Fast Prediction of Transient and Short-term Voltage Instability Employing System Integrity Protection Scheme

Mahmoud Lashgari  
Center of Excellence for Power System Automation and Operation  
Iran University of Science & Technology  
Tehran, Iran  
lashgari@elec.iust.ac.ir

S. Mohammad Shahrtash  
Center of Excellence for Power System Automation and Operation  
Iran University of Science & Technology  
Tehran, Iran  
shahrtash@iust.ac.ir

Abstract—This paper presents a unified model-free scheme as a part of system integrity protection schemes (SIPS) with the ability to early predict transient and short-term voltage (STV) instability. In the proposed scheme, the frequencies measured by PMUs have been used and then both transient instability and STV instability are predicted by tracking the trajectories of the inertia frequency response (IFR) and the frequency deviation. The results of the performance evaluation of the proposed scheme on single machine infinite bus (SMIB) system, single machine load bus (SMLB) system and IEEE 39-bus system show the proposed scheme is accurate in predicting unstable and stable conditions at an early time.

Keywords-component; Transient stability; Short-term voltage stability; Early prediction; System integrity protection schemes

I. Introduction

Preparing a bright and early view of power system post-disturbance state, with effective and accurate decisive alarms, will provide the data needed to manage any incepted/incoming disturbances [1-2]. This preparation is more needed, whenever there is not so much time between the inception of disturbance and the time that brownout or worse blackout happens, as a post-disturbance consequence. Voltage instability occurs due to the inability of power system to maintain a stable and acceptable voltage at buses under normal operating conditions and following a disturbance [3]. Rotor angle stability refers to the generator's ability to maintain synchronism [3]. Following a large disturbance in power system, voltage and rotor angle stability are known as short-term voltage (STV) and transient stability, respectively.

The presented methods in the literature for investigating transient or STV stability statues can be grouped in time-domain simulation based, transient energy function based [5-6], maximum Lyapunov exponents based [7-8], and artificial intelligence based [9-10], and hybrid approaches [11-12]. The main gap in transient and STV stability status prediction methods is the pervious methods have assumed that only one of the two phenomena exists, i.e. either transient instability or STV instability, but these two phenomena exists simultaneously with one of them being dominant, according to the operating point of the system and disturbance condition [4].

In order to have a practicable and useful prediction method for system operators, it should meet the following requirements:

1) **Timely:** To provide timely information, the prediction method must be implemented in online condition and data processing be real-time. With the aid of PMUs in the power system, the prediction method can be implemented online.

2) **Data-driven:** Data analytics refers to the knowledge of analyzing raw data to produce precise information and it is broken down into four basic types following, descriptive analytics, diagnostic analytics, predictive analytics and prescriptive analytics. Predictive analytics aims to predict events such as the stability status, and has significant application in the power system. In contrast to the model-driven methods, the methods based on data analytics have the advantages of higher accuracy, faster speed and widespread applicability [13].

3) **Autonomous:** In order to increase the reliability, the prediction method must be autonomous. In this paper, autonomous means that the prediction method is not relying on announcing disturbance inception and clearance instants by other equipment such as protection relays.

4) **Dependable:** In order to make the information be dependable, the prediction method must be evaluated not only on different test systems, but also under
different conditions, such as topology changes, different operating points, and symmetrical and asymmetrical faults at different locations. Another important situation for evaluating is fault clearance at different times including the critical clearing time (CCT). The CCT is the longest fault duration that does not cause IM stalling and loss of synchronism in any generator [14], and it has been considered as assessment index for the STV in [15].

5) Comprehensive: The comprehensive criterion in this paper refers to the simultaneous investigation of both transient and STV stability status.

6) Fine Selection: In order to enhance the selectivity of the prediction method, it is crucial to distinguish between normal stable case and critical stable case (such as fault clearance at the CCT).

By using the frequency of the synchronous generator, a new stability assessment plot has been proposed in this paper that by tracking the trajectory on the plot and checking some simple defied rules, early prediction of both the transient and STV can be achieved. Early prediction of both the transient and STV stability status is the main advantage of the proposed method compared with other published methods. Also, the proposed algorithm is a response-based and rule-based method and it can be employed without using the offline studies-based threshold values. The results show that the proposed algorithm is capable of early predicting STV instability and both first-swing and multi-swing transient instability.

