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MULTI-OBJECTIVE DIFFERENTIAL EVOLUTION BASED ELECTROMAGNETIC DESIGN OF WIND-TURBINE GENERATOR

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Abstract
Renewable energy particularly solar and wind are now being considered as mainstream energy source and are competing at par with conventional ones. Technological innovations and cost efficiencies are driving their growth across the globe and fast increasing their penetration into power grids. In wind generators, doubly fed induction generators (DFIG) have gained popularity due to their efficiency, speed variation, need for less control circuit power and four quadrant operations. However, power grid requirements are becoming stringent in performance needs requiring DFIGs to comply with the technical needs in steady and in power system fault conditions.
In this paper, multi-objective differential evolution with dominance filter and Pareto analysis has been used to optimise the electromagnetic design of DFIG.
The specific design objectives considered are efficiency, weight reduction, reactive power capability, fault current reduction and transient torque. In all the cases, nine direct variables from magnetic core i.e. stator lamination details, stack length, radial airgap and two indirect variables like stator winding copper and rotor winding copper sections are considered. The constraints used are limiting flux density values, minimum efficiency, limiting manufacturing dimensions like minimum radial airgap, minimum core diameter, maximum weight. The reactive power capability depends on generator and grid side and rotor side controllers. In this paper, possibility of increasing the reactive power capacity of generator at design stage, has been studied under different wind speeds conditions. The results are compared and discussed for single objective and multi objective differential evolution.

Introduction
Doubly fed induction generators (DFIG) have gained popularity in power generation to grid primarily due to their superior techno-economic factors over constant speed induction generators and synchronous generators. Some of the key factors include speed variation, four quadrant operation, reactive power and control power requirements. Power grid sector demands DFIG's performance requirements both in steady state and grid fault conditions. Although construction of DFIG is similar to normal wound rotor induction machine but for the electromagnetic design, one needs a clear understanding of present-day grid requirements. For satisfying one specific need, techniques like differential evolution can be used. [1]. However, the demanding requirements can be more than one and could be contradictory requiring the use of techniques such as Multi-Objective

Differential Evolution (MODE). In this paper, five objectives have been identified.

1. Minimization of electromagnetic weight
2. Maximization of DFIG efficiency
3. Minimization of DFIG's fault current contribution
4. Minimization of transient torques in 3-phase fault condition
5. Maximization of DFIG inbuilt reactive power capability

As seen above, Case 2 and 5 are maximization objectives while Cases 1, 3 and 4 are minimization objectives and therefore could be competing objectives at times. For example, 'the efficiency objective' calls for liberal electro-magnetic loadings on materials. This leads to increased material weight. Whereas 'weight reduction objective' calls for maximize the loadings to limits. This is determined by 'non-dominance'.

Approach

All the five objectives mentioned above are highly complex and nonlinear. There are many optimization techniques available to achieve an ideal solution. However, each tool has its own limitations. For example, in direct search optimization technique, it starts with one feasible solution and terminates mostly at local minimum [2]. Differential evolution technique can overcome this problem.

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 [3]. 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 [4]. 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. Flow chart for the computer program is shown in Fig 1.

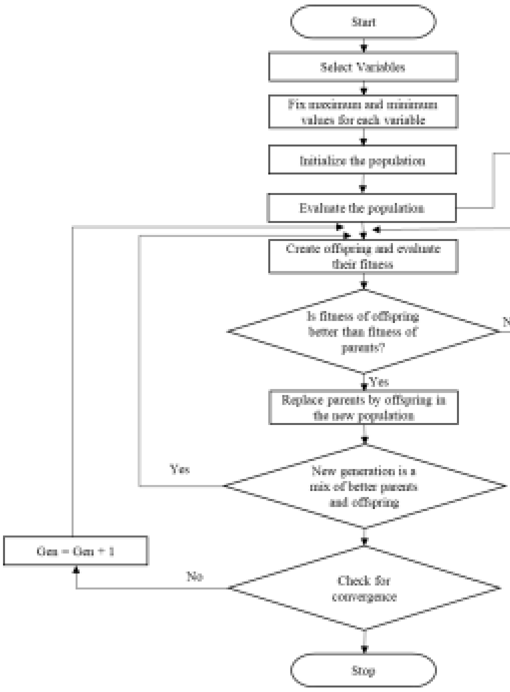

fig. 1 Flow Chart for the Computer Program (DE)

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 [5].

