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Original Article

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, starting, will have torque pulsations due to non-uniform reluctance in the air gap. These pulsations can cause fatigue damage leading to the failure of associated mechanical components. At the motor design stage, it is possible to analyse the variables responsible for torque pulsation. This paper uses a novel optimization technique, 'Whale Optimization Algorithm (WOA)', to reduce pulsating torque during starting by choosing optimium variables. Further, the optimization technique has been extended to two objectives using the Non-Dominated Sorting Whale Optimization Algorithm(NSWOA).*

Keywords *- Salient-pole synchronous motor, Torque pulsation, Whale Optimization.*

1. Introduction

In refining and chemical industries, synchronous motors are used to drive slow-speed reciprocating compressors. In these applications, current pulsations are 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 will reduce 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 the shaft and other associated mechanical component failures. To reduce the torque pulsations during starting, synchronous motor design is optimized using the "Whale Optimization Algorithm(WOA)" and "Non-Dominated Sorting Whale Optimization Algorithm" (NSWOA).

The two objectives are considered in the optimization.

- Minimization of torque pulsation during starting
- Minimization of fault current in stator winding during three-phase balanced fault conditions.

2. Synchronous Motor-Pulsating Torque

A 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 the stator passes around the rotor, the torque developed is not uniform. The developed torque is minimum in the interpolar region and maximum under the poles. The torque varies from maximum to minimum at twice the slip frequency at any given speed. At a standstill, the torque pulses at 120 Hz or 100Hz, depending on the power supply frequency. At 95% speed, the torque has 6Hz; at 80% speed, it is a 24Hz pulsating component.

3. Synchronous Motor-Under Analysis

A 16 pole, 11kV, 1691 kW salient pole generator is considered for analysis. The resistance and reactance values are calculated from magnetic core lamination dimensions, armature, and field winding data [1]. Per-Unit (pu) values are calculated as per MATLAB [2]. The air gap under the pole shoe is sinusoidal.

Table 1. Synchronous motor data

Particular	Value
Power output (kW)	16910
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

Table 2. 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
f	Machine operating frequency (Hz)
F,*k*	Field and damper winding quantity
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)

4. Equivalent Circuit

The equivalent circuit of salient pole synchronous motor with dampers during starting is shown below [15]

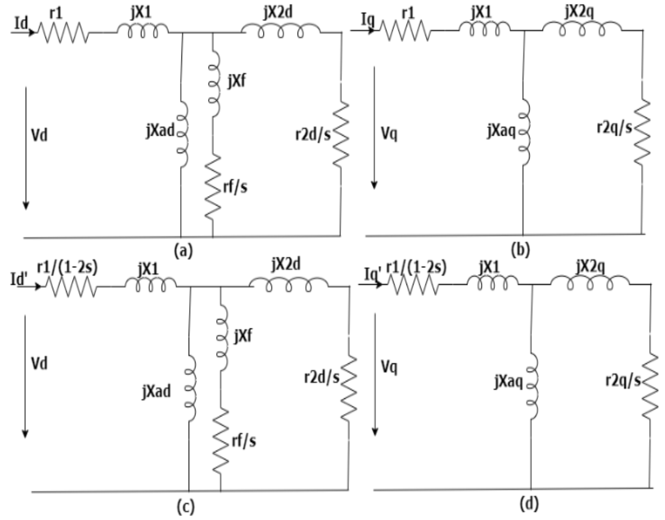

Fig. 1 Salient pole synchronous motor with dampers during starting. a) d-axis equivalent circuit b) q-axis equivalent circuit c) d-axis equivalent circuit for (1-2s) components d) q-axis equivalent circuit for (1-2s) components

The derivation for average torque and pulsating torque is given in detail ref [15]. The equations for impedances, currents and torques are shown below.

Using the equivalent circuit, the impedances are given by

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

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

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

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

And the stator currents are derived as follows

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

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

The average torque is given by

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

The pulsating torque is given by

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

5. Optimization

5.1. Whale Optimization Algorithm (WOA)

WOA is a population-based nature-inspired meta-heuristic optimization algorithm. It is based on the 'hunting behavior of humpback whales-bubble net hunting strategy". The details and mathematical model of WOA are available in reference [4].

Mirjalili and Lewis proposed WOA in 2016.The idea is to solve the problem by imitating the whale's predatory behavior. This behavior is called the 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 this are named 'upward spirals' and 'double loops'.

