Power system transient stability analysis based on descriptive study of electrical indices

H. Bevrani, A. G. Tikdari, G. Ledwich

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تحلیل پایداری گذراي سیستم قدرت بر اساس مطالعه توصیفی شاخه های الکتریکی

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شهریور ماه ۱۳۸۹
چکیده

امروزه، با توجه به گسترش و پیچیدگی روزافزون سیستم‌های قدرت بدلیل تجدید ساختار، با کارگیری مانع تجدیدپذیر انرژی و تولید پراکندگی، اهمیت تحلیل دینامیکی و ارزیابی امکان این سیستم‌ها دوچندان شده است. بعد از وقوع یک خطا در سیستم قدرت، این خطا در شبکه انتشار پیدا می‌کند و در صورتی که این خطا بزرگ باشد و یا اینکه خطا در محدوده انتشار به‌داشت هم‌زمان حاکم باشد، سیستم‌ها و دیگر موانع در مواردی ممکن است همین مسئله ابعاث ناپایداری سیستم قدرت شود.

مشارکت‌های های مهم الکترونیکی در نقاط مختلف سیستم شبکه از وقوع خطا و بررسی نحوه انتشار آن می‌تواند در بررسی پایداری یک سیستم قدرت به صورت توصیفی مفید واقع شود. در این پروژه هدف تحلیل پایداری یک سیستم قدرت بر اساس مطالعه توصیفی شاخص مهم زاویه می‌باشد. چگونگی تغییر این شاخص الکترونیکی در نقاط مختلف سیستم قدرت پس از وقوع خطا مورد بررسی قرار می‌گیرد و بر اساس مطالعات انجام شده، ابزار توصیفی-تحلیلی مناسب برای ارزیابی امکان شبکه، پایداری و وضعیت لینک های شبکه ارائه می‌شود.

در پایان، با استفاده از مطالعه این شاخصها و انتشار امواج الکترونیکی، یک راهکار جدید برای کنترل اضطراری سیستم‌های قدرت ارائه شده است. این راهکار می‌تواند در روتی با هنگام شرایط اضطراری و به کارگیری موتور تکنیک-های پارادایم و جزیره‌ای که سیستم قدرت استفاده از روتر گربرد. این پژوهش نشان می‌دهد که سرفا با ابزارهای گیری و مشاهده شاخصهای مهم الکترونیکی (نظر روتی روتر زنراهرو، و شناز باها) در نقاط مختلف (پس از وقوع خطا) و بدون نیاز به محاسبات ریاضی و با مدلهای کامپیوتر، می‌توان اطلاعات ارزشمندی را در موارد رفتار دینامیکی و پایداری سیستم قدرت به دست آورد.

واژه‌های کلیدی:

انتشار امواج، ناپایداری روتی، کنترل اضطراری، پارادایم، پایداری روتر
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Title:

Power System Transient Stability Analysis
Based on Descriptive Study of Electrical Indices

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Power System Transient Stability Analysis based on Descriptive Study of Electrical Indices

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ABSTRACT

Power system dynamic analysis and security assessment are becoming more significant today due to increase the size and complexity because of restructuring, emerging new uncertainties, integration of renewable energy sources, distributed generation and micro grids. Precise modeling of all contributed elements/devices, understanding interactions in detail, and observing hidden dynamics using existing analysis tools/theorems are difficult, and even impossible.

In this project, the power system is considered as a continuum and the propagated electromechanical waves initiated by faults and other random events are studied to provide a new scheme for stability investigation of a large dimensional system. For this purpose, the measured electrical indices (such as rotor angle and bus voltage) following a fault in different points among the network are used, and the behavior of the propagated waves through the lines, nodes and buses is analyzed. The impact of weak transmission links on a progressive electromechanical wave using energy function concept is addressed.

It is also emphasized that determining severity of a disturbance/contingency accurately, without considering the related electromechanical waves, hidden dynamics and their properties is not secure enough. Considering these phenomena needs heavy and time consuming calculation which is not suitable for online stability assessment problems. However, using a continuum model for a power system reduces the burden of complex calculations.

