Dynamic Voltage Restorer using Lemurs-Optimized Cascaded ANFIS-controller for Distributed Power Systems

[1]Reddy G.S., [2] Reddy S.K., [3]Athimamula S.

[1]Jyothishmathi Institute of Technology and Science, Karimnagar, Telangana, India.
[2] CVR College of Engineering, Mangalpally, Ibrahimpatnam, Hyderabad, India.
[3]Vidya Jyothi Institute of Technology, Hyderabad, India.

***Abstract*.** The main objective of this study is to reduce disturbances, such as voltage sags, swells, and fluctuations, increase stability of voltage and Power Quality (PQ) in distributed power systems using an optimized Dynamic Voltage Restorer (DVR) control strategy. These objectives are achieved through the design and optimal tuning of a Cascaded Adaptive Neuro-Fuzzy Inference System (ANFIS) controller using the Lemurs optimization algorithm (LOA). The proposed controller is verified in the MATLAB/Simulink environment systematically for nonlinear and sensitive load conditions, which is a complete verification and testing to establish controller performance for voltage stability, improving dynamic responses, and reliably operating the system under disturbance operating conditions. According to the simulation study, the results show that the DVR controller is able to maintain a consistent load voltage under disturbance, therefore the connected loads are effectively and efficiently utilized within the controlled system. The proposed solution achieves a performance effectiveness of 96%, ensure effective and consistent operation of the system under changing load conditions. The proposed central controller enhances the dynamic performance of the DVR by reducing the settling time to 0.08 s, thus ensuring that performance is better than conventional approaches with fast transient response and higher accuracy. The significance of the results lies in validate that the cascaded ANFIS controller with LOA optimization is a legitimate and computationally efficiency substitute for real-time voltage compensation. This enhances the robustness of sensitive loads, minimizes possible consequences of economic losses and enhances the reliability of distributed networks in modern smart grid infrastructure.
Keywords: dynamic voltage restorer, lemurs optimized algorithm, cascaded adaptive neuro fuzzy inference system, power quality, voltage sag, swell.

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Regenerator dinamic de tensiune în cascadă optimizat prin metoda Lemur, bazat pe un controler logic neuro-fuzzy adaptiv pentru sisteme de alimentare cu energie distribuite

[1]Reddy G.S., [2] Reddy S.K., [3]Athimamula S.

[1]Institutul de Tehnologie și Știință Jyothishmathi, Karimnagar, Telangana, India
[2]Colegiul de Inginerie CVR, Mangalpally, Ibrahimpatnam, Hyderabad, India
[3]Institutul de Tehnologie Vidya Jyothi, Hyderabad, India

Rezumat. Obiectivul principal al acestui studiu este de a reduce perturbațiile, cum ar fi căderile de tensiune, supratensiunile și fluctuațiile, de a crește stabilitatea tensiunii și a calității energiei (PQ) în sistemele de energie distribuită utilizând o strategie optimizată de control al restauratorului dinamic de tensiune (DVR). Aceste obiective sunt atinse prin proiectarea și reglarea optimă a unui controler de tip Sistem de Inferență Neuro-Fuzzy Adaptiv în Cascadă (ANFIS) utilizând Algoritmul de Optimizare Lemurs (LOA). Controlerul propus este verificat sistematic în mediul MATLAB/Simulink pentru condiții de sarcină neliniare și sensibile, ceea ce reprezintă o verificare și testare completă pentru a stabili performanța controlerului pentru stabilitatea tensiunii, îmbunătățirea răspunsurilor dinamice și funcționarea fiabilă a sistemului în condiții de funcționare perturbatoare. Conform studiului de simulare, rezultatele arată că controlerul DVR este capabil să mențină o tensiune de sarcină constantă sub perturbații, prin urmare, sarcinile conectate sunt utilizate eficient și eficace în cadrul sistemului controlat. Soluția propusă atinge o eficiență a performanței de 96%, asigurând funcționarea eficientă și constantă a sistemului în condiții de sarcină schimbătoare. Controlerul central propus îmbunătățește performanța dinamică a DVR-ului prin reducerea timpului de stabilizare la 0.08 s, asigurând astfel o performanță mai bună decât abordările convenționale, cu un răspuns tranzitoriu rapid și o precizie mai mare. Semnificația rezultatelor constă în validarea faptului că controlerul ANFIS în cascadă cu optimizare LOA este un substitut legitim și eficient din punct de vedere computațional pentru compensarea tensiunii în timp real. Acest lucru sporește robustețea sarcinilor sensibile, minimizează posibilele consecințe ale pierderilor economice și sporește fiabilitatea rețelelor distribuite în infrastructura modernă a rețelelor inteligente.

Cuvinte-cheie: regenerator dinamic de tensiune, algoritm de optimizare Lemurs, sistem de inferență neuro fuzzy adaptiv în cascadă, calitatea energiei electrice, căderi de tensiune, creșteri de tensiune.

Оптимизированный методом Лемура каскадный динамический восстановитель напряжения на базе каскадного адаптивного нейро-нечеткого логического контроллера для распределенных энергосистем

[1]Редди Г.С., [2]Редди С.К., [3]Анимамула С.

[1]Института технологий и науки Джьотишмати, Каримнагар, Телангана, Индия.

[2] Инженерный колледж CVR, Мангалпалли, Ибрагимпатнам, Хайдарабадб Индия.

[3]Технологического института Видья Джьоти, Хайдарабадб Индия.

Аннотация. Основная цель данного исследования — снизить такие помехи, как провалы, выбросы и колебания напряжения, повысить стабильность напряжения и качество электроэнергии в распределенных энергосистемах с помощью оптимизированной стратегии управления с использованием динамического восстановителя напряжения. Эти цели достигаются посредством проектирования и оптимальной настройки каскадного адаптивного нейро-нечеткого логического контроллера (АННЛК) с использованием алгоритма оптимизации Лемур (АОЛ). Предлагаемый контроллер систематически верифицируется в среде MATLAB/Simulink для нелинейных и чувствительных условий нагрузки, что представляет собой полную проверку и тестирование для определения характеристик контроллера с точки зрения стабильности напряжения, улучшения динамических характеристик и надежной работы системы в условиях возмущений. Результаты моделирования показывают, что контроллер динамический восстановитель напряжения (ДВН) способен поддерживать постоянное напряжение нагрузки в условиях возмущений, что обеспечивает эффективное и рациональное использование подключенных нагрузок в управляемой системе. Предлагаемое решение достигает КПД 96%, обеспечивая эффективную и стабильную работу системы в условиях изменяющейся нагрузки. Предлагаемый центральный контроллер улучшает динамические характеристики ДВН, сокращая время установления до 0.08 с, что обеспечивает более высокую производительность по сравнению с традиционными решениями, быструю переходную реакцию и более высокую точность. Значимость результатов заключается в подтверждении того, что каскадный контроллер АННЛК с оптимизацией АОЛ является законной и вычислительно эффективной заменой компенсации напряжения в реальном времени. Это повышает устойчивость чувствительных нагрузок, минимизирует возможные экономические потери и повышает надежность распределенных сетей в современной интеллектуальной инфраструктуре.

Ключевые слова: динамический восстановитель напряжения, оптимизированный алгоритм Lemurs, каскадная адаптивная нейронечеткая система вывода, качество электроэнергии, падение напряжения, выброс.

