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Adaptive TS-ANFIS neuro-fuzzy controller based single phase shunt active power filter to mitigate sensitive power quality issues in IoT devices

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A R T I C L E I N F O

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A B S T R A C T

The emergence of Internet of Things (IoT) offers numerous functions, such as intelligent sensor integration, remote sensing, and high-speed data transmission, which have found widespread applications in the smart industry and commercial applications. The associative nonlinear effects of a variety of undesirable power quality concerns were resolved by using harmonic mitigation in nonlinear loads and high-performance converters were built on power electronics in conventional systems. Among other performance objectives, total harmonic (THD) distortion analysis and higher order harmonics mitigation is given main concern in smart electronics equipment. This paper proposes an approach to minimize higher-order harmonics due to nonlinear load disturbances in smart IoT devices using the Takagi–Sugeno (TS) Neuro Fuzzy (TS-ANFIS) supervised shunt APF. The proposed work elicits the novel adaptive harmonic mitigation technique in hybrid IoT embedded systems to protect from malfunctioning and to deal with the uncertainty of harmonic signal stimuli in sensitive sensors-based IoT systems. Hysteresis current control is used for the ignition of reference signal under uncertainty of harmonic stimuli. The single phase shunt APF is used to mitigate higher-order harmonics from supply mains, while the implementation of TS-ANFIS supervises the controller action to generate a trigger signal for adequate single phase APF gate excitation. The higher order harmonic current data set is used for error deviation for training neural networks and adaptive control. The estimated adoption of the neuron's empirical weight reduces the total THD to a significant reduction rate of 72.8 % to 0.78 %. The control mechanism is feasible for a range of smart IoT systems to adhere to the standard of 519 (IEEE).

1. Introduction

The National Institute of Standards and technologies early describe current IoT or network of things models (NoT) to realize IoT systems, sensors, aggregators, communication channels, e-utilities, and decision triggers are described as the essential primitives [1]. The components of self-adaptive IoT models include cutting-edge technologies and device accessories. For remote sensing and control, the IoT consists of several interconnected heterogeneous hybrid models. The power electronics elements are the primary components in the embedded system in the variety of Internet of Things applications. Fig. 1 shows an architectural view of IoT power distribution and conditioning system. Based on the study, the effects of power electronics equipment in commercial and industrial applications are investigated for nonlinear characteristics. It is interesting to note that in a distributed power system, harmonic disturbances are more likely to be introduced by power electronics devices. Eventually, the distribution systems' power electronic components lead several undesired reflective power quality problems [2]. In the long-term evolution of IoT, the nonlinear attributes of the V-I characteristics of power electronics devices have serious impacts on functioning of devices. Such nonlinear loads cause the distribution of current to produce undesired harmonics, which lowers the quality of the distribution supply. The Shunt APF and ANFIS implementation are quite popular among researchers due to their versatility for a wide area of applications. However, power management units are a newly emphasized area of integration of soft computing algorithms. Especially, sensitive electronic sensor-based IoT systems need more attention towards malfunctioning of devices due to harmonic current insertion.

The sensitive IoT devices need a soft computing technique to deal with uncertain harmonic stimuli through an adaptive learning based controller to activate shunt APF functioning. The novelty of this work is to mitigate harmonic distortions in PMU of highly sensitive IoT devices using TS-ANFIS supervised shunt APF. The obtained results are quite

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Nomenclature

DSTATCOM	distribution static compensator
FLC	fuzzy logic controller
TshAPF	transformer less shunt active power filter
ANFIS	adaptive neural fuzzy interface system
APF	active power filter
ANN	artificial neural network
THD	total harmonic distortion
VSI	voltage source inverter
RES	renewable energy source
UPQC	unified power quality control
IOT	Internet of Things
PMU	power management unit
SHAPF	shunt active power filter
PID	proportional integrator derivation
PFC	power factor correction

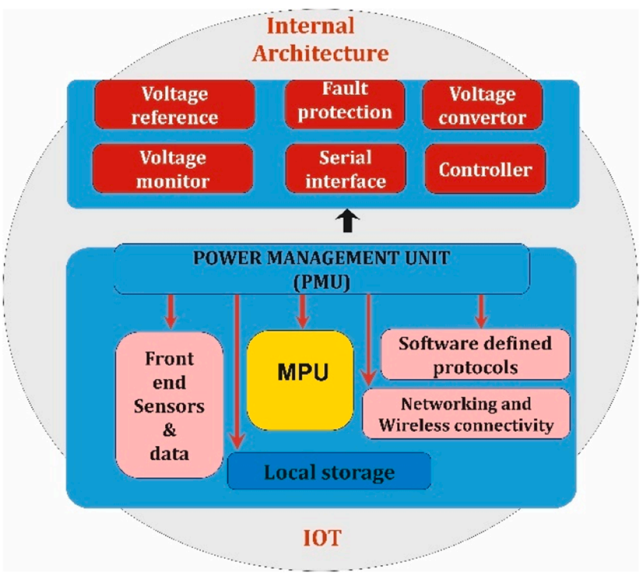

Fig. 1. PMU and internal IoT architecture.

interesting and highly feasible for sensor operations, it is unique in its class to integrate ANFIS with PMU of IoT and ANFIS performance is optimized to minimum level of THD. This paper is organized in five major sections which includes introduction to elaborate conceptual understanding of the issue with existing state of art techniques based on literature review. Second section elicits the modeling of power management units (PMU) in internet of things devices. Third section demonstrates the hysteresis current control technique for compensation of harmonic current. Fourth section describes the implementation of adaptive neural fuzzy interface system (ANFIS). Fifth section explains the findings and achievements of the proposed work followed by the conclusion.The introduction leads to identification of major challenge associated with the IoT devices or nonlinear loads. The next section describes the related literature survey for concept deliberation.

2. Literature review

A number of parametric issues of power quality (PQ) reduce the economic and environmental performance of the system [3]. Machine-to-machine communication (MMC) is the recent advancement in the industrial or commercial sectors to implement real-time remote access for device monitoring and control. 5 G has invited the attention of technocrats to facilitate more devices on connected networks. The National Institute of Standards and Technology (NIST) has released guidelines for the use of connected devices and their models under the effective integral applications of the Internet of Things (IoT). The models are conceptualized with the effective functioning of major entities such as application utility, remote sensing & triggering, communication network and sensors & aggregators. The complexities of assembling multiple hybrid device models on a common network in IoT systems generate many associative issues. The power conversion units are the essential attributes of each segment of IoT systems. The electronic components are the precious entities of the main embedded system in smart devices. The power quality issues develop various other parametric deficiencies and directly affect the performance of the device [3]. Especially, in smart devices, the insertion of harmonic distortion deviates the performance of the device from its absolute estimation and failure of the sensitive device over long-term utility. This work identifies the multiplayer challenges of PMU in smart IoT devices and networks of connected devices with smart controllers. The focus is oriented towards the effects generated in the internal circuitry of PMU and power converters in small-scale smart machine networks. The conventional state of the art of compensation of harmonics is satisfactorily exterminating the unwanted current harmonics with existing limitations [4]. The conventional active power filters were modified through manipulative association in series or shunt with the main circuitry. The shunt active power filters become more popular due to better harmonic current compensation tuning and power factor improvement [5]. The accuracy in the estimation of the reference current plays an important role in the performance analysis of shunt APF. Conventionally, active-reactive power theory, synchronous frame theory and phase-locked loop were reported for the generation of the reference current. The continuous improvement brought soft computing-based technologies such as sliding mode control (SMC), gravitational search algorithm (GSA), fuzzy logic control (FLC) and deep learning-based advanced artificial neural network (ANN) for optimization of control strategies to produce adequate reference current [6–8]. Power quality improvement or harmonic mitigation is an essential action entity, which requires adequate frequency sync and minimum response time. While taking significant consideration of a complex mesh network of IoT-connected devices, immediate control and real-time monitoring are essential. The response time is an important entity for fast smart devices to efficiently control power quality. This paper contributes to providing an efficient solution to reduce harmonics at a significant level along with enhancing system adaptability to deal with the uncertainty of stimuli. The deep learning-based soft computing techniques are associated to control the reference compensation current to the parallel hybrid filtering system. The novelty of this paper is the implementation of an Artificial Intelligence (AI) based Adaptive Neuro-Fuzzy Inference System (ANFIS) to the conventional active power filter system. The ANFIS is a deep learning technique which has an integrated ability to extract the utility of artificial neural networks and fuzzy inference. This emphasizes the implications of fuzzy logic to deal with uncertainty in the IO framework and ANN creates and refines the fuzzy rules based on training algorithms [9]. It elaborates on the structure of the power management unit of the IoT devices, advanced active power filter and soft computing-based deep learning model to control compensation current to reduce higher order harmonics. Shunt Active Power Filters (SAPFs) are used in power systems to mitigate harmonics and improve power quality. Soft computing techniques, which encompass a range of methods inspired by human intelligence and adaptability, can be applied to enhance the performance of SAPFs. Some commonly used soft computing techniques for SAPFs are illustrated here, Fuzzy logic provides a way to model and control systems with uncertainties [10]. Fuzzy logic controllers can be applied to SAPFs to handle the complex and nonlinear nature of power systems. Fuzzy controllers can adapt and optimize their performance based on changing operating conditions. Neural networks, especially artificial neural networks (ANNs), can be employed for SAPF control. They can learn the non-linear relationships within the power system and provide adaptive control strategies. Training neural networks on historical data can improve the ability of the SAPF to respond to varying harmonic conditions [11]. Genetic algorithms are optimization algorithms inspired by the process of natural selection. They can be used to optimize the control parameters of SAPFs, helping to achieve better filtering performance. GAs can search through a large solution space to find optimal or near-optimal solutions for the filter parameters. PSO is an optimization technique inspired by the social behavior of birds and fish. It can be applied to optimize the parameters of SAPFs for harmonic mitigation. PSO algorithms are particularly useful when searching for optimal solutions in a multidimensional parameter space. ACO is inspired by the foraging behavior of ants and is used for optimization problems. It can be applied to find optimal configurations for SAPFs by simulating the pheromone-based communication and cooperation seen in ant colonies. Combining multiple soft computing techniques or integrating them with traditional control methods can lead to improved performance. Hybrid approaches can exploit the strengths of different techniques to address various aspects of SAPF control. Soft computing techniques, such as adaptive neuro-fuzzy inference systems (ANFIS), can adapt the control parameters of SAPFs in real-time based on the changing conditions of the power system. The choice of the soft computing technique depends on the specific requirements of the SAPF application and the characteristics of the power system it is intended to improve. Additionally, the development of intelligent controllers for SAPFs is an active research area, and new techniques may emerge over time [12–14]. On the basis of state of art, it has been observed that the uncertainty and network stimuli in PMU of IoT are not emphasized much. However, the nonlinear load and harmonic distortion mitigation is dealt in various literature and conventional techniques are much popular. The next section elicits the architecture design of PMU model of IoT devices and harmonic distortion analysis. The main objective of the proposed work is to develop an efficient soft computing supervised self-adaptive shunt APF to minimize the harmonic distortions in PMU of highly sensitive sensor based IoT devices.

