LITERATURE SURVEY OPEN ACCESS

Design Improvement in Salient-pole Synchronous Motor for torque pulsation reduction during starting by Non-Dominated Sorting Whale Optimization Algorithm (NSWOA)

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ABSTRACT
Salient-pole synchronous motors , during starting, will have torque pulsations which is due to non-uniform reluctance in the air gap. These pulsations can cause fatigue damage leading to failure of assosiated mechanical components. At motor design stage, it is possible to analyse the variables which are responsable for torque pulsation. In this paper, novel optimization technique, 'Whale Optimization Algorithm (WOA)'is used to reduce pulsating torque during starting by choosing optimium variables. Further, the optimization technique has been extended to two objectives by using ' Non-Dominated Sorting Whale Optimization Algorithm(NSWOA)

Keywords–Salient-pole synchronous motor, Torque pulsation, Whale Optimization

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I. INTRODUCTION

In refinerry and chemical industries, salient pole synchronous motors are used to drive slow-speed reciprocating compressors. In these applications, current pulsationsare expected during motor starting.Salient pole synchronous motors exhibit a pulsating torque with twice the slip frequency of the rotor.The frequency of torque pulsation is maximum at stand still and will reduces from 100Hz at zero speed to approximately 5 Hz just before synchronization. The pulsating torque can be amplified by Torsional Natural Frequency (TNF) and can cause fatigue damage leading to shaft and other associated mechanical component failure.To reduce the torque pulsations during starting, synchronous motor design is optimized using"Whale Optimization Algorithm(WOA)" and "Non-Dominated Sorting WhaleOptimization Algorithm" (NSWOA).

The two objectives are considered in the optimization.

a) minimization of torque pulsation during starting

b) minimization of fault current in stator winding during three-
phase balanced fault conditions.

II. SYNCHRONOUS MOTOR -PULSATING TORQUE

Salient pole synchronous motor has poles and interpole spaces making the magnetic circuit reluctance vary from point to point around the rotor.So, when the flux produced by stator, passes around rotor, the torque developed is not uniform. The developed torque is minimum in inter polar region and maximum under the poles. At all speeds during starting, the torque varies from maximum to minimum at twice slip frequency. At standstill, the torque pulses at 120 Hz or 100Hz, depending on power supply frequency.At 95% speed, the torque has 6Hz and at 80% speed, it is 24Hz pulsating component.

III SYNCHRONOUS MOTORUNDER ANALYSIS

A 16 pole, 11kV, 16,910kW salient pole synchronous motor is considered for analysis. The resistance and reactance values are calculated from magnetic-core-lamination dimensions and armature and field winding data [1]. Per-Unit (pu) values are calculated as per MATLAB [2]. The air gap under pole shoe is sinusoidal.

TABLE I
SYNCHRONOUS MOTOR DATA

Particular	Value
Power output (kW)	16,910
Frequency(Hz)	50
Speed (rpm)	375
Rated Voltage (Volts)	11,000
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 stator slot	10

TABLE II
NOMENCLATURE

Symbol	Description
D	Stator inside diameter (mm)
d,q	d and q axis quantity
L	Active core length (mm)
l , m	Leakage and magnetizing inductance
f	Machine operating frequency (Hz)
g	Radial minimum air-gap length (mm)
I_s ,I'_s	Stator currents of frequency ω_1 and (1-2s) ω_1
n	Rotational speed in revolutions per second.
P	Number of poles
T_a	The average torque
T_p	The Pulsating torque
φ_1	The angle I_s lags V_s
φ_2	The angle I'_s lags V_s
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)

IV EQUIVALENT CIRCUIT

The equivalent circuit of salient pole synchronous motor with damper bars in rotor, during starting is shown below [3]

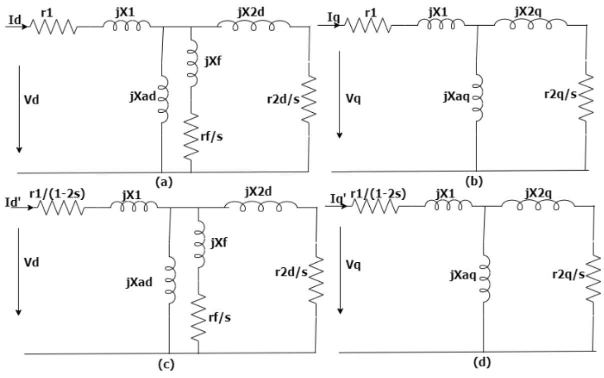

Fig 1. Salient pole synchronous motor with dampers during starting. a) d-axis equivalent circuit b) q-axis equivalent circuit
c) d-axis equivalent circuit for (1-2s) components d) q-axis equivalent circuit for (1-2s) components.

