Transient stability based dynamic security assessment indices

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Waheed Ayinla Oyekanmi¹, Ghadir Radman² and Titus Oluwasuji Ajewole*¹

Abstract: As power systems become increasingly stability constrained, the need for dynamic security assessment (DSA) becomes important. However, the resources and technology required to achieve on-line DSA at reasonable cost for utility companies are not easily come by. Therefore, an offline method is needed to examine and screen all likely contingencies to determine those that may lead to instability. Some indices and techniques have been proposed to tackle this problem but are mostly for small disturbances which are not really threats when timely cleared. Some methods are based on evolutionary computation which comes with a lot of drawbacks as there is no guarantee of finding optimal solutions within a finite time and parameter tuning are mostly by trial-and-error. In this paper, a simpler approach to power system DSA indices is proposed using time domain transient stability analysis simulations. A conventional power system which synchronous machines are modeled with two-axis dynamic model, and modeled by Differential and Algebraic Equations, is used and solved numerically taken advantage of MATLAB ODE solver. The proposed indices are tested by carrying out $N-1$ contingency on the transmission network of an IEEE 57-Bus test system to determine contingency cases that are likely to lead to system instability. The indices are validated by comparing their results with those obtained through an established DSA index called Angle Index in literature. Finally, effects of synchronous machine models on the indices are tested by comparing the results of the proposed functions with those obtained through synchronous machine classical model.

Subjects: Power & Energy; Systems & Control Engineering; Electrical & Electronic Engineering

Keywords: angle index; differential and algebraic equations; dynamic security assessment; transient stability

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PUBLIC INTEREST STATEMENT
The complexity of electrical power system grids has made them vulnerable to instability due to some unforeseen circumstances such as faults. Therefore, there is a need for tools which can be used to capture the state of the power systems under different contingencies. These tools will be helpful for system planners and operators to foresee the behaviour of power systems and therefore plan against any undesirable events. In this paper, dynamic security indices are presented which can be used to determine the state of power systems using time-domain simulations. These indices can give useful information to power system planners to plan for credible contingencies and therefore ensure the reliability of the grid.
1. Introduction

The continuous increase in human activities or power consumptions has made power systems to become security constrained. Security in power systems is categorized into two groups namely: Static Security Assessment (SSA) and Dynamic Security Assessment (DSA). A lot of research work has been done in the area of SSA with tangible results achieved. In SSA, load flow constitutes the basis of assessments and limit violations are adequately evaluated. However in the DSA, little has been achieved regarding power system assessments under contingencies. Inability to accurately capture and determine the security level in terms of DSA is detrimental to reliability of the system which can lead to system instability during a credible contingency.

In DSA state responses are computed and evaluated for the possibilities of instability. As power systems become increasingly stability constrained, the need for DSA becomes important. However, the resources and technology required to achieve on-line DSA at a reasonable cost for large power systems are somehow difficult to come by today for small power or utility companies. Therefore, an offline method is still very much needed by the utility to examine and screen all likely contingencies to determine those that may lead to instability for planning and operation purposes.

Several techniques and approaches have been put forward by researchers to address the issue of DSAs. Some of the recent techniques are risk-based or probabilistic, pattern recognition approach or time domain analysis techniques. For instance, Preece and Milanovic (2015), Dissanayaka, Annakkage, Jayasekara, and Bagen (2011), and da Silva, Violin, Ferreira, and Machado (2014) proposed risk-based approaches. Preece and Milanovic (2015) proposed a risk-based probabilistic small-disturbance security analysis methodology for use with power systems with uncertainties. In the work, probability density function is established for damping of the critical oscillatory electromechanical modes by modeling the stochastic variation of system uncertainties. This approach did not give account for large disturbances which are the main concern in DSA. In Dissanayaka et al. (2011), risk-based DSA is also presented where a linearized technique to determine a risk-based index for dynamic security is proposed. The research work as presented in da Silva et al. (2014) proposed a new methodology to evaluate the criticality of electrical substations taking into accounts their possible operating states, and associate probabilities; tow reliability indices are then presented to express the dynamic and static adequacy levels that a substation provides to the power network. Pattern discovery-based fuzzy classification scheme is proposed for DSA in Luo (2015). The pattern discovery algorithm is improved by integrating the proposed centroid deviation analysis technique and the prior knowledge of the training data-set. This approach is however difficult to implement if the prior knowledge of the training data-set is vague.

