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A New Efficient Self-Adjusting PSO Algorithm to Enhance Reactive Power Response of VSC-HVDC System

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ABSTRACT This paper presents an artificial approach for optimizing parameters of the proportional-integral (PI) controller in a reactive power control loop of voltage source converters high-voltage direct current (VSC-HVDC) transmission systems. The control strategy is based on a PI controller due to its simple structure and strong robustness. The Sharaf algorithm particle swarm optimization (SAPSO) is a heuristic optimization method that is used in this paper to get optimal values of PI parameters. This modification based on the inertia weight parameter to speed up the convergence towards the optimal values. SAPSO has many merits, such as easiness in control its parameters and its simple implementation compared to other artificial approaches. VSC-HVDC system is established in MATLAB/Simulink to apply the SAPSO. This system is exposed to different disturbances to evaluate its dynamic response. The objective function is minimizing the error between the measured and reference value of reactive power to get a better dynamic response. The obtained results showed that there is a significant improvement in reactive power dynamic response in a system with optimized parameters.

Keywords: Voltage Source Converter High Voltage Direct Current (VSC-HVDC), Reactive power · proportional and integral, Particle swarm optimization, Sharaf Algorithm Particle Swarm Optimization (SAPSO)

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1. INTRODUCTION

The transmission system is considered one of the main components in an electrical system. Therefore, selecting a proper transmission system is crucial. There are two basic transmission systems used for long-distance, high-voltage alternating current (HVAC) and HVDC. HVDC is profusely used in many projects all over the world especially in a grid connection between the countries in the past five decades. HVDC has many advantages, such as its losses are small, its cost is relatively cheap, and it can transmit enormous power over long distances. Also, it can be used in connecting two electrical systems that have different frequencies without needing synchronization.

In the past, conventional HVDC transmission systems used the line commutated converter (LCC) is based on current source converter (CSC) in which thyristor is in the conversion process. The main drawback of this technology is difficulty in controlling the thyristor as it cannot be directly turned-off with a gate signal [1].

With the expansion in power electronics technology, CSC becomes rarely used due to the development of voltage source converters (VSC). These converters use gate turn-off thyristor (GTO) or the insulated gate bipolar transistor (IGBT) in the conversion process. The gate signal of these converters is obtained by pulse width modulation (PWM) technology [2].

Therefore, in this paper, the VSC HVDC transmission system is used due to its advantages, such as possibility of controlling active and reactive power independently, supplying power directly to the weak electrical power system, and passive networks. VSC can also be used as a reactive power compensator, so system voltage stability is improved. There is no limitation on transmission capacity and transmission distance, and it can be used for grid-connection of off-shore wind farm [3].

In the future, VSC-HVDC will be one of the main components of power systems. The operating characteristics of the VSC-HVDC system determined by system parameters and controllers. The control strategy used in this paper is the hierarchical structure with outer-loop controllers and inner loop controllers. These loops involved vector oriented PI controllers as these controllers have many merits, strong robustness, and simple structure in a wide range of operating conditions. Therefore, it is necessary to choose better PI parameters for achieving rapid response, better dynamic performance, and perfect stability VSC-HVDC transmission system [4].

In HVDC, the reactive power must be attained at a suitable level to ensure steady-state operation. The reactive power at either end of the link can be controlled separately by the converters [5].

There are several published researches related to how to select PI parameters and on the optimization methods that can be used to get optimum parameters associated with VSC control systems. Yong and et al applied a trial and error method to get better parameters of the PI controller for ensuring the transient stability performance [6]. This work did not present an efficient method as it does not depend on the theoretical evaluation method. A frequency response analysis is used to obtain favourable values of PI controller but, it did not provide any vision on how to adjust multiple PI parameters simultaneously and require a lot of computation time [7]. Classical optimization techniques are applied to different VSC-HVDC transmission systems based on the simplex algorithm but, this method tried to find local optimum values rather than finding global optimum for PI controller parameters [8, 9]. Different methods, such as artificial frequency, direct control, and vector control, are used to find proper PI controller parameters [10,11].

Ramadan and et al. used sliding mode control and apply mine blast and artificial bee colony algorithms to obtain the optimal gain of this controller [12]. A Gravitational Search Algorithm (GSA) and Sine Cosine Algorithm (SCA) were used to get better values of PI parameters of VSC-HVDC [13].

The proposed work in this paper is applying an artificial method called particle swarm optimization (PSO) is motivated by the social attitude of fish and bird flocking in searching food to get the optimum values of PI parameters. The objective function is minimizing the error between the reference and the measured reactive power. There is a modification based on inertia weight that is applied to PSO to get better convergence. Results show that the dynamic response of the reactive power is improved. Validation of the proposed method was carried out through comparison with GSA and SCA methods [13].

