Adaptive Mitigation of Out-of-Step Transients Based on Equal Area Criterion and Energy Balance

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Adaptive Mitigation of Out-of-Step Transients Based on Equal Area Criterion and Energy Balance

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Abstract—**Electrical power transmission systems are susceptible to dynamic transients that can result in out-of-step conditions. These conditions can result in potentially damaging stresses to rotating equipment attached to the grid. When these conditions are identified, mitigation actions typically involve separation of the out-of-step portions of the power system. Unplanned separation can lead to system instability and cascading outages. This paper proposes a new adaptive method that provides both early detection of potentially unstable transient situations and specific control parameters by which to stabilize the system without resorting to separation.**

***Index Terms*—Power system control, Power system dynamics, Power system stability, Power system transients, Stability criteria**

I. INTRODUCTION

Electric power systems comprise expansive sets of power transmission apparatus, control equipment, and attached load and generation equipment. Much of the load and generation equipment consists of rotating machinery operating synchronously across the network. Certain initiating events can result in transient behavior leading to a loss of synchronization. This type of transient is known as an out-of-step condition and can result in potentially damaging mechanical stresses on the rotating machinery [1] or unintended remedial action by protective relays [2].

One popular method employed by the electric power industry to detect out-of-step events involves analysis of the relative machine angle, δ, at either end of a transmission path. Through analyzing the trajectory of δ and its first two derivatives, a stability metric can be determined. In this paper, we focus on improving the speed and accuracy of this method.

In Section II, we review existing algorithms and their benefits and limitations. In Section III, we propose a new out-of-step protective remedial engine (OoSPRE). We demonstrate the performance of OoSPRE in comparison to existing methods using a basic two-machine system in Section IV.

II. EXISTING OUT-OF-STEP METHODS BASED ON MACHINE ANGLE

A. Method Overview

1) Angle Estimation

Although various methods of angle-based out-of-step protection exist, each requires a robust estimate of the relative angle. This angle, δ, typically relates the rotor angle of a specific machine to a remote center of inertia, but may also be used to relate local and remote centers of inertia.

From a single measurement location, δ can be estimated using (1) along with parameter estimates [3], [4] for the values shown in Fig. 1. This method is effective as long as the system parameters are accurate; however, potential out-of-step transients are often initiated by events that change these parameters [2]-[6]. For example, loss of a parallel line will result in an instantaneous change in effective path impedance [4].

Other methods use synchronized phasor measurements at both ends of a transmission path to measure the voltage angle at locations close to critical machinery [6]. The machine angle can then be similarly estimated using machine parameters. Recently, new methods have been employed which allow for direct measurement of the machine angle [7]. These methods are less susceptible to system parameter changes, but introduce a reliance on precise time synchronization and robust, deterministic communication capabilities.

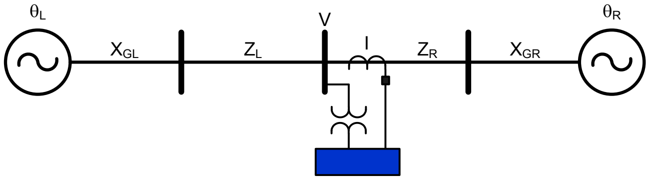

Figure 1. Illustrated parameters for angle estimation.

$$\theta_L = angle(V - I(Z_L + jX_{GL}))$$
$$\theta_R = angle(V + I(Z_R + jX_{GR}))$$
$$\delta = \theta_L - \theta_R \qquad (1)$$

2) *Out-of-Step Transient Detection*

Once δ is known, an estimate of stability can be accomplished through analysis of the angle (δ), slip (dδ/dt), and acceleration ($d^2\delta/dt^2$). This determination is predominantly accomplished through the establishment of restraint and trip regions bordered by linear blinders on the angle-slip plane [8]. The linear blinder is specified by two parameters: slope and angle-intercept. These parameters can be determined through offline study [10]. The angle-intercept can alternatively be estimated by using the pre-transient angle to estimate the critical angle [9].

A similar restraint-trip region can be defined on the slip-acceleration plane as a confirmatory metric to prevent unnecessary trips. This region, however, is dependent on the present value of δ, so determining a set of restraint blinders is necessary for transients with a range of initial angles.