3. Design and risk analysis of PMU of IoT-based devices

The power management unit (PMU) has a number of operational units to tackle different power management challenges for IoT devices. This prompts a large need for controller subsets for the faster conversion of converted for Internet of Things devices. Fig. 2 shows the fundamental layout of how electricity is distributed in Internet of Things devices, which includes a basic power converter unit for both server terminals and edge devices that is controlled by the main processing unit (MPU). The performance of the gadget and channel RF tuning are directly impacted by this power conversion. Hence, any quality problem may have a negative impact on network connections and device applications.

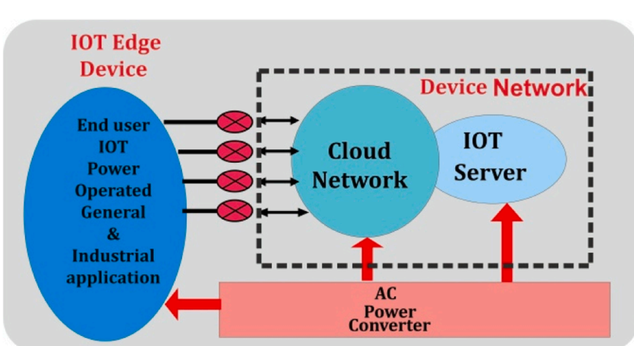

Fig. 2. IoT module AC power converters.

At the initial level, the architecture and the technical issues associated with the PMU are shown through the formal layout of the IoT power management unit. A sectional view is shown in Fig. 3, which consists of power supply distribution in any IoT-based board chip. The sensor-based onboard and off board devices need adequate power conversions & signal conditioning. For the same, converters and controllers become an essential need of smart devices from the level of the embedded board to the network interface. It elicits, such smart device system architecture possesses a high risk of harmonic distortions in the main source of supply.

Fig. 4 indicates the actual flow of compensation mechanism to compensate higher order harmonic current. The impact of association of nonlinear load is depicted in both the condition under compensation or without compensation. The converter unit in the power flow mechanism of the embedded system in a smart device is associated with main processing unit (MPU) in soft computing controlled systems. MPU supervises the distribution of driving power in end terminal edge devices and cloud server terminals. The need for this conversion harms device performance and radio frequency tuning with the network. The signal processing under the entire system undergoes irregular conditioning and led back to severe performance degradation attributes. Fig. 5 shows that the two major challenges are observed due to insertion of higher order harmonics in distribution circuit. The performance impact in the transmission module of IoT devices and another in instrumental model of the system is significant. While, the overall risk analysis is shown in Fig. 6, it shows that all the attributes are at high risk due to the insertion of higher order harmonics.

The two major analytics related to harmonic distortions are seen in IoT PMU, one transient response deviation and another steady state disturbance. Notches, swells, sags, flickers, impulses, low power factor, noise, heating etc. are quite often due to harmonic distortions. IEEE-1159 standard defines the category of faults under three major category such as sustainable, instantaneous and momentary. Especially in IoT systems, an equal probability is observed of the above three classes of faults at the consumer edge device and in a communication network. The main risk attributes are compiled in Table 1, which exhibits the mapping of risk analysis caused by the harmonic distortions to physical and virtual primitives. Qualitative analysis indicates that for the long-term persistence of harmonic distortion, the risk analysis will be higher in IoT systems. At various layers of action, the risk of reliability exhibits the adequate need for harmonic compensation techniques. This indicates the PMU architecture experiences several issues at different layered structure and architecture is subjected to current compensation technique. The next section elicits the proposed novel methodology and ANFIS compensation technique for harmonic current mitigation.

4. TS-ANFIS supervised harmonic current compensation methodology

The three major compensation controllers are used for the reduction of harmonics such as active, passive and the combination of both, hybrid filters [15]. The adequate choice of controller depends upon the tolerance limit of power dissipations and device sensitivity. Especially, IoT networks are much more sensitive and connected devices require fast response time. The minimum delay and stable performance characteristics are the main attributes of the compensation technique over

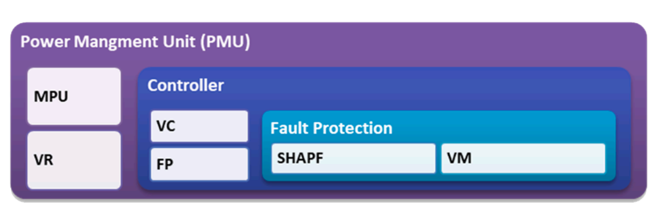

Fig. 3. PMU model of IoT.

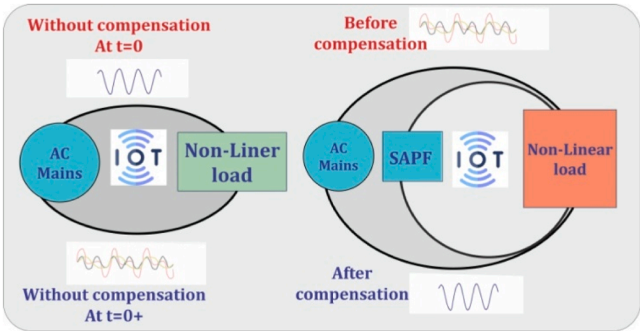

Fig. 4. Effect analysis under compensation.

uncertain harmonic agitation. One such technique is proposed as Takai Sugeno (TS) fuzzy rule-based adaptive neuro fuzzy interface system (TS-ANFIS) to not only train the system to respond according to training protocols but also to deal with fuzzy rule based uncertainty. Combining time series analysis with adaptive neuro-fuzzy techniques can be powerful for modeling and control, especially in applications like shunt Active Power Filters (APF). Before TS-ANFIS implementation, the basic modelling of harmonic distortions are described here. The mathematical model of this disturbance can be illustrated by the total harmonic distortion as a phasor sum of respective harmonic frequency current components [16–19]. The mean square is the common mathematical modelling of determination of the presence of higher harmonics current component and can be presented as D as shown in Eq. (1).

$$D = \frac{\sqrt{i_2^2 + i_3^2 + i_4^2 + \ldots + i_n^2}}{i_1} \tag{1}$$

The phenomenon behind the main control strategy is to filter out undesirable harmonic components of the current. Active, passive and hybrid filters are the choices to compensate for the harmonic current components in IoT nonlinear load devices. Regarding the demand for stable transient response of sensitive IoT devices, the SAPF compensation is better among the three. The nonlinear model of IoT devices is configured for basic parameters and the feedback control strategy generates hysteresis current control. Error detection, control and minimization are the key attributes of the control strategy as shown in Fig. 7.