The rest of the paper is sectioned as follows: In section two, modeling of the VSC HVDC transmission system is introduced while VSC control system is described in section three Optimization methods are introduced in section four, simulation results are introduced in section five, and section six includes a conclusion.

2. MODELING OF VSC-HVDC TRANSMISSION SYSTEM

The main structure of the VSC HVDC link between two AC systems is shown in Figure 1. It consists of two transformers, phase reactors, high-pass filters, two converters, DC-link capacitors, and DC cable.

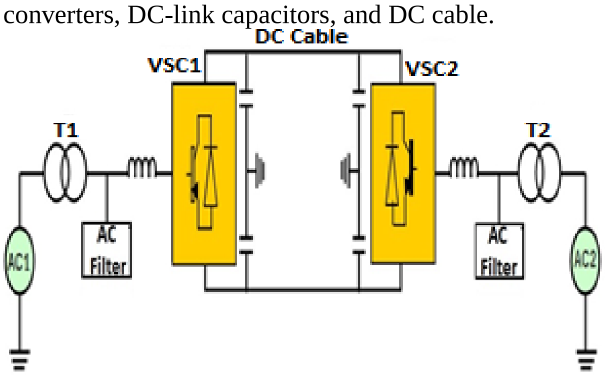


Fig. 1. The basic structure of VSC HVDC

The two VSC is identical, and consists of six pulse bridge equipped with (IGBTS) connected with anti-parallel diodes are as shown in Figure 2. One of the two converters works as a rectifier (converting from AC to DC), while the other one works as an inverter (converting from DC to AC). The DC voltage must be maintained at a constant value, so the control strategy is increased complexity compared with the classical HVDC system.

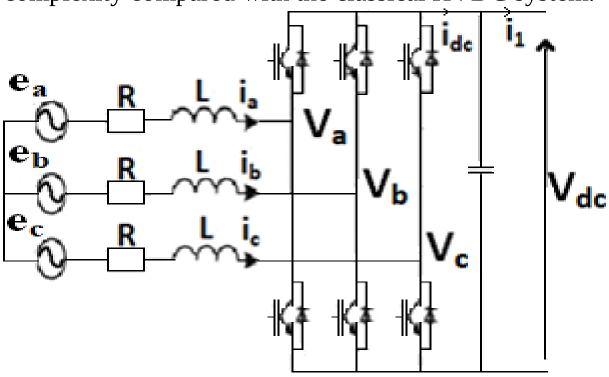


Fig. 2. The basic structure of the proposed VSC

2.1. Mathematical models of VSC-HVDC

The mathematical model of the VSC-HVDC per phase in a static frame is given in Equations 1 and 2.

$$e_a - v_a = L\frac{di_a}{dt} + Ri_a \quad (1)$$

$$C\frac{dV_{dc}}{dt} = i_{dc} - i_l \quad (2)$$

Where e_a is the phase voltage of for AC system, v_a is the phase voltage at the AC side of the converter, R and L are the equivalent resistance and reactance of the transformer and phase reactor respectively, and V_{dc} is the DC voltage.

The previous equations are transformed into a d-q rotating frame. Therefore, the active power (P) and reactive power (Q) can be expressed in the $d-q$ rotating coordinates using Equations 3 and 4.

$$\mathrm{p} = \frac{3}{2}(\mathrm{e_d i_d} + \mathrm{e_q i_q}) \quad (3)$$

$$\mathrm{Q} = \frac{3}{2}(\mathrm{e_d i_q} - \mathrm{e_q i_d}) \quad (4)$$

where; e_d is the d-component of the AC system phase voltage, and e_q is the q-component of the AC system phase voltage.

Neglecting the power loss of the converter, filter, and transformer also assuming d axis is aligned with the voltage phasor so $e_q = 0$, then active power P and reactive power Q can be expressed using the following equations:

$$p = \frac{3}{2} e_d i_d \quad (5)$$

$$Q = \frac{3}{2} e_d i_q \quad (6)$$

3. VSC-HVDC CONTROL SYSTEM

The controller of VSC of sending end is used to control active and reactive power that consists of two loops: inner loop and outer.

The outer loop consists of a PI controller produce reference values of the current that is the input of the inner loop as shown in Figure 3.