II. Basic Principles

A. Stability assessment plot (SAP

In the proposed scheme, the frequencies measured by the PMUs have been used and then the frequency deviation and inertial frequency response have been calculated. The frequency deviation, $\Delta F_i$, is calculated at each time step as follows:

$$\Delta F_i(j \Delta t) = (f_i(j \Delta t) - f_0) - 1$$

(1)

where $f_i(j \Delta t)$ denotes the frequency of the $i$th generator at the $j$th time step and $f_0$ is the nominal frequency.

Also, the inertia frequency response (IFR), $\Delta P_i$, is calculated at each time step as follows:

$$\Delta P_i(j \Delta t) = -\frac{2H_i}{f_0} S_{Ni} \frac{df_i(j \Delta t)}{dt}$$

(2)

where $S_{Ni}$ and $H_i$ represent the rated apparent power (MVA) and the inertia constant (s) of the $i$th generator, respectively.

By drawing the trajectories of the $\Delta F_i$ signal and $\Delta P_i$ signal, SAP is created as shown in Figs. 1 (b) and (c). The proposed scheme in this paper is based on the determination of four critical positions on SAP.

The critical positions are as follows:

- **$p_1$ position**: The $p_1$ position is equal to the fault clearing time. Since the proposed algorithm is a response-based method, it is needless of receiving any information about the fault clearing time by other equipment.
- **$p_2$ position**: The $p_2$ position can be in either of the two forms:
  1. **A relative maximum point**: As shown in case 1 in Fig. 1 (a), the process of increasing the frequency has been stopped at the $p_2$ point, so this position is a relative maximum and the frequency derivative is zero. Since $\Delta P_i$ depends on the frequency derivative, it is expected that the $p_2$ position on SAP is close to the origin of the $\Delta P_i$-axis, as shown in Fig. 1 (b).
  2. **An inflection point**: As shown in case 2 in Fig. 1 (a), the frequency is increasing until it reaches an inflection point. Whenever the trajectory on SAP reaches a point where $\Delta F_i$ has an upward trend and meet conditions (3), the point is designated as the $p_2$ position, as shown in Fig. 1 (c).

$$\Delta F_i((m - n) \Delta t) < \Delta F_i(m \Delta t) < \Delta F_i((m + n) \Delta t)$$

(3)

where $m \Delta t$ and $n \Delta t$ is the time step corresponding to the $p_2$ position and the $n$th time step, respectively.

- **$p_3$ position**: After the $p_2$ position, whenever the trajectory on SAP reaches a point where both $\Delta F_i$ and $\Delta P_i$ are decreasing, the point is designated as an inflection point and it is called the $p_3$ position, as shown in Fig. 1 (b).

- **$p_4$ position**: The $p_4$ position is a point where the frequency increases again. Therefore, this position is a relative minimum point and the frequency derivative is zero, and the $p_4$ position is close to the origin of the $\Delta P_i$-axis, as shown in Figs. 1 (a) and (b).

![Fig. 1. (a) Frequency variations, (b) Trajectory on SAP (case 1), (c) Trajectory on SAP (case 2).](image-url)
B. Improved Morphological Gradient (IMG) Filter

The mathematical morphology (MM) is a non-linear time processing tool with a very low computation burden. Dilation and erosion are two basic operations of the MM, and some crucial operators are made by using them. One of the powerful operators is the morphological gradient (MG) filter that by using a probe named structure element (SE), can detect the edges of the signal as follows [16]:

\[
MG(n)=(si \otimes g)(n)-(si \Theta g)(n)=si(n)-si_e(n)
\]

(4)

where \(si\) is the main signal, \(g\) is the SE and \(\otimes\) and \(\Theta\) are the dilation and erosion operations, respectively. \(si_d\) and \(si_e\) denote the dilation and erosion signals, respectively. A flat SE has been used in this paper.

The polarity of the MG is always positive, and the polarity of the proposed filter in [17-18] is proportional to the polarity of the signal. In fact, none of them discriminates between positive and negative edges. In order to address this issue, an IMG filter has been introduced in this paper. The proposed IMG filter is as follows:

\[
IMG(n) = \begin{cases} 
+MG(n); & \text{if } \left[ \frac{si_j(n) - si_j(n-1)}{si_i(n) - si_i(n-1)} \right] > 0 \\
-MG(n); & \text{if } \left[ \frac{si_j(n) - si_j(n-1)}{si_i(n) - si_i(n-1)} \right] < 0 
\end{cases}
\]

(5)

The outputs of MG, IMG in [17], and the proposed IMG in this paper on a signal have been shown in Fig. 2.

![Image 2](image2.png)

Fig. 2. Main signal and its MG and IMG outputs. (a) Main signal (b) MG output (c) IMG output (d) Proposed IMG output.

