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Parameter Optimization of Salient-pole Synchronous Generator for Small Disturbance Steady State Stability by Multi-Objective-Optimization Techniques

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ABSTRACT
Stability in power system may be classified into voltage stability, frequency stability and rotor angle stability. The Rotor angle stability is the ability of synchronous machine, running in the power system to remain in the state of synchronism. The response factors for rotor angle stability are generator initial operating point, transmission strength, generator excitation system controls and generator parameters like its reactance and time constants. In the present paper the generator parameters are optimized for minimum rotor frequency of oscillations under small signal stability conditions. Not only in stability analysis, but in fault condition also, reactance play a major role. Hence, 'minimizing fault current' objective is also considered for optimization. The multi objective optimization methods used are 'multi-objective differential evolution (MODE)', 'Multi Objective Multi-Verse Optimizer (MOMVO)' and 'Pareto front Optimal Solution (POS)'

In all the optimization techniques, four critical parameters are selected. They are magnetic core stack length, radial air gap between armature bore and salient pole, and the ratio of pole arc and pole pitch.

The optimization output results are compared and analyzed. POS gave better optimization results for the objective functions in the subject.

Keywords-Salient pole synchronous generator, small disturbance stability analysis, multi-objective optimization

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I. INTRODUCTION

Power system stability may be broadly classified into Rotor angle stability, frequency stability and voltage stability. Further, the rotor angle stability is subdivided into small disturbance-angle-stability and transient stability. In this paper, rotor angle small signal stability is dealt.

During perturbation, the generator rotor either accelerate or decelerate giving rise to stability problems like non-oscillatory instability or oscillatory instability. The air gap torque can be resolved into two components. They are synchronizing torque and damping torque. Synchronizing torque, when inadequate, results in non-oscillatory instability and damping torques, when not enough, results in oscillatory instability [1]

In power system, various types of faults can occur. 'The three phase short-circuit' is most severe and the fault currentcontribution of generator is significant. [2]

For both stability and fault current analysis, understanding of synchronous machine parameters is necessary. The generator electrical parameters are -resistance and reactance in steady state and transient conditions. The generator resistance is small compared to reactance and its effect is not significant and therefore the machine resistance values are not considered in optimization. During faults and stability analysis, the total reactance, comprises generator reactance, transformer reactance and in-line reactance contribute to the fault currents. In the paper, only generator-reactance values are considered for optimization.

The two objectives in optimization are

a) Minimization of undamped natural frequency of rotor vibration in small disturbance stability
b) Minimization of generator fault current in three phase fault.

The multi-objective optimization is done by three methods -

a) Multi Objective Differential evolution (MODE)
b) Multi Objective "Multi-Verse Optimizer (MOMVO)
c) Pareto front Optimal Solution (POS)
d)

II. SYNCHRONOUS GENERATOR UNDER ANALYSIS

A 16 pole, 11kV, 17800 KVA salient pole generator is considered for analysis. The resistance and reactance values are calculated from magnetic core lamination dimensions and armature and field winding data [3]. Per-Unit (pu) values are calculated as per MATLAB [4]. The air gap under pole shoe is not uniform but it is sinusoidal. The reactance values are calculated as per the formula [3].

TABLE I
NOMENCLATURE

Symbol	Description
D	Stator inside diameter (mm)
d,q	d and q axis quantity
R,s	Rotor and stator quantity
L	Active core length (mm)
l , m	Leakage and magnetizing inductance
H	Inertia constant (MJ/MVA)
f	Machine operating frequency (Hz)
F,*k*	Field and damper winding quantity
g	Radial minimum air-gap length (mm)
n	Rotational speed in revolutions per second.
p	Pole number
‘	Transient condition parameter
“	Sub-transient condition parameter
a	Subscript – armature component
d	Subscript- ‘d’axis parameter
q	Subscript- ‘q’ axis parameter
q	Number of slots per pole per phase
μ_o	Permeability of vacuum= 4 π 10^{-7}
ϕ	Flux per pole (Wb)