In recent years, several severity indices have also been proposed for DSAs for large power systems. In Sevilla and Vanfretti (2014), time-domain simulation technique is used to present a small-signal stability index for power system dynamic impact assessment. The index is calculated from an estimate of the eigenvalues of the system, which are determined using time-series from dynamic simulations. This index as presented suffers a drawback when large disturbances which are the causes of instabilities. In the same vein, time series from dynamic simulations is also used in Vanfretti and Sevilla (2015) to propose a three-layer severity index for power system voltage stability assessment. In the first layer, a two-element vector indicates if a power or voltage limit was violated while in the second layer a vector is used to specify which power and voltage loading level was violated. Finally, the third layer a matrix is used to retrieve precise information about which power and voltage limit has been violated in pre- or post-contingency. Several indices are presented in Grillo, Massucco, Pitto, and Silvestro (2010) and Ming, Song, Shi, and Kuo (2010) for DSA. In Grillo et al. (2010) for example, some practical and heuristic indices for fast contingency ranking in large power systems based on transient stability are proposed. The proposed indices are basically classified into two called Individual Transient Instability Indices (ITI) and Global Transient Instability Indices (IGI). Ming et al. (2010) provide some indices and methods for power system security assessment based on dynamic fuzzy theory. Some of the methods presented are based on the element transient security-angle stability discriminant index, frequency stability discriminant index, and transient voltage stability discriminant index.
In Kamwa, Samantaray, and Joos (2010), Dehghani, Shayanfard, and Khayatian (2013) and He, Vittal, and Zhang (2013), phasor measurement unit (PMU) approaches to DSA are proposed. In Kamwa et al. (2010), Catastrophe predictors from ensemble decision-tree learning of wide-area severity indices are presented. The wide area severity indices derived from PMU measurements serve as the basis for building fast catastrophe predictors using random-forest learning. PMU ranking based on singular value decomposition of dynamic stability matrix is presented in Dehghani et al. (2013). In this approach PMUs are placed on the buses which can provide the most useful information for assessing dynamic stability. However in the work presented by He et al. (2013), a data mining approach is used for online DSA with missing PMU measurements. Ensemble decision trees learning are used with the objective of mitigating the impact of possibly missing PMU data.

Intelligent system (IS) algorithms are fully used in Xu (2012a, 2012b) for power systems DSAs. While Xu (2012a) looked at an intelligent DSA framework for power systems with wind power, Xu (2012b) proposed a reliable intelligent system for real-time DSA of power systems without wind powers. The work in Xu (2012a) basically consists of a DSA engine whose role is to perform real-time DSA of the power system, a wind power and load demand forecasting engine for offline and online predicting wind power generation and electricity load demand, a database generation engine for generating instances to train the DSA engine, and a model updating engine for online updating the DSA. In Kamwa, Samantaray, and Joos (2009), rule-based classifiers for rapid stability assessment of wide-area post-disturbance records are developed for use in DSA. The classifiers are initialized by large accurate decision trees. The technique is usually started by strategically select monitoring buses where PMUs are placed to capture the wide-area response signals in real-time operation.