As shown in Fig. 2(d), the proposed IMG, in addition to detecting the edges in the signal, indicates whether they are ascending or descending.

C. System Integrity Protection Schemes (SIPS)

Conventional protection equipment focuses on the proper operation and performance of a component, while SIPS focuses on the safe and efficient operation of the entire system [19]. SIPS is designed to take timely, effective and coordinated action when the power system is exposed to abnormal conditions such as transient instability, voltage instability, etc. Effective implementation of SIPS can minimize the adverse effects of disturbances.

Different architectures such as flat, hierarchical, distributed, and centralized are used in SIPS [20]. As shown in Fig. 3, all data in a centralized architecture is collected from monitored substations and elements and then transmitted into one central location [20]. The data processing and the decision-making unit are performed at this central location. A centralized SIPS architecture is used in the proposed prediction algorithm in this paper.

![Image 3](image3.png)

Fig. 3. Centralized architecture of SIPS [20]

III. Proposed scheme

The stages of the proposed scheme are as follows:

**Step 1: Determination of Stability Boundary (Optional)**

Under the base case condition, the CCT is calculated for a three-phase fault at the generator bus. When the fault clearing time is \(CCT+\Delta t\), the coordinates of \(p_1\) and \(p_2\) positions on SAP are assigned as \(A \Phi(p_1, \Theta_1)\) and \(A \Phi(p_2, \Theta_2)\), respectively. This process is performed for all synchronous generators.

**Step 2: Fault detection**

In this paper, the proposed IMG filter in (6) has been applied to the bus voltage variations for edges detection. In the method, the mean (\( \mu \)) and standard deviation (\( \sigma \)) are calculated for 20 samples at each time step. Whenever the proposed IMG output fulfills the following condition for the first time, their corresponding times are designated as the inception time (\( t_1 \)) and clearing time (\( t_2 \)), respectively, as shown in Fig. 4.

\[
[ \text{if } IMG[m] < \mu[m] - \sigma[m] \Rightarrow m = \text{inception time} ] \\
[ \text{if } IMG[n] > \mu[n] + \sigma[n] \Rightarrow n = \text{clearing time} ]
\]

(6)

![Image 4](image4.png)

Fig. 4. (a) Voltage phasor (b) Proposed IMG output
Step 3: Candidate Generators Selection

When a disturbance occurs in power system, the generators with the least electrical distance to the disturbance location are most affected, so their frequency variations are more significant and faster.

In the method, $\Delta P_i$ values during the first five-time steps after the fault inception time are gathered in a centralized SIPS architecture. Then, the generators whose average value of $|\Delta P_i|$ are more than five-tenths of the maximum value are selected as the candidate.

Step 4: Evaluation of Prediction Criteria

In this paper, five criteria including two threshold-based and three rule-based, have been defined for predicting transient and/or STV instability. The threshold values are determined in offline studies. If threshold-based criteria are not considered in the assessment process, the proposed algorithm will predict both transient and STV instability using the other three rule-based criteria, i.e. the threshold-based criteria are optional criteria.

The prediction criteria are as follows:

- $p_1$ position criterion (threshold-based):

  If $\Delta F_i$ exceeds $\Delta F_{(p_1, \text{th})}$ value, the proposed algorithm will predict transient and/or STV instability. $\Delta F_{(p_1, \text{th})}$ is the threshold value corresponding to the $p_1$ position. Before reaching the $p_1$ position, the $p_1$ criterion is checked at each time step, so the algorithm is able to predict instability if the fault clearing time is a long time.

- $p_2$ position criterion (threshold-based):

  Instability is predicted when $\Delta F_i$ at the $p_2$ position be greater than $\Delta F_{(p_2, \text{th})}$ and $\Delta P_i$ be lower than $\Delta \Delta P_{(p_2, \text{th})}$.

- $p_3$ position criterion (rule-based):

  If the $p_3$ position is an inflection point and satisfies conditions (3), the instability will be predicted.

- $p_4$ position criterion (rule-based):

  At the $p_4$ position, if the condition (7) is fulfilled and $D_i$ signal as (8) is ascending, transient and/or STV instability will be predicted.

\[
\frac{[\Delta F_i]}{[\Delta F_{(p_4, \text{th})}]} \times \alpha > \alpha
\]

\[D_i(t) = \Delta P_i(t - \Delta t) - \Delta P_i(t)\]  

The condition (7) means that there is no chance to reach a stable equilibrium point due to the increase in frequency. Based on the offline studies, $\alpha$ has been chosen equal to 0.5 in the proposed method.

