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Original Article

Optimal Reactive Power Control Strategy of a Hybrid Power System Using Sine Cosine Algorithm and STATCOM-POSICAST Controller

Gomar Bam[1], Pabitra Kumar Guchhait[2], Abhik Banerjee[3]

[1,3]*Department of Electrical Engineering, National Institute of Technology, Jote, Arunachal Pradesh, India.*
[2]*Department of Electrical Engineering, G H Raisoni College of Engineering and Management, Pune, Maharashtra, India.*

[3]*Corresponding Author : abhikbanerjee86@gmail.com*

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Abstract *- Reactive power mismatches in power systems can cause serious problems, especially making the system unstable. This instability can damage the power grid very quickly, in just a few milliseconds. So, it's very important to manage reactive power properly during disturbances to keep the system operating safely. Reactive power in power systems is managed by the proper use of FACTS devices. They precisely modify reactive power to correspond with the demands of the system's load. This study has applied an alternative optimal reactive power management technique to enhance system performance and stability in the presence of minor disturbances. The main goal of this work is to improve reactive power regulation in a standalone wind-diesel hybrid power system. It takes advantage of a POSICAST controller and a FACTS device known as a static synchronous compensator (STATCOM). The desired results obtained through the proposed control strategy are compared with the model without using the controller. To modify the controller parameters, similar comparisons are made between the outcomes and the used soft computing algorithms, such as the Sine- Cosine Algorithm (SCA) and Gravitational Search Algorithm (GSA).*

Keywords *- Hybrid power system, Reactive power compensation, STATCOM controller, Soft computing.*

1. Introduction

Nowadays, the increasing use of renewable energy sources comes with a pledge to reduce the dependency on fossil fuels [1]. This growth is largely attributed to the considerable distance from the grid network, and this type of distributed generation (DG) can be operated in both grid-connected mode or isolated mode. It is more effective to work in an isolated mode at sea and in hilly regions far away from the main grid because of its cost-effectiveness and enhanced reliability [2]. The DG system encompasses multiple generating systems that balance the supply and demand for a particular region, often known as the Hybrid Power System (HPS) [3]. In addition, there's a good chance that an energy system powered by diesel engines and another energy system powered by wind may be put into place here. A diesel and wind-powered isolated HPS has been developed to satisfy the area's peak load requirements. The wind turbine under consideration in this system is linked to an induction generator. Choosing induction generator (IG) coupled renewable sources has many benefits, including brushless operation, no need for a DC excitation source, fault self-protection, and cost-effectiveness, but in order to function, reactive power is needed [4]. Also, the majority of loads are inductive and require reactive power for their operation. The synchronous generator (SG) coupled diesel engine only provides reactive power in the considered isolated HPS. Reactive power imbalances between generation and demand cause unpredictable voltage swings at the terminal, which lower HPS stability and may result in major breakdowns. By utilizing the HPS's efficient reactive power control, such circumstances should be reduced. A STATCOM may afford the necessary reactive power to the system in a range of perturbed conditions, which helps the system to stay healthy. When compared to STATCOM and other FACTS devices, its reactive power compensation capability for the HPS system is better than that of others [5, 6]. Lately, there has been a significant surge in the utilization of algorithms across various domains, particularly in science and engineering applications, due to their greatly enhanced optimization capabilities. Additionally, these algorithms offer perceptions of actual system situations. To improve the parameters of isolated HPS, a variety of nature-inspired algorithms have been used, including the Gravitational Search Algorithm, Seeker Optimization Algorithm, Binary Genetic Algorithm (BGA), and various soft computing techniques [10-12].

This paper discusses parameter optimization in an HPS using the SCA algorithm [13] and compares the results with

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other well-known algorithms. Thus, employing a POSICAST controller in conjunction with STATCOM to examine proper reactive power flow in the HPS model under study was the main focus of this article.

