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Controller Parameters Optimization for Multi-Terminal DC Power System Using Ant Colony Optimization

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ABSTRACT Voltage source converter based multi – terminal DC grids (VSC – MTDC) are widely used for integration of renewable resources. Control of these grids requires vector control method, which includes inner and outer current controllers, tuning of these controllers is very important. Conventionally used tuning methods consider approximated linear model to tune the proportional – integral (PI) parameters of voltage source converter (VSC) which fails to produce optimum disturbance rejection results. In this research an Ant Colony Optimization (ACO) technique is used to get the optimum parameters of inner and outer power control layers for multi – terminal DC system. ACO is applied simultaneously on inner and outer control layers and results are compared with classical tuning method and well established meta - herustic technique, Particle Swarm Optimization (PSO) using MATLAB software. Dynamic models of VSC – MTDC are developed in PSCAD/EMTDC to exalt the qualities of the presented tuning method. In this paper, a four terminal VSC – MTDC has been used under different sequence of events of disturbances e.g. load change on AC side, active power reference change for inverter and rectifier mode and disconnection of one terminal to evaluate the robustness of ACO algorithm with respect to classical method. The proposed tuning method gives superior results under different disturbance compared to conventional method.

INDEX TERMS DC grid, VSC, multi-terminal DC grid, PI controllers, ant colony optimization, disturbance rejection, MTDC controllers.

I. INTRODUCTION

With the passage of time, contribution of renewable and clean energy is increasing in the conventional power grid. Most of the renewable energy resources are usually remotely located from the load centers and provide intermittent output [1], [2]. Therefore, these resources require careful consideration for harvesting their energy, integrating with AC grid and power dispatching for loads. Literature depicts that energy harvesting from distributed renewable resources is possible through multi-terminal HVDC system [3]–[6]. Voltage source converter (VSC) has flexibility to integrate with different types of AC (i.e. stiff, weak and passive) systems and bidirectional control of both active and reactive powers. Therefore, power dispatch to loads can be realized through voltage source converter [4]. Thyristors have high current and voltage ratings along with lower prices. Hence it is expected that classical HVDC will be dominant in long distance and submarine bulk power transmission only [7]. However, the researchers [3], [7], [8] have opinion that VSC – MTDC will be the future modern power system owing to its black start ability, decoupled control of reactive and active power. VSC – MTDC system has versatile design to integrate with other models of power system. Most important job of VSC – MTDC is to

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maintain voltage at-least at one terminal. Different sequence of events of disturbance can be used to test the performance of a VSC – MTDC system. Optimal performance of a system requires best control scheme with optimized parameters of controllers [9], [10].

Some papers addressed the parameters optimization of proportional-integral (PI) DC voltage controllers [11], [12]. Proportional gains are used to fulfill settling time requirement whereas integral gain decreases the steady state error. PI controller parameters selection for HVDC systems are often established based on operator's knowledge. Currently, nature inspired optimization techniques like particle swarm optimization (PSO), honey bee mating optimization (HBMO), simplex algorithm (SA) and genetic algorithm (GA) have been used in VSC – MTDC to optimize the inner and outer controllers [12]–[14]. Conventional tuning methods uses approximated linear model of VSC – MTDC to optimize the both inner and outer control loops. In references [15], [16], comparison of classical method and PSO algorithm for the tuning of VSC controllers shows significant improvement in rise time and stability margin. Several papers have used different meta-heuristic optimization methods to get the optimal parameters of controllers for disturbance rejection in different control applications [17]–[19]. Ant colony optimization (ACO), a new meta-heuristic algorithm has been used for the optimum solutions of power system problems like economic power dispatch and power system stabilization [20], [21]. Recently ACO algorithm has been used for optimal tuning of gain parameters to enhance the stability of multi-machine power systems [22]. Also, ACO has been used to get the optimal parameters of controller for disturbance rejection in induction motor and magnetic levitation control system respectively [23], [24]. Therefore, it is decided to use ant colony optimization method in order to get optimum disturbance rejection in VSC – MTDC network.

In this research, control model of inner current controller and outer power controllers are used for optimization. A probabilistic technique, ant colony optimization (ACO) is adopted to find the proportional – integral (PI) optimal parameters of inner and outer power controllers simultaneously, in terms of minimizing the Integral Time Absolute Error (ITAE). A four-terminal VSC - MTDC system is created in PSCAD/EMTDC software environment to validate the PI parameters obtained through ACO. A sequence of events is applied on four terminal VSC – MTDC system, developed on PSCAD/EMTDC software to test the disturbance rejection performance of suggested method. The remaining sections of the paper are summarized as:

Section 2 explains the VSC - MTDC system and control structure. Section 3 introduces ant colony optimization (ACO) and objective functions. Section 4 depicts simulation results and last section is the conclusions of paper.

