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Improvement of Transient Stability of VSC HVDC System with Particle Swarm Optimization Based PI Controller

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***Abstracts :** This paper proposes the improvement of power flow during transient condition of HVDC light using PI Controller. The Optimal design of PI controller for a HVDC light is a challenging task and time consuming using the conventional techniques. This work presents analysis of transient stability of HVDC link using PI controller, and the stability has been improved by optimized gains of PI controller. The simulation results are presented to show the effectiveness of the proposed Particle swarm Optimization Technique (PSO) based approach for the design of optimal conventional controller for a HVDC light in a single machine decoupled power system.*

***Index Terms:** HDVC light, PSO, Transient Stability, PI controller*

1.Introduction

High voltage direct current (HVDC) transmission is an economic way for long distance bulk power delivery and/or interconnection of asynchronous system with different frequency [1]. HVDC system plays much more important role in power grids due to their huge capacity and capability of long distance transmission. Conventional HVDC transmission system is based on line commuted thyrister rectifiers [2]. Insulated gate bipolar transistor, (IGBT) is recently replaced by the conventional thyrister based HVDC link, due its fast controller action of GTO. Insulated-gate controlled Thyristers (IGCT) high power solid state switches have symmetrical turn on and turn off capabilities. They have given a new innovation of HVDC stations. HVDC light is also called voltage source convert HVDC or VSC HVDC [3].

The conventional HVDC scheme employ line commuted current source converter (CSC) based Thirsters. HVDC light is a new technology utilising forced commuted voltage source converters [4]. HVDC light can control both active and reactive power independently without commutation failure in the inverter side. It does not require reactive power compensator resulting much smaller equipment size. HVDC light can be applied to the voltage support in the receiver system [5]. It provides inter-connection between two asynchronous power systems [6], grid connection of large wind farm, [8] and undersea power transmission [9], Bidirectional power flow 12 HVDC light projects for different purposes already in operation worldwide.

For a single M/C power system connected to infinite bus the introduction of HVDC light can enhance the voltage support and improve the system stability. In this study problem of PI controller design to formulated as a multi objective optimization problem.

section 1 represents the introduction part of thesis work and section 2 describes the fundamentals of HVDC system and VSC-HVDC system. It includes the construction operating principle and the type of HVDC links and their advantages and disadvantages along with its applications. section3 describes the particle swarm optimization technique (PSO) it describes the different parameters of PSO like velocity parameters, search technique etc. Section 4 describes the HVDC system under our study. It describes the mathematical modelling of synchronous generator, voltage sources converter (VSC), voltage source inverter (VSI) and the DC link. section 5 includes the simulation result and application of PSO to optimize the gains of PI controller used for HVDC light. It describes the quick response of PI controller with PSO and is compared with the results without PSO. section 6 contains conclusion of this work and at last section gives the bibliography and references of the present work.

2.Mathematical Modelling of Synchronous Machine

A power system can be modeled by a set of non-linear differential equations as

$dX/dt = f(X, U)$ ----(1)

Where X is the vector of the state variables and U is the vector of input variables. In this study, the fourth order model as given below is used for non-linear time domain simulation.

$d\delta/dt = \omega - \omega_0$ -------- (2)

$d\omega/dt = (P_m - P_e)/M$ ----- (3)

$dE_q/dt = (E_{fd} - (X_d - X_{dd})\ I_d - E_q)/\ T_{do}$ ------ (4)

$dE_{fd}/dt = (K_a(V_{ref} - V_t - V_{PSS}) - E_{fd})/T_a$ ------ (5)

Where

δ = Rotor angle

ω = Rotor speed

P_m = Mechanical Power

P_e = Electrical Power

E_{fd} = Equivalent excitation voltage

d and q = direct and quadrature axes respectively

E_q = Internal voltages behind the reactance X_d & X_q

T_a = Regulator time constant
T_{do} = Time constant of excitation circuit
K_a = Regulator gain

The d-q axis conversion of machine frame to network frame is expressed as following:

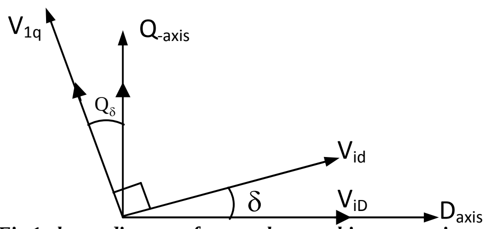


Fig.1.phasor diagram of network to machine conversion

Here V_{id} and V_{1f} are the direct axis and quadrature axis voltage across the terminals in machine frame and V_{iD} and V_{iQ} are the terminal voltage in network frame.

$$V_{1D} = -V_{1f}\sin\delta + V_{1d}\cos\delta$$

$$V_{1Q} = V_{if}\cos\delta + V_{1d}\sin\delta$$

In matrix form it can be written as

$$\begin{bmatrix} V_{1D} \\ V_{1Q} \end{bmatrix} = \begin{bmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} V_{1d} \\ V_{1f} \end{bmatrix} \quad (6)$$

The machine terminal voltages

$$\left.\begin{aligned} V_{1d} &= V_{1D}\cos\delta + V_{1Q}\sin\delta \\ V_{iq} &= -V_{1D}\sin\delta + V_{1Q}\cos\delta \end{aligned}\right\} \quad (7)$$

Similarly direct and quadrature axis current injected by the machine, is given by

$$\left.\begin{aligned} I_{1d} &= I_{1D}\cos\delta + I_{1Q}\sin\delta \\ I_{iq} &= -I_{1D}\sin\delta + I_{1Q}\cos\delta \end{aligned}\right\} \quad (8)$$

Where, d, q represents machine frame

3. Modelling of vsc **HVDC**

HVDC light is composed of transformer filters, converters and D.C. capacitors. Transformer is used to step down the A.C. voltage to the converter rating value, and the self commuted solid state devices such as series and parallel of GTOS, IGBTs or IGCTs. High frequency components caused by the switches of the valves are isolated from power system, by filters. The heart of HVDC light is converters which can realize the conversion from AC to DC bi-directionally. DC capacitors are used as DC voltage sources in HVDC light which need being charged and recharged.

Our analysis is based on a HVDC light used in a single m/c power system which is connected to infinite bus.

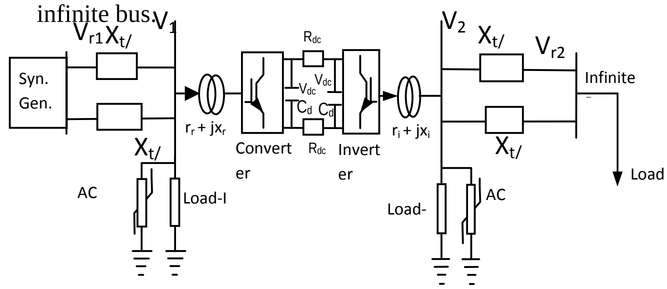


Fig.2.Model of decoupled VSC-HVDC with single machine connected to infinite bus

VSCI or Rectifier of HVDC light applies the active and reactive power control. But the VSC II i.e., inverter applies DC and AC voltage control. The active power is control by the phase angle of converter output voltage, and the reactive power is controlled by magnitude of converter voltage. In that sense active and reactive power controlled independently.

The rectifier controller is shown in the fig.(4). The controller consists of four parts. Power flow control loop, reactive power flow loop, phase locked loop (PLL) and PWM pulse firing.

A typical VSC HVDC transmission link consists of two converter stations one station operates as rectifier and other one operates as inverter station as shown in the fig.3.The mathematical model developed in this paper depends on a rotating d.q frame. transform RYB to D Q frame. With the increasing the application of voltage source converter.,

The dynamic equations of rectifier and inverter in the rotating d-f frame can be written as follows:

3.1.Rectifier

$$\dot{I}_r D = -\frac{(r_r . I_D)}{L_r} + \omega_1 I_{rQ} + \frac{V_{1D}}{L_r} - \frac{V_{rD}}{L_r} \quad (1)$$

$$I_{dc} = I_{dc1} - \frac{Vldc1}{R_{sh1}} \quad (2)$$

$$\dot{I}_{rQ} = -\frac{(r_r . I_{rQ})}{L_r} - \omega_1 I_{rD} + \frac{V_{1Q}}{L_r} - \frac{V_{rQ}}{L_r} \quad (3)$$

$$V_{dc1} = \frac{P_{dc1}}{(V_{dc1}C_{dc})} - \frac{I_{dc}}{C_{dc}}$$

(4)

