Voltage Control of Compensated Self-Excited Induction Generator using Genetic Algorithm

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Abstract: Analysis of self-excited induction generator reveals that these machines are not capable to maintain the terminal voltage and frequency in the absence of expensive controllers. A simple way to control the voltage is through series compensation whereas frequency control is possible through operating speed. In this paper Genetic Algorithm has been used to model the control strategy for proper reactive compensation under different operating conditions. A new methodology is proposed to estimate the values of shunt and series excitation capacitance to maintain the terminal and load voltage. Simulated results as obtained from the proposed control technique have been verified using experimental results on a test machine. Closeness between simulated and experimental results confirms the validity of proposed model.

Key-Words: - Genetic Algorithm, Optimization, Self-Excited Induction Generator, Wind Energy Generation.

1. Introduction

A rapid depletion of fossil fuels as well as a fast growing power demand has attracted the attention of scientists from conventional to non conventional sources of energy such as wind energy, solar energy, tidal energy, etc.. Out of these wind energy seems to be more attractive and viable. It is observed that winds carry enormous amount of energy and the regions in which strong winds prevail for a sufficient time during the year may use it for electrical energy generation. In addition to this wind energy generation provides a clean and pollution free environment and does not lead to global warming. Further a wind turbine generator may be a worthwhile proposition for an isolated remote area due to absence of power grid. There are many considerations in the choice of generators for the wind turbine applications and several views prevail. However most of the researchers are in the favour of induction generators in self-excited mode due to its ability to convert mechanical power over a wide range of rotor speeds. Induction generators are also preferred due to several other advantages such as low cost, less maintenance and easy operation. The self-excited induction generators (SEIG) are also found suitable for few other applications such as tidal and small hydroelectric energy conversion. Operation of induction generator in self-excited mode is useful under variable speed operation especially when wind speed is fluctuating within a wide range.

To compute the steady state performance of SEIG, researchers adopted different models [1-9]. Major observation, which was seen in case of self-excited induction generator, is its poor voltage regulation. Various regulating schemes were proposed by research persons to overcome this issue. However it has been realized that such schemes makes the system complicated and expensive. Reference [10] found the series compensation a simple and cheap alternative to such schemes. Many research scholars [11-15] studied the effects of series compensation using different techniques. It has been observed that such analysis requires the solution of higher degree of polynomial equation in unknown frequency due to the presence of series capacitor.

In this paper GA has been proposed to estimate the generated frequency, shunt and series capacitance for different operating speeds and under
different load conditions. Proposed modeling does not need the solution of higher degree polynomial equations as required in most of the previous research works. A control strategy using GA is proposed to control the terminal and load voltage of SEIG. Simulated results have been verified using experimental results on a test machine. A close agreement between computed and experimental results proves the validity of proposed model.

2. Genetic Algorithm

Over the past few years, many researchers have been paying attention to real-coded evolutionary algorithms, particularly for solving real-world optimization problems. Genetic Algorithm (GA) [16] is one of them. Since the performance variables evaluation ($a$, $C_{sh}$, and $C_{se}$) in SEIG may take any real number, therefore, in this paper a real-coded genetic algorithm has been used to investigate the performance. In a real-coded GA, variables are coded in real numbers itself. GA operators are directly applied on the real numbers ($a$, $C_{sh}$, and $C_{se}$). Three main operators responsible for the working of the GAs are reproduction, crossover, and mutation. Reproduction operator allows highly productive strings to live and reproduce, where the productivity of an individual is defined as a string’s non-negative objective function value. There are many ways to achieve effective reproduction. Here, tournament selection is used instead of roulette-wheel selection, which is generally used. Higher values of tournament size give higher selection pressure, making the convergence faster. The second operator, crossover, exchanges genetic information. The study reveals that a number of crossover operators such as blend crossover (BLX), simulated binary crossover (SBX), unimodal normal distribution crossover (UNDX), simplex crossover (SPX) are commonly used. Here parent centric recombination operator (PCX) has been used, as this operator assigns more probability for an offspring to remain closer to the parents than away from parents. The search power of this crossover is better than the simple crossover i.e. local or broader search can be done. Different mutation operators are used based on the coding of the variable. Since continuous variables are coded directly, the algorithm is flexible in nature. As PCX and the real-coded mutation operators have been used to have a search power similar to their counterparts, the overall algorithm performs better than the binary-coded GAs. Modified GA [16, 17] processes fast convergence in comparison to conventional GA as reported in [18].

3. Modeling for Steady State Analysis

The steady-state operation of the self-excited generator with series and shunt capacitors may be analyzed by using the equivalent circuit representation as shown in Fig. 1.

Fig. 1. Per phase equivalent circuit representation for two capacitor self-excited induction generator.

Fig 2. Per phase modified equivalent circuit representation.

In this circuit model all parameters are assumed to be independent of saturation except for magnetizing reactance. The core losses have been ignored. The network above can be further transformed into Fig. 2.