I. INTRODUCTION

The ability of the distributed electrical system to transmit power in its pristine form, which is always sinusoidal, steady and noise-free in nature is termed as PQ. However, the disruptions caused by the inclusion of several non-linear loads to system results in power supply deviations, which affect the PQ. The PQ crisis is also stimulated due to the presence of transformers, harmonic pollution peak value, reduced capacitor life, malfunctioning of controllers, cables, failure of premature distribution transformers, relays, heating, protective devices and reduced capacitor life. Numerous PQ difficulties, comprising voltage sags and swells, transients, harmonics, and interruptions, are present in distributed systems [1-5]. Among all these PQ issues, electronic equipment used in applications such as power conversion, control, and computation are extremely sensitive to voltage fluctuations. Hence, to prevent equipment failure that disrupts an operation of the entire distributed power system, the effects of voltage fluctuations has to be minimised [6-9]. To overcome the aforementioned issues, Flexible Alternating Current Transmission System (FACTS) devices, which are capable of voltage stabilization, harmonic mitigation, power factor correction and PQ enhancement is used. These devices also provide voltage regulation, power flow control, steady state voltage stability, quality enhancement, power conditioning and power loss reduction [10].

A Static VAR Compensator (SVC) [11, 12] is a thyristor-controlled shunt compensated impedance matching device that establishes voltage balance and enhances load PQ through single point or distributed reactive power injection. However, it has certain limitations that includes resonance with source impedance, harmonic amplification in addition to harmonic current injection. The Thyristor Controlled Series Compensation (TCSC) is another frequently used FACTS device to provide voltage support by minimization of sub-synchronous and active power oscillations. It is less expensive, since the implementation of an interfacing device in the form of high voltage transformer is not essential. Due to fluctuating inductive or capacitive impedance in series with the protected line, the inclusion of TCSC in error loop requires a detrimental effect on fault current along with transient and steady-state voltage [13, 14]. Similar to SVC, the Static Synchronous Compensators (STATCOM) is a shunt compensator, which is capable of providing voltage stability through quick dynamic response. They are commonly used in an electrical network for achievement of voltage regulation, flicker attenuation, active power oscillation damping and reactive power compensation [15]. Despite the enhanced PQ, the amount of active power needs some limitations [16]. This work uses a DVR, a series compensator, to increase PQ and voltage stability of distributed scheme by overcoming the limitations of other facts devices. A controlled sinusoidal load voltage is created via DVR injecting a voltage with a specific magnitude, frequency, and phase angle in series with distribution route [17, 18].

To further heighten the operation of DVR, the PI controller with simple design is adopted generally. However, the required control performance is not attained in non-linear conditions using PI controller owing to its fixed value of PI gains. A Fuzzy Logic Controller (FLC) is used in [19], which has a better voltage compensation capability than conventional PI controller in case of non-linear conditions. The fundamental issue with fuzzy controllers is that the parameters related to rules and membership functions are heavily reliant on expert perception, thus the parameter change is only possible using trial and error method. In additional, the transformation of membership function takes a significant amount of time. The Artificial Neural Network (ANN) however has quicker computational time and has the capability of learning from available data but it does not provide accurate results. Hence the hybrid controller technique of ANFIS was developed by combining both ANN and FLC. Thereby the ANFIS controller inherits the learning capability of ANN in addition to the capability of FLC to tackle complex and non-linear issues [20-22]. In spite of its high accuracy level, the efficiency of ANFIS is hindered by few setbacks in the form of computational burden, time consumption, application restriction and curse of dimensionality [23]. In this work, the LOA based Cascaded ANFIS controller is used for DVR control in order to get over the drawbacks of the conventional ANFIS controller.

The working principle of DVR with optimized Cascaded ANFIS controller in a distributed power system is discussed in this work. The proposed novel control strategy with ANFIS parameters optimally tuned using the LOA, effectively resolves PQ related problems and improves distributed power system's voltage stability.

A. Problem statement

In modern distributed electrical systems, maintaining high PQ has become increasingly challenging due to the widespread integration of non-linear and sensitive loads. These loads introduce significant disturbances like harmonics voltage swells, sags and transients, which adversely impact the performance and lifespan of critical equipment and components. Conventional PQ improvement devices though effective in certain aspects, exhibit limitations such as harmonic amplification, resonance issues, and restricted active power support. The DVR emerges as a promising solution for voltage compensation and PQ enhancement; however, its performance largely depends on the control strategy employed. Traditional controllers like PI and FLC suffer from inadequate adaptability to non-linear conditions and require extensive tuning. Even advanced approaches despite improved accuracy, face challenges related to computational complexity and scalability. Therefore, there is a need for an intelligent, efficient, and adaptive control method for DVRs to ensure robust voltage regulation and improved PQ in distributed systems under diverse and dynamic operating conditions.

B. Review of the literature

M. Manikandan *et al* (2025) [24] have proposed Artificial Neural Networks (ANN) for power distribution in systems to reduce voltage disturbances. ANN-based controllers are used to enhance dynamic response under various load circumstances and represent nonlinear system behavior. The system also employs Levenberg-Marquardt back propagation method for effective training Because of its great accuracy and quick convergence. ANN are used in DVR control to improve voltage swell and sag compensation by anticipating the best course of action. ANNs have the ability to model intricate, non-linear relationships, learn from data, and adjust to changing circumstances. However, the effectiveness of ANNs is highly reliant on the quality of training data and improper tuning leads to overfitting.

Shah *et al* (2022) [25] have introduced Sliding Mode Control (SMC) based DVR systems due to its efficiency against external disturbances and parameter changes. Traditional SMC High-frequency chattering leads to the decrease in power of electronic components.

A Real Twisting Sliding Mode Controller (RTSMC) is used in combination with SMC and Real-Twisting Algorithm (RTA), a second-order sliding mode approach to solve this problem. This fused method decreases chattering while preserving stability and quick dynamic responsiveness. Even though, it faces difficulty in design and tuning, the proposed RTSMC with classical SMC provides accurate tracking and disturbance rejection.

Laghari *et al* (2024) [26] have presented Sliding Mode Control (SMC) with PI sliding surface in DVR applications because of its ability to tackle changes in parameters and unwanted disturbances.

This method is used for reducing voltage problems in delicate load systems with its high-speed dynamic response and low steady-state inaccuracy.

By combining SMC with a three-phase matrix converter it provides direct AC to AC conversion and eliminates the needs for large Energy Storage Devices (ESD) by simplifying the system. However, implementation of matrix converters are difficult in commutation and it requires sophisticated control algorithms. Still it have increased Voltage stability, even though it require a lot of computing power to implement.

Nouman *et al* (2023) [27] have implemented Smooth Super Twisting Algorithm (SSTA), a second-order sliding mode technique to minimizes chattering without sacrificing resilience or quickness of reaction.

The Smooth Super Twisting Sliding Mode Controller (SSTSMC) improves DVR performance by delivering a continuous control signal under quickly changing load conditions and SSTA provides more accurate tracking and smoother control action than Real Twisting Algorithm (RTA). \

This approach provides Strong disturbance rejection, enhanced transient response, and decreased chattering but, it requires more computing power and accurate parameter adjustment compared to conventional controllers.

C. Materials and methods

To investigate the efficacy of the proposed LOA tuned Cascaded ANFIS-related control strategy for DVR, a detailed simulation model is developed using MATLAB/Simulink.

The DVR is designed as a series-connected compensator integrated into a distributed power system to inject compensating voltage during sags, swells, and other disturbances. The LOA tuned Cascaded ANFIS controller is implemented in a two-stage configuration, where the first stage estimated the nature and extent of voltage deviation, and the second stage generated appropriate control signals for the DVR's voltage source inverter. \

The ANFIS parameters are optimally tuned using LOA to enhance convergence, adaptability and control precision under changing operating condition.