3.2.Inverter:

$$\dot{I}_{iD} = \frac{-r_i I_{iD}}{L_i} + \omega_2 I_r Q - \frac{V_{2D}}{L_r} + \frac{V_{iD}}{L_i}$$

(5)

$$\dot{I}_{iQ} = \frac{-r_i I_{iQ}}{L_i} - \omega_2 I_{iD} - \frac{V_2 Q}{L_i} + \frac{V_{iQ}}{L_i}$$

(6)

$$\dot{V}_{dc_2} = \frac{I_{dc}}{C_{dc}} - \frac{I_{dc}}{C_{dc}V_{dc}}$$

$$I_{dc_2} = I_{dc} - \frac{V_{dc_2}}{R_{sh_2}}$$

(7)

Where I_rD, I_rQ, V_1D, V_1Q are d-f axis currents of rectifier side, and I_iD, I_iQ, V_2D and V_2Q are the d-f axis current and voltages of inverter side. $r_r + jx_r$ and $r_i + jx_i$ are the complex impedance of rectifier and inverter respectively. L_r and L_i are the inductance of smoothing reacts used in converter and inverter respectively. V_{dc_1}, V_{dc_2} and I_{dc} are the d.c. link voltage and current. C_{dc} is the cap air of the d.c. link, R_{sh_1} and R_{sh_2} are the shunt resistances of the HVDC system.

The switching frequency of the rectifier is 2050 Hz where as the switching frequency of the inverter station is 2460 Hz making V_{rD} and V_{rQ} are the control input to the rectifier V_{iD} and V_{iQ} to the inverter, Expanding the P_{dc_1} in (3) the system equation can be written as

$$\dot{I}_{rD} = \frac{(r_r.I_{rD})}{L_r} + \omega_1 I_{rQ} + \frac{V_{1D}}{L_r} - \frac{u_1}{L_r}$$

(8)

$$\dot{I}_{rQ} = \frac{(r_r.I_{rQ})}{L_r} - \omega_1 I_{rD} + \frac{V_{1Q}}{L_r} - \frac{u_2}{L_r}$$

(9)

$$\dot{V}_{dc_1} = \left\{ \left(V_{1D}I_{rD} + lV_{1Q}I_{rQ} \right) - r_r\left(I_{rD}^2 + I_{rQ}^2 \right) \right\} - \frac{\left(V_{dc_1} - V_{dc_2} \right)}{R_{dc}C_{dc}}$$

$$\dot{I}_{iD} = \frac{r_i I_{iD}}{L_r} + \omega_2 I_{iQ} - \frac{V_{2D}}{L_i} + \frac{u_3}{L_i}$$

(10)

$$\dot{I}_{iQ} = -\frac{r_i I_{iQ}}{L_i} - \omega_2 I_{iD} - \frac{V_{2Q}}{L_i} + \frac{u_4}{L_i}$$

(10)

4. Particle Swarm Optimization

Particle Swarm Optimization (PSO), one of the latest metaheuristic algorithms, was first introduced by Kennedy and Eberhart 1995. PSO is based on the metaphor of social interaction and communication such as bird flocking and fish schooling. Since PSO is population based and socially cognitive in nature, the members in a swarm tend to follow the leader of the group, i.e., the one with the best performance. In a PSO algorithm, each member is called a “particle”, and each particle flies around in the mutli-dimensional search space with a velocity, which is updated according to the particle’s current velocity, the particle’s own experience and the experience of the neighbors. Depending on the size of neighbors, two types of basic PSO algorithms were developed-PSO with a local neighborhood and PSO with global neighborhood of Kennedy et al. 2001. In the former model, called the *lbest*, each particle moves towards its best previous position and towards the best particle in its restricted neighborhood. While in the latter model, called the *gbest,* each particle moves towards its best previous position and towards the best particle in the entire swarm.