MATLAB version of MODE algorithm by Gilberto Reynoso Meza [6] has been used for optimization. In DE algorithm, greedy selection is performed using a dominance relation. Code has been suitably modified for DFIG. A simplified flow chart is shown in Fig. 2

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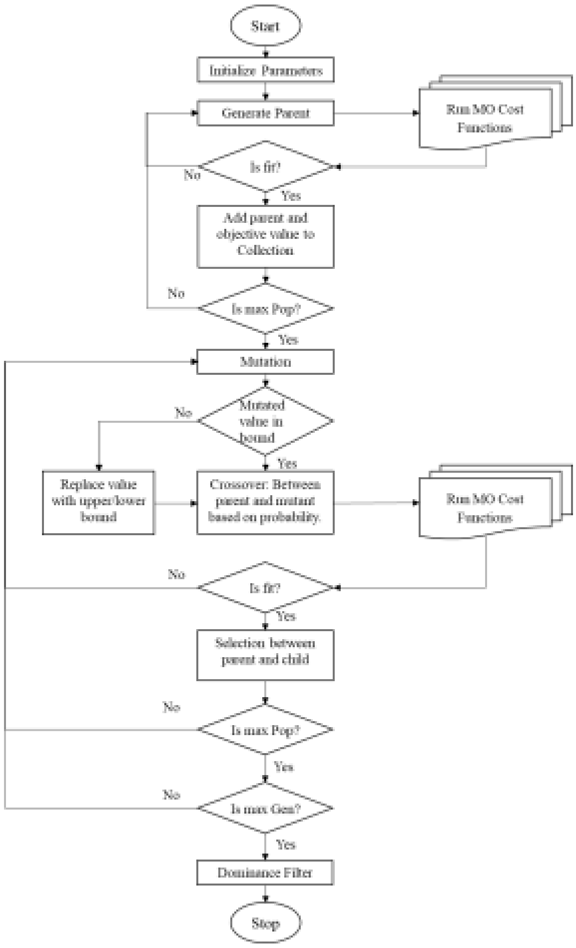

Fig. 2 Flow Chart for the Computer Program (MODE)

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

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Objective functions and fitness function along with a detailed electromagnetic calculation have been developed. Nine variables were chosen which will generate the remaining variables to analyse the performance. The number of stator and rotor slots, stator and rotor winding turns per phase are static. 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 technical limitations.

TABLE II OPTIMIZATION VARIABLES

Variable	Limits
Rotor inner diameter	$390.0 < D2_{in} < 500.0$
Rotor core depth	$90.0 < CD_2 < 120.0$
Rotor minimum teeth width	$15 .0 < TW_2 < 25.0$
Rotor teeth height	$55.0 < TH_2 < 70.0$
Radial air gap	$2.5 < AG < 5.0$
Stator minimum teeth width	$15.0 < TW_1 < 25.0$
Stator teeth height	$45.0 < TH_1 < 60.0$
Stator core depth	$90.0 < CD_1 < 130.0$
Stack length	$850.0 < CL < 1000.0$