1.1. Motivation of the Work

- Designs of PID controllers' parameters are not fruitful, which introduces the response of the system model instability [5, 6].
- The controller design approach makes the system local optima [7, 8].
- Sometimes, higher amplitude disturbances lead to system instability [9].
- Difficulties in accurately defining rule-based functions as well as Membership functions.

To fill this gap, this research is intended to enhance the system stability by controlling reactive power. The research employs a STATCOM and POSICAST controller in a wind-diesel HPS model to achieve this. Various soft computing techniques are used to precisely select parameter values, improving the system's performance and achieving desired outcomes effectively.

Therefore, the main contributions of this paper are:

- Improving reactive power control through an optimized STATCOM and POSICAST controller.
- Examining the isolated wind-diesel isolated HPS model alongside other controllers.
- Comparing algorithms (SCA and GSA) used to optimize parameters for reactive power control.

2. Theoretical Framework of the Investigated Hybrid System

The hybrid power system is the combination of more than one energy source. This study considers an SG-based diesel engine and an IG-based wind energy source. The transfer function-based block diagram of the considered HPS is shown in Figure 1. For the healthy operation of the HPS, the real and reactive power balance equations are given as

$$\Delta P_{ig} + \Delta P_{sg} = \Delta P_{load} \tag{1}$$

$$\Delta Q_{sg} + \Delta Q_{com} = \Delta Q_{load} + \Delta Q_{ig} \tag{2}$$

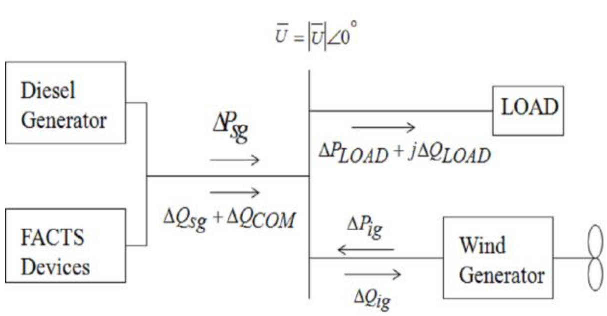

Fig. 1 Illustration presenting the examined system

But, in any changes in load as well as wind power variations, the reactive power demand changes, which will affect the terminal voltage. So, the net change in voltage with the net change in reactive power in the system may be written as in equation (3), and the transfer function-based linear model is given in Figure 2.

$$\Delta V(s) = \frac{K_v}{1+sT_v}[\Delta Q_{Statcom} + \Delta Q_{SG} - \Delta Q_{load} - \Delta Q_{IG}] \tag{3}$$

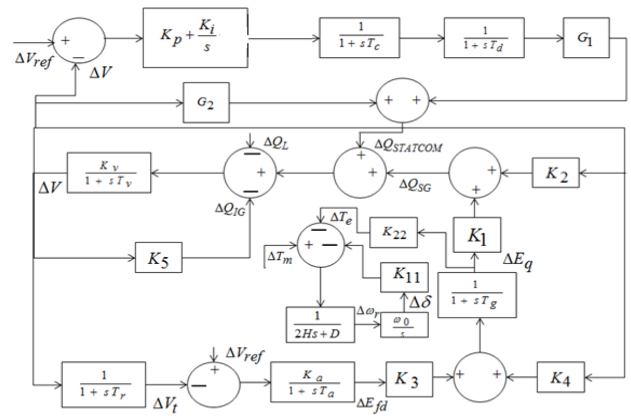

Fig. 2 Representation of the model with STATCOM Controller in the Laplace domain

Variations in the terminal voltage of the isolated HPS result in corresponding adjustments to the reactive power supply and consumption across many components, including loads, synchronous generators, induction generators, and FACTS devices.

The variations in reactive power for each of these system elements are covered in detail in the following sections.