The simulation incorporated nonlinear and sensitive loads to replicate realistic industrial and commercial scenarios.

Key performance indicators such as load voltage profile THD, settling time and voltage compensation accuracy were analyzed. Comparative evaluations were also performed against traditional PI and standalone ANFIS-controlled DVRs to validate the supremacy of the developed approach in dynamic voltage regulation and harmonic suppression.

II. PROPOSED SYSTEM DESCRIPTION

The ability of the distributed power system to transfer power in its pristine form without distortions is referred to as PQ.

However, recently the adverse effects of low PQ have aroused a huge amount of attention, due to its impact on sensitive loads, which results in economic losses for both the industrial and commercial customers.

Some of the common PQ issues encountered in distributed power system are flickers, voltage harmonics, interruptions, voltage sag and voltage swell.

Despite an existence of the aforementioned PQ issues, the working of sensitive load is mostly disrupted by voltage fluctuation in the form of voltage swell/sag.

Here, in this paper, a DVR based on a LOA tune the Cascaded ANFIS controller is used to compensate voltage related PQ issues. Fig. 1 gives the structure of the proposed power compensation approach using Optimized Cascaded ANFIS based DVR.

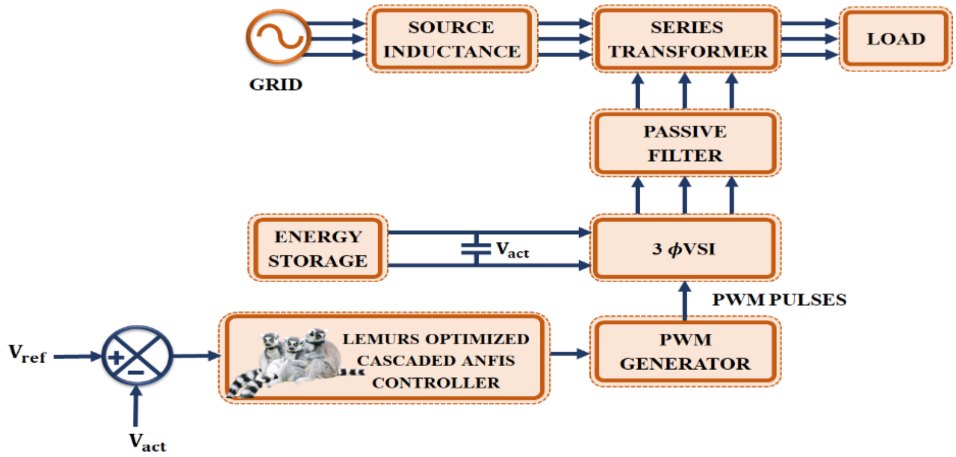

Fig. 1. Proposed cascaded ANFIS based DVR control scheme.

The structure of DVR comprises of an injection transformer, a VSI, a capacitor in addition to an ESD. The reactive power required for balancing the voltage fluctuation is supplied using an injection transformer. The functioning of the VSI of DVR is controlled using LOA based Cascaded ANFIS controller. The voltage is compared to reference voltage V_{ref} and is fed as input to Cascaded ANFIS controller. It comprises of two ANFIS controllers, which are connected in series. The output from controller is the change in duty ratio knowledge for three phase VSI. The proposed LOA based Cascaded ANFIS using DVR technique is enhancing voltage profile of the distributed control system via successfully eliminating the negative impacts of PQ issues.

III. PROPOSED SYSTEM MODELLING

A. Dynamic voltage resonator (DVR)

An ESD, an injection transformer, an IGBT based VSI, and a capacitor comprises the solid state power electronic switching device, or DVR. In the event of a distribution system, DVR will generate the necessary phase angle and high frequency regulated voltage to provide a steady supply of voltage to the load. The source voltage harmonics are kept from reaching the load by the DVR. The structure of DVR mainly comprises of a power circuit and a control circuit. The various issues that affect the reliability and PQ of a power system such as voltage unbalances, voltage harmonics, voltage swell/sag and power factor are corrected using DVR. The DVR injects series voltage explored as,

$$V_{DVR} = V_L + Z_{TH} I_L - V_{TH} \tag{1}$$

Here, V_L and V_{TH} refers to load voltage and fault voltage of system respectively and load impedance is specified using Z_{TH}. The value of load current I_L is given as,

$$I_L = \frac{P_L + jQ_L}{V} \tag{2}$$

Here, active power used up through load is P_L and reactive power used up through load is Q_L. On considering the reference as V_L, Eq (1) is rewritten as,

$$V_{DVR}^{*} = V_L^{\angle 0} + Z_{TH}^{\angle(\beta-\theta)} - V_{TH}^{\angle\delta} \tag{3}$$

With,

$$\theta = \tan^{-1}\left(\frac{\theta_L}{P_L}\right) \tag{4}$$

The term $V_L^{\angle 0}$ is the reference load voltage with zero phase angle, $Z_{TH}^{\angle(\beta-\theta)}$ is Thevenin impedance with phase angle adjusted by $\beta-\theta$ and $V_{TH}^{\angle\delta}$ is source voltage with same angle δ. The output power of the DVR is given as,

$$S_{DVR} = V_{DVR} I_L^{*} \tag{5}$$

Here, S_{DVR} is the complex apparent power injected by DVR and I_L^{*} is the complex conjugate of load current. The basic components that together constitute a DVR are explained in the subsequent section.

Energy storage unit (ESU). DVRs have a variety of energy storage components, including flywheels, lead acid batteries, super-capacitors, and super conducting magnetic energy storage. In the event of voltage sags, an ESD's primary purpose is to provide the essential real power. The active power produced via ESD detects DVR's compensating capacity. Their response times for charging and discharging must be quick, and the rate at which they discharge regulates an internal space is accessible for energy storage.

Voltage source inverter. A DVR frequently uses pulse width modulated VSI to convert DC voltage from ESU to AC voltage and send it to series transformer. The series transformer acts as a step-up voltage distribution transformer, generating a higher magnitude voltage to compensate for the voltage sag condition. A low voltage from VSI is therefore seen as adequate. In a DVR, a by-pass switch is frequently utilized for security.

Passive filters. To eliminate high frequency harmonic contents from the output of VSI, low passive filters are used in a DVR. Passive filters are typically used on load side of high voltage or the inverter side of low voltage, as seen in Fig. 2. By using the passive filter on the inverter side, the amount of stress on distributed transformer is significantly reduced. Similarly, the harmonic content's amount from the transformer's secondary side is minimized by implementing the passive filter on the load side.

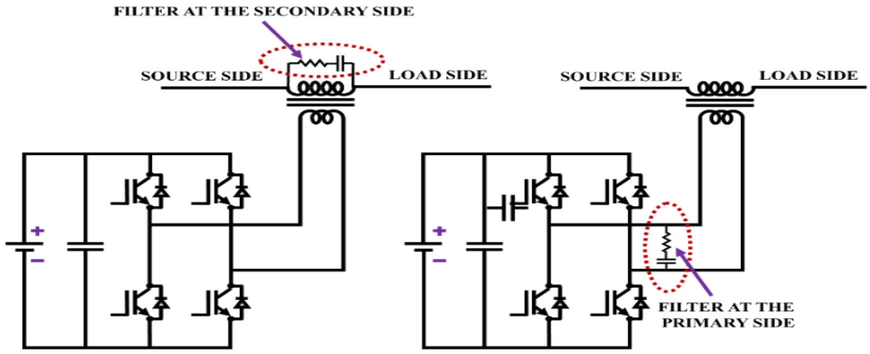

Fig. 2. Different placements of Filter in DVR.