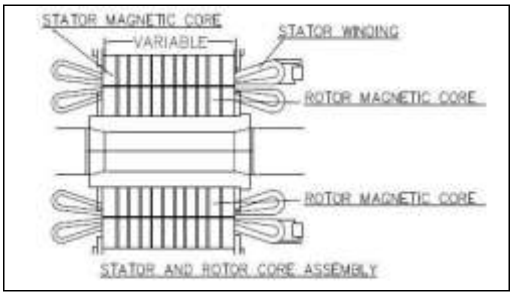

Fig. 3 Stator and Rotor Core Assembly

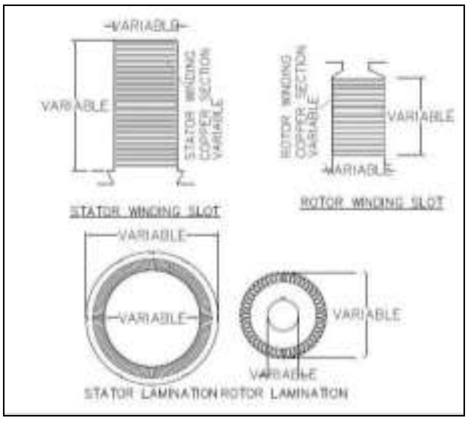

Fig. 4 Stator and Rotor Winding Slots and Lamination

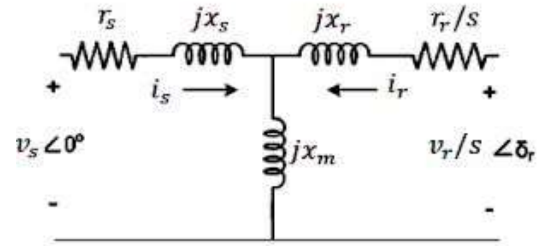

Fig. 5 Equivalent circuit of the doubly-fed induction machine in steady state.

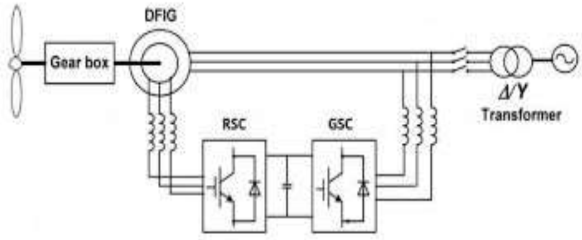

Fig. 6 Schematic diagram of a DFIG wind turbine

Calculations

For optimization and analysis, a 2100kW 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	1,500 RPM
Maximum speed	1,900 RPM
Minimum speed	1,000 RPM
Torque	13,504 Nm
Power factor	0.95 Cap / 0.95 Ind
Reactive Power	690.0 kVAR

DFIG equivalent circuit is shown in Fig 5.[7] The equivalent circuit parameters are calculated using [8] and [9] .

DFIG Reactive Power Capability:

The voltage control capability of DFIG is an important parameter during short circuits, low voltage periods and Low Voltage fault Ride-Through capability (LVRT) situations. The reactive power capability of DFIG is controlled by Rotor Side Converter (RSC) and Grid side converter (GSC) but the capability limitation is decided by the induction generators stator current limit, rotor current limit and rotor voltage limits [10]. They in turn depend on the operating slip of the machine. This paper is focused on increasing the inbuilt capability of generator to deliver more reactive power to grid at design stage. At rated speed, full active load, when supplying reactive kVA to grid, the reactive capability is targeted to increase by a prefixed amount of 15%.

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 current depends on voltage dip which in turn depends on fault severity [11]. In case of rotor, to avoid damage to RSC,

crowbar resistances are inserted during fault. The rotor slip at the time of fault occurrence may not be zero and has to be considered during calculations.
Considering the effect of crow bar resistance, the maximum stator fault current contribution is approximately given by [12].

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

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

It can be noted from the equation 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:
In general, power system faults could be either line to ground, line to line, double line to ground or balanced three phase faults. The effect of three phase fault is more severe when compared to others. Due to generated transient torque there could be mechanical failures of the motor or associated gears. MODE is used to optimize DFIG parameters for minimizing the transient torque.
The transient torque is derived considering the rotor in short circuited condition. From equivalent circuit parameters, the transient torque for 3-Phase short circuit can be derived as

$$T_{sc} = 3.0\ V_s^2 / ((L1 + L2 - 2.0*M) *\omega^2) \text{ where}$$

$$L1 = (X_s+X_m) / \omega$$

$$L2 = (X_r+X_m) / \omega$$

$$M = X_m / \omega$$

DFIG Weight:
The generator weight consists of active and inactive weights. For optimization, active weight is considered. Active weight is sum total of winding copper weight (stator and rotor) and magnetic laminations weight (stator and rotor).

