Enhancing low voltage ride through capability of grid connected DFIG based WECS using WCA-PSO tuned STATCOM controller

Irene Ndunge Muisyo a,*, Christopher Maina Muriithi b, Stanley Irungu Kamau c

a Pan African University Institute for Basic Sciences, Technology, and Innovation (PAUSTI), Kenya
b Murang’a University of Technology (MUT), Kenya
c Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya

ARTICLE INFO

Keywords:
LVRT
PSO
STATCOM
VSI
WCA

ABSTRACT

This paper investigates the utilization of a STATCOM to enhance the LVRT capability of a 9 MW DFIG based Wind Power Plant (WPP) during grid faults. The STATCOM under investigation is tuned using the Water Cycle Algorithm (WCA), Particle Swarm Optimization (PSO) and a hybrid algorithm of both WCA and PSO. Simulations are carried out in MATLAB programming software, using SimScape toolbox. Performance analysis is done by investigating the ability of the test system to ride through voltage sags on the grid side, with incorporation of the STATCOM tuned using WCA, PSO and further with the hybrid WCA-PSO algorithm. To confirm effectiveness of the proposed algorithm, simulation results for the three scenarios are compared. Results show that LVRT capability of the Danish power system was met for L-G faults. However, without a STATCOM, the WPP could not ride through LLL-G faults. When STATCOM was incorporated, LVRT capability requirements were met. Voltage fluctuations reduce from 17% to 3%, without STATCOM and with WCA-PSO tuned model, respectively, during L-G faults. During LLL-G faults, voltage magnitude fluctuates from 60% to 25%, without STATCOM and with WCA-PSO tuned model respectively. WCA-PSO tuned STATCOM also resulted in the least voltage, active and reactive power overshoots.

1. Introduction

Wind energy is among the fastest growing renewable energy resources. The installed capacity of wind power generation globally was 744 GW by the end of 2020, which represented about 26% of renewable energy generation. China and US are the world’s largest onshore wind power producers, together accounting for more than 60% of the new capacity in 2020 [1, 2]. Previously, wind power generators were allowed to disconnect from grids during power system faults. With increasing levels of wind power integration into grids, disconnecting wind power generation during faults can negatively impact the stability of a power system. Therefore, power system operators worldwide have revised their Grid Code Requirements (GCRs) to incorporate Fault Ride Through (FRT) capability of wind farms. FRT capability is the ability of Wind Power Plants (WPPs) to remain connected to the grid during power system faults [3, 4]. Under different undervoltage or overvoltage conditions, WPPs are required to stay online for a short, specified duration of time. FRT capability of WPPs is classified into Low Voltage Ride Through (LVRT) capability (during grid voltage sags) and High Voltage Ride Through (HVRT) capability (during voltage swells). Voltage sags are the most frequent power system faults, hence LVRT is the most significant GCR for wind power generating plants [3, 5]. LVRT capability is demonstrated by profiles of voltage and time duration for which a generator must stay connected to the grid, based on reduction in the voltage level during faults. LVRT grid codes differ for each country based on the Transmission System Operator (TSO) requirements and grid strength. LVRT requirements are represented by voltage against time profile as shown in Figure 1.

From Figure 1, x-axis shows the time, while y-axis depicts the highest value of grid voltage at the point of common coupling (PCC). Grid connected WPPs must stay in operation if voltage at the PCC remains above the solid line [6]. From Figure 1 for instance, German regulations impose the most restrictive LVRT capability requirements for wind turbines, as the wind farms must withstand up to zero voltage value for 150 ms. If the voltage is below the profiles illustrated in Figure 1, the wind turbine should be disconnected from the mains supply [7]. When the fault is cleared, voltage at the PCC should recover to 0.9 p.u. within 1500 ms. A

* Corresponding author.
E-mail address: muisyoirene@jkuat.ac.ke (I.N. Muisyo).

https://doi.org/10.1016/j.heliyon.2022.e09999
Received 2 November 2021; Received in revised form 26 January 2022; Accepted 14 July 2022
2405-8440/© 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Many techniques have been proposed in literature to improve the LVRT capability of DFIG based WPPs. The main methods often employed for LVRT capability enhancement of grid connected WPPs include utilization of crowbar circuits, braking resistors, Fault Current Limiters (FCLs), and Flexible AC Transmission System (FACTS) devices. A list of related research work on LVRT capability enhancement of WPPs is presented in Table 2.

The Dynamic Voltage Restorer (DVR) and Static Synchronous Compensator (STATCOM) are the most utilized FACTS devices in enhancing performance of grid connected WPPs [16, 17]. The DVR and STATCOM are Voltage Source Converter (VSC) based FACTS devices which can independently exchange active and reactive power with a grid. VSC FACTS device operation is based on PI controllers whose gains are obtained using conventional methods such as Ziegler-Nichols (Z-N), pole placement and graphical tuning. With the advancement of artificial intelligence-based technologies, various optimization algorithms are increasingly being applied in controller parameter tuning and optimization. Techniques such as Fuzzy Logic (FL) based control, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) methods have been proposed for FACTS device controller tuning. New algorithms are being developed to overcome some shortages (such as premature convergence or long computation time) encountered in existing meta-heuristic optimization methods. This paper investigates the LVRT capability of a DFIG based, grid connected 9MW WPP with STATCOM utilization. The STATCOM controller is independently tuned using three algorithms, viz, the Water Cycle Algorithm (WCA), Particle Swarm Optimization (PSO) and a hybrid algorithm of both WCA and PSO.

The main contribution of this research is the simultaneous tuning of all three STATCOM controllers, using the newly proposed Water Cycle Algorithm (WCA). Hybridization of WCA and PSO algorithms has not been done and tested on power system applications. The WCA-PSO hybrid algorithm has not been applied previously in the dynamic tuning of STATCOM controllers. The organization of the rest of this paper is as follows: Section 2 presents Wind Energy Conversion Systems (WECS), whereas in Section 3, the proposed controller tuning is explained. In Section 4, effectiveness of the WCA-PSO tuned STATCOM to enhance the LVRT capability is verified using the 9 MW grid connected WPP. Section 5 provides conclusions and suggestions for future work.