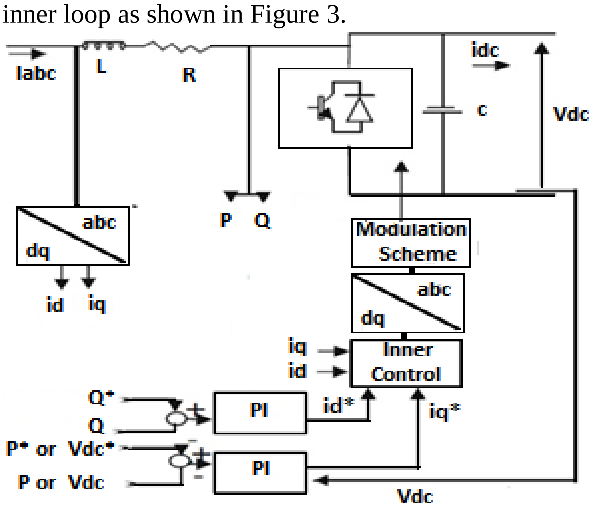


Fig. 3. Schematic diagram of VSC controller

The inner current control loop provides effective decoupling of active and reactive power control as it depends on the two-axis $(d\!-\!q)$ reference values of current as shown in Figure 4.

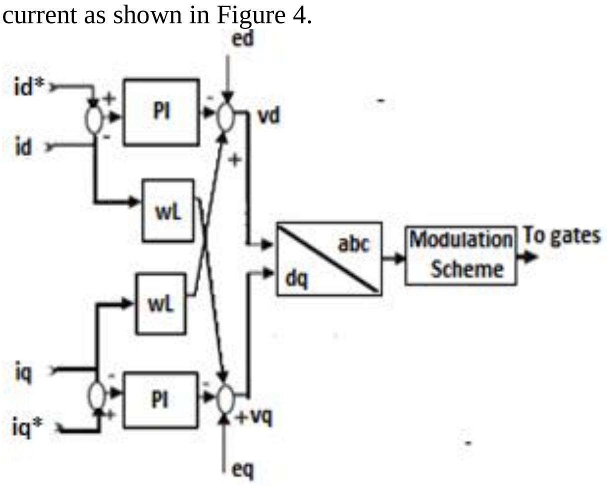


Fig. 4. Structure of inner current loop

The VSC of station two (receiving end) is used to control the DC link voltage and reactive power. The controller is similar to the controller of station one, but there is a phase-locked loop (PLL) that is used to track the frequency and phase of the grid voltage.

4. OPTIMIZATION METHODS

The process of finding the best value of any parameter to get the minimum or maximum of a specific function is called optimization. The optimization problem consists of the objective function, decision variables, and constraints. There are many categories of optimization problems based on its items such as mono or multi-objective function, discrete or continuous decision variables values and equality, or inequality constraints. On the other hand, there are many methods to solve optimization problems. The function of the optimization method is helping in decision-making by creating one optimal or a set of optimal solutions from a set of initial input values. There are two main optimization approaches as follow:

4.1. Classical methods

These approaches are based on calculus theory by using some operators, such as gradient or Hessian matrix. Newton method [14] and the simplex method [15] are of examples of these methods. These methods usually need longer computational times than the heuristic methods, and the problem becomes complex in case of high dimension problem.

4.2. Meta Heuristics methods

There is a new branch of optimization methods which is called metaheuristic methods. These methods present a better and faster solution to the optimizations problem when compared with conventional techniques. They have beneficial features such as remembering past findings, learning and adjusting their performance, and planning their forward path. There are many heuristic methods such as genetic algorithms (GA) [16], artificial bee colony (ABC) algorithm [17], gravitational search algorithm (GSA) [18], and mine blast algorithm (MBA) [19].

In this paper, the particle swarm optimization (PSO) and Sharaf Algorithm PSO (SAPSO) are used as an optimization method.

4.2.1. Particle Swarm Optimization (PSO)

PSO is a heuristic optimization approach that was designed in 1995 by Kennedy and Eberhart [20]. The social attitude of fish and bird flocking in searching for food was inspiration for this method. The obvious features of PSO are robustness to control its parameters, it is easy implementation, and computation efficiency compared with other heuristic approaches. PSO can be applied to non-linear, non-differentiable, and big search space problems.

This algorithm starts with a population of random solutions that is called particles. These particles flow in the search space with random velocity, and they have memory. Each particle remembers the track of its previous best position is called p_{best}. There is another value which is called g_{best} represents the best value of all the particles p_{best} in the swarm. The concept of PSO is trying to accelerate each particle towards its p_{best} and the g_{best} locations at each iteration as shown in Figure 5.