DFIG Efficiency:
Overall efficiency is the product of turbine efficiency, gearbox efficiency, generator efficiency, converters (RSC and GSC) efficiency. In optimization, only generator efficiency is optimized. Losses in generator are stator and rotor copper loss, iron loss, friction and windage loss and stray loss. In optimization, at a specific speed, efficiency improvement is done by decreasing copper and iron loss.

MODE was applied with two, three and four objective functions.
i. **Two objective functions** - Weight reduction and efficiency maximization. Weight reduction calls for maximum utilization of electromagnetic materials i.e. going to its loading limits. Efficiency improvement calls for liberal magnetic loadings so that loss is minimum.
ii. **Three objective functions** - Weight reduction, efficiency maximization and fault current contribution.
iii. **Four objective functions** – Weight reduction, efficiency maximization, fault current contribution and transient torque reduction

In all the cases, the variables selected and constraints are same.

Results
Pareto Front for objective functions

Figures 7, 8, 9 and 10 show Pareto Front obtained from MODE. The best sets obtained from Pareto front are represented in Table IV.
The Fig 11 shows the improvement of each objective function value with generation progress. Fig 12 shows, the optimized weight as obtained, with the increase the number of objectives. It is observed that, when optimized as a single objective, the weight reduction is maximum.

In Fig 7 and 8, 'before MODE' is represented in red dots, obtained after 2 generations. 'After MODE' is represented in blue dots (after 270 generations). The tendency of function values, as expected, is to move towards maximum efficiency.

Figure 8, bar chart shows the gradual improvement in weight and fault current of 10th generation and 270th generation values. Red colour indicates before MODE and yellow colour indicates after MODE.

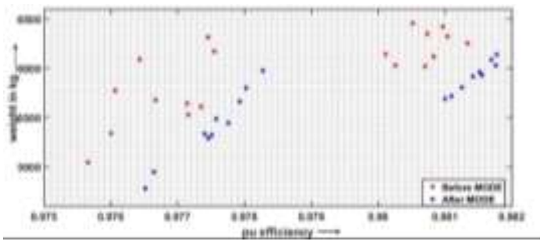

Fig. 7 MODE with two objective functions (weight and efficiency)

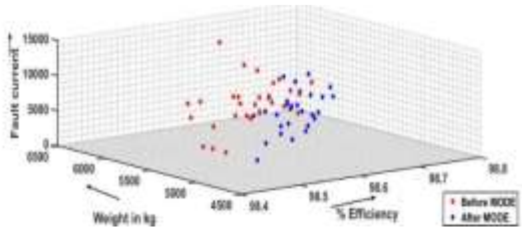

Fig. 8 MODE with three objective functions

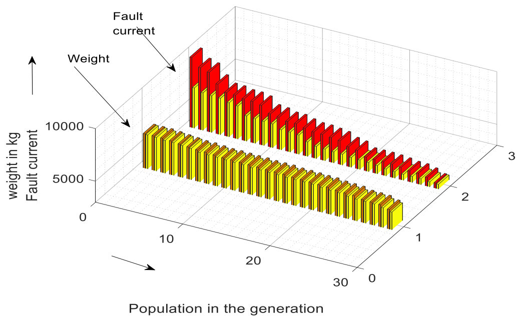

Fig. 9 MODE with 3 objective functions

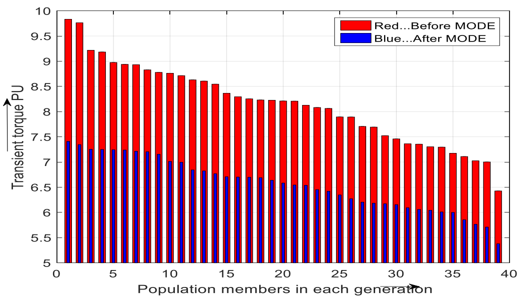

Fig. 10 MODE with 4 objective functions

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Fig 9 shows the improvement of transient torque with generation progress in MODE with 4 objectives.