II. VSC–MTDC MODEL AND CONTROL STRUCTURE

A VSC - MTDC system has the ability to connect more than two VSC systems [25]. The VSC – MTDC test system is shown in Fig.1. It consists of four terminals namely; AC grid A, B, C and D. Control objectives of all four terminals are as; terminal A is stiff grid and regulates DC voltage, terminal B is a passive grid and only regulates the AC voltages for passive loads, terminal C is a stiff grid and provides constant active power and terminal D is a weak grid which control AC voltage and active power both. Active power, DC voltage, AC voltage and reactive power are monitors on point of common coupling (PCC).

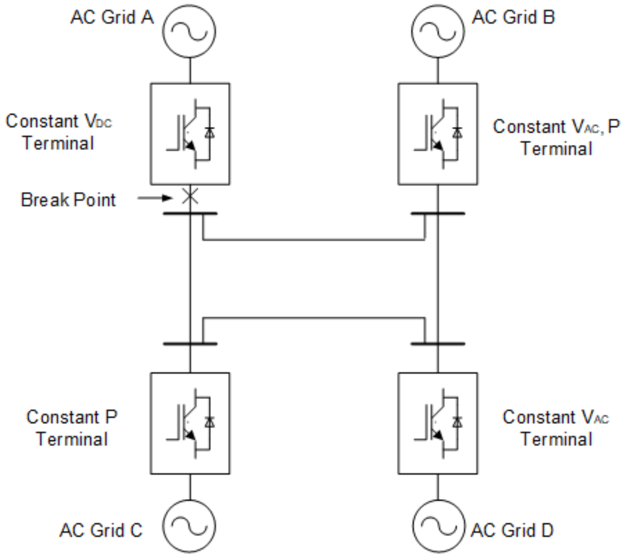

FIGURE 1. Four terminals VSC–MTDC system.

TABLE 1. Specifications of VSC system.

Parameters Description	Parameters Rating
Apparent Power	100 MVA
DC Voltage	50 kV
AC Voltage	24.5 kV$_{LL}$
Filter Impedance	$(0.01 + j0.25)pu$

Rating of four terminal system is given in Table 1 [25].

Generalized control structure of a voltage source converter (VSC) station using vector control method is shown in Fig.2.

Vector control method is a frequently used approach for reactive and active power control in voltage source converter (VSC) [26]. In vector control method, AC currents and voltages of VSC at PCC are transformed into rotating direct – quadrature (d - q) reference frame through phase locked loop (PLL). This approach helps in synchronization of VSC voltages with AC system's voltages. Decoupling of active and reactive power assist in DC and AC voltage regulation respectively [25].

A. INNER CURRENT CONTROLLER

The inner current controller in d – q frame, consisting of fast proportional – integral (PI) controller, is responsible for generating reference signal for the VSCs. Relationship between VSC and PCC voltage is given as:

$$V_c - V_s = L\frac{di_s}{dt} + Ri_s \tag{1}$$

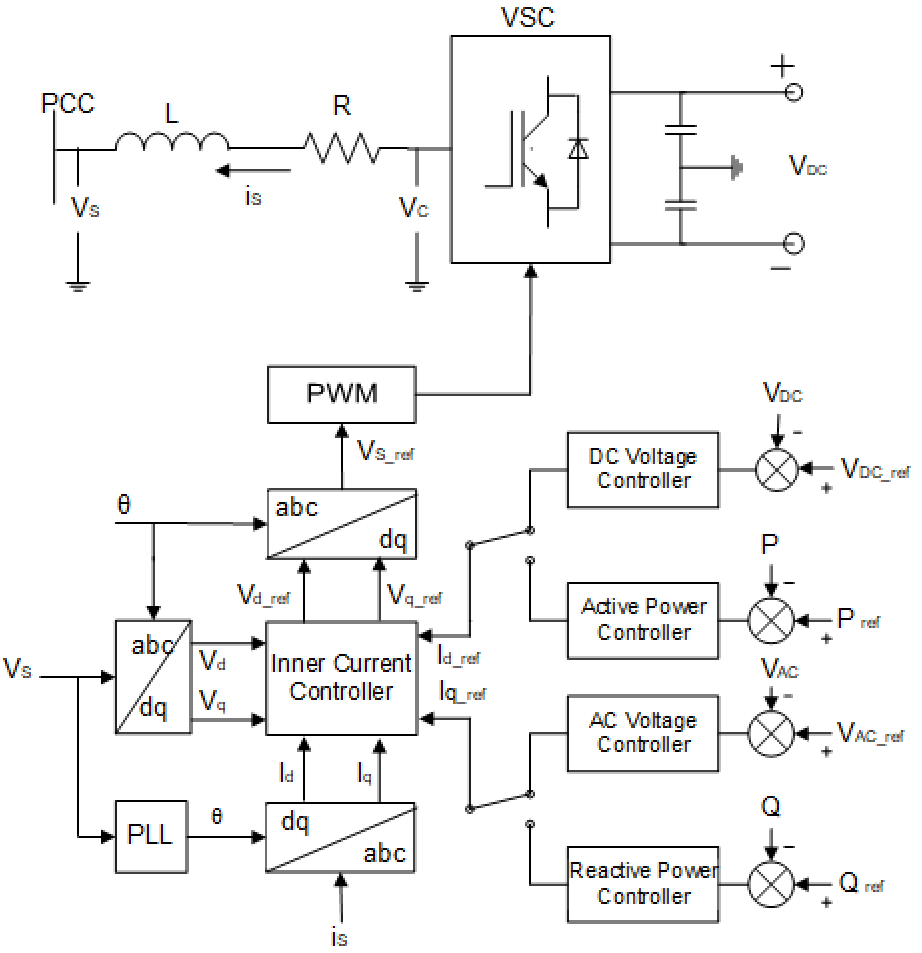

FIGURE 2. **D - Q control structure for VSC.**

where i_s current is flowing from VSC to PCC through R and L shown in Fig.2. Equation (1) in d – q reference frame is presented as:

$$V_{cdq} - V_{sdq} = L\frac{di_{dq}}{dt} + j\omega Li_{dq} + Ri_{dq} \tag{2}$$

where ω is angular frequency of AC system at point of common coupling. Equation (2) is used to model the AC reactor and can be written in matrix form as:

$$\begin{bmatrix} V_{cd} \\ V_{cq} \end{bmatrix} - \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} I_d \\ I_q \end{bmatrix} + \omega L\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}\begin{bmatrix} I_d \\ I_q \end{bmatrix} + R\begin{bmatrix} I_d \\ I_q \end{bmatrix} \tag{3}$$

Converter model is considered as time delay $e^{(-T_a s)} \approx \frac{1}{1+ST_a}$ due to PWM switching frequency of converter. Based on (3) and converter model expression, layout of inner current controller with compensation of feed forward terms is shown in Fig.3.

B. OUTER CONTROLLER

The outer controllers create reference signals for inner current controller as shown in Fig.2. The d-reference controls DC voltage and active power while q-reference controls AC voltage and reactive power control. Mathematical relation of P and Q with the power invariant d – q transformation and assumption $V_q = 0$ [27], as d-reference axis is aligned with AC grid voltage by PLL, are:

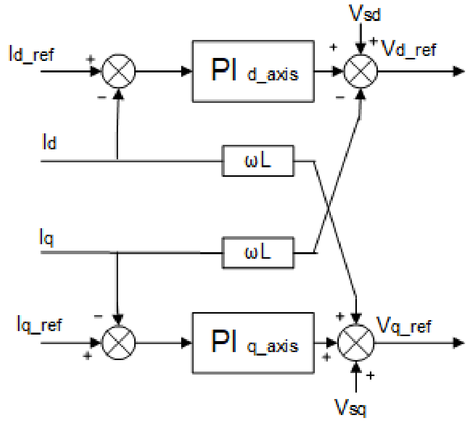

FIGURE 3. **Inner current controller structure.**

$$P = V_d I_d \tag{4}$$

$$Q = -V_d I_q \tag{5}$$

III. ANT COLONY OPTIMIZATION (ACO) AND OBJECTIVE FUNCTIONS

A. ACO ALGORITHM

Ant Colony Optimization (ACO) is first suggested by Marco Dorigo in his Ph. D thesis [28]. It is a recent metaheuristic algorithm to stochastic combinatorial optimization. This technique is inspired by the fact that ants of a colony find the nearest path between nest and food source. Ants deposit pheromones on the trail when they move. Higher the concentration of pheromones, greater is the probability of food source and ants follow that better trail. The deposited pheromone trail will attract the other ants towards search area. If further pheromone is not laid down then the pheromone trail evaporates with the passage of time and leads to search of more promising area.

The basic procedure of ant colony optimization is divided into four crucial stages as

1) Initialization
2) Probabilistic Movement of Ants
3) Pheromone Updating
4) Stopping Condition

Stage – 1: Initialization

Initially ant colony is created randomly and objective is to find shortest path between two towns occurring at the vertices of solution space. Initialization includes the amount of pheromone at the edges, heuristic value and decision of the ant.

Stage – 2: Probabilistic Movement of Ants

At each stage of the solution, ants move in a probabilistic way based on the statistical data and pheromone value to take the decision to find good solution.

This will lead the k_{th} ant transition probability from town i to j is as follows;

$$P_{ij}^{k}(t) = \frac{[\tau_{ij}(t)]^{\alpha}[\eta_{ij}]^{\beta}}{\sum\limits_{k \in allowed_k} [\tau_{ik}(t)]^{\alpha}[\eta_{ik}]^{\beta}} \tag{6}$$

where P_{ij}^{k} is the probability among two towns i and j, τ is pheromone, η is heuristic value (inverse of distance between two towns), α and β are constant parameters that control comparative significance of pheromone versus heuristic value on the decision of the ant. Selection of the next tour or iteration starts after the visit of all the nodes according to probability (6).