Finally, a new power system emergency control framework based on descriptive study of electrical measurements and electromechanical wave propagation in large electric power systems is introduced. Since, fast and accurate detection of instability is essential in initiating certain emergency control measures, the proposed methodology could be also useful to detect the contingency condition and performing the well-known islanding and load shedding techniques. The work is supplemented by some illustrative nonlinear simulations on large scale test systems.

Key Words: Wave propagation, Angle instability, emergency control, Load shedding, PMU
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1. INTRODUCTION

Power system angle instability following loss of synchronism of the generators can be considered as a fast instability phenomena (Kundur, 1994, and Bevrani 2009). Detecting of this phenomena and performing adequate emergency actions are important issues to maintain the power system stability. When a disturbance takes place in a power system, the rotor angle of the generators near the occurred fault deviates from their base frames. This deviation propagates through the power system. So, for large disturbances, this may lead to the catastrophic outages, and finally blackout.

Because of deregulation and economical issues in power system management and fast growing of electrical power consumers, the transmission lines are usually working close to their stability limits. In other words, nowadays power systems are working under stress. One of problems that a stressed power system is encountered with, is the prediction of instability location. Occurring of a disturbance in a point of large scale power system may initiate instability in another point of the grid. In this work, it is shown that the reason of this problem can be found out from electrical wave propagation phenomenon and identifying the weak links of the system.


Emerging Phasor Measurement Units (PMUs) makes it possible to easily monitor the angle wave propagation throughout the power systems. They use Global Positioning Systems (GPS) to provide a synchronous time throughout the power systems which may be distributed through the continents. A methodology for islanding and identifying the weak links of a complex power system is proposed in (You, 2006 and Yang, 2006); they used the slow coherency approach.

In this report, first as a background, the different types of traveling waves in power systems and islanding control are addressed in Section 2. In Section 3, the problem at hand and the system modeling are described. In Sections 4 and 5, the islanding problem is re-analyzed concerning the wave propagation problem, and the proposed descriptive approach for power system stability assessment is explained. Some simulation results on two ring power system (64-bus and 200-bus), a 400-bus meshed system, and the 24-bus IEEE Reliability Test System (RTS-79) are presented. Further research directions are addressed in Section 6, and the report is concluded in Section 7.

2. BACKGROUND

2.1 Wave Propagation

Wave propagation is a phenomenon appeared in many studying fields. In civil engineering, for example, it is used to study on propagation of earthquake waves through the structures components. Propagation of electromagnetic waves in different environments is an example of this phenomenon in physics and communication. When you move one end of a rope which another end is fixed, you can see a one-dimensional (1-D) wave that propagates through the rope and then back propagates. Indeed wherever there is a flexible material affected by a perturbation, the wave propagation phenomenon will appear.

Observing the propagation of a wave through an environment makes it so useful for analyzing the related problems. Also wave propagation phenomenon is an interesting problem in studying of large scale power grids (Thorp, 1998, Parashar, 2004, Phadke, 2008, Wagner, 1950). A large electric power system can be introduced as a very complex and nonlinear dynamic system which is always subjected
by small/large disturbances. In many articles, it has been shown that the disturbances propagate through the system like a wave (Thorpe, 1998, Parashar, 2004, Phadke, 2008, Wagner, 1950). Propagation of a disturbance through a power system may threat the stability if becomes large or if it passes through the weak lines/elements. Furthermore, it may cause undesirable tripping of some protection devices (Phadke, 2008). To study about electromechanical transients usually a large detailed model of the whole power system is needed. Preparing such system models and solving the heavy equations are so time-consuming; and often it will not give us a suitable sense on the global power system and its phenomenon such as electromechanical wave propagation.

Studying a system based on wave propagation analysis is needed to observe an overall view of the system. Therefore, a descriptive approach could be considered as a good alternative to analyze a power system based on wave propagation.

All performed studies on the wave propagation over the years, can be categorized into two groups. The first group considers voltage wave propagation (Wagner, 1950, Sluis, 2001). The voltage-type wave propagation may be created following a switching or lighting. However, the second group is electromechanical wave propagation which is produced when a rotor angle of a synchronous generator deviates from its base frame following another disturbance. These phenomena are introduced in the below subsections.

