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Power quality improvement in distributed generation system using intelligent control methods

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ABSTRACT

Hybrid electric power generation and its integration with the grid to supply consumer demand is main focus of this paper. The use of nonlinear load and advanced power electronic equipment-based devices at the consumer end introduces power quality issues in the power system network in terms of voltage and current. This paper explains the design of a control algorithm for a unified power quality conditioner used for mitigating both voltage and current-based power quality issues. The dynamic voltage restorer of unified power quality controller (UPQC) is designed with a unit vector control algorithm and the distribution static synchronous compensator (DSTATCOM) is designed with fuzzy logic and adaptive network-based fuzzy inference system based instantaneous reactive power theory control algorithm. The simulation model built using the MATLAB platform includes a three-phase voltage source along with hybrid electric power generation connected to linear and non-linear loads operating under different conditions. The result is analyzed in terms of voltage and current total harmonic distortion compared with IEEE 512 power quality standards and power factor improvement. The paper shows the adaptive neuro-fuzzy inference systems (ANFIS)-based control algorithm gives better results in terms of total harmonic distortion (THD) compared to the fuzzy-based control algorithm. The power factor is improved using ANFIS-based controller proving the efficiency of the controller.

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1. INTRODUCTION

Power quality has become significant due to the use of advanced equipment which operates using microprocessors, microcontrollers, and power electronic devices. It is ultimately a consumer-driven issue that mainly aims at providing quality power to consumers. Different control algorithms are designed to improve power quality. Instantaneous reactive power theory (IRPT) and current theory along with proportional integral (PI) and fuzzy controller for power quality improvement are explained along with the advantages of fuzzy over PI controller [1]–[3]. Adaptive neuro-fuzzy inference systems (ANFIS) over PI controllers and implementation of fuzzy and ANFIS for various operating conditions of source and load are discussed in [4]–[9].

Different compensation strategies for mitigating current harmonic and current distortion due to the nonlinear load is discussed and a comparison based on the implementation process and error using a sinusoidal waveform reference is obtained [10]–[15]. Different fuzzy membership functions to eliminate harmonics and distortion in current due to nonlinear load and advantages of using the Mamdani type of fuzzy controller over the PI controller are justified in [16]–[21]. The design of the microgrid, protection configuration, power quality monitoring, control and power energy metering are explained in [22]–[26].

This paper aims to identify power quality issues in terms of current distortion due to nonlinear load and voltage distortion due to voltage sag, swell and harmonics introduced in a three-phase programmable voltage source with hybrid electric power generation comprising solar and wind power. It encompasses the design of unified power quality controller (UPQC) with fuzzy and ANFIS for IRPT controller in shunt active filter and unit vector control (UVC) algorithm for a series active filter followed by analysis in terms of compensation provided by using UPQC. The 3ϕ voltage source of 415 V, 50 Hz is connected with hybrid renewable electric power generation connected to linear and nonlinear load is shown in Figure 1. The photovoltaic array is designed using the sun power SPR 305-WHT model from the MATLAB simulation library consisting of module characteristics from National renewable energy laboratory (NREL) system advisor model standards. The wind generation is designed using a permanent magnet synchronous machine fed by wind turbine.

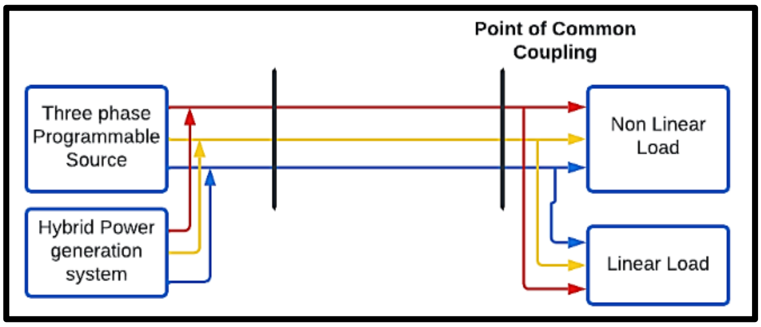


Figure 1. Simulation block diagram representing three-phase supply with hybrid power generation connected to the linear and nonlinear load

Case 1: implementation of voltage-related issues: the voltage sag of 0.40 pu is induced at t=0.1 s to t=0.2 s obtaining the magnitude of voltage as 90.8 V and swell of 1.4 pu at t=0.2 s to t=0.3 s resulting in voltage magnitude of 321.5 V. The 5th and 7th harmonics are introduced at t=0.3 s to t=0.35 s resulting in voltage magnitude of 284.6 V which leads to power quality issues is shown in Figure 2. The use of nonlinear load with a diode rectifier connected to RL load introduces harmonics in the current is shown in Figure 3. The real and reactive power is decreased to 448.9 W and 115.9 volt-amp reactive (VAR) due to the voltage sag of 0.4 pu at a time interval of t= 0.1 s to t=0.2 s. At time t=0.1 s to 0.2 s, the real and reactive power is increased to 1604 W and 365.6 VAR due to a voltage swell of 1.4 pu. The variation in real and reactive power is depicted in Figure 4 and Figure 5.

