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A Novel Approach for Power Quality Improvement Using D-STATCOM in Wind Integrated Distribution System

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Abstract

Objectives: The major goal of the proposed article is to enhance the power quality of a wind-integrated radial distribution network utilizing D-STATCOM. It is done by the appropriate allocation of wind turbine-based DGs and D-STATCOM. **Methods:** The multi-objective optimization problem is implemented using a novel and effective Prairie Dog Optimization (PDO) to attain the best-compromised solutions. This optimization tool is well suited for solving complex, non-linear voltage stability problems. The proposed approach is validated for the modified IEEE-13 bus highly unbalanced system using MATLAB. **Findings:** The findings indicate enhancements in the voltage profile, system losses, and total harmonic distortion (THD). The THD for the load current is 18%, while the THD for the source current is 2.54% for nonlinear loads using the proposed methodology. The voltage profile of 3.25% is enhanced as compared with the existing method, which is 2.15% better than the other obtainable method. **Novelty:** Prairie Dog Optimization (PDO) was chosen over traditional algorithms for its nature-inspired approach, simplicity, and efficacy in exploring complicated search fields. Its robust exploration and exploitation skills make it excellent for multi-modal optimization challenges.

Keywords: Radial distribution system (RDS); D-STATCOM; Power quality; Prairie Dog Optimization; THD

1 Introduction

Throughout the years, the re-establishment of optimal power quality with the secured level in the distribution system has shown an important role. Advanced power electronic devices and computer-controlled devices utilization affect the PQ and create disturbances like voltage swell, sag, and harmonic distortion. The objective of ensuring power quality (PQ) within permitted ranges has consistently introduced significant complications. Power quality (PQ) challenges can culminate in insufficient power quality, potentially arising from escalated losses, the undesirable and irregular features of equipment, and the existence of interference[1]. The suitable arrangement and size specifications of D-STATCOM systems within the distribution infrastructure, emphasize the need for more advanced optimization approaches and comparative

assessments. It also emphasizes the significance of addressing many devices, and imbalanced networks and minimizing harmonic distortion in future studies. A D-STATCOM with Gradient Descent Back Propagation (GDBP) improves power quality by effectively addressing power quality concerns[2].

The efficacy of various optimization methodologies, including particle swarm optimization (PSO), a hysteresis-based PWM current controller, hybrid PSO-Firefly optimization, and fuzzy-controlled D-STATCOM in stabilizing microgrid functionalities is critically assessed[3,4]. To compute both active and reactive power, the study employs the instantaneous d-q theory as its foundational methodology. Additionally, a hysteresis-based PWM current controller is incorporated to facilitate the operational efficacy of the D-STATCOM[5]. An algorithm designed for a D-STATCOM utilizing an LCL filter aims to enhance power quality through the implementation of dual modes of operation, specifically current control and voltage control mode, achieved via the regulation of the point of common coupling (PCC) voltage. The implementation of regulation in adaptive voltage diminishes the requisite voltage of the dc-link, consequently improving performance in terms of voltage level and operational efficiency[6]. In order to mitigate neutral current issues arising from non-linear and unbalanced loads and to guarantee sinusoidal source currents, four D-STATCOM topologies utilize different inverter configurations in combination with either a zig-zag or a transformer having T-connected. When compared to TPFL and TPSC topologies, these designs offer reduced costs and ratings, effective compensation in extreme load conditions, and the ability to handle short-term overloads[7]. A 48-pulse voltage source inverter-based DSTATCOM can significantly enhance power quality within a microgrid by effectively managing power flow, reducing total harmonic distortion, and stabilizing voltage profiles[8]. The DSTATCOM plays a crucial role in enhancing the quality of electrical power within microgrids by regulating power flow and diminishing the overall harmonic distortion[9].

A wide range of DSTATCOM configurations and control approaches are implemented to alleviate power quality concerns stemming from current fluctuations[10]. The application of a solar photovoltaic system, which is interconnected with the grid, is employed to energize a 3-phase 3-wire system Distributed Static Compensator, aimed at enhancing power quality for a distribution system having a low voltage level[11,12]. The significance of inductive as well as capacitive loads, in terms of both the presence and absence of STATCOM, is diligently investigated, and a sophisticated mathematical framework is delineated[13]. The Voltage Reference Configuration (VRC) control algorithm, which is predicated on frequency domain analysis, is implemented within a D-STATCOM framework characterized by 3-phase operation[14].