The deviation in the compensation current and significant error is dealt with in the closed loop hysteresis current control (CLHCC) scheme. Consistent tracking of reference current is executed over the deviation in observed hysteresis current. The hysteresis current limits are defined for the upper high range and lower range for controlling the variable compensation current [20]. The functional and economic trade-offs of the power quality are the most significant attributes of the controller design. Here, the difference between reference and control entities is the respective equivalence of effective error due to the difference between positive and negative hysteresis [21–23]. This triggers to control of the action to SAPF to shift the controlling attributes over the side of the error coefficient (positive or negative). The adequacy of control depends upon schemes such as PI, PID, fuzzy, ANN, and advanced soft computing-based controllers [24]. The process flow is shown in Fig. 8. This will lead to another section for the development of the TS-ANFIS controller and its implementation to shunt active power filters for mitigation of harmonic current in PMU of IoT devices. The following are common steps to implement a TS-ANFIS model in the context of a shunt APF used for harmonic current mitigation in IoT devices.

Step 1: Define the Problem: Clearly define the problem you want to

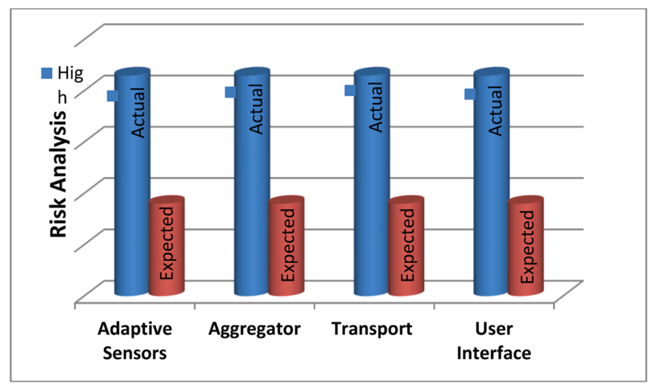

Fig. 6. Risk analysis of poor power quality in IoT devices.

Table 1
PMU parameters.

Particulars	Initial attributes
Input Feed	220 V, 50Hz
Capacitance DC	Cdc = 1200F
Range of Hysteresis band	0.5 Amp
Line resistance, inductance	Rs = 0.1ohm, Ls = 0.15mH
PID gain coefficient	KP = 0.032, KD = 0.01, KI = 0.00004
Balancing linear load	RL = 3ohm, LL = 70mH
Filter parameters	RF = .0001ohm, LF = 10mH
RLC components of nonlinear load	RN = 95ohm, LN = 1mH, CN = 470µF
Switching/Sampling Frequency	10 kHz-20 kHz

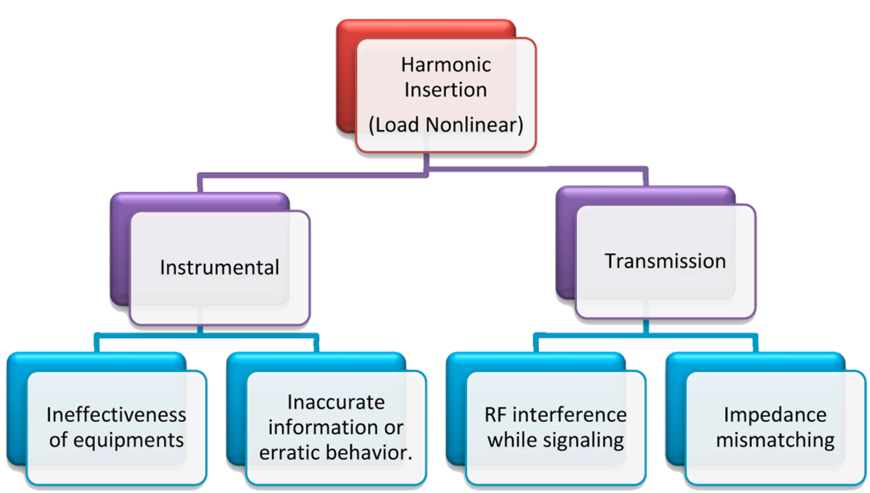

Fig. 5. Harmonic insertion effect and issues.

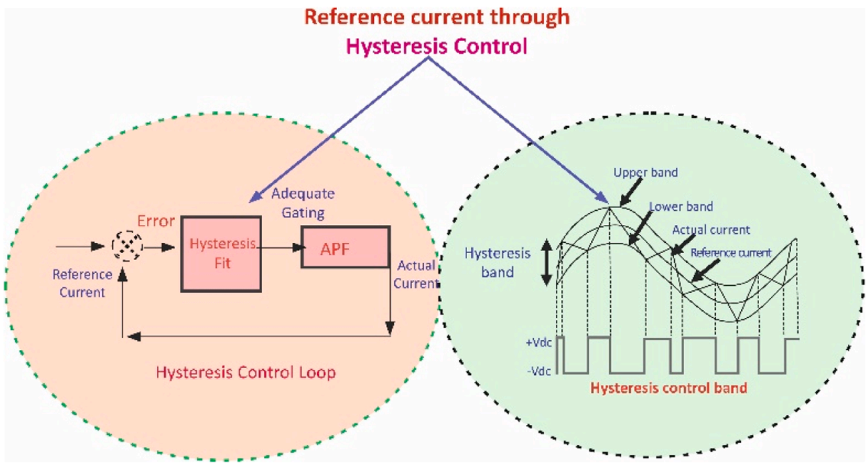

Fig. 7. Current compensation through Hysteresis control.

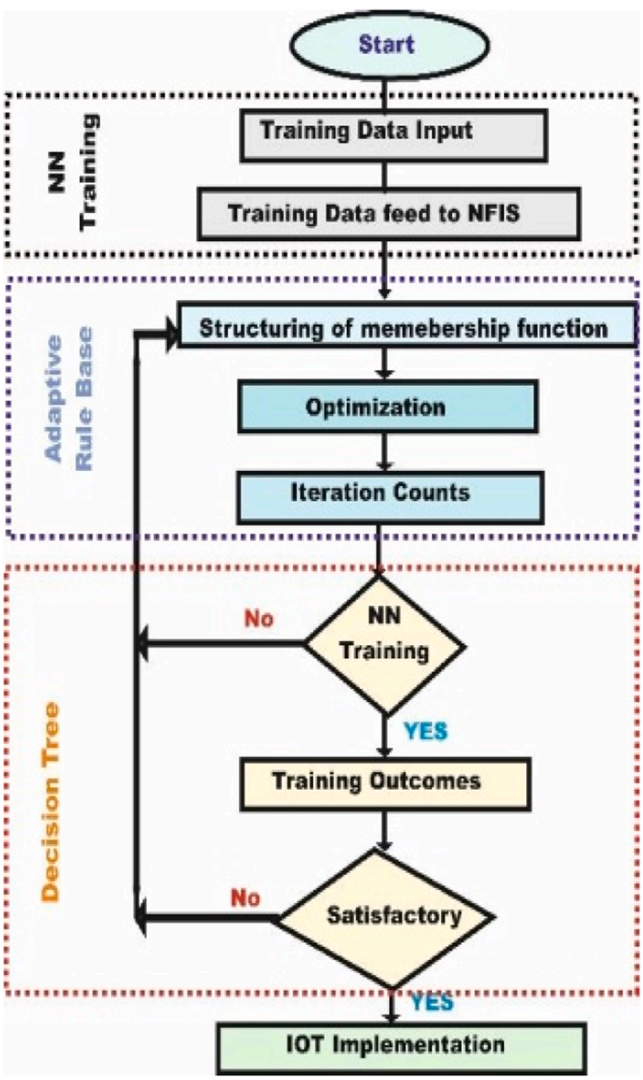

Fig. 8. process flow of ANFIS scheme.

solve using the TS-ANFIS model within the shunt APF context. Specify the performance metrics and goals you aim to achieve.