2.2 Voltage Wave Propagation

Studying about power system stability can be divided into two general groups: static stability and transient stability. In static stability study, the goal is to verify the system stability when encountered with low-amplitude slow disturbances. However, in the transient stability problems, a large and suddenly disturbance is occurred. The dynamic stability is an improved form of static stability in the case of low amplitude disturbances with longer life time (Kundur, 1994).

In static stability study the wave length is about 6000 Km for 50 HZ (Sluis, 2001). Therefore, in these studies a lumped model of a line is adequate. But for the transient stability problems, that the higher frequencies are exist, the traveling waves cannot be ignored. In other word, in this situation when a signal exists at one end of a line, there is no guarantee to appear it at another end of line, at the same moment. Indeed, the wave travels through the lines with a delay. This delay is actually because of charging the capacitance and inductance elements of the line (Sluis, 2001). In the lumped $\pi$-model, only two capacitors and one inductor are used; and in the T-model there are only two inductors and one capacitor. So, the voltage variations are immediately sensed at another end of line. But as shown in Figure 1, a distributed model contains a lot of elements that each element includes one inductor and one capacitor. When a voltage source is applied at one end of the line, the first capacitor is immediately charged; but because of first inductor, the second capacitor charges when the inductor is charged, and it makes a delay. This delay also exists for the next elements.

One of most important parameters in this issue is the characteristic impedance which is calculated by

$$Z = \sqrt{\frac{L}{C}}$$  \hspace{1cm} (1)

![Figure 1. Distributed model of a transmission line](image-url)
where, $L$ and $C$ are defined as line inductance and capacitance values per length of line, respectively. When a voltage wave passes through a point in which the characteristic impedance is changed, the magnitude of reflected wave and the magnitude of the wave that lets through are dependent on the value of characteristic impedances of two lines (for example when an overhead transmission line is connected to an underground cable).

The wave propagation velocity is another important parameter that can be calculated as follows.

$$v = \sqrt{\frac{1}{LC}}$$

### 2.3 Rotor Angle Wave Propagation

As discussed, the angle wave propagation which is called electromechanical wave propagation starts when a generator rotor deviates from its base frame. Then, it propagates throughout the power system. The velocity of angle wave propagation is slower than voltage wave propagation (Thorp, 1998 and Phadke, 2008). As has argued in (Phadke, 2008), the nature of this phenomenon is not completely clear. It seems to be the result of local inertias. As the waves may lead to loss of synchronism for under stressed power systems, studying of them is one of the interested issues in power systems stability analysis and security assessment.

Formulation of wave motion as nonlinear partial differential equations in a two-dimensional surface is introduced in (Thorp, 1998). This formulation is in form of wave equations. The swing equation of a generating unit can be expressed as follows:

$$\begin{align*}
\frac{2H}{\omega} \left( \delta + \omega D \dot{\delta} = P_a = P_m - P_e \right)
\end{align*}$$

where, $H$, $\omega$, $D$, $\delta$, $P_a$, and $P_m$ are inertia constant, angular speed, damping factor, rotor angle, electrical output power, and mechanical input power, respectively.

The above swing equation is introduced as a second-order hyperbolic wave equation in (Thorp, 1998). Using of these equations lets us to introduce a power system as a continuum system. The methodology of extracting the continuum model for a two-dimensional (2-D) power system is well-established in (Parashar, 2004). For a mesh network power system, which the generators and loads are located at distributed discrete points, introducing a 2-D continuum model needs to introduce the system parameters in form of smooth functions. To distribute the parameters, a Gaussian filter which is the most common smoothing tool can be suggested (Parashar, 2004).

### 2.4 Islanding Control

In fact, the angle instability is the loss of synchronism of the system synchronous generators. Angle instability is usually started when the synchronism between two generators which are located at two sides of a line is loosed. In other words, the angles of two generators are separated, may because of overloading a link which connects two generators, directly or indirectly. This link may be a weak link or a link which encountered a suddenly overload due to some connections in the network.

There are many technical reports representing various methodologies for detection/prediction the angle instability situation. For example, using of energy function concept is suggested in (Padiyar, 2006). Based on this concept, for the purpose of stability, a system should be able to convert whole of kinetic energy achieved throughout a disturbance into potential energy. On the other words, when in a stable swing, the potential energy reaches its maximum value, the kinetic energy should be zero.

