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Design Optimization of Doubly Fed Induction Generator Performance by Differential Evolution

Mamidi Ramakrishna Rao

Abstract**—**Doubly-fed induction generators (DFIG) due to their advantages like speed variation and four-quadrant operation, find its application in wind turbines. DFIG besides supplying power to the grid has to support reactive power (kvar) under grid voltage variations, should contribute minimum fault current during faults, have high efficiency, minimum weight, adequate rotor protection during crow-bar-operation from +20% to -20% of rated speed. To achieve the optimum performance, a good electromagnetic design of DFIG is required. In this paper, a simple and heuristic global optimization – Differential Evolution has been used. Variables considered are lamination details such as slot dimensions, stack diameters, air gap length, and generator stator and rotor stack length. Two operating conditions have been considered - voltage and speed variations. Constraints included were reactive power supplied to the grid and limiting fault current and torque. The optimization has been executed separately for three objective functions - maximum efficiency, weight reduction, and grid fault stator currents. Subsequent calculations led to the conclusion that designs determined through differential evolution help in determining an optimum electrical design for each objective function.

Keywords**—**Design optimization, performance, doubly fed induction generators, DFIG, differential evolution.

I. Introduction

DFIG based system has become common in wind power generation. This is due to its features like variable speed operation, four quadrant operation and relatively economical control system. This has resulted in high penetration of DFIG based Wind Turbines (WT) in power system. The construction of DFIG is similar to normal wound rotor induction motor. However, its critical application in grid-connected power system requires many international standards to be met. Besides delivering power at low and high wind speeds, DFIG has to supply or absorb reactive power in normal and power system disturbed conditions. To maintain power stability at the substation, fault current contribution from DFIG needs to be minimized. In addition, to reduce mechanical forces, weight of DFIG should be minimized. To meet all the above, DFIGs should to be optimum. To achieve this, several optimization programing techniques are available. However, each tool has its own limitations. Differential Evolution (DE) surpasses these limitations. DE is population-based search method and performs well with benchmark functions. In this paper, DE is used to optimize DFIG design for weight reduction under constraints like meeting reactive power requirement, minimum fault current and minimum transient torque. Similarly, optimization designs have been worked out for maximizing the efficiency and fault current reduction keeping the same constraints.

Mamidi Ramakrishna Rao was associated with WEG, India He is now a Senior Design Consultant, residing in Visakhapatnam 530043, India (phone: 91-996-335-1515; e-mail: mamidimr@ gmail.com).

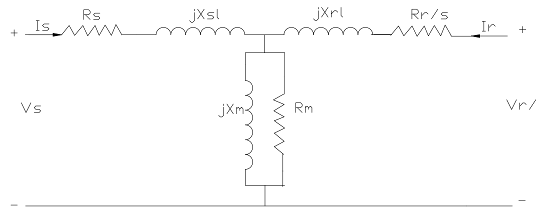

Fig. 1 DFIG Equivalent Circuit

II. Approach

Optimization of efficiency or weight reduction or cost in DFIG is complex as the functions are non-linear and non-differentiable. Direct search approaches are often the most suited options; however, these methods may get trapped in local minimum. DE is an easy-to-use minimization method and has the ability to handle non-differentiable, non-linear and multi-modal function [1].

TABLE I
NOMENCLATURE

Symbol	Description
f	Supply frequency
I	Phase current
L	Self-inductance
L_{sl} L_{rl}	Stator and rotor self-leakage inductances
L_m	Mutual Inductance
P	Pole pairs
P, Q	Active and reactive power
R	Winding resistance referred to stator
R_{cb}	Crow bar resistance
R_m	Core loss resistance
X_{sl}, X_{rl}	Stator and rotor winding leakage reactance referred to stator
X_m	Magnetizing reactance
X_s'	Stator transient reactance
S	Rotor slip
s, r	Stator and rotor subscripts
T_{em}	Electro-magnetic torque
U	Stator to rotor effective turns ratio
V	Volts per phase
ω	Synchronous angular frequencies

To optimize DFIG's performance, objective function and fitness function have been developed and the DE program of [2] has been used. Nine variables were chosen. The variables are shown in Fig. 2. These variables generate the remaining variables to analyze the performance [3]. The number of stator and rotor slots, stator and rotor winding turns per phase are fixed. The variables and the minimum and maximum limiting values are shown in Table II. The limits on variables are fixed by the designer, after considering manufacturing aspects and other limitations.