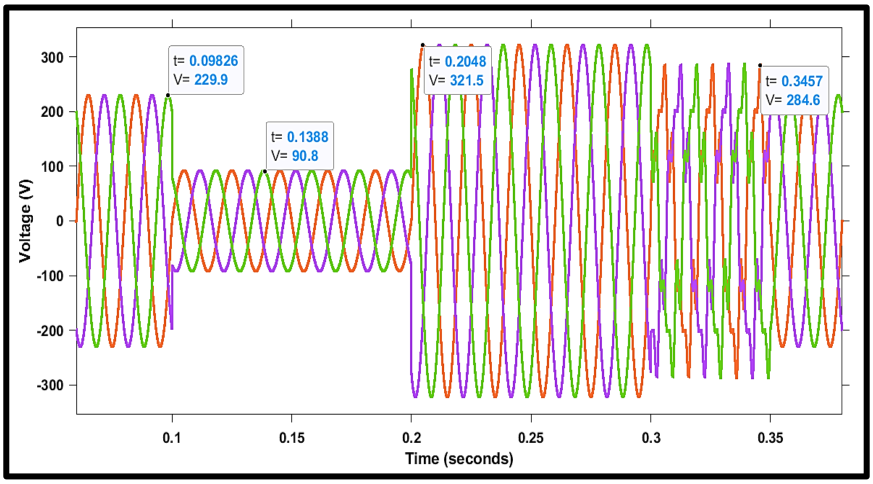


Figure 2. Waveform representing voltage sag, swell and harmonics

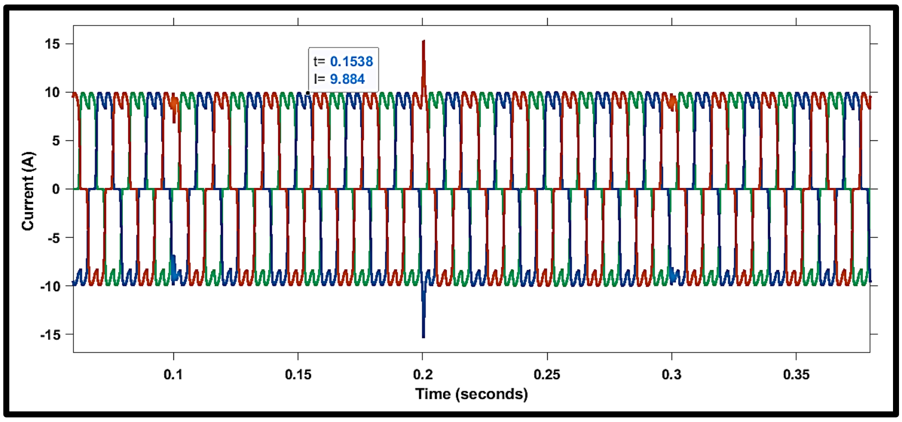


Figure 3. Waveform indicating current distortion due to nonlinear load

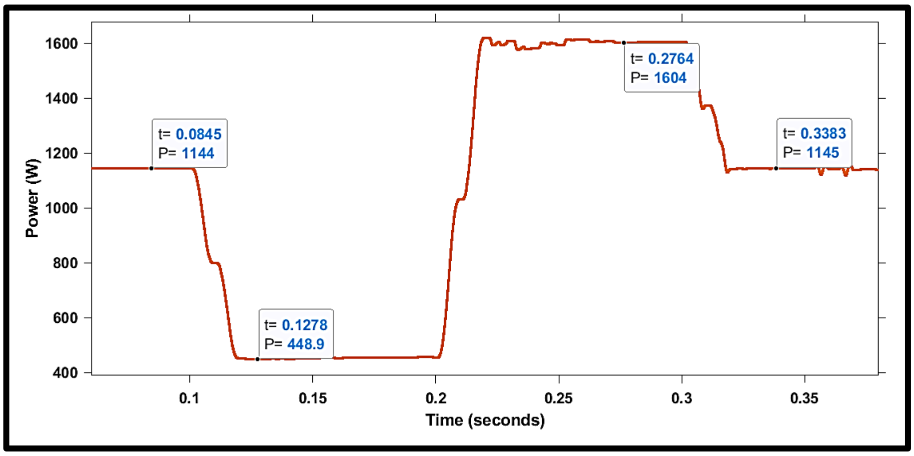


Figure 4. Waveform representing real power (W) for voltage sag, swell, and harmonic conditions