In complex power systems, there are usually more than one inter-islands connection line. Therefore, to validate the system stability, maintaining only one line is not adequate. Based on the given idea in (Padiyar, 2006 and Wang, 2004), the change of power in all lines belonging to a cutest
called critical cutest determines the stability or instability situation. As argued in (Padiyar, 2006), the potential energy, under certain assumption, can be considered as sum of energies of the lines belonging to the cutest; and also, the kinetic energy is a function of voltage angle gradient of the cutest.

When a power system is becoming unstable at the location of a cutest, it means that the angle of a portion of power system that connected to the system (with the critical cutest) moves in opposite direction of angle motion of the other parts of system. In this situation, the islanding control is the most effective control action. Therefore, the unstable part of system is separated by tripping the lines in the critical cutest. The detection of critical cutest/weak link is the first step, and the islanding control must be executed. Following the islanding process, we are in face of some islands with excess load or generation. Load-generation imbalance in an isolated island leads the island into another form of instability, but with a slower dynamic than angle instability. Therefore, the island formation may not be the final stabilizing step. However, it can be considered as a way to arrest the fast angle instability. Following the islanding, the other emergency control actions such as load shedding and generation tripping are usually needed (Tikdari, 2009 and Bevrani 2010).

Slow coherency is a suitable and usual methodology for islanding formation (You, 2004). Following a fault, there are some groups of generators based on their angle variations. The angle changes in a group are similar, but the different groups of generators behave in opposite directions. This is the concept of slow coherency theory. One may introduce every coherent group of generators as an island. The lines that connect the islands may also provide the power system weak links (You, 2004, Yang, 2006, Wang, 2004).

Slow coherency is known as a good example for application of singular perturbation theory in power systems (You, 2004, Yang, 2006, Wang, 2004, Ourari, 2003 and Sowa, 2004). Using this method, the groups of generators with coherent angle behaviors can be determined. In transient stability issues, the slow coherency can also be used to find out the equivalent dynamic model of a power system (Ourari, 2003 and Sowa, 2004). In the slow coherency, it is assumed that state variables of an n-degree performance can be divided into two categories: \( r \) slowest states and \( n-r \) fast states. The \( r \) slowest states represent the groups of generators with slowest coherency. In slow coherency-based islanding, two assumptions can be considered to simplify the process of finding coherent groups of generators: i) the groups of coherent generators are independent to size of disturbance; and ii) the groups of coherent generators are independent to the modeling accuracy of the generator unit. These assumptions are important to perform the continuum model of power system, which is main interest in the present work.

3. PROBLEM ILLUSTRATION AND MODELING

In this section, the problem that we are attempting to solve is described. Suppose a high stressed large scale power system which its elements are working near their stability margins. When a system is explored near the stability of limits, disturbances may easily force the system to a cascading failure and even blackout. The goal is to widely monitor system in order to effective protection against large disturbances. For this purpose, an online stability/security assessment program is needed.

On the other hand, following a contingency, the voltage/angle deviations propagate through the power system. These traveling waves may pass through the high stressed elements and trigger an instability event. By using of wave propagation phenomenon, a descriptive approach for power system stability assessment can be proposed. In a power system, the operators and engineers will be able to use this descriptive tool to track the system dynamic behaviors, to validate the system performance against likelihood events, and to predict the next stable point.

The methodology will be described in the next sections. As it can be seen, the main aim is looking for an approach to help the system operators to immediate identify the proper emergency action. Following dangerous events, the system operators have some choices as emergency control actions. Sometimes a load shedding scheme or a generation rescheduling action can maintain the system stability. However, for very large disturbances, it may be needed to separate the system into two or more islands and control them separately.
3.1 Solutions and Recommendations

Based on power-voltage curves, there is a maximum value for transmission line loadability (Kundur, 1994 and Miller, 1982). A transmission line may encounter overloading following a contingency. But, it is important to know that what happens when an overloading is appeared.