Computational time for four objective functions increased from 62 seconds (for 3 MO) to 118 seconds i.e. nearly 1.9 times.

TABLE IV Best sets taken from Pareto Front

Sets	Weight (kg)	Efficiency (%)	Fault current (PU)	Transient Torque (PU)
2 Objective Functions				
Set 1	**4951.9**	97.66	-	-
Set 2	6145.6	**98.1**	-	-
3 Objective Functions				
Set 1	**4674**	98.45	3.14	-
Set 2	5482	98.61	**3.03**	-
Set 3	6111.8	**98.76**	6.01	-
4 Objective Functions				
Set 1	**4893**	98.596	5.345	7.2385
Set 2	5320.4	98.4991	**3.088**	6.3477
Set 3	6432.4	97.803	3.6108	**5.3793**
Set 4	6072.9	**98.74**	5.4236	6.7688

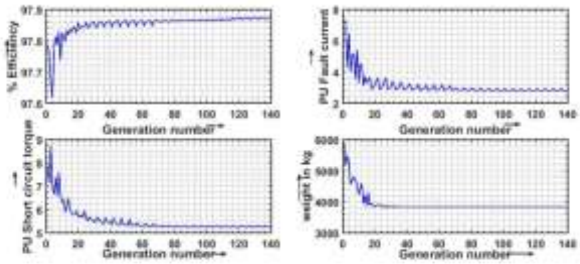

Fig. 11 Convergence of objective functions after MODE

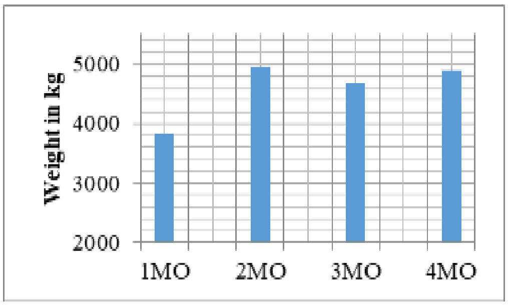

Fig. 12 Optimized weight comparison with number of objectives in MOs

Combining objectives functions in MODE:
For better data handling and data visualization, objective functions 'fault current contribution' and 'three phase short circuit torque reduction' have been combined with selected factors. Thus, four objective MODE is reduced to three and MODE optimization was carried out. Table V shows the results and comparison with base values.

TABLE V Comparison of 4 MO optimized values with base values

Objective Function	Base design	MODE (4 objectives*)
Weight (kg)	4626.1	4379

Efficiency %	96.73	96.97
Fault current (PU)	9.192	6.67
Transient torque (PU)	8.502	5.81
*4 objectives reduced to 3 objectives		

Results of 'DFIG Reactive Power calculations': In the above analysis and results, many optimum designs are worked out. Detailed analysis of one design is shown below.

Turbine power curve data is supplied by wind turbine manufacturer along with cut-in wind speed and cut-out wind speed. Typical curve for 2 MW turbine is shown below.

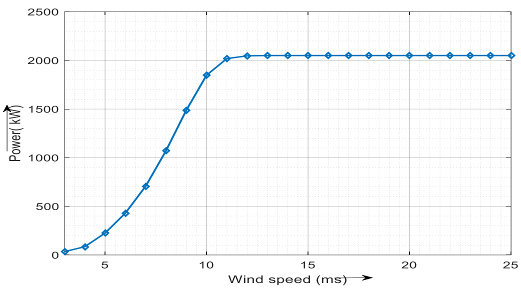

Fig. 13 Power curve of 2 MW turbine

Using this curve and gear ratio, wind generator i.e. DFIG speed vs power are calculated. Considering gear ratio 1:80, DFIG speed and power are computed. The graph is shown below.