The Hysteresis Current Controller (HCC), alongside the Synchronous Reference Frame (SRF) regulation, predominantly focuses on the technology pertaining to D-STATCOM. The operational mechanism of D-STATCOM involves the injection of compensatory current at the point of common coupling to mitigate reactive power generated by non-linear loads and harmonics. The implementation of H-bridge D-STATCOM control methods tailored for power quality assessment in various industrial loads across a range of loading scenarios[15]. In a three-phase, seven-level voltage-boosting approach for D-STATCOM applications aimed at resolving power-quality challenges in distribution systems[16,17].

An advanced wavelet controller is designed with the objective of enhancing power quality in a 3-phase 4-wire Distribution Static Synchronous Compensator (D-STATCOM). Experimental findings illustrate the WTSKFNN's strong performance across varying load conditions, highlighting its effectiveness for power quality management in contemporary electrical systems[18]. To enhance the reconfiguration of imbalanced distribution networks, AEFAPS is a hybrid algorithm aimed at reducing losses, voltage sag, unbalance, and energy shortfalls. The findings indicate that AEFAPS outperforms traditional methods such as PSO and GWO[19]. A unique parallel-VSI-based DSTATCOM configuration and DBSCAN topology are presented in this study with the goal of improving three-phase distribution systems' power quality (PQ), especially in the case of non-linear load situations[20,21]. A controller based on ADALINE for a PV-DSTATCOM, designed to enhance the quality of electrical power within distribution networks across various load conditions[22].

Various studies about power quality enhancement have been discovered, and gaps have been identified as various previous studies were ineffective in imbalanced nature, or nonlinear loads, convergence issues. Very few works are concerned with THD minimization. Prairie Dog Optimization (PDO) is utilized to solve previously identified power quality difficulties. PDO beats rival algorithms in terms of updating behavior, capability, and performance. The PDO method beats other commonly used optimization strategies in various ways, including better exploration and exploitation strategy balance, greater capabilities, the ability to predict the global optimum for true optimization issues, and more consistent convergence.

2 Methodology

A comprehensive examination of the existing literature concerning various prevalent optimization strategies has been undertaken. The PDO methodology is derived from the behavioral patterns observed in the natural habitat of prairie dogs. Four distinct activities related to prairie dogs are proposed, encompassing the exploration phase and the exploitation phase. The PDO algorithm is employed for the optimal placement of the D-STATCOM, aiming to enhance voltage profiles, mitigate harmonic distortion, and reduce power losses.

2.1 Mathematical Modeling of D-STATCOM:

The instantaneous voltages across the three phases at the Point of Common Coupling (PCC) are represented as follows:

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} V_s \begin{bmatrix} sin\omega t \\ sin\left(\omega t - \frac{2\pi}{3}\right) \\ sin\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \tag{1}$$

The correlation between the PCC voltages, the inverter's output voltages, and the associated currents is established through the derivation of the KVL equation relevant to D-STATCOM.

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -\frac{R_f}{L_f} & 0 & 0 \\ 0 & -\frac{R_f}{L_f} & 0 \\ 0 & 0 & -\frac{R_f}{L_f} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{L_f}\begin{bmatrix} V_{sa} - V_{ca} \\ V_{sb} - V_{cb} \\ V_{sc} - V_{cc} \end{bmatrix} \tag{2}$$

The aforementioned equations delineate the system's differential equations within the abc reference framework.

To regulate the current introduced by the Voltage Source Converter (VSC), it is imperative to convert these equations into the synchronous reference frame. The Park transformation serves as the methodology for transitioning from the ABC reference frame to the synchronous qd0 reference frame.

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_f}{L_f} & \omega \\ -\omega & -\frac{R_f}{L_f} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \frac{1}{L_f}\begin{bmatrix} V_{sd} - V_{cd} \\ V_{sq} + V_{cq} \end{bmatrix} \tag{3}$$

The Unified power quality index (UPIQ) for the ith bus is expressed as:

$$U_i = \frac{v_i^T \times F_i}{v_i^T \times F_{th}} \tag{4}$$

Where F_i is the individual indices vector for PQ phenomena and F_{th} is the threshold values vector for the ith bus .

