Abstract

In this paper a theoretical approach has been developed to address the stability problem of permanent magnet synchronous generator (PMSG). It is used because of great advantages such as reliability and effectiveness. The proposed technique is obtained through three stages. First stage is to apply linear approximation to the original system. The second stage is to obtain the transfer function in Laplace domain. The last stage is to separate the unstable zero from the original system. Once it's separated a suitable feedback will be designed to treat the instability phenomena. The proposed technique is simulated and tested using MATLAB program. The results show that the developed approach proof to be a powerful tool for controlling the permanent magnet synchronous generator.

Keywords: Permanent Magnet Synchronous Generator (PMSG); Stability Analysis; Nyquist plot; PID control; Micro turbine; Multi input, Multi output system.

1. Introduction

Due to the great cost of power generation in economical and environmental sides, it became necessary to benefit from all accessible resources. Micro turbine introduces a very powerful solution for remote sites located far from the utility. It used variable speed wind turbine to create an autonomous system. Micro turbine system help avoid the
high costs of having utility power lines extended to a remote location add to that it has zero emission and pollution in the environment. It also helps uninterruptible power supplies ride through extended utility outages [1]-[3]. Permanent Magnet Synchronous Generator (PMSG) forms an important role as a main component of wind turbine. The wind is fed as an input to the generator at variable speeds. According to the input varies the output electricity. Permanent magnet synchronous generator offers a variety of advantages such as: reliability, compact size, loss reduction, higher power density and finally optimal efficiency [4]-[6]. In the last decades a lot of researches have been introduced in the control area of Permanent magnet synchronous generator. In 2006 Kenji Amei and his colleagues introduces a quite interesting solution to generate electricity at maximum point. The paper suggested using a boost chopper for generation control of Permanent magnet synchronous generator [7]. The technique is useful but it still doesn't solve the problem of transient stability. Another example is novel where, direct torque control (DTC) scheme for an interior permanent magnet synchronous machine is introduced. The proposed technique has great advantage as its simple control structure. On the other hand it only uses a controller for torque and I have no say on the flux and this might be quite not useful [8]. Finally one of the updated papers demonstrates a multiplatform hardware in-the-loop (HIL) approach to observe the operation of a high speed permanent-magnet synchronous generator coupled with a microturbine in an all-electric-ship power system [9]. Even though there are a lot of promising and powerful solution discussed in the past few years but not much of them deal with stability occurrence. Because of the nature of wind it's so hard to obtain a constant production of electricity at all times.

In this paper a new approach regarding permanent magnet synchronous generator stability is proposed. The strategy is build on the base of dealing with the transient stability occurs as a result of variable speed and nature of wind. The proposed technique is obtained through three stages. First stage is to apply linear approximation to the original system. The second stage is to obtain the transfer function in Laplace domain. The last stage is to separate the unstable zero from the original system. Once it's separated a suitable feedback will be designed to treat the effect of unstable zero. The paper is organized as follows. In section 2 permanent magnet synchronous generator modeling is recalled. The proposed control approach is introduced in section 3. Following that is the simulation and tested results. The results show that the approach proved to be a very powerful tool in treating and enhancing permanent magnet synchronous generator stability.

2. Permanent Magnet Synchronous Generator (PMSG) Modelling

The permanent magnet synchronous generator is represented in two phase synchronous rotor reference frame q-axis and d-axis. The electrical and mechanical model is going to be used to represent proposed model

The electrical equations [10]:

\[
\frac{di_d}{dt} = \frac{v_d}{l_d} - Rsi_d + \frac{1}{l_d} + \frac{l_d}{l_q} pwi_q
\]

\[
\frac{di_q}{dt} = \frac{v_q}{l_q} - Rsi_q - \frac{1}{l_q} + \frac{l_d}{l_q} pwi_d - \frac{p}\omega \tau
\]

\[
T_e = p(\tau i_q + (l_d - l_q) i_q)
\]
The mechanical equation [10]:

\[
\frac{dw}{dt} = \frac{1}{j} (T_e - f w - T_m)
\]  