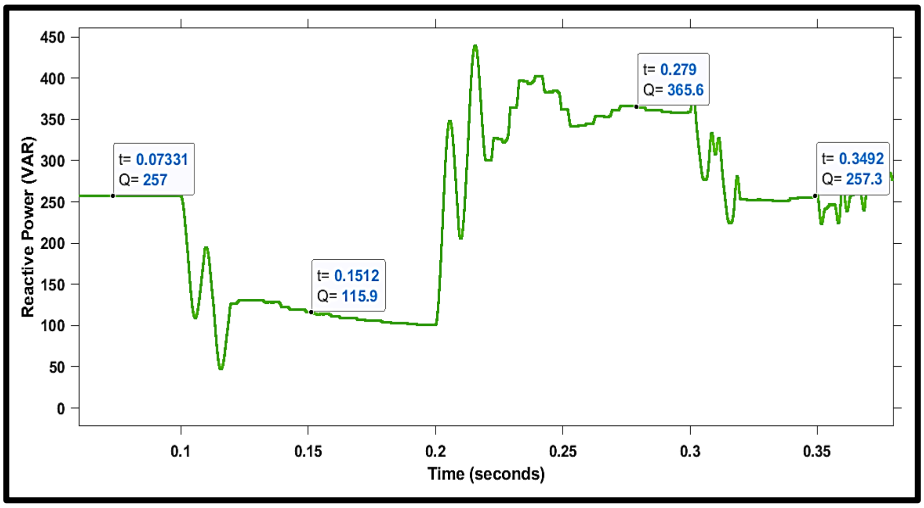


Figure 5. Waveform representing reactive power (VAR) for voltage sag, swell and harmonic condition

Case 2: implementation of voltage interruption: the voltage is interrupted from t= 0.1 s to t=0.2 s to indicate the occurrence of fault or components malfunctioning is shown in Figure 6. It is observed that the magnitude of voltage is zero at t=0.1 s to t=0.2 s causing loss of power at a particular instance. Voltage interruption leads active and reactive power to zero depending on the load considered. The magnitude of the power under normal operating duration at t=0.08 s to t=0.1 s is 1,144 W and during an interruption the voltage at t=0.1 s to 0.2 s is 0 W is shown in Figure 7. The decrease in power to 0 W reduces the system performance at the consumer end. Due to voltage interruption, the reactive power becomes equal to almost zero and it is 257.3 VAR at the time interval t=0.08 s to t=0.1 s is observed in Figure 8.

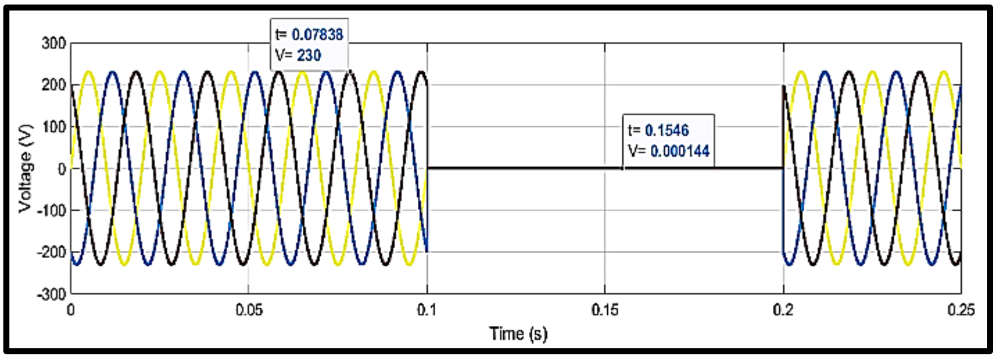


Figure 6. Simulation waveform indicating Interruption in voltage at t=0.1 s to t=0.2 s