Furthermore, looking at the research work presented in Liu (2014), a systematic approach for DSA is proposed. The corresponding preventive control scheme based on decision trees is also presented. This technique adopts a new methodology that trains two contingency-oriented decision trees on a daily basis by the databases generated from power system simulations and a cost-effective algorithm is adopted to optimize the trajectory of preventive control. In order to reduce the computation burden associated with time domain simulations for DSA, Huang, Chen, Shen, Xue, and Wang (2012) proposed feasibility study on online DSA through distributed time domain simulations in a wide area network (WAN). A high performance distributed transient simulation algorithm is also presented in Heyde and Styczynski (2009), Han, Zheng, Tian, and Hou (2009) and, Yare and Venayagamoorthy (2010), DSAs with respect to voltage and angle stability are presented. In Heyde and Styczynski (2009) and Han et al. (2009), voltage stability analysis as part of an online DSA system is presented and some indices and their algorithms based on the time domain simulations are proposed. The online DSA algorithms as proposed by Heyde and Styczynski (2009) collects information from four different modules, the voltage stability module, small signal stability module, the transient stability module and the protection module while in Han et al. (2009), voltage stability assessment is based on Back Propagation (BP) Neural Network. However, in the work of Yare and Venayagamoorthy (2010), the authors proposed some indices for DSA based on real-time transient stability assessment of a power system during energy generation shortfall. Some of the indices presented are Real-Time Transient Stability Index (TSAI), Dynamic Voltage Index (DVI), and Quasi-Stationary Voltage Index (QSVI).

In this paper, transient stability based severity indices are proposed by using time-domain simulations to determine the severity of a disturbance at any time and consequently the dynamic stability state of the power system, modeled by differential and algebraic equations (DAE), and under a large disturbance. The structure of this paper is as follows. Section 2 gives the detailed DAE models of power systems with conventional sources while the detailed formulation of the proposed DSA severity indices and functions are given in Section 3. Section 4 describes the simulation procedures and results while Section 5 discusses the results and the work is concluded in Section 6.
2. Power system modeling

In this section, power system DAE model is presented, as well as two different synchronous machine dynamic models used for power systems. The DAE model are presented as given in Sauer and Pai (1998). These are two-axis dynamic and classical models of synchronous machines.

2.1. Synchronous machine two-axis dynamic model

Using \( d-q \) axis transformation and synchronous reference frame, and if the stator or network and fast damper winding dynamics are eliminated then the two-axis model along with IEEE type-I exciter and governor dynamics are as given in Sauer and Pai (1998) as follows:

\[
T_{\text{do}} \frac{dE_q}{dt} = -E_q' - (X_{di} - X_{dq}) I_{di} + E_{fdi} 
\]

\[
T_{\text{qo}} \frac{dE_d}{dt} = -E_d' + (X_{dq} - X_{di}) I_{dq} 
\]

\[
\frac{d\delta}{dt} = \omega_i - \omega_s 
\]

\[
\frac{2H}{\omega_s} \frac{d\omega_i}{dt} = T_M - E_d' I_{di} - E_q' I_{dq} - (X_{dq} - X_{di}) I_{di} - D_i (\omega_i - \omega_s) 
\]

\[
T_{\text{ei}} \frac{dE_{fdi}}{dt} = -(K_{\text{ei}} + S_{\text{ei}} (E_{fdi})) E_{fdi} + V_{ri} 
\]

\[
T_{\text{fi}} \frac{dR_{fi}}{dt} = -R_{fi} + \frac{K_{\text{ei}}}{T_{\text{fi}}} E_{fdi} 
\]

\[
T_{\text{ai}} \frac{dV_{ri}}{dt} = -V_{ri} + K_{\text{ai}} R_{fi} - \frac{K_{\text{ai}} K_{\text{fi}}}{T_{\text{fi}}} E_{fdi} + K_{\text{ai}} (V_{\text{refi}} - V_{ui}) 
\]

\[
T_{\text{chii}} \frac{dT_M}{dt} = -T_M + P_{svi} 
\]

\[
T_{svi} \frac{dP_{svi}}{dt} = -P_{svi} + P_{ci} - \frac{1}{R_{di}} \left( \frac{\omega_i}{\omega_s} - 1 \right) 
\]

Equations (1)–(9) represent the two-axis dynamic model of a synchronous generator including the speed governor dynamics and IEEE Type-I exciter. These equations also represent the differential equation part of a DAE model of a power system. The algebraic equations are obtained from synchronous machine two-axis dynamic circuit model stator and network algebraic equations (Oyekanmi, Saladi, & Radman, 2014; Sauer & Pai, 1998).