B. *Limitations of Existing Methods*

Variations of the existing methods for detecting unstable out-of-step transients as described in II.A. Method Overview have been employed by the electric power industry for more than 30 years. However, reliance on potentially out-of-date system parameter values means that these methods are typically not suitable for a standalone application. Instead, these methods are typically employed as part of a remedial action scheme (RAS), where extensive offline studies have been employed to determine the parameters associated with key initiating events [10].

Even in situations where the parameter changes are anticipated and compensated for, the linear blinder locations may still result in undesired tripping. To allow sufficient time for breaker operation, protection designers must derate the restraint region sufficiently for the transient to be detected and the breakers to open *before* the angle is so large that it results in currents above the breaker's capacity [4] (which could result in a stable transient potentially triggering protective action).

In addition, because existing algorithms only provide a determination between stable and unstable transients [1]-[6], the primary remedial action for an out-of-step transient is path separation via breaker operation (assuming no RAS is present).

III. ADAPTIVE OUT-OF-STEP DETECTION

A. *Navigating an Out-of-Step Transient*

The equal area criterion (EAC), which represents a transient in terms of the power capability curve, is a staple of power system rotor stability analysis [1]. By assuming that deviations in voltage magnitude and frequency remain small, the torque capability path can be calculated as shown in (2).

$$\tau = \frac{|V_1||V_2|}{\omega X}\sin(\delta) = \tau_{max}\sin(\delta) \tag{2}$$

Fig. 2a shows the EAC as it is typically formulated to calculate the critical clearing time for a fault. The destabilizing work, represented by area A1, is a function of the initial, clearing, and equilibrium angles (δ_{init}, δ_{clear}, and δ_{Eq}, respectively) and the prefault, fault, and post-fault capacities. The difference between the torque demand and the torque capability described in (2) represents a net torque unbalance. This unbalance imparts a relative acceleration between rotating machinery at the two ends of the path. Integrating this torque unbalance yields destabilizing work (A1) and stabilizing work (A2), as shown in Fig. 2.

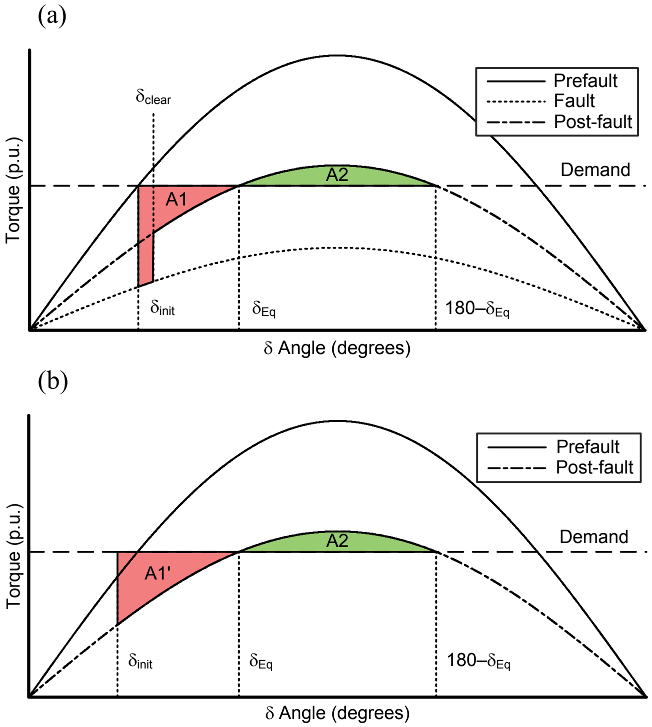

Figure 2. Equal area criterion with delayed fault clearing (a) and instantaneous fault clearing (b).

For angles beyond δ_{clear}, the EAC can be reformulated for the post-fault transient using only prefault and post-fault capacities. This is accomplished by calculating a compensated value of δ_{init} that produces an area A1' equivalent to A1. Fig. 2b shows this reformulated EAC for the critical transient initiated by a rapid decrease in path capacity to 60 percent of its prefault value.