(4)

\[
\frac{dw}{dt} = \frac{1}{j} (p l_d l_d i_d - p l_q l_d i_q + p \tau i_q - f i_q - T_m)
\]  

(5)

\[
\frac{dw}{dt} = \frac{1}{j} (p l_d l_d i_d - p l_q l_d i_q + p \tau i_q - f i_q - T_m)
\]  

(6)

Where,
- \(i_d, i_q\) Current of d&q axis
- \(l_d, l_q\) Inductance of d&q axis
- \(v_d, v_q\) D,q axis voltage
- \(R_s\) Stator winding resistance
- \(p\) Number of pole pairs
- \(w\) Angular velocity
- \(\tau\) Induced flux by stator
- \(j\) Inertia
- \(f\) friction
- \(T_m\) Shaft mechanical torque

The previous equations are going to be used to put system in the standard form:

\[
\dot{x} = f(x) + \sum_{i=1}^{m} g(x)_i u_i
\]  

(7)

State vector is chosen as follows:

\[
X(t) = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \\ \omega \end{bmatrix}, \quad U(t) = \begin{bmatrix} v_d \\ v_q \end{bmatrix}
\]  

(8)

\[
f(x) = \begin{bmatrix} \frac{\tau}{l_d} x_1 + \frac{i_q}{l_d} p x_2 x_3 \\ \frac{\tau}{l_q} x_2 - \frac{i_d}{l_d} p x_1 x_3 - x_3 \frac{p \tau}{l_d} \\ \frac{p l_d}{j} x_1 x_2 - \frac{p l_q}{j} x_1 x_2 + \frac{p \tau}{f} x_2 - \frac{f}{j} x_2 - \frac{T_m}{j} \end{bmatrix}
\]  

(9)

\[
g(x) = \begin{bmatrix} \frac{1}{l_d} & 0 \\ 0 & \frac{1}{l_q} \\ 0 & 0 \end{bmatrix}
\]  

(10)
3. Control Approach

In this section the control approach will be illustrated. First consider a class of multi input multi output non linear system

\[
\dot{x} = f(x) + \sum_{i=1}^{m} g(x)u_i \tag{11}
\]

\[
y_1 = h_1(x) \tag{12}
\]

\[
y_{1m} = h_m(x) \tag{13}
\]

In which \(f(x), g_1, \ldots, g_m\) are smooth vector field and \(h_1(x), \ldots, h_m(x)\) smooth function defined on an open set of \(\mathbb{R}^n\). For more simplicity the above equation will be rewritten in the more condensed form

\[
\dot{x} = f(x) + u \tag{14}
\]

\[
y = h(x) \tag{15}
\]

Where \(x \in \mathbb{R}^n\) is the state, \(u \in \mathbb{R}^m\) is the input, and \(y \in \mathbb{R}^l\) is the output. The system assumed to have equilibrium point at the origin \(X = 0, f(Xe) = 0\). The system relative degree \(r<n\) Euler system \([11]\) is applied to obtain linear approximation around equilibrium point, the result obtained as follows:

\[
f(x) = f(Xe) + (x - xo)\frac{\partial f}{\partial x} \bigg|_{x = xo} \tag{16}
\]

\[
g(x) = g(Xe) + (x - xo)\frac{\partial g}{\partial x} \bigg|_{x = xo} \tag{17}
\]

\[
h(x) = h(Xe) + (x - xo)\frac{\partial h}{\partial x} \bigg|_{x = xo} \tag{18}
\]

Consider:

\[
\delta = (x - xo) \tag{19}
\]

\[
\Delta = h(x) - h(Xe) , \text{ the new system is:}
\]

\[
\dot{\delta} = A\delta + Bu \tag{19}
\]

\[
\Delta y = c\delta \tag{20}
\]

Where \(A = \frac{\partial f}{\partial x}, B = g(0), C = \frac{\partial h}{\partial x}\)