Stage – 3: Pheromone Updating

When all the ants find solutions then each ant deposit pheromone ($\Delta\tau_{ij}$) on the path. At this stage, the pheromone is updated according to (7).

$$\tau_{ij}(t) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t) \tag{7}$$

where ρ is pheromone evaporation rate ($0 < \rho \leq 1$); evaporation is used to avoid poor convergence and bad decisions. And $\Delta\tau_{ij}(t)$ is given by (8).

$$\Delta\tau_{ij}(t) = \sum_{k=1}^{NA} \Delta\tau_{ij}^{k}(t) \tag{8}$$

where NA is total quantity of ants and $\Delta\tau_{ij}^{k}(t)$ is the amount of pheromone on each path left by k ant at edge (i, j); it is given by

$$\Delta\tau_{ij}^{k}(t) = \begin{cases} \frac{Q}{L_k}, & \text{if kth ant uses edge (i,j) in its tour} \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

where length of the tour performed by k_{th} ant is L_k and Q is a constant.

Stage – 4: Stopping Condition

When all the paths are evaluated by ants then feasibility of each tour and cost are considered. If minimum stopping condition is met, the program stops; otherwise again starts from stage - 2 and continue to find optimal solution without considering number of iterations.

B. OBJECTIVE FUNCTIONS

The main objective of ant colony optimization is to find the best tour (L_k) having lowest cost in the search space [29]. Parameters optimization often requires an objective function that gives quantitative description of system performance index [30]. Generally, the dynamic performance of a closed loop control system is evaluated in terms of transient response, steady state error and stability [31]. In this study, to trace the output of the system alongside a path, an objective (fitness) function is adopted to reduce the error. The adopted objective function is established on Integral Time Absolute Error (ITAE) performance index because it is more selective on long duration transients and disturbance rejection. It is given as:

$$L = \int_{0}^{T} t \mid e(t) \mid dt \tag{10}$$

where T is the finite time is usually equal to settling time, t is time of the disturbance applied, and $\mid e \mid$ is the absolute error of control variables (e.g. DC and AC voltages, active power and reactive power). The discrete form of (10) is:

$$L = \sum_{k=0}^{N} kT \mid e(kT) \mid \tag{11}$$

where T is simulation time step, N is the points of simulation calculations. Integral Time Absolute Error (ITAE) performance index will evaluate the dynamic response to optimize the controller gains.

C. ACO ALGORITHM FOR VSC–MTDC CONTROLLERS

In the beginning, classical methods have been used to find the parameters of PI controller for VSC – MTDC [32]. This paper focuses on the minimization of ITAE performance index for inner current controller and outer active power controller. The performance of VSC – MTDC depends on the accurate tuning of its PI controllers. So, a nature inspired heuristic algorithm, ant colony optimization is used for the controllers' optimization in this paper. As this algorithm provides best solution for disturbance rejection, therefore a sudden load change at VSC converter station will be compensated by the