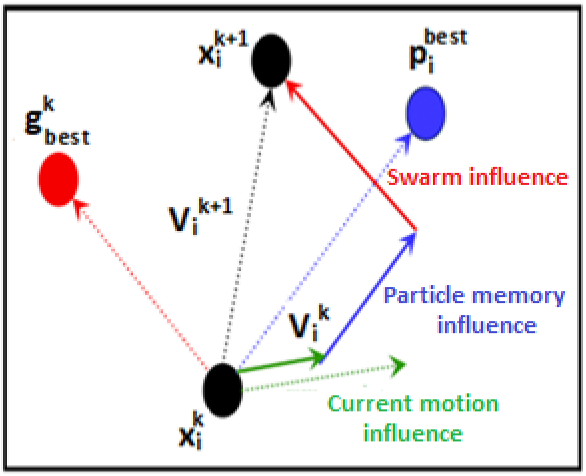


Fig. 5. Model of updating position and velocity in PSO

Therefore, the two equations which are used in updating the velocity and position of each particle in a swarm are shown in Equation 7 and 8 respectively.

$$v_i^{k+1} = v_i^k + r_1 c_1 \left(p_{best_i}^k - x_i^k\right) + r_2 c_2 \left(g_{best_i}^k - x_i^k\right) \quad (7)$$
$$x_i^{k+1} = x_i^k \quad (8)$$

Where; k is the index of iteration, $\boldsymbol{v}$ is the velocity of the particle, and x is the position of a particle, p_{best} is the previous best-visited position for the particle, g_{best} is the best particle's position in the swarm. c_1 and c_2 are called cognitive constants, and r_1 and r_2 are called social constants usually (c_1 = c_2) and $r_{1,}\, r_2$ are random numbers given by a uniform distribution.

The flow chart that describes the iterative process of PSO is shown in Figure 6.

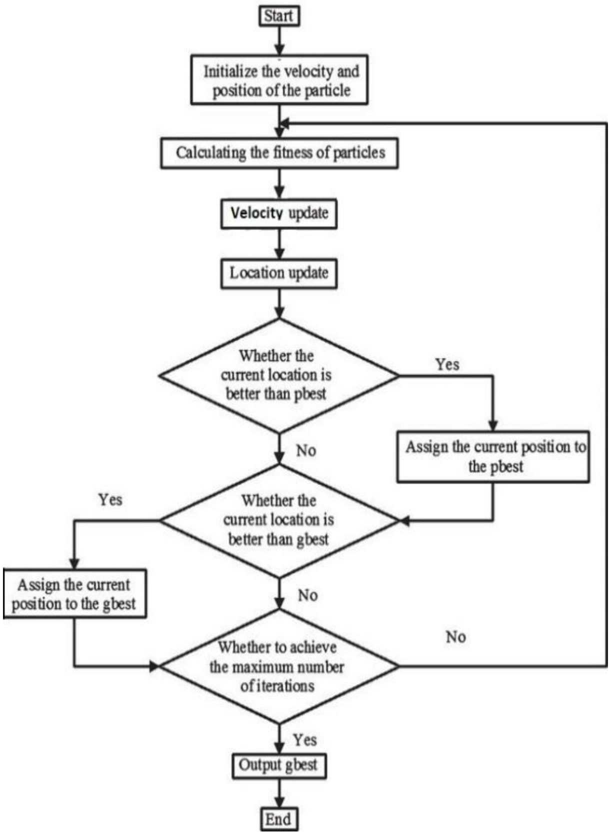


Fig. 6. Flow chart of PSO

4.2.2. Modified PSO (SAPSO)

In the PSO algorithm, there is a maximum velocity denoted by V_{max} which represents a constraint to limit the velocity of particles to control the global exploration ability of particles swarm. Therefore the concept of an inertia weight (w) was developed by Eberhart and Shi [21] in 1998 to get better control exploration and exploitation and to eliminate the need for V_{max}. Hence the velocity updating equation becomes as follow:

$$v_i^{k+1} = \omega_k * v_i^k + r_1 c_1 \left(p_{best_i}^k - x_i^k\right) + r_2 c_2 \left(g_{best_i}^k - x_i^k\right) \quad (9)$$

There are various attempts in the literature that focused on how to get the best value for inertia weight. In this paper, there is a new modification applied PSO based on inertia weight developed by Sharaf and it is denoted as SAPSO [22]. In general, adjusting the value of inertia weight should rely on the error in the global best value between two successive in iterations.

The proposed concept is smaller error refers that the particle is probably moving in the correct direction. Therefore, inertia weight must be larger to accelerate the speed of particle to reach optimum solution faster. On the other hand, when the error is increasing, it is required to diverge from this direction, so that the inertia weight must be smaller. The SAPSO algorithm is explained in details as follow:

In this algorithm, the error in k^{th} iteration (the difference between the global best value in the current iteration and the previous iteration) is calculated by Equation 10.

$$\Delta e_k = GB_k - GB_{k-1} \quad (10)$$

Then an auxiliary variable for each iteration is calculated by making normalization for the error using the maximum global best which is called ε_k is given by Equation 11.

$$\xi_k = \frac{\Delta e_k}{\max(GB_k)} \quad (11)$$

Equation 12 represents the expression that evaluates the inertia weight for each iteration (ω_k).

$$\omega_k = \omega_0 + \omega_1 * \xi_k * \frac{k-1}{d} \quad (12)$$

Where; ω_0 and ω_1 are the inertia weight in first and second iterations respectively, d is a number between 10 & 100, and k is the index of the iteration. The values of ω_0, ω_1, and d are obtained by trial and error.