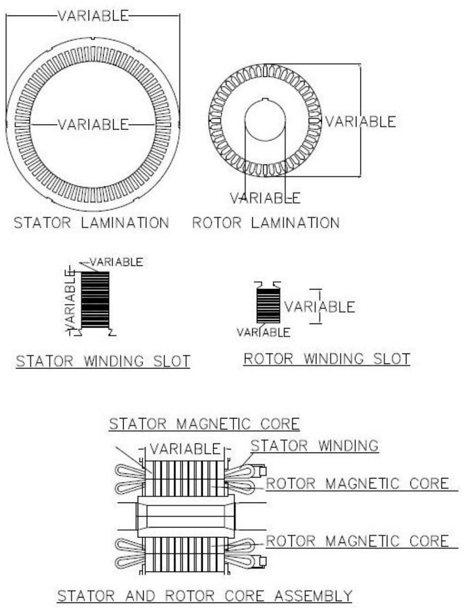

Fig. 2 Variables selected in DE optimization

TABLE II
OPTIMIZATION VARIABLES

Variable	Limits
Rotor inner diameter	$390 < D2_{in} < 500$
Rotor core depth	$90 < CD_2 < 120$
Rotor minimum teeth width	$15 < TW_2 < 20.0$
Rotor teeth height	$55 < TH_2 < 70$
Radial air gap	$2.5 < AG < 5.0$
Stator minimum teeth width	$15 < TW_1 < 20.0$
Stator teeth height	$45 < TH_1 < 60$
Stator core depth	$90 < CD_1 < 130$
Stack length	$850 < CL < 1000$

The constraints are

i) Maximum rotor voltage and current during DFIG operation
ii) Minimum efficiency
iii) Maximum allowed fault current
iv) Maximum permissible transient torque
v) Maximum permissible winding operational current densities.

The constraints have been considered after understanding the converter specifications, manufacturer specifications and DFIG thermal limits.

The fitness function communicates between DE and objective function. Through fitness function, all the performance parameters as received from objective function are checked against constraints for confirmation. Penalty function is applied on those parameters when violated.

III. CALCULATIONS

For optimization and analysis, a 2100 kW DFIG design has been selected (Table III).

TABLE III
DFIG RATING DETAILS

Particular	Value
Rating	2100 kW
Voltage	690 Volts ± 10%
Frequency	50 Hz
Poles	4
Synchronous speed	1500 RPM
Maximum speed	1900 RPM
Minimum speed	1000 RPM
Torque	13504 Nm
Power factor	0.95 Cap / 0.95 Ind
Reactive Power	690.0 kvar

The objective function is an analysis program that calculates parameters like efficiency, stamping and winding copper weights, active and reactive power supplied/received from the grid, stator and rotor currents, fault current and torques due to three-phase short circuits. The calculations for optimization of efficiency and weight reduction have been performed using [4]-[6] and the calculation procedure is given in [7], [8]. The flow chart for optimization is shown in Fig. 3.

Grid fault stator currents: During grid faults, DFIG, stator and rotor contribute to fault current as stator and rotor are connected to grid. The stator fault current consists of DC transient term and steady state AC current. The magnitude of the current depends on voltage dip which in turn depends on fault severity [9]. In case of rotor, to avoid damage to Rotor Side Converter (RSC), crowbar resistances are inserted. Also, the rotor slip at the time of fault occurrence need not be zero and cannot be ignored. It could be anywhere between the operating speed limits.