Series transformer. The distribution line is connected to series transformer's primary end, while the DVR circuit is connected to transformer's secondary end. Three 1φ transformers or one 3φ transformer are used in case of 3φ DVR and for 1φ DVR, one 1φ transformer is used. The interaction between three 1φ transformers and a 3φ DVR is established using a Delta-Delta type of construction.

B. DVR operation overview

When there is a difference between pre sag voltage and sag voltage, the DVR is supplied with stored power and reactive energy by the ESD. The injected voltages have a phase angle and frequency that are similar to the system voltages. In case of three 1φ transformers, independent evaluation of the injected voltage is also possible. In normal operating condition, when there is no voltage swag/swell issue, there is no injection of voltage to the load by the DVR. ESDs function in standby or self-charging modes once they are fully charged. In the result of a malfunction or short circuit, the by-pass switches safeguard the inverter. The several sag compensation techniques of DVR are as,

In-phase compensation. In this technique, by introducing an in-phase voltage supply of lower magnitude to the sagged grid voltage, the process of voltage compensation is achieved by the DVR. However, using this technique the correction of phase jump is not possible as shown in Fig. 3(a). The angle and magnitude of the voltage introduced by DVR is given as,

$$V_{DVR} = \sqrt{2}\left(V_L - V_G^{'}\right) \quad (6)$$

$$\angle V_{DVR} = \theta_L \quad (7)$$

Where, $V_G^{'}$ specifies the sagged grid voltage and the load current's phase angle is θ_L.

Quadrature injection (Reactive compensation). DVR introduces a voltage quadrature of load current, which is used in this technique. Voltage sag is corrected by using reactive power. Fig. 3(b) presents voltage injection's magnitude and angle, which are as follows:

$$V_{DVR} = \sqrt{2}\sqrt{V_L^2 + V_G^{'2} - 2V_L V_G^{'}\cos\left(\alpha + \delta\right)} \quad (8)$$

$$\angle V_{DVR} = \frac{\pi}{2} \quad (9)$$

Where, phase jump in grid voltage owing to injected grid voltage and reactive power sag is specified as α and δ respectively. The maximum amount of voltage sag that is compensated using this method is dependent on the value of load power factor,

$$\Delta V_{sag-max} \le (1-\cos\theta_L) \tag{10}$$

Here, $\cos\theta_L$ is the power factor component. The corresponding value of maximum voltage injected is,

$$V_{DVR-max} = \frac{V_G^{'}}{1-\Delta V_{sag.max}} sin\theta_L \tag{11}$$

Here, $sin\theta_L$ is the sine component of load power factor angle. When grid operates at unity power factor, the DVR is capable of supporting full load reactive power in case of quadrature injection.

Energy optimized injection. This method enhances the quadrature injection method's performance for sag depths greater than those found in Equation (10). Fig. 3(c) provides the voltage injection's magnitude and angle as follows:

$$V_{DVR} = \sqrt{2}\sqrt{V_L^2 + V_G^{'2} - 2V_L V_G^{'} \cos(\theta_L)} \tag{12}$$

$$\angle V_{DVR} = \tan^{-1}\left(\frac{V_L(sin\theta_L)}{V_L^{'}\cos\theta_L - V_G\cos\theta_L}\right) \tag{13}$$

Where, the term V_G refers to the rated grid voltage.

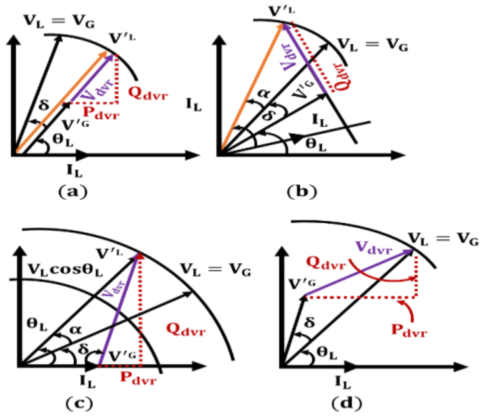

Fig. 3. DVR voltage injection methods: (a) In-phase, (b) Quadrature, (c) Energy-optimized, and (d) Pre-sag.

Presag compensation. This voltage compensation approach restores both load voltage's magnitude and phase to presag values. The presag compensation method is highly successful in compensating the phase jump compared to the other techniques as represented in Fig. 3 (d). Here the DC link capacitor provides additional active power for the correction of phase jump. While a negative phase jump raises an active power burden on DVR, a positive phase jump increases angle among load current and grid voltage. The following are the magnitude and angle of the voltage injection:

$$V_{DVR} = \sqrt{2}\sqrt{V_L^2 + V_G^{'2} - 2V_L V_G^{'} \cos(\delta)} \tag{14}$$

$$\angle V_{DVR} = \tan^{-1}\left(\frac{V_L \sin\theta_L - V_G^{'}\sin(\theta_L-\delta)}{V_G^{'}\cos(\theta_L-\delta) - V_L\cos\theta_L}\right) \tag{15}$$

It is an energy intensive method, where even a small sag depth is compensated using higher level of injected power.

C. LOA based Cascaded ANFIS controller for DVR

Cascaded ANFIS controller

The operation of the VSI in the DVR is regulated by a Cascaded ANFIS controller. The controller is based on the two-input, one-output ANFIS model, which allows for simple computation and efficient handling of huge input datasets while minimizing the error between real and reference voltages. The controller has two main stages: pair selection and training. Fig. 4 presents the flowchart of Cascaded ANFIS controller.

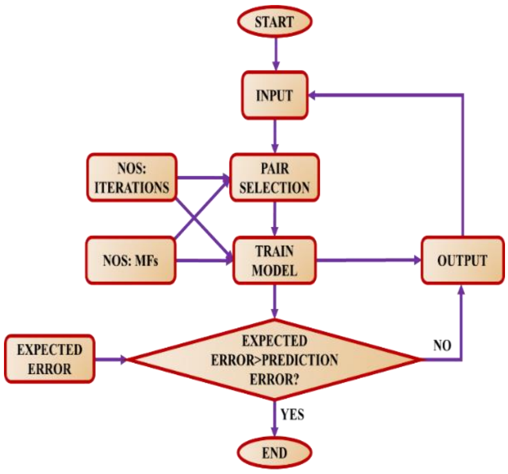

Fig. 4. Cascaded ANFIS flowchart.

Pair selection module. It pairs the inputs given to the controller. The ideal match for every input is acquired using an ANFIS model of one-output and two-input. The entire working of this module is presented in Fig. 5. Here, every pairs are analysed using nestled loop to determine the matching pair that is obtained as output. The algorithm 1 for pair selection module is as follows, *Algorithm 1* Cascaded ANFIS pair selection module

initialization

$Max\ Iterations = x$

$\left(data_{input}, data_{output}\right) = Load\ data$

$ni = size\left(input\ variables\right)$

While $Max\ Iterations\ is\ not\ equal\ to\ 0$ ***do***

if $Max\ Iterations = 1$ ***then***

$input = data_{input}$

else

$input = output_{prev}$

end

for $i = 1 : ni$ ***do***

for $j = 1 : ni$ ***do***

$\left(network, output_{prev}, RMSE\right) = ANFIS\left(input\left(i\right), input\left(j\right), data_{output}\right)$

if $RMSE$ ¡min_{error} ***then***

$min_{error} = RMSE$

$Pair\ Num1 = i$

$Pair\ Num2 = j$

else

$pair = pair + 1$

end

$iterations = iterations - 1$

end

The amount of given inputs to the controller is specified as NI and the initially chosen input variables is known as $input_i$ and $input_j$. Root Mean Square Error (RMSE E_p) value is calculated, and the result is saved in the controller and compared with the prior value (E_{prev}). By predicting the lowest RMSE value at the conclusion of the second loop, the matched pairings are identified. The training process begins after choosing the matching pair.