It is clear from the previous equation that in the first iterations the change in the value of ω_k is small to let the initial population spread all over the search space. In the latter iteration, the value of inertia weight decreases so the speed of the particle will be small to make the particle converge from the optimum solution.

5. SIMULATION RESULTS

The system model used is established in MATLAB/ Simulink is shown in Figure 7. It is developed to transmit 200 MW at 100 kV DC between two AC grids. The ratings of system components in this system are shown in

Appendix 1. Getting optimal values of the PI controller to enhance the performance of reactive power is the objective of this paper when the system is exposed to different disturbances. There are three cases study in this paper to check the robustness of reactive power response. The first case study is applying a severe three-phase fault and trying to enhance the performance of reactive power during and after this fault. The second case is making voltage sag in one AC system and studying its effect on reactive power. A step changing in the reference values of DC voltage, active power, and reactive power is the last case study.

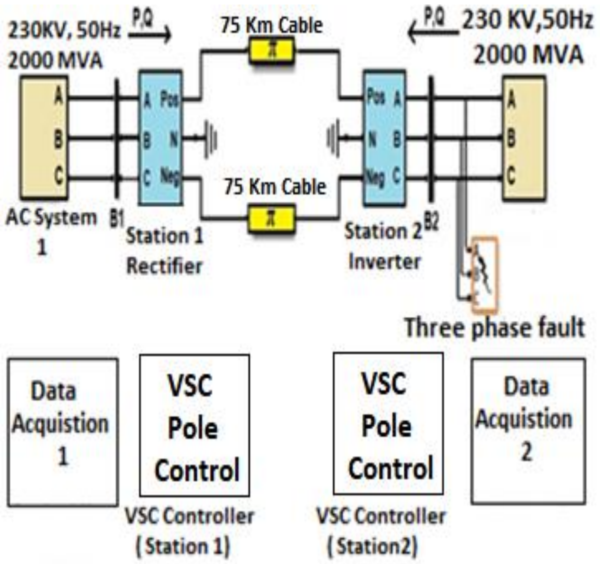


Fig. 7. Simulink model of the proposed system

5.1. Getting optimal parameters using PSO methods

There are six control parameters to be optimized (K_1, K_2, and K_3 of the reactive power control loop in station one and K_4, K_5, and K_6 of the reactive power control loop in station two). K_1 and K_4 are the integral gains of regulator controller in station one and station two respectively which their function is regulating reactive power within the required range. K_2 and K_5 are the proportional gains of the reactive power controller in station one and station two respectively. K_3 and K_6 are the integral gains of the reactive power controller in station one and station two respectively. The system model is running with default values which are given in Table 1.

Three disturbances are applied to the system as a case study to check the dynamic response of reactive power and improve it. PSO and modified PSO (SAPSO) are used to get better values for controller parameters that minimize the objective value. The objective function is minimizing the error between the measured and reference value of reactive power in both stations. The stopping criterion is the maximum number of iterations which is set to 200 iterations. The default values and optimized values of controller parameters for each case study are presented in the next part.

5.2. Reactive power dynamic response comparison

The proposed system is run for three seconds, and during this period it will be exposed to three different disturbances as a case study. The response of reactive power will be observed in the case of the system with default values of PI and system with optimized ones using PSO methods. Also, a graphical comparison will be carried out between these methods and (GSA & SCA) methods [13].

52.1. Case study 1

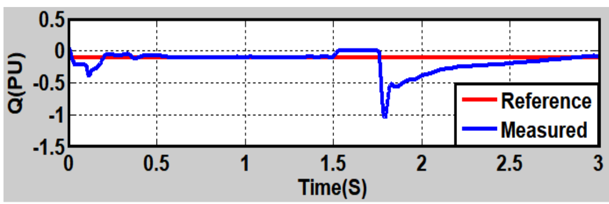
A Three-phase fault is applied at the bus of AC system two after 1.5 seconds from starting, and it is cleared after 0.25 sec. The reference value of the reactive power of AC system two is -0.1 pu. Table 1 shows the lower and upper values for the proposed controller parameters, the default values for these parameters, and the optimized values of parameters after applying PSO and SAPSO.