### 2. Wind Energy Conversion Systems (WECS)

Wind Energy Conversion Systems (WECS) convert the kinetic energy in wind into mechanical energy, by means of wind turbine rotor blades. The mechanical power developed by a wind turbine depends on the wind velocity and air density, given in (1) as,

\[ P_m = \frac{1}{2} \rho A_r v_w^3 C_p(\lambda, \beta) \]

where \( \rho \) is the air density (kg/m³), \( A_r (\pi R^2) \) is the area swept by rotor blades (m²), \( v_w \) is the wind speed (m/s), \( C_p \) is the power coefficient which is a function of Tip-Speed Ratio (TSR) \( \lambda \) and the blade pitch angle \( \beta \). The mechanical energy is then converted into electrical energy, which is fed to the grid.

#### 2.1. Topologies of WECS

Generally, WECS can be classified in terms of power yield, type of generator, operating speed, and orientation of wind turbine. The commonly used WECS classification based on power delivering capabilities and type of machine involved gives rise to four topologies, viz., fixed

| Table 2. Related work of LVRT capability of WPPs. |
| Authors | Method | Controlling technique | Strengths | Weaknesses |
|----------|--------|------------------------|-----------|------------|
| Akanto et al. [9] (2021) | RSC to inject Q to SCIG | PI controller | Minimum power rating for DFIG | Requires combined WFs |
| Boulouatzq et al. [10] (2021) | DVR | Active Disturbance Rejection Control (ADRC) strategy | DFIG has no transient voltages | DVRs are expensive |
| Gebre et al. [11] (2020) | Crowbar resistance protection | Dissipate fault current | Reduced harmonics | No reactive power support |
| Ma and Shi [12] (2022) | Distributed compensator | Silicon carbide (SiC)-based inverters | Economical and effective | Several modules needed |
| Ahmed et al. [13] (2022) | DVR | Adaptive Noise Cancellation (ANC) technique | Fast response | Expensive, harmonics |
| Hague et al. [14] (2021) | FCL | Series and parallel resonance switching devices | Reduced SSR and low THD | Cannot model adaptive impedance based on fault severity |
| Omar et al. [15] (2020) | STATCOM | PSO-ACO tuning | Fast response | Transients during fault period |

### Table 1. LVRT capability requirements for various countries.

| S. No. | Country | Voltage level | LVRT capability | Fault duration | Voltage drop level | Recovery time |
|-------|---------|---------------|-----------------|----------------|-------------------|---------------|
| 1.     | Denmark | DS/TS         | 100 ms          | 25%            | 1 s               |               |
| 2.     | Ireland | DS/TS         | 625 ms          | 15%            | 3 s               |               |
| 3.     | Germany | DS/TS         | 150 ms          | 0%             | 1.5 s             |               |
| 4.     | Great Britain | DS/TS | 140 ms | 15% | 1.2 s |               |
| 5.     | Spain   | TS            | 500 ms          | 20%            | 1 s               |               |
| 6.     | Italy   | >35kV         | 500 ms          | 20%            | 0.3 s             |               |
| 7.     | United States | TS | 625 ms | 15% | 2.3 s |               |
| 8.     | Ontario | TS            | 625 ms          | 15%            | 3 s               |               |
| 9.     | Quebec  | TS            | 150 ms          | 0%             | 0.18 s            |               |

DS – Distribution System, TS – Transmission System.
speed wind turbines, limited variable speed wind turbines, variable speed with partial scale frequency converter and variable speed with full scale frequency converter [20, 21]. The fixed speed wind turbine configuration is simple but is unable to extract maximum power at varying wind speed, since its slip can only be varied over a very small range.

On the other hand, variable speed wind turbine technology allows speed control, improving efficiency, and reducing mechanical stress for a wider range of wind speeds. The variable speed wind turbine can comprise a partial scale or a full-scale power electronic converter. The partial-scale power converter rating defines the speed range, typically ±30% of the synchronous speed. On the other hand, the full-scale power converter transforms variable frequency AC power into fixed-frequency AC power. The main drawback of the full-scale power converter is that output filter ratings are about 1 p.u. of the total system power, which results in a more expensive device [22, 23]. This work investigates the variable speed wind turbine with partial scale power converter.

### 2.2. DFIG modeling and operation

The variable speed wind turbine with partial scale power converter is based on a Double Fed Induction Generator (DFIG). DFIG based WECS take up more than 50% of the total installed WPPs worldwide. The DFIG has advantages such as variable speed capability, low initial cost, low converter rating, and active and reactive power controllability. However, DFIGs are susceptibility to faults at the grid side [4, 24]. The DFIG has its stator connected directly to the grid, while its rotor is connected to the grid through a Power Electronic Converter (PEC), as shown in Figure 2 [3].

In Figure 2, the Rotor Side Converter (RSC) controls active and reactive power flow from the stator to the grid while the Grid Side Converter (GSC) maintains the DC link voltage constant, thus controlling the grid current [18, 25]. Equivalent circuit of the DFIG in d-q reference frame is shown in Figure 3.

In Figure 3, subscripts d and q indicate direct and quadrature axis components, whereas s and r refer to stator and rotor quantities, respectively. The two-axis fourth-order model of the DFIG in the synchronously rotating reference frame is employed to study the dynamic performance under the grid voltage sag. The d–q stator and rotor voltages are given in (2) as,

\[
\begin{align*}
    v_{ds} &= R_s i_{ds} + \frac{di_{ds}}{dt} - \omega_s \lambda_{qs} \\
    v_{qs} &= R_s i_{qs} + \frac{di_{qs}}{dt} + \omega_s \lambda_{ds} \\
    v_{dr} &= R_r i_{dr} + \frac{di_{dr}}{dt} - (\omega_r - \omega_s) \lambda_{qr} \\
    v_{qr} &= R_r i_{qr} + \frac{di_{qr}}{dt} - (\omega_r - \omega_s) \lambda_{dr}
\end{align*}
\]