The reactive power fluctuations in IG attached through the wind turbine at a constant slip (s) are represented by equation (4).

$$\Delta Q_{ig} = K_1 \Delta V(s) \tag{4}$$

In the Equation 4, the constant K_1 is given by

$$\left[\frac{2V(X_1 + X_2)}{(r_p + r_{eq})^2 + (X_1 + X_2)^2}\right]$$

Where r_p and r_{eq} written as $r_p = (1-s)\frac{r_2}{s}$ and $r_{eq} = r_2 + r_1$.

The IG parameters value is regarded as s = -3.45%, $r_1 = 0.185 p.u.$, $r_2 = 0.195 p.u.$, $x_1 = 0.45 p.u.$, $x_2 = 0.55 p.u.$

Furthermore, the alteration in reactive power in the diesel engine-based synchronous generator can be expressed as considered in equation (5).

$$\Delta Q_{sg} = K_2 \Delta E_q(s) + K_3 \Delta V(s) \tag{5}$$

When operating in a steady state, Equation (5) shows a direct relationship between the internal armature electromotive force and the direct axis field flux. Equation (6) considers how minor perturbations affect the armature electromotive force adjustment.

$$\Delta E_q = (\Delta E_{fd}(s)K_4 + \Delta V(s)K_5)\left(\frac{1}{1+sT_g}\right) \tag{6}$$

The constants referenced, *i.e.,* K_2, K_3, K_4, and K_5in Equations (5) and (6) are elaborated upon in the Appendix section.

A FACTS controller is used in the considered HPS to reduce the reactive power deficit because of its better operational characteristics than those of capacitor banks [14]. Statcom stands out among the variety of FACTS controllers as being particularly effective at controlling reactive power during disruptions in the Hybrid system model. A transfer function-based small signal STATTCOM modelling for reactive power management is depicted in Figure 2, which helps to improve the stability of the system.

2.1. Modelling of Posicast Controller

O. J. Smith first introduces a controller, namely, the Posicast controller, which helps suppress the oscillations of the lightly damped systems [15]. The controller achieves its goal by performing two steps of operation. The first step is scaled with the first peak of the oscillatory response and exactly meets its desired value. In the later step, a time delay is introduced with the input that cancels the remaining oscillatory portion of the system. In that way, the system's desired output should be achieved by applying a Posicast controller in the system. In the considered system for stability improvement purposes, the Posicast controller has been used for its excellent characteristics; the modelling of this controller is given in Figure 3, and the mathematical representation of the transfer function is given in (7) [16].

$$P(s) = \frac{\xi}{1+\xi}\left[-1 + e^{-s(\frac{T_d}{2})}\right] \tag{7}$$

For the optimum control of the system, the controller parameters (*i.e.,* K_s and T_s) should be set properly.

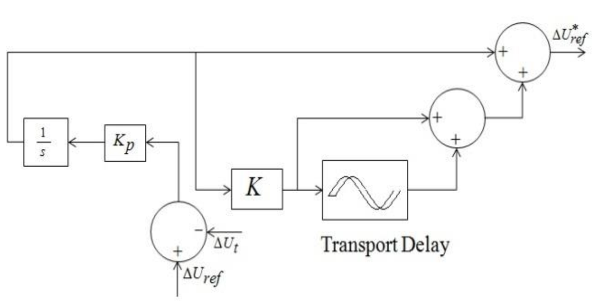

Fig. 3 Modelling of Posicast Controller

3. State Space Modelling Wind Diesel Hybrid Model is outlined as follows

The state equations for the examined Wind diesel HPS model are expressed in Equation (8) format, as referenced in [8].

$$\dot{\underline{Y}} = [A]\underline{Y} + [B]\underline{N} + [C]\underline{U} \tag{8}$$

In this equation, Y, N, and U correspond to state, control, and disturbance vectors, respectively, and A, B, and C are the corresponding matrices dealing with the vectors.

The transfer function model for the studies wind-diesel hybrid system for the controlling of reactive power is indicated in Figure 2. State space analyses for the studies system model are as follows.