The relation between angle and power across a line is shown in equation 4 (Kundur, 1994 and Miller, 1982).

\[ P = \frac{E_s E_r}{Z_0 \sin \theta} \sin \delta \]  \hspace{1cm} (4)

where, \( \theta \) is the length of transmission line in Radian; \( E_s \) and \( E_r \) are the voltage magnitudes at two ends of the line; \( Z_0 \) is the characteristic impedance; \( P \) is the active power passes through the line; and \( \delta \) is the angle difference between \( E_s \) and \( E_r \). The \( \delta \) is also known as transmission and load angle (Miller, 1982).

Based on equation (4), if a line active power increases, the angle across that link also increased. In this situation, if two synchronous machines are connected at two ends of the line, increasing of \( \delta \) which is the difference between the positions of rotors of the machine may lead to loss of their synchronism.

Therefore, there is also a maximum value for load angle of a line. Eq. (4) shows that this maximum value is 90°. However, based on experiences it is not safe to let \( \delta \) to increase more than 30° if the transmission line is not compensated (Miller, 1982).

In transient stability studies, there are some approaches for the system stability assessment, following a contingency. For example Equal area criterion is one of them which is only used for one machine connected to an infinite bus or for two-machines system (Kundur, 1994). Padiyar, 2006 used energy function criterion for online stability assessment of a large power system. Major of proposed criteria say that a system can stay stable if the generators can release the complete energy value that they obtained following a contingency.

Because of oscillations and uncertainty in a real power system, the proposed algorithms for online stability assessment that uses instance values of power, angle and the other indices may need many considerations. While, in these situations it is needed to know the behavior of the indices that propagates through the power system like a wave.

3.2 System Modeling

3.2.1 A Ring System

If the number of elements in a power system is large with a set of distributed generators parameters, the discrete model simulation results are also close to the continuum model (Thor, 1998). The following equations can be used for modeling of an N-bus ring power system:

\[ \delta_k + D\dot{\delta}_k = P_{m^k} \left[ 2 - \cos(\delta_k - \delta_{k-1}) - \cos(\delta_k - \delta_{k+1}) \right] - b \left[ \sin(\delta_k - \delta_{k-1}) + \sin(\delta_k - \delta_{k+1}) \right]; \text{ for } k = 2,3,\ldots,N-1 \]

\[ \delta_l + D\dot{\delta}_l = P_{m^l} \left[ 2 - \cos(\delta_l - \delta_N) - \cos(\delta_l - \delta_2) \right] - b \left[ \sin(\delta_l - \delta_N) + \sin(\delta_l - \delta_2) \right] \]
\[ \delta_N + D\delta_N = P_m^N - [2 - \cos(\delta_N - \delta_{N-1}) - \cos(\delta_N - \delta_1)] - b[\sin(\delta_N - \delta_{N-1}) + \sin(\delta_N - \delta_1)] \]  

(5)

The value of \( P_m^k \) can be achieved from steady states values of angles \(( \delta_k = \dot{\delta}_k = 0 \)). The steady state values of angles for an N-bus ring system can be calculated as,

\[ \delta_k^e = \frac{2\pi k}{N} \]  

(6)

Now, consider the 64-bus ring power system given in (Thorp, 1998). A Gaussian disturbance around line 15-16 can be implemented as follows.

\[ \delta_k = \delta_k^e + \frac{1}{2} e^{-0.1(k-15.5)^2} \]  

(7)

The simulation results are illustrated in Figure 2. This is a regeneration of the given example in (Thorp, 1998). In Figure 2, the wave propagation is illustrated versus time. However in Figure 3, the angle of wave is plotted versus bus number for different time slots. Figure 3b shows the normalized version of Figure 3a. As can be seen, when a deviation appears in rotor angle of a generator, it propagates and in the traveling path, it may encounter a weak link and may lead to a cascading failure.