where, \(v\) and \(i\) denote voltage and current, respectively, \(R\) is the resistance (\(\Omega\)), \(\lambda\) is the flux linkage (\(V\cdot s\)), \(\omega_s\) is the supply angular frequency (rad/sec), \(\omega_r\) is the rotor angular frequency (rad/sec) [26, 27]. During normal operating conditions with constant stator voltage (\(V_s\)), the stator flux linkage \((\lambda_s)\) remains almost constant, therefore \(\frac{d\lambda_s}{dt}\) can be neglected. However, during voltage sags, \(V_s\) dips and \(\lambda_s\) decreases proportionally with the grid voltage. The magnitude of natural component of \(\lambda_s\) depends on the amplitude of voltage dip, and during faults, it generates a large EMF in the rotor windings. This can damage the PEC. In addition, low voltage at the PCC reduces the capacity of the GSC to transfer active power to the grid. This leads to excess power in the DC-link capacitor, resulting in increased DC link voltage [25, 28]. Conventionally, the PEC is protected from rotor over currents using a crowbar, as shown in Figure 2.

A crowbar consists of a set of switches usually implemented between the rotor circuit and the RSC to provide a bypass for the high transient rotor current during faults. Once triggered by DC capacitor overvoltage or rotor overcurrent, the crowbar short-circuits the RSC, thus control of active and reactive power is lost. During this period, the DFIG absorbs reactive power from the grid, which negatively impacts voltage at the PCC. If the fault persists, the DFIG is finally disconnected from the grid [27, 28]. Due to the significant increase in grid connected wind power generation, disconnecting large WPPs from a power system during disturbances can contribute to instability. Power system operators have stipulated guidelines for WPPs to be able to ride through grid faults, with LVRT being the most significant grid code. In literature, several methods are being explored for enhancement of the LVRT capability of DFIG based wind power generating plants. These methods include:

i. use of a crowbar which provides an additional path for the rotor current, thus the DFIG stays connected to grid [16, 29],

ii. a DC chopper connected in parallel with the PEC to dissipate excessive energy thus suppress the DC-link capacitor voltage [30, 31],

iii. Series Dynamic Breaking Resistors (SDBR), activated during fault conditions to limit the rotor current, thus avoid DC-link capacitor overvoltage [16, 31],

iv. Flexible AC Transmission System (FACTS) devices such as DVR [6, 32], SVC [3] and STATCOM [15, 33].

The DVR is a series connected custom power device which can be used to inject a dynamically controlled voltage at the PCC of a wind power plant. Chung in [6] employs a DVR in a wind farm to improve its FRT capability. During faults, the DC-link, GSC of the first wind turbine,
and the series transformer play the role of DVR, injecting reactive power to maintain the collector line voltage at the pre-fault value. Results show that during faults, the stator terminal voltage is maintained at the desired level, and rotor side current and rotor speed deviation were reduced significantly during grid faults. The DVR is seen to be robust, however its rating should be same as the rated output of the Wind Turbine Generator (WTG). Moreover, DVRs are expensive due to many ancillary components required during installation [34, 35]. The STATCOM is a shunt FACTS device primarily used to supply or absorb reactive power to support a specified bus voltage magnitude. It can control output voltage independently of the AC system voltage, with a very fast response. STATCOM modules are easier to incorporate in existing power systems since they are shunt devices and do not require system modification such as in series devices [15, 33]. In this work, the STATCOM is investigated for enhancement of LVRT capability of WPPs.

3. STATCOM operation and control

3.1. STATCOM configuration

The STATCOM is a shunt FACTS device used to inject or absorb reactive power to a specified bus. It comprises of a Voltage Source Inverter (VSI), DC source and a coupling transformer, connected in shunt with the AC system [36], as shown in Figure 4.

The VSI is the heart of a STATCOM consisting of self-commutating power electronic devices (GTO or IGBT), together with a reverse blocking diode in parallel. From Figure 4, Vg is the bus voltage, Vdc is the VSI voltage, P is the active power of the VSI, and Q is the reactive power of the VSI. The DC input voltage from the capacitor is converted into a set of controllable three phase AC output voltages. The STATCOM can operate in capacitive or inductive modes based on the difference between the PCC voltage and the reference voltage. If the PCC voltage amplitude decreases, a leading current is injected from STATCOM to the grid at PCC, while in inductive mode, a lagging current is injected from STATCOM to the grid at PCC [36]. The fundamental component of Vg is proportional to Vdc. VSI controller operation starts with a measurement system which obtains DC capacitor voltage Vdc, STATCOM reactive current Iq, and bus line voltage Vabc, as shown in Figure 5 [37] [38].

From Figure 5, the Phase Locked Loop (PLL) system generates synchronizing signals (θPLL) for abc/dq transformation of Vg, abc and Iacb. In the voltage regulator loop, the actual PCC bus voltage (Vg) is compared with the reference value (Vref) and the difference is applied to the PI controller to generate the reference reactive current (Iqref). The current regulation loop compares injected or absorbed reactive current (Iq) with the reference value (Iqref) to produce the desired phase angle (α). α is the phase shift of STATCOM voltage (Vg) with respect to the grid voltage (Vg). Conduction angle of the inverters (β) is fixed at 172.5° to minimize 23rd and 25th harmonics of generated voltage. The positive and negative voltages of the DC capacitor are maintained equal using offset (Δα) from the DC voltage regulator. The firing pulses generator uses the signals to generate switching pulses for the GTO inverters. The switching pulses control magnitude and phase of the VSI output voltage [25, 38]. The three regulators (voltage regulator, current regulator, and DC-link voltage regulator) are based on a Proportional Integral (PI) controller. Their outputs are given in (3),

\[ I_{qref} = (V_{ref} - V_g) \left( K_p + \frac{K_i}{s} \right) \]

\[ \alpha = (I_{qref} - I_q) \left( K_p + \frac{K_i}{s} \right) \]

\[ \Delta\alpha = (V_{dc2} - V_{dc1}) \left( K_p + \frac{K_i}{s} \right) \] (3)