TABLE II
SALIENT POLE YNCHRONOUS MACHINE PU PARAMETERS

	Description
RS_PU	Stator resistance per phase (pu)
XD_PU	Direct axis magnetizing reactance(pu)
XQ_PU	Quadrature axis magnetizing reactance (pu)
XL_PU	Stator leakage reactance (pu)
RF_PU	Field winding resistance (pu)
XF_PU	Field leakage reactance (pu)
RDD_PU	Direct axis Damper winding resistance (pu)
XDD_PU	Direct axis Damper winding reactance (pu)
RDQ_PU	Quadrature axis damper winding resistance(pu)
XDQ_PU	Quadrature axis damper winding reactance (pu)

III. SMALL DISTURBANCE STEADY STATE STABILITY

Calculation of small disturbance stability from machine parameters is given in ref [2]. Small-disturbance stability of a single machine infinite bus system is considered. The various steps are

TABLE III
COMMON DATA IN OPTIMIZATION

Particular	Value
Power output (KVA)	17800
Frequency	50
Speed (rpm)	375
Rated Voltage (Volts)	11000
Number of slots	144
Winding coil pitch	8
Number of poles	16
Field winding turns per pole	34
Number of damper bars per pole	9
Number of conductors per slot	10

3.1 FIX THE STEADY STATE OPERATING POINT

When the saliency effect is considered, the initial power angle is given by (page 468 equation 11.33) [2]

$$\delta_o = tan^{-1} \frac{X_q |I_a| \cos\theta}{|V| + X_q |I_a| sin\theta} \quad (1)$$

3.2 THE VOLTAGE BEHIND TRANSIENT REACTANCE

The transient voltage is given by (page 469 equation 11.35)[2]

$$|E_q'| = \frac{X_d'|E| + (X_d - X_d')|V| cos\delta}{X_d} (2)$$

3.3 THE SYNCHRONIZING POWER COEFFICIENT P_s

Where steady state excitation voltage |E| is given by

$$|E| = |V| \cos\delta + X_d |I_a| \sin(\delta + \theta) \quad (3)$$

and $X_d' = \omega * L_d'$ (3.1)

$$L_d' = L_{ssig} + \frac{L_{md} L_{fsig}}{L_{md} + L_{fsig}} \quad (3.2)$$

and $L_{md} = X_d / \omega$; $L_{fsig} = X_{fl}/\omega$; $L_{ssig} = X_{al}/\omega$

3.4 THE TRANSIENT POWER ANGLE EQUATION Pe

Pe =($|E_q'|$ $|E_t|$ /X_d') sin(θ)
+ $|E_t|^2(X_d' - X_q)/(2.0\, X_d' X_q)$ *sin(2θ)(4)

$$P_{max} = \max(Pe) \ (5)$$

$$P_s = P_{max} \cos(\delta_o) \quad (6)$$

3.5 NATURAL FREQUENCY OF OSCILLATION
The undamped frequency of oscillation is given by (page 473 equation 11.42) [2]

$$\omega_n = \sqrt{(\pi * f_o / H) P_s} \qquad (7)$$

Damped frequency of oscillation(page 474 equation 11.50)[2]

$$\omega_d = \omega_n \sqrt{1 - \zeta^2} \qquad (8)$$

where ζ is the damping ratio is given by

$$\zeta = \frac{D}{2} \omega_n \quad (9)$$

and D is the damping coefficient Damping torques are caused by prime mover and the load dynamics.

3.6 SYNCHRONIZING TORQUE AND DAMPING TORQUE:

The rotor angle stability is of two types, 'small disturbance stability' and 'transient stability'. Small disturbance instability is mainly attributed to in-sufficient damping torque and transient instability is attributed to in-sufficient synchronizing torque.

In the analysis we consider synchronizing torque coefficient K_s and damping torque coefficient K_D. The synchronizing component is in phase with the rotor angle and responsible for restoring the rotor angle. The damping torque is in phase the rotor speed and damps out speed variation. Insufficient synchronizing torque leads to 'non-oscillatory instability' and insufficient damping torque leads to 'Low frequency oscillations'

The two torque components are used as a measure of power system dynamic stability. For stable operation both synchronizing and damping torque must be positive.