The stator algebraic equations are given in (10) and (11).

\[
E_q' - V_i \cos (\delta_i - \theta_i) - R_{si} I_{di} - X_{dq} I_{di} = 0 
\]

\[
E_d' - V_i \sin (\delta_i - \theta_i) - R_{si} I_{dq} + X_{di} I_{dq} = 0 
\]
The network algebraic equations are obtained when the two-axis dynamic model circuit of the synchronous machine is interconnected with the static network and load. Consider the interconnection of \( m \) number synchronous machines with the rest of the network in a power system which consists of \( n \) number of buses and \( n - m \) number of load, then the following equations can be written load flow as network algebraic equations.

\[
I_{q1}V_i \sin (\delta_i - \theta_i) + I_{d1}V_i \cos (\delta_i - \theta_i) - P_{e1}(V_i) - \sum_{k=1}^{n} V_k V_k Y_{ik} \cos (\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (12)
\]

\[
I_{d1}V_i \cos (\delta_i - \theta_i) - I_{q1}V_i \sin (\delta_i - \theta_i) - Q_{e1}(V_i) - \sum_{k=1}^{n} V_k V_k Y_{ik} \sin (\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (13)
\]

\[
i = 1, 2, \ldots, m
\]

\[
P_{e1}(V_i) - \sum_{k=1}^{n} V_k V_k Y_{ik} \cos (\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (15)
\]

\[
Q_{e1}(V_i) - \sum_{k=1}^{n} V_k V_k Y_{ik} \sin (\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (16)
\]

\[
i = m + 1, \ldots, n
\]

Therefore, (1)–(17) represent the DAE model of a multi-machine power system using synchronous machine two-axis dynamic model with its various controls (excitation and speed governor dynamics).

### 2.2. Synchronous machine classical model

The classical model of a synchronous machine is given by the following two differential equations as given in Sauer and Pai (1998) and Oyekanmi et al. (2014):

\[
\frac{d\delta_i}{dt} = \omega_i - \omega_s \quad (18)
\]

\[
\frac{2H_i}{\omega_s} \frac{d\omega_i}{dt} = T_{Mi} - \text{Real} \left[ E_{i}^{\omega} e^{j(\delta_i - \omega_s t)} \left( I_{di} + jI_{qi} \right) e^{-j(\delta_i - \omega_s t)} \right] - D_i(\omega_i - \omega_s) \quad (19)
\]

where \( E_{i}^{\omega} \) is the assumed constant voltage behind the direct transient reactance and is defined by:

\[
E_{i}^{\omega} \triangleq \sqrt{(E_{di}^{\omega} + (X_{qi}' - X_{di}')T_{qi})^2 + (E_{qi}^{\omega})^2} \quad (20)
\]

and the constant angle, \( \delta_{i}^{\omega} \), is defined by the following equation

\[
\delta_{i}^{\omega} \triangleq \tan^{-1} \left( \frac{E_{qi}^{\omega}}{E_{di}^{\omega} + (X_{qi}' - X_{di}')T_{qi}} \right) - \frac{\pi}{2} \quad (21)
\]

Similarly, algebraic constraints can be obtained from the synchronous machine classical model dynamic circuit as given in Sauer and Pai (1998) as follows:

\[
V_i e^{j\theta_i} + (R_{di} + jX_{di}') \left( I_{di} + jI_{qi} \right) e^{j(\delta_i - \omega_s t)} - E_{i}^{\omega} e^{j(\delta_i - \omega_s t)} = 0 \quad (22)
\]
Note very importantly that all the variables and parameters are in per-unit except rotor angle, rotor speed/frequency, and Bus angle ($\delta_i$, $\omega_i$, and $\theta_i$).

3. Proposed severity indices and functions

When a power system is subjected to a large disturbance, the algebraic variables change instantly while the dynamic variables may need some transient time to change in state values. Upon clearing the fault, the variables are expected to return to their initial operating values or attain a new and acceptable steady state operating values. However, this is not always the case due to the severity of the disturbance in question. Consider the dynamic response to a disturbance of a state variable related to a machine as shown in Figure 1.