PSO was first developed to optimize continuous nonlinear functions. Since PSO is easy to implement and is efficient to obtain quality solutions, it has attracted much researchers' attention in recent years. The application of PSO consists of neural network training, power and voltage control, optimal power system design, feature selection, mass-spring system, electromagnetic, clustering, logic circuit design, lot sizing problem, task assignment problem, automated drilling, and scheduling problems. More literature can be found in the reference of Kennedy et al. 2001. Besides the wide range of applications above, the nonlinear continuous function optimization is still considered the benchmark problem when exploring the properties and performance of PSO algorithms. Therefore, this paper aims at employing PSO on optimizing 14 newly developed test problems in Congress on Evolutionary Computation 2005.

4.1. PSO Algorithm

The *gbest* model of Kennedy et al. 2001 is followed in this study. According to the *gbest* model, each particle moves towards its best previous position and towards the best particle in the whole swarm. In the PSO algorithm, parameters were initialized and the initial population was generated randomly. Each particle will then be evaluated to compute the fitness function value. After evaluation, the PSO algorithm repeats the following steps iteratively.

With its position, velocity and fitness value, each particle updates its personal best (best value of each individual so far) if an improved fitness value was found.

The basic elements of PSO algorithm is summarized as follows:

Particle

X_i^t denotes the i[th] particle in the swarm at iteration t and is represented by n numbers of dimensions as $X_i^t = \left[x_{i1}^t, x_{i2}^t, ...x_{in}^t\right]$ where x_{ij}^t is the position value of the i[th] particle with respect to the j[th] dimension (j = 1, 2, …., n).

Population

X^t is the set of NP particles in the swarm at iteration t, i.e.,

$$X^t = \left[X_1^t, X_2^t, ...X_{NP}^t\right]. \quad (11)$$

Particle Velocity

V_i^t is the velocity of particle I at iteration t. It can be defined as $V_i^t = \left[v_{i1}^t, v_{i2}^t, ...v_{in}^t\right]$, (12)

where v_{ij}^t is the velocity of particle I at iteration t with respect to the j[th] dimension.

Inertia weight and acceleration co-efficients

w^t is a parameter to control the impact of the previous velocities on the current velocity. It has an impact on the trade-off between the global and local exploration capabilities of the particle. At the beginning of the search, large inertia weight is used to enhance the global exploration while it is reduced for better local exploitation later on in the search. c_1 and c_2 are constant parameters called acceleration coefficient which control the maximum step size that the particle can do.

Personal best

P_i^t represents the best position of the particle with the best fitness value until iteration t, so the best position associated with the best fitness value of the particle obtained so far is called the *personal best*. For each particle in the swarm, P_i^t can be determined and updated at each iteration t. In a minimization problem with the objective function $f\left(X_i^t\right)$, the personal best P_i^t of the i[th] particle is obtained such that $f(P_i^t) \le f(P_i^{t-1})$. To simplify, the fitness function of the personal best is denoted as $f_i^{pb} = f(P_i^t)$. For each particle, the personal best is defined as $P_i^t = \left[p_{i1}^t, p_{i2}^t, ..., p_{in}^t\right]$ where P_{ij}^t is the position value of the i[th] personal best with respect to the j[th] dimension (j = 1, 2, …., n).

Global Best

G^t denotes the best position of the globally best particle achieved so far in the whole swarm. For this reason, the global best can be obtained such that $f(G^t) \le f(P_i^t)$ for I = 1, 2, ….NP. To simplify, the fitness function of the global best is denoted as $f^{gb} = f(G^t)$. The global best is then defined as $G^t = \left[g_1^t, g_2^t, ...g_n^t\right]$ where g_j^t is the position value of the global best with respect to the j[th] dimension (j =1, 2, …..n).

Termination Criterion

It is a condition that terminates the search process. It might be a maximum number of function evaluations or a maximum CPU time that terminates the search.