Case 1: Considering Wind diesel model with STATCOM and POSICAST controller

$$\Delta\underline{Y} = [\Delta\alpha, \Delta\omega_r, \Delta\delta, \Delta E_{fd}, \Delta E_q, \Delta V_t, \Delta V, \Delta Y_1, \Delta Y_2,]^T$$
$$\Delta\underline{N} = [\Delta T_m, \Delta V_{ref}]^T$$
$$\Delta\underline{U} = [\Delta Q_{ref}]$$

The adjustable factors for this case-1 are Kp, K_i, T_c, T_d, K_s, and T_s

4. Mathematical Formulation of the Problem for the Studied Hybrid Wind Diesel System

The reactive power output of the STATCOM controller varies in response to changes in the voltage and firing angle. Voltage deviation acts as the controller's reference signal and guides the firing angle adjustment for Reactive Power Compensation (RPC). Also, the RPC is enhanced effectively by the specific tuning of Kp, Ki, Tc, Td, Kp1, and Td1.

Identifying the proper controller parameter set is the objective of the parameter optimization procedure. Using optimization strategies based on SCA and GSA procedures, the ideal parameter settings were found.

The utilization of the optimization procedure is to improve the damping of power system oscillations after disturbances, and it is perhaps fulfilled by enhancing the damping ratio of eigenvalues in the suggested model that has been examined but is not sufficiently damped.

A criterion associated with the WDHPS eigenvalues is used to fine-tune the parameters. The objective function (J) directs the process of adjustment and is provided in Equation (9)

$$J = J_1 + 10J_2 + 0.01J_3 + J_4 \tag{9}$$

4.1. Performance Indices Measurement

Performance metric optimization is carried out to maximise the HP's stability margin by means of better dampening and a small increase in load voltage. This denotes the reduction of steady-state error (Ess) in the output voltage response. Here, in this study, we are focusing on three performance indices related to measurement, namely, Integral Absolute Error (IAE), Integral Time Square Error (ITSE), and Integral Square Error (ISE) as defined in (10-12)

$$IAE = \int_0^\infty |U_t(t)|dt \tag{10}$$

$$ITSE = \int_0^\infty tU_t^2(t)dt \tag{11}$$

$$ISE = \int_0^\infty U_t^2(t)dt \tag{12}$$

5. Discussions on the Application of SCA Algorithm

The sine-cosine algorithm is a heuristic algorithm constructed on the concept of the mathematical function of sine and cosine. This algorithm is easy to understand as it is based on trigonometric functions and achieves the global optimum compared to other algorithms like GA and BGA; this SCA is better as time increases and the function decreases gradually.

The sine and cosine functions form the basis of the SCA algorithm. The parameters and constraints determine the output of any algorithm. The variables that are in need of optimization are called parameters, whereas the limitations affecting the system are classified as constraints.

Other than these primary inputs, this algorithm also has to take into consideration the secondary inputs, which affect the output of the system but do not necessarily need optimization.

The SCA optimization technique is a population-based optimization technique. Random solutions are taken initially. There is a need for an objective function that evaluates the random set, which is improved upon by a defined set of rules. Then, a repeated iteration process is employed to determine the global optimum because of the stochastic solution sets.

There are two phases in this optimization process: exploration and exploitation. Firstly, the algorithm tries to find the most promising search spaces using the set of random solutions.

In the exploitation phase, which is the second phase, changes are made gradually, and the randomness in the solution is decreased to discover the best possible solution.