Step 2: Data Collection: Collect time-series data related to the power system, including voltage, current, harmonics, and other relevant parameters. This dataset will be used for training and testing the TS-ANFIS model.

Step 3: Preprocessing: Preprocess the collected data by cleaning, normalizing, and splitting it into training and testing sets. Ensure that the data is representative of various operating conditions.

Step 4: TS-ANFIS Model Architecture: Design the architecture of the TS-ANFIS model. It typically involves defining the number of fuzzy rules, membership functions, and the structure of the neural network. The time series aspect can be incorporated by considering temporal dependencies in the data.

Step 5: Training: Train the TS-ANFIS model using the training dataset. The training process involves adjusting the parameters (weights and biases) of the fuzzy system and neural network to minimize the error between the predicted and actual outputs.

Step 6 Validation: Validate the trained TS-ANFIS model using a separate validation dataset. This helps ensure that the model generalizes well to unseen data and is not overfitting.

Step 7: Testing: Evaluate the performance of the TS-ANFIS model using the testing dataset. Measure its ability to predict the desired outputs accurately for different operating conditions.

Step 8: Integration with Shunt APF: Once the TS-ANFIS model is trained and validated, integrate it with the shunt APF control system. The model's predictions can be used to adjust the parameters of the APF in real-time to optimize its performance for harmonic mitigation and power factor correction.

Step 9: Implementation Considerations: Address real-time constraints: Ensure that the TS-ANFIS model operates within the time constraints imposed by the shunt APF control system.

Hardware and computational efficiency: Consider the hardware specifications of the platform where the model will run and optimize the model for computational efficiency.

Step 10: Robustness: Validate the model's robustness against variations in operating conditions and potential disturbances

Step 11: Iterative Improvement: Monitor the performance of the integrated TS-ANFIS and shunt APF system in real-world conditions. If necessary, fine-tune the model or consider retraining it with updated data to improve its accuracy and adaptability.

The implementation details may vary based on the specific requirements of the shunt APF application and the characteristics of the power system it is intended to control. Additionally, relevant fields of application can provide valuable insights for specific implementation and parameter adjustments. The above strategy is integrated with the PMU of IoT devices and the implementation process is described in the next section.

5. ANFIS contoller implementation and harmonic mitigation

The ANFIS Shunt Active Power Filter (AFIS-APF) technique is a power quality enhancement method primarily used in power systems to mitigate harmonics and improve power factors. While its application in the Internet of Things (IoT) domain might not be direct, we can explore its adaptability and robustness in various scenarios related to IoT applications. IoT devices often have power supplies that may introduce harmonics. AFIS-APF can be adapted to mitigate harmonics in the power supply of IoT devices, ensuring clean power for efficient and reliable operation. Data centers supporting IoT applications require stable and high-quality power. AFIS-APF can enhance power quality by compensating for harmonic distortions and reactive power, ensuring the uninterrupted and reliable operation of IoT data centers. IoT devices are deployed in diverse environments with varying power conditions. AFIS-APF's adaptive nature allows it to respond to changes in the power system, providing robust performance under different operating conditions such as voltage fluctuations and load variations. Many IoT applications incorporate renewable energy sources. AFIS-APF can be employed to enhance power quality in systems where renewable sources introduce fluctuations, ensuring a stable and reliable power supply for IoT devices. IoT plays a crucial role in smart grids, and power quality is vital for their reliable operation. AFIS-APF can contribute to maintaining a stable grid by mitigating power quality issues arising from nonlinear loads in smart grid applications. Industrial IoT applications often involve dynamic and rapidly changing loads. The adaptability of AFIS-APF makes it suitable for compensating harmonic distortions and reactive power in real time, ensuring stable power conditions for industrial IoT devices. Some IoT applications operate in harsh environmental conditions. The robustness of AFIS-APF can make it suitable for maintaining power quality in challenging environments where power fluctuations and distortions may occur. The adaptability and scalability of AFIS-APF make it suitable for deployment in diverse IoT networks with varying power demands, ensuring that the technique can be tailored to meet the specific requirements of different IoT applications. When investigating the adaptability and robustness of AFIS-APF in different IoT applications, it is essential to consider the specific power quality challenges associated with each application and tailor the AFIS-APF parameters accordingly. Additionally, real-world testing and simulations can help validate the effectiveness of the technique in diverse IoT scenarios. Soft computing-based shunt APF can effectively mitigate harmonics, improving the power quality for IoT devices. This is particularly crucial for sensitive electronic components in IoT devices that may be affected by harmonic distortions. Soft computing techniques, such as fuzzy logic or neural networks, can enhance the adaptability of the APF to varying load conditions and harmonic profiles, making it suitable for dynamic and diverse IoT environments. The APF can contribute to power factor correction, leading to better energy efficiency in IoT devices and reducing reactive power losses. Soft computing algorithms can be integrated into IoT control systems seamlessly, allowing for real-time adjustments and optimization based on dynamic operational conditions. Soft computing approaches often exhibit a degree of fault tolerance, which can be beneficial in maintaining APF functionality even in the presence of uncertainties or disturbances in the power system. The flexibility of soft computing allows for customization of the APF parameters to address the specific power quality requirements of different IoT applications [20–22]. Soft computing algorithms, especially neural networks, may have high computational requirements. Implementing these algorithms in real-time on resource-constrained IoT devices might pose challenges in terms of processing power and energy consumption. Training soft computing models requires historical data and adaptation to changing conditions. Ensuring accurate and timely training in real-world IoT environments can be challenging due to evolving load patterns and system dynamics.

Soft computing techniques might introduce delays in decision-making or control actions, which can be critical in real-time applications. Ensuring that the APF responds promptly to dynamic changes in the power system is a significant challenge. Soft computing models may face challenges in generalizing well to diverse operating conditions. Robustness against variations in load characteristics and system parameters is crucial for reliable APF performance. Soft computing algorithms often rely on sensor data for accurate decision-making [23–25]. Ensuring the availability and reliability of relevant data from sensors in the IoT environment is essential for the effective operation of the APF. Implementing soft computing-based control in IoT devices raises security concerns, especially in applications where malicious attacks on the control algorithms could compromise the stability and effectiveness of the APF.

Integrating advanced soft computing algorithms may increase the cost and complexity of IoT devices, and this needs to be justified by the benefits gained in terms of improved power quality. In conclusion, while soft computing-based shunt APF approaches offer significant advantages in enhancing power quality for IoT devices, addressing the associated challenges is crucial for successful and practical deployment in real-world scenarios. This involves careful consideration of computational efficiency, real-time constraints, adaptability, and security. Additionally, ongoing research and advancements in soft computing and IoT technologies may contribute to overcoming these challenges over time [26–30]. The PMU model of IoT devices has been conceptualized in the previous section, and integration of an adaptive algorithm will be implemented in association with a PID-controlled shunt active power filter [31]. The motivation for the deployment of ANFIS is the performance gap of the traditional compensation control [32]. The electrical equivalence of the model is presented in Table 1, the system parameters are more generalized and influenced by the conventional IoT PMU model. The mathematical model of the linear and nonlinear load can be conceived through the resistive, inductive and capacitive load. The gap identification is extracted from the voltage-current characteristics of the onboard components of the devices. With the help of the above step rules of the fuzzy controller are decided, however the following are initially declared model parameters. Based on the training and learning capacity of the ANN model, if-then fuzzy rules are generated with adequate membership functions.

Adaptive learning elicits high precision efficiency and optimizes the performance coefficients of the auxiliary converter. The trained neural network helps to generate a triangular membership function to design a fuzzy rule. Table 2 shows the effect of prime actions on the model. The control model is shown in Fig. 9. The proposed work describes the hysteresis control technique as a primary current compensation. Fig. 9 consist of two major section, ne is the harmonic compensation through shunt APF, while the second is ANFIS controller. The controller has input feed (as 1, 2, 3 and 4 - go to controller) as an error signal (from, from1, from 2 and from3) or the deviation in current compensation, while ANFIS controller output is fed to shunt APF for gate triggering (go to g).

The graphics user interface (GUI) expresses the membership function and neural network training. The following process produces the desired soft-computing ANFIS algorithm;

Process 1: The collected data of the error signal creates the state variable.

Process 2: The error estimation and deviation signal jointly produce control variables of the fuzzy logic controller.

Table 2
ANFIS strategic implementation and impact analysis.