IV. BALANCED FAULTS

If the short circuit is applied at the instant when rotor axis is along the magnetic axis of phase a i.e.$\delta = 0$, for three phase short at generator terminals then p 338 eqn 8.57 [2]

$$I_d = \frac{E_0}{X_d} \qquad (10)$$

$$I_d' = \frac{E_0}{X_d'} \qquad (11)$$

$$I_d'' = \frac{E_0}{X_d''} \qquad (12)$$

and for the short circuit wave form is given by

$$i_{ac}(t) = \sqrt{2}E_0[(\frac{1}{X_d''} - \frac{1}{X_d'})e^{t/\tau_d''} + (\frac{1}{X_d'} - \frac{1}{X_d})e^{t/\tau_d'} + \frac{1}{X_d}] \sin(\omega t + \delta) \quad (13)$$

Where the direct axis open circuit transient time constant is given by

$\tau_d' = \frac{X_d'}{X_d} \tau_{d0}'$ and $\tau_{d0}' = \frac{X_f}{R_f}$ and

theδ is the angle between rotor direct axis and the magnetic axis at the instant of short circuit

V. OPTIMIZATION

Critical designparameters, which are responsible for stability and fault currents are optimized by multi-objective-optimization methods. The methods are

i) Multi-objective-differential-evolution (MODE)
ii) a)Pareto front Optimal Solution (POS)
b) Genetic-Algorithm-Multi-Objective(gamultiobj)
iii) Multi-objective-multiverse-optimization (MOMVO)

5.1 DIFFERENTIAL EVOLUTION (DE**)**

Differential Evolution is one of the most powerful optimization techniques widely used for single and multi-objectives optimization. It is an easy-to-use minimization method and has the ability to handle non-differentiable, non-linear and multi-mode function[5][6]. Differential Evolution is an evolutionary algorithm which works on the concept of 'Exploration' and 'Exploitation' to achieve the global minimum. It requires maintaining a population of candidate solutions which are then subject to iterations of recombination, evaluation and selection. It consists of 4 main operators. They are initialisation, mutation, crossover and selection. Scale factor F (ranging between 0 and 1) determines the pace from exploration to exploitation. The larger the F, the more is exploration and vice versa. The other factors include, 'selection of vectors', 'population size' and 'number of generations'. Cross over probability (ranging between 0 and 1) controls the extent of replacement in parent and child solutions.

5.2 MULTI-OBJECTIVE DIFFERENTIAL EVOLUTION (MODE)

MODE is an extended method of Differential Evolution for studying multi-objective optimization or Pareto optimization. It is used for solving optimization problems when two or more conflicting objectives (for e.g. maximizing efficiency while simultaneously reducing weight) need to be optimized simultaneously. The objective functions are conflicting when no single solution exists that simultaneously optimizes each objective. A solution is non-dominated or Pareto optimal if none of the objective functions can be improved without degrading other objectives

MATLAB version of MODE algorithm by Gilberto Reynoso Meza [7] has been used for optimization. In DE algorithm, greedy selection is performed using a dominance relation. Code has been suitably modified for Salient pole synchronous machine. A simplified flow chart is shown in Fig. 1

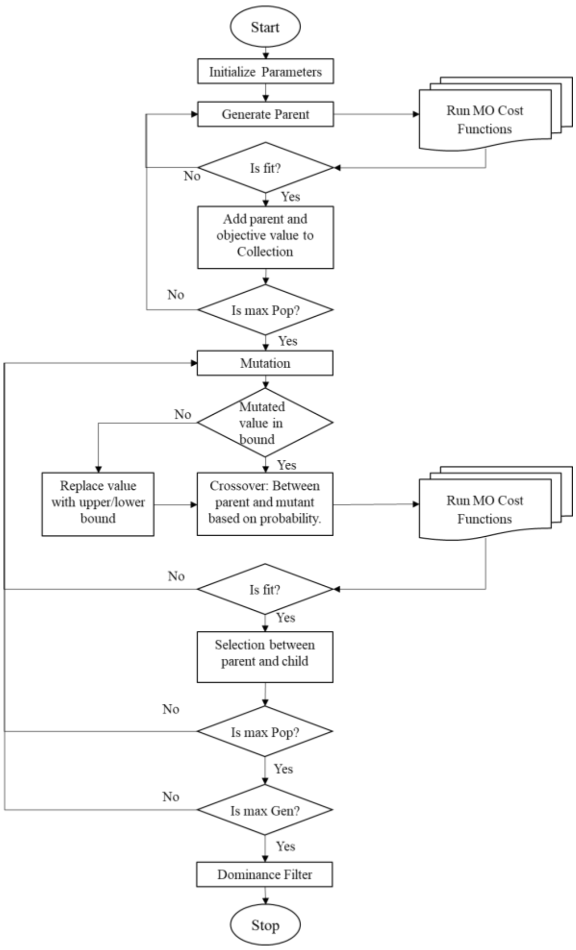

Figure 1.Flow Chart for the Computer Program (MODE).