Equations are used to update the positions, and they are presented as follows:

$$X_i^{t+1} = X_i^t + r_1 \times \sin(r_2) \times |r_3 P_i^t - X_i^t| \tag{13}$$

$$X_i^{t+1} = X_i^t + r_1 \times \cos(r_2) \times |r_3 P_i^t - X_{ii}^t| \tag{14}$$

The equations stated above can be combined in the following way:

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times \sin(r_2) \times |r_3 P_i^t - X_i^t|, & r_4 < 0.5 \\ X_i^t + r_1 \times \cos(r_2) \times |r_3 P_i^t - X_i^t|, & r_4 \geq 0.5 \end{cases} \tag{15}$$

Where X_i^t denotes the current position in the *i*-th dimension for the *t-th* iteration,

$r_1/r_2/r_3$ are numbers which are stochastic in nature whereas $r_4$is in the interval [0,1],

P_i denotes the designated final position in the *i*-th dimension,

|| indicates that the utilized value is the absolute one.

The four important parameters according to the given equations are:

- r_1 gives the region for the next position
- r_2 shows the range of movement
- r_3 will define the weight of the movement and can be greater or less than 1
- r_4 can switch between sine and cosine equally.

The working flow of the SCA is given in Figure 4.

6. Simulation Results and Discussions

The described proposed wind diesel HPS model with STATCOM-POSICAST Controller was simulated using MATLAB software.

In this test scenario, two algorithms (namely, SCA and GSA) were used to optimise different parameters. Following that, the simulation results were examined and debated under various input scenarios.

6.1. Analysis based on the Objective Function

Table 1 displays some Case parameters examined through various soft computing methods. Equation (8) is used as the objective function in this analysis.

According to Table 1, the SCA algorithm optimizes the objective function J to a lower value by parameter optimization approaches compared to GSA optimization techniques.

This implies that the objective function, in this case, has been reduced as a result of the model parameters being fine-tuned utilising SCA approaches.

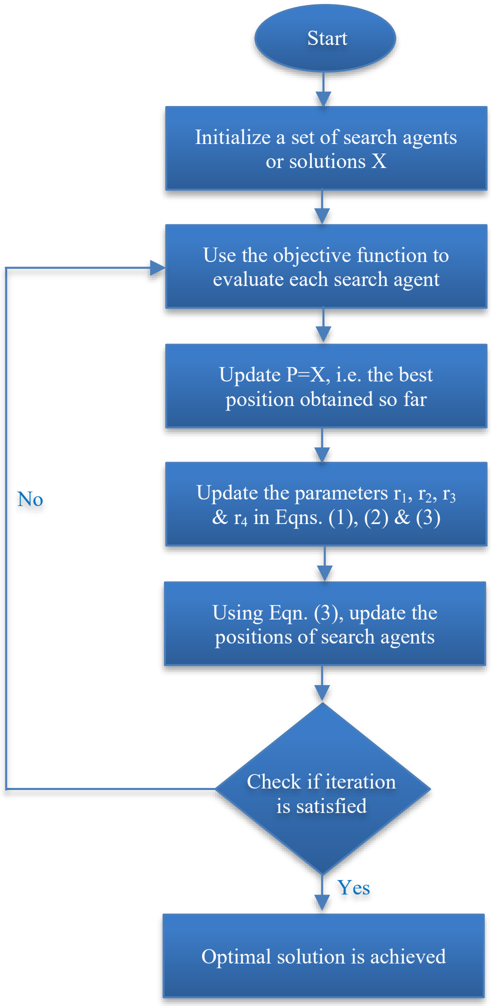

Fig. 4 Flowchart of SCA Algorithm

6.2. Transient Voltage Analysis

The superiority of the employed algorithms has been explored in this part, with convergence profiles considered. The suggested SCA algorithm for creating STATCOM-POSICAST is contrasted with the other algorithms that have been studied, such as GSA with STATCOM.

Three distinct optimisation strategies' effects on J are shown in Figure 5. Although J always drops, the rate at which it does so differs depending on the technique used. Compared to the other approaches, SCA optimisation, in particular, demonstrates quick convergence to a lower ultimate value of J. The number of iterations required for convergence for each algorithm is given in Table 2. The suggested method for optimised STATCOM with POSICAST controller, utilising SCA, outperforms the other algorithms described, as shown in Table 2 and Fig. 5.