Table 1. Values of controller parameters (Case study 1)

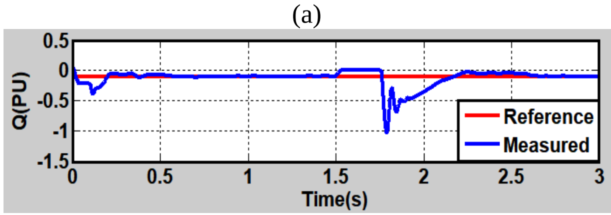
Parameters	K_1	K_2	K_3	K_4	K_5	K_6
Lower bounds	1	0. 1	0. 1	1	0. 1	0. 1
Upper bounds	40		20	40	20	20
Default	20	3	3	20	3	3
PSO	18.5	10.7	17.8	19.6	13.7	13.8
SAPSO	10	1	10.2	30	6.82	1

Figure 8(a) shows the measured reactive power response of the AC system 2 for the default system. This figure explains that the system did not reach fast enough to the reference value after clearing the fault. Figure 8(b) on the other hand, shows the reactive power response of an optimized system using PSO, and it is obvious that the system reaches the reference faster than the default case but has more deviation from reference after clearing the fault.

Figure 8(c) shows the optimized system using SAPSO. It is noted that the response is improved after clearing the fault as the deviation from the reference becomes very small and its performance is better than the PSO case. Figure 8(d) shows the reactive power response of the proposed method (SAPSO) with GSA and SCA cases [13] in one graph to get better comparison which illustrates that the system with SAPSO has the best response as it has less deviation from the reference value after clearing the fault.



(a)



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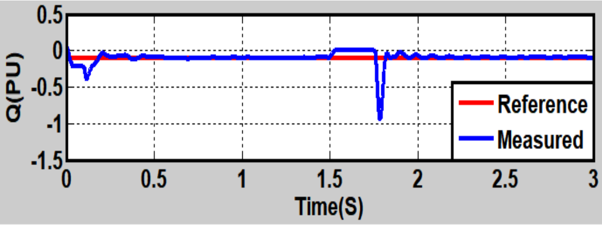

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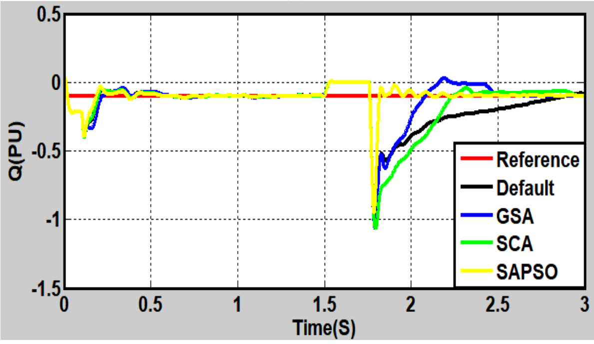


(d)

Fig. 8. Reactive power response, (a) Reactive power response for the default case, (b)Reactive power response for PSO case, (c)Reactive power response for SAPSO case, (d) Reactive power response for case study one

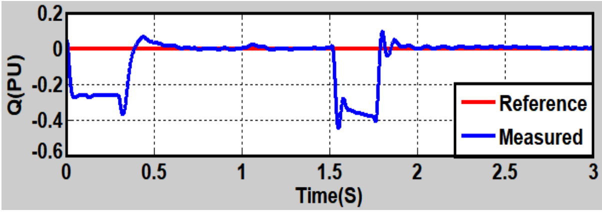
5.2.2. Case study 2

A step-change in AC voltage is applied in AC system 1 by using three phases programmable voltage source in the system one. The amplitude of the AC voltage of the system 1 is changed from 1 pu to 0.8 pu at 1.5 seconds for 0.25 seconds. Table 2 shows the lower and upper values for the proposed controller parameters, the default values for these parameters, and the optimized values of parameters after applying PSO and SAPSO.

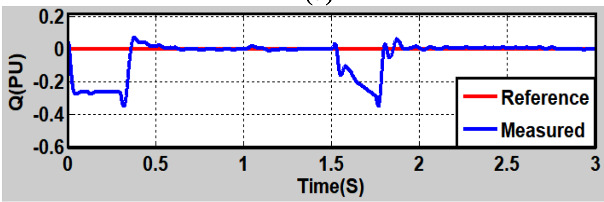
Table 2. Values of controller parameters (Case study 2)

Parameters	K_1	K_2	K_3	K_4	K_5	K_6
Lower bounds	10	0.1	0.1	10	0.1	0.1
Upper bounds	40	20	20	40	20	20
Default	20	3	3	20	3	3
PSO	30	1	6.4	26.4	1.8	18.1
SAPSO	30	1	1	18	10.5	6.7

