DYNAMIC SIMULATION, ANALYSIS AND CONTROL OF SELF-EXCITED INDUCTION GENERATOR USING STATE SPACE APPROACH

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Abstract: The Based upon state space approach, this paper presents a Matlab model which may be used to describe the transient behaviour of self-excited induction generator. An attempt has been made to design an electronic load controller with resistive as well as inductive elements as dump load to absorb excessive real and reactive power during mismatch of power generated and power required by the consumers. These It has also been observed that terminal voltage of the machine may be maintained, even in the absence of excitation and speed controllers.

Key words: Renewable energy source, Wind, Self-excited induction generator, Matlab

1. Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{ds}, V_{dr}, V_{qs}, V_{qr}</td>
<td>Stator and rotor d, q axis voltages</td>
</tr>
<tr>
<td>i_{ds}, i_{dr}, i_{qs}, i_{qr}</td>
<td>Stator and rotor d, q axis currents</td>
</tr>
<tr>
<td>V_{kl}, V_{ki}</td>
<td>d,q axis terminal voltage per phase</td>
</tr>
<tr>
<td>i_{kd}, i_{ki}</td>
<td>d,q axis load current per phase</td>
</tr>
<tr>
<td>V_{cd}, V_{eq}</td>
<td>d,q axis voltage across excitation capacitor per phase</td>
</tr>
<tr>
<td>i_{kd}, i_{eq}</td>
<td>d,q axis current in excitation capacitor per phase</td>
</tr>
<tr>
<td>L_{m}</td>
<td>Magnetizing inductance</td>
</tr>
<tr>
<td>I_{m}</td>
<td>Magnetizing current</td>
</tr>
<tr>
<td>\Psi_{m}</td>
<td>Magnetizing flux</td>
</tr>
<tr>
<td>w_{r}</td>
<td>Rotating speed in rad/sec</td>
</tr>
<tr>
<td>C</td>
<td>Exciting capacitance per phase</td>
</tr>
<tr>
<td>R_{r}, R_{e}</td>
<td>Stator and rotor resistance</td>
</tr>
<tr>
<td>L_{ds}, L_{dr}</td>
<td>Stator leakage reactance</td>
</tr>
<tr>
<td>R</td>
<td>Resitive load per phase</td>
</tr>
<tr>
<td>L</td>
<td>Inductive load per phase</td>
</tr>
<tr>
<td>P</td>
<td>Differential operator</td>
</tr>
</tbody>
</table>

2. Introduction

Due to rapid decrease in conventional power generating sources and radical increase in fuel cost, power generation through non-conventional sources using self-excited induction generator (SEIG) is gaining importance over the years. Besides low cost and pollution free power generation, wind is preferred for power generation due to its presence in abundance. SEIG is an externally driven induction machine with a capacitor bank connected across its terminals for self-excitation. Along with other features, SEIG has the scope to generate power for broad range of speeds which let the induction generator to get operated in self-excited/isolated mode [1-20]. This feature of SEIG is helpful to meet local energy demands of remote areas like Islands, river banks, remotely located villages, hilly areas where extension of grid is either not possible or uneconomical.

There are two approaches for analysis of SEIG: a) Steady state equivalent circuit approach wherein loop impedance method and nodal admittance method is used b) Generalized machine theory based approach which uses d-q modeling for analysis. The two approaches are not compatible with each other and the equations hence obtained cannot be used interchangeably [14]. The transient analysis of SEIG is presented by many authors [6-9]. For transient analysis, state space approach seems to be quite simple and has better way of representation of transient analysis of SEIG [18-19].

The major bottleneck in the usage of power generated by SEIG is poor voltage and frequency regulation. Researchers have proposed many control techniques to regulate voltage and frequency of SEIG [10-16]. Electronic load controller (ELC) is one of the methods to regulate voltage and frequency for constant power applications [15-17]. An electronic load controller is a set up connected in parallel to the
consumer load and work in such a way to control the terminal voltage and frequency for any load variation. An ELC normally consist of uncontrolled rectifier bridge, a chopper circuit and a resistor as dump load which enables to control real power of the machine. An excitation capacitance along with assistance in self-excitation process will also provide reactive power required by the load [5-6]. It has been assumed that total power generated by induction machine remain constant. So, the rating of capacitor bank in that case will be large and hence reduces overall efficiency of the system.