The procedure of obtaining Kp and Ki which would result in the desired performance is called tuning. Controller tuning can be done using conventional methods such as Ziegler-Nichols (Z-N), pole placement and graphical tuning, or by intelligent optimization algorithms such as Fuzzy Logic (FL) based control, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), among other methods. Intelligent optimization algorithms are increasingly being applied in controller parameter tuning and optimization. These algorithms have merits of robustness and universality, but they also have challenges such as premature convergence or slow convergence rate [39, 40]. From literature review, STATCOM controller tuning using intelligent optimization algorithms has not been investigated broadly. Rashad et al. in [33] (2019) use Artificial Neural Networks (ANN) to tune a STATCOM, to improve the performance of a wind power plant during symmetrical faults. Performance of the wind farm with a STATCOM tuned by ANN was compared with that of a STATCOM tuned by the Multi-Objective Genetic Algorithm (MOGA) and Whale Optimization Algorithm (WOA). From the results, ANN tuned STATCOM gave a better voltage profile for the windfarm during three-phase faults. Active power output of the windfarm with ANN tuned STATCOM was also greater than when the other two algorithms were utilized. Omar et al. in [8] (2020) investigate the ability of a STATCOM to enhance the FRT capability of DFIG wind turbines. STATCOM PI regulators were tuned using classical methods, fuzzy logic, PSO, Ant Colony Optimization (ACO), and the hybrid PSO-ACO. It was observed that the fuzzy control method and meta heuristic methods (PSO, ACO, PSO-ACO) resulted in a better dynamic performance for the STATCOM as compared to the classical tuning method. The authors observe that the hybrid PSO-ACO method was able to obtain proper gains for the STATCOM in a very short time, and the method can be exploited to realize dynamic behavior needed in FACTS devices. From the sample of ongoing research work mentioned above, it is evident that dynamic tuning of FACTS devices can improve the LVRT capability of WPPs. Bakir et al. in [41] model a Solar PV-Wind Hybrid Micro-grid and incorporate a Genetic Algorithm (GA) tuned STATCOM to the increase the system voltage stability. With the conventional controller, voltage fluctuation between ±10% is observed, as opposed to by ±8% witnessed when GA is used. In this work, the Water Cycle Algorithm (WCA) and Particle Swarm Optimization (PSO) techniques will be used to tune the three PI STATCOM regulators.

3.2. Problem formulation

STATCOM controller tuning was converted to an optimization problem, with the aim of minimizing the error between reference and measured values. Time domain integral error functions can be used as objective functions for metaheuristic optimization techniques. These include Integral of Squared Error (ISE), Integral of Absolute Error (IAE) and Integral of Time Absolute Error (ITAE). The ITAE function was adopted in this work since overshoots are reduced faster and has a
shorter settling time than IAE and ISE tuning methods [42, 43]. The optimization problem is stated in (4) as, minimize

\[
J(X) = \int_0^T e_{\text{vac}} \, dt + \int_0^T e_{\text{ac}} \, dt + \int_0^T e_{\text{dc}} \, dt
\]

Subject to

\[
K_{\text{min}} \leq K \leq K_{\text{max}}
\]

where \( X = [K_{P1}, K_{I1}, K_{P2}, K_{I2}, K_{P3}, K_{I3}] \), \( T \) is the time range of the simulation, and \( t \) is the discrete solver step time (50µs). The constraints were obtained from a conventional STATCOM as given in Table 3.

The optimization algorithms minimize total ITAE error value and returns the final fitness value, and the corresponding six gains at the optimal output. STATCOM controller gains were evaluated using the algorithms independently, and performance comparison done.

### 3.3. Water Cycle Algorithm (WCA)

The Water Cycle Algorithm (WCA) is a meta-heuristic optimization algorithm inspired by the water cycle process. The algorithm describes river creation and the travel of water to sea. It was proposed by Hadi Eskander et al in 2012 [44]. At the start of the WCA, an initial population of raindrops \( N_p \) is generated. The cost function of each raindrop is evaluated using (4), and the costs sorted in ascending order. The best raindrops \( N_{sr} \) are assigned to a number of rivers \( N_r \) and one sea, given by (6),

\[
N_{sr} = \text{round} \left\{ \frac{C_n}{\sum_{i=1}^{N_r} C_i} \times N_s \right\}, \quad n = 1, 2, \ldots, N_s
\]

Where, \( N_{sr} \) is the number of streams flowing into certain rivers and sea. The streams move towards the rivers and the rivers towards the sea. The updated positions, for the streams and the rivers, are given by (8),

\[
\begin{align*}
X_{\text{stream}}^{i+1} &= X_{\text{stream}}^i + \text{rand} \times C \times (X_{\text{river}}^i - X_{\text{stream}}^i) \\
X_{\text{river}}^{i+1} &= X_{\text{river}}^i + \text{rand} \times C \times (X_{\text{sea}}^i - X_{\text{river}}^i)
\end{align*}
\]

Where, \( \text{rand} \in [01] \) and \( C \) is greater than 1. Costs of the new positions are evaluated again and if the stream cost is less than the river cost, their positions are exchanged. If the cost of a river is less than that of the sea, their positions are exchanged. To avoid premature convergence, evaporation is conducted. We check whether the river or stream is sufficiently close to the sea to enable evaporation. Raining and evaporation are conducted if (9) is not met.

\[
|X_{\text{sea}}^i - X_{\text{river}}^i| < d_{\text{max}}
\]

Where, \( i = 1, 2, \ldots, N_{sr} \) and \( d_{\text{max}} \) is a very small number. Therefore, the intensity of search near the sea can be controlled by \( d_{\text{max}} \), which is updated as given in (10),

\[
d_{\text{max}}^{i+1} = d_{\text{max}}^i - d_{\text{max}}^{\text{max_iter}}
\]

Where \( i = 1, 2, \ldots, \text{max_iter} \). The optimization algorithm will continue with the search process until termination criteria is met. Raindrops at the optimal solution correspond to the optimal PI parameters [45, 46, 47]. A flowchart of the WCA is given in Figure 6.

The WCA has been observed to be efficient and simple compared to other methods. It has also shown a good performance in terms of convergence, computation, and precision [44, 47]. The parameters used in WCA optimization in this work are given in Table 4.