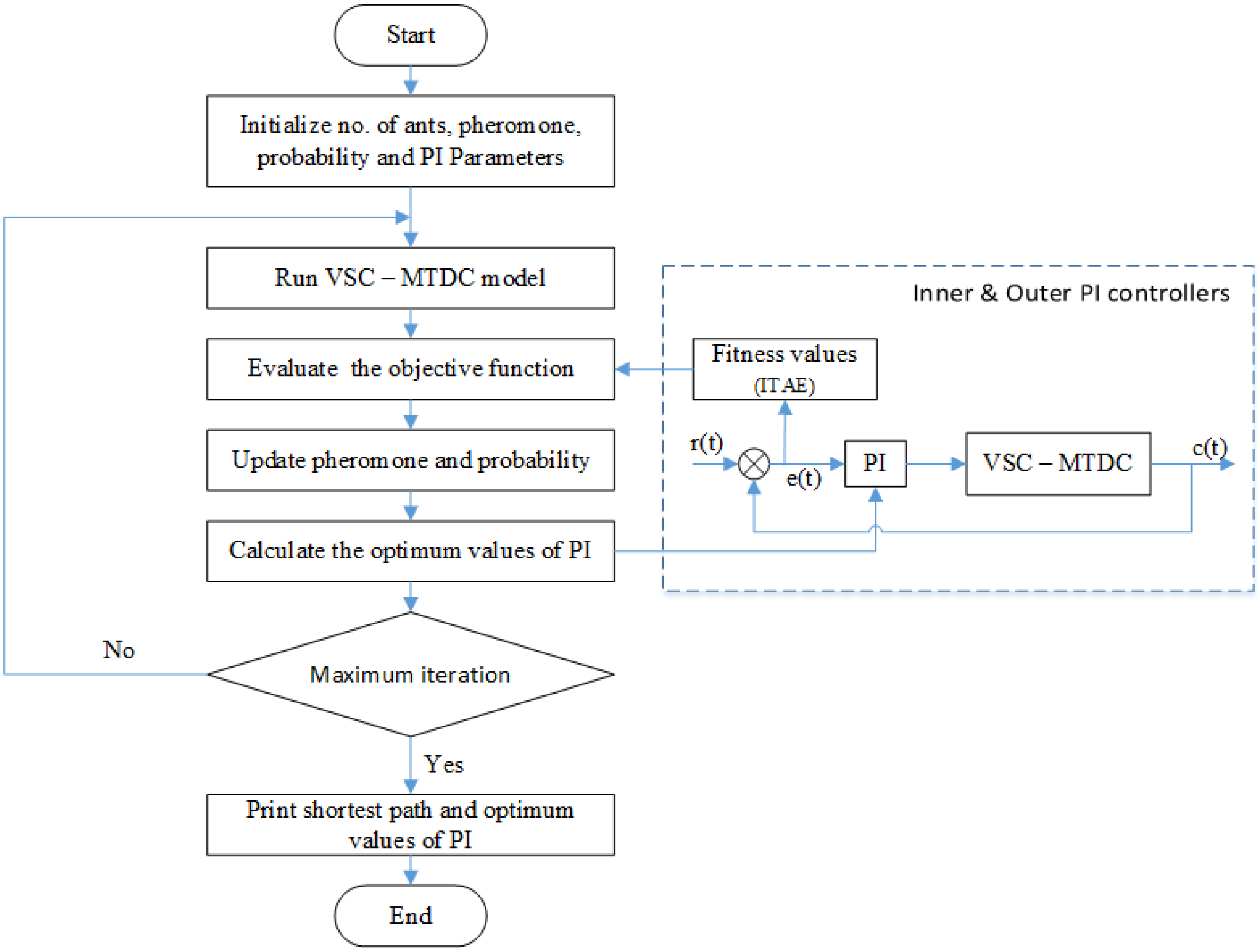

FIGURE 4. **Implementation of ACO on VSC–MTDC control system.**

optimally tuned PI controllers. Operation of ACO for VSC – MTDC is shown in Fig.4. The ACO algorithm works in three phases for the tuning of controllers. In the first phase, ACO parameters are initialized, which are; number of ants, pheromone, evaporation parameter, number of iterations and PI values. Second phase is constructing ACO solution, based on probability from (6); next node is selected, objective function is evaluated based on fitness values and pheromones are updated according to (7), (8), and (9). In the final stage, optimum values of PI controllers are obtained and updated. In this case, inner and outer controllers of VSC – MTDC system are tuned optimally in simultaneous operation. Inner current controller is a core part of VSC – MTDC converter station. The schematic of inner current controller is shown in Fig.3. The objective function for inner current controller based on ITAE is given as:

$$Minimize : L_{ICC} = \int_0^T t \mid I_d - I_{dref} \mid dt \tag{12}$$

The outer control loops for VSC – MTDC are shown on the right side of Fig.2. Simultaneous tuning of inner and outer controllers will give the optimized gains. The described objective function for active power loop based on ITAE is:

$$Minimize : L_{OCC} = \int_0^T t \mid P - P_{ref} \mid dt \tag{13}$$

IV. SIMULATION RESULTS

In simulation section, initially inner and outer controllers are tuned by classical method; then optimal parameters of both controllers are achieved by ACO algorithm. The results of classical and ACO method are compared with well established meta - heuristic method, PSO [15]. Robustness of these controllers are validated on four terminal HVDC system.

A. OPTIMIZATION OF INNER AND OUTER CONTROLLERS USING ACO

In this section, the optimized results of one VSC – MTDC station are obtained and then other VSCs are adopted likewise. The value of performance index for inner and outer controllers using ACO algorithm is shown in Fig.5 and 6 respectively. As per Fig.4, the optimized gains of PI controllers for

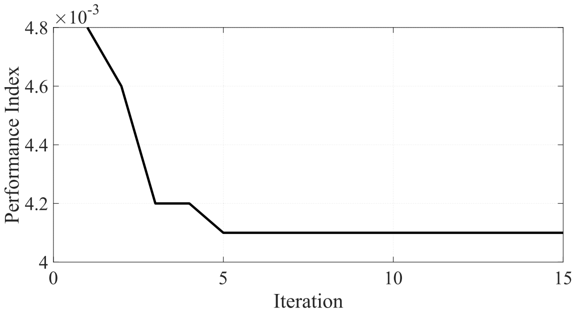

FIGURE 5. Performance index of inner current controller.

inner and outer controllers are obtained after certain iterations.

B. TUNING OF INNER AND OUTER CONTROLLERS USING CLASSICAL METHOD

Classical tuning of PI controller is based on the following rules [33]:

1) closed loop bandwidth of inner controller should not be larger than 0.2 times of angular switching frequency.
2) inner controller should be 10 times faster than outer controller to avoid oscillatory response.

PI parameters of inner current controller based on first rules can be selected as:

$$K_p = \alpha L \tag{14}$$

$$K_i = \alpha R \tag{15}$$

where α is closed loop bandwidth of inner current controller, L and R are per unit inductance and resistance of filter. For 5 kHz switching frequency, closed loop bandwidth $\alpha = 0.2(2\pi f) = 2k\pi$ rad/sec.

Similarly, PI parameters of outer controller based on second rules can be selected as:

$$\alpha_o = 0.1\alpha \tag{16}$$

$$K_{po} = \alpha_o C \tag{17}$$

$$K_{io} = \alpha_o^2 C \tag{18}$$

where α_o is closed loop bandwidth of outer controller and C is capacitance of DC link in per unit.

