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Research on intelligent auxiliary regulation technology of large power grid section based on artificial intelligence

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Abstract: - In the modern era, large-scale renewable energy systems are integrated with advanced power systems and provide efficient operations. Also, optimized power systems require accurate energy generation and effective control systems to manage and ensure a stable power supply. Nevertheless, uncertainties are the intermittent balance of supply and high electricity demand. In addition, conventional power sources are not applicable for this challenging task and increase electricity costs. Therefore, an efficient Neuro Fuzzy Single phase Unified Power Quality Conditioner with Maximum Power Point Tracking (NF-SP UPQC -MPPT) strategy is developed for enhancing the grid-connected power systems. Here, Neuro-fuzzy logic is used as dynamic reactive power compensation in the grid. Also, this logic can efficiently handle the Energy storage system (ESS). Then SP UPQC was used to enhance power quality in electrical distribution systems. It combines both series and shunt compensators to mitigate various power quality issues such as voltage sags, harmonics, and unbalance. After that MPPT was utilized to extract the maximum power from the grid system. Model Predictive Control (MPC) controller to determine the overall stability and performance of the system. Moreover, the developed model was implemented on the MATLAB platform and performance is analyzed in terms of voltage deviation, grid current, reactive power fluctuations and Total Harmonic Distortion (THD).

Keywords: Energy storage system, large scale renewable energy systems, Neuro Fuzzy, grid connected power systems, voltage sags, harmonics, unbalance, Maximum Power Point Tracking, Model Predictive Control, Single phase Unified Power Quality Conditioner

1 Introduction

Environmental safety and serious pollution are caused by the careless use of nuclear power and hydrocarbons [1]. The world is shifting to environmentally safe renewable energy sources, such as photovoltaic (PV), wind, and other technologies, in light of the reality of this energy source [2]. Because of the emphasis on clean power generation, distributed electricity generation systems made of renewable energy have attracted a lot of attention. The commercial and household sectors have quickly embraced solar photovoltaic (PV)-based renewable energy generation as a result of recent breakthroughs in photovoltaic technology [3]. The integration of distributed solar photovoltaic (PV) generation systems can provide several advantages to the distribution grid, such as decreased load on the main power system, maximum savings, and support for reactive power [4]. As solar PV power reduces the load on the central grid, it also improves power quality and reliability [5]. When non-linear loads are used more frequently, the energy quality typically decreases. Similarly, it is well acknowledged that electronic power equipment comprises the majority of non-linear loads that require reactive power and generate more complicated harmonics [6]. The voltage distortion resulting from this behaviour affects all further loads that are connected to the same PCC [7].

The inconsistent sun irradiation prevents solar photovoltaic inverters from functioning to their maximum potential. Reducing source current harmonics and correcting reactive load power are two examples of auxiliary services that can be provided by the inverter's excess capacity [8]. MPPT is widely utilised in PV-integrated systems to

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minimise harmonics. For example, the integrated sliding mode control improved adaptive P&O (perturb and observation) MPPT algorithm was used to minimise the grid current harmonics of a PV system [9].

Auxiliary regulation involves the adjustment of power system parameters to counteract fluctuations, imbalances, and disturbances that impact grid stability. But the grid operates within acceptable limits and responds effectively to changes in demand and generation [10]. It involves adjusting power generation or consumption to maintain the grid frequency within specified limits. Focuses on maintaining voltage levels within acceptable ranges to ensure the proper operation of electrical devices. Balances the generation and consumption of active and reactive power to optimize system performance [11]. Traditional methods such as Deep leaning (DL) [12], Machine leaning (ML) [13], etc. These systems are frequently investigated as potential instruments for power system forecasting, optimisation, and control performance. Numerous system functions are still carried out at low levels of automation at the moment since there is a shortage of advanced automation infrastructure. An increasing amount of research, technical reports, and case studies predict that artificial intelligence (AI) will be a major component of the power system of the future, reducing the need for manual intervention and introducing cutting-edge methods of system optimisation. Currently, the majority of research focuses on using AI to optimise power flow inside grid systems.

The organization of the presented research work is sequenced as below; the research articles related to the developed framework are described in section 2, the problem statement are described in section 3, the proposed hybrid framework is explained in section 4, the outcomes of the proposed methodology were analyzed in section 5, and the research conclusion is described in section 6.