3.3 Initial Population

A population of particles is constructed randomly for the PSO algorithm. The continuous values of positions are established randomly. The following formula is used to construct the initial continuous position values of the particle uniformly:

$$x_{ij}^0 = x_{\min} + (x_{\max} - x_{\min}) * r_1 \quad (13)$$

Where *x_{max} and x_{min} are given* bounds of the continuous functions and r_1 is a uniform random number between 0 and 1. Initial velocities are generated by a similar formula as follows:

$$v_{ij}^0 = v_{\min} + (v_{\max} - v_{\min}) * r_2 \quad (14)$$

where $v_{\max} = (x_{\max} - x_{\min})/2$ and $v_{\min} = -v_{\max}$, and r_2 is a uniform random number between 0 and 1. Continuous velocity values are restricted to some range, namely

$$v_{ij}^t = \left[v_{\min}, v_{\max}\right]$$

During the reproduction of the PSO algorithm, it is possible to extend the search outside of the initial range of the search space. For this reason, the position values violating the initial range are restricted to the feasible range as follows:

$$x_{ij}^t = x_{\min} + \left(x_{\max} - x_{\min}\right) * r_1 \quad (15)$$

The only exception was the problem 7 for which the optimal was not inside the search limits. The population size is taken as 100. As the formulation of 14 functions suggests that the objective is to minimize 14 continuous functions, the fitness function value is the objective function value of the particle X^t. That is $f_i^t(X_i^t)$. For simplicity, $f_i^t(X_i^t)$ will be denoted as f_i^t.

4.2. Computational Procedure of PSO

The complete computational procedure of the PSO algorithm can be summarized as follows:

Initialization

Set t = 0, NP = 100

Generate NP particles randomly as explained before, $\left\{X_i^0, i = 1, 2, ...NP\right\}$ where $X_i^0 = \left[x_{i1}^0, x_{i2}^0............, x_{in}^0\right]$

Generate the initial velocities for each particle randomly. $\left\{V_i^0, i = 1, 2, ...NP\right\}$ where $V_i^0 = \left[v_{i1}^0, v_{i2}^0, ...v_{in}^0\right]$.

Evaluate each particle in the swarm using the objective function f_i^0 for I = 1, 2, ……NP.

For each particle in the swarm, set $P_i^0 = X_i^0$, where

$P_i^0 = \left[p_{i1}^0 = x_{i1}^0, p_{i2}^0 = x_{i2}^0, ..., p_{in}^0 = x_{in}^0\right]$

together with its best fitness value f_i^{pb} for I = 1, 2, …. NP.

First the best fitness value among the whole swarm such that $f_i = \min\left\{f_i^0\right\}$ for I = 1, 2, ….. NP with its corresponding positions X_1^0. Set global best to $G^0 = X_1^0$ such that $G^0 = \left[g_1 = x_{i1}, g_2 = x_{i2}, ...g_n = x_{in}\right]$ with its fitness value $f^{gb} = f_1$.

Update iteration counter

t = t +1

Update inertia weight

$$w^t = \left((\max\_fes - FES) / \max\_fes\right) * (w_0 - w_n) + w_n$$

where max_fes, FES, w_0, and w_n are the maximum number of function evaluation, number of function evaluations, initial inertia weight, and final inertia weight respectively.

Update velocity

$$v_{ij}^t = w^{t-1} v_{ij}^{t-1} + c_1 r_1 \left(p_{ij}^{t-1} - x_{ij}^{t-1}\right) + c_2 r_2 \left(g_j^{t-1} - x_{ij}^{t-1}\right)$$

where c_1 and c_2 are acceleration coefficients and r_1 and r_2 are uniform random numbers between (0, 1).

Update Position

$$x_{ij}^t = x_{ij}^{t-1} + v_{ij}^t$$

Update personal best

Each particle is evaluated by using the permutation to see if the personal best will improve. That is, if $f_i^t < f_i^{pb}$ for I = 1, 2, …..NP then personal best is updated as $P_i^t = X_i^t$ for $f_i^{pb} = f_i^t$.

Update global best

Find the minimum value of personal best. That is, $f_1^t = \min\left\{f_i^{pb}\right\}$, I = 1, 2, ….. NP; $l \in \left\{i : i = 1, 2, ...NP\right\}$.