Considering the effect of crow bar resistance, the maximum stator fault current contribution is approximately given by [7]

$$I_s \max \cong 1.8\, V_s / (\sqrt{}\, (X_s'^{2} + R^2_{cb})$$

$$X_s' = X_{sl} + (X_m * X_{rl}) / (X_m + X_{rl})$$

It can be noted from the equations that the machine leakage, magnetizing reactance and crow bar resistance play significant role in estimating fault currents. In the present paper, crow bar resistance has been taken as 15 times rotor resistance

Transient torques: Power system faults may be categorized as one of four types. They are line to ground, line to line, double line to ground and balanced three-phase faults. The effect of three-phase fault is more severe when compared to others. Considering three-phase fault, electro-magnetic torque is calculated with rotor in short-circuited condition. The limiting torque is specified by gear manufacturer. The optimized design should not exceed the limiting tor.

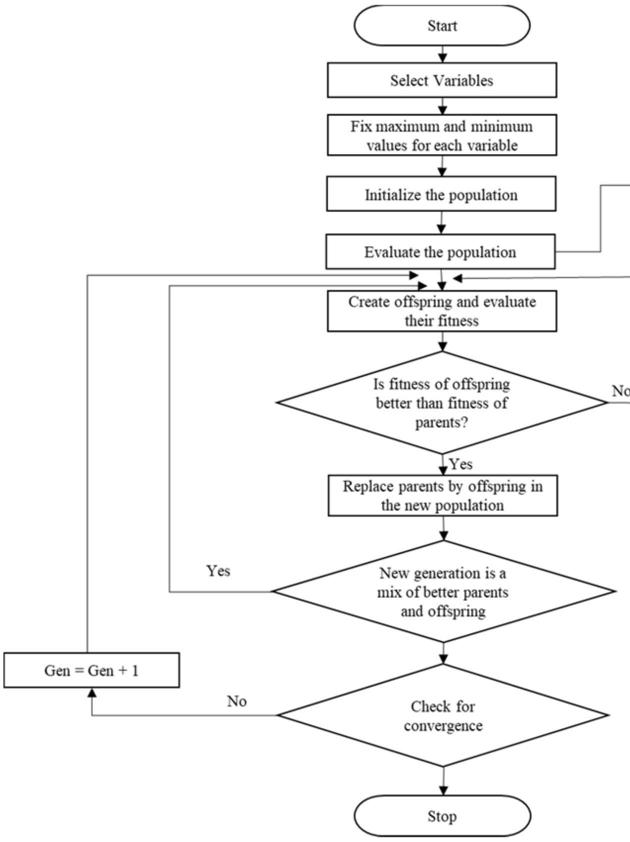

Fig. 3 Flow Chart for the computer program

TABLE IV
COMPARISON OF VARIABLES, EQUIVALENT CIRCUIT PARAMETERS AND PERFORMANCE

VARIABLES	Units	Initial design (1)	Efficiency optimized Design (2)	Weight reduction optimized design (3)	Fault current optimized design (4)
Stator core outer diameter	mm	1060	1161	933	1124
Stator core inside diameter	mm	750	783.00	686	760
Rotor core inside diameter	mm	410	419.0	397	428
Radial air gap between stator and rotor	mm	3	2.63	2.50	2.59
Core length	mm	900	783.0	813.0	1070
Stator winding slot width	mm	18.80	20.28	12.43	9.53
Stator winding slot depth	mm	49.00	55.76	34.26	72.86
Rotor winding slot width	mm	10.00	13.64	9.37	6.93
Rotor winding slot depth	mm	53.12	72.34	50.48	67.46
Stator winding section area	mm^2	118.49	147.5	51.76	88.87
Rotor winding section area	mm^2	152.58	356.64	143.14	119.45
EQUIVALENT CIRCUIT PARAMETERS					
R_s(at 20 °C)	Ohms	0.0019	0.0014	0.0041	0.0028
R_r (at 20 °C)	Ohms	0.0044	0.00176	0.00448	0.00623
X_{sl}	Ohms	0.032	0.0306	0.0336	0.0758
X_{rl}	Ohms	0.0631	0.0554	0.0545	0.107
X_m	Ohms	2.43	2.03	1.66	4.25
R_{fe}	Ohms	93.62	116.6	90.64	113.5
PERFORMANCE					
Efficiency	%	96.73	97.14	96.31	96.63
Electro Magnetic Material weight (approx.)	kg	4626.1	5294.3	3103	6251
Transient Peak three phase fault current	PU	8.53	11.96	8.80	4.99
Transient short circuit torque	PU	6.77	10.17	9.482	4.803
Stator winding current density	Amp/mm^2	2.39	1.93	5.72	3.25
Rotor winding current density	Amp/mm^2	4.27	1.81	4.57	5.69