2. Related works

Virtual power plants are the integrated distributed system to enhance the electricity supply as well as flexibility. But that are cannot applicable for long term use so, Liu et al, [14] have introduced a demand side frequency control strategy to improve the stability of the system. Here, renewable energy systems are considered as future direction of power grid for further enhancing the reliability of the power imbalance systems. However, high power capacity can cause the system efficiency.

Traditional power generation systems are lacks the efficient energy storage system for the continues power generation. Therefore, Mehdi et al [15] have developed the hybridized energy storage system with DC microgrid for manage the PV and wind energy system. Also, Artificial Neural Networks are utilized to train the datasets such as temperature and solar irradiance. Then, to regulate the output DC voltage integral terminal sliding mode controller is used. After that, Lyapunov stability is applied to enhance the overall system stability.

Advance controller algorithms are provides better frequency support for the grid regulation systems. However, electricity transmission and energy penetrations varying according to the system frequency. Thus, Akpinar et al,[16] have introduced grid connected BESS for applying different conditions. Consequently fuzzy logic is adapted to make the best decision for the power output and manage the algorithms. Here, 2MW or 1MWh power is considered and optimally enhance the state of charge conditions.

Increasing demand of HESS like solar and wind system has connected with electricity grid for analysing the power quality issues. Therefore, Vineeth al, [17] have developed the multi converter based Unified Power Quality Conditioner (UPQC) to reduce the power quality issues in three categories. Initially, power quality is analysed and verify the reliability of the power supply system. Finally, UPQC model is linked in voltage source converter in parallel structure to compensate the voltage and current issues.

To enhance the power quality Modular Multilevel Converter (MMC) is integrated with UPQC model proposed by et al, [18]. It has mitigated the THD and reduce the DC voltage as well as voltage regulation system. Moreover, compound control algorithm is adapted in shunt active power filter to manage the non-linear load system. Consequently, input and output systems are mapping with the fuzzy rules to validate the system performance.

3. Motivation

By growing the demand of large power grid connected system can faces so many challenges such as power quality, stability, reliability and power supply management. Also, power quality issues can damages or malfunctions the overall system performance due to the fluctuations. According to the power consumption and generation frequency variations may be imbalanced [19]. Then, power factor issues like low power factor can leads to cause the increased energy consumption, higher power losses from the power distribution system. Non-linear and linear faults are occur due to the voltage instability [20]. Power grid systems are continuously utilized the inadequate control mechanism so the resultant voltage regulation can be poor. Regulations and standards that define acceptable power quality levels also play a crucial role in ensuring the reliability and performance of large power grids [17]. Therefore, an effective intelligent auxiliary regulation technology is required to reduce the challenges on grid systems.

4 Proposed methodology

The proposed work aims to propose an intelligent algorithm for the grid connected PV systems for controlling the power quality issues. The developed approach named as Neuro Fuzzy based Single phase UPQC with maximum power point tracking (NF-SP UPQC -MPPT) strategy, which is mentioned in fig.1. Here, Model Predictive control (MPC) is used to enhance the grid stability, energy management and efficiency. Also, MPC creates the control signals for minimizing the harmonics current. Why because grid connected PV systems are efficiently transferred the energy source from electricity generation system.