If $f_l^t < f^{gb}$, then the global best is updated as $G^t = X_l^t$ and $f^{gb} = f_l^t$

Stopping criterion

If the number of function evaluations exceeds the maximum number of function evaluations, that stop; otherwise go to step 2.

5. PI Controller

The State variables of rectifier station are I_{rd}, I_{rq} and V_{dc1} for connivance dc voltage and reactive power of the rectifier are taken as the output variables. Since the reference bus d-axis voltage is taken as zero the reactive power directly controlled by I_{rd}.

The State variables of inverter station are I_{id}, I_{iq} and V_{id} and V_{iq} . Since the inverter station is operating in the active and reactive control mode the output states are I_{id}, I_{iq}. As the reference bus in the inverter side is chosen as one the d-axis current represent reactive power whereas q-axis current represents the active power flow in the inverter station, the whole PI controller strategy is describe by the following diagram. In the figure 4.3.

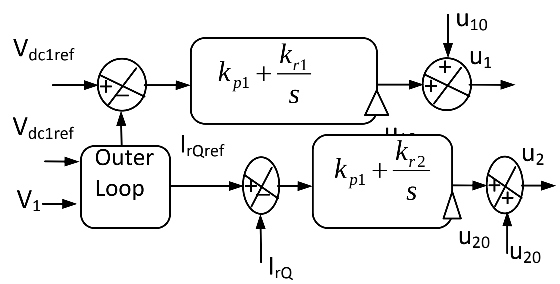


Fig.3. PI controller for rectifier station

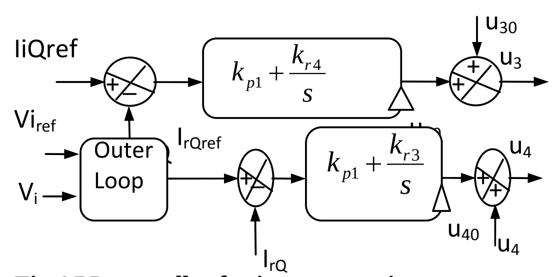


Fig.4.PI controller for inverter station

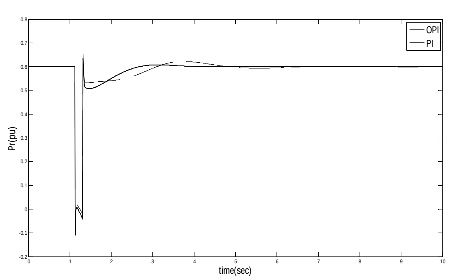
Table-5.1

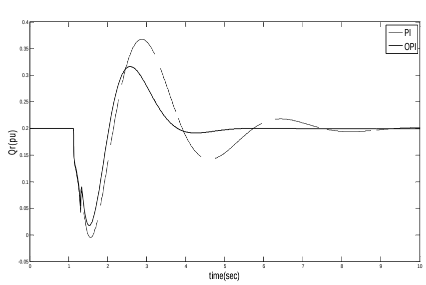
	Converter Controller gain				**Inverter gain**			
	Kp_1	Kp_2	Kp_3	Kp_4	Ki_1	Ki_2	Ki_3	Ki_4
Conventional PI	0.2	0.2	0.3	0.22	-0.22	-0.22	-0.1	-0.1
With PSO	0.14	0.29	0.1	0.13	-0.23	-0.28	-0.2	0.05

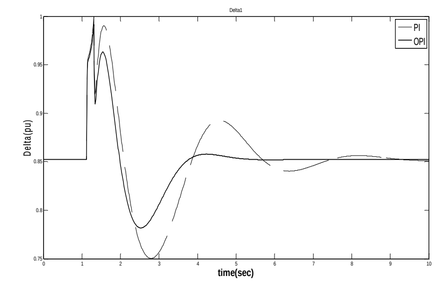
6.Simulation Result

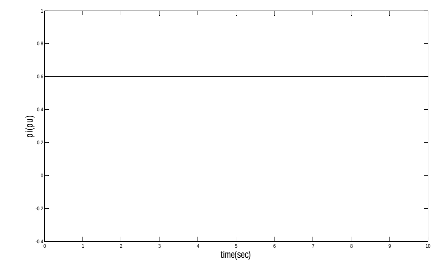
In this paper the conventional PI controller has been simulated in MATLAB. The performance of PI controller is tested under various conditions with normal gains. The result is compared with the performance with optimized gains of PI controller used PSO .