5.3VARIABLES USED IN OPTIMIZATION

The generator parameters which are responsible for controlling the stability and fault currents are

1) Air gap diameter (D)
2) Active core length(L)
3) Pole-arc topole-pitch ratio
4) Radial minimum air gap between armature and pole centre

The limits of variables are shown in table IV

TABLE IV
LIMITS OFOPTIMIZATION VARIABLES

Variable	Limits
Armature inner diameter (cm)	$236.0 < D_{in} < 261.0$
Radial air gap (cm)	$1.5 < g_{min} < 2.5$
Pole-arc to pole-pitch	0.65<alpha<0.85
Stack length (cm)	75.0 < CL < 90.0

TABLE V
OPTIMIZED VARIABLES IN ‘MODE’

Obj 1	Obj 2	Variables			
ω_{dmin}	Iscmax	Bore dia (cm)	airgap (cm)	Stack length (cm)	Pole-arc to pole-pitch
2.98	7.34	244.61	2.33	79.41	0.84
2.93	7.50	261.00	2.18	90.00	0.85
3.15	6.54	238.73	1.54	81.79	0.82
2.79	8.33	257.27	2.50	77.39	0.85
3.04	6.99	251.49	1.93	88.86	0.84
2.91	7.60	261.00	2.50	90.00	0.85
3.11	6.80	246.78	2.03	89.82	0.78
3.08	6.83	243.77	1.75	83.24	0.83
3.12	6.75	247.54	1.50	88.83	0.76
2.95	7.47	256.45	2.24	87.82	0.82

5.4 COMPUTATION TIME IN ‘MODE’

TABLE VI
COMPUTATION TIME FOR ‘MODE’

Time	VALUE
Maximum Generations	120
TIC TOC for MOMVO	55.7903
CPUTIME (seconds)	145.016
CLOCK	55.789

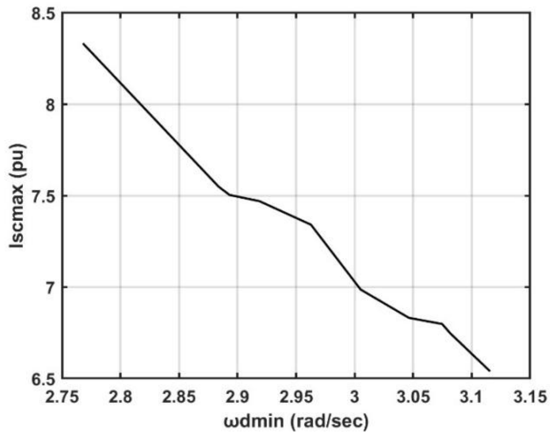

Figure 2.Pareto obtained by‘MODE’ optimization.

5.5 .PARETO FRONT OPTIMALSOLUTION (POS)

The common approaches formultiobjectiveoptimization are ‘Goal attainment’, ‘Minimax’, and ‘Pareto front’.Pareto front finds noninferior solutions. In pareto front, an improvement

in one solution of one objective requires a degradation in another objective.
The solver 'fgoalattain' is used. The same solver is used in 'gamultiobj'(based on the genetic algorithm) and 'pareto search' (pattern search algorithm) [8]. In paretosearch, pattern search algorithm is used. These solvers find points on pareto front,have the same syntax in MATLAB. Therefore, the problem is solved by both the methods and the results are compared. The results are shown in the Fig 3. To get a smoother Pareto Front, the number of points are increased from default value of 60 to 160.