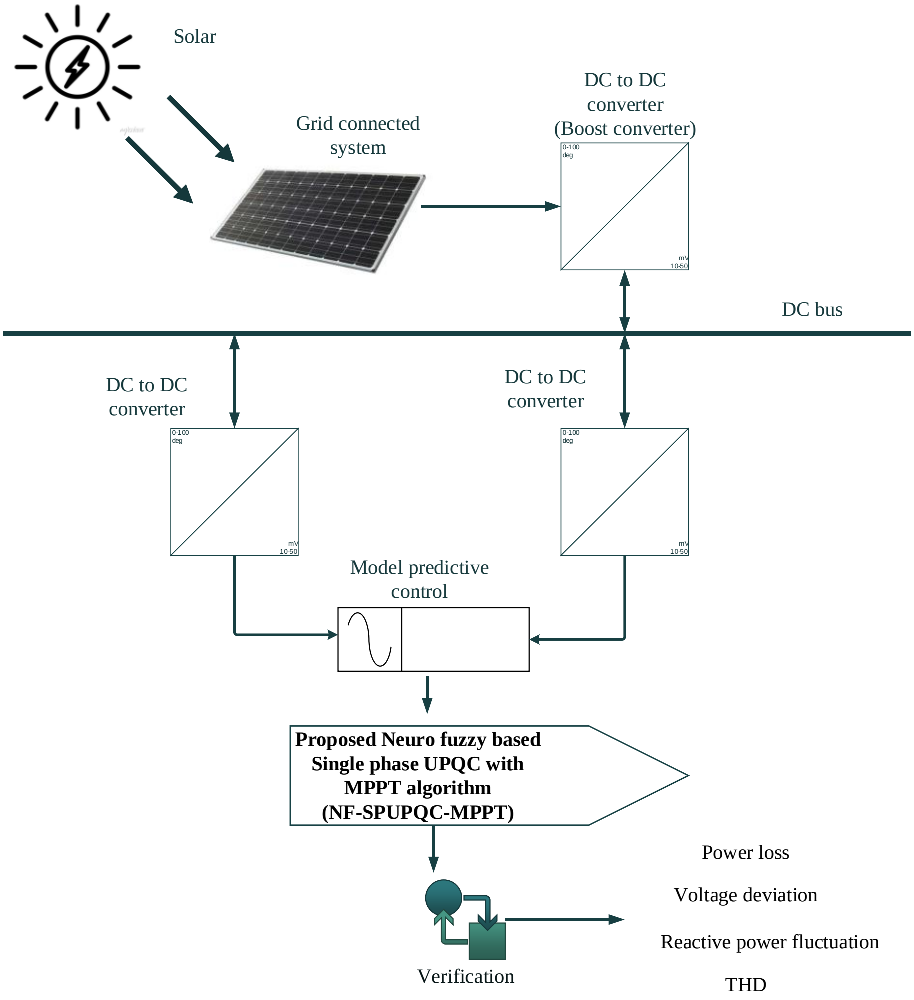

Fig.1 proposed NF-SPUPQC-MPPT model

Furthermore, the developed NF-SPUPQC –MPPT algorithm has mitigate the power quality problems kike voltage distortions, THD, power fluctuations of the grid connected PV systems. Initially, solar energy is captured and transformed into the PV panels then convert it into the electric power. Moreover, PV panels are creates the direct current (DC) so, DC-DC boost converter is adapted with the DC bust system. Then MPPT algorithm was enabled to track the maximum power from the PV panels and adjust the voltage level to match the required level. After that DC power is converted in AC power using DC-AC converter. Secondly, the SP UPQC model is mitigate the current and voltage problems due to the power distribution process. Finally the performance is analyzed in terms of power loss, voltage deviation, , reactive power fluctuation and THD.

4.1 Neuro Fuzzy based Single phase UPQC

In order to obtain the optimal hybrid energy mix at the lowest possible cost, the energy regulation operation was implemented using the fuzzy logic model. Based on the pre-determined rules, the fuzzy logic system uses linguistic parameters at the point of inference to make intelligent control decisions. The input data are first fuzzified to the Membership Function (MF), followed by the method of inference with the rules, and finally the defuzzification stage in the implementation phases. The time of day, at daily energy cost, the solar PV, battery status, and grid power are the four input factors used by the fuzzy logic operation to make decisions. Then update the fuzzy logic to control the power loss as well as minimize the energy cost of the designed Grid connected PV system using eqn. (1),

$$f(n)=\begin{cases} C'_j(n)(n-\Delta n)\cup[EV(\Delta n)], & if\ n^f \le n \\ W'_{ess}(\Delta n)[EV(\Delta n)] & if\ n^f \le n \\ f(n)\ \ otherwise & \end{cases} \tag{1}$$

Where, Δn is denoted as fuzzification process membership function, here, the fuzzy classification system enables the fuzzification output variables. Control variables are normalized as fuzzy rules to verify the energy loss and cost function. The iteration is continued until it reaches the finest solution. The fuzzy section of the input MF layer: At this point, the pre-processed, fine-tuned data has been incorporated into the model, where each input x_i in this layer is an adaptive MF to produce the linguistic variables' membership degree. Here triangular MF has used to reflect the three variables as p, q, r that is p<r<q, which is described in below eqn. (2),

$$\mu_p x)=\begin{cases} 0, if\ \ x \le p \\ \dfrac{x-p}{r-a}, if\ \ p < x \le r \\ \dfrac{q-x}{q-r}, if\ \ r < x \le q \\ 0, if\ \ q \le x \end{cases} \tag{2}$$