At time $t_1$ a large disturbance occurred and cleared at $t_2$. At any time $t$, the severity of the fault can be determined based on the deviation from the initial steady state operating point $x(t_o)$. The severity index is the weighted sum of squares of error and can be defined as given in (27)–(30):

$$SI(t) = 1/m \sum_{i=1}^{m} \sum_{j=1}^{k} w_{ij} \left( x_{ij}(t) - x_{ij}(t_o) \right)^2$$

$$SI = 1/m \int_{0}^{\infty} \sum_{j=1}^{k} w_{ij} \left( x_{ij}(t) - x_{ij}(t_o) \right)^2 dt$$

$$\sum_{j=1}^{k} w_{ij} = 1$$

$$w_{1j} = w_{2j} = w_{3j} = \cdots = w_{mj} \forall j$$

where $w_j$ is the weight associated with the state variable $x_j$, $m$ is the number of machines and $k$ is the number of the state variables. Using the differential state variables associated with the machines ($\delta_j$, $\omega_j$) the following equations can be obtained:

$$DSVI(t) = 1/m \left( \sum_{i=1}^{m} w_{i1} \left( \frac{\delta_i(t) - \delta_i(t_o)}{\pi} \right)^2 + \sum_{i=1}^{m} w_{i2} \left( \frac{\omega_i(t) - \omega_i(t_o)}{\omega_S} \right)^2 \right)$$

Figure 1. Dynamic response of a machine state variable.
DSVI(t) is known as the Dynamic State Variable Index function and DSVI is the Dynamic State Variable Index value.

Similarly by using the algebraic variables that are related to the machines \( V_i, \theta_i, I_{di}, I_{qi}, i = 1, 2, \ldots, m \) and neglecting \( I_{di} \) and \( I_{qi} \) because they are not real quantities, then the following severity indices and functions are obtained.

\[
\text{ASVI}(t) = \frac{1}{m} \left( \sum_{i=1}^{m} w_{i,1} (V_i(t) - V_i(t_0))^2 + \sum_{i=1}^{m} w_{i,2} \left( \frac{\theta_i(t) - \theta_i(t_0)}{\pi} \right)^2 \right)
\]  

(33)

\[
\text{ASVI} \triangleq \int_0^\infty \text{ASVI}(t)\,dt
\]

(34)

Also, ASVI(t) stands for Algebraic State Variable Index function of time and ASVI is the Algebraic State Variable Index value. Also It is important to note that (32) and (34) represent the area under DSVI(t) and ASVI(t) and time-axis respectively and their unit is \( \text{s} \) (seconds). The higher the values of the respective areas, the higher the severity of the disturbance and likelihood of system instability. It is very important to note that the weights associated with variables can be assigned arbitrarily but (29) and (30) must be obeyed.

4. Simulation and results

In this section, the proposed dynamic security indices are used to carry out DSA on a multi-machine power system using time domain simulation. IEEE 57-Bus test system is used and the results of the severity indices are compared with an already established dynamic index called Angle Index (AI) given in Ruhle and Lerch (2010) and in the Appendix A. IEEE 57-Bus test system (Appendix B) consists of 78 Transmission lines, 7 synchronous generators and 42 load substations as shown. The data for the entire system can be obtained from reference University of Washington Electrical Engineering Resources (2015). The effects of different models of synchronous machine on the proposed DSA indices are also looked into by comparing the results of the indices obtained using power system whose synchronous machines are modeled by the two-axis dynamic model with that of the one modeled by the classical models as discussed in Section 3. The indices are also use to rank the transmission lines in the test system based on their susceptibility to system instability when perturbed.

In the simulation, a three-phase short circuit fault was used as the disturbance and applied at the middle of each transmission line at 0.5 s and cleared after 0.2 s. In each case the severity functions (DSVI(t) and ASVI(t)) and indices (DSVI and ASVI) were computed and compared with the AI. It is very important to note that the two-axis dynamic model of synchronous machine was primarily used in this research and the classical model was only used to see how the severity functions would be affected using a less accurate model of synchronous machines.
Therefore, the DAE model (1)–(17) were solved by using MATLAB ODE solver algorithm to obtain all the variables needed for the proposed indices. All the indices were normalized by the highest value of the respective indices. More weight (0.6) was assigned to angle variables ($\delta_i$ and $\theta_i$) while lesser weight was assigned to other variables. In all, (29) and (30) were obeyed. The transmission line joining Bus 7 and Bus 13 (line number 24), gave the highest values for all the indices and hence most critical line in the power system. Also, the transmission line number 56 gave the least DSA indices values. Table 1 shows the first three most critical lines in red, and their respective indices and the three least critical line while Figures 2 and 3 show the plots of comparison of DSVI and ASVI with AI for all the contingency cases respectively.