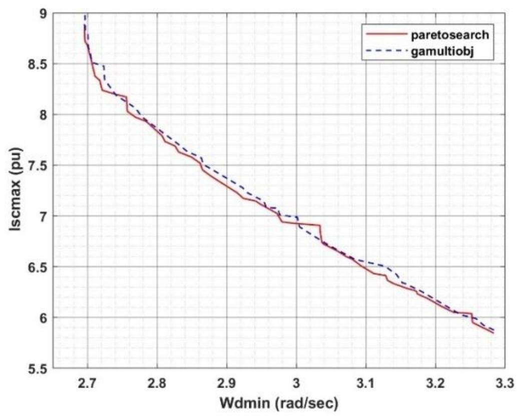

Figure 3. Comparison of pareto points in 'pareto-search' and 'gamultiobj'

TABLE VII
PARETO (PF) PERFORMANCE COMPARISON

	ga output	ps output
spread	0.1123	0.2252
average distance	0.0033	0.0053
function count	13681	590
Generations	114	10
CPU time (seconds)	1710	617

5.6 MULTI OBJECTIVE MULTI-VERSE OPTIMIZER (MOMVO)

This is a nature-inspired algorithm, based on cosmology concepts – white hole, black hole and worm hole. It is a population-based stochastic optimization. As per theory, white holes are generated where parallel universes collide. Black holes are radically different from white holes. They have tremendously strong pull and they attract everything including light beams. Worm holes operate as time/space travel tunnels.

The initial random solutions, over a predefined generations, are combined, moved or evolved to get the solutions in a different way to other stochastic algorithms. The details of the method are explained in reference [9] and the code is available in MATLAB. Briefly it is as follows:

a) The white hole, black hole, and wormhole are mathematically modeled.
b) It is considered that each solution is an object in the universe.
c) each solution is assigned an inflation rate, which corresponds
to the fitness function value.
d) the term 'time' is used instead of iteration.

The inflation rate decides the probability of having white hole and black hole and sending the objects through white holes. Mathematically, 'roulette wheel mechanism' is used for modeling white/black hole tunnels, exchange the objects of universe.

Two coefficients namely i) worm hole existence probability (WEP) ii) Travelling distance rate (TDR) areused. WEP is used for defining the probability of worm hole existence. TDR is for teleporting the objects by a worm hole. The general steps of the algorithm are shown in "Appendix 1" of ref [9] [10]

MATLAB software referred in [9] is run with the objectives, variables, and constraints of the present problem. Four critical variables and two objectives considered for optimization by MOMVO.
For the selection of one universe, using Roulette wheel mechanism, model for one universe mathematically is given by

$$U = \begin{cases} x_k^j & , r_1 < normalized\ inflation\ rate\ (U_i) \\ x_i^j & , r_1 < normalized\ inflation\ rate\ (U_i) \end{cases}$$

$$U = \begin{bmatrix} x_1^1 & \cdots & x_1^d \\ \vdots & \ddots & \vdots \\ x_n^1 & \cdots & x_n^d \end{bmatrix}$$

Where d = number of parameters
N = total number of universes

$$x_i^j = \begin{cases} \begin{cases} X_j + TDR \times ((Ub_j - Lb_j) \times r3 < 0.5 & r_2 \geq WEP \\ X_j - TDR \times ((Ub_j - Lb_j) \times r3 < 0.5 & r_2 \geq WEP \end{cases} \\ x_i^j r_2 \geq WEP \end{cases}$$

$$WEP = \min + l * \left(\frac{max - min}{L}\right)$$

$$TDR = 1 - \frac{l^{\frac{1}{p}}}{L^{\frac{1}{p}}}$$ where p = exploitation accuracy

Time complexity of MVO is related to 5.6.2

a) number of iterations (l)
b) number of universe (n) and the number of objects (d).

Then the complexity is given by

O(MVO) = O (l (QuickSort) + n *d* (O (Roulette Wheel)))

In every iteration 'Quick-Sort' algorithm is used which has complexity O (n^2). For every variable in the universe, we use Roulette Wheel, which has complexity of O (log(n)), then complexity of MVO is

O(MVO) = O (l (n^2 +n * d * log(n)))

5.6.1QUALITY INDICATORS

The quality indicators for multiobjective optimization algorithms is dealt in detail with expression in reference [11] and therefore, here the calculated values are given.