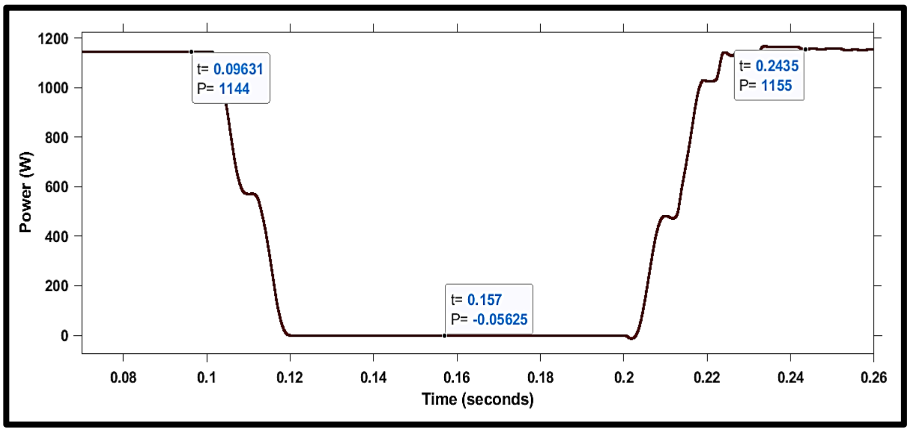


Figure 7. Waveform representing power (W) for voltage interruption condition

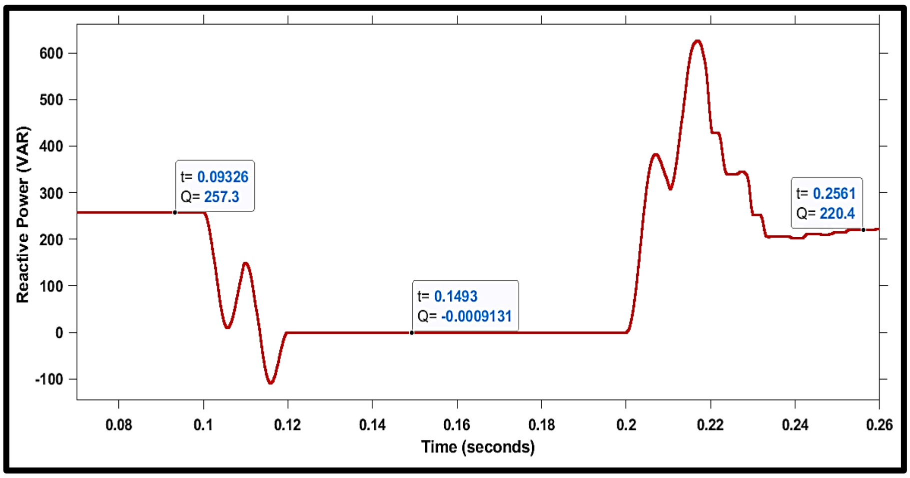


Figure 8. Waveform representing reactive power (VAR) for voltage interruption condition

2. DESIGN AND SIMULATION OF UNIFIED POWER QUALITY CONTROLLER

Power quality issues explained in section 1 are mitigated using UPQC. The series active power filter (APF) in UPQC is modeled using a unit vector template (UVT) algorithm which provides voltage compensation and the shunt APF is modeled using IRPT providing current compensation. The series and shunt APF are cascaded using a DC link capacitor is shown in Figure 9.

The design of the series and shunt active filter and associated equations for series APF and shunt APF are as explained by Vijayshree and Sumathi [27]. The voltage error is calculated across the DC link capacitor which is fed as input to the fuzzy interface system to generate a control signal for the IRPT algorithm to provide shunt compensation. The fuzzy interface system is designed with fuzzy logic (3 membership functions (MF), 5MF, 7MF) and ANFIS controller.

Method 1: fuzzy logic - in this method, the error voltage calculated from the DC link capacitor is fed as one input to the fuzzy block which is input 1, and delayed voltage error acts as input 2 is shown in Figure 10. The fuzzy uses Sugeno type, triangular membership function with AND method as a prod, OR method as probor and wtaver method for defuzzification, aggregation as maximum and implication as a minimum. The number of MF defined for fuzzy execution is 3MF, 5MF, and 7MF respectively. The 3MF fuzzy structure is shown in Figure 11. The surface structure is shown in Figure 11(a) and rule structure for is shown in Figure 11(b) indicating 3X3=9 rules under three different boundary conditions.

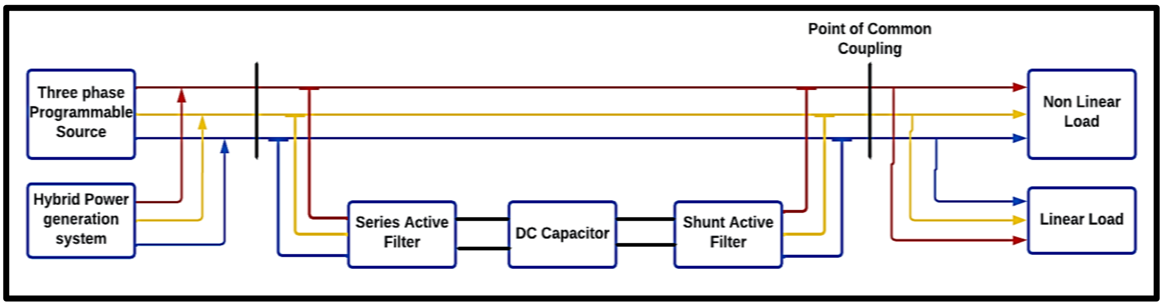


Figure 9. Simulation block diagram of power system network with UPQC compensation (combination of series and shunt APF)