Neuro-fuzzy classification systems provide a way for a learning algorithm to provide fuzzy classification rules. By learning from data, a good fuzzy classifier can typically be found; however, obtaining a classifier that is easily interpretable can be challenging. After that predict the Grid connected PV charge using below eqn. (3),

$$\begin{cases} Cg(n)=1\ ; & if\ G(n)\ is\ higher\ P_d \ge SoC_g \\ D_g(n)=0\ ; & otherwise \end{cases} \tag{3}$$

Where, C_g and D_g is denoted as charging and discharging power of Grid connected PV system respectively.

Moreover, P_d is power demand Grid connected PV charging station with objective function and SoC_{EV} is denoted as sate of charge of Grid connected PV charging station.

4.2 Maximum Power Point Tracking (MPPT)

The dual function of the DC-DC boost converter is to control the output of PV cells. It guarantees accurate control over the output voltage and makes MPPT easier. In order to maximise power extraction from PV panels, a DC-to-DC converter is combined with the commonly used MPPT algorithm in this work. In order to account for changing climatic circumstances, this entails dynamically altering the operational point to the Maximum Power

Point (MPP). The MPC algorithm was selected for MPPT because of its affordability and ease of use. To predict the effect of a voltage adjustment, the MPC algorithm measures minute variations in the PV array's voltage and current. Although this method requires more processing power, it can quickly adjust to changing circumstances. In that energy storage device some energy is stored in time seconds and also it is evaluated using discharged as well as charged power of the storage device. Moreover, charging and discharging rates of the constrains is integrated with battery efficiency during all periods, which is described in following eqn. (4)

$$W'_{ess}(n) = W'_{ess}(n-1) + \alpha_c p'_c \Delta n - \frac{1}{\alpha_d} p'_d \Delta n$$

$$\begin{cases} W'_{ess} \le W'_{ess}(n) \le W'_{ess}.\max \\ p'_c(n) \le p'_{c.\max} \\ p'_d \le p'_{d.\max} \end{cases} \tag{4}$$

Where, W'_{ess} is denoted as energy storage constraints, p'_c is charging power, p'_d discharging power, α_c is battery efficiency charging and discharging of the storage device system.

- ***Cost function***

To design the net cost function of the jth grid system with the help of three important elements such as 1) discharging rate and its energy of each grid system, 2) discharging rate with degradation cost of battery, 3) operation cost of other functions such as service chargers, cable wear, etc. Initially, denote the grid system discharging rate using following eqn. (5)

$$U_j \left[C'_j(n)\right] = p'(n) C'_j(n) \tag{5}$$

Where, unit price is represented as $p'(n)$ with grid aggregator at time n, $C'_j(n)$ is denoted as discharging rate of each grid system at particular time n. here, more energy is dissipated at the grid system to indicate the level of obtained aggregator grid system. So, degradation cost is enabled in grid power station to meet the specific requirement id discharging point of grid system. Moreover, quadratic function is used to modelled the degradation cost which is enabled in eqn. (6),

$$d'_j \left[c'_j(n)\right] = \delta_j c'_j(n)^2 + \mu_j c'_j(n) + \lambda_i \tag{6}$$

Where, δ_j, μ_j and λ_i is denoted as operational cost parameters, degradation cost function is expressed as $d'_j \left[c'_j(n)\right]$. Here, the operational cost parameters are weakly integrated with discharging rate of grid system so, constant value must be correlated with discharge rate of grid system. But, the simplicity of cost function be related with following context using eqn. (7),

$$f'_j \left[c'(n), p'(n)\right] = d'_j \left[c'(n)\right] + o'_j - U_j \left[C'_j(n)\right] \tag{7}$$

Where, o'_j is denoted as lumped cost function. Here, net cost rate of the grid system is delivered the power as per the electricity price unit with off-peak time tariff or peak-time tariff. Moreover, the original cost function is deviated into the fixed price unit.