In this paper transient analysis of SEIG using d-q modeling of SEIG has been proposed with classical state space approach. All the non-linear parameters like main and cross flux are considered while determining the solutions of the equations in state space which otherwise has not been taken into consideration by many of the previous reported studies [8-9].

In this paper, for the first time an attempt has been also made, to develop an ‘ELC comprising of resistive and inductive elements’ as dump load to control both real and reactive power.

3. SEIG Modeling

Equivalent circuit of SEIG supplying inductive load, using d-q modeling is shown in Fig. 1. Matrix representation using classical state space approach for representation of generator dynamics is given by equation (1) and (2). This matrix represents the instantaneous voltage and current obtained during the self-excited process and also during the load variations [19].

The generalized dynamic SEIG model consists of eight differential equations in terms of \(i_{ds}, i_{qr}, i_{qs}, i_{q}, v_{ld}, v_{lq}, i_{ld}, \) and \(i_{lq}\) as given by equation (2).

These equations can be solved simultaneously using Runge-Kutta 4th order integration method.

Following assumptions are made during dynamic analysis of SEIG: 1) Except the magnetizing inductance \(L_m\), all the machine parameters are assumed to be constant. 2) Mechanical and core losses in the machine are neglected. 3) Load, stator windings and excitation capacitors are connected in star.

![Fig. 1 d-q axes based equivalent circuit of SEIG](image-url)

The non-linear relation of magnetizing inductance with magnetizing current can be obtained using synchronous speed test.
For machine-1 given in Appendix-1, the magnetization curve is represented as below:

\[ L_{m} = -6.89 \times 10^{-6} I_{m}^4 + 1.38 \times 10^{-4} I_{m}^3 - 1.22 \times 10^{-3} I_{m}^2 + 1.28 \times 10^{-3} I_{m} + 4.62 \times 10^{-2} \text{ henrys} \]  

(3)

where:

\[ I_{m} = \sqrt{(I_{ds} + I_{dr})^2 + (I_{qs} + I_{qr})^2} \]  

(4)

The residual magnetism is also taken into account, without which self-excitation seems to be impossible and hence initial voltage across excitation capacitance is also considered.

3.1 Self-excitation and load modeling

The capacitor voltages and currents in terms of d-q axes are given by equation (5) - (8) [19].

\[
V_{cd} = V_{ds} = V_{cq} = V_{qs} \tag{5}
\]

\[
i_{ds} = i_{cd} + i_{ld} \quad i_{qs} = i_{cq} + i_{lq} \tag{6}
\]

\[
V_{cd} = \frac{1}{C} \int i_{cd} \, dt + V_{cd} \bigg|_{t=0} \tag{7}
\]

\[
V_{cq} = \frac{1}{C} \int i_{cq} \, dt + V_{cq} \bigg|_{t=0} \tag{8}
\]

where \( V_{Cd} \bigg|_{t=0}, V_{Cd} \bigg|_{t=0} \) are the initial voltages of capacitors used for self-excitation, without which the voltage will not build up in SEIG. d-q axis load voltage and current is given by equation (9) - (12).

\[
V_{ld} = L \frac{d}{dt} i_{ld} + R i_{ld} \tag{9}
\]

\[
V_{lq} = L \frac{d}{dt} i_{lq} + R i_{lq} \tag{10}
\]

\[
\frac{d}{dt} i_{ld} = \frac{1}{L} V_{ld} - \frac{R}{L} i_{ld} \tag{11}
\]

\[
\frac{d}{dt} i_{lq} = \frac{1}{L} V_{lq} - \frac{R}{L} i_{lq} \tag{12}
\]

![MATLAB SIMULINK model of Self-Excited Induction Generator](image)

Fig. 2 MATLAB SIMULINK model of Self-Excited Induction Generator
Fig. 3 and Fig. 4 show the simulated results for voltage, current, active and reactive power, without any controller.

It is clear from Fig. 3 that terminal voltage varies with load variation. There is sudden rise or dip in terminal voltage when the load varies from full load to no load and vice-versa. Such variation in voltage at the load end is not permissible and it needs some control to maintain the power quality. These are due to the changes in real and reactive power of the load (Fig. 4).

5. Controller concept and model

The variation in terminal voltage and frequency is due to the imbalance in the power generated by generator and power absorbed by the load. The controller will regulate the terminal voltage and frequency of the generated power by balancing the real and reactive power produced and absorbed. The controller must be able to divert the extra power to the alternative load which is not absorbed by the consumer load.