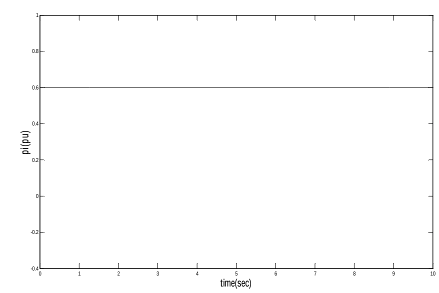
Case 1: Here during a LLLG fault at bus 1 from 1s to 1.2 sec. Due to the fault the a.c. voltage, has decreased to a critical value.In Fig(4) it is shown the improvement of damping of V_{dc1} and the performance of the PSO based PI controller restores the system than the earlier conventional PI controller., in bus 1, rectifier output and respective reactive power with normal PI controller and the result is compared with performance with optimized PI controller . Due to decoupling effect the active and reactive power , the rectifier station does not change at inverter station fault as shown











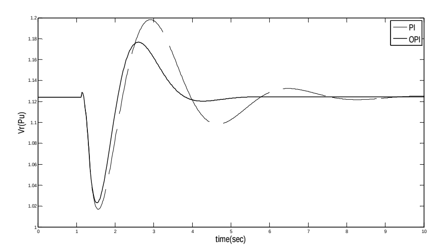
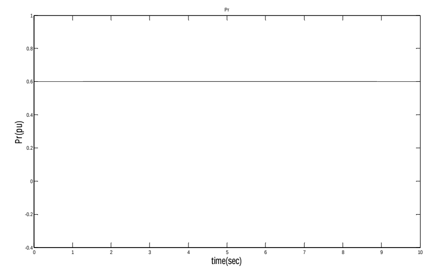
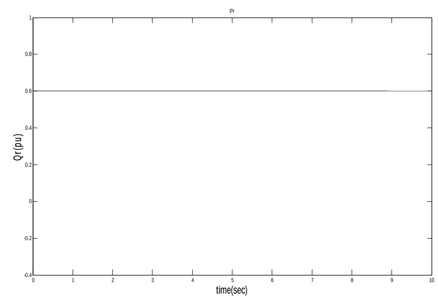
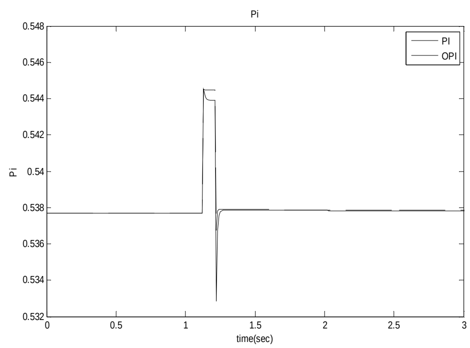


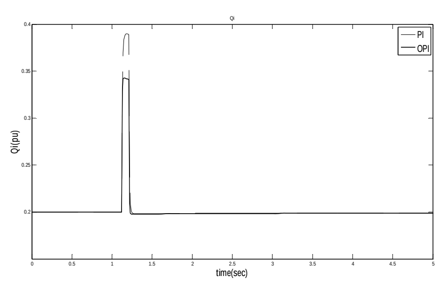
Fig.5. Performance comparison of the controller under resistance fault at bus1

Case 2: Here a 1 cycle LLLG fault at bus 2 with same earthing operating condition is simulated on the inverter side, Fig. 5shows the satisfactory improvement of damping in , active and reactive power, power angle, rotor angular velocity in both rectifiers and inverter side, With deferential evolution based PI controller. Due to decoupling effect the active and reactive power of rectifier station does not change at inverter station fault