Quality indicators for measuring the quality are 5.6.3

i) Inverted Generational Distance (IGD)
ii) Hypervolume (hv)
iii) Epsilon
iv) Spread indicator

1) IGD

The inverted generational distance (IGD) uses the true Pareto front as a reference and measures the distance of each of its elements from the true Pareto front to the non-dominated front obtained by an algorithm. It is mathematically defined as:

$$\text{IGD} = \frac{\sqrt{\sum_{i=1}^{Q} d_i^2}}{Q}$$

where Q is the number of solutions in the true Pareto 5.6.4 front andis the Euclidean distance between each of the solution and the nearest member from the set of non-dominated solutions found by the algorithm. This metric measures both the diversity and the convergence of an obtained non-dominated solution set. the value of this metric, the closer the obtained front is to the true Pareto front.

TABLE VIII
QUALITY INDICATOR-IGD

IGD	VALUE
Max IGD	35.821
Min IGD	35.173
Average IGD	35.39
SD_IGD	0.2744

HYPERVOLUME METRIC

It is known as S-metric or Lebesgue measure, is widely recognized as an unary value which is able to measure both convergence and diversity. This metric calculates the normalized volume of the objective space covered by the obtained Pareto set Q bounded by a reference point r. Therefore, higher values are preferable. For each solution i∈ Q, a hypercube $c_i$from solution i and the reference point r is measured. The hypervolume HV is calculated as:

$$\text{HV} = \text{volume}\left(\cup_{i=1}^{|Q|} c_i\right)$$

TABLE IX
QUALITY INDICATOR-HV

HV	VALUE
Min_hypeIndicatorExact8	20.93
Max_hypeIndicatorExact8	21.453
Average_hypeIndicatorExact8	21.095
SD_hypeIndicatorExact8	0.227
hv	21.538

EPSILON INDICATOR

The ∈ indicator gives the minimum factor ∈ such that any objective vector in R is ∈ dominated by at least one objective vector A. Smaller values of I∈ are preferable.

TABLE X
QUALITY INDICATOR-epsilon

epsilon	VALUE
Max_epsilon	6.966
Average_epsilon	6.883
Min_epsilon	6.84

SPREAD INDICATOR

The spread indicator measures the extend of spread achieved among the obtained solutions.

TABLE XI
QUALITY INDICATOR-SPREAD

SPREAD	VALUE
Max_generalizedsoread	1.012
Min_generalized spread	0.991
Average generalized spread	1.0005
SD_generalized spread	0.0079

5.6.5COMPUTATION TIME FOR MOMVO

TABLE XII
COMPUTATION TIME FOR MOMVO

Time	VALUE
Ini time	395.188
Fin time	3586.98
TIC TOC for MOMVO	1656.76
CPUTIME (seconds)	3191.8
CLOCK	1656.76

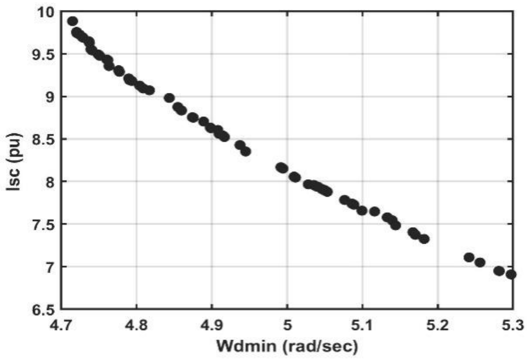

Figure 4. Pareto obtained by 'MOMVO' optimization

5.6.6'MOMVO' RESULTS*:*

The results are given below.

Pareto points obtained by MOMVO method

Best_universe_postion: [237.911.5 88.01 0.85]
Best _universe_score: [5.255 7.0485]

TABLE XIII
OPTIMUM PARAMETERS

Optimum Parameter	VALUE
Stator bore diameter (cm)	237.91
Minimum radial air gap (cm)	1.5
Stack length of magnetic core (cm)	88.01
The pole arc / pole pitch ratio	0.85
Rotor frequency of oscillation ω	5.255
Maximum short circuit current (pu)	7.0485

VI. ANALYSIS OF OPTIMIZATION RESULTS

From Pareto Optimal Front (POF), two points are selected for detailed analysis and comparison. For'Min vibration' objective the optimization results, are shown in column 1 of the table XIVFor 'fault current minimum', the optimization results are shown in column 2 of the table XIV.