Consider the critical transient as a function of the initial angle, δ_{init}. For each value of δ_{init}, the EAC defines a unique critical transient. Dependent parameters such as reduction in path capacity and the critical equilibrium angle ($\delta_{Eq\text{-}crit}$) can be calculated using the EAC. $\delta_{Eq\text{-}crit}$ is typically calculated through the solution of a nonlinear equation; however, in practice, we have found that a third order polynomial fit provides accuracy within one degree [9] while being immune to convergence issues.

During an observed transient, the new post-transient equilibrium angle (δ_{Eq}) is the point at which the system switches from acceleration to deceleration. δ_{Eq} can therefore be measured directly by monitoring the system acceleration and noting the value of δ at which the acceleration passes through zero. This is discussed in more detail in III.D. Online Parameter Identification.

B. *Early Detection of Pending Out-of-Step Condition*

During a potential out-of-step transient, we desire to make a metric available by which to identify whether a system is likely to go out-of-step. Using the EAC as formulated above, we can see that during the critical transient, the power system will undergo positive acceleration from δ_{init} to $\delta_{Eq\text{-}crit}$. Any stable transient will cease its positive acceleration prior to reaching $\delta_{Eq\text{-}crit}$. Therefore, if OoSPRE observes a system continuing to accelerate past the point where $\delta = \delta_{Eq\text{-}crit}$, we know that the transient is likely to result in an out-of-step condition.

In practice, a system may experience momentary dips in voltage magnitude during a dynamic transient such as those described in this paper. If the loads in a power system consist of constant impedance or constant current loads, the power demand, and therefore torque, will likely decrease. This decrease can result in a less-severe event with additional margin. We therefore desire a secondary metric to confirm the impending out-of-step condition.

As a secondary validation of an impending out-of-step condition, consider the steady-state operating limit for a lossless line as shown in (2). This limit exhibits a maximum torque capacity when the angle across the path is 90 degrees. Therefore, any positive acceleration observed after the angle across the path passes 90 degrees provides confirmation of the impending out-of-step condition.

A basic out-of-step tripping scheme might be implemented as follows:

1. Observe the pre-transient angle.
2. Once a transient is detected, assign the pre-transient angle to δ_{init}.
3. Calculate $\delta_{Eq\text{-}crit}$ from δ_{init}.
4. Monitor the system acceleration.
5. If positive acceleration is observed after δ exceeds $\delta_{Eq\text{-}crit}$, perform initial mitigation such as minor load shedding.
6. If positive acceleration is observed after δ exceeds 90 degrees, perform secondary mitigation such as system separation.

C. *Energy-Based Detection*

The EAC also lends itself well to an energy-based metric for identifying impending out-of-step conditions. During pre-transient conditions, slip (the first derivative of angle) is approximately zero. Similarly, acceleration (the second derivative of angle) is also approximately zero.

The initiation of the transient applies a torque unbalance to the system. This unbalance results in a non-zero acceleration of the system as described by the swing equation (3), which relates the system inertia (J), acceleration, and torque unbalance.

$$J \frac{d^2}{dt^2}\delta = \tau_{demand} - \tau_{max} sin(\delta) \qquad (3)$$

As the transient progresses, the acceleration results in a non-zero slip, converting the potential energy contained in the torque unbalance into kinetic energy. During a critically stable transient, the system continues to accelerate up to $\delta_{Eq\text{-}crit}$, at which point the system begins to decelerate. The value of the kinetic energy is now equal to the area A1' of Fig. 2b.

At each point during this critical transient, we can relate the kinetic energy of the critical transient to the system slip as shown in (4). Using this relationship, we can plot the trajectory of the critical transient during its outswing on the angle-slip plane as shown in Fig. 3. A stable transient will tend to stay fully inside the region contained by the critical transient. An unstable transient will tend to stay fully outside.

$$\frac{J}{2}\left(\frac{d}{dt}\delta\right)^2 = \int_{\delta_{init}}^{\delta} \left(\tau_{demand} - \tau_{max} sin(x)\right) dx \qquad (4)$$

Fig. 3 also shows this critical transient restraint region (yellow) overlaid with the traditional linear restraint region (red) [3]. In the situation of an unstable transient, Fig. 3 shows that a traditional linear restraint region will not detect the impending out-of-step condition until δ reaches 90 degrees, whereas OoSPRE can identify the condition by $\delta_{Eq\text{-}crit}$ or earlier.