The derivation for average torque and pulsating torque is given in detail ref [3]. The equations for impedances, currents and torques are shown below.

Using the equivalent circuit, the impedances are given by

$$Z_d = r_1 + jx_1 + \frac{1}{\frac{1}{jx_{ad}} + \frac{1}{\frac{r_{2d}}{s} + jx_{2d}} + \frac{1}{\frac{r_f}{s} + jx_f}}$$
(1)

$$Z_q = r_1 + jx_1 + \frac{1}{\frac{1}{jx_{aq}} + \frac{1}{\frac{r_{2q}}{s} + jx_{2qd}}}$$
(2)

$$Z'_d = \frac{r_1}{1-2s} + jx_1 + \frac{1}{\frac{1}{jx_{ad}} + \frac{1}{\frac{r_{2d}}{s} + jx_{2d}} + \frac{1}{\frac{r_f}{s} + jx_f}}$$
(3)

$$Z'_q = \frac{r_1}{1-2s} + jx_1 + \frac{1}{\frac{1}{jx_{aq}} + \frac{1}{\frac{r_{2q}}{s} + jx_{2qd}}}$$
(4)

And the stator currents are derived as follows

$$I_s = V_s \frac{z'_q + z'_d}{z_d z_q' + z_q z_d'}$$
(5)

$$I'_s = V_s \frac{z_q - z_d}{z_d z_q' + z_q z_d'}$$
(6)

The average torque is given by

$$T_a = \frac{2p}{\omega_1}\left(V_s + I_s cos\varphi_1 - {I_s}^2 r_1 - {I_s'}^2 \frac{r_1}{1-2s}\right)$$
(7)

The pulsating torque is given by

$$T_p = \frac{2p}{\omega_1}\{V_s I'_s \cos(2s\omega_1 t + \varphi_2)$$
$$- \; I_s I'_s \frac{r_1}{1-2s} \cos(2s\omega_1 t - \varphi_1 + \varphi_2)$$
$$- \; I_s I'_s r_1 \cos(2s\omega_1 t - \varphi_1 + \varphi_2)\}$$
(8)

VI. OPTIMIZATION

4.1 WHALE OPTIMIZATION ALGORITHM (WOA)

WOA is a population-based nature inspired meta-heuristic optimization algorithm. It is based on 'hunting behavior of humpback whales-bubble net hunting strategy". The details and mathematical model of WOA are explained in detail in reference [4].
WOA was proposed by Mirjalili and Lewis in 2016.The idea is to solve the problem by imitating the whale's predatory behavior. This behavior is called bubble net feeding method(Figure 2). The foraging is done by creating distinctive bubbles along a circle or '9'shaped path. Two maneuvers associated with, are named 'upward spirals' and 'double loops'.

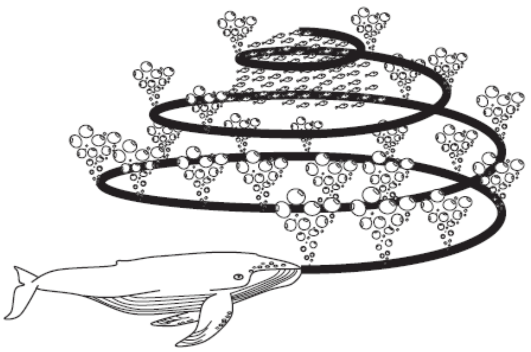

Figure 2.Bubble net feeding behaviour of humpback whales.

The details and mathematical modelling for optimization are described in [4]. The Pseudo-code of the WOA algorithm is given below.

```
Initialize the whales population Xi(i = 1, 2, ..., n)
Calculate the fitness of each search agent
X*=the best search agent
While (t < maximum number of iterations)
  for each search agent
  Update a, A, C, l, and p
     if1 (p<0.5)
       if2 (|A|< 1)
            Update the position of the current search agent by the Eq.(2.1)
       else if2 (|A|≥ 1)
            Select a random search agent ()
            Update the position of the current search agent by the Eq.(2.8)
       end if2
     elseif1 (p≥0.5)
            Update the position of the current search by the Eq. (2.5)
     end if1
  end for
  Check if any search agent goes beyond the search space and amend it
  Calculate the fitness of each search agent
  Update X* if there is a better solution
  t=t+1
end while
```