### 3.4. Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) algorithm is a biologically inspired computational search and optimization method developed in 1995 by Eberhart and Kennedy. The algorithm simulates the behavior of birds or fish when looking for the place with the most adequate food. The PSO algorithm starts by randomly generating particles in the search space. Next, fitness value of each particle is evaluated, and the position corresponding to the best fitness value is called the local best position. The local best of all particles is compared and the best position in the swarm is defined as global best. At every iteration, the

\[
\text{fitness value of each particle is evaluated, and the position corresponding to the best fitness value is called the local best position. The local best of all particles is compared and the best position in the swarm is defined as global best. At every iteration, the}
\]

---

**Table 3. STATCOM PI gain constraints.**

| PI controller       | Constraints                      |
|---------------------|----------------------------------|
| AC voltage regulator| \( 5 \leq K_{P1} \leq 25, 1000 \leq K_{I1} \leq 3000 \) |
| AC current regulator| \( 0.3 \leq K_{P2} \leq 12, 10 \leq K_{I2} \leq 100 \) |
| DC voltage regulator| \( 0.0001 \leq K_{P3} \leq 1, 0.02 \leq K_{I3} \leq 1 \) |
termination criteria are checked, and if not met, an update of the velocity and position of all particles is done \[36, 48\]. The velocity of particles is given in \(11\),

\[ V_{i}^{k+1} = wV_{i}^{k} + C_{1}r_{1}(P_{i} - X_{i}^{k}) + C_{2}r_{2}(G_{i} - X_{i}^{k}) \]  

\(11\)

while the position of individual particles is updated by \(12\),

\[ X_{i}^{k+1} = X_{i}^{k} + V_{i}^{k+1} \]  

\(12\)

where, \(X_{i}^{k}\) is the particle position, \(V_{i}^{k}\) is the particle velocity, \(P_{i}\) is the individual particle best position, \(G_{i}\) is swarm best position, \(w\) is the weight inertia used to ensure convergence, \(C_{1}\) and \(C_{2}\) are the cognitive and social parameters while \(r_{1}\) and \(r_{2}\) are random numbers between 0 and 1 \[36, 49\]. The flowchart of PSO algorithm is shown in Figure 7.

The PSO algorithm has been gaining popularity due to its simple structure and efficiency. Additionally, it outperforms gradient based optimization methods which require the optimization problem to be differentiable. However, the PSO algorithm can result in sub-optimal solutions in the event a particle gets stuck in a local optimum \[50, 51\]. The PSO parameters utilized in this work are given in Table 5.

3.5. WCA-PSO hybridization

The WCA was hybridized with PSO to take advantage of the strengths of each algorithm. In this hybrid, the WCA first explores the search place to identify the most promising region, thus rule out the challenge encountered by the PSO of particles being stuck in a local optimum. Next, starting with the solution obtained by WCA, the PSO is introduced to continue with the search until termination criteria is met. The flowchart of the hybridized WCA-PSO algorithm is shown in Figure 8.

The parameters used in this work for the hybridized algorithm are given in Table 6.

4. Test system and results

4.1. 9MW WPP test system

LVRT capability investigation was done for a power system integrated with a 9 MW DFIG based wind power generating plant. The test system was developed by aggregating six, 1.5 MW DFIG wind turbines into a 9 MW Wind Power Plant. The output of the wind power generating plant is injected into a 25 kV distribution system through a three phase 12 MVA transformer. A single line diagram of the test system is shown in Figure 9.

A medium transmission line of 30 km length connects the WPP to a 120 kV grid through a three phase 47 MVA transformer at bus feeder B2. A 2300 V, 2-MVA plant consisting of a motor load (1.68 MW induction motor at 0.93 PF) and of a 200-kW resistive load is connected on the same feeder. The DFIG wind turbine and generator parameters are given in Table 8 and Table 9 respectively, whereas the transmission line parameters are found in Table 10. The wind turbines have a protection system monitoring voltage, current and machine speed, and the wind turbine protection system data is given in Table 11. All test system data was obtained from \[15\].

The test system was independently subjected to L-G and LLL-G, 75% voltage sags on the grid side for 100 ms, to investigate the Danish LVRT

\[ \text{Table 4. WCA parameters.} \]

| Parameter name | Variable | Value |
|----------------|----------|-------|
| No. of variables | \(N_{vars}\) | 6     |
| Population size | \(N_{p}\) | 50 |
| No. of rivers + sea | \(N_{sr}\) | 4 |
| Evaporation condition constant | \(d_{max}\) | \(10^{-16}\) |
| Maximum no. of iterations | Max_iter | 100 |

Figure 6. Water Cycle Algorithm flowchart.
Simulations were carried out on the test system with each STATCOM independently incorporated, and performance analysis done. In the next section, the dynamic performance of the power system with the proposed STATCOM controller is presented.

4.3. Single line to ground fault

4.3.1. WPP active power output

Active power output of the WPP for L-G, 75% grid voltage sag of 100 ms is given in Figure 10.

At \( t = 15 \) s, a fault is simulated in which grid voltage drops to 0.25 p.u. for 100 ms. From Figure 10, without STATCOM, active power output drops from 8.8MW to -1MW, due to the low voltage at the connection bus. Once the DFIG protection system detects an under voltage at 0.75 p.u., the crowbar is activated (protection parameters are given in Appendix). The RSC is bypassed and the DFIG acts as a Squirrel Cage Induction Generator (SCIG). As the voltage drops, active power supply to the grid falls to zero and the WPP draws active power from the grid. When either conventional or tuned STATCOM is incorporated, voltage support is provided at the PCC, and the WPP maintains active power output during the fault period. LVRT capability requirements of Danish utility state that grid connected wind power plants should be able to withstand voltage sags of up to 25% for 100 ms, a requirement already met. Without, and with conventional STATCOM, settling time is longer by 150 ms, as compared to tuned models. Active power fluctuations are smallest (7%) for WCA-PSO tuned STATCOM, as opposed to 19% for conventional STATCOM.

4.3.2. Voltage profile at WPP terminals

The voltage profile at WPP terminals is shown in Figure 11, for L-G 75% voltage sag of 100 ms on the grid side.

