TRANSIENT STABILITY ASSESSMENT OF POWER SYSTEMS USING SUPPORT VECTOR MACHINE (SVM) WITH DISTRIBUTED GENERATION UNITS

HOOMAAN HOUSHMANDAN BEHBAHANI\textsuperscript{1a}, ALI ZANGANEH\textsuperscript{b}, BABAK ABDI\textsuperscript{c}

\textsuperscript{1a}Damavand Science and Research Branch, Islamic Azad University, Tehran, Iran.
\textsuperscript{b}Electric And Computer Faculty, Shahid Rajaee Teacher Training University, Tehran, Iran.
\textsuperscript{c}Department Of Electrical Engineering, Azad University Damavand Branch, Tehran, Iran.

ABSTRACT

The main purpose of this paper is to evaluate the transient stability of power systems with increased penetration level of distributed generation resources based on calculating the maximum rotor speed deviation index. In this method, the transient stability of power systems with increased penetration level of distributed generation resources evaluated and the results in an operating point for different studied modes are trained by means of support vector machine (SVM). Then in terms of loading and different penetration level of distributed generation resources, the stable and unstable systems approximated and estimates.

KEYWORDS: Distributed Generation, Support Vector Machine, Maximum Rotor Speed Deviation, Transient Stability.

Nowadays the tendency of distributed generations on future power systems for technical, environmental and economical reasons is increased. Significant use of distributed generation in a power system, transform vertical power systems to horizontal one. Thus the power can flow both 'vertically', i.e. from the higher to the lower voltage levels, as well as ‘horizontally’ from one MV or LV network to another or from a generator to a load within the same MV or LV network leading to a new term.

It is well-known that the implementation of DG influences the technical aspects of the distribution grids. The impact of a small amount of DG connected to the grid on the power system transient stability is not significant. When the penetration level of DG increases, its impact is no longer restricted to the distribution network but begins to influence the whole system.

(M. Reza et al., 2005) presents a scenario of a ‘vertical-to-horizontal’ transformation of power systems and analysis the impacts on the power system transient stability. This paper assumed that the load is constant, thus increasing the penetration level of DGs may shut down the most inefficient units when the power output falls below their minimum generated power requirement. In (M. Reza et al., 2003) the impact of DG on the transmission system transient stability is investigated by considering different types of DG technologies and various penetration levels. The maximum rotor speed deviation and the oscillation duration are two indicators that is used to assess transient stability. In (M.Z.C Wanik et al., 2010) transient stability of the power system with the large penetration of wind turbine connected to LV levels operating parallel with large wind turbine connected to HV bus is studied. Grid code which demands fault ride through and at the same time providing a reactive support, is considered. The impacts of synchronous and asynchronous generator interfaced DGs on power system transient stability are investigated more analytically in (Davood Khani et al., 2012). Investigation about the transient stability of a real distribution system with multi distributed synchronous generators that all modeled as sixth order round rotor studied in (Lisias et al., 2004).

In this paper the impacts of distributed generation units with synchronous generator and solar cell technology on IEEE 9 bus test system for various penetration levels of distributed generation based on maximum rotor speed deviation indicator is investigated. Then support vector machine (SVM) trained by this results. Finally, the trained SVM has been used to estimate the influence of transient stability of the system for other penetration levels of DGs.

The structure of this paper is to proceed as follows. In Section 2, the method of transient stability assessment and indicator are provided. The overall structure of the support vector machine (SVM) is presented in Section 3. Section 4 deals with the stated problem and simulation results. The conclusion is presented in Section 5.

Method for assessing the transient stability and indicator

Large-disturbance rotor angle stability or transient stability referred to the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship (P. Kundur et al., 2004).

Transient stability depends on the initial operating state of the system and the type, severity and location of the

\textsuperscript{1a}Corresponding author
disturbance. Instability is usually in the form of aperiodic angular separation due to insufficient synchronizing torque, manifesting as first swing instability. However, in large power systems, transient instability may not always occur as first swing instability.

As identified in Figure 1, transient stability are categorized as short term phenomena. There are many different methods for transient stability analysis in power systems based on the swing equation. During the normal operation, the relative position of the rotor axis and outcome axis is fixed. When the disturbance applied to the machine, the rotor with respect to the magneto motive force of air gap, accelerate or decelerate.