6.3. Response during Standard Loading Conditions

The validation of Wind diesel hybrid system model performance under an incremental mechanical torque (T_m) at a percentage of 0.01 p.u. for the generator and a small disturbance in reference voltage (V_{ref}) has been established. Figure 6 illustrates the impact on the output voltage of the Wind diesel model due to V= 1.01 and Xeq=1.0p.u. Step load disturbances and it is evident that the system stabilized with the recommended SCA optimized STATCOM- POSICAST exhibits superior stability compared to GSA optimized STATCOM-POSICAST. Additionally, the rise time, peak time, maximum overshoot, and steady-state error required to attenuate system oscillations are approximately 2.0312s, 2.8724s, 0.0438, and -0.0070 respectively, with SCA-STATCOM, while it is 2.0212s, 2.8161s, 0.602 and 0.0068 for GSA-STATCOM under the load disturbance.

Table 1. Optimized fitness value and optimized controller parameters of the considered HPS under different input load variations

Input Conditions (V &Xeq in p.u.)	Applied Algorithms	Fitness Value	Optimal Parameters (Kp, Ki, Tc, Td, Ks and Ts)					
0.99, 0.97	GSA	308.0175	-2.1926	12.2469	0.9092	0.0713	9.9044	0.3152
	SCA	**303.0282**	**-3.2220**	**10.0000**	**0.0620**	**1.0100**	**10.0000**	**0.2081**
1.0, 0.97	GSA	332.7224	-3.0180	46.8504	0.9650	0.0697	10.0000	0.2253
	SCA	**303.2112**	**-3.0571**	**10.0000**	**0.0559**	**1.0100**	**10.0000**	**0.0920**
1.01, 1.0	GSA	437.2372	-1.0255	13.8542	1.0100	1.0100	10.0000	0.2840
	SCA	**303.3178**	**-3.0952**	**10.0000**	**0.0537**	**1.0100**	**10.0000**	**0.0837**
1.03, 0.97	GSA	327.0805	-2.9273	41.0200	0.0704	1.0100	10.0000	0.5545
	SCA	**303.9219**	**-2.7069**	**10.2911**	**0.9877**	**0.0469**	**10.0000**	**0.0559**
1.03, 0.99	GSA	444.2045	-1.6325	28.9210	1.0100	1.0100	7.2680	0.1794
	SCA	**303.7606**	**-2.8168**	**10.0000**	**1.0100**	**0.0581**	**10.0000**	**0.2354**
1.03, 1.01	GSA	312.2467	-1.8669	14.1161	0.0798	0.9299	10.0000	0.3636
	SCA	**303.3085**	**-3.0235**	**10.0000**	**1.0100**	**0.0666**	**10.0000**	**0.0500**

Table 2. Estimated iterations to converge the system

Applied algorithms	Number of iterations
SCA	76
GSA	68

6.4. Evaluation of Performance Indices

The values of the IAE, ITSE, and ISE under specified load disturbances are shown in Table 3. The outcomes show a decreasing trend in these indices, starting from the Wind Diesel hybrid model application and ending with the Wind Diesel Hybrid System model, which includes the STATCOM-POSICAST controller. Moreover, using the SCA optimisation technique yields better performance results.

6.5. Comparison of Control Strategy for the Proposed Controller

Figure 7 illustrates that the suggested STATCOM-POSICAST controller achieves a superior performance curve than the only PI-STATCOM controller considered for comparison.