From Figure 11, voltage fluctuations are seen at the WPP terminals. Voltage magnitude drops from 1 p.u. to 0.83, 0.94 and 0.97 p.u., without, with conventional and with tuned STATCOM models; corresponding to 17%, 6% and 3% variation, respectively. Hale Bakir et al. [52] used Genetic Algorithm (GA) and Bacteria Foraging Algorithm (BFA) and obtained 30% and 20% voltage fluctuations respectively, for L-G faults. Thus WCA-PSO shows better results. Fluctuations settle within 100 ms and 200 ms, after fault clearance respectively, for WCA-PSO tuned and conventional STATCOM. Thus, voltage fluctuations are minimum at the WPP terminals during, and after fault clearance for WCA-PSO tuned STATCOM. Omar et al. in [36] hybridized Ant Colony and Particle Swarm Optimization techniques and observed a settling time of 350 ms for a similar fault. Thus, WCA-PSO tuning results in a shorter settling time than ACO-PSO. When the fault is cleared, voltage rises momentarily to 1.12 p.u., 1.08 p.u., and 1.02 p.u., without, with conventional, and with WCA-PSO tuned STATCOM, respectively. Overvoltage is caused by excess reactive power supplied by the GSC and STATCOM during the fault period.

4.3.3. WPP reactive power output

Reactive power output of the WPP for L-G, 75% voltage sag of 100 ms on the grid side is given in Figure 12.

From Figure 12, without a STATCOM, when the L-G grid fault occurs, the GSC injects up to 6.5MVAr to support voltage at the WPP terminals. With STATCOM incorporation, GSC injects less reactive power. The PEC is not bypassed, thus the DFIG generates active power during the grid fault. Reactive power oscillations are higher for conventional STATCOM as opposed to WCA-PSO tuned STATCOM.

4.3.4. DC link capacitor voltage

DC link capacitor voltage of the DFIG for L-G 75% voltage sag of 100 ms on the grid side is shown in Figure 13.

From Figure 13, the DC link capacitor voltage fluctuates from a reference value of 1200 V to around 1140 V at the onset of the voltage

| Parameter name       | Variable | Value |
|----------------------|----------|-------|
| Population size      | \( N_p \) | 100   |
| Maximum number of iterations | \( \text{Max}_{\text{iter}} \) | 100   |
| No. of variables     | \( N_{\text{vars}} \) | 6     |
| Minimum inertia weight | \( w_{\text{min}} \) | 0.4   |
| Maximum inertia weight | \( w_{\text{max}} \) | 0.9   |
| Cognitive component  | \( C_1 \) | 1.4   |
| Social component     | \( C_2 \) | 1.4   |
| Random numbers       | \( r_1, r_2 \) | U (0,1) |

Table 5. PSO parameters.
sag, and back to about 1280 V at the end of the fault period, when a STATCOM is not utilized. Without a STATCOM, the crowbar is activated, which limits DC link capacitor overvoltage. The GSC injects reactive power which contributes to 6% voltage spike after fault clearance. The WCA-PSO tuned STATCOM results in the least fluctuations.

4.4. Three lines to ground (LLL-G) fault

4.4.1. WPP active power output

Active power output of the WPP for LLL-G, 75% voltage sag of 100 ms on the grid is shown in Figure 14.

From Figure 14, during the LLL-G fault, active power output at the WPP rapidly drops from about 8.8 MW up to the point of disconnection at \( t = 15.12 \) s, before STATCOM incorporation. This is attributed to the low voltage on the connection bus. The WPP gets disconnected and active power output reduces to zero.

---

Table 6. WCA-PSO parameters.

| Parameter name                      | Variable | Value |
|-------------------------------------|----------|-------|
| No. of variables                    | \( N_{\text{vars}} \) | 6     |
| Population size                     | \( N_{\text{pop}} \) | 50    |
| Maximum no. of iterations (PSO)    | \( \text{Max}_\text{iter} \) | 50    |
| Maximum no. of iterations (WCA)    | \( \text{Max}_\text{iter} \) | 50    |
| Minimum inertia weight             | \( w_{\text{min}} \) | 0.4   |
| Maximum inertia weight             | \( w_{\text{max}} \) | 0.9   |
| Cognitive and social components    | \( C_1 = C_2 \) | 1.4   |
| Random numbers                     | \( r_1, r_2 \) | U (0,1) |
| No. of rivers (sea)                | \( N_{\text{sr}} \) | 4     |
| Evaporation condition constant     | \( d_{\text{max}} \) | \( 10^{-16} \) |

---

Figure 8. WCA-PSO flowchart.
power generation does not resume. The LVRT capability requirement of Denmark utility is not met. With incorporation of all STATCOM models, the WPP rides through the LLL-G fault. For conventional STATCOM, oscillations are significantly high. For instance, 100 ms after fault...
Figure 10. WPP active power output.

Figure 11. Voltage profile at WPP terminals.

Figure 12. WPP reactive power output.

Figure 13. DC link capacitor voltage.

Figure 14. WPP active power output.

Figure 15. Voltage profile at WPP terminals.
clearance, oscillations are at 19% and 2% for conventional and WCA-PSO tuned STATCOM respectively.

4.4.2. Voltage profile at WPP terminals

The voltage profile at the WPP terminals is shown in Figure 15 for LLL-G 75% grid voltage sag of 100 ms.

From Figure 15, voltage at the WPP terminal dips by 60%, 35%, 45%, 45% and 25%, respectively, without, with conventional, PSO, WCA and WCA-PSO tuned STATCOM. When the fault is cleared, there is an overvoltage due to the reactive power supplied by the STATCOM during the fault period. The highest overshoot (30%) occurs with conventional STATCOM, after fault, whereas the WCA-PSO tuned STATCOM results in highest overshoot of 20%. Fluctuations take about 150 ms to settle, for WCA-PSO tuned STATCOM, as opposed to 300 ms for conventional STATCOM.

4.4.3. WPP reactive power output

Figure 16 shows reactive power output of the WPP for LLL-G, 75% grid voltage sag of 100 ms.