Swing equations of a power system is as follows:

1. \[ \int \frac{d^2 \beta_m}{dt^2} = T_m - T_e \]

   with \( \beta_m \) the angular displacement of the rotor with respect to a stationary axis and \( T_e \) is net accelerating torque. \( T_m \) and \( T_e \) are the driving torque of the prime mover and the net electromagnetic torque, respectively. The inertia of rotor is showed as \( J \). The machine is said to be working in synchronous speed (or in synchronism) if \( T_a = 0 \), i.e. \( T_m = T_e \) (M. Reza et al., 2004).

The angular displacement(\( \beta_m \)) can be written as:

2. \[ \beta_m = \omega_m t + \delta_m \]

   where \( \delta_m \) is the angular displacement of the rotor from the synchronously rotating reference axis. By introducing the angular velocity of the rotor from the synchronously rotating reference axis \( \omega_m = \frac{d\beta_m}{dt} \) for a convenient notation and twice differentiating (2) with respect to time, combining it with (1) and recalling that power (P) equals torque (T) times angular velocity (\( \omega \)) one arrives at the equation:

3. \[ M \frac{d^2 \delta_m}{dt^2} = P_a = P_m - P_e \]

   where \( M = J\omega_m \) is the inertia constant of the machine, and \( P_a \), \( P_e \) and \( P_m \) are the accelerating, the electrical and the mechanical power, respectively. The above equation (3) can be further normalized in terms of unit inertia constant H, defined as the kinetic energy at rated speed divided by the rated apparent power of the generator \( \frac{S_{\text{mach}}}{\text{mach}} \) as:

\[
4. \quad H = \frac{1}{2} \frac{\omega_0^2}{2 \text{mach}}
\]

Or

\[
5. \quad H = \frac{1}{2} \frac{\omega_0}{2 \text{mach}}
\]

Yielding

\[
6. \quad \frac{2H \frac{d^2 \delta_m}{dt^2}}{\omega_m} = P_a = P_m - P_e
\]

Moreover, by noting that both \( \delta_m \) and \( \omega_m \) are expressed as mechanical speed, provided both \( \omega \) (the synchronous speed of the rotor) and \( \delta \) (the angular displacement of the rotor from the synchronously rotating reference axis) have consistent units, (6) can be written as

\[
7. \quad \frac{2H \frac{d^2 \delta}{dt^2}}{\omega} = P_a = P_m - P_e
\]

Equation (7) is called the swing equation of the machine. It is the fundamental equation in the stability study, governing the rotational dynamics of a synchronous machine.

However, when simulations are to be done on large power systems, as well as on a more general case than a simple power system (e.g. two-machine system or one machine infinite bus system) cannot be explicitly found without computer simulation. One of the practical methods is the time-domain numerical integration method (the step-by-step time domain simulation), where used in this paper.

**Maximum rotor speed deviation**

The maximum rotor speed deviation is defined as the maximum rotor speed value attained during the transient phenomenon (M. Reza et al., 2005).

This indicator is proposed to assess the rotor-angle-stability performance of (centralized) synchronous generators that drive a transmission system with limited inertia. It suggests that the more/faster the rotor speed (of the synchronous generators) deviates from the rated value when a disturbance occurs, the more unstable the system becomes. Thus when two cases are compared, as a fault is simulated, at a certain clearing time a higher maximum rotor speed deviation (the faster the rotor accelerates) suggests a lower stability margin (M. Reza et al., 2005).

---

**Figure 1: Classification of power system stability.**
Support Vector Machine (SVM)

One of the most effective human abilities are learning abilities. When a problem in a new domain is introduced to a person, the ability to solve the problem by this person compared to an expert person is very small. But over the time, amateur people by means of trial and error and induction ability can know the environment and improve their ability to solving problem.

There is a general algorithm same as humans that can be used as a mechanism for learning. Thus, the planner will be able to change their behavior in dealing with any issue. For this purpose it is necessary to extract knowledge from domain, and by this knowledge some parts of the algorithm will be changed.

Support Vector Machines (SVMs) were first introduced by Vladimir Vapnik between the late seventies and early eighties (Vapnik, 1982) and they are based on the Structural Risk Minimization (SRM) principle from statistical learning theory.