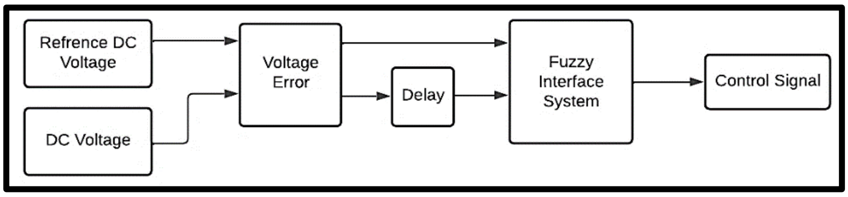
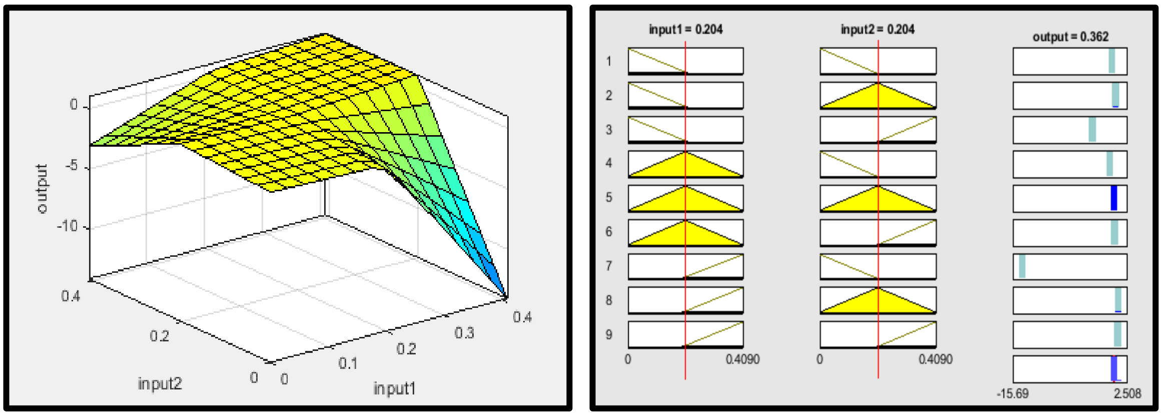


Figure 10. Block diagram representation of control signal generation for IRPT using fuzzy



(a) (b)

Figure 11. Surface structure (a) rule structure and (b) for three membership functions

Method 2: ANFIS is an intelligent control algorithm that includes training, testing, and validating the set of data inputs. The reference data for training is obtained by using a PI controller. The trained data is tested for the simulation model with the ANFIS controller and validated for the same. The ANFIS structure for the 3 membership functions is shown in Figure 12.

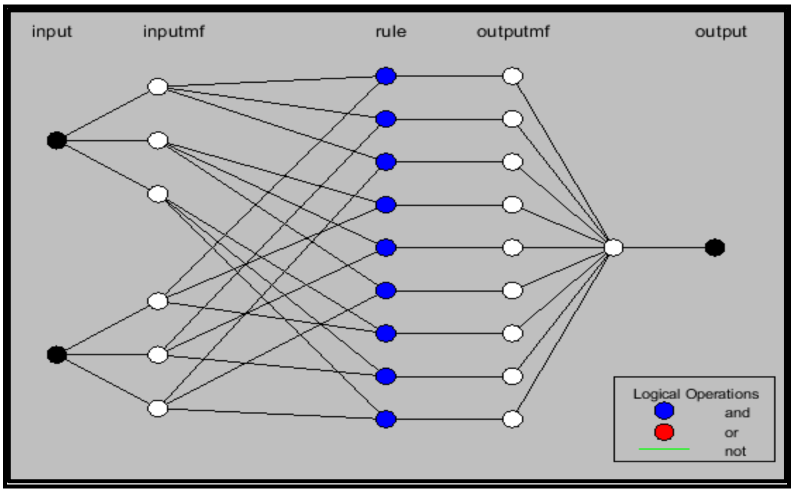


Figure 12. ANFIS structure for three membership functions

The MATLAB window representing ANFIS training data is shown in Figure 13 and the validation of ANFIS training is done using checking data as shown in Figure 14. The testing data for ANFIS is shown in Figure 15 and the corresponding FIS output is indicated in Figure 16. The simulation block diagram for a grid with hybrid electric power generation connected to linear and nonlinear load is shown in Figure 17. The voltage control block derives the control signal for designing IRPT for the shunt active filter. The control signal is derived using PI, fuzzy, and ANFIS controllers. The data is extracted from the PI controller which is used to derive fuzzy rules and training and testing data for ANFIS as explained.