Without STATCOM, GSC injects 4MVAr before WPP disconnection. For other scenarios, STATCOM and GSC inject maximum reactive power, to aid grid recovery. Highest transients are observed for WCA model, whereas WCA-PSO has a smoother output. Transients for conventional STATCOM take 100 ms longer to decay than tuned models. Severe transients are observed at the beginning and end of the fault interval, which can be eliminated by using FCLs.

4.4.4. DC link capacitor voltage

The DC link capacitor voltage of the DFIG for LLL-G, 75% grid voltage sag of 100 ms is shown in Figure 17.

From Figure 17, the DC link capacitor voltage drastically increases at the start and end of fault. Fluctuations are caused by inability of GSC to regulate DC capacitor voltage. WCA-PSO tuned model has the least fluctuations during fault onset (10%), as compared to 27% for PSO tuned. Voltage fluctuations settle within 200 ms after fault for WCA-PSO model as opposed to conventional STATCOM with 320 ms.

5. Conclusion

In this paper, the LVRT capability of grid connected 9 MW DFIG WPP is investigated against requirements for Danish utility grid. The STATCOM has been utilized for reactive power compensation to enhance LVRT capability and improve the dynamic performance of the grid connected WPP. STATCOM controller tuning has been done using WCA, PSO and WCA-PSO hybrid algorithms. The WCA is a recent optimizer which has not been employed in controller tuning. It is observed that STATCOM controller tuning can be carried out using meta-heuristic optimization techniques. The hybrid algorithm of WCA-PSO is seen to have superior performance as compared to the individual algorithms. Validity of the proposed STATCOM controller tuning was verified during a 75% grid voltage sag of 100 ms. Simulations were carried out using MATLAB/Simulink toolbox. Performance comparison was done for conventional, WCA, PSO and WCA-PSO tuned STATCOM, in terms of voltage profiles, active and reactive power, under L-G and LLL-G faults independently. LVRT capability of the Danish power system was met for L-G faults. During LLL-G faults, without a STATCOM, the WPP could not ride through the fault. When STATCOM was incorporated, LVRT capability was met. Voltage fluctuations reduce from 17% to 3%, without STATCOM and with WCA-PSO tuned model, respectively, during L-G faults. During LLL-G faults, voltage fluctuates from 60% to 25%, without STATCOM, and with WCA-PSO tuned model, respectively. WCA-PSO tuned STATCOM utilization had less voltage, active and reactive power overshoots. Transients were observed at the beginning and end of fault period. Since the STATCOM provides reactive power support, an additional technique of limiting the fault current can be incorporated, such as the FCL, SDBR or a DC chopper, thus ensure the WPP meets LVRT capability requirements during LLL-G faults. WCA-PSO algorithm can further be applied in various power system optimization problems. STATCOM controller tuning using other metaheuristic optimization algorithms should be explored further and tested on larger practical power systems.

Declarations

Author contribution statement

IRENE NDUNGE MUISYO; CHRISTOPHER MAINA MURIITHI & STANLEY IRUNGU KAMAU: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This work was supported by Pan African University Institute for Basic Sciences, technology and Innovation (PAUSTI).

