A New Algorithm Applied to the Evaluation of Self Excited Induction Generator Performance

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Abstract: - The paper presents the application of DIRECT algorithm to analyse the performances of the Self-excited induction generator. It is used to minimize the induction generator admittance yielding the solution which consists of the magnetizing reactance and the frequency. These parameters are the keys to find out the self excitation process requirements in terms of the prime mover speed, the capacitance and the load impedance and finally the output performances such as the voltage, output power, etc. A comparison with other powerful optimization algorithms is investigated to obtain DIRECT algorithm performances.

Key-Words: - SEIG, optimization, DIRECT algorithm.

1 Introduction

Owing to its many features such as: inherent ruggedness, lower unit cost, maintenance free, self protection against overload and short-circuit faults and its ability to generate power at various speeds the induction machine dominates in wind energy conversion applications particularly in remote area (standalone) [1], [2]. Besides, the induction machine may generate a voltage across it stator windings if it's driven by prime mover with sufficient speed and a capacitor bank with required VAr is connected to the stator. This process, known as self excitation, is considered as an optimization problem where the cost function to be minimized is the equivalent circuit's admittance (or impedance) with two constraints, the first one involves that the induction generator must operate in the saturation region which means the magnetizing reactance is always less than the unsaturated value and the second constraint involves that the obtained frequency must be less than the prime mover's speed, in other words negative slip. The cost function is minimized using an optimization algorithm in a way to find out the required values of the external parameters namely speed, load impedance and capacitance leading to values of frequency and magnetizing reactance which satisfy the previous constraints.

Newton-Raphson algorithm has been mostly used to solve this optimisation problem. First the impedance (or the admittance) must be resolved to real and imaginary parts then solved for one of the following configurations: frequency and magnetizing reactance, frequency and speed, frequency and load impedance or frequency and capacitive reactance. The solution yields to the required value of the parameter at hand for the self excitation process. However, despite the good optimization accuracy, separate the admittance's complex function to real and imaginary parts and the Jaccobian matrix calculation are tedious tasks. Besides, the solution is very sensitive to the initial solution, that's the optimization diverges in case of incorrect initial guess. MATLAB built-in minimization routines [3] and MathCAD functions [4] have been used to minimize the impedance. The advantage is that no algebraic derivations are required for optimization process, but both of them need the knowledge of the initial guess. Global optimization as Genetic Algorithm (GA) and Simulated Annealing (SA) has been used to solve the above optimization problem, the advantage of GA is the no need of both cost function derivative and the initial guess. However, the optimization accuracy is not satisfied. For this reason, mostly GA is used to bring the values of the unknown variables close to the region of the optimality then a classical constrained optimizer will take over to fine tune these unknowns [5]. Singaravelu S. *et all.* proposed a fuzzy logic- based optimization approach [6] to determine the capacitive VAr requirements for voltage regulation of three phase induction generator, the algorithm avoids the tedious and erroneous manual work of segregating the real and imaginary components of the impedance. However, the algorithm requires the calculation of the determinant to check the matrix singularity.

In this paper a new global search optimization algorithm, known as DIRECT algorithm, is employed to minimize the admittance of the self excited induction generator. The convergence of the algorithm is guaranteed when the cost function is continuous over the search space or at least in the neighbourhood of the optimum point which is the case of the induction machine. The accuracy of the algorithm is very satisfied without affecting the running time. Besides, the advantage of this algorithm is the convergence for a very large variation of prime mover speed and capacitance. The paper is organized as follows: the second section is devoted to problem formulation of SEIG analysis. Direct Algorithm principle and its application to the SEIG performance analysis are detailed respectively in section 3 and 4. The performance of this algorithm is pointed out by comparison with other methods in Section 5. Finally, the paper ends up by a general conclusion.

2 Problem formulation

The SEIG analysis is based on the equivalent circuit of the induction machine shown in fig.1. The iron loss is neglected and all the parameters are considered constant except the magnetizing reactance which varies according to the saturation characteristics given in appendix A.

It is obvious from the equivalent circuit, fig.1, that two methods can be used to analyse the self-excitation process of the induction generator namely, loop-impedance method or nodal-admittance method [3]. As both of them lead to the same results, the nodal-admittance is chosen in this paper for the application of DIRECT algorithm.