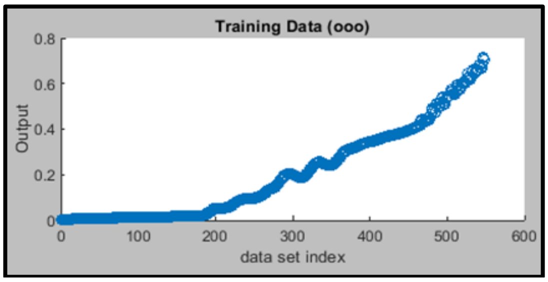


Figure 13. ANFIS training data in MATLAB

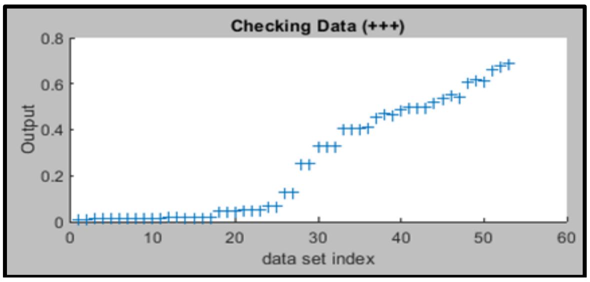


Figure 14. ANFIS checking data in MATLAB

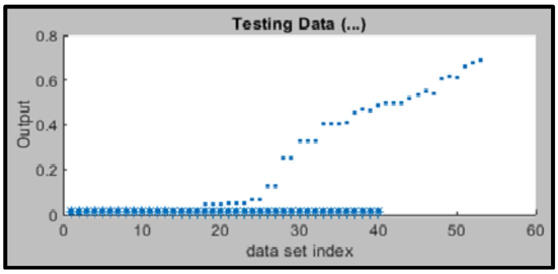


Figure 15. ANFIS testing data in MATLAB

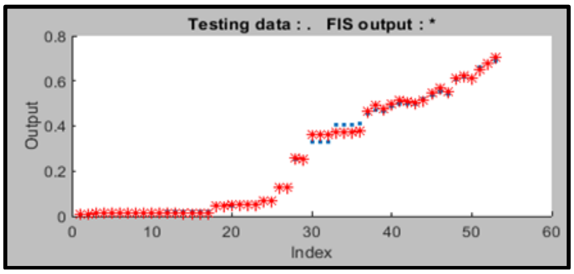


Figure 16. ANFIS testing data and FIS output in MATLAB

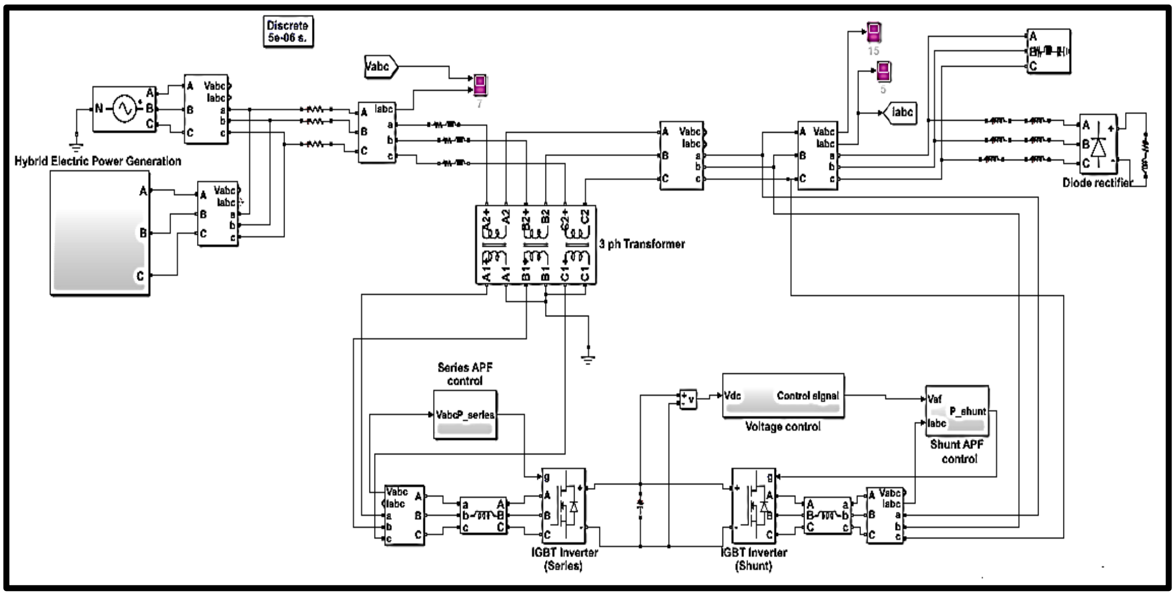


Figure 17. Simulation block diagram for grid with renewable generation connected to the linear and nonlinear load

3. RESULTS AND DISCUSSION

3.1. Compensation for voltage sag, swell, and harmonics induced

The simulation results with UPQC compensation for the problem formulated in case 1 have been illustrated. The voltage sag, swell, and harmonics are eliminated by providing suitable compensation. The grid voltage is maintained at 230 V is shown in Figure 18. The harmonics are eliminated in the current waveform to obtain pure sinusoidal waveform illustrating the effect of UPQC compensation shown in Figure 19.