Therefore, the aggregate UPIQ for the distribution network is as:

$$UPQI_{aggregate} = A_a \sum_{i=1}^{a} w_i \times U_i + A_b \sum_{i=1}^{b} w_i \times U_i + A_c \sum_{i=1}^{c} w_i \times U_i \tag{5}$$

$$UPQI_{aggregate} = \left(A_a \times UPQI_a\right) + \left(A_b \times UPQI_b\right) + \left(A_c \times UPQI_c\right) \tag{6}$$

Aa is the utility score at buses group

Ab is the utility score at DG buses group

Ac is the utility score at load buses group

$$UPQI_{aggregate} = \frac{\sum_{i=1}^{a}\left(w_i \times U_i\right) + \sum_{i=1}^{b}\left(w_i \times U_i\right) + \sum_{i=1}^{c}\left(w_i \times U_i\right)}{(a+b+c)} \tag{7}$$

2.2 Prairie Dog Optimization (PDO)

The PDO methodology demonstrates superiority over other frequently employed optimization strategies in numerous aspects, such as improved balancing between exploration and exploitation strategies, enhanced capabilities, the potential to ascertain the optimal solution for practical challenges, and the fast convergence issue, among others. The schematic representation of the PDO methodology is illustrated in Figure 1.

The mathematical expression representing the objective function is articulated as follows:

$$OF = Min\{E\} \tag{8}$$

where error in terms of voltage profile improvement and power loss reduction is represented as E.
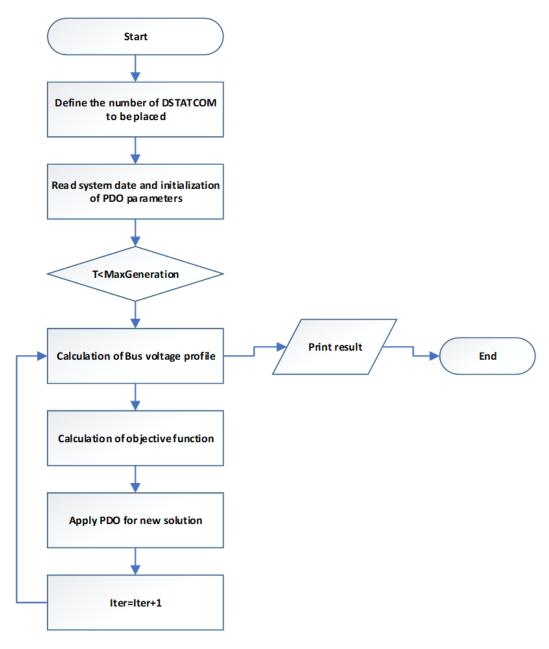
Fig 1. Flow chart of Prairie Dog Optimization

2.3 Wind-based Radial Distribution System

This particular circuit model is characterized by its compact dimensions and operated at a level of 4.16 kV. This model is notably recognized for its brevity, significant load capacity, a singular voltage regulation device located at the substation, as well as its combination of overhead and underground cabling, shunt capacitors, an integrated transformer, and the presence of unbalanced loading conditions. The conventional framework is interconnected with wind turbine generators (WTGs) at various bus locations, as illustrated in Figure 2.

In the present investigation, D-STATCOM is utilized within voltage control management (VCM) to address voltage quality challenges resulting from the intermittency of renewable energy sources (RES). Figure 3 and Figure 4 illustrate the configurations of distribution networks incorporating D-STATCOM in both VCM and conventional control management (CCM), respectively.
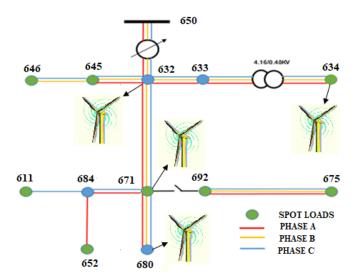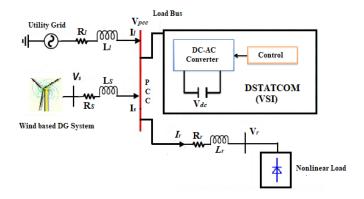
Fig 2. IEEE-13 bus test system

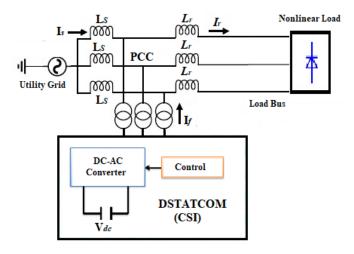**Fig 3. Distribution network with STATCOM (VSI mode)**

Fig 4. Distribution network with STATCOM (CSI mode)