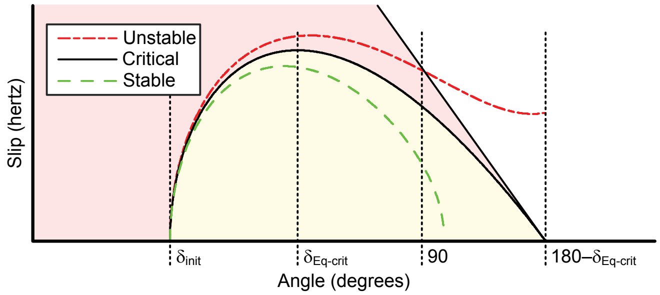

Figure 3. Angle-slip trajectories for critical, stable, and unstable transients.

D. *Online Parameter Identification*

One limitation for this energy-based criterion is that (4) is dependent on the ratio of τ_{max}/J. Because most rotor-angle transients are initiated by step changes in one or more of these values (e.g., loss of path capacity reduces τ_{max}), an online parameter update procedure such as that described in [9] is desired once a transient is detected.

If δ_{init} is known, a closed-form solution for τ_{max}/J is obtained by observing the value of δ when acceleration passes through zero (i.e., δ_{Eq}). We can then evaluate (4) with δ_{Eq} as the upper limit of the integral and solve for τ_{max}/J.

If δ_{init} is not known, or if the transient is so severe that the acceleration does not return to zero, a nonlinear optimization of the parameters δ_{init}, τ_{max}/J , and δ_{Eq} can be performed using the measurements from the beginning of the transient. This method is more computationally intense, but potentially provides an earlier estimate of τ_{max}/J because it can be performed after only n measurements, where n is determined by the measurement noise and sampling rate.

E. Mitigating an Unstable Transient

We now propose a new method that both confirms the instability and provides data on minimal mitigation response. Up to this point, we have focused on identifying whether a transient will be stable or unstable. A system might be stabilized by shedding kinetic energy (e.g., via dynamic brake insertion) or by unloading the path (e.g., via load and/or generation shed). From the EAC, we can derive a new process by which we can calculate the minimum required mitigating action to adjust an unstable transient into a stable trajectory.

Consider again the critically stable transient with respect to the EAC. For a present value of δ during a transient, we can use the relationship between kinetic energy, potential energy, and torque unbalance to determine stability. Specifically, the steps for calculating required path unloading are as follows:

1. Calculate the present value of kinetic energy from measurements of slip.
2. Calculate the value of $\delta_{Eq\text{-}crit}$ for the present values of δ and kinetic energy using (4).
3. Calculate the acceleration for a critical transient given δ and $\delta_{Eq\text{-}crit}$.
4. Using the difference between the as-measured acceleration and critical acceleration, calculate the excess torque using (2).

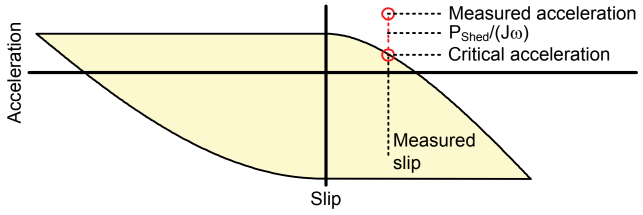

Figure 4. Operating point of 83.3 mHz slip and 55.6 mHz/s acceleration shown with restraint region for $\tau_{max}/J = 1.0\ s^{-2}$ and angle = 45°.

Fig. 4 shows this process graphically. The restraint region is uniquely calculated from τ_{max}/J and the present angle. The operating point of 83.3 mHz slip and 55.6 mHz/s acceleration can be moved into the restraint region via downward (e.g., path unloading) and/or leftward (e.g., dynamic brake) adjustments. This example focuses primarily on the former. The critical acceleration for the measured slip of 83.3 mHz is 18.6 mHz/s. Reducing the system acceleration from its measured value of 55.6 mHz/s to the 18.6 mHz/s will restore stability. We can now employ (3) to calculate the required torque, and therefore power, by which to unload the path.