By applying KVL to circuit of fig.1 and as the self-excitation process implies that the stator voltage is not zero that is, the total circuit admittance is null:

$$Y_{LCS} + Y_m + Y_r = 0 \quad (1)$$

Where:

$$Y_{LCS} = \frac{1}{(\frac{R_l}{F} + jX_l)//(-j\frac{X_c}{F^2}) + (\frac{R_s}{F} + jX_s)}$$

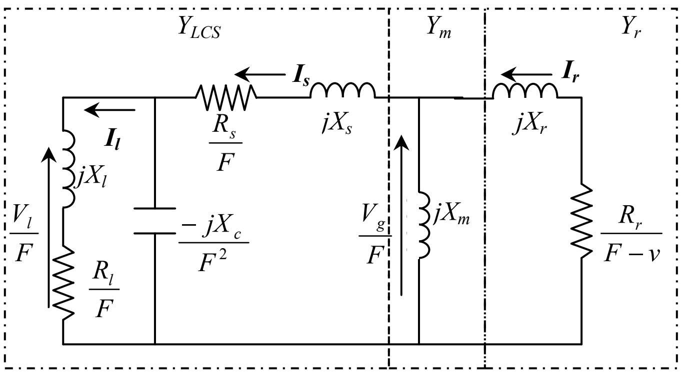

Fig.1 Per phase equivalent circuit of self-excited induction generator

$$Y_m = -\frac{j}{X_m}$$

$$Y_r = \frac{1}{\frac{R_r}{F-v} + jX_r}$$

To apply conventional methods (1) must be separated into two parts, real and imaginary equations with two unknowns, the magnetizing reactance (X_m) and the frequency (F). Their values are obtained once the iterative method reaches the minimum of the non-linear equations (2).

$$\begin{aligned} f(X_m, F) = 0 \\ g(X_m, F) = 0 \end{aligned} \quad (2)$$

As stated in the introduction, the solution of (1) or (2) is obtained by using any conventional iterative method such as Newton-Raphson which requires the Jacobian of (2) and the initial guess (X_{m0}, F_0), by using Matlab buil-in functions such as “constr” or “fmincon” for later versions of Matlab or by using MathCAD “Given” and “Find” solving block where only positive real values of frequency will be accepted for the unknowns. Three external parameters, speed, capacitance and load impedance are varied and the optimization algorithm solves (1) or (2) for X_m and F corresponding to the minimum of the admittance.

3 DIRECT algorithm

The DIRECT optimization algorithm was first introduced by Jones *et all.* [7]. It was created in order to solve difficult global optimization problems with bounds constraints and real-valued const function. The name DIRECT come from the shortening of the phrase “DIviding RECTangles” which describes the way the algorithm moves towards the optimum point. The algorithm is the modified version of the standard Lipschitzian approach that eliminates the need to specify the Lipschitz constant.

DIRECT is a sampling algorithm, that is, it samples the points in search space of the cost function and uses the information has obtained to decide where to search next. The first step is to transform the real search space $[a_i, b_i]^n$ in a unit hypercube $[0, 1]^n$. The function is sampled at the center of the hypercube $c1$ (computing the function value at center-point instead of doing it at the vertices is an advantage when dealing with problems with higher dimensions [8]). The hypercube is then divided to into smaller hyper-rectangles whose center points are sampled too, $f(c1-\delta e_i)$ and $f(c1+\delta e_i)$, where δ is one third the side-length of the hyper cube, and e_i is the ith unit vector (i.e. a vector with a one in the *i*th position and zeros elsewhere) . Instead of using Lipschitz constant to determine the next rectangle to sample, DIRECT identifies a set of potentially optimal rectangles. All potentially optimal rectangles are further divided into smaller rectangles and their centers are sampled Fig. 2 shows an example how DIRECT algorithm samples and divides potentially optimal rectangles during the three first three iterations. The advantage of DIRECT is that it converges as long as the cost function is continuous or at least in the neighborhood of the global minimum [7]. The DIRECT algorithm is summarized in the following steps:

Algorithm DIRECT (‘*f*’, bounds);
Normalize the search space to be the unit hypercube $[0, 1]^n$
Calculate the hypercube center *c1*;
Find $f(c1)$, $f_{min}=f(c1)$, $x_{min}=c1$, $\boldsymbol{i}=0$, $\boldsymbol{m}=1$;
Find $f(c1\pm\delta e_i)$, $1 \le \boldsymbol{i} \le n$, and divide hypercube
While $\boldsymbol{i}\le$maxiter & $\boldsymbol{m}\le$ maxeval Do
Identify the set of all Pot. Opt. Rectangles
For $k=1$ to length (s)
Identify the largest side (S) of rectangles (k)
Evaluate ‘*f*’ at center points of new rectangles and divide ***k*** into smaller rectangles
Update f_{min}, x_{min} and ***m***
End for
$\boldsymbol{i}=\boldsymbol{i}+1$;
End of while
End.

5 DIRECT algorithm performances

To find out the advantages of DIRECT algorithm, it has been compared with two algorithms taking into account the minimization accuracy and the running time as performance indices. The Real-valued Genetic Algorithm has been chosen since it’s considered as one of the most powerful global search optimisation algorithms. The reader can refer to Rand L. Haupt’s book [9] for description of its different steps. Regarding the second algorithm, recently, more interests are given to dedicated software such as Matlab and MathCAD. Optimization toolbox of Matlab offers several algorithms for optimization purposes, “constr” function or “fmincon” function that is available only in recent versions of Matlab are mostly employed to minimize functions subjected to equality and inequality constraints. In this paper it is used for comparison purpose with DIRECT algorithm. Two external parameters namely load impedance and prime mover speed are varied and the three optimizations algorithms are used to minimize the SEIG equivalent circuit admittance (1).

5.1 Variation of load impedance

Fig. 3.a shows the solution obtained by DIRECT, GA and “constr” function of the admittance (Xm F) versus the load impedance and fig. 3.b illustrates the accuracy of the minimization process along the load impedance variation. Different parameters required for the implementation of the three algorithms are listed below:

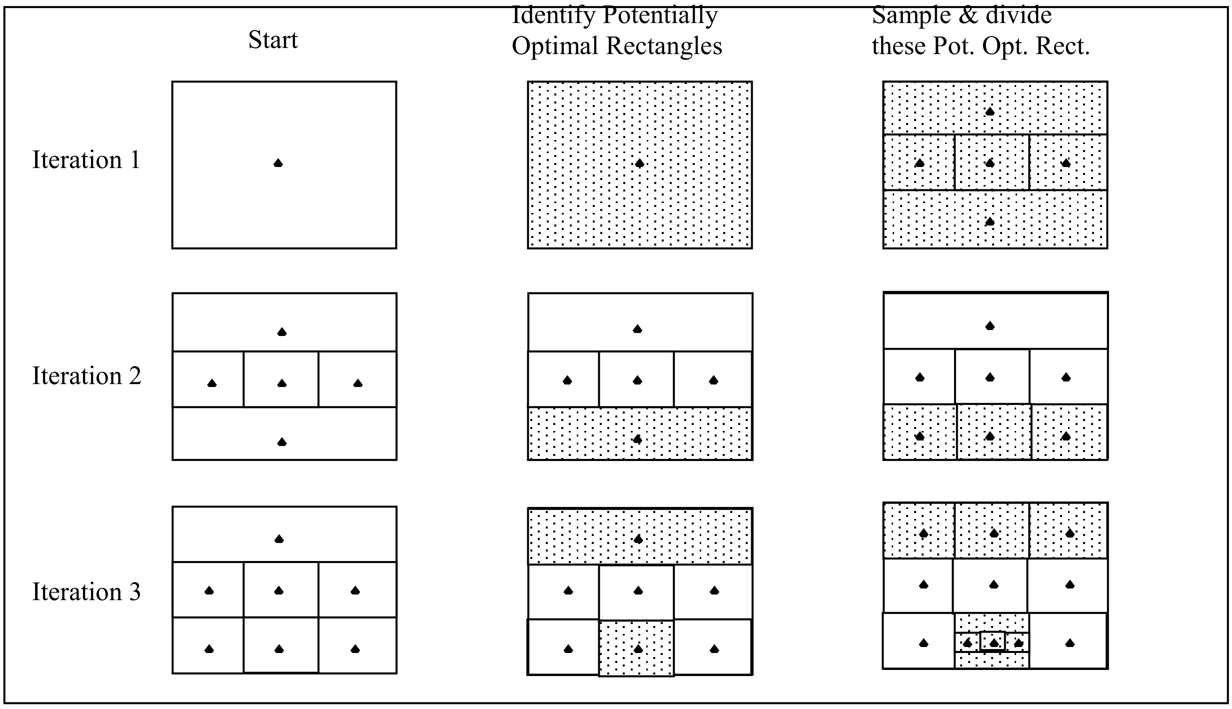

Fig.2. First three iterations of DIRECT

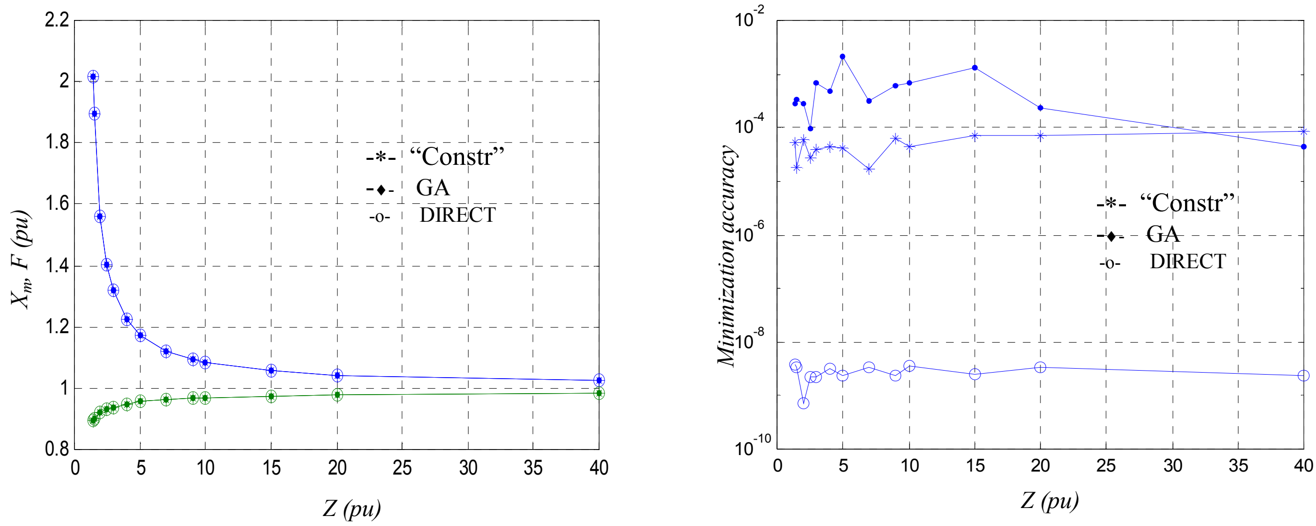

Fig.3. X_m and F and minimization accuracy versus load variation using: DIRECT, "constr" and GA.