After the system converted into linear form it became easier to obtain transfer function.

\[
T.F = \frac{C(SI - A)^{-1}}{B} = \frac{G(s)}{1 + G(s)H(s)} \tag{21}
\]
The next step is to separate the unstable part as follows:

\[
T.F = \frac{G'(s)}{D(s)} \cdot w(s)
\]

Where,

\[W(s)\] is the unstable part of the system

\[
\frac{G'(s)}{D(s)} = G'' \text{ is the stable part of the system}
\]

Subsequent is designing a suitable feedback \(E(s)\) to amend stabilization of the system. From the definition of closed loop system it is known that:

\[
T' = \frac{w(s)}{1 + w(s)E(s)}
\]

Assume \(w'(s)\) to be the desired stable function

\[
w'(s) = \frac{w(s)}{1 + w(s)E(s)}
\]

\[
\frac{w'(s)}{w(s)} = \frac{1}{1 + w(s)E(s)}
\]

\[
w'(s)(1 + w(s)E(s)) = w(s)
\]

\[
\frac{w(s)}{w'(s)} - 1 = w(s)E(s)
\]

\[
E(s) = \frac{w(s)}{w'(s)} - 1 \cdot \frac{1}{w(s)}
\]

\[
E(s) = \frac{1}{w'(s)} - \frac{1}{w(s)}
\]

\[
E(s) = \frac{w - w'}{ww'}
\]

From the general case a more specific concept can be extended regarding the improvement of zero stability. Figure 1 illustrate the steps for developed approach

\[w' = (s + c)\]

\[w = (s - x)\]

\(c\) is the desired zero, \(x\) is the unstable system zero
\[ s + c = \frac{s - x}{1 + (s - x)E(s)} \]  \hspace{1cm} (30)

\[ s - x = (s + c)(1 + (s - x)E(s)) \]  \hspace{1cm} (31)

\[ \frac{s - x}{s + c} - 1 = (s - x)E(s) \]  \hspace{1cm} (32)

\[ E(s) = \left( \frac{s - x}{s + c} - 1 \right) \cdot \frac{1}{s - x} \]  \hspace{1cm} (33)

\[ E(s) = \frac{1}{(s + c)} - \frac{1}{(s - x)} \]  \hspace{1cm} (34)

\[ E(s) = \frac{-x - c}{(s + c)(s - x)} \]  \hspace{1cm} (35)

According to stability definition the new zero "c" will vary between these bands

\[ 0 < c < \frac{1}{x} \]

3.1 Permanent Magnet Synchronous generator model after applying the approach

First step is to apply the linear approximation. Assume that the initial condition is at the origin and without loss of generality \( f(Xe) = 0 \). Followed by the system form is:

\[
A = \begin{bmatrix}
-\frac{R_s}{l_d} & \frac{1}{l_d} & \frac{1}{l_d} \\
-\frac{l_d}{p} & \frac{-R_s}{l_d} & \frac{-p \tau}{l_d} \\
\frac{p l_d}{j} & \frac{l_d}{p} & \frac{p \tau}{j} & f & 0
\end{bmatrix}, \quad B = \begin{bmatrix}
1 \\
0 \\
0 \\
0
\end{bmatrix}, \quad c = \begin{bmatrix}
1 \\
0 \\
0
\end{bmatrix}
\]

The following step is to design a suitable feedback \( E(s) \). The main idea is manipulating the zero in order to enhance the system stability.

\[ E(s) = \frac{-x - c}{(s + c)(s - x)} \]
Finally the new system can be represented as

\[ GH(S) = \frac{(s^2 + 2\omega_0^2 s + \omega_0^4)(s^2 + 2\omega_0^2 s + \omega_0^4)}{a_0 s^N + a_1 s^{N-1} + \cdots + a_N} \frac{s^3 + QS^2 + MS + V}{s^2 - 2\omega_0 s + \omega_0^2} \]  

(37)