Out of four variables selected, it is observed that, two variables play a more significant role in stability analysis of rotor. The airgap and pole-arc to pole-pitch ratio plays significant role The air gap is maximum and pole pitch ratio is minimum for low rotor frequency of oscillations and vice versa for low fault current.

The real part of eigen values, lamda 1 and 2 are negative showing the system in both cases, is stable. The synchronizing torque coefficient, and Pmax differ significantly in case 1 and 2.

From the faults currents shown in the table, the transient and sub transient components in column 1 are significantly high compared to the values in 2.

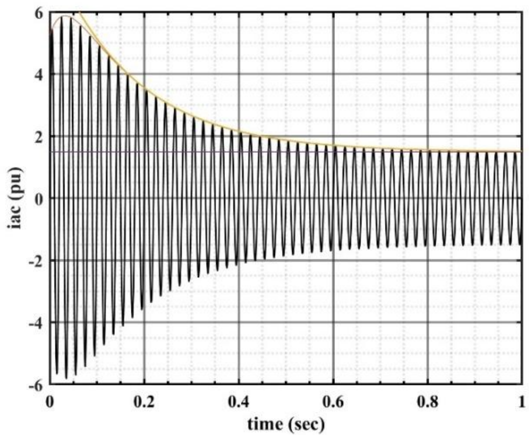

Figure 5. Three phase fault current for 'min fault current'

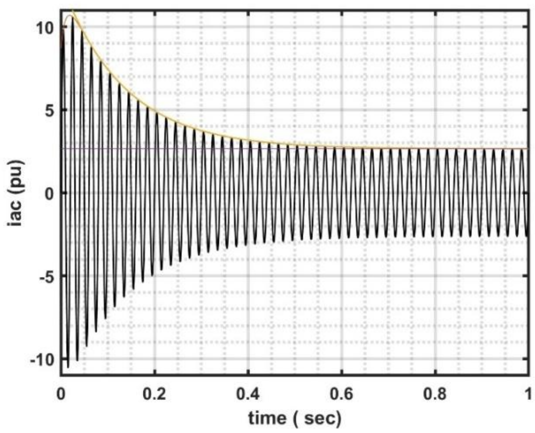

Figure 6. Three phase fault current for 'rotor min vibration'

TABLE XIV
DETAILED PARAMETERS FOR EXTREME POINTS IN PF

Parameter	Vibration (min)	Fault Current (min)
Objective Number	1	2

Undamped frequency of oscillation (wdmin)	2.7201	3.309
Iscmax	8.9192	5.8504
Variables		
Armature bore diameter (cm)	261	236.0539
Min air gap (cm)	2.5	1.5
Stack length (cm)	75	89.531
Pole arc / Pole pitch ratio	0.78454	0.85
PU reactances		
RS_PU	0.0033	0.0054
XD_PU	0.5022	0.9488
XQ_PU	0.2322	0.4566
XL_PU	0.0959	0.1462
RF_PU	0.0043	0.0048
XF_PU	0.0911	0.1421
RDD_PU	0.0106	0.011
XDD_PU	0.0366	0.0443
RDQ_PU	0.0053	0.0068
XDQ_PU	0.0268	0.0327
Rotor angle stability		
lamda 1	-0.171+j2.714	-0.2550 +j 3.3092
lamda 2	-0.171-j2.714	-0.2550 - j 3.3092
Synchroizing Torque coefficient (Ks)	5.4033	3.6889
Synchronizing power coefficient (Ps)	6.3689	4.2778
Pmax	6.4321	4.3714
Undamped frequency of oscillation (wn)	2.7201	3.319
Damping ratio	0.063	0.0768
Damped frequency of oscillation (wd)	2.7147	3.3092
Iscmax		
Iscmax	8.9192	5.8505
Sub-transient component	11.7142	7.9084
Transient component	2.8159	1.4905

6.1 COMPARISON OF OPTIMIZATION METHODS

TABLE XV
COMPUTATION TIME

Optimization Method	CPU TIME (seconds)
MODE	145.016
MATLAB PARETO FRONT	617
gamultiobj	1710
MOMVO	3191.8

From the above table XV, it can be seen that, MODE is fastest and takes minimum time where as MOMVO takes significantly more time.