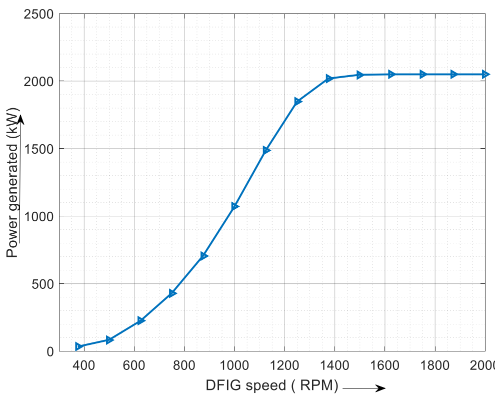

Fig. 14 Generator speed vs power generated

TABLE VI COMPARISON OF VARIABLES, EQUIVALENT CIRCUIT PARAMETERS AND PERFORMANCE
(Base design and increased reactive power capability design)

VARIABLES	Units	Initial design (1)	Rkva optimized design (2)
Stator core outer diameter	mm	1060	1075.0
Stator core inside diameter	mm	750	749.00
Rotor core inside diameter	mm	410	405.00
Radial air gap between stator and rotor	mm	3	2.98
Core length	mm	900	850
Stator winding slot width	mm	18.80	18.32
Stator winding slot depth	mm	49.00	57.38

Rotor winding slot width	mm	10.00	9.58
Rotor winding slot depth	mm	53.12	70.26
Stator winding section area	mm^2	473.99	557.99
Rotor winding section area	mm^2	304.56	453.28
R_s(cold)	Ohms	0.0019	0.0016
R_r (cold)	Ohms	0.0044	0.00289
X_{sl}	Ohms	0.0332	0.0343
X_{rl}	Ohms	0.0636	0.0670
X_m	Ohms	2.43	2.11
At full load:			
Stator winding current density	Amp/mm^2	2.39	2.06
Rotor winding current density	Amp/mm^2	4.27	2.86
Stator copper loss	kW	8.93	7.65
Rotor copper loss	kW	14.66	9.69

Considering Fig. 5 (equivalent circuit) and equations in Appendix, the reactive power supplied to grid, copper loss in windings, stator and rotor currents are calculated. The equivalent circuit parameters are taken from MODE, when optimized for maximizing 'reactive power capability'. The equivalent circuit parameters and values of variables are shown in Table VI. Negative sign is used during calculations to indicate power supplied by DFIG and the reactive power supplied to grid in operating speed range.

Fig. 15 shows, the amount of reactive power which can be delivered by DFIG after MODE design. Fig. 16 shows performance sub plots of currents, copper loss in windings and reactive power supplied by stator and rotor to grid.

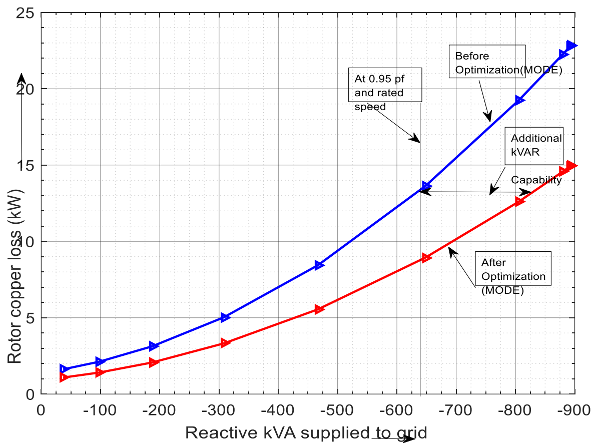

Fig.15 Improvement of reactive power capability after optimization

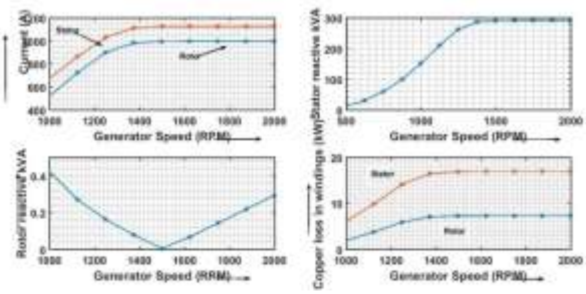

Fig.16 Currents, loss, reactive power before and after MODE

Fig 17 shows 3-dimensional plots of variation of stator and rotor copper loss with respect to speed and reactive kVA before and after optimization