Data availability statement

Data included in article/supp. material/referenced in article.
Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] IRENA, Renewable Capacity Statistics, International Renewable Energy Agency, Abu Dhabi, 2020.
[2] A. Ibrahim, S. Gawish, N. El-Amary, S. Sharaf, STATCOM controller design and experimental investigation for wind generation system, IEEE Access 7 (2019) 150453–150462.
[3] H. Rezaie, M. Hossein, Enhancing voltage stability and LVRT capability of a wind-integrated power system using a fuzzy-based SVC, Eng. Sci. Technol. an Int. J. 22 (2019) 827–839.
[4] M.J. Mosaad, A. Abou-Siada, M.M. Iqbal, H. Albalawi, A. Fahmy, Enhancing the fault ride-through capability of a DFIG-WECS using a high-temperature superconducting coil, Energies 14 (2021) 6319.
[5] L. Yuan, K. Meng, J. Huang, Z. Dong, W. Zhang, X. Xie, Development of HVRT and LVRT control strategy for PMMSG-based wind turbine generators, Energies 13 (5442) (2020) 1–16.
[6] P.D. Chung, Voltage enhancement on DFIG based wind farm terminal during grid faults, Eng. Technol. Appl. Sci. Res. 9 (5) (2019) 4783–4788.
[7] M. Duong, S. Leva, M. Mussetta, K. Le, A comparative study on controllers for improving transient stability of DFIG wind turbines during large disturbances, Energies 11 (2018) 461.
[8] O. Kamed, A. Diab, T. Do, M. Mosa, A novel hybrid Ant colony-particle swarm optimization techniques based tuning STATCOM for grid code compliance, IEEE Access 8 (2020) 41566–41587.
[9] J. Akanto, M. Hazari, M. Mannan, LVRT and stability enhancement of grid-tied wind farm using DFIG-based wind turbine, Applied Sys. Innov. 4 (31) (2021) 1–14.
[10] E. Boulountaya, Y. Baala, S. Mouline, M. Oubella, A. Rachdy, Enhanced LVRT capability of wind turbine based on DFIG using dynamic voltage restorer controlled by ADRC-based feedback control, E2S Web Conf. 229 (1016) (2021) 1–9.
[11] F. Gebra, B. Khan, H. Albelou, Analyzing low voltage ride through capability of doubly fed induction generator based wind turbine, 106727, Comput. Electr. Eng. 86 (2020) 1–19.
[12] C.T. Ma, Z. H. Shi, A distributed control scheme using SIC-based low voltage ride-through compensator for wind turbine generators, Micromachines 13 (39) (2022) 1–20.
[13] M. Ahmed, T. Kundli, E. Ahmed, Enhancing doubly fed induction generator low-voltage ride-through capability using dynamic voltage restorer with adaptive noise cancellation technique, Sustainability 14 (859) (2022) 1–21.
[14] Y.-Y. Haque, J. Hasan, R. Islam, R. Islam, Low-voltage ride through capability augmentation of DFIG-based wind farms using series-parallel resonance-type fault current limiter, Wind 1 (2021) 20–43.
[15] O. Makram, A. Diab, T. Duc, M. Mosa, A novel hybrid Ant colony-particle swarm optimization techniques based tuning STATCOM for grid code compliance, IEEE Access 8 (2020) 41566–41587.
[16] A.A. Jerin, P. Kaliannan, S. Padmanaban, V. Ramachandaramurthy, Improved Fault Ride through capability in DFIG based wind turbines using dynamic voltage restorer with combined feed-forward and feed-back control, IEEE Access 5 (2017) 20494–204105.
[17] J. Mvanik, H. Lin, Z. Dai, A concise presentation of doubly fed induction generator wind energy conversion systems challenges and solutions, Hindawi J. Eng. (2017) 1–13.
[18] S. Zain, L.A. Ahmed Helal, Low voltage ride through capability techniques for DFIG-based wind turbines, Int. J. Energy Power Eng. 10 (7) (2016) 910–919.
[19] Y. Qu, L. Gao, G. Ma, H. Song, S. Wang, Crowbar resistance value-switching scheme conjoint analysis based on statistical sampling for LVRT of DFIG, J. Modern Power Syst. Clean Eng. 7 (3) (2019) 558–567.
[20] D. S. K. T, Review of control strategies for DFIG wind turbine to enhance LVRT Capability, Int. J. Inov. Sci. Eng. Tech. 2 (4) (2015) 339–343.
[21] B. Qin, H. Li, Z. Zhou, J. Li, W. Liu, Low-voltage-ride-through techniques in DFIG-BasedWind turbines: a review, Appl. Sci. 10 (2154) (2020) 1–25.
[22] D. Zhang, H. Xu, L. Qiao, L. Chen, LVRT capability enhancement of DFIG based wind turbine with coordination control of Dynamic Voltage Restorer and inductive Fault Current Limiter, PloS One 14 (8) (2019).
[23] A. Rashad, S. Kamel, F. Juras, M. Nassen, K. Mahmoud, ANN-based STATCOM tuning for performance enhancement of combined wind farms, Electric Power Comp. Sys. (2019) 1–17.
[24] A. Benali, M. Khair, T. Allsou, M. Denai, Power quality improvement and low voltage ride through capability in hybrid wind-PV farms grid-connected using dynamic voltage regulator, IEEE Access 6 (1) (2018) 68634–68649.
[25] T. D. R. A. Jerin, P.K., U. S, Power quality improvement of grid connected wind farms through voltage restoration using dynamic voltage regulator, Int. J. Renew. Energy 33 (6) (2016).
[26] M.J. Mosaad, H. Ramadan, M. Aljouhni, M. El-Naggar, Near-optimal PI controllers of STATCOM for efficient hybrid renewable power system, IEEE Access 9 (2021) 34119–34131.
[27] A. K. P. S. Jian Shi, Improving power quality and stability of wind energy conversion system with fuzzy-controlled STATCOM, Aust. J. Electr. Electron. Eng. (2015) 1–10.
[28] Mathworks, MATLAB Programming Software, 2018.
[29] Y.-Y. Hong, M.-T. Nguyen, H. Zeng, Studies on optimal controller design of STATCOM in power system with large wind farms, International Conference on Electrical Engineering, Korea, 2018.
[30] H. Wu, W. Su, Z. Liu, PID controllers: design and tuning methods, IEEE Conference on Industrial Electronics and Applications, Hangzhou, 2014.
[31] H. Bakir, A. Kulaksiz, Modelling and voltage control of the solar- wind hybrid micro-grid with optimized STATCOM, Eng. Sci. Techn. Int. J. 23 (3) (2020) 576–584.
[32] G. Ahmed, Y. Mohmed, O. Kamel, Optimal STATCOM Controller for Enhancing Wind Farm Power System Performance under Fault Conditions, IEEE, Cairo, 2016.
[33] M. Sahib, B. Ahmed, A new multiobjective performance criterion used in PID tuning optimization algorithms, J. Adv. Res. 7 (2016) 125–134.
[34] H. Hasanien, M. Matar, Water cycle algorithm-based optimal control strategy for efficient operation of an autonomous microgrid, IET Gener., Transm. Distrib. 12 (21) (2018) 5739–5746.
[35] M. Juybari, M. Ardakan, H. Davari-Ardakani, An adjusted water cycle algorithm for solving reliability-redundancy allocation problems with cold-standby components, Int. J. Supply Oper. Manag. 5 (3) (2018) 218–233.
[36] E.-S. Badr, H. AlGendy, A hybrid water cycle particle swarm optimization for solving the fuzzy under-ground water confined steady flow, Indonesian J. Electr. Eng. Comp. Sci. 19 (1) (2020) 492–504.
[37] A. Sadollah, H. Eskandar, H. Lee, G. Yoo, J. Kim, Water Cycle Algorithm: A Detailed Standard Code, 5, Elsevier SoftwareX, 2016, pp. 37–43.
[38] T.-Y. Wu, T.-Z. Jiang, T.-F. Su, W.-C. Yeh, Using simplified swarm optimization on multiloop fuzzy PID controller tuning design for flow and temperature control system, Appl. Sci. 10 (2020) 1–23.
[39] T. Eswaran, S. Kumar, Particle swarm optimization (PSO)-based tuning technique for PI controller for management of a distributed static synchronous compensator (DSTATCOM) for improved dynamic response and power quality, J. Appl. Res. Technol. 15 (2017) 173–189.
[40] A. Hosain, H. Roy, S. Squartini, A. Fathi, Modified PSO algorithm for real-time energy management in grid-connected microgrids, Renew. Energy 136 (2019) 746–757.
[41] Y. Zhang, L. Zhang, Z. Dong, An MEA-tuning method for design of the PID controller, Mathematical Probsms. Eng.: Hindawi (2019) 1–11.
[42] H. Bakir, A. Kulaksiz, Modelling and voltage control of the solar-wind hybrid micro-grid with optimized STATCOM using GA and BPA, Eng. Sci. Techn. Int. J. 23 (2020) 576–584.