PARETO FRONT: The PF obtained by MATLAB POF and gamultiobj is very close to each other. The limits obtained in PF, by MOMVO are different. This may be due to the stochastic nature of the method and or accuracies considered

6.2RANGE COMPARISON:

TABLE XVI
COMPARISON PARETO FRONT VALUES

	Pareto Front			
	ω_d min (lower)	ω_d min (upper)	Iacmax (lower)	Iacmax (upper)
MODE	2.767	3.115	8.331	6.538
MATLAB PARETO	2.694	3.283	8.887	5.845
gamultiobj	2.696	3.287	8.9779	5.863
MOMVO	4.964	5.288	9.761	6.835

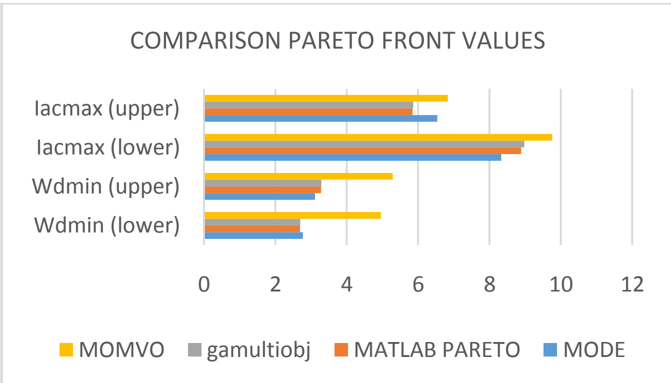

Figure 7. Comparison of Pareto front values

From table XVI and Figure 7, when the extreme points of Pareto Front are compared,the optimization methods ‘MATLAB PARETO’ and “gamultiobj’ gives close vales, where as in case of ‘MOMVO’, the range (4.964 to 5.288) covered for shaft vibration

'$\omega_d$min' is higher than the range (2.7 to3.2) by MODE and 'MATLAB PARETO'.

6.3. BEST VALUE COMPARISON:

TABLE XVII
BEST VALUE COMPARISON

	ω_d min (best)	Iscmax (best)
MODE	3	7
MATLAB PARETO	2.97	7.02
gamultiobj	2.97	7.01
MOMVO	5.255	7.0485

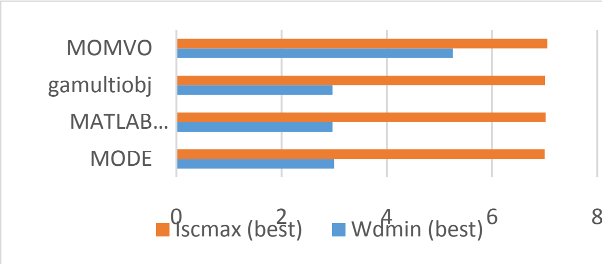

FIGURE 8. BEST VALUE COMPARISON

MOMVO gives the 'Best_universe_score' and 'Best_universe_position'. The 'Iscmax', and'$\omega_d$min' values of MODE, MATLAB PARETO, gamultiobj are shown in the above Fig 8.
The best values are from 'PARETO_FRONT_SOLUTIONS'(POS) and are encouraging for the objective functions considered .

APPENDIX1 [9] [10]

```
Algorithm 1: Multi-verse Optimizer
Create random universes (U)
Initialize WER, TDR, and Best Universe
SU = Sorted universes
NI = Normalize inflation rate (fitness) of the universes
while the end criterion is NOT satisfied do
    Evaluate the fitness of all universes
    for each universe indexed by i do
        Update WEP and TDR
        Black hole index = i;
        for each object indexed by j do
            r1 = random([0, 1]);
            if r1 < NI(Ui) then
                White hole index = RouletteWheelSelection(-NI);
                U(Black hole index, j) = SU(White hole index,j);
            end
            r2 = random([0, 1]);
            if r2 < WEP then
                r3 = random([0, 1]);
                r4 = random([0, 1]);
                if r3 < 0.5 then
                    U(i,j) = Best Universe(j) + TDR
                      ×((ub(j) − lb(j)) × r4 + lb(j));
                else
                    U(i,j) = Best Universe(j) - TDR
                      ×((ub(j) − lb(j)) × r4 + lb(j));
                end
            end
        end
    end
end
Return the Best Universe
```

Figure7. Multi-verse Optimizer algorithm

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