4.3 Design of MPC

The derived reference grid currents are thoroughly assessed, accounting for a number of variables including dynamic fluctuations in PV power, DC link voltage control, and the existence of nonlinear loads at the Point of Common Coupling (PCC). The MPC controller receives this reference current as an input and determines the amount of switching pulses needed for optimal operation. The system may efficiently provide reference grid currents that support efficient operation by taking into account the dynamic variations in PV power, guaranteeing stable regulation of the DC link voltage, and accommodating nonlinear loads at the PCC. The MPC controller uses these currents to determine the proper switching pulses, which improves the system's overall performance and stability. Consequently, net cost function of the charging station has delivered the essential function in terms of multi-objective optimization problems, which is described in following eqn. (8), (9), (10), (11),

$$\min C_j(n) = \sum_{j \in T(n)} s_j \left[C_j(n) + G(n) \right] \tag{8}$$

$$C_j(n) = C_j(n) \quad \forall j \neq i \in T(n) \tag{9}$$

$$C_{\min}^{j} \leq C_j(n) \leq C_{\min}^{j} \quad \forall j \in T(n) \tag{10}$$

$$SOC_{\min}^{j} \leq SOC_j(n) \leq 100\% \forall j \in T(n) \tag{11}$$

Where, $C_j(n)$ is denoted as minimization of net cost function for all grid system charging stations, $G(n)$ is represented as cost function of grid system charging station, $\sum_{j \in T(n)}$ is denoted as energy cost function with j[th] user with time period t. Moreover, fig.2 demonstrates flow chart of proposed NF-SPUPQC-MPPT model.