| Transmission line number | Normalized DSVI | Normalized ASVI | Normalized AI |
|--------------------------|-----------------|-----------------|---------------|
| 7–13                     | 24              | 1.000           | 1.000         |
| 12–13                    | 23              | 0.923           | 0.925         |
| 6–12                     | 10              | 0.735           | 0.739         |
| 11–41                    | 22              | 0.003           | 0.005         |
| 14–15                    | 27              | 0.001           | 0.003         |
| 15–45                    | 56              | 0.000           | 0.000         |

Table 1. DSA indices for most and least critical lines

Figure 2. DSVI and AI indices comparison for all contingencies.

Figure 3. ASVI and AI indices comparison for all contingencies.
5. Discussion

It can be seen from the results of simulations shown in Table 1 and Figures 2–15 that the proposed indices have been to give clues to the contingencies that are likely to lead to system instability if not timely cleared. Table 1 shows the DSA indices obtained for the three most critical contingencies and the three least critical contingencies in the transmission network of the test system. The three most critical transmission lines are shown with red colors on the table and they correspond to the highest values of the proposed indices (DSVI and ASVI). The least critical lines show indices values that are approximately zero in values. The results also show the same trend when compared to the results of an established DSA index called AI in literature.

In the same vein, the time function DSA indices proposed (DSVI(t) and ASVI(t)) which give the performance of a power system with time before, during, and after a contingency were also observed for all the contingency cases. Figures 4–7 show the result of the simulations obtained for the most critical scenario corresponding to the transmission line joining Bus 7 and Bus 13 and the least critical scenario corresponding to the line joining Bus 15 and Bus 45. Looking at these figures, it can be seen that for the critical case (Figures 4 and 6), the indices went as high as 7.0 for DSVI(t) and around 8.0 for ASVI(t). The high values (7 and 8) of DSVI(t) and ASVI(t) imply from (31) to (33) that at least one machine has exceeded its maximum allowed rotor angle deviation and machine bus angle deviation respectively. These can be seen in the rotor angle dynamic response in Figure 8 and machine bus angle dynamic response of Figure 14. Therefore, if the fault was not timely cleared the system would become unstable. However, looking at the indices for the least critical case (Figures 5 and 7), it can be observed that the highest values were extremely low and around 0.0025 for DSVI(t) and 0.0035 for ASVI(t). These results indicate that the stability of the system can be maintained with fault on this line. Looking at Figures 5 and 7 further, it would also be observed that the trajectories...
of the indices returned to zero immediately the fault was cleared while for the critical case in Figures 4 and 6 still maintained some relatively high values after the clearance of the fault.

The roles of the synchronous machine model used in the system were underscored during the most critical scenario as they responses of the indices were different when classical model of synchronous machine was used (Figures 4 and 6). However, for the least critical contingency, there were no noticeable differences between the two-axis dynamic model of synchronous machine and classical model the indices were all approximately zero for almost all the time (Figures 5 and 7). These show that to actually capture the state of power systems, a more detailed model for machines would be desirable.