Scheme	Prime action	Efficacy
FLC	design of fuzzy rule based on membership function	deal with uncertainty
ANN	neural network training	trains FLC to create a rule
ANFIS	adaptive learning to interface between neural network and FLC	adaptive learning to minimize error and deal with uncertain stimuli

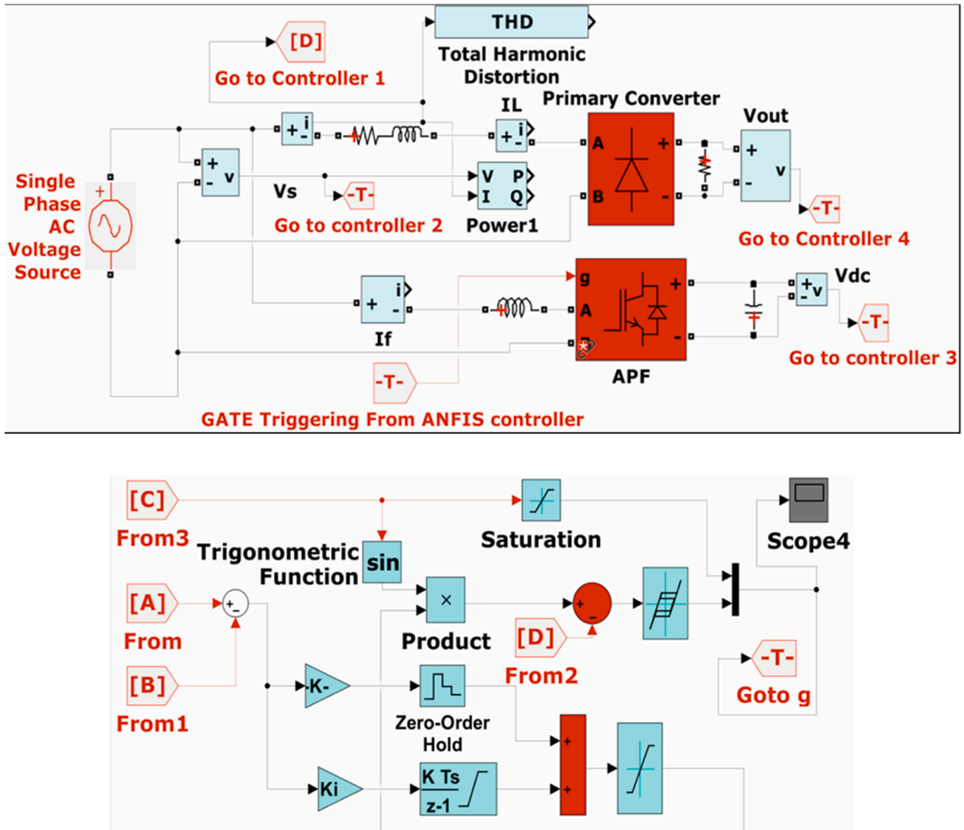

Fig. 9. Proposed compensation model.

Process 3: Based on neural network learning control variables are reconfigured for a respective number of epochs.

Process 4: The error and deviation in error are the two main arbitrary inputs provided to ANFIS.

Process 5: The number of epochs is set to reduce the RMSE.

Process 6: The trained ANFIS model is deployed to an auxiliary PMU converter.

A five-layered Takai Sugeno (TS) fuzzy rule-based FIS and neural network is shown in Fig. 10. The architecture shows layer management as the generation of input state variable on layer 1, rule conveys assignment on layer 2, defining of parameters on layer 3, strengthening of rules on layer 4 and decision refinement and deployment to the output signal. The independent and dependent nodes of the layered structure of the neural network depend upon the state variables and their dependencies on the chosen parameters. Dedicatedly, the dependent nodes are prominent to adjust the neuron weights concerning the change in the error signal.

Layer 1: Input feed as an error X1 & deviation in error X2;

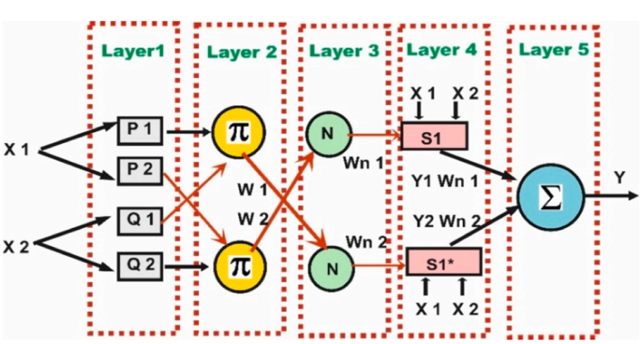

Fig. 10. Proposed ANFIS layer model.

Layer 2: Implementation of if-then Fuzzy Rule;

Layer 3: Hidden layer strengthens the neuron's weight;

Layer 4: Allow input feed to follow square law to minimize MSE;

Layer 5: Integrates all the incoming neurons from previous layers and validates the decision based on the threshold. The steps in the ANFIS control protocol were as follows:

Step 1: A matrix solution using values from a big data set is used to produce the state variable.

Step 2: The information base has been saved based on variances in hysteresis current control and error estimation. As a result, combinations of such state variables create FLC control variables.

Step 3: Using neural network adaptive learning, parameter reconfiguration for huge sets of data is obtained. The data captured on the MatLab workspace is fed in accordance with the predetermined values for epochs neuron training.

Step 4: ANFIS configuration is obtained when there are two defined arbitrary inputs.

Step 5: Epochs have been set, and the guidance fault is examined in relation to the drop curve. This prototype implements the Interface for real-time regression in MatLab and trains the network sufficiently.

6. Results, discussion & future scope

The effectiveness of the modeling of the compensation controller depends upon the analysis outcomes over three major phases. First, the determination of the extent of harmonic distortions under nonlinear modelling of IoT-PMU; second, compensation of harmonic current through shunt APF and third, the fitness of the ANFIS model to deal with error minimization. The modeling, simulation and cross-validation of the harmonic disturbance data set are executed on the MatLab workspace platform in association with python 3.0 IDE. The model is tested for various parametric values of the nonlinear PMU model of IoT devices and SHAPF compensation for hysteresis current control. The SHAPF excitation and phase synchronization depend upon the gate pulse injection, initialized by the adaptive controller. Fig. 11 shows the reference input feed voltage with standard AC parameters at 50 Hz fundamental frequency to PMU. However, as discussed and modelled power converters and load segments of IoT devices comprise the large number of onboard nonlinear components, and the effect of harmonic insertion is significant on distribution current as shown in Fig. 12.

The detailed description of harmonic ripples in the time domain distribution of distorted waves is shown in Fig. 13. The phasor sum of these flickers is the main cause of disturbances and reduces the overall quality of the power. The sensitive sensors receive an immediate impact on precision and response time due to these instantaneous flickers in the distribution current. The analytics show a very high rise in THD value and reaches to 72.8 % of the fundamental current component, this is determined through fast Fourier transform (FFT) as shown in Fig. 14.

The controller training response is shown in Fig. 15 to validate the performance of ANFIS control in terms of mean square error and epoch. The successive iteration reaches the best fit of the model and the mean square error reduces to a significant threshold. The successive iteration reaches the best fit of the model and the mean square error reduces to a significant threshold of error deviation. The iteration gradient reaches high values of epoch and achieves its goal of minimum MSE. This way controller performs an efficient task of harmonic filtration and achieves a quick switching speed. The prominent feature of the proposed model is the adaptive feature against power signal agitation. Based on the statistical analytics of harmonic distortion for a nonlinear load of IoT, compensation by SHAPF, controller action, and ANFIS algorithm, the model is validated and subjected to the real-time deployment of the model. A basic Arduino uno board is considered the main board of IoT devices and system SMPS is referred to as PMU for the system. The nonlinear load variation on the passive lamp load is recorded on a digital storage oscilloscope (DSO). Fig. 16 shows the USB port interfacing of the embedded board to the MatLab interface to run the ANFIS algorithm. The SHAPF bridge firing and equivalent response are analyzed to incorporate the dataset for the training of the neural network. MSE minimization is a target entity of the adaptive algorithm with parametric sustainability of other decision factors. The successful deployment of the proposed model yields the smoothening of the distributed current concerning the same input feed voltage. The respective power quality components are shown in Fig. 16 as distributed compensated current. The FFT analysis of the compensated current shows a significant fall in the THD component concerning fundamental frequency components. The effectiveness of the proposed model is validated by the 0.78 % THD value on the nonlinear IoT load model after the deployment of adaptive compensation. Fig. 17 shows the elimination of higher-order harmonics and improvement in the quality of power of the distributed current in the IoT system. To check the fitness of the trained model towards the target goal, a performance test is executed. Additionally, the transient response test is executed as shown in Fig. 18 and it shows that the model achieves a steady state in marginal delay time. The low settling time indicates the efficacy of the model for transient response. The model proves validated for adequate switching, error minimization, and adaptation to the uncertainty of electrical signal stimuli. Moreover, any incorrect deviation causes eventual fluctuation in SAPF performance, which is compensated for by these training qualities. The training sets and feed inputs are compared during the current compensation procedure to achieve the optimum performance. This results in the Analytical analysis of the system's brief response and training error is sufficient. The regression analysis is shown in Fig. 19 of the neural network.