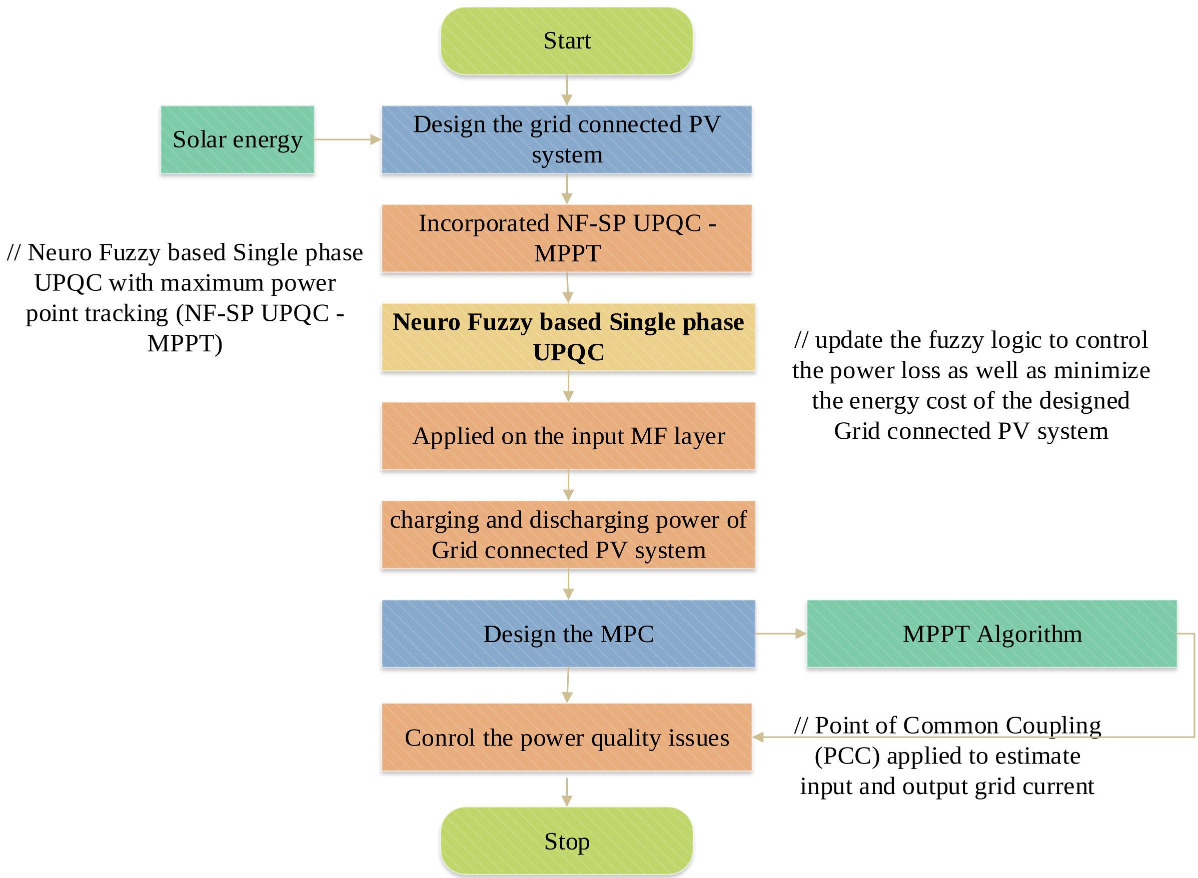

Fig.2 Flowchart of proposed NF-SPUPQC-MPPT

5 Result and discussion section

This section includes a description of the experimental setting and an assessment of the efficacy of the suggested technique. The system's performance is evaluated using a number of measures, such as power loss, voltage deviation, grid current, and grid voltage, by utilising the novel NF-SPUPQC-MPPT algorithm. Neuro-fuzzy systems help power grids operate more efficiently by distributing loads and scheduling generating units. By controlling reactive power, voltage regulation, and harmonic compensation within the grid, neuro-fuzzy controllers can maximise power quality. To maximise power quality, the system continuously modifies control parameters based on fuzzy rules and real-time measurements.

5.1 Performance analysis

When electrical energy dissipates as heat while being transmitted and distributed from power plants to end consumers, it results in power loss in a grid system. This phenomenon is also known as transmission or distribution losses. Lower current levels for a given amount of power are typically the outcome of higher voltages. Imbalances in a three-phase system's voltage or current between the phases. Uneven power distribution due to imbalanced loads or voltages increases losses. When there is an imperfect phase relationship between voltage and current, low power factor results. Reactive power rises with low power factor, increasing transmission and distribution system losses, which in demonstrated in fig.3.

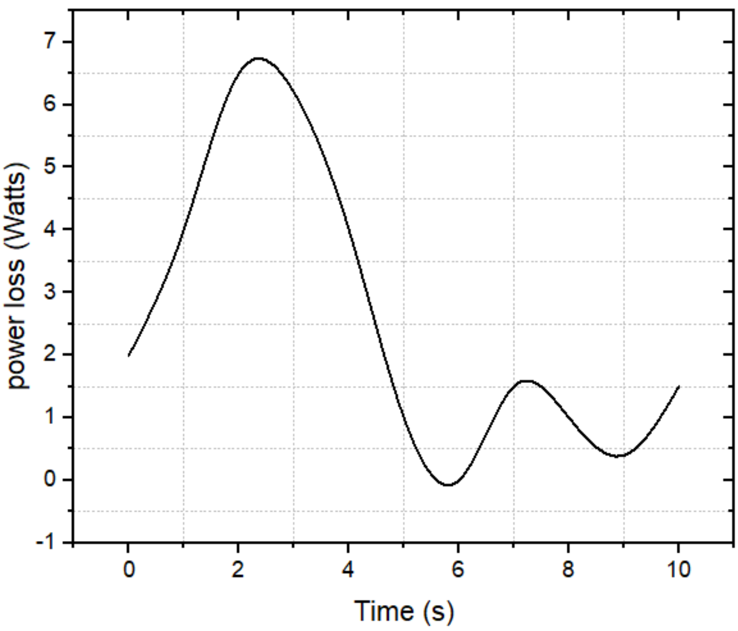

Fig.3 Power loss

In a grid system, voltage deviation is the difference between the nominal or desired values of voltage levels. 230V, 400V, and other standards are common nominal voltage levels, and they might vary based on the area and kind of electrical system. For electrical devices and equipment connected to the grid to operate dependably, voltage must be kept steady and under control. Voltage variations can affect an electrical device's lifespan and function for a variety of reasons. Overvoltage occurs when the actual voltage is higher than the nominal voltage. Under voltage is the word used when the actual voltage is lower than the nominal voltage, which in demonstrated in fig.4.