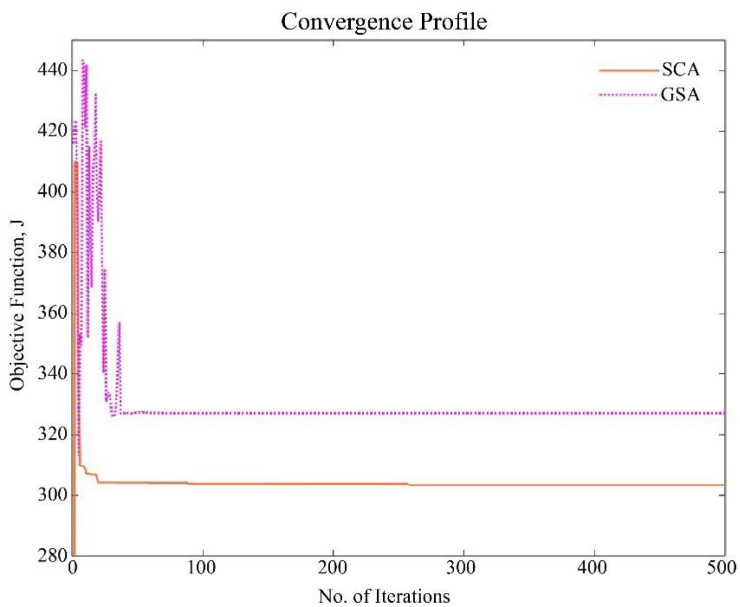

Fig. 5 Convergence characteristics observed during a test load condition

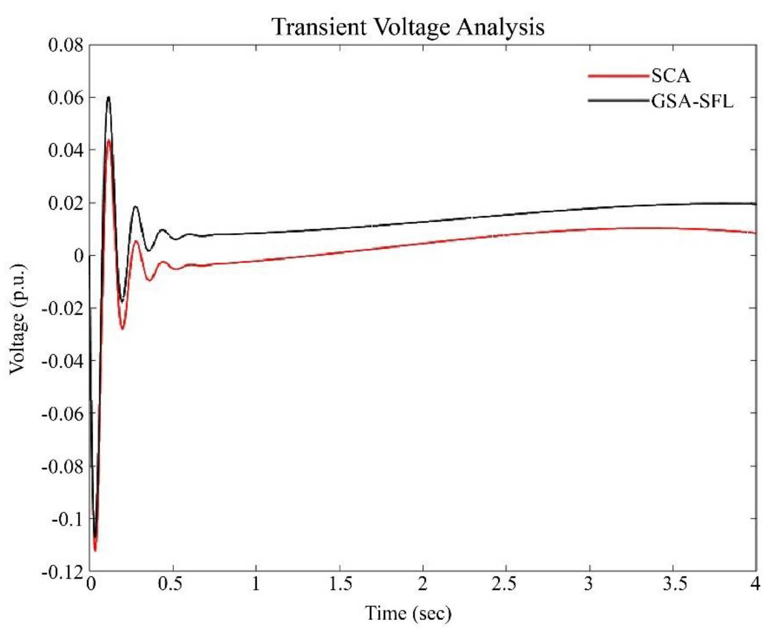

Fig. 6 Transient response under V=1.01 and Xeq=1.0p.u. Load disturbance.

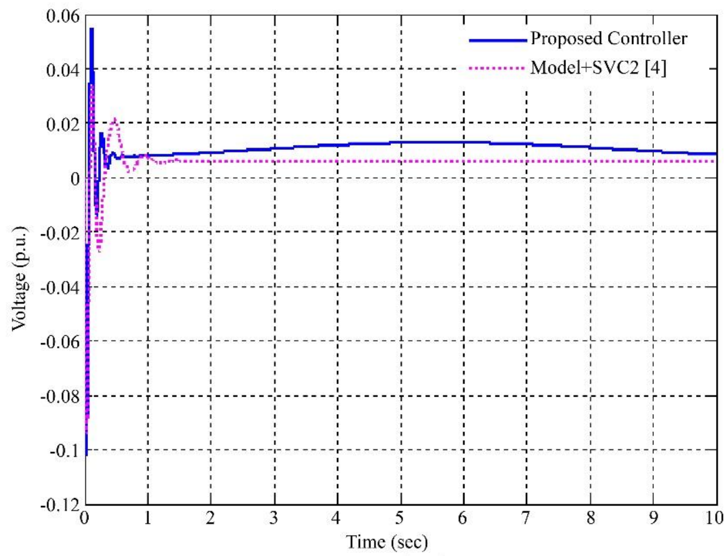

Fig. 7 Controller comparison between a) proposed STATCOM-POSICAST and b) SVC +Model