Figure 9(a) shows the reactive power response of the default system of station 1 which explains that there is a high deviation from the reference value during the voltage change period reaches -0.48 pu. Figure 9(b) shows the optimized system response using PSO that shows that the response is improved as the deviation from the reference value decreases and reaches to -0.32 pu only during the sag. Figure 9(c) shows the optimized system response using SAPSO which is better than the default and PSO cases as it has less overshoot and reaches to -0.1 during the sag. Figure 9(d) shows the reactive power response of the proposed method (SAPSO) with GSA and SCA cases [13]. In one graph to get a better comparison. It illustrates that the system response with SAPSO case is the best since the deviation from the reference value is very small during and after clearing the fault.



(a)



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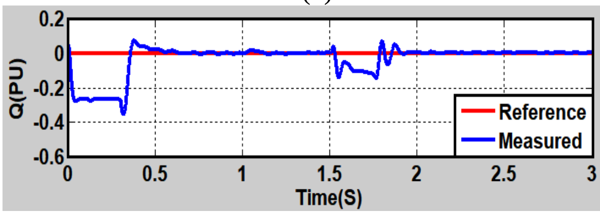

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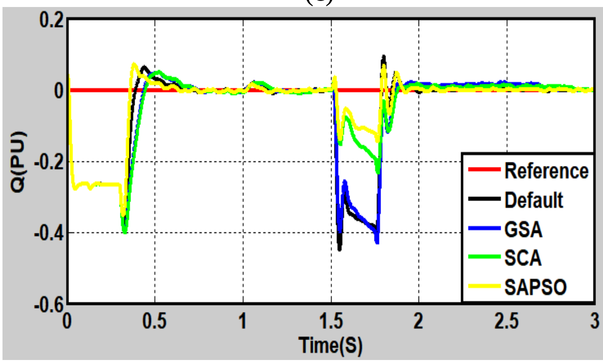


(d)

Fig. 9. Reactive power response, (a) Reactive power response for the default case, (b) Reactive power response for PSO case, (c)Reactive power response for SAPSO, (d) Reactive power response of case study two

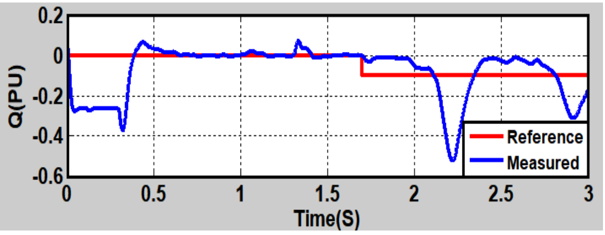
5.2.3. Case study 3:

A step-change in regulators reference values is applied to the system. After the system is reached to the steady-state, the DC voltage reference is changed from 1 pu to 0.85 pu in 1.3 seconds. Then a step-change in reactive power reference is applied at station one from 0 pu to -0.1 pu at 1.7 seconds. Finally, a step-change inactive power reference is applied at station one from 1 pu to 0.9 pu at 2.3 seconds. Table 3 shows the lower and upper values for the proposed controller parameters, the default values for these parameters, and the optimized values of parameters after applying PSO and SAPSO.

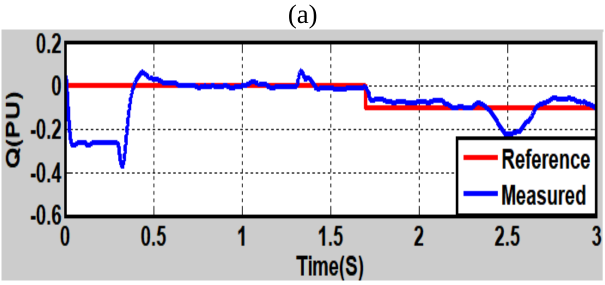
Table 3. Values of controller parameters (Case study 3)

Parameters	K_1	K_2	K_3	K_4	K_5	K_6
Lower bounds	10	1	0.01	10	1	0.01
Upper bounds	30	20	20	30	20	20
Default	20	3	3	20	3	3
PSO	20	3.4	1	28	2.9	2.8
SAPSO	28	8.9	13.5	25.2	12.4	4.8

Figure 10(a) shows the dynamic reactive power response of the default system in station 1 to illustrates that the measured reactive power has a high deviation from the reference value, and the measured value does not reach the reference value during the simulation time. Figure 10(b) shows the optimized system response using PSO is better than the default case, but there is a small deviation starting from 2.3 seconds. Figure 10(c) shows the optimized system response using SAPSO which has almost no deviation from the reference value of reactive power, and it reaches the reference value faster. Figure 10(d) shows the reactive power response of the proposed method (SAPSO) with GSA and SCA cases [13] in one graph to confirms that SAPSO has a very small deviation from the reference and has a better stability.