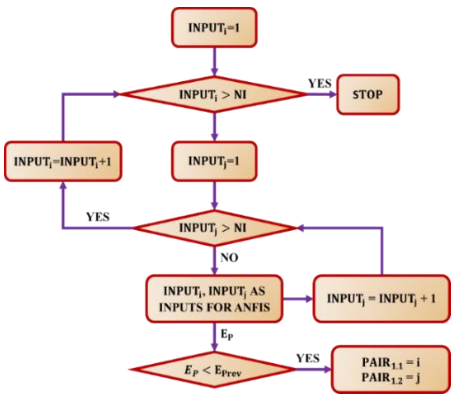

Fig. 5. Structure of pair selection module.

Training module. The training process is also carried out using an ANFIS model of two input and one output. The matching pairs obtained from the pair selection component is fed as input to the training module and for every given inputs, outputs are generated. Every RMSE value is analogised with a predefined error target and after the achievement of the required error target, the operation terminates. If the required error target is not reached, the process advances to the next iteration. The working structure of Training module is given in Fig. 6. The algorithm 2 for the training module is given below,

Algorithm 2 Cascaded ANFIS training module

initialization

$MaxIterations = x$

$\left(data_{input}, data_{output}\right) = LoadData$

$ni = size\left(input\ variables\right)$

while $MaxIterations\ is\ not\ equal\ to\ 0$ ***do***

if $MaxIterations = 1$ ***then***

$input = data_{input}$

else

$input = output_{prev}$

end

for $i = 1 : ni$ ***do***

for $j = 1 : ni$ ***do***

$\left(network, output_{prev}, RMSE\right) = ANFIS\left(input\left(i\right), input\left(j\right), data_{output}\right)$

if $RMSE$ ¡min_{error} ***then***

$min_{error} = RMSE$

$PairNum1 = i$

$PairNum2 = j$

else

end

$Pair = pair + 1$

end

$Iterations = Iterations - 1$

end

The inputs given to the pair selection module is represented by V_1, V_2, V_3 and V_4 respectively.

$$input = \{V_1, V_2, V_3, V_4\} \tag{16}$$

The matched pairs obtained from the pair selection module is given as,

$$input_{pairs}\ \{V_1, V_3\}, \{V_2, V_1\}, \{V_3, V_4\}, \{V_4, V_1\} \tag{17}$$

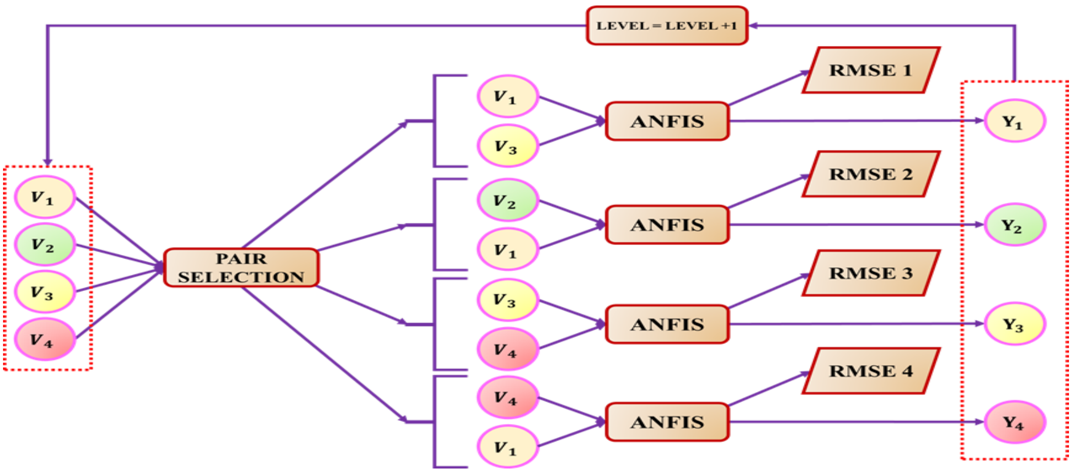

Fig. 6. Structure of training module.

The outputs obtained are $RMSE_i$ and Y_i, which are given as,

$$RMSE = \sqrt{(A-P)^2} \quad (18)$$

$$RMSE_{A,P} = \left[\sum_{i=1}^{N} \frac{(O_{Ai} - O_{Pi})^2}{N}\right]^{\frac{1}{2}} \quad (19)$$

$$f = \frac{w_1}{w_1+w_2} f_1 + \frac{w_2}{w_1+w_2} f_2 + \frac{w_2}{w_2+w_3} f_3 + \frac{w_4}{w_3+w_4} f_4 \quad (20)$$

Where, the term P specifies the predicted results, the term A specifies the actual results and the term N specifies the sample size. The process of first iteration completes after the estimation of Y and RMSE. If the acquired RMSE value is not equivalent to the error target, the next iteration of the training process takes place. The outputs Y_1, Y_2, Y_3 and Y_4 from the previous iteration are served as inputs to the next iteration. To improve the performance of the Cascaded ANFIS controller, the LOA is used to optimize ANFIS parameters including membership functions and rule weights.

Lemurs Optimization Algorithm

Inspirations

LOA is designed for tuning the parameters of a cascaded ANFIS controller. In the LOA-based cascaded ANFIS controller, each lemurs is a candidate ANFIS parameter set, and the lemurs population samples the search space to find a solution that maximize output power. The decision variables are initialized randomly and uniformly within their bounds, while mean fitness is evaluated for all lemurs evaluated based on their performance. The lemurs are updated from a set of two strategies: dancing upwards (dance-hup) towards the best lemurs for local exploitation, and jumping-even higher (leap-up) for global exploration. The Free Risk Rate (FRR) maintains this balance between exploitation and exploration, initially a relatively high FRR near 1 for exploration, gradually decreasing as iterations progress for a focus on exploitation later in the optimization process. This optimization process repeats into iterations until a convergence point is reached, resulting in the optimal set of ANFIS parameters for reliably and efficiently execute tuning.

Mathematical model

In the LOA-based cascaded ANFIS in Fig.7, the lemurs symbolizes a candidate solution to the ANFIS parameters, while the lemurs population explores the search space in pursuit of improving output power. The lemur's population is defined as follows:

$$T = \begin{bmatrix} l_1^1 & l_1^2 & \cdots & l_1^d \\ l_2^1 & l_2^2 & \cdots & l_2^d \\ \vdots & \vdots & \ddots & \vdots \\ l_s^1 & l_s^2 & \cdots & l_s^d \end{bmatrix} \quad (21)$$

Where s stands total number of candidate solutions (lemurs), and d stands total number of ANFIS parameters (decision variables). Each variable is automatically initialized to a random number between 0 and 1 in a manner, as follows:

$$l_i^j = rand\,().\left(ub_j - lb_j\right) + lb_j \quad (22)$$

The lemur parameter update happens using the two different strategies, which is either toward best nearest lemur (dance-hup) or leap-up to global best lemur. Two strategies are shown below:

$$L_i^j = \begin{cases} l(i,j) + |l(i,j) - l(bnl,j)|.(rand - 0.5).2, \\ \quad if\ rand < FPR \\ l(i,j) + |l(i,j) - l(bnl,j)|.(rand - 0.5).2, \\ \quad otherwise \end{cases} \quad (23)$$

Where $l(i,j)$ is the current lemurs parameter, $l(bnl,j)$ is the best nearest lemurs, $l(gbl,j)$ stands global best lemurs, and FRR is the free risk rate, defined as:

$$FPR = FPR_{high} - CurrIter.\frac{(FBR_{high} - FPR_{low})}{MaxIter} \quad (24)$$

FRR is initialized to be 1 (high), which means that more exploration is conducted (dance-hup), and as the iterations progress, it is lowered to mean more exploitation (leap-up). This repeat until convergence, displaying optimal ANFIS parameters.

