control approaches. Future work should focus on hardware implementation, experimental validation in real time and integration with optimization techniques such as metaheuristic algorithms and predictive control techniques to improve the system's durability and efficiency. The key to building a fully-fledged solar, wind and

advanced energy storage hybrid renewable energy system is important to overcome global energy sustainability, reliability and environmental protection goals towards the future autonomous microgrid.

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