TABLE 2. Inner current controller and outer power controller parameters obtained from classical, ACO and PSO techniques.

Controllers	Classical PI Gains		ACO PI Gains		PSO PI Gains	
	K_p	K_i	K_{po}	K_{io}	K_{ps}	K_{is}
Inner Current Controller	5.02	62.83	5.30	7.70	5.60	69.16
Outer Controller (Power)	1.51	947.48	0.49	1145.38	0.41	593.23

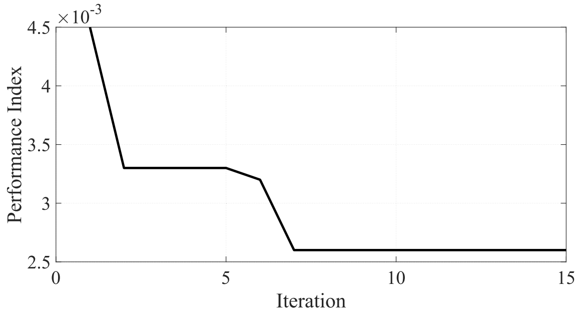

FIGURE 6. Performance index of outer power controller.

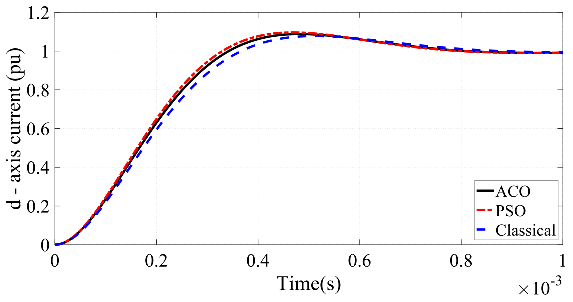

FIGURE 7. Step response of inner current controller for classical, ACO and PSO.

C. COMPARISON WITH EXISTING METHODS

Classical controllers for VSC-MTDC are load dependent and needs to be adjusted for every operating condition. Therefore, dynamic behavior and wide range of operating conditions of VSC-MTDC system are improved using modified genetic algorithm (MGA) and particle swarm optimization (PSO) methods [34]. Several researchers have used particle swarm optimization (PSO), honey bee mating optimization (HBMO), simplex algorithm (SA) and genetic algorithm (GA) meta – heuristic algorithms for tuning of multi – terminal DC system controllers and power system optimization problems [12]–[14].In this study, to show the practicality of ant colony optimization (ACO) algorithm for VSC – MTDC controllers tuning, results are compared with another meta – heuristic algorithm, particle swarm optimization (PSO) and classical tuning methods. Inner and outer PI controllers of VSC – MTDC are optimized by PSO algorithm explained in reference [15].

The resulting parameters of PI inner current controller and outer controller obtained using ACO [35] in subsection IV-A, classical methods [33] in subsection IV-B and PSO are presented in Table 2.

After optimization of controllers, the performance of objective function in ACO algorithm is assessed by step response and the results are compared with classical and PSO method. The responses of inner current controller and active power profile are shown in Fig.7 and 8. These figures shows considerable improvement in performance in terms of definite faster rise time, settling time and reasonable peak time in ACO than classical and PSO tuning. In Fig.8, the step response of outer controller tuned by classical method shows shock during the rise of response. Whereas response of controller tuned by PSO has slow speed.

Comparison of performance parameters of classical, ACO and PSO method is shown in Table 3. Performance parameters of inner current controller for ACO and PSO have almost same results except higher percentage overshoot in PSO results. Whereas classical method shows inferior results for inner current controller. In case of outer controller,

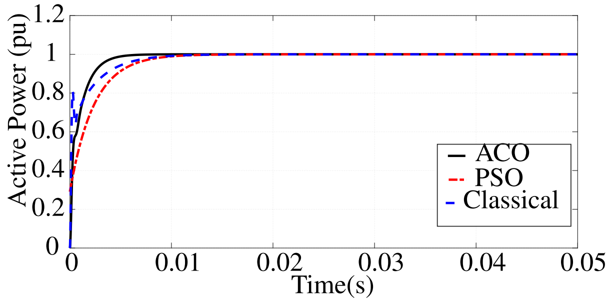

FIGURE 8. Step response of outer power controller for classical, ACO and PSO.

TABLE 3. Performance parameters of classical, ACO and PSO method.

Performance Parameters	Inner Current Controller			Outer Controller (Power)		
	Classical	ACO	PSO	Classical	ACO	PSO
Rise Time (ms)	0.244	0.23	0.225	3.5	2.2	5.2
Settling Time (ms)	0.756	0.720	0.720	7.7	4.3	9.3
Overshoot(%)	7.75	8.0	9.6	0.0	0.0	0.0
Peak Time (ms)	0.516	0.480	0.475	19.9	7.2	25.1

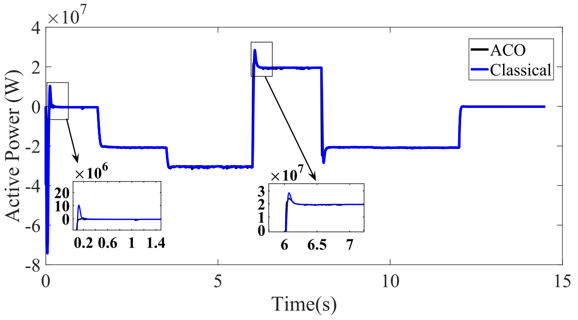

FIGURE 9. Smooth response of ACO due to change in active power at terminal A.