Table 3. Performances indices value of the system under various tested load situations

Load disturbances in p.u. (V and Xeq)	Applied algorithms	IAE	ITSE	ISE
0.99, 0.97	GSA	1174.7	802.2099	26.6313
	SCA	**669.7981**	**304.3607**	**17.5133**
1.0, 0.97	GSA	919.8438	421.4869	22.6581
	SCA	**643.4297**	**277.9405**	**16.3987**
1.01, 1.0	GSA	1202.0	1060.5	27.3065
	SCA	**633.6847**	**271.6379**	**15.8697**
1.03, 0.97	GSA	859.9476	333.4758	19.7271
	SCA	**583.7562**	**222.6002**	**13.7766**
1.03, 0.99	GSA	1246.1	1105.1	27.3154
	SCA	**593.4277**	**238.3891**	**14.0739**
1.03, 1.01	GSA	1128.5	725.4829	23.4323
	SCA	**607.7987**	**256.3761**	**14.4349**

6. Conclusion and Future Scope of Work

This research successfully integrated a STATCOM-POSICAST controller into the Wind Diesel Hybrid model for reactive power compensation. Compared to other controllers investigated in the literature, this controller improves stability by efficiently managing reactive power under various disturbances. Reactive power compensation in the Wind Diesel Hybrid system is now much more effective thanks to controller parameter optimisation employing various soft computing techniques.

The SCA method is especially good at optimising certain parameters; it performs better than the GSA-applied algorithm. Therefore, there is a great deal of promise for improving the stability of Wind Diesel Hybrid systems through the use of the SCA algorithm.

The efficacy of the controller may be further investigated for complex systems, and the simulated results may be compared with the hardware results.

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Appendix

The different constant parameters related to eqs. (4-5) are given following.

$$K_2 = \frac{V\cos\delta}{X_d'} \tag{A1}$$

$$K_3 = \frac{(E\cos\delta - 2V)}{X_d'} \tag{A2}$$

$$K_4 = \frac{X_d'}{X_d} \tag{A3}$$

$$K_5 = \frac{(X_d' - X_d)\cos\delta}{X_d'} \tag{A4}$$

$$T_G = T_{d0}' \frac{X_d'}{X_d} \tag{A5}$$

The different data considered to simulate the proposed STATCOM- POSICAST based hybrid system considered as in previous study: δ=17.2483^0, T_{d0}'=0.05 s, X_d=1.0 p.u. and X_d'=0.15 p.u., $P_{SG} = 0.4 p.u.\ kW$, $Q_{SG} = 0.2 p.u.\ kVAr$, $E_q = 1.12418 p.u.$, $E_q' = 0.9804 p.u.$, $P_{in} = 0.667 p.u.\ kW$, $\eta = 90\%$, power factor in IG=0.9, $P_{IG} = 0.6 p.u.\ kW$, $Q_{IG} = 0.291 p.u.\ kVAr$, $P_{load} = 1.0 p.u.\ kW$, $Q_{load} = 0.75 p.u.\ kVAr$, power factor of load=0.8, $Q_{STATCOM} = 0.841 p.u.\ kVAr$ and $\alpha = 53.32^{\circ}$, G_1 =1.478, G_2 =3.8347, K_A =200, T_A =0.05, T_R =0.02, K_V =0.667, T_V =7.855×10^{-4}, H=1.0, D=0.8, $\omega_0 = 314$.