Where,

$$R_L = \frac{RX_{sh}^2}{a^2R^2+(X_{sh}+X_{sc})^2}$$

and

$$X_L = \frac{X_{sh}X_{sc}(X_{sh}+X_{sc})+a^2R^2X_{sh}}{a^2(a^2R^2+(X_{sh}+X_{sc})^2)}$$

As Fig.2 does not contain any e.m.f. or current source, therefore for successful generator operation, nodal analysis results into;
\[
Y = Y_r + j Y_i = 0 
\]  
(1)

\[
Y_m = -j \frac{1}{X_m} 
\]

\[
Y_s = \frac{R_L + \frac{R_1}{a}}{(X_1 - X_L)^2 + \left(R_L + \frac{R_1}{a}\right)^2} - j \frac{(X_1 - X_L)}{(X_1 - X_L)^2 + \left(R_L + \frac{R_1}{a}\right)^2} 
\]

\[
Y_e = \frac{R_2}{a-b} \frac{X_2}{X_2^2 + \left(\frac{R_2}{a-b}\right)^2} - j \frac{X_2}{X_2^2 + \left(\frac{R_2}{a-b}\right)^2} 
\]

Equation (1) may also be defined as;

\[
Y = Y_r + j Y_i 
\]  
(2)

Where,

\[Y_r = \text{Real part of } Y\]

\[Y_i = \text{Imaginary part of } Y\]

In case of generation equations (1) and (2) are to be satisfied for unknown values of ‘generated frequency’ and ‘magnetizing reactance’.

‘a’ may be evaluated by minimizing the real part of (2) and ‘Xm’ magnetizing reactance to be estimated using imaginary part of this equation.

### 3.1 Selection of \( C_{sh} \) at no load

GA has been used to find the shunt capacitance at different speeds to maintain the rated voltage across the stator terminals at no load. The fitness function (FF) used here is,

\[
FF = Y_{RR} + V_{terr} 
\]  
(3)

Where

\[Y_{RR} = Y_R \ast Y_R\]

\[V_{terr} = (1.0 - V_t \text{ pu}) \ast (1.0 - V_t \text{ pu})\]

The value of \( R \) is \( \infty \) and \( X_{se} = 0 \) for computation of \( Y_R \) in FF.

The first part of the fitness function has been used to find the generated frequency ‘a’ and second part is used to maintain the voltage. Application of GA through (1) to (3) results into the computation of shunt excitation capacitance requirement at no load to maintain the rated voltage at a given operating speed. Such results may be used to establish the relation between operating speed and shunt excitation capacitance. Fig. 3 shows the variation of shunt capacitance with speed for induction machine (Appendix-1) to maintain the terminal voltage as 1.0 pu at no load. It is observed reactive VARs requirement decreases with an increase in operating speed.

![Fig. 3. Variation of shunt excitation capacitance with speed.](image)

Curve in Fig.3 may be represented mathematically using MATLAB as;

\[C_{sh} = Ab^{-x}\]

Thus any variation in speed may be accommodated by proper control of shunt excitation capacitance through GA controller as shown in Fig. 4. Constants \( A \) and \( x \) are dependent upon machine parameters.

![Fig. 4. GA Controller for variable speed operation.](image)

### 3.2 Selection of \( a \) and \( C_{se} \) under loaded condition

For given value of operating speed and shunt capacitance as calculated above, GA may be used to find the optimum values of generated frequency, \( a \) and series capacitance \( C_{se} \) for a given load impedance and corresponding to operating speed. The fitness function (FF) used here is;
\[ FF = Y_{RR} + V_{err} + I_{1err} \]

Where

\[ Y_{RR} = Y_R \cdot Y_R \] and \( Y_R \) has been computed for a given load resistance ‘R’.

\[ V_{err} = (1.0 - V_{pu}) \cdot (1.0 - V_{pu}) \]
\[ I_{1err} = (1.0 - I_{1pu}) \cdot (1.0 - I_{1pu}) \]

This fitness function is useful to control the voltage and stator current of SEIG.

This will lead to the estimation of ‘a’ and ‘C_{se}’ through GA for constant voltage for any operating speed ‘b’ and load resistance ‘R’.

Fig. 5 shows the variation of computed values of \( C_{se} \) with operating speed for different values of load resistance. It is observed that with an increase in speed, initially the value of series capacitance \( C_{se} \) decreases and after attaining a minimum value it starts increasing. These characteristics are also useful to determine the operating speed for any load resulting in to minimum series capacitance with desired voltage regulation. Mathematical modeling for various curves shown in Fig. 5 yields the following expression for \( C_{se} \) corresponding to operating load \( (i_r) \).

\[ [C_{se}]_i = A_i \cdot b^{-x_i} \]

Thus any variations in speed under loaded condition may be accommodated by proper control of \( C_{se} \) as shown in Fig. 6. Constants \( A_i \) and \( x_i \) depend upon load current and machine parameters.