### 3.2.2 2-Dimensional System

Now, consider a meshed power system with a configuration shown in Figure 4, in the Cartesian characteristic. Each point represents a bus and each connection represents a transmission line. For simplicity, assume that each bus consist of a generator or a load, or nothing. To obtain the necessary equations, assume that a generator with a mechanical power of \( P_m^A \) is connected to the point A (Figure 4). Considering the connections, \( P_e^A \) is the sum of electrical powers transferred from bus A to its neighbor buses 1, 2, 3, and 4. Therefore, \( P_e^A \) can be calculated as

![Figure 2. Electromechanical wave propagation on 64-bus ring system](image)
\[ P_e^A = \sum_{k=1}^{4} P_{e^k} + P_{L}^A \]  

(8)

where,

\[ P_{e^k} = \frac{V^A V^T}{x^{d_k}} \sin \delta^{d_k}, \quad k = 1, 2, 3, 4 \]  

(9)

\textbf{Figure 3.} Wave propagation; a) angle versus bus number for different time slots, and b) normalized plot
Now, the swing equations can be easily written for each point (Bevrani and Tikdari, 2010). Using above descriptions, an example is presented in Figure 5 which illustrates the propagation of angle wave through a 2-D power system. At $t=0$, a disturbance occurs on the middle of the network then, it propagates throughout the system. The system situation following the disturbance is shown in a few time slots.

**Figure 4. Network configuration**

Now, the swing equations can be easily written for each point (Bevrani and Tikdari, 2010). Using above descriptions, an example is presented in Figure 5 which illustrates the propagation of angle wave through a 2-D power system. At $t=0$, a disturbance occurs on the middle of the network then, it propagates throughout the system. The system situation following the disturbance is shown in a few time slots.

4. PROPOSED METHODOLOGY

This section describes the process of using islanding formation, performing a continuum model for system stability assessment, and predicting suitable emergency actions following a contingency. The overall view of the algorithm is demonstrated in Figure 6.

Angle instability is a fast instability phenomenon. Therefore, predicting its situation and performing suitable actions are very important. Having a continuum model of a power system can be helpful for predicting the trajectory of the disturbances, by using of disturbance conditions as initial states of the continuum model. Here, the power system continuum model is used to provide descriptive tool for stability analysis in emergency conditions.

As introduced in the previous section, the slow coherency theory can be used to identify system islands. Determining the islands leads to identify the weak links or critical cutset. Having knowledge on system weak links/islands helps one to determine most suitable connections/locations for performing a more carefully islanding plan, when the system needs to be separated. Here, a slow coherency is suggested to find weak links and islands. The weak links are used to check whether islanding is needed or not. The weak links can be considered as the locations should be tripped when the system operator recommends the islanding.

It can be shown that following a contingency, if the weak links are not collapsed and the instability is also not observed in the links close to the contingency, the system remains stable. Therefore, the overall stability can be validated by monitoring of just few links, i.e. the weak links and the links near to the contingency location. Furthermore, observing the trajectory of bus voltage angles helps the operators to choose a suitable islanding plan. As already mentioned, following an islanding action, the power system is divided into some islands with excess load/generation. Therefore, other emergency control actions (Bevrani and Tikdari, 2010, and Bevrani, 2009) such as load shedding and generation tripping should be performed as shown in Figure 6.
Figure 5. Wave propagation through a network
Indeed, following a certain contingency, the most important goal of the proposed algorithm is to determine if islanding is needed or not. If the contingency is not very dangerous and the angle across a link does not exceed from a certain value (for example, $30^\circ$ for non-compensated lines), islanding is not needed. However, for the higher value of transmission angles, the other emergency action will not be able to restore the system stability. For more clarification, assume the angle across a link is increasing and exceed $90^\circ$. After that, decreasing of active power by, for example, load shedding could not restore the system because the angle may track the power at low side of $P-\delta$ curve; so, $\delta$ increases, thus instability occurs. If these circumstances to be predicted, the system will undoubtedly need to be separated. The critical angle values (thresholds) should be determined based on desired level of security.

Operators and engineers can validate the power system stability at control rooms by observing the wave propagation at human machine interface (HMI). Three modes may be defined for this tool: real-time, prediction, and test modes.