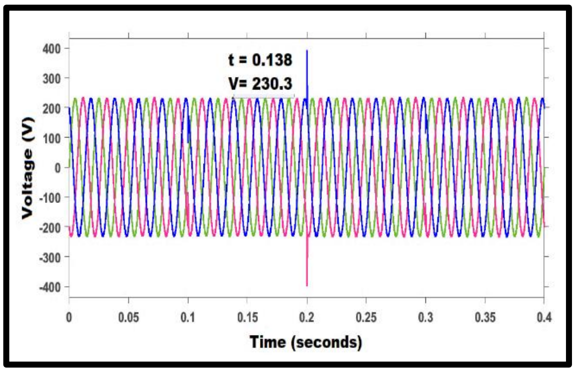


Figure 18. Simulation output for voltage with UPQC compensation for voltage sag, swell and harmonics

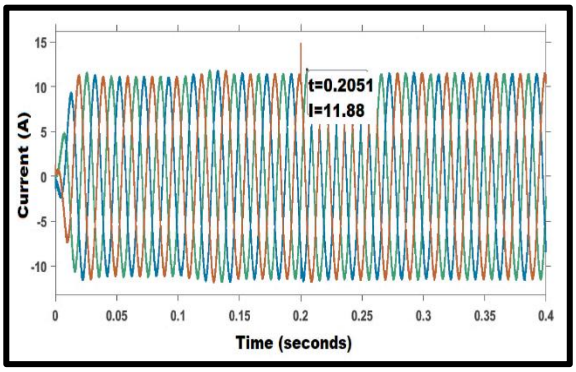


Figure 19. Simulation output for current with UPQC compensation for voltage sag, swell and harmonics

The real power after providing UPQC compensation is maintained between P=1212 W to P=1259 W is shown in Figure 20 which was decreased and increased due to voltage sag and swell respectively when compared to Figure 4. The reactive power is compensated to Q=257 VAR is shown in Figure 21 which was reduced to 115.9 VAR due to voltage sag and increased to 356.6 due to voltage swell is shown in Figure 5. The power factor is improved from 0.94 to 0.98 by providing UPQC compensation. If the sag is 0.8 pu and swell of 1.8 pu, the real, reactive power compensation and power factor improvement plays a very important role which can be obtained by the above defined compensation.

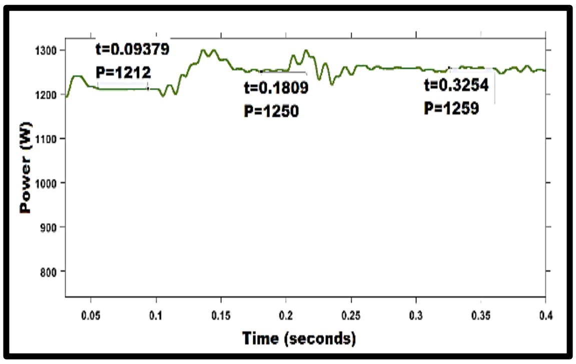


Figure 20. Simulation output for real power with UPQC compensation for voltage sag, swell and harmonics

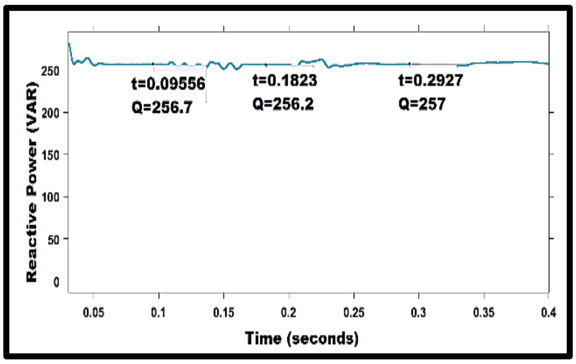


Figure 21. Simulation output for reactive power with UPQC compensation for voltage sag, swell and harmonics

3.2. Compensation for voltage interruption

For case 2 problem formulation, the voltage compensation at t=0.1 s to t=0.2 s of 230 V is shown in Figure 22 compared to the interruption is shown in Figure 6. The real and reactive power compensation is represented in Figures 23 and 24 which was zero during the interval of voltage interruption is shown in Figures 7 and 8. The power factor is improved from 0.84 to 0.97.