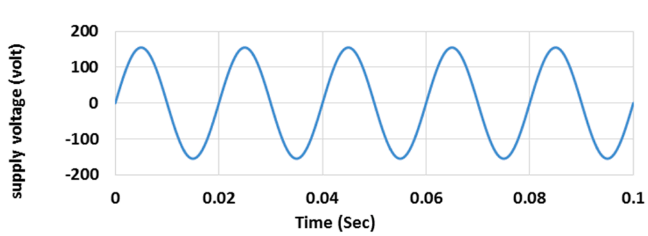

Fig. 11. Input supply voltage.

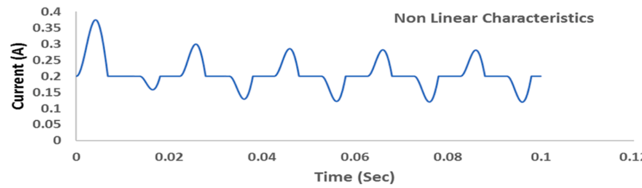

Fig. 12. Nonlinear effect on supply current.

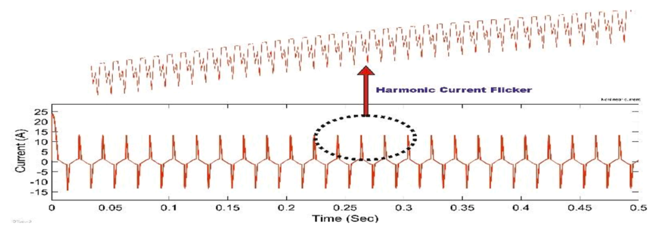

Fig. 13. Flickers in IoT devices due to harmonic insertions.

Fig. 20 illustrates how well the trained controller responses' transient stability and error deviation minimization were validated. It demonstrates that the system achieves its objectives in marginal epochs and stabilizes the gradients over time. With the IoT-based system, the initiator elicits a prompt and effective nonlinear disturbance reaction. The PMU (power management unit) of server terminals and IoT-based devices uses the soft computing technique to shunt APF excitation to compensate for harmonic disturbances. The suggested system's novel feature, self-additivity, significantly improves the power quality. The performance results are compared with the existing models and validated for their feasibility for smart IoT PMU. The descriptive analysis is shown in Table 3, it consists of the percentage THD concerning transient response time and power factor.

Based on the summary of Table 3, the proposed adaptive controller satisfies the mitigation strategies in nonlinear load smart IoT devices as per permissible limits of THD declared by the IEEE519 standards. Validation table indicates the scalability of the proposed work for real-world application. IEEE 519 standards allows device functionality under the permissible limits of THD as 5 %. The proposed work has novelty in terms of application in nonlinear load-based IoT devices for sensitive and sophisticated sensor-based applications. Fuzzy rule-based TS-ANFIS deals with signal stimuli under uncertainty of harmonic current insertion. The adaptive rule-based TS can be utilized for PMU integration for real-world systems in IoT devices.

However, the simulation results on MATLAB are quite acceptable and exhibit a good validation for real-world applications. For future validation, the model can be realized on real-time simulator OPAL-RT. Deploying a Soft Computing-based Shunt Active Power Filter (APF) approach in real Internet of Things (IoT) devices comes with several practical implications and challenges. Soft computing-based shunt APF can effectively mitigate harmonics, improving the power quality for IoT devices. This is particularly crucial for sensitive electronic components in IoT devices that may be affected by harmonic distortions. ANFIS-supervised shunt APF can enhance the adaptability of the APF to varying load conditions and harmonic profiles, making it suitable for dynamic and diverse IoT environments. The APF can contribute to power factor correction, leading to better energy efficiency in IoT devices and

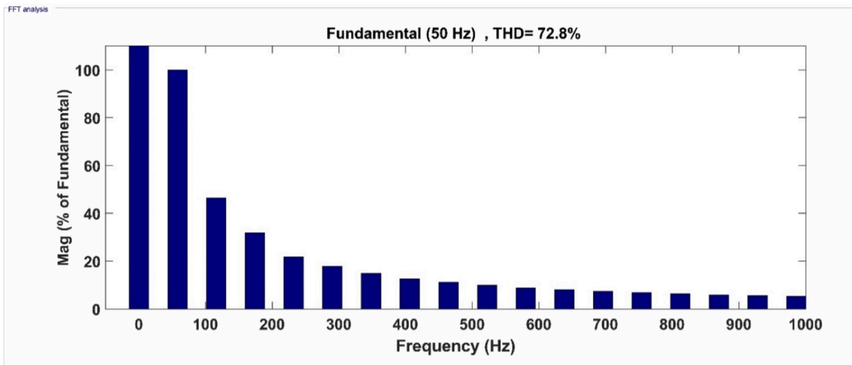

Fig. 14. FFT analysis of THD.

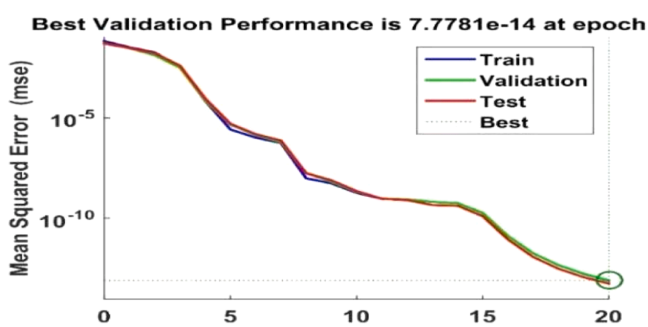

Fig. 15. MSE estimation.

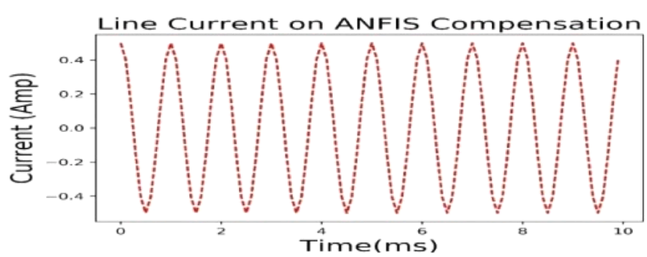

Fig. 16. ANFIS compensated current.

reducing reactive power losses. Soft computing algorithms can be integrated into IoT control systems seamlessly, allowing for real-time adjustments and optimization based on dynamic operational conditions. It often exhibits a degree of fault tolerance, which can be beneficial in maintaining APF functionality even in the presence of uncertainties or disturbances in the power system. The flexibility of TS-ANFIS allows for customization of the APF parameters to address the specific power quality requirements of different IoT applications. Especially neural networks may have high computational requirements. Implementing these algorithms in real-time on resource-constrained IoT devices might pose challenges in terms of processing power and energy consumption. Training soft computing models requires historical data and adaptation to changing conditions. Ensuring accurate and timely training in real-world IoT environments can be challenging due to evolving load patterns and system dynamics. It might introduce delays in decision-making or control actions, which can be critical in real-time applications. Ensuring that the APF responds promptly to dynamic changes in the power system is a significant challenge. Soft computing models may face challenges in generalizing well to diverse operating conditions. Robustness against variations in load characteristics and system parameters is crucial for reliable APF performance. TS-ANFIS algorithms often rely on sensor data for accurate decision-making. Ensuring the availability and reliability of relevant data from sensors in the IoT environment is essential for the effective operation of the APF. Implementing soft computing-based control in IoT devices raises security concerns, especially in applications where malicious attacks on the

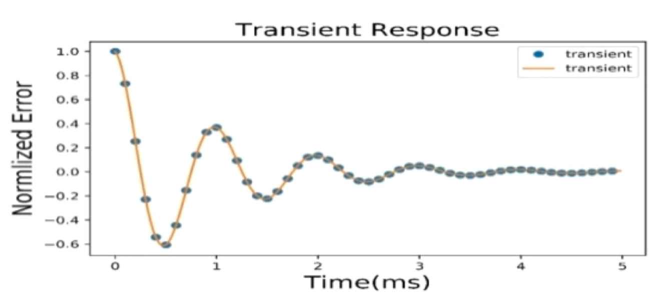

Fig. 18. Stability analysis of proposed SHAPF.