In antithesis to the Empirical Risk Minimization principle, which is used by neural networks to minimize the error on the training data, SRM minimizes a bound on the test error, thus allowing SVMs to generalize better than conventional neural networks.

The VC dimension is a property of a set of functions \( \{f(\alpha)\} \). Here we will only consider functions that correspond to the two-class case, so that \( f(x, \alpha) \in \{-1, 1\} \forall x, \alpha \).

Now if a given set of 1 points can be labeled in all possible \( 2^j \) ways, and for each labeling, a member of the set \( \{f(\alpha)\} \) can be found which correctly assigns those labels, we say that, that set of points is shattered by that set of functions. The VC dimension for the set of functions \( \{f(\alpha)\} \) is defined as the maximum number of training points that can be shattered by \( \{f(\alpha)\} \).

Suppose that the space in which the data live is \( R^2 \), and the set \( \{f(\alpha)\} \) consists of oriented straight lines, so that for a given line, all points on one side are assigned the class 1, and all points on the other side, the class \(-1\).

The VC dimension thus gives concreteness to the notion of the capacity of a given set of functions. Note that if the VC dimension is \( h \), then there exist at least one set of \( h \) points in input space that can be shattered. This does not mean that every set of \( h \) points can be shattered by a given set of indicator functions (see figure 4) (Vojislav Kecman et al., 2001).

Vapnik and Chervonenkis described the Generalized Portrait algorithm for constructing separating hyperplanes from empirical data. This learning algorithm was proposed for separable problems and it is based on the fact that among all possible separating hyperplanes there exists a unique one with maximum margin of separation from the classes (an optimal margin hyperplane) and the capacity decreases with increasing margin (figure 5) (Konstantinos Veropoulos).
from [16]. Fig. 6 shows the test system used throughout the simulations.

![Figure 6. IEEE 9 bus test system.](image)

The impacts of DG on power system transient stability are evaluated by investigating the following two different technologies:

a. Synchronous generator with grid voltage and frequency control,
b. Solar cell with grid voltage and frequency control.

For the central synchronous generator, a standard round rotor generator model with AVR type II is used. The synchronous DG was modeled as 4th order synchronous generator with AVR type II [16]. The solar cell are modeled as a source of active power (P) and reactive power (Q) [17]. The loads are modeled in constant impedance.

The following cost function with constrains was assumed for central synchronous generators that updated active power for each penetration level of DGs:

9. \[
\begin{align*}
F_1 &= 150 + 5P_1 + 0.11P_1^2 \quad 50 \leq P_1 \leq 250 \\
F_2 &= 150 + 5P_2 + 0.11P_2^2 \quad 50 \leq P_2 \leq 250 \\
F_3 &= 335 + P_3 + 0.1225P_3^2 \quad 75 \leq P_3 \leq 270 
\end{align*}
\]

The DG penetration level in the system is defined as:

10. \[
PL = \frac{P_{DG}}{P_{Load}} \times 100\% 
\]

where \(P_{Load}\) is the total amount of real load within the test system and \(P_{DG}\) is the total amount of real power generated by the DG.

In this simulation distributed generation units are connected through a transformer to the load bus. Thus the penetration level are equally divided between three DG units.

The transient stability of the test system is investigated by applying a permanent three-phase fault to all possible branches cleared by tripping the faulty line after 150 ms with 26 scenario for increasing penetration level up to 50%.

As an example, the simulation results of applying a fault on bus 7 and clearing by tripping the faulty line between bus 5 and 7 is presented. The transient stability of system with penetration levels of distributed generation in steps of 2% (even penetration levels) by the index of maximum rotor speed deviation for each of the main synchronous generator by means of PSAT is investigated. By use of data taken from time domain simulation, support vector machine by means of LIBSVM is trained and for the other penetration level (odd penetration level) transient stability are estimated. Finally the estimation results of the stability/instability of the support vector machine are compared with the results of time domain simulation of odd penetration levels.

The results of simulation showed that using distributed generation depends on location, the size and the technology has a great impact on the transient stability of the system.

The results for the time domain simulation without DG are presented in Figure 7. Figures 8 and 9 showed rotor speeds of main generator at penetration level of 24% and 44%, respectively.