Figure 3. Pseudo-code of theWOA algorithm [4]

The equations 2.1, 2.8 and 2.5 mentioned in the Pseudo-code are given below for convenience.[4]

$\vec{D} = |\vec{C}.\vec{X^*}(t) - \vec{X}(t)|$ (2.1) of [4]

$\vec{X}(t+1) = \vec{D'} e^{bl} cos(2\pi l) + \vec{X^*}(t)$
where $\vec{D'} = |\vec{X^*}(t) - \vec{X}(t)|$ (2.5) of [4]

$\vec{X}(t+1) = \vec{X_{rand}} - \vec{A}\vec{D}$ (2.8) of [4]

4.2VARIABLES USED IN 'WOA' OPTIMIZATION

The variables considered for minimization of torque pulsations in salient pole synchronous motors are

1) Stator bore diameter(D)
2) Active core length(L)
3) Pole-arc topole-pitch ratio (τ)
4) Radial minimum air gap between armature and pole centre (g)
5) Damper winding bar diameter (DD)
6) Stator lamination teeth width (STW)
7) Stator lamination slot depth (SH)

The upper and lower limits of variables are shown in table III

TABLE III
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	0.75<alpha<0.85
Stack length (cm)	75.0 < CL < 90.0
Stator teeth width (cm)	4.2<STW<5.0
Stator slot depth (cm)	11.0<SH<13.0

Damper bar diameter (cm)	0.8<DD<1.8

'WOA' optimization program is run with the above variables and an analysis program developed exclusively for salient pole synchronous motors. Program is run in MATLAB code for one objective, 'Minimization of starting torque pulsations'. The optimized best variables obtained from WOA are shown in table IV.

TABLE IV
VARIABLES OF BEST SOLUTION OBTAINED by WOA

Variable	Best solution
Armature inner diameter (cm)	241.172
Radial air gap (cm)	1.807
Pole-arc to pole-pitch	0.844
Stack length (cm)	89.99
Stator teeth width (cm)	4.621
Stator slot depth (cm)	12.895
Damper bar diameter (cm)	1.503

With the best solution variables obtained from WOA optimization, a detailed synchronous machine analysis is carried out. The pulsating torque vs Speed is shown in figure 4. The average starting torque vs speed is shown in figure 5

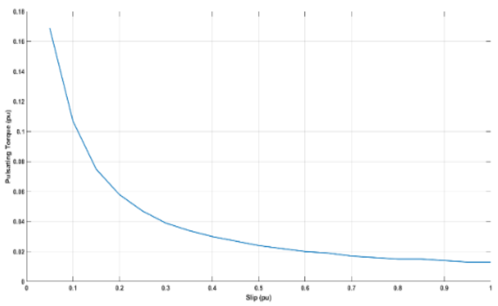

Figure 4. Pulsating Torque vs Speed

The magnitude of pulsating torque is minimum at start (slip=1) and increases with increase in speed. It is to be noted that the frequency of pulsation is maximum at start and reduce as the rotor picks up speed.

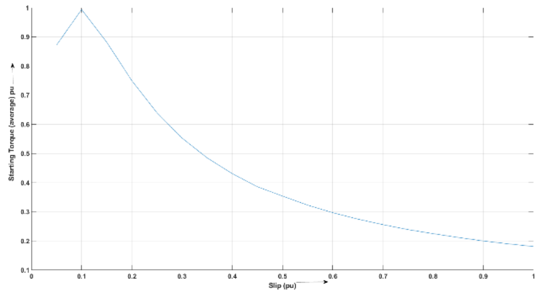

Figure 5. Starting torque vs Speed

The motor per unit average torque during starting is shown in figure 5. The shape of the curve is similar to normal induction motor starting characteristics except at 50 % speed. This is due to (1-2s) component as shown in equivalent circuit fig 1 (c) and (d). The 50% speed phenomena is not shown in the above figure 5.

V. BALANCED FAULTS

Faults in three phase power systems are 'short circuits'. They vary from most common to least common. The least common type of fault is symmetrical fault. Neglecting generator resistance, the fault current may be expressed as follows

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 page 341 equation 8.60 [5].

$$I_d = \frac{E_0}{X_d} \quad (9)$$

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

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

and for the short circuit wave form is given by

$$i_{ac}(t) = \sqrt{2}E_0[(\frac{1}{X_d''} - \frac{1}{X_d'})e^{t/\tau_d''} + (\frac{1}{X_d'} - \frac{1}{X_d})e^{t/\tau_d'} + \frac{1}{X_d}] \sin(\omega t + \delta) \quad (12)$$

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

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

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

VI. NSWOA

In 'WOA' optimization'minimization of torque pulsation', a single objective is considered. When a second objective is added, an extended version of optimization of WOA, known as Non-Dominated Sorting Whale Optimization (NSWOA) is necessary. The details of multi-objective optimization (NSWOA)for two objectives are given below.