IV. Results

Table IV shows the comparison of variables, parameters and performance. In case of weight reduction optimization, the material weight has a substantial reduction of 49% from 4,626.1 kg of base design to 3,103 kg of optimum design. However, efficiency change is only from 96.73% to 96.31%. This implies effective utilization of electromagnetic material. Further weight reduction can be achieved with the use of superior magnetic material.

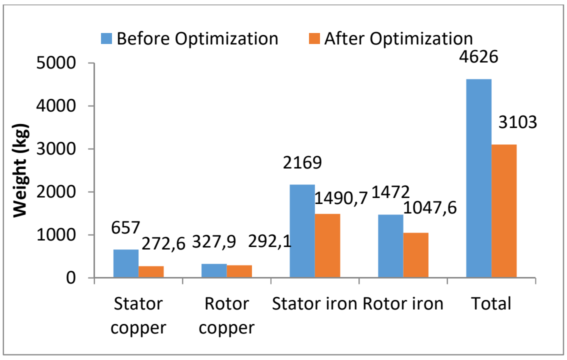

Fig. 4 Active material weight comparison in "weight reduction optimization"

In case of efficiency maximization, the improvement was from 96.73% to 97.14%. Loss distribution can be seen in Fig. 5. Sum total of stator and rotor copper loss reduction is more than 65% and constant loss increased by 6.3%. From temperature rise of windings point of view, this is a good design. Active material weight increased from 4,626.1 kg of base design to 5,294.3 kg, of 'maximum efficiency optimum' design, an increase of 14.0% in weight.

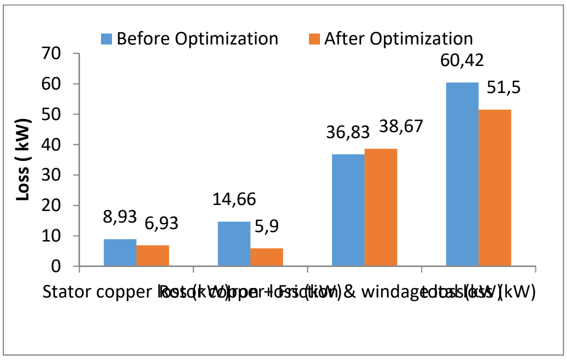

Fig. 5 Loss comparison in "maximum efficiency optimization"

Fig. 6 shows the part load efficiency comparison, for efficiency optimized design. There is no improvement in efficiency at loads less than 50%. This is due to the fact the optimization focus is on variable loss i.e. stator and rotor copper loss. Friction and windage loss are not modified.

In case of fault current reduction optimization, the fault current reduced from 8.53 PU to 4.99 PU which is significant but generator weight increased by 35% of base design. This is shown in Fig. 7.