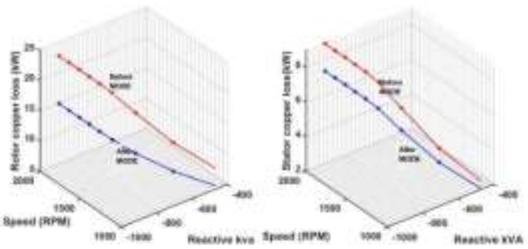

Fig. 17 Variation of winding copper loss with speed and reactive kVA

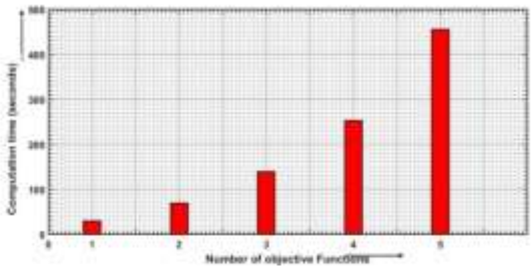

Fig. 18 Increase of computational time with number of objective function

Fig 18 shows, the increase of computation time in MODE when the number of objective cost functions to be optimized. The increase is not linear. The increase is exponential. The computational time depends upon computer and its processor. In this case, the MODE calculations are done using computer used is Windows 7 Ultimate ,32-bit Operating system and Intel Core2 CPU RAM of 4GB.

Conclusion

In an electrical machine design, single objective optimization is not sufficient requiring multi-objective optimization. MODE is a fast technique and relatively easy to adopt.

As MODE progresses with Pareto optimal conditions [12], the optimized weight is more than the optimum weight in single objective DE. This is similar for transient torque and fault current too. Fig. 12 shows optimum weight with 1,2,3 and 4 MO.

When number of objectives are more than one, MODE is a useful tool. Pareto front gives a set of solutions which are non-dominating and are better than the initial population. However, it was observed that, the individual function values do not reach its best optimum values. An improved extension is to use ‘composite fitness’ or ‘Lexicographic approach’. In composite fitness, based on importance of the objective, the weights are assigned to normalized objectives and optimized for single objective function. In Lexicographic approach, the most important objective is optimized first then the rest. This approach may be considered in future work.

Appendix

For DFIG non-unity power factor operation, stator current rotor voltage and current are given below [13].

The stator current when reactive power is supplied to grid is

$$\underline{I}_s = \frac{P_s}{3V_s}(1 - j\frac{\sqrt{1-\cos^2\varphi}}{\cos\varphi})$$

(where φ is power factor angle and P_s is negative for generator and cosφ is negative.)

The rotor current I given by

$$\underline{I}_r = \frac{-P_{s,rated}}{3V_s}\left[1 - j\left(\frac{K_m + \sqrt{1-\cos^2\varphi}}{\cos\varphi}\right)\right]$$

Where K_m is given by the ratio of magnetizing current (I_m) / rated full load current ($I_{s,}$ rated). For a given Qs and T_{em}, the rotor voltage and current are given by

$$\underline{V}_r = \omega_r\left[\frac{\omega_s T_{em}}{3pV_s}\frac{\sigma L_s L_r}{L_m}\right] + j\omega_r\left[\frac{V_s}{\omega_s}\frac{L_r}{L_m} - \frac{Q_s}{3V_s}\frac{\sigma L_s L_r}{L_m}\right]$$

$$\underline{I}_r = \left[\frac{V_s}{\omega_s}\frac{1}{L_m} - \frac{Q_s}{3V_s}\frac{L_s}{L_m}\right] - j\left[\frac{\omega_s T_{em}}{3pV_s}\frac{L_s}{L_m}\right]$$

$$K_m = \frac{I_m}{I_{s,rated}} \Rightarrow I_m = K_m I_{s,rated}$$

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