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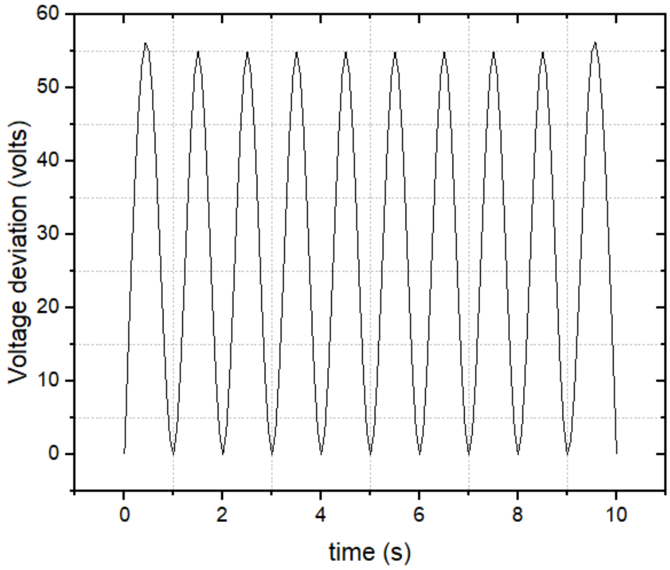

Fig.4 Voltage deviation

Reactive power variations in a grid system can affect the electrical network's overall performance, stability, and efficiency. Reactive power is required to support the operation of inductive loads and keep voltage levels within allowable bounds. Reactive power fluctuations can have unfavourable consequences and stem from a number of causes. The part of electrical power known as reactive power oscillates between the source and the load without accomplishing any beneficial activity. The unit of measurement is reactive volt-amperes. Variations in reactive power can result from modifications to the load profile, particularly when inductive loads are added or removed. Reactive power can be impacted by variations in generator output, particularly in synchronous generators, which in demonstrated in fig.5.

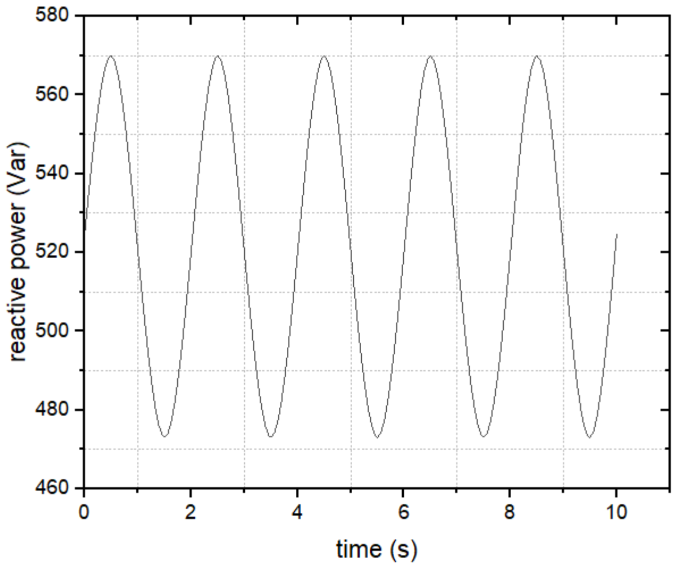

Fig.5 Reactive power fluctuation

When harmonic components exist in the voltage or current waveform relative to the fundamental frequency, it is referred to as total harmonic distortion (THD) in a grid system. Multiples of the fundamental frequency, which in power systems is usually 50 or 60 Hz, are known as harmonics. Non-linear loads, switching activities, and other factors can also produce harmonics.

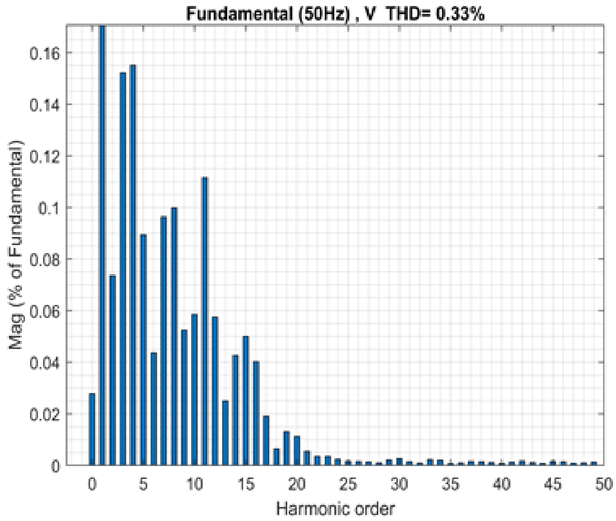

Fig.6 THD

The root mean square (RMS) value of the harmonic content divided by the RMS value of the fundamental frequency yields the total harmonic distortion (THD). The common way to express THD is as a percentage of the basic frequency. Moreover, THD is demonstrated in fig.6.