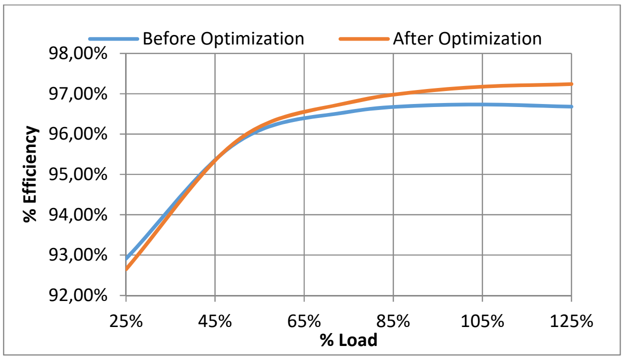

Fig. 6 Efficiency comparison in "maximum efficiency optimization"

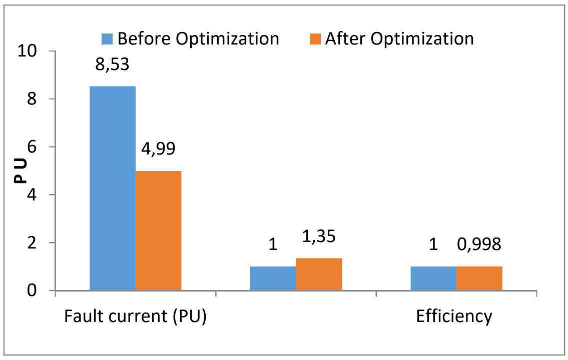

Fig. 7 Fault current reduction optimization

Fig. 8 shows the function value variation (weight) in weight reduction optimization. It can be observed that when DE method is adopted, local minima in each population member and global minimum can be seen. Similar trend was observed when optimized for other objective functions like efficiency maximization and fault current minimization.

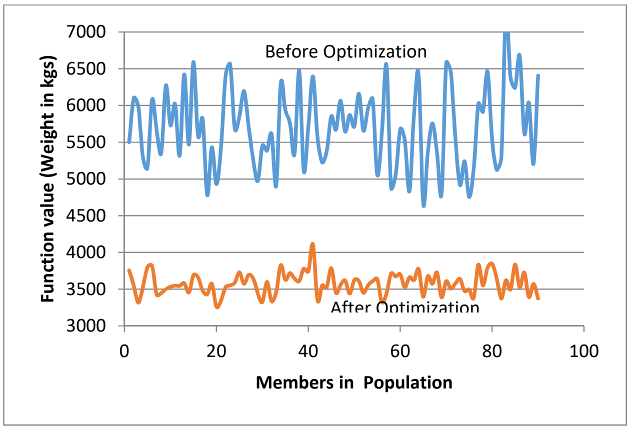

Fig. 8 Variation of function value (for weight reduction) before and after optimization in population

Fig. 9 shows the improvement of 'best efficiency selected from each generation' with generation increase. After meeting the desired accuracy of function value, the curve is flat. There is no effect of increasing number of generations.

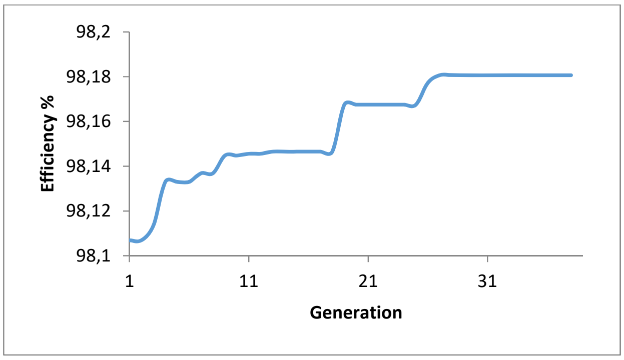

Fig. 9 Efficiency improvement with generation progress

V. Conclusion

DE is simple and easy to use optimization method. Many parameters are in users' control such as the maximum and minimum values of all variables can be chosen by user. The population size can be varied. 'cross-over' and 'factors' are defined by the user. This helps in choosing 'cross over' scheme. All these user-defined parameters aid in developing an optimized design.

In the present work, selection of variables is restricted to continuous variables like stack length, air-gap length and slot profiles. Integer variables like number of turns and wire sizes which are discrete in are not considered. It is possible to apply DE to integer-discrete-continuous variables [10].

Use of DE optimization wind generator design, can be extended to other critical cases in DFIG like reactive power capability, fault ride capability and other critical cases.

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