4. Proposed Control Strategy

Fig. 7 shows the control strategy to achieve constant voltage operation for SEIG for any operating speed and loading condition. GA controllers have been used to obtain the appropriate value of shunt excitation capacitance for any speed under no load conditions and series capacitance under loaded conditions. Capacitance selection through GA results in constant voltage operation, without exceeding the rated current for induction generator.
Table 3 Simulated results on SEIG, b=1.01

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>( L_{pu} )</th>
<th>( C_{sh}(\mu F) )</th>
<th>( C_{se}(\mu F) )</th>
<th>( a )</th>
<th>( V_{pu} )</th>
<th>( V_{pu} )</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>0.1154</td>
<td>20.67</td>
<td>12.61</td>
<td>0.0022</td>
<td>1.0000</td>
<td>1.0515</td>
</tr>
<tr>
<td>2</td>
<td>0.2939</td>
<td>20.67</td>
<td>16.00</td>
<td>0.9945</td>
<td>0.9999</td>
<td>1.0763</td>
</tr>
<tr>
<td>3</td>
<td>0.3297</td>
<td>20.67</td>
<td>19.25</td>
<td>0.9933</td>
<td>0.9999</td>
<td>1.1072</td>
</tr>
</tbody>
</table>

5. Results and Discussions

Table 1 shows the comparison of simulated results using proposed control strategy and experimental results on induction machine [Appendix-1]. A close agreement between the two proves the validity of model proposed. Table 2 shows the computed results on test machine using proposed methodology for different operating speed and load current. GA has been used to compute the shunt excitation capacitance and series capacitance corresponding to given operating speed and load current. Selection of \( C_{sh} \) using GA at no load ensures rated voltage for any operating speed. Further such control is useful in case it is difficult to maintain the speed due to frequency variations in wind speed. It is observed that there is a need of simultaneous control of shunt and series capacitance to achieve a constant voltage operation without exceeding the thermal limits (to be decided by stator current). Constant voltage variable frequency operation as given by proposed modeling may be useful for frequency insensitive loads such as heating etc. in remote and windy areas. Further it has been observed through Table 3 that rated value of generated voltage and frequency is possible only and only if operating speed is maintained slightly above the rated speed.

6. Conclusions

Compensated Self-excited induction generators are found to be most useful for wind energy conversion in remote and windy locations. Such units seem to be very attractive in case terminal voltage is controllable under variable speed operations. In this paper a new control technique based on Genetic Algorithm has been proposed to achieve the constant voltage operation for SEIG. Proposed scheme results into the appropriate selection of shunt and series capacitors for any operating speed and load. Terminal and load voltage is maintained near to the rated value without exceeding the rated current of induction generator.

Nomenclature

- \( a \): Per unit frequency
- \( b \): Per unit speed
- \( C_{sh} \): Shunt excitation capacitance per phase
- \( C_{se} \): Series excitation capacitance per phase
- \( E_1 \): Air gap voltage per phase at rated frequency
- \( f \): Rated frequency
- \( I_1 \): Stator current per phase
- \( I_2 \): Rotor current per phase, referred to stator
- \( I_L \): Load current per phase
- \( I_m \): Magnetizing current per phase
- \( R \): Load resistance per phase
- \( R_1 \): Stator resistance per phase
- \( R_2 \): Rotor resistance per phase, referred to stator
- \( V \): Load voltage per phase
- \( V_t \): Terminal voltage per phase
- \( X_1 \): Stator reactance per phase
- \( X_2 \): Rotor reactance per phase, referred to stator
- \( X_{sh} \): Capacitive reactance due to \( C_{sh} \) at rated frequency
- \( X_{se} \): Capacitive reactance due to \( C_{se} \) at rated frequency
- \( X_m \): Magnetizing reactance per phase at rated frequency

Appendix 1

The details of the induction machine used to obtain the experimental results are;

3-phase, 4-pole, 50 Hz, star connected, squirrel cage induction machine, 750W/1HP, 380 V, 1.9 A

The equivalent circuit parameters for the machine in pu are
$R_1 = 0.0823, R_2 = 0.0696, X_1 = X_2 = 0.0766$

Base values as used are:

Base voltage = 219.3 V

Base current = 1.9 A

Base Impedance = 115.4 Ω

Base frequency = 50 Hz

Base speed = 1500 rpm

The variation of air gap voltage with magnetizing reactance at rated frequency for the induction machine is as given below.

\[ X_m < 169.2 \quad E_1 = \frac{512.69 - 2.13X_m}{179.42 > X_m \geq 169.2} \quad E_1 = \frac{891.66 - 4.37X_m}{184.46 > X_m \geq 179.42} \quad E_1 = \frac{785.79 - 3.78X_m}{X_m \geq 184.46} \quad E_1 = 0 \]

References:


Biographies:

Dheeraj Joshi was born in Kota, Rajasthan, India in 11th July 1978. He received B.E. (Electrical) degree from University of Rajasthan, Jaipur, India, in 1998 and M.E. (Power Apparatus and Electric Drives) degree from Indian Institute of Technology, Roorkee (Formerly University of Roorkee, Roorkee, India), in 2000. He joined Electrical Engineering Department, National Institute of Technology, Kurukshetra (Formerly Regional Engineering College, Kurukshetra) in September 2001. Currently, he is Lecturer in the same institute and doing PhD in the area of wind energy conversion. His areas of interest are artificial intelligence, power electronics, electric drives and self-excited induction generators. He is a Life Member of the Indian Society of Technical Education.

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