5.2 Comparative analysis

Better results from the performance evaluation of the suggested work were obtained by the performance comparison. It is confirmed by the comparison evaluation that the suggested model has reduced the THD to the greatest extent feasible. It can therefore be applied to grid-connected PV systems. Furthermore, table 1. Shows the state of art comparison.

Table. 1 State of art comparison

Artificial neural framework [21]	**UPQC [22]**	**Fuzzy based ant-lion PID controller [23]**	**Classical PID controller [24]**	**Proposed NF-SPUPQC-MPPT algorithm**
Power gain:6.4% (inc) [2], power saving:5248 kWh/day; grid current: 5.4, power loss: 2.8MW, grid voltage: 552, harmonic order: 3, rise time:, 32.6s solar power: 12MW, THD: 2.4, voltage deviation:47V	Power gain:7%, power saving:3451 kWh/day; grid current: 4.7, power loss: 3MW, grid voltage: 510, harmonic order: 7 rise time: 12s, solar power:4MW, THD: 6.23, voltage deviation: 28V	Power gain:2%, power saving:5241 kWh/day; grid current: 6.21, power loss: 4.1MW , grid voltage:560, harmonic order: 2 rise time: 31s, solar power: 7.2MW, THD: 5.43, voltage deviation:35V	Power gain: nil, power saving:1931 kWh/day; grid current: 4.5, power loss: 2MW, grid voltage: 498, harmonic order: 5, rise time:7.8s, solar power: 45MW, THD: 2.21, voltage deviation:54V	Power gain:5.4% (in, power saving: 9428kWh/day; grid current:0.59, power loss: 0.2MW, grid voltage: 412, solar power: 7MW, THD: 0.56, voltage deviation: 26.42V, power fluctuations:0.2MW

[2] increment

Table.2 Research gap

Author name	Techniques	Merits	Demerits
Liu et al, [14]	demand side frequency control strategy	Computational burden is low and mitigate voltage deviations	higher power capacity can cause the system efficiency
Mehdi et al [15]	hybridized energy storage system with DC microgrid	Efficiently enhance the large sale grid system	it can use various stability condition to prove the performance of grid system
Akpinar et al,[16]	grid connected BESS for fuzzy logic	Power quality drawbacks are reduced	power flow rate is adjusted
Vineeth al, [17]	multi converter based Unified Power Quality Conditioner (UPQC)	Enhance the power constrains	higher computation cost
et al, [18]	Modular Multilevel Converter (MMC) is integrated with UPQC model	lower cost and ease to design	non-linear control system not applicable
Proposed	Neuro Fuzzy based Single phase Unified Power Quality Conditioner with Maximum Power Point Tracking (NF-SP UPQC -MPPT) strategy	low power loss and voltage deviations	-

6 Conclusion

This paper proposed a novel NF-SP UPQC -MPPT strategy for enhancing the grid connected PV systems. Here, power quality improvement performance are done with the help of UPQC model that ensures the increased power quality by controlling voltage and current related issues. Moreover, maximum solar power is extorted by MPPT algorithm, which dynamically operating the grid system. Neuro fuzzy logic is enabled to coordinate the operation of MMPT and UPQC with optimized power quality in the grid system. Consequently, the evaluation metrics consist of voltage deviation, power loss, THD and reactive power fluctuations. Also, the achieved parameter considerations are compared with conventional models. The comparison demonstrates that developed NF-SP UPQC -MPPT model has minimized the power loss as 4% while comparing other models. Then, 26.42V voltage deviation and 0.56THD. In future, the work will further extended by adapting the optimization algorithms and DL models are applied on hybrid renewable energy system will enhance the BESS.

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