Where

\[ Q = c - 2x, m = -x, c, V = cx^2, T = x \cdot c \]

4. Simulation and Results

In this paper, the stability of permanent magnet synchronous generator has been investigated. An approach has been introduced to refinement stability bandwidth and deal with transient stability problem. The permanent magnet synchronous generator has been modeled using Math Lab program. The values chosen for PMSG model is listed in Table 1. The work is progressed through three steps (shown in Fig.1):

![Fig.1 Work Progressed Diagram](image)

<table>
<thead>
<tr>
<th>PMSG</th>
<th>No of Poles</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rated Current</td>
<td>10A</td>
</tr>
<tr>
<td></td>
<td>Rated Speed</td>
<td>600 rad/sec</td>
</tr>
<tr>
<td></td>
<td>Armature Resistance</td>
<td>0.32ohm</td>
</tr>
<tr>
<td></td>
<td>Stator inductance</td>
<td>8.3mH</td>
</tr>
<tr>
<td></td>
<td>Rated Torque</td>
<td>60Nm</td>
</tr>
<tr>
<td></td>
<td>Rated power</td>
<td>50 kW</td>
</tr>
<tr>
<td></td>
<td>Magnetic flux linkage</td>
<td>0.42 wb</td>
</tr>
</tbody>
</table>

Table 1 PMSG Parameter

The first step is divided into two parts. The first part is to represent system in the non linear standard form:

\[ f(x) = \begin{bmatrix} -38x_1 + 0.2px_2x_3 \\ -20x_2 - 0.2x_1x_3 - 2x_3 \\ 6x_1x_2 - 4x_1x_2 + 2x_2 - T_m \end{bmatrix} \quad g(x) = \begin{bmatrix} 3.12 \\ 0 \\ 12 \end{bmatrix} \]

Second part is to implement the PMSG parameters into Mat Lab and run the program. Figure 2 show the rotor speed generated from Mat Lab simulink. It is clear that system response will suffer from some instability problem as the system goes beyond the required reference. Nyquist plot was chosen to analysis the whole system stability behaviour. Figure 3 shows the nyquist plot of the PMSG transfer function extracted from non linear form. The system will go beyond the limits of unity circle \(-1 < G(S)H(S) < 1\), which coincides with result generated from simulink model.
The second step is to execute the proposed control approach. The aim is to improve system stability whether to enlarge the range if it is too small or to reduce it if the situation verses. In this case the target is to enhance the stability by drove the system back in to the unity circle.

\[
A = \begin{bmatrix}
-38 & 0.1 & 0.4 \\
-20 & -0.2 & -2 \\
4 & 2 & 0
\end{bmatrix},
B = \begin{bmatrix}
3.12 & 0 \\
0 & 12 \\
0 & 0
\end{bmatrix},
c = \begin{bmatrix}
1 \\
0 \\
1
\end{bmatrix}
\]

The following steps is to designing a suitable feedback \( E(s) \). In order to determine the feedback, the value of zero "c’ will be assigned. According to Routh stability definition the value of new zero will be chosen to be \( c=0.5 \).

Final step is to feed the new parameter to the simulink to see the affect in the rotor speed. The Nyquist plot will be plotted with respect to new transfer function. Figure 4 and 5 show the rotor speed and nyquist plot respectively. It is clarified that the system stability is improved by the developed approach.
5. Conclusion

This paper is dedicated to investigate the instability of permanent magnet synchronous generator (PMSG). A developed approach is introduced to enhance system performance in the occurrences of instability. The work is progresses through three stages. First stage is to build the PMSG model. The second main stage is to execute the control approach. The technique is based on transforming system into Laplace domain by means of linear approximation and transfer function methods. After obtaining transfer function a suitable feedback will be designed. The value of the feedback varies according to the situations. Finally the last stage is to implement the new system in the MAT LAB and investigate the new system reliability. Nyquist and bode plot is used to rule the effectiveness of the proposed approach. The results show that the introduced control strategy prove to provide good results.

References