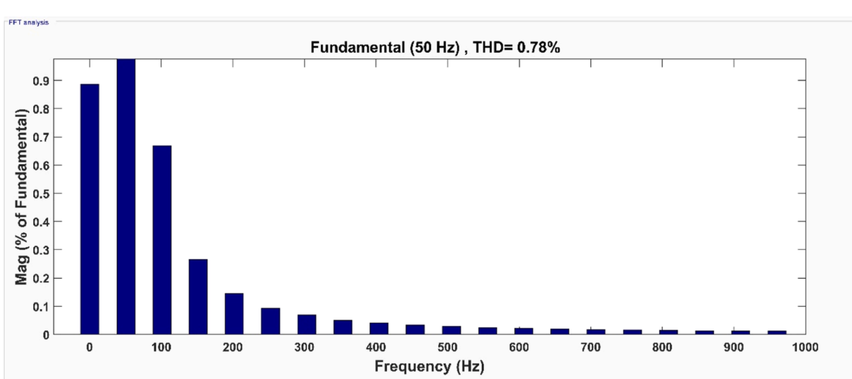

Fig. 17. FFT analysis of THD on ANFIS deployment.

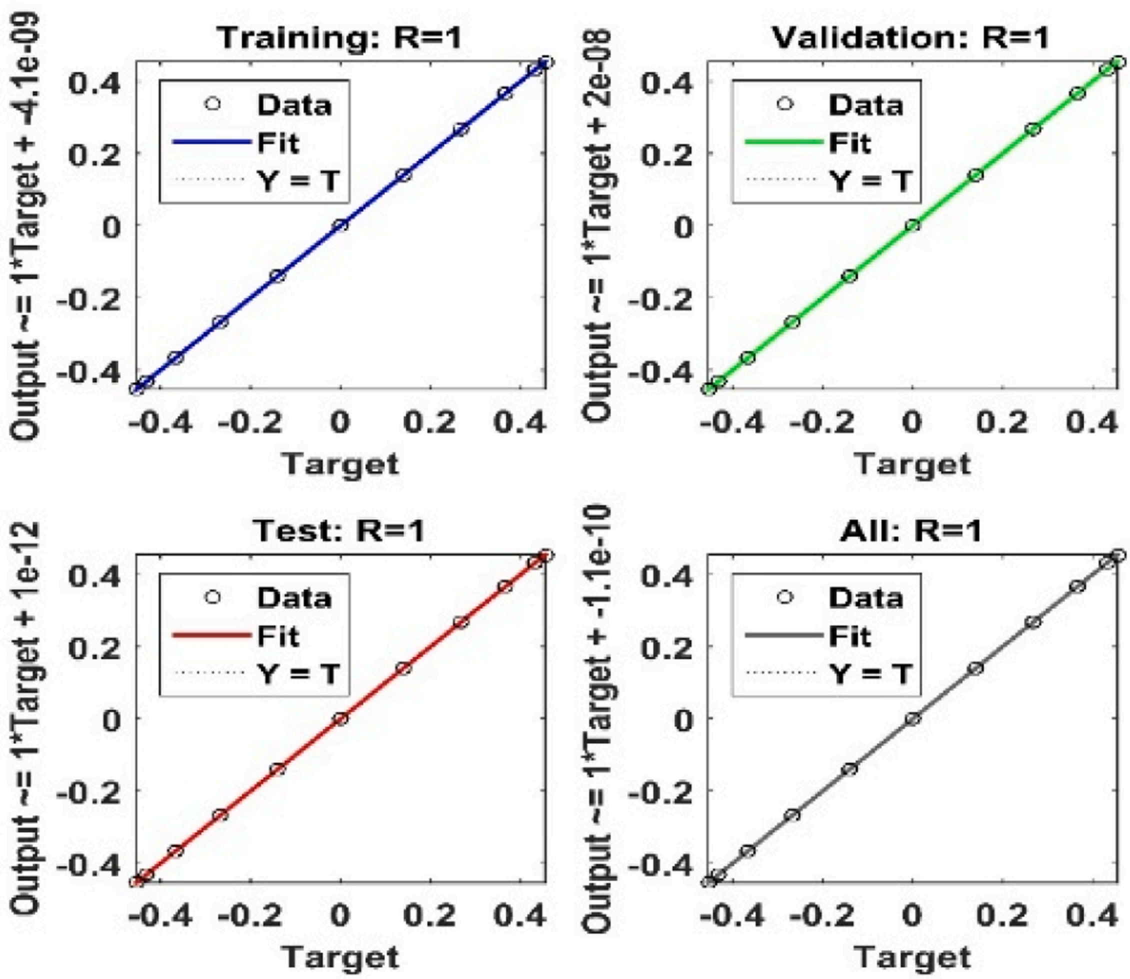

Fig. 19. Regression analysis of NN training.

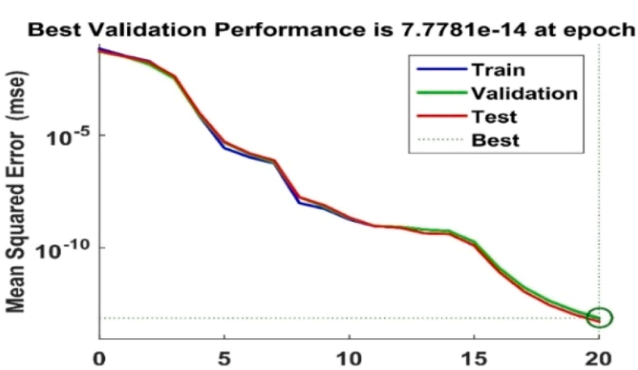

Fig. 20. Training evaluation and ANFIS control performance validation.

control algorithms could compromise the stability and effectiveness of the APF. Integrating advanced soft computing algorithms may increase the cost and complexity of IoT devices, and this needs to be justified by the benefits gained in terms of improved power quality. In conclusion, while TS-ANFIS shunts APF approaches offer significant advantages in enhancing power quality for IoT devices, addressing the associated challenges is crucial for successful and practical deployment in real-world scenarios. This involves careful consideration of computational efficiency, real-time constraints, adaptability, and security. Additionally, ongoing research and advancements in soft computing and IoT technologies may contribute to overcoming these challenges over time.

7. Conclusion

The nonlinearity of load is observed as a prime cause of harmonic distortions in IoT devices and the increasing demand for a network of devices has raised severe issues of power quality. The onboard nonlinear components cause the low sensitivity and malfunctioning of the IoT devices due to the insertion of higher-order harmonics of distribution current. The adaptive ANFIS supervised PID controlled SHAPF is modeled, trained, tested for nonlinear IoT prototypes, and deployed successfully. The process involved the development of adequate SHAPF, design of the controller, training of the neural network, deployment of fuzzy rules, and minimization of mean square error. The proposed model mitigates the harmonics on the nonlinear load model for a value of 72.8 % to 0.78 %. This is a remarkable compensation of THD in PMU of IoT devices and comes under the permissible limit of IEEE 519 standard of 5 % to protect against malfunction of devices. However, sensor-based smart devices elicit more attention towards the minimization of THD, therefore the proposed scheme is the best fit for controlling harmonic distortion in IoT devices. The TS-ANFIS supervised PID controlled SHAPF is an auxiliary compensation system and is feasible to deploy with the main converter unit of the PMU of IoT devices in real-time applications.

Table 3
proposed work validation table.

THD (%)	Switching Frequency	Power Factor consideration	Design Scheme	Remarks	Refs.
6.52%	-	More reactive losses	Switching Cell (CSC) converter-PFC	High THD is not suitable for IoT devices	[19]
2.5 %	33 MHz	The power factor is low	APF compensation through PI and PID	Extremely high switching frequency affects the sensitivity of sensors.	[20]
3.5 %	16kHz	Need to be discussed	DSTATCOM-DSP	Complexed design architecture not feasible for IoT	[21]
4.5 %	5kHz	0.79 not adequate	DSTATCOM-PI	Complexed design architecture not feasible for IoT	[22]
2.1 %	8kHz	Approaching to unity	TSh-APF	Unable to deal with uncertainty and bulky	[23]
0.97 %	20 kHz	0.97	ANFIS-APF	Low portability	[24]
3.47 %	12kHz	Need to elaborated	Sh-APF with solar hybrid	Switching frequency is a constraint	[25]
0.9 %	12 kHz	Adequacy is sustainable	SHAPF with P-SSI	MSE = 0.15 RMSE = 3.17 significant reduction in error.	[26]
3.59 %	–	UPQC	UPQC-PAC	High THD not feasible for IoT devices.	[27]
1.83 %	–	Need to be highlighted for reactive power	SCIG -PMSG	Massive and not compatible for sophisticated PMU	[28]
0.81%	10MHz	Expression is not expressed	Adaptive converters for conventional devices	IoT requires soft computing sensitive controllers	[30]
0.78%	10KHz	Least THD with Improved Transient response and power factor improvement from 0.653 to 0.999.	TS-ANFIS	Feasible for sensitive devices and uncertainty	Proposed

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Voas, J. NIST special publication 800-183. Networks of 'Things', 2016. Available online: https://csrc.nist.gov/publications/detail/sp/800-183/final.