![Figure 7. Rotor speeds of synchronous generator versus time without DG](image)
Figure 8. Rotor speeds of synchronous generator versus time for 24% penetration level of distributed generation based on synchronous generator and Solar cells, respectively.

Figure 9. Rotor speeds of synchronous generator versus time for 44% penetration level of distributed generation based on synchronous generator and Solar cells, respectively.

According to the results of the time domain simulation, if the penetration level of distributed generation reach 24% (Fig 8), the power of generator 3 is based on constraint of cost function goes under minimum power and therefore this unit is shutting down.

This caused the network to become unstable in the presence of solar cells while in the presence of distributed generation based on synchronous generator due to the inertia, the network is stable.

With training support vector machine (SVM) based on RBF kernel and Precomputed kernel, the estimation of the other state has done with good accuracy that can reduce the simulation time of larger networks.

Table 1. Comparison the results of estimation from SVM based on training data with time domain simulation for distributed generation based on synchronous generator.

<table>
<thead>
<tr>
<th>Penetration Level [%]</th>
<th>Time Domain Simulation</th>
<th>SVM Kernel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RBF</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>21</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>23</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>27</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>29</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>31</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>33</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>35</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>39</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>41</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>43</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>45</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>47</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>49</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Accuracy 96% 96%

Table 2. Comparison the results of estimation from SVM based on training data with time domain simulation for solar cell

<table>
<thead>
<tr>
<th>Penetration</th>
<th>Time</th>
<th>SVM Kernel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 10 presented the maximum rotor speed deviation for all penetration levels. Support vector machine based on data taken from time domain simulation (even penetration level) trained and estimated through the other levels (odd penetration level) according to Tables 1 and 2. In order to determine the accuracy of the estimation, results of support vector machine compared with time-domain simulation of penetration levels that had not been previously simulated. As it is clear from the tables based on the limited training, support vector machine is able to accurately estimate the transient stability of the system.

<table>
<thead>
<tr>
<th>Level [%]</th>
<th>Domain Simulation</th>
<th>RBF</th>
<th>Precomputed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>21</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>23</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>25</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>27</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>29</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>31</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>33</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>35</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>39</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>41</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>43</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>45</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>47</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>49</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Accuracy</td>
<td>100%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

Figure 10. Maximum Rotor Speed Deviation index with penetration level of distributed generation based on synchronous generator and Solar cells, respectively.

CONCLUSION

The transient stability analysis at constant load with different penetration levels of DG technologies based on synchronous generators and solar cells has been carried out. Based on the simulations, the power of main synchronous generator for maintaining the power balance of the system, decreases. Specific features of distributed generation units and their low inertia, regardless of system stability create a lot of technical and operational challenges. Distributed generation units are installed near the load, so this arrangement feeding part of the load by distributed generation sources and the remainder will be supplied by main synchronous generators.

The terms of oscillatory behavior of network during a small disturbance depends on network structure, operating condition and controller configuration. Due to economic conditions, a conventional power grids operate near the limit of stability.

From the simulation results application of distributed generation reduces the maximum rotor speed deviation. This indicator suggest that the use of distributed generation units sufficiently improves transient stability. It means by increasing
the penetration level of distributed generator, the maximum rotor speed deviation is reduced.

Due to location of distributed generation that are near load centers it is expected that the voltage profile in the distribution network improved. The use of distributed generation reduces the power losses of the entire network due to the reduction of power transferred from the HV network.

In modeling of solar cells in the form of active power P and reactive power Q source, because controllers create a constant active power, so reactive power does not drop sharply. Based on what was described earlier and identified by the simulation results, this technology of distributed generation does not contribute in the system inertia (kinetic energy storage). According to economic dispatch and power updated of main synchronous generators at each penetration level, when unit 3 (23% penetration level of distributed generation) is removed from network, this technology has not been able to balance power and consequentially unstable condition appeared.

As it is clear from the estimation results of SVM for two different kernel based on training data on the steps of 2% penetration level of distributed generation, other states estimated more accurate. Furthermore, by using of support vector machine for evaluating transient stability, simulation time should be avoided.

REFERENCES


Klaus-Robert Müller, Sebastian Mika, Gunnar Rätsch, Koji Tsuda, and Bernhard Schölkopf. An Introduction to Kernel-Based Learning Algorithms.