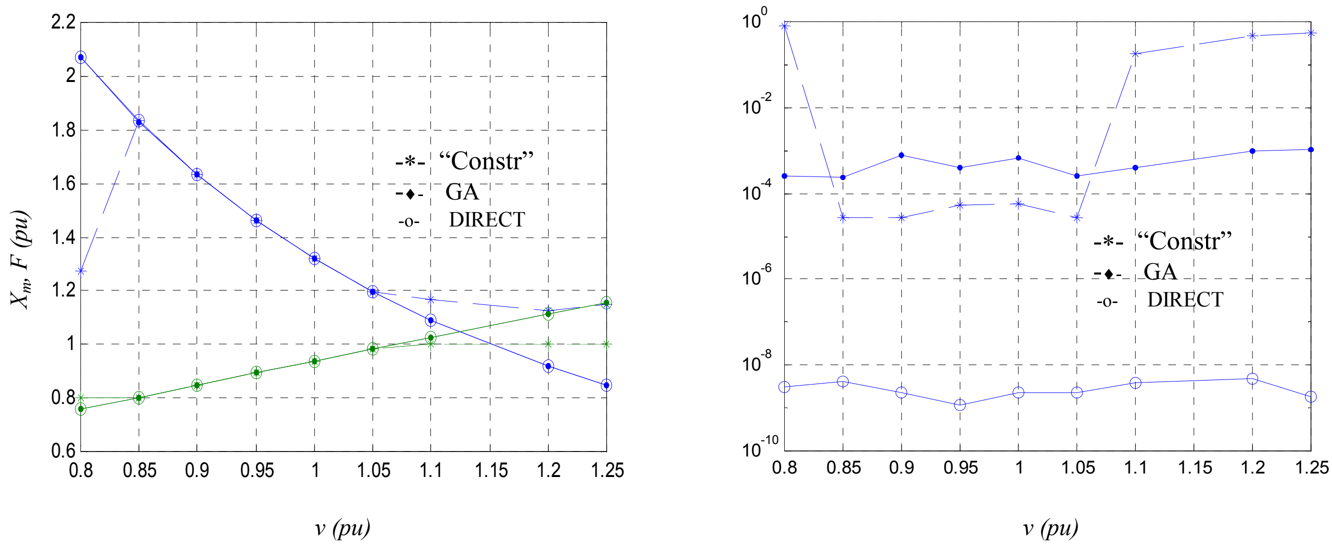

Fig.4. X_m and F and minimization accuracy versus speed variation using: DIRECT, "constr" and GA.

- The same search space for the unknowns (X_m and F) is considered for each algorithm, that's $X_m \in [0, 40]$ and $F \in [0{,}01, 4]$.
- The cost function to be minimized is the induction generator the admittance,
- As "constr" function is gradient based method, the initial solution [1, 0.98] has been considered,
- The population size in real valued GA is 600 chromosomes, roulette method combined elitism strategy is used for parent selection, crossover probability is 0.8 and mutation probability is 0.05.

4.2 Variation of speed

In the case of speed variation, the above data are maintained. From fig. 4.a, one can notice that the local search algorithm, "constr", has failed to reach the solution. The initial guess which has lead to solution in the case of load impedance variation seems not valid in the case of speed variation; this explains the divergence of "constr" function outside the speed interval [0.85, 1.05]. The solution of the GA is acceptable since the minimization accuracy is around 10^{-3} along the speed variation interval. However, the time required by algorithm is too much higher than those of DIRECT and "constr", as shown in table 1. It's important to mention that the accuracy of real-valued GA depend on the initial population size which is evenly distributed over the variation range of X_m and F. The GA combines the characteristics of parents and the best of them are transmitted to their offspring but it cannot dig as DIRECT does by dividing rectangles wherever the area of a local minimum is found.

6 Conclusion

This paper investigates the application of DIRECT algorithm to analyse the SEIG's performances. The analysis consists on the minimization of the real and the imaginary parts of the self excited induction generator's admittance (or impedance) function. The disadvantage of conventional optimization algorithms when used for this purpose, such as Newton-Raphson algorithm, is that they require the segregation of the admittance complex function to real and imaginary nonlinear equations before to proceed solving them. This long procedure limits their use as an analysis tool. Matlab built-in functions and those of Math CAD can be used to minimize the admittance without going through lengthy and tedious derivation for the coefficients of a set of nonlinear equations. However, as the admittance (or impedance) minimization problem accepts several local minima, these functions cannot ensure the search convergence to the global minimum. In fact, these functions require the knowledge of the initial guess to reach the right solution. In this paper, it has been shown the effectiveness of DIRECT algorithm by the comparison with experimental results and its superiority in term of minimization accuracy, initial guess needless and convergence guaranty in finding the minimum of the admittance.

Appendix

The rating of the induction machine and its parameters given in pu are obtained from [3]. Rated power: 750W, rated voltage: 220V, rated phase current : 2,31A, rated frequency, f =60Hz, Rated speed, N=1800rpm. Its equivalent circuit parameters are given in pu : Rs=0.111, Rr=0.132, Xs=Xr=0.157, Xo=2.64. The magnetizing curve shown by triangles in fig. 8 is approximated by the following 3rd order polynomial equation:

$$Eg/F=2.5954-2.92318.X_m+1.8711.X_m^2-0.418359.X_m^3$$

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