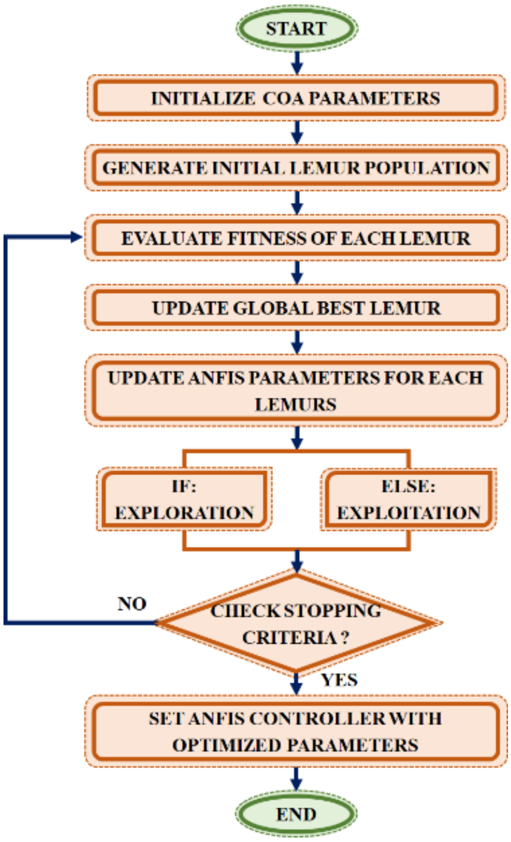

Fig. 7. Flowchart of LOA based ANFIS.

The complexity of LOA tuning the cascaded ANFIS controller is a number of lemurs, number of ANFIS parameters and maximum number of iterations. The complexity denoted as:

$$O(LO) = O(MaxIter \times s \times d) \quad (25)$$

This means that the computational complexity grows linearly with respect to the population size, number of ANFIS parameters, and number of iterations, which demonstrates that the LOA is suitable for real-time optimization. The LOA provides an efficient search for the optimal membership function parameters and rule weights of the ANFIS controller, while also enabling faster convergence, better accuracy, and robust performance in reducing voltage fluctuations. LOA increases the controller's convergence speed, adaptability, and resilience under changing load and disturbance situations. This optimization assures that the DVR maintains voltage stability while providing faster dynamic response, lower error, and higher control efficiency

IV. RESULT AND DISCUSSIONS

Improved PQ is required, as evidenced by the increasing number of sensitive loads connected to distributed power systems. The degradation of PQ incurs serious economic losses for both industrial and commercial users. Thus, an effective power compensation technique based on DVR is adopted in this work for enhancement of PQ. The control of DVR is established using LOA based Cascaded ANFIS controller and the entire power compensation method is simulated using MATLAB. Table 1 gives the parameter specifications of DVR.

*Table 1.*Parameter Specifications

Parameters	Values
Source Voltage	$450V$
Frequency	$50\ Hz$
Resistance	$1.30\ \Omega$
Inductance	$9.24\ mH$
Load	$16.8\ MW$
V_{act}	$800V$
Switching frequency	$10\ KHz$

An AC supply of ± 450 V has been applied as the source input as shown in Fig. 8(a). The input voltage stays constant at ±450 V throughout 0 to 0.3 s and 0.5 to 0.6 s, while a voltage dip of ± 300 V occurs from 0.3 s to 0.5 s. Fig. 8(b) shows the waveform of the AC source current, which is sinusoidal but has its amplitude varying from ± 100 A to minimum $\pm 50\ A$ over the simulation period.

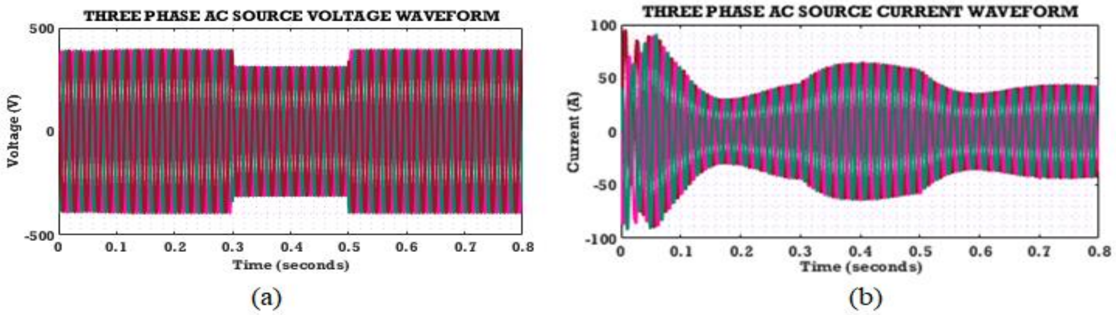

Fig. 8. AC source (a) Voltage waveform and (b) Current waveform.

The load voltage and load current waveforms are shown in Fig. 9(a). The dip in the input voltage did not affect the load voltage, which sustained a stable value of 450 V throughout the disturbance. The unstable input current also had a negligible effect on the load current level. The load current in Fig. 9(b) fluctuated slightly initially but stabilized at 35 A. Overall, these results indicated that the DVR is successfully improving the PQ of the distributed power system.

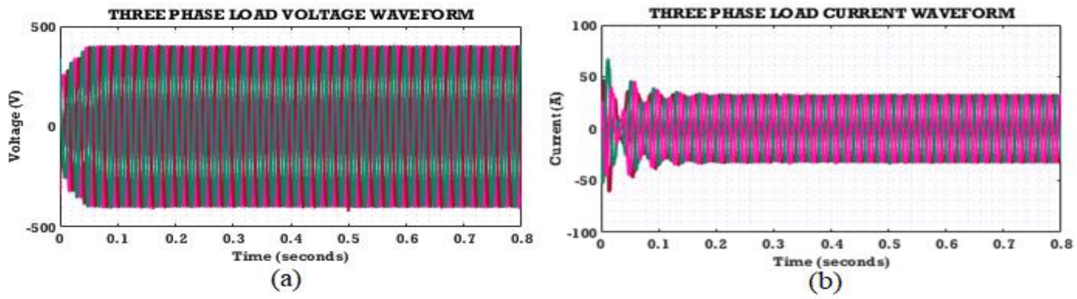

Fig. 9. Load side (a) Voltage waveform and (b) Current waveform.

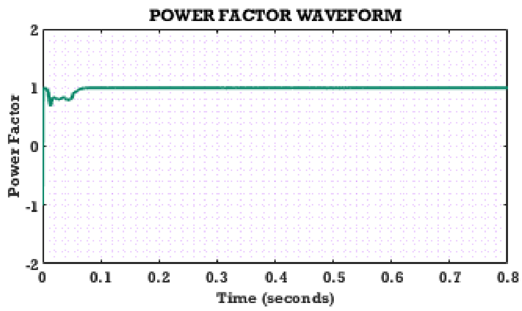

Fig. 10. Power factor waveform.