In furtherance of the validity of these DSA indices, dynamic responses of the variables involved in the formulation of the indices were plotted for the same time span as shown in Figures 8–15. Looking at the dynamic responses of the variables corresponding to the most critical contingency case (Figures 8, 10, 12 and 14) it could be observed that these variables were highly distorted by the disturbance from the excursions experience. But for the least critical contingency case (Figures 9, 11, 13 and 15), it could be seen that little or no excursions were experienced by these same set of variables. For instance, the machine rotor angle dynamics shown in Figure 8 for the most critical case showed a lot of excursions and the pre-fault operating values were totally different from the post-fault operating values and with an average of about 100° deviation per machine. For the same rotor machines for the least critical case shown in Figure 9, the dynamics showed no difference in pre-fault, on-fault and post-fault operating conditions and no excursions were noticeable. It was exactly like a base case scenario where there was no fault in the system (no contingency case). The same could be observed for frequency, machine Bus voltage magnitudes and machine Bus angle.
The proposed severity functions which show the dynamics of the system at any time as defined in (31) and (33) were also plotted and the effects of different synchronous machine models were also taken into account. The severity functions (DSVI(t) and ASVI(t)) obtained for the most critical and the least critical scenarios are shown in Figures 4–7.
In the same vein, dynamic response of the various variables used in the formulation of the proposed DSA indices were observed and plotted for the most critical and the least critical contingency scenarios as shown in Figures 8–15.
6. Conclusion
The continuous increase in power demand has made DSA a key part of power systems reliability assessments. In this paper, a technique and transient stability based DSA indices using time domain simulation are proposed. The approach and indices are relatively simpler and can easily be integrated into Energy Management System (EMS) or Remedial Action Scheme (RAS) for determining the state of power system in case of large disturbances. The approach and indices could also be used offline to examine and screen all likely contingencies that could lead to system instability since the resources and cost for online DSA are not easily come by for power companies or utilities. A conventional power system modeled by DAEs where synchronous machines are modeled by two-axis model is used and solved taken a full advantage of MATLAB ODE solver. Two sets of indices are proposed (DSVI and ASVI) based on the system variables.

The proposed DSA indices are tested on IEEE 57-Bus test system to carry out N-1 contingency in the transmission network to determine those contingencies that are likely to lead to system instability. The results of these simulations were compared with the results obtained by using an established AI in literature and found to produce similar contingency rescreening and results. The results also showed the importance of using more detailed machine model for system modeling in DSA.

List of symbols

- $D$: Damping constant
- $E_d$: $d$-axis machine internal voltage
- $E_q$: $q$-axis machine internal voltage

Figure 14 Machine Bus angle dynamic response for the most critical scenario.

Figure 15. Machine Bus angle dynamic response for the least critical scenario.
| Symbol | Description |
|--------|-------------|
| $E_{fi}$ | Field excitation voltage |
| $f$ | Frequency |
| $f_0$ | Nominal frequency |
| $H$ | Machine inertia constant |
| $I_d$ | $d$-axis stator current |
| $I_q$ | $q$-axis stator current |
| $K_A$ | Amplifier gain |
| $K_E$ | Exciter constant |
| $P$ | Active power |
| $P_C$ | Speed governor input power setting |
| $P_{CH}$ | Output power of steam chest |
| $P_{SV}$ | Output power of steam valve |
| $Q$ | Reactive power |
| $R_f$ | Rate feedback in exciter |
| $R_d$ | Speed regulation quantity (droop) |
| $S$ | Complex power |
| $S_k$ | Saturation constant |
| $T_m$ | Mechanical torque |
| $t$ | Time |
| $V$ | Bus voltage magnitude |
| $V_E$ | Exciter input |
| $V_{ref}$ | Input reference voltage |
| $X$ | Reactance |
| $Y$ | Admittance |
| $Z$ | Impedance |
| $\theta$ | Bus voltage angle |
| $\omega$ | Angular speed |
| $\omega_0$ | Nominal angular speed |
| $\delta$ | Machine rotor angle |

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Source: Authors.

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Appendix A

\[
AI = \min \left\{ 1, \max_{i=1, \ldots, NG} \left[ -\frac{\delta_{c,\text{max}}}{\delta_{c,\text{max,adm}}} \right] \right\}
\]

where NG is the number of generators, \(\delta_{c,\text{max}}\) is the deviation of the rotor angle of the ith generator and \(\delta_{c,\text{max,adm}}\) is the maximum admissible rotor angle. The index ranges from 0 for a case when no rotor angular deviation is produced to 1 for a case when rotor angular deviation reaches a maximum admissible value.
Appendix B