In real-time mode, the real-time data which are gathered from the network by the PMUs are shown as a surface. The operator can see the real-time states of whole the network. In prediction mode, the online data are used as initial values of a continuum model, and the system states at a certain time value later will be predicted. In the test mode, the operator or engineer can validate a certain contingency based on real states of the system. In this mode the system real-data are used as initial values of a continuum model and the certain test is used as a deviation from initial state; then the post contingency condition will be shown in HMI for a certain time interval.
5. SIMULATION RESULTS

5.1 A Ring System and Islanding

To illustrate the concept of a coherent group of generators following a contingency, a 200-bus ring system is simulated. For simplicity, it is assumed that there is only one generator or one load at each bus. All generators are similar with equal amount of power, and all loads are also equal. The number of generators \((N_G)\) is equal to the number of loads \((N_L)\), so \(N_G = N_L = 100\). The system data is determined as follows:

\[
P_m = 0.3, \quad P_L = 0.3, \quad H = 1, \quad D = 0.2
\]

The system is examined under two different configurations. In the first configuration (config-1), all generators and loads are distributed throughout the power system by a uniform random function. In the second configuration (config-2), the generators and loads are distributed in a three areas ring system, as shown in Figure 7. In this case, all line impedances are assumed to be fixed at 0.1 p.u., except three lines that their impedances are \(Z_{75-76} = 0.2, \ Z_{130-131} = 0.15, \ Z_{200-1} = 0.3\). For both configurations, a large disturbance, i.e. tripping line 200-1, is applied. The angle deviations are illustrated for config-1 and config-2 in Figures 8.a and 8.b, respectively. The ring system is opened due to occurred disturbance.

For both cases, the angle deviation behavior across link 75-76 is illustrated in Figure 9. As shown, for the unstable case (config-2), the angle across link 75-76, i.e. \(\delta_{75-76} = \delta_{75} - \delta_{76}\), is continually growing and finally this situation leads toward separation and instability. However, for the stable case (config-1); although the angle across link deviates, the system is remained in a limited boundary and moves to a constant value.

The kinetic energy, potential energy, and total (kinetic plus potential) energy across link 75-76 are also depicted in Figure 10. As already mentioned, the system to be stable if it can be able to convert all amount of its kinetic energy achieved during a contingency into potential energy. This simulation (Figure 10) also shows that following mentioned fault, config-2 is going to an unstable condition, while config-1 holds its stability.

![Figure 7. 200-bus ring system (config-2)](image-url)
As another example, assume a Gaussian distribution that affects the angles of a system depicted in Figure 7 (config-2). Post-contingency wave propagation is illustrated in Figure 11. In this case, the center of disturbance is bus 60; however, it can be seen that the system is separated at line 75-76, which is a weak link. Actually, when a disturbance reaches a weak link through its propagation trajectory, may lead to an unstable operating point.

Figure 11b clearly shows the behavior of wave propagation when it reaches a weak links. For plotting this figure, the angle variations versus bus number for each time slot is calculated. As it can be seen, angle wave is reflected when it reaches to a transmission line without enough stability margin, and the system is separated exactly at the weak point.

*Figure 8. Wave propagation for: a) config-1; b) config-2*
Figure 9. Angle across link 75 in a) config-1; b) config-2

Figure 10. Energy across link 75: a) kinetic energy for config-1; b) kinetic energy for config-2; c) potential and total energy for config-1; d) potential and total energy for config-2
Figure 11. Wave propagation following a Gaussian disturbance which its center is bus 60 (the system is separated at link 75-76): a) 2D plot, and b) 3D plot
5.2 Application to 24-bus test system

Here, the 24-bus reliability test system (RTS) is used to investigate the effectiveness of the proposed strategy. Single line diagram of RTS is illustrated in Fig. 12. The RTS with its full data is introduced in (IEEE RTS Task Force 1979 and 1999); and the generators data are selected the same as given typical data in (Anderson, 2003). Here, the test system is divided into three areas. While most of the generation is located in area 1, most of the load is located in area 3. In area 2, load and generation are approximately the same. Area 1 delivers its over generation into area 2 and area 3 through three tie-lines: line 16-19, line 16-14, and line 24-3.

As a serious fault, the connections between area 1 and area 2 are loosed. Now, the angle instability on link 24-3 can be considered as a good example to examine the proposed methodology. Assume lines 16-19 and 16-14 to be tripped at t=2 seconds. Following this large disturbance, line 3-24 will be encountered with a high over-loading problem. This over-loading is larger than its angle stability limit. Therefore, as shown in Figure 13, the angles of generators G1 and G15 located at two sides of the line, are separated; and the angle instability phenomena is immediately occurred. To save system in this dangerous condition, one solution is the use of islanding control (You, 2003).