IV. PERFORMANCE

A. Test System

We tested the above algorithms on the two-machine test system shown in Fig. 5 with line impedances given in Table I. Generator models are based on [1] with parameter values shown in Table II.

TABLE I. LINE PARAMETERS

Z_{L1}, Z_{L4}	Z_{L2}	Z_{L3}
0.010∠84.3°	0.069∠84.3°	0.276∠84.3°

The system was simulated using fourth order Runge-Kutta integration [1] with an update rate of 60 samples/second. Rotor angle is estimated using the voltage angles at their respective generator terminals (Bus B1 for Generator 1 and Bus B2 for Generator 2).

Figure 5. Two-machine test system.

TABLE II. GENERATOR PARAMETERS

X_d	X'_d	X_q	X'_q
0.18	0.03	0.17	0.055
J	K_D	**R**	τ_A
$65/(2\pi 60)\ s^{-2}$	10	5%	0.01 s

For this simulation, the pre-transient angle between Buses 1 and 4 is 11.13 degrees. At T = 15 s, Line 2 is opened, reducing the overall path capacity by 80 percent. OoSPRE processes measurements at 60 samples/second using a 4-point backwards difference method to estimate smoothed values for angle, slip, and acceleration.

B. EAC Energy-Based Out-of-Step Protection

Applying the method described above to this transient, OoSPRE initially detects a potentially unstable transient when the magnitudes of both slip and acceleration exceed predetermined threshold values. Once detected, OoSPRE collects the first eight samples (blue Xs in Fig. 6) and uses them to calculate a new estimate for τ_{max}/J at 8.91 s^{-2}. The previous value of τ_{max}/J is discarded and OoSPRE then recalculates the restraint region with the updated parameters as shown in Fig. 7a.

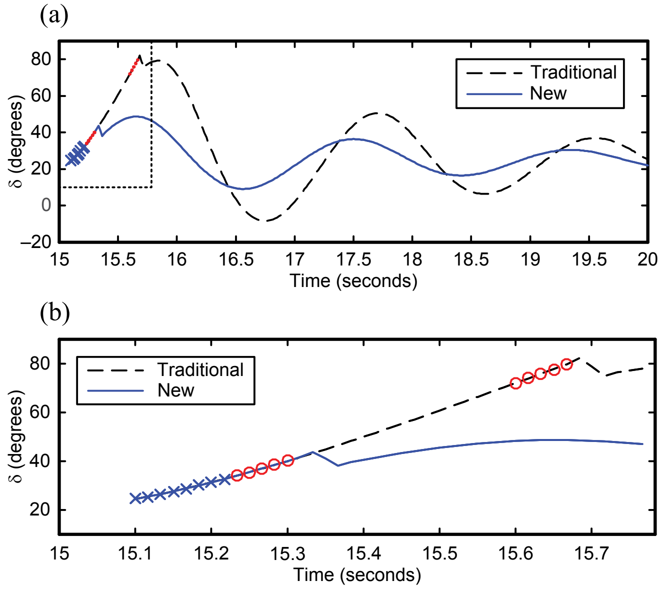

Figure 6. Angle vs. time for first 5 seconds (a) and first 0.7 seconds (b), showing samples for parameter estimation (Xs) and pickup timer samples (circles).

By comparing the angle-slip trajectory to this angle-slip restraint region, OoSPRE identifies that the angle-slip trajectory lies outside the angle-slip restraint region. A pickup timer is started that triggers remedial action if the trajectory remains outside the angle-slip restraint region for more than five sequential samples (dots in Figs. 6 and 7). At T = 15.33 seconds and an angle of 44.3 degrees, the pickup timer output asserts and OoSPRE initiates remedial action by applying a load shed at Bus 3.

Fig. 6 shows the new trajectory of the system angle (solid line) following a remedial action. Fig. 7a shows the trajectory on the angle-slip plane.