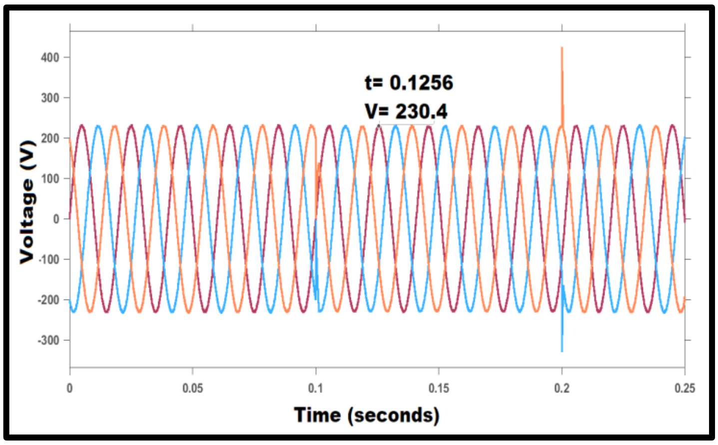
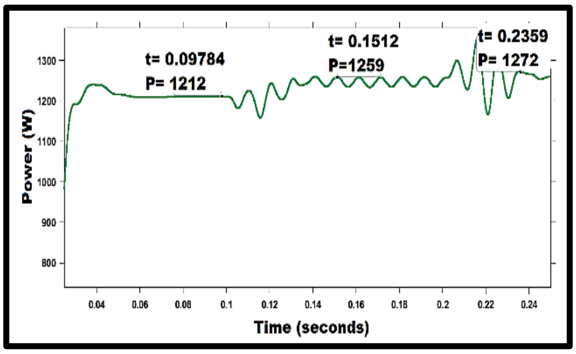


Figure 22. Simulation output for voltage with UPQC compensation for voltage interruption



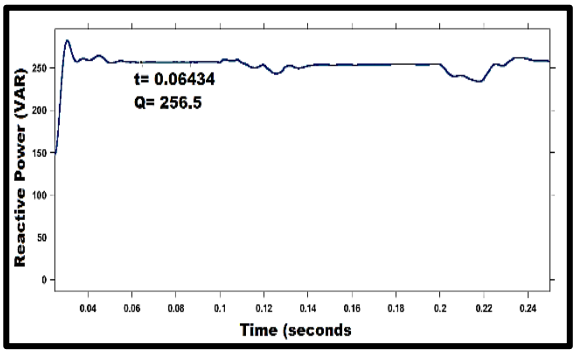


Figure 23. Simulation output for real power with UPQC compensation for voltage interruption

Figure 24. Simulation output for reactive power with UPQC compensation for voltage interruption

Table 1 explains voltage total harmonic distortion (THD) and current THD under voltage sag of 0.4 pu and voltage swell of 1.4 pu with fuzzy and ANFIS controller. Without compensation for a voltage sag of 0.4 pu, the THD is 15.8%. By providing compensation with fuzzy 3MF the voltage THD is reduced to 2.98%, with 5MF it is 0.90% and with 7MF it is 0.62%. ANFIS compensation reduces the voltage THD to 0.49%. Without compensation for voltage sag of 0.4 pu, the current THD is 25.22%. By providing compensation for the shunt active filter with fuzzy 3MF the current THD is reduced to 4.03%, with 5MF it is 3.84% and with 7MF it is 3.39%. ANFIS compensation reduces the current THD to 2.09%.

Table 1. Comparison of THD for voltage sag and voltage swell using fuzzy and ANFIS

The magnitude of voltage sag and swell	THD Without UPQC	Fuzzy-3MF	Fuzzy-5MF	Fuzzy-7MF	ANFIS
0.4 pu (Voltage THD)	15.8%	2.98%	0.90%	0.62%	0.49%
1.4 pu (Voltage THD)	8.51%	1.82%	1.40%	0.67%	0.46%
0.4 pu (Current THD)	25.22%	4.03%	3.84%	3.39%	2.09%
1.4 pu (Current THD)	25.2%	3.86%	3.74%	3.29%	2.02%

Without compensation for a voltage swell of 1.4 pu the THD is 8.51%. By providing compensation with fuzzy 3MF, the THD is reduced to 1.82%, with 5MF it is 1.40% and with 7MF it is 0.67%. ANFIS compensation reduces the voltage THD to 0.46%. Without compensation for a voltage swell of 1.4 pu the current THD is 25.22%. By providing compensation for the shunt active filter with fuzzy 3MF the current THD is reduced to 3.86%, with 5MF it is 3.74% and with 7MF it is 3.29%. ANFIS compensation reduces the current THD to 2.02%. The simulation is performed for different voltage sag and swell conditions and reduction is observed in voltage and current THD. The compensation also becomes beneficial by delivering power factor improvement.

4. CONCLUSION

Power quality improvement aims to deliver pure sinusoidal voltage and current to consumers. Renewable generation contributes to distributed generation system constituting more use of renewable sources and less dependency on non-renewable sources for power generation. The use of renewable generation by solar and wind reduces greenhouse gas emissions and also operates more reliably. The simulation is performed using fuzzy and ANFIS controllers. From the simulation results, it is concluded that the ANFIS controller is more efficient, flexible and more reliable in providing power quality compensation compared to other controllers such as PI and fuzzy controllers. The effectiveness of the controller is analyzed based on voltage THD, current THD and power factor improvement.

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