- Final criterion (rule-based):

  Both $\Delta F_i$ and $\Delta P_i$ signals are monitored for all samples and as soon as the final criterion is satisfied, the transient and/or STV instability is predicted. The final criterion is $\Delta F_i$ and $D_i$ signal values are ascending and the $\Delta P_i$ values are descending for ten consecutive time steps, while the value of $\Delta P_i$ signal is greater than its value at the $p_1$ position.

As soon as one of the criteria is met, the scheme will predict transient and/or STV instability. The flowchart of the proposed scheme has been shown in Fig. 5.

Fig. 5. Flowchart of the proposed scheme.

IV. Simulation and results

In DiGilSILENT Power Factory software, the detailed model 2.2 [21], with IEEET1 exciter model and a third-order model, have been considered for synchronous generators and IMs, respectively.

In the following, the performance of the scheme has been investigated on SMIB system, SMLB system, and IEEE 39-bus system.

A. SMIB system

In a SMIB system as shown in Fig. 6, because there is no load dynamics to be considered, just pure angle instability can happen [22],[23].

A three-phase fault has been applied at 5% of the line $L_1$ in Fig. 6 at $t=1s$ and then the line $L_1$ has been removed. Two fault durations of 290 and 300 ms have been considered and the rotor angle variations have been shown in Fig. 7 (a).

Fig. 6. SMIB system

Fig. 7. (a) Rotor angle variations in SMIB, (b) IM bus voltage variations in SMLB
As shown in Fig. 7 (a), the system is stable and unstable for fault durations of 290 and 300 ms, respectively. The trajectories on SAP have been depicted in Figs. 8.

As one can be seen in Fig. 8 (a), none of the prediction criteria have been met, so the algorithm is successful in detecting the stable condition. In the unstable case in Fig. 8 (b), none of the p₁, p₂ and p₃ position criteria have been met, but at the p₄ position, its condition has been satisfied and pure transient instability has been predicted at t=1.57 s.

**B. SMLB system**

In contrast to a SMIB system, the swing equation has no role to play in stability analysis in a SMLB system and just pure voltage instability can happen [23].

![SMLB system](image)

A three-phase fault has occurred at 90% of line L₁ at t=1s in Fig. 9 and the faulty line L₁ has been removed at times 1.175s and 1.185s which leads to stable and unstable STV situations, respectively. As can be seen in Fig. 7 (b), the voltage has not been recovered in the unstable case and the voltage collapse has occurred. The trajectories on SAP in both stable and unstable STV cases have been illustrated in Figs. 10.

![Trajectory on SAP in SMLB system](image)

In contrast to the stable case in Fig. 10 (a) that none of the prediction criteria has been fulfilled, the p₄ condition in Fig. 10 (b) has been fulfilled. Therefore, STV instability has been predicted at time t= 1.52 s.

**C. IEEE 39-bus system**

In IEEE 39-bus system [24], shown in Fig. 11, the detailed model 2.2 has been used for generators and the units have been equipped with automatic voltage regulator (AVR), governor and power system stabilizer (PSS).

In the following, the performance of the proposed procedure has been presented for two cases.

**Case I) F₁ fault at 75% of the transmission line 21-22 with 5 cycles fault duration**

In case I, the rotor angle variations and the trajectory on SAP have been illustrated in Fig. 12. G₆ and G₇ generators have been selected as the candidate generators and the trajectory on the SAP has been illustrated for G₆.

As shown in Fig. 12 (a), three criteria for p₁, p₂ and p₃ positions have not been fulfilled. At the p₄ position, its condition has been met; hence, instability has been predicted at t=1.81 s.

**Case II) F₂ fault at 50% of the transmission line 17-27 with 5 cycles fault duration**

In case II, the bus voltage of the IMs and the trajectory on SAP for the candidate generator have been shown in Fig. 13. In this case, only G₉ has been selected as the candidate generator. In Fig. 13 (b), STV instability can be seen at the IM bus voltages and also the synchronism loss of G₉ has occurred; hence, transient instability and STV instability have been intertwined.

As shown in Fig. 13 (a), the p₄ position criteria has been met and the instability has been predicted at time t=1.21 s.
V. Conclusion

In this paper, based on PMU data a novel scheme has been presented to simultaneously evaluate the stability status of both transient and STV. The scheme is capable of early predicting instability while transient and STV instability exists simultaneously or one of them exists purely. In the proposed method, using the frequency of the synchronous generators, some simple criteria are investigated at each time step and transient and/or STV instability is predicted as soon as one of the criteria is met. The proposed scheme is model-free and needless of receiving any information by other equipment.

REFERENCES