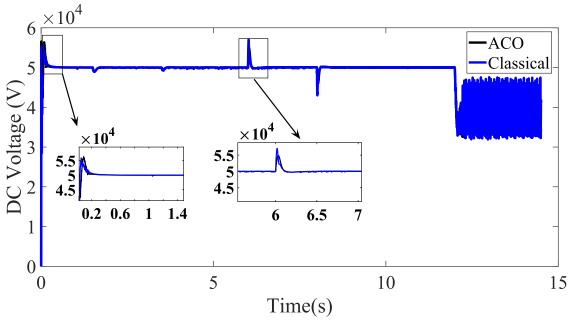

FIGURE 10. Better transient response of ACO with the change in DC voltage near terminal A.

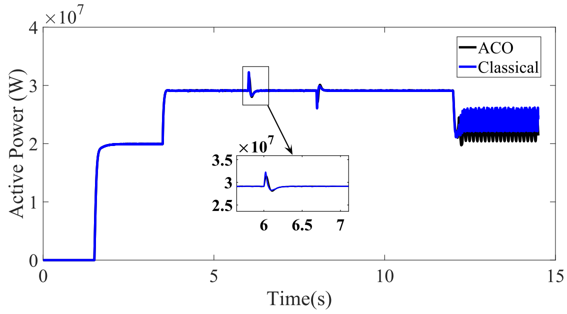

FIGURE 11. Less oscillations of ACO due to change in active power at terminal B.

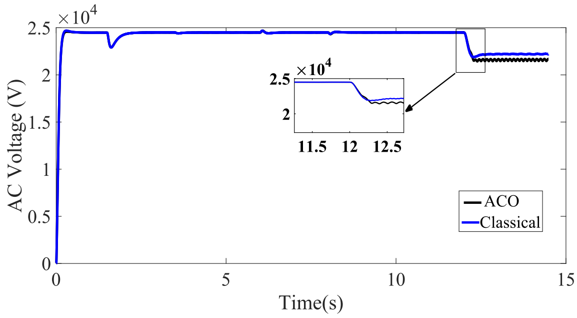

FIGURE 12. Slighter voltage rise of ACO with the change in AC voltage at terminal B.

performance parameters of ACO shows better results than classical and PSO method. Therefore, it has been found that both inner and outer controllers optimized using ACO depicts better results than classical and PSO method. Based on the simulation results shown in Table 3, it was decided to employ the controller gains obtains through ACO and classical method for transient analysis under different sequence of events on PSCAD/EMTDC software.

D. PERFORMANCE OF OPTIMIZED CONTROLLERS IN FOUR TERMINAL VSC–MTDC SYSTEM

The proposed four terminal VSC – MTDC system is shown in Fig.1. It is modelled in PSCAD/EMTDC software for the parameters rating presented in Table 1. VSC - MTDC controllers of multi – terminal DC systems are primarily responsible for the control of active power, reactive power, AC voltage and DC voltage. Coordinated operation of multi – terminal DC systems requires control scheme which can endure the loss of some terminals, as MTDC requires a minimum of one constant DC voltage terminal. In this case terminal A is considered as DC voltage regulating terminal. In Fig.1, terminal A and C are connected with stiff grids whereas B and D terminals are attached with passive and weak grids respectively. Terminal B controls the AC voltage and C and D terminals operate in fixed power mode. In this simulation, PI parameters obtained offline through ACO algorithm on MATLAB and classical method are updated on PSCAD/EMTDC model simultaneously. Robustness of controllers were evaluated with the following sequence of events during the simulation.

At time t = 0 s, reference values for the controllers on all four terminals of VSC – MTDC system are as; DC voltage = 50 kV (Terminal A), AC voltage line - line = 24.5 kVrms (Terminal B), active power = 0 MW (Terminal C) and active power = 0 MW (Terminal D). At time t = 1.5 s, unity power factor load of 10 MW is added on AC side of terminal B. At time t = 3.5 s, 0.8 power factor load of 11.8 MVA is added on AC side of terminal B. At time t = 6 s, active power reference at terminal D is changed from 0 MW to – 50 MW to work in rectification mode. At time t = 8 s, active power reference at terminal C is changed from 0 MW to 40 MW to work in inverter mode. At time t = 9.5 s,

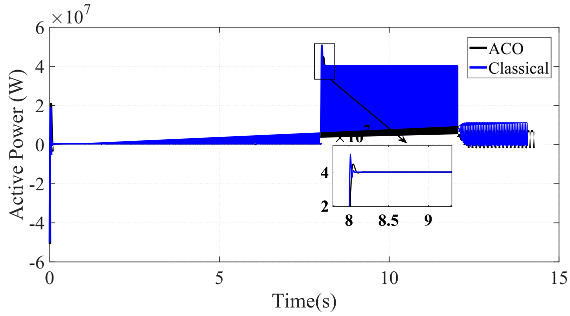

FIGURE 13. Reduced spike and oscillations in ACO response due to change in active power at terminal C.