(a)



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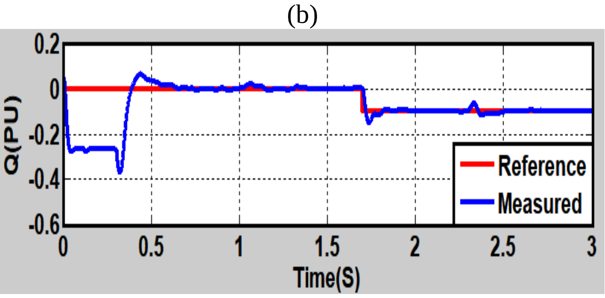

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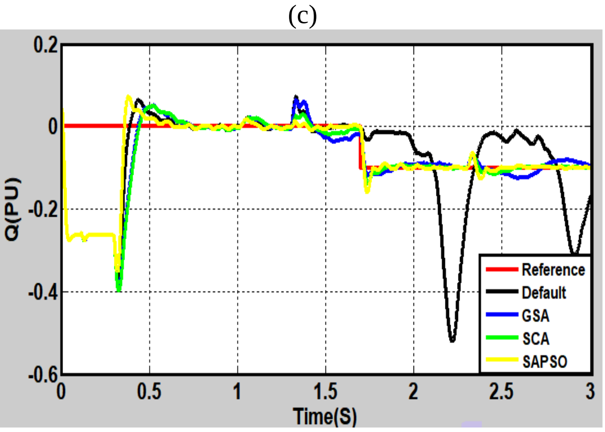

(d)

Fig. 10. Reactive power response, (a) Reactive power response for the default case, (b) Reactive power response for PSO case, (c) Reactive power response for SAPSO case, (d) Reactive power response for case study 3

6. CONCLUSION

This work deals with the VSC-HVDC system as a transmission system to connect two AC systems due to its multiple advantages. Enhancing the dynamic response of reactive power during abnormal conditions was the core of this paper. This improvement is achieved by getting the optimal values of PI controller gains. PSO and SAPSO are two optimization methods that are used to get these values. The system is exposed to different disturbances such as three-phase fault, voltage sag, changing in reference values. SAPSO presented the best convergence towards better values of PI parameters in all case studied.

Appendix A

The values of parameters and the ratings of components of the used system are listed in Table A.1.

Table A.1. Values of system parameters

Parameter		*Value*	*Unit*
Rated Apparent Power(S)		2000	MVA
AC System (1 & 2)	AC Voltage	230	kV
	Equivalent Resistance	13.79	Ohm
	Equivalent inductance	$31.02*10^{-3}$	Henry
Rated Frequency		50	Hz
Switching Frequency		1350	Hz
Phase Reactor		0.15	pu
Transformer	Ratio	230: 100	kV
	Equivalent inductance	0.15	pu
AC Filters		40	MVAr
Rated DC Voltage		100	kV
DC Capacitor		70	µF
DC Link Cable (Two pi sections)	Resistance	$1.39 *10^{-2}$	Ω/km
	inductance	$1.59*10^{-4}$	Henry/Km
	capacitance	$2.31*10^{-7}$	Farad/ Km
	Length	75	Km

Appendix B

The conventional PSO parameters are listed in Table B.1.

Table B.1. Parameters of conventional PSO

Parameter	*Value*
Number of variables	6
Population size	20
Learning constants(c_1=c_2)	2
Social constants (r_1, r_2)	Random
Initial inertia weight (w_0)	0.3
Maximum number of iterations	200

Appendix C

The updating equation for inertia weight in SAPSO is;

$$\omega_k = \omega_0 + \omega_1 * \xi_k * \frac{k-1}{d} \qquad (C.1)$$

Where:

ω_0 is the initial value of inertia weight.

ω_1 is the value of inertia weight in the first iteration.
k is the index of iteration.
d is arbitrary constant between 10 and 100.
ξ_k is an auxiliary variable and is obtained by normalization the error between the global best value in two successive iterations as shown in this equation.

$$\xi_k = \frac{GB_k - GB_{k-1}}{\max(GB_k)} \qquad (C.2)$$

The SAPSO parameters are listed in Table C.1.

Table C.1. Parameters of SAPSO

Parameter	*Value*
Number of variables	6
Population size	20
Learning constants(c_1=c_2)	2
Social constants (r_1, r_2)	Random
Initial inertia weight ($\boldsymbol{\omega_0}$& $\boldsymbol{\omega_1}$)	0.3 & 0.4
d	10
Maximum number of iterations	200

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