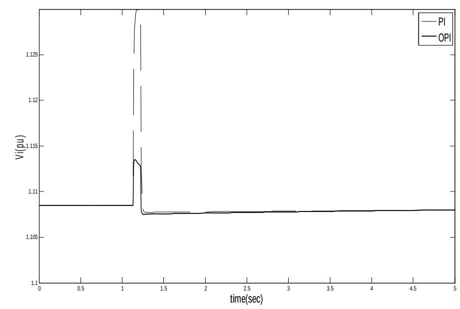
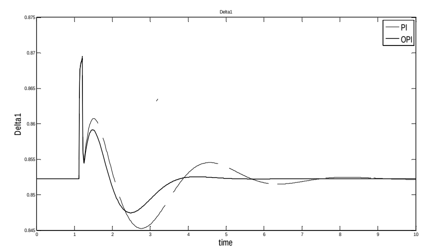
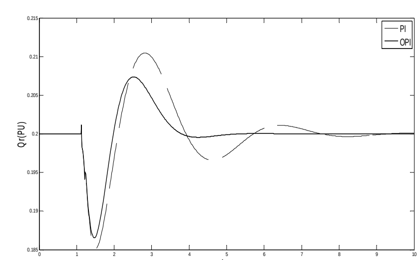


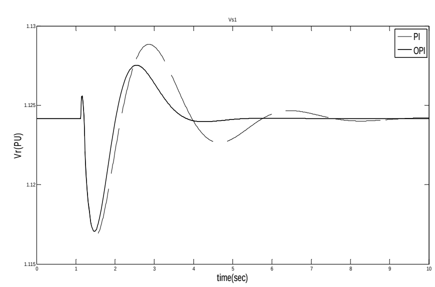
Fig.5. Performance comparison of the controller under resistance fault bus2

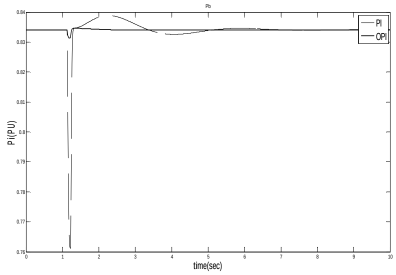
Case 3:

Here a 1 cycle fault at bus 2 is created by increasing the load in the inverter side(20 percent of the original value) with same earthling operating condition is simulated on the inverter side, Fig. 6 shows the satisfactory improvement of damping in , active and reactive power, power angle, rotor angular velocity in both rectifiers and inverter side, With PSO based PI controller.









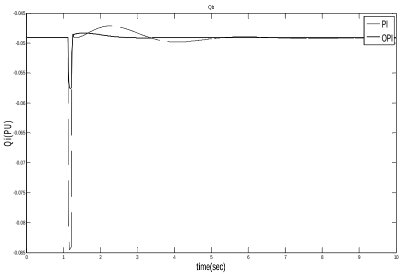


Fig.6. Performance comparison of the controller under load fault at bus2

7. Conclusion

In this paper transient stability performance of VSC-HVDC is improvement by a PI controller is investigated. The gains of PI controllers for rectifier and inverter are optimised by use of Particle swarm optimizationtechnique. The effectiveness of the proposed HVDC controller for improving transient stability are demonstrated by a decoupled power system with VSC-HVDC subjected to different severe disturbances. In all the cases it is realised that the PSO based PI controller stabilize the system quicker than the conventional PI controller.

8.Appendix

Base voltage = 132 KV(a.c.) 150 V_{dc}
Pass power = 100MVA
Initial Operating Point 60 MW and 10 MVAR
Load 1 : (Converter side)
3 MW and 2 MVAR
$R_1 - 0.02H$
Load 2 : (Inverter side)
30 MW and 20 MVAR
$R_2 = 10,000\Omega$
$L_2 = 0.02H$
Transmission Line Parameter
$xt_{11} = x_{22} = 0.05\Omega/km$ (25 Km
d.c. transmission line resistance
$R_{dc} = 0.01\Omega/km$ (50 Km)
Shunt resistance $R_{sh_1} = R_{sh_2} = 10000\Omega$
Converter Station
$r_r = 1.452\Omega$, $r_i = 1.452\Omega$
$x_r = 2.9\Omega$, $x_i = 2.9\Omega$
D.c. link capacitor $C_{dc} = 5000\mu F$
a.c. filter capacitor = $10\mu F$.

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