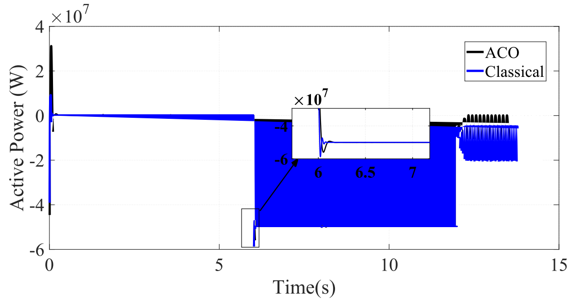

FIGURE 14. Less oscillations in ACO response due to change in active power at terminal D.

reactive power of 30 MVA is produced at terminal C. At time t = 12 s, terminal A is disconnected from VSC – MTDC system and at time t = 14.5 s, active power load of terminal B is disconnected.

On terminal A, response of classically tuned and ACO based tuned active power controller is shown in Fig.9. It shows that at t = 0 s, t = 6 s and 8 s classically tuned controller gives spikes of active power whereas ACO based controller gives smooth response. DC voltage behavior of terminal A is shown in Fig.10. After disconnection at t = 12 s, classical controller gives large oscillation in DC voltage. Similarly on terminal B, response of classically tuned controller during switching is poor compared to ACO based tuned controller as shown in Fig.11. Also the AC voltage on terminal B shown in Fig.12 has more voltage rise and oscillations from t = 12 s to t = 14.5 s for classically tuned controller than ACO based. On terminal C, active power response for classical tuned controller exhibits oscillations and spikes at t = 0 s and t = 8 s shown in Fig.13. Similarly on terminal D, active power response for classical tuned controller exhibits oscillations and spikes at t = 0 s and t = 6 s shown in Fig.14. Response of AC voltage based on classical controller on terminal D shown in Fig.15 also exhibits oscillations after the loss of terminal A.

Finally the response of PI active power controller optimized based on ACO algorithms has less oscillations and spikes during load switching or the loss of terminal A than classical controller response.

Actually, the simulation results for DC voltage shown in Fig.10 indicates that multi – terminal DC system works properly provided that the DC voltage regulating terminal A is connected. Under the large disturbances of load switching and changes in reference of active power controllers the DC voltage is constant. This is true until DC voltage regulating terminal is available before t = 12 s. After that deficit of power inflow results in voltage drop. Excessive power inflow will result in DC voltage rise due to disconnection of terminal C at t = 14.5 s. After t = 14.5 s, the large oscillations in all the plots are due to absence of DC regulating terminal.

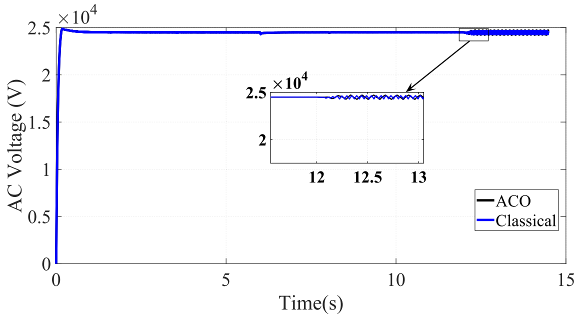

FIGURE 15. Smaller oscillations in ACO result due to change in AC voltage at terminal D.

V. CONCLUSION

The key focus of this research is to increase the control performance of VSC - MTDC system by nature inspired algorithms. For this purpose, optimal tuning techniques ACO and PSO are considered to optimize and compare PI controller parameters on MATLAB software. The control scheme used for the control of VSC – MTDC system is vector control method. The inner current and outer power PI controllers of VSC - MTDC were optimized simultaneously by ACO algorithm. The controller parameters and performance parameters obtained by ACO were compared with a well established meta - heuristic algorithm PSO, for multi-terminal DC power system and classical method, which shows that rise time, settling time and peak time are significantly improved in ACO. Finally the PI parameters obtained by ACO and classical method were applied on four terminal VSC – MTDC system and dynamic performance was accessed under different sequence of events of disturbance like sudden load change on AC side, active power exchange between AC and DC system and disconnection of one terminal on PSCAD/EMTDC software. Results for the ACO algorithm shows that substantial improvement in the oscillations and voltage and power spikes were observed during the switching intervals without violating voltage and active power limits.

The future research work includes statistical analysis of ACO and PSO algorithms for optimal tuning of VSC - MTDC controllers to check the performance measures. Moreover, wind and solar energy sources can be integrated to the proposed VSC - MTDC grid to further investigate the economics dispatch applications using PSO and ACO.

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