3 Results and Discussion

The system under consideration is illustrated in figure 2 for the different scenarios that have been evaluated in terms of UPQI for power quality assessment. The first case is the case when no WTG is connected and the evaluated voltage profile is within permissible limits as per the standard voltage profile. In the second case, when WTGs are connected to the buses in the proposed system, the voltage profile increases, and the losses are reduced due to optimal placement. In the third case, when D-STATCOM is introduced at bus 680 in the distribution system, then it has a significant result in various bus voltages. The voltage profiles in phases A, B, and C are illustrated in Figures 5, 6 and 7, respectively.
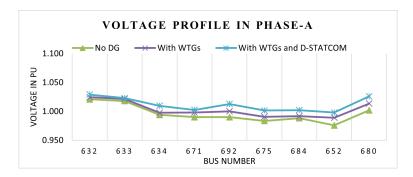

Fig 5. Voltage magnitudes at various bus locations within phase-A

In Figure 5, the bus voltage in phase-A at bus 634 is 0.994 p.u. at standard case, but due to proper placement of a D-STATCOM, the voltage level is increased to 1.010 p.u., which improved the voltage profile. In phase B, the voltage at bus 634 is improved from 1.02 p.u. to 1.0226 p.u., while in phase C it is improved from 0.996 p.u. to 0.989 p.u.
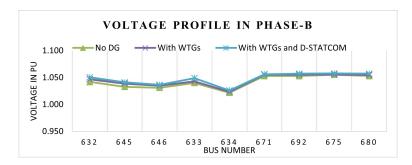

Fig 6. Voltage magnitudes at various bus locations within phase-B

In Figure 6, the impact of WTG and D-STATCOM is represented for phase B. The voltage profile at bus 634 is apparently low as compared to other buses due to non-linearity in load.
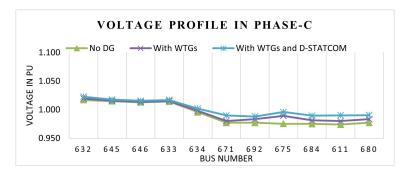

Fig 7. Voltage magnitudes at various bus locations within phase-C

In Figure 7, the voltage magnitude in phase-C clearly indicates that due to the proper placement of WTGs and D-STATCOM, the voltage profile is improved. Due to this, the active losses were reduced from 100 kW to 94 Kw and the reactive losses from 320 kVAR to 290 kVAR. The power quality assessment of the proposed system is assessed based on UPQI and shown in Figure 8.
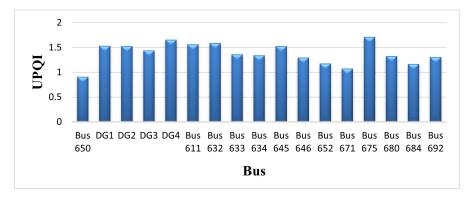

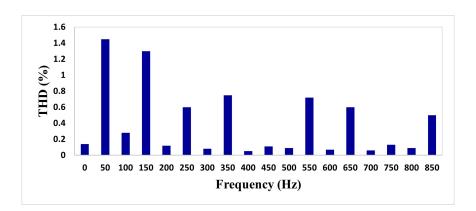**Fig 8. Analysis of UPQI at different buses**

Fig 9. THD for source current

Figure 9 and Figure 10 show the simulation results of a DSTATCOM radial distribution system using the suggested PDO approach under non-linear load elements, with source current THD (2.74%) and load current THD (18%), respectively.
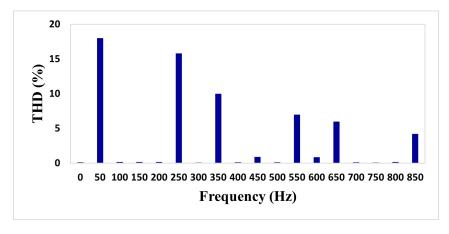

Fig 10. THD for load current

Table 1. HD (%) and voltage profile of IEEE-13 bus system comparisons with existing methods

Parameters	PDO	(4)	(17)
THD (%) in case of nonlinear load	2.54	5.10	2.790
Voltage profile (Overall in %)	3.25	2.950	2.760

The proposed method represented that the voltage profile and THD are enhanced as compared to the existing methods, as shown in Table 1.

4 Conclusion

The suggested grid-tied DSTATCOM system was developed in MATLAB/Simulink utilizing a Prairie Dog Optimization (PDO) technique for an IEEE 13 bus system to improve power quality for both the radial distribution system (RDS) and non-linear loads. The voltage profile is enhanced by 3.25% when compared to the existing method, which is 2.15% better than the other available methods or approaches. PDO has been reported to offer a superior voltage profile than conventional techniques. Furthermore, PDO outperforms other techniques in terms of voltage profiles, delivering the IEEE-13 bus voltage with the least amount of THD (%). In the future, hybrid optimization approaches, such as PQ improvement with DSTATCOM, may be utilized to further minimize THD and power losses in the distribution system.

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