The angle deviations reduced by PMUs from the system buses are illustrated in Figure 14. As it is shown, following the contingency the connection between area 1 and area 3 (link 3-24) is encountered a separation as well as separation of area 2 and area 1. It demonstrates that the islanding between area 1 and area 3 at link 3-24 is a good idea to protect the system stability. Figure 15 illustrates how an islanding improves the voltage behavior that has been suddenly depressed following the mentioned event.

Therefore, the remaining tie-line may be tripped when appropriate algorithms are not used to stabilize the resulted two islands. To save an island with excess load, an under frequency load shedding (UFLS) algorithm, like those suggested by the Florida Reliability Coordinating Council (FRCC) (FRCC Automatic UFLS Program, 2009) or (Tikdari, 2009, Bevrani & Tikdari, 2010, and Bevrani, 2009) should be used. However, for the islands with excess generation, some loads must be switched on.

6. FUTURE RESEARCH DIRECTIONS

By using the PMUs, one can monitor the thorough behavior of a power system. The PMUs use Global Positioning Systems (GPS); so, they can offer a synchronous time for all of data gathered from the whole network. Therefore, it is possible to improve a continuum model to a trainable one, as a future work. The model uses the data gathered from the system at times $t$ and $t+1$. By comparing the output of the model and the actual values from the PMUs at time $t+1$, the error can be computed. By using the error value, the continuum model can be trained and improved.

There are many researches that offer optimal islanding. As another future work, these approaches may be included into the proposed methodology to prepare a more effective approach. In order to use wave propagation studies as an automatic tool instead of descriptive tool by the power system operators, some additional algorithms may needed. Pattern recognition methods may be used in these situations. Some features can be extracted from the angle surface variation, following different contingencies. They can produce special patterns and may be used in stability assessment problems, more effectively.

Moreover, some important research needs in future are the updating of existing emergency frequency control schemes for N-1 contingency, economic assessment/analysis the frequency regulation prices (considering various control strategies, penetration level, and installation location of renewable energy sources units), further study on frequency/voltage stability using dynamic demand control and ratios of renewable energy sources technologies, and quantification of reserve margin due to increasing renewable energy penetration.
Figure 12. 24-bus Reliability Test System (RTS)
Figure 13. Angles of generators: $G_1$ and $G_{15}$

Figure 14. Bus voltage angles deviations following the contingency
7. CONCLUSION

In a power network, when a propagation energy wave caused by a disturbance hits a weak link, a reflection is appeared and a part of energy is transferred across the link. Based on this basic fact, the present work proposes an analytical descriptive methodology to study the dynamical stability and security of a large scale power system, following serious disturbances. The possibility of simultaneous remote measurement of bus voltage, rotor angle and system frequency through synchronized PMUs and intelligent electronic devices emphasizes the significance of the proposed descriptive scheme for real-world complex power systems.

In this report, first an overview on the electromechanical waves in power systems, mathematical formulation and their interesting properties with a brief literature review is presented. The amplification of a propagated wave due to reflections or in combination with waves initiated from other disturbances is studied and it is shown how the occurrence of a large disturbance in a power system may lead to an uncontrolled tripping of generators and cascading failures, and may finally result in a blackout; if proper actions are not taken.

Finally, based on given descriptive study of electrical measurements and electromechanical wave propagation in large electric power systems, a power system emergency control scheme is introduced to detect possible plans. The report is supplemented by several simulations on standard 24-bus, 200-bus, and 400-bus test systems.

Acknowledgements

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8. REFERENCES


### 9. ADDITIONAL READING


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10. KEY TERMS AND DEFINITIONS

Wave Propagation: Propagation of a disturbance through the power system network like a propagated wave.

Islanding Control: Separate of power system into some isolated sub-systems following large disturbances, in order to prevent a global black out.

Angle Instability: Angle instability is a very fast instability that leads to loss of synchronism

Slow Coherency: A method which is used in islanding control problems. Using this methodology, the system islands and weak links can be identified

PMU: Power measurement unit is a device which uses GPS to collect data from the various points of network in a synchronous time

Emergency Control: Control of a power system in dangerous conditions, where the system is going to the instability or blackout

Load Shedding: An emergency control action to curtail a part of load, and is useful where the amount of load is larger than available generation