In this paper an ELC is used as a controller connected in parallel with the load connected to SEIG. The ELC used consists of resistive and inductive elements as dump load along with uncontrolled rectifier-chopper system. The power absorbed by the dump load is controlled by duty cycle of the chopper to maintain the generated power equal to power consumed by the consumer load and the dump load. The duty cycle of the chopper depends on the difference between the reference terminal voltage and the actual voltage at the load end. The chopper will generate the gating signal to the insulated gate bipolar transistor (IGBT) which acts as a switch to control power input to dump load in ELC.

The control strategy of the IGBT’s used in controller is based on measuring the real and reactive power absorbed by the consumer load. The strategy is shown in Fig. 5. There are present five IGBT’s acting as switches. Fig. 6 depicts the steps of switching ON and OFF of IGBT’s using flow chart.
6. Results and discussion

It is clear from Fig. 3 that as the load varies, variation in terminal voltage appears and it results in variation of real or reactive power or both. This variation in terminal voltage can be controlled by varying excitation capacitance, rotor speed or load impedance. Increasing capacitance will increase the size of the system and reduces the overall efficiency of the system. The rotor speed range of such generators is limited. The electronic load controller will maintain the load on the machine and it is due to consumer and dump load. Hence it maintains the total power generated equal to total power absorbed by controlling resistive and inductive element present as dump load in the controller. The rms value of variation in terminal voltage and load current in SEIG with variation in load, using controller is shown in Fig. 7. Real and reactive power variation in load is shown in Fig. 8.

Fig. 9 shows variation of real and reactive power absorbed in dump load. It is clear from Fig. 8 and Fig. 9 that the sum of total power absorbed in consumer load and dump load will always remain constant at any instant of time in order to maintain constant terminal voltage. At No load (NL), whole of the power will be absorbed by dump load and in case of full load (FL), the consumer load will take the total power generated by the machine, hence maintaining the relation of power generated equal to power consumed. Fig. 10 and Table 1 gives a comparison of the terminal voltage of SEIG without controller and with controller. It is shown in Table 1 that with the use of controller, the percentage deviation of the terminal voltage of SEIG with the rated terminal voltage (i.e. 240v) is very low (minimum 0% and maximum of 3.8%) while this percentage deviation rises to very high value (minimum of 2.1% and maximum of 10.8%) in case of SEIG without using controller.
Fig. 7 Variation in terminal voltage and load current (with controller)

Fig. 8 Variation of real and reactive power in consumer load (with controller)

Fig. 9 Variation of real and reactive power in dump load
Conclusion

The paper proposed a nonlinear generalized state space dynamic model of self-excited induction generator for lagging power factor loads. It is shown that using d-q modeling in state space approach for SEIG, the transient analysis becomes an easy task. The terminal voltage obtained varies with the load variation and hence their utility decreases due to poor power quality supply. Here an attempt has been made to design an electronic load controller consisting of dump load having resistive and inductive elements in it, to control real and reactive power in order to maintain power generated equal to power consumed. Using such Electronic Load Controller will significantly reduce the variation in terminal voltage with variation in lagging power factor load.

Appendix

Machine-1

Induction machine specifications and parameters:

<table>
<thead>
<tr>
<th>Machine Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
</tr>
<tr>
<td>3HP</td>
</tr>
<tr>
<td>Rated line to Line voltage</td>
</tr>
<tr>
<td>440v</td>
</tr>
<tr>
<td>Rated frequency</td>
</tr>
<tr>
<td>50 Hz</td>
</tr>
<tr>
<td>Number of poles</td>
</tr>
<tr>
<td>4 poles</td>
</tr>
<tr>
<td>Stator resistance $R_s$</td>
</tr>
<tr>
<td>0.32Ω</td>
</tr>
<tr>
<td>Rotor resistance $R_r$</td>
</tr>
<tr>
<td>0.41Ω</td>
</tr>
<tr>
<td>Stator leakage reactance $X_{ls}$</td>
</tr>
<tr>
<td>0.8Ω</td>
</tr>
<tr>
<td>Rotor leakage impedance $X_{lr}$</td>
</tr>
<tr>
<td>0.8Ω</td>
</tr>
</tbody>
</table>

References