Fig. 10 illustrates power factor waveform, which remains unity before changing slightly during the transient response but eventually returns to 1.0, confirming that the proposed DVR control strategy compensates effectively.

DC link voltage is significant to maintain the DVR effective operation by given that energy storage and voltage support during disturbances. As shown in Fig. 11, DC link voltage reaches a peak of 700 V, and then stabilizes at a constant voltage value of 600 V at 0.1 s, which also indicates that the DC link behaves as a stable DC voltage source and is able to deliver the required compensation for voltage sags and swells and to operate reliably during events of disturbance, confirming that LOA based Cascaded ANFIS controlled DVR system is effective.

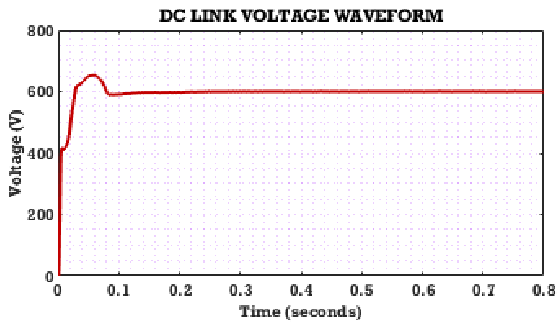

Fig. 11. DC link voltage waveform.

The efficiency of the adopted proposed controller is compared to the efficiency of other existing controllers that includes ANFIS, Fuzzy in addition to PI controller. Among all these controller techniques, the proposed method has an exceptional efficiency of 96% as displayed in Fig. 12 (a).

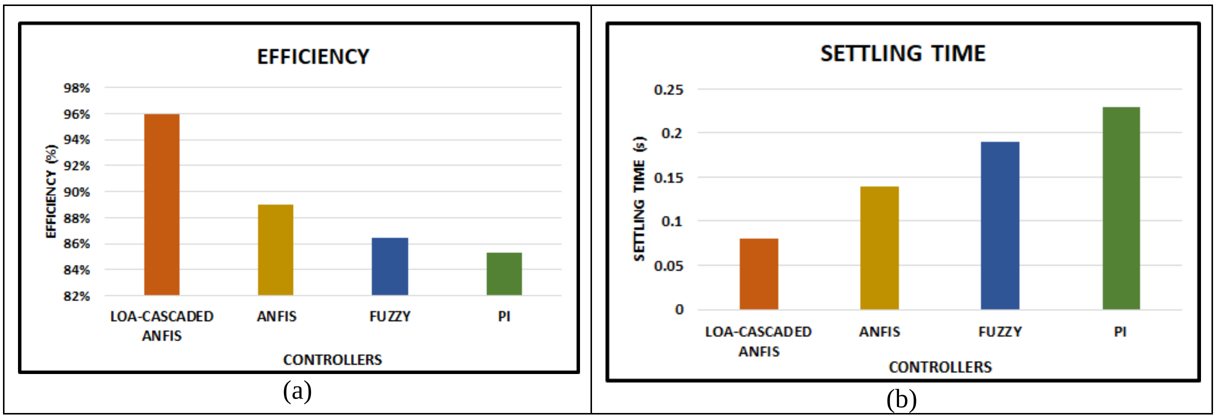

Fig. 12. Comparison chart for (a) Efficiency and (b) Settling time.

The settling time achieved by using different controllers is compared in Fig. 12 (b). The proposed controller achieves a quick settling time of 0.08s, whereas the ANFIS controller takes 0.14s to settle. The fundamental controllers like fuzzy and PI take longer time to settle. From the obtained simulation outcomes, it is concluded that an impressive performance is delivered by the proposed method-based DVR in minimizing voltage fluctuations and enhancing the stable and reliable working of the distributed power system.

Table 2. Voltage regulation Accuracy

Controller Type	Voltage regulation Accuracy (%)
PI	89.6%
Fuzzy	92.5%
ANFIS	94.2%
Proposed	98.3%

Voltage Regulation Accuracy (%) indicates in Table 2 successfully the controller maintains the load voltage close to the target reference value during disturbances. Higher values indicate better voltage stability. The proposed improved controller achieves 98.3% accuracy, demonstrating its capacity to maintain constant voltage under changing situations.

V. CONCLUSION

An effective power compensation method based on DVR, which alleviates the adverse effects of voltage sags/swells and harmonics that deteriorates PQ of distributed power system is addressed in this work. By maintaining the transmitted power in its pristine form without fluctuations, the protection of the sensitive loads interfaced to the network is successfully established. The adopted series compensated device displays exceptional performance in stabilizing the load voltage with reduction of harmonics. The controller for the DVR is implemented via a Cascaded ANFIS controller optimized using the LOA. This scheme, which includes a pair selection and training procedure, is computationally feasible and process large amounts of input data. Due to the tuning of parameters with LOA, the Cascaded ANFIS controller can achieve improved adaptation and accuracy for dynamic operating conditions. The LOA-tuned Cascaded ANFIS controller has demonstrated considerably enhanced efficiency and settling time compared with conventional controller techniques. Therefore, the DVR-based power compensation technique provides a very good efficiency of 96% while reducing PQ disturbances.

REFERENCES

[1] Hossain E., Tür M.R., Padmanaban S., Ay S., Khan I. Analysis and Mitigation of Power Quality Issues in Distributed Generation Systems Using Custom Power Devices. *In IEEE Access*, vol. 6, pp. 16816-16833, 2018, doi: https://doi.org/10.1109/ACCESS.2018.2814981.

[2] Sudharani S., Immanuel D. G. Mitigation of voltage sag/swell by dynamic voltage restorer using fuzzy based particle swarm controller. *Materials Today: Proceedings*, 2021, doi: https://doi.org/10.1016/j.matpr.2020.11.609.

[3] Guergah M., Nebti K., Rezgui S.E., Benalla H., Ould-Abdeslam D. Power quality enhancement using active power filter five-level cascade H-bridge under unbalanced and distorted grid. *Electrical Engineering & Electromechanics*, vol. 1, pp. 20-24, 2023, doi: https://doi.org/10.20998/2074-272X.2023.1.03.

[4] Manohara M., Reddy V.V., Kumar M.V. Exploration and mitigation of power quality problems in radial distribution system by placing distributed generation through voltage stability index. *Electrical Engineering & Electromechanics*, pp. 79-85, 2023, doi: https://doi.org/10.20998/2074-272X.2023.2.12.

[5] Bousnoubra C., Djeghader Y., Belila H. Contribution of using a photovoltaic unified power quality conditioner in power quality improvement. *Electrical Engineering & Electromechanics*, vol. 4, pp. 42-47, 2024, doi: https://doi.org/10.20998/2074-272X.2024.4.05.

[6] Molla E.M., Kuo C. C.Voltage Sag Enhancement of Grid Connected Hybrid PV-Wind Power System Using Battery and SMES Based Dynamic Voltage Restorer. *In IEEE Access*, 2020, vol. 8, pp. 130003-130013, doi: https://doi.org/10.1109/ACCESS.2020.3009420.

[7] Jiang F., Tu C., Shuai Z., Cheng M., Lan Z., Xiao F. Multilevel Cascaded-Type Dynamic Voltage Restorer with Fault Current-Limiting Function. *In IEEE Transactions on Power Delivery*, vol. 31, no. 3, pp. 1261-1269, 2016, doi: https://doi.org/10.1109/TPWRD.2015.2474703.