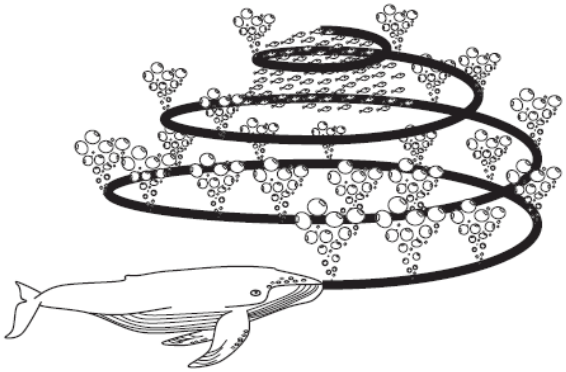

Fig. 2 Bubble net feeding behaviour of humpback whales.

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, I, and p
      if 1(p<0.5)
        if 2(|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)
     else if2
else if1(p>=0.5)
        Update the position of the current search agent by the Eq(2.5)
    end if1
end for
Check if any search agent goes beyond the search space and amend it
```

Fig. 3 Pseudo-code of the WOA algorithm [4]

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

$$\vec{D} = \left|\vec{C}.\overrightarrow{X^*}(t) - \vec{X}(t)\right| \qquad (2.1) \text{ of } [5]$$

$$\vec{X}(t+1) = \overrightarrow{D'}\, e^{bl} \cos(2\pi l) + \overrightarrow{X^*}(t)$$

$$\text{where } \overrightarrow{D'} = \left|\overrightarrow{X^*}(t) - \vec{X}(t)\right| \qquad (2.5) \text{ of } [5]$$

$$\vec{X}(t+1) = \overrightarrow{X_{rand}} - \vec{A}\ \vec{D} \qquad (2.8) \text{ of } [5]$$

5.2. Variables used in 'WOA' Optimization

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

1) Stator bore diameter (D)
2) Active core length (L)
3) Pole-arc to the pole-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 IV

Table 3. Limits of Optimization 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

Table 4. Variables of the 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

Detailed synchronous machine analysis is carried out with the best solution variables obtained from WOA optimization. The pulsating torque vs speed is shown in figure 4. The starting torque vs speed is shown in figure 5

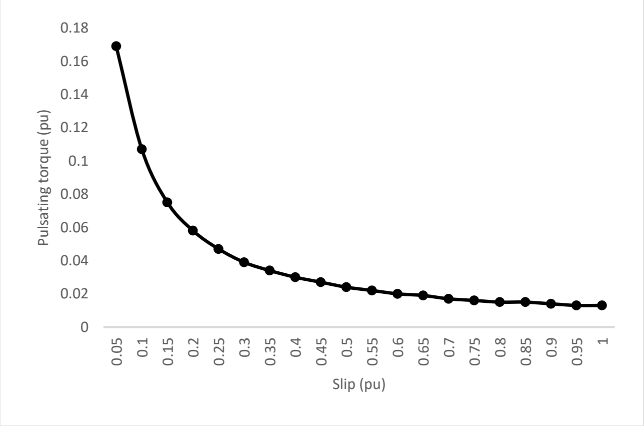

Fig. 4 Pulsating Torque vs Speed

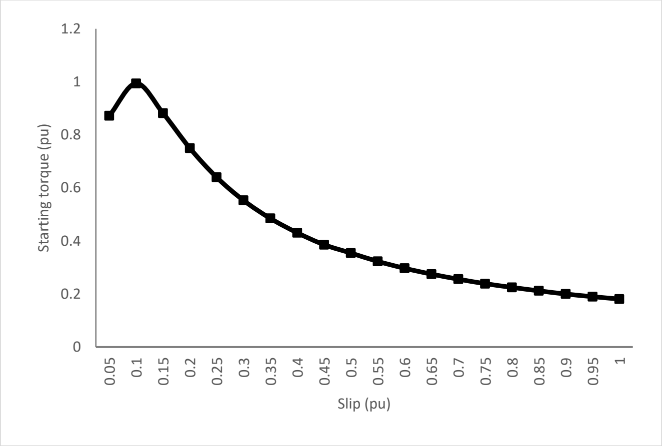

Fig. 5 Starting torque vs Speed

6. 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 a symmetrical fault. Neglecting generator resistance, the fault current may be expressed as follows

If the short circuit is applied at the instant when the rotor axis is along the magnetic axis of phase an, i.e. = 0, for three-phase short at generator terminals, then page 341 equation 8.60 [5].

$$I_d = \frac{E_0}{X_d} \tag{9}$$

$$I'_d = \frac{E_0}{X'_d} \tag{10}$$

$$I''_d = \frac{E_0}{X''_d} \tag{11}$$

and for the short circuit waveform is given by

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

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

$$\tau'_d = \frac{X'_d}{X_d}\tau'_{d0} \text{ and } \tau'_{d0} = \frac{X_f}{R_f} \text{ and}$$

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

A single objective is considered in WOA optimization, ' minimization of torque pulsation'. When a second objective is added, an extended version of the optimization of WOA, known as Non-Dominated Sorting Whale Optimization (NSWOA), is chosen. The details of multi-objective optimization (NSWOA) with optimization results for two objectives are shown below.