[2] S. Kewat, B. Singh, Modified amplitude adaptive control algorithm for power quality improvement in multiple distributed generation system, IET Power Electron. Vol. 12 (Iss. 9) (2019) 2321–2329.

[3] X. Jinwei He, Y.W. Li, Active harmonic filtering using current-controlled, power control, IEEE Trans. Power Electron. 29 (2) (2014) 642–653.

[4] J.P. Bonaldo, H.K.M. Paredes, J.A. Pomilio, Control of single-phase power converters connected to low-voltage distorted power systems with variable compensation objectives, IEEE Trans. Power Electron. 31 (3) (2016) 2039–2052.

[5] T.D.C. Busarello, J.A. Pomilio, M.G. Simões, Passive filter aided by shunt compensators based on the conservative power theory, IEEE Trans. Ind. Appl. 52 (4) (2016) 3340–3347.

[6] S. Hu, Y. Li, B. Xie, M. Chen, Z. Zhang, L. Luo, Y. Cao, A. Kubis, C. Rehtanz, A Y-D multi-function balance transformer based power quality control system for single-phase power supply system, IEEE Trans. Ind. Appl. 52 (2) (2015) 1270–1279.

[7] G. Goswami, P.K. Goswami, ANFIS supervised PID controlled SAPF for harmonic current compensation at nonlinear loads, IETE J. Res. (2020), https://doi.org/10.1080/03772063.2020.1770134. June.

[8] Y. Singh, I. Hussain, S. Mishra, B. Singh, Adaptive neuron detection-based control of single-phase SPV grid integrated system with active filtering, IET Power Electron. Vol. 10 (Iss. 6) (2017) 657–666.

[9] S. Agrawal, D.K. Palwalia, M. Kumar, Performance analysis of ANN based three phase four-wire shunt active power filter for harmonic mitigation under distorted supply voltage conditions, IETE J. Res. (2019), https://doi.org/10.1080/03772063.2019.1617198.

[10] G. Goswami, P.K. Goswami, Energy efficient ANFIS supervised ShAPF for harmonic mitigation in PV based micro-grid & smart electrical systems, Water Energy Int. 66r (8) (2023) 36–41. A-366.

[11] A. Sharma, G. Goswami, Adaptive learning-based controller to mitigate energy losses in internet of things devices and power quality improvement, Water Energy Int. 66r (6) (2023) 44–52.

[12] Gupta, U.K., Sethi, D., Goswami, P.K., Goswami, G., Gautam, K."Harmonic distortions in smart devices: a comprehensive survey from conventional to future smart IoT devices" Adaptive Power Quality for Power Management Units using Smart Technologies, 2023, pp. 175–196.

[13] B. Ahmad, G. Goswami, M.F. Khan, implementation of automatic excitation initiator circuit using microcontroller based plc for standalone induction generator, Water Energy Int. 65r (9) (2022) 29–36. A –290.

[14] B. Ahmad, G. Goswami, M. Khan, Implementation of automatic excitation initiator circuit using microcontroller based PLC for standalone induction generator, Water Energy Int. 65 (9) (2022) 29–36.

[15] International Electrotechnical Commission, Electromagnetic Compatibility (EMC). Part 4-7: Testing and Measurement Techniques—General Guide on Harmonics and Inter Harmonics Measurements and Instrumentation, For Power Supply Systems and Equipment Connected Thereto, IEC 61000-4-7:2002+A1:2008, IEC, Geneva, Switzerland, 2018.

[16] S.M. Blair, C.D. Booth, G. Williamson, A. Poralis, V. Turnham, Automatically detecting and correcting errors in power quality monitoring data, IEEE Trans. Power Deliv. 32 (2) (2017) 1005–1013.

[17] E. Dehnavi1, S. Afsharnia1, K. Gholami, Optimal allocation of unified power quality conditioner in the smart distribution grids, Electr. Eng. (springer) (2019), https://doi.org/10.1007/s00202-019-00861-2. November.

[18] G. Goswami, P.K. Goswami, Power quality improvement at nonlinear loads using transformer-less shunt active power filter with adaptive neural fuzzy interface system supervised PID controllers, Int. Trans. Electr. Energ. Syst. (2020) 1–14, https://doi.org/10.1002/2050-7038.12415.

[19] B. Singh, S. Pal, A. Shrivastava, A universal input PFC CSC converter in low power consumer lighting applications, IETE Tech. Rev. (2019), https://doi.org/10.1080/02564602.2019.1645621.G, 07 Aug.

[20] P. Karuppanan, K. Mahapatra, PI, PID and fuzzy logic controlled cascaded voltage source inverter based active filter for power line conditioners, WSEAS Trans. Power Syst. 6 (4) (2011) 100–109.

[21] M. Badoni, A. Singh, B. Singh, Control algorithm for DSTATCOM, IEEE Trans. Power Electron 30 (5) (2015) 2353–2361.

[22] S.R. Arya, R. Niwas, K.K. Bhalla, B. Singh, A. Chandra, K. Al-Haddad, Power quality improvement in isolated distributed power generating system using DSTATCOM, IEEE Trans. Ind. Appl. 51 (6) (2015) 4766–4774.

[23] A. Javadi, A. Hamadi, A. Ndtoungou, K. Al-Haddad, Power quality enhancement of smart households using a multilevel-THSeAF with a PR controller, IEEE Trans. Smart Grid 8 (2016) 465–474.

[24] Kumar R., Bansal H.O., "Real-time implementation of adaptive PV-integrated SAPF to enhance power quality" International Transactions on Electrical Energy Systems-Wiley, 2019, 10.1002/2050-7038.12004.

[25] V.N. Jayasankar1, U. Vinatha, Advanced control approach for shunt active power filter interfacing wind-solar hybrid renewable system to distribution grid, J. Electr. Syst. vol.14 (2) (2018) 88–102.

[26] S. Nelson, R. Helder, O. Flavio, C. Wanderley, C. Daniel, P. Esequie, A proposal to power quality improvement based on SHAPF with P-SSI controller parameters optimized by multi-objective optimization and applied through gain scheduling technique, Electr. Power Syst. Res. 177 (2019), https://doi.org/10.1016/j.epsr.2019.105939. December.

[27] A. Patel, H.D. Mathur, S. Bhanot, An improved control method for unified power quality conditioner with unbalanced load, Electr. Power Energy Syst. 100 (2018) 129–138, https://doi.org/10.1016/j.ijepes.2018.02.035.

[28] R. Mishra, T.K. Saha, Modelling and analysis of distributed power generation schemes supplying unbalanced and non-linear load, Electr. Power Energy Syst. 119 (2020) 105878.

[29] H. Zang, L. Cheng, T.D. Kwok, W. Cheung, Z. Wei, G. Sun, Day-ahead photovoltaic power forecasting approach based on deep convolutional neural networks and meta learning, Electr. Power Energy Syst. (2020), https://doi.org/10.1016/j.ijepes.2019.105790. June.

[30] G. Goswami, P.K. Goswami, Self-adaptive learning based controller to mitigate PQ issues in internet of things devices, Int. Trans. Electr. Energ. Syst. (2021) e12888, https://doi.org/10.1002/2050-7038.

[31] T. Han, K. Muhammad, T. Hussain, J. Lloret, S.W. Baik, An efficient deep learning framework for intelligent energy management in IoT networks, IEEE Internet Things J. (2020), https://doi.org/10.1109/jiot.2020.3013306, 1–1.

[32] S. Nelson, R. Helder, O. Flavio, C. Wanderley, C. Daniel, P. Esequie, A proposal to power quality improvement based on SHAPF with P-SSI controller parameters optimized by multi-objective optimization and applied through gain scheduling technique, Electr. Power Syst. Res. Vol.177 (2019), https://doi.org/10.1016/j.epsr.105939. Dec.

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