[8] Kim S., Kim H.G., Cha H. Dynamic Voltage Restorer Using Switching Cell Structured Multilevel AC–AC Converter. *In IEEE Transactions on Power Electronics*, vol. 32, no. 11, 2017, pp. 8406-8418, doi: https://doi.org/10.1109/TPEL.2016.2645722.

[9] Pradhan M., Mishra M.K. Dual P-Q Theory Based Energy-Optimized Dynamic Voltage Restorer for Power Quality Improvement in a Distribution System. *In IEEE Transactions on Industrial Electronics*, vol. 66, no. 4, pp. 2946-2955, 2019, doi: https://doi.org/10.1109/TIE.2018.2850009.

[10] Gandoman F.H., Ahmadi A., Sharaf A.M., Siano P., Pou J., Hredzak B., Agelidis V.G. Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems. *Renewable and sustainable energy reviews*, vol. 82, 2018, doi: https://doi.org/10.1016/j.rser.2017.09.062.

[11] Liu Y.W., Rau S.H., Wu C.J., Lee W.J. Improvement of Power Quality by Using Advanced Reactive Power Compensation. *In IEEE Transactions on Industry Applications*, vol. 54, no. 1, pp. 18-24, 2018, doi: https://doi.org/10.1109/TIA.2017.2740840.

[12] Yu S., Chau T.K., Fernando T., Savkin A.V., Iu H.H.C. Novel Quasi-Decentralized SMC-Based Frequency and Voltage Stability Enhancement Strategies Using Valve Position Control and FACTS Device. *In IEEE Access*, vol. 5, pp. 946-955, 2017, doi: https://doi.org/10.1109/ACCESS.2016.2622709.

[13] Mohamed A.A.R., Sharaf H.M., Ibrahim D.K. Enhancing Distance Protection of Long Transmission Lines Compensated With TCSC and Connected With Wind Power. *In IEEE Access*, vol. 9, pp. 46717-46730, 2021, doi: https://doi.org/10.1109/ACCESS.2021.3067701.

[14] Ibrahim D.K., Abo-Hamad G.M., Zahab E.E.D.M.A., Zobaa A.F. Comprehensive Analysis of the Impact of the TCSC on Distance Relays in Interconnected Transmission Networks. *In IEEE Access*, vol. 8, pp. 228315-228325, 2020, doi: https://doi.org/10.1109/ACCESS.2020.3046532.

[15] Li C., Burgos R., Wen B., Tang Y., Boroyevich D. Stability Analysis of Power Systems with Multiple STATCOMs in Close Proximity. *In IEEE Transactions on Power Electronics*, vol. 35, no. 3, pp. 2268-2283, 2020, doi: https://doi.org/10.1109/TPEL.2019.2931891.

[16] Babu V., Ahmed K.S., Shuaib Y.M., Manikandan M. Power Quality Enhancement Using Dynamic Voltage Restorer (DVR)-Based Predictive Space Vector Transformation (PSVT) With Proportional Resonant (PR)-Controller. *In IEEE Access*, vol. 9, pp. 155380-155392, 2021, doi: https://doi.org/10.1109/ACCESS.2021.3129096.

[17] Sagha H., Mokhtari G., Arefi A., Nourbakhsh G., Ledwich G., Ghosh A. A New Approach to Improve PV Power Injection in LV Electrical Systems Using DVR. *In IEEE Systems Journal*, vol. 12, no. 4, pp. 3324-3333, 2018, doi: https://doi.org/10.1109/JSYST.2017.2755075.

[18] Ye J., Gooi H.B. Phase Angle Control Based Three-phase DVR with Power Factor Correction at Point of Common Coupling. *In Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 1, pp. 179-186, 2020, doi: https://doi.org/10.35833/MPCE.2018.000428.

[19] Benali A., Khiat M., Allaoui T., Denai M. Power Quality Improvement and Low Voltage Ride Through Capability in Hybrid Wind-PV Farms Grid-Connected Using Dynamic Voltage Restorer. *In IEEE Access*, vol. 6, pp. 68634-68648, 2018, doi: https://doi.org/10.1109/ACCESS.2018.2878493.

[20] Abdulrahman I., Radman G. Wide-Area-Based Adaptive Neuro-Fuzzy SVC Controller for Damping Interarea Oscillations. *In Canadian Journal of Electrical and Computer Engineering*, vol. 41, no. 3, pp. 133-144, 2018, doi: https://doi.org/10.1109/CJECE.2018.2868754.

[21] Liu F., Wang H., Shi Q., Wang H., Zhang M., Zhao H. Comparison of an ANFIS and Fuzzy PID Control Model for Performance in a Two-Axis Inertial Stabilized Platform. *In IEEE Access*, vol. 5, pp. 12951-12962, 2017, doi: https://doi.org/10.1109/ACCESS.2017.2723541.

[22] Saroha J., Singh M., Jain D.K. ANFIS-Based Add-On Controller for Unbalance Voltage Compensation in a Low-Voltage Microgrid. *In IEEE Transactions on Industrial Informatics*, vol. 14, no. 12, pp. 5338-5345, 2018, doi: https://doi.org/10.1109/TII.2018.2803748.

[23] Rathnayake N., Dang T.L., Hoshino Y. A Novel Optimization Algorithm: Cascaded Adaptive Neuro-Fuzzy Inference System. *International Journal of Fuzzy Systems*, vol. 23, no. 7. 2021, doi: https://doi.org/10.1007/s40815-021-01076-z.

[24] Mani M., Khekare G. The Power Quality Enhancement in Distribution Networks Using Soft computing with Artificial Neural Networks in

Dynamic Voltage Restorer: ANN Based DVR. *SGS-Engineering & Sciences*, vol. 1, no. 1, 2025.
[25] Shah M. S., Mahmood T., Ullah M. F., Manan M. Q., Rehman A. U. Power quality improvement using dynamic voltage restorer with real twisting sliding mode control. *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8300-8305, 2022, doi: https://doi.org/10.48084/etasr.4734.
[26] Laghari I. A., Kaloi G. S., Sohoo Z., Khatoon S. Robust Voltage Sag Compensation Using a Matrix Converter DVR and Sliding Mode Control Technique. *Sir Syed University Research Journal of Engineering & Technology*, vol. 14, no. 2, pp. 114-120, 2024, doi: https://doi.org/10.33317/ssurj.660
[27] Nouman D., Sajjad I. A., Ali A. Distribution Network Voltage Improvement using Dynamic Voltage Restorer with Smooth Super Twisting Sliding Mode Control. *In 1st International Conference on Scientific and Innovative Studies (ICSIS)*, vol. 1, 2023.

Information about authors.

Sanepalle Gopal Reddy completed Ph.D from Annamalai University, Tamil Nadu in 2025. His areas of interest are Electro Magnetic Fields, High Voltage Engineering, Renewable energy sources and Power Systems. E-mail: sanepallegopalreddy447@gmail.com
ORCID: https://orcid.org/0000-0001-7439-1380

Kotha Shashidhar Reddy completed Ph.D from JNTUH, Hyderabad, Telangana in 2015. His areas of interest are Power Transformers, High Voltage Engineering, Renewable energy sources and Power Systems. E-mail: drshashidhar@cvr.ac.in
ORCID: https://orcid.org/0000-0003-1223-4421

Athimamula Srujana completed Ph.D from JNTU, Hyderabad in 2011. Her areas of interest are Power Electronics and Power Systems. E-mail: srujanaa@yahoo.com
ORCID: https://orcid.org/0009-0003-0581-5620