The first step in 'NSWOA'is, to collect all non-dominated Pareto optimal solutions and then choose the best solution using crowding distance mechanism and bubble-net hunting strategy [6] [7].

The two objectives considered in NSWOA are :
a) Minimization of torque pulsation for salient pole synchronous motors with dampers winding.
b) Minimization of fault current in balance faults

'NSWOA' optimization program is run with the same variables used in WOA, analysis program for two above mentioned objectives.The results 'Pareto front' are shown in figure 6.
Table VI shows Pareto Front specific points with variable values and objective values.

The variation of pulsation torque with slip is shown for both minimum torque pulsation case and minimum fault current case in figure 6. Motor starting torque variation with slip in both the cases, is shown figure 7.
The computation time taken for single objective case (WOA) and two objective case (NSWOA) is shown in table V.

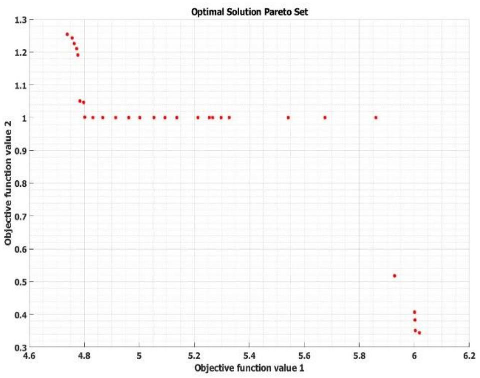

Figure 6. Optimal solutions Pareto front for two objectives.

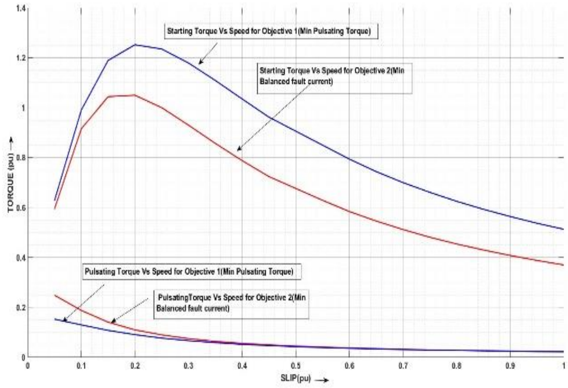

Figure 7. Variation of Pulsation and starting torques with slip.

TABLE V
COMPUTATION TIME

Time	WOA	NSWOA
Maximum Generations	300	500
Number of variables	7	7
Number of objectives	1	2
TIC TOC	208.407	295.767
CPUTIME (seconds)	235.859	243.547
CLOCK	208.408	295.767

TABLE VI
PARAMETERS FOR SPECIFIC POINTS IN PARETO FRONT (PF) (NSWOA)

Parameter	Pareto front extreme points	
Objective Number	1	2
Tpulsemin	0.153	0.249
Min of Iscmax	6.018	4.7384
Motor starting current pu	5.406	4.018
VARIABLES		
Armature bore diameter (cm)	236	236.05
Min air gap (cm)	2.293	1.50
Stack length (cm)	76.641	89.531
Pole arc / Pole-pitch ratio	0.656	0.85
Teeth width	3.874	4.52
Slot depth	11.878	13

DISCUSSION:

The results obtained from NSWOA optimization are quite encouraging. The pulsating torque is not a constant value during starting. It is a function of rotor speed, and the speed is function of starting time. Further, from the analysis, it is clear, the pulsating torque depends on design objective. When the design objective is for minimizing the pulsation torque, the maximum pulsation torque is 0.15 pu. However, when the design objective is 'minimum fault current'the maximum pulsation torque is 0.25 pu which is relatively high.At start (at slip is 1), there is no significant difference in pulsating torque value for both objectives. As the motor picks up speed, the pulsating torque difference is significantly noticeable.

From thefigure7, it is observed, that the starting torque characteristics are superior in performance in case of 'minimizing pulsating torque objective design'.

From the results it is evident that, minimum torque pulsation design needs larger airgap and shorter core length, and minimum fault current design needs larger core length and minimum air gap.

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