7. Non-Dominated Sorting Whale Optimization Algorithm (NSWOA)

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

The two objectives considered in NSWOA are as follows:

- Minimization of torque pulsation for salient pole synchronous motors with dampers.
- Minimization of fault current in balance faults

The results of 'Pareto front' are shown in figure 6. Table VI shows Pareto Front specific points with variable values and objective values.

The analysis program used in WOA and NSWOA optimization is elaborated for more detailed calculations. A detailed analysis program is used with optimized variables. The variation of pulsation torque with slip for both the minimum torque pulsation case and minimum fault current case is in figure 6. Motor starting torque variation with slip in both cases is shown in figure 7.

The computation time taken for a single objective case (WOA) and two objective cases (NSWOA) is shown in table V.

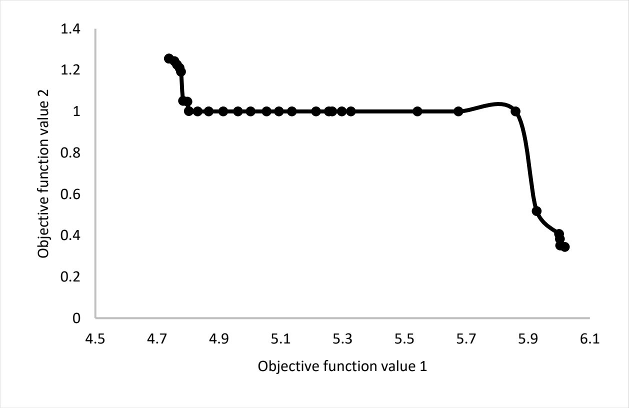

Fig. 6 Optimal solutions Pareto front for two objectives.

Table 5. 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

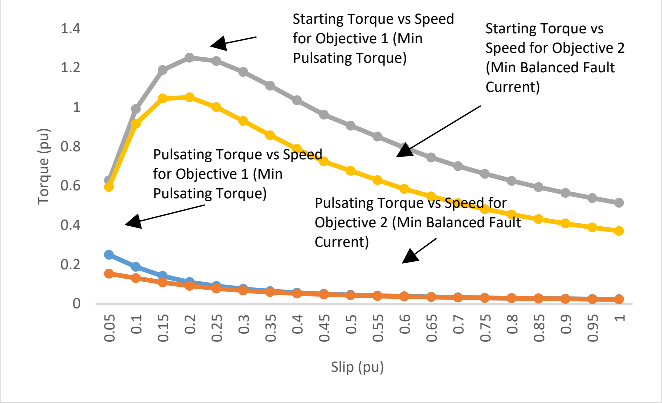

Fig. 7 Variation of Pulsation and starting torques with slip.

Table 6. 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	1.5
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

8. 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 the function of starting time. Further, from the analysis, it is clear that the pulsating torque depends on the design objective. When the design objective is to minimize 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 the start (at slip is 1), there is no significant difference in pulsating torque value with the design objective. The pulsating torque difference is significantly noticeable as the motor picks up speed.

From figure7, it is observed that the starting torque characteristics are superior in performance in the case of 'minimizing pulsating torque objective design'.

9. Conclusion

The algorithm NSWOA is relatively new. This algorithm has already been tested and studied on 17 standard test functions [7] to prove its capability. This paper uses the NSWOA algorithm to reduce the torque pulsations of the salient pole synchronous motor. The torque pulsation function is derived from the motor's basic machine magnetic core lamination dimensions. This function is quite complex and lengthy. The constraints are nonlinear. Seven variables are considered. The NSWOA algorithm can be used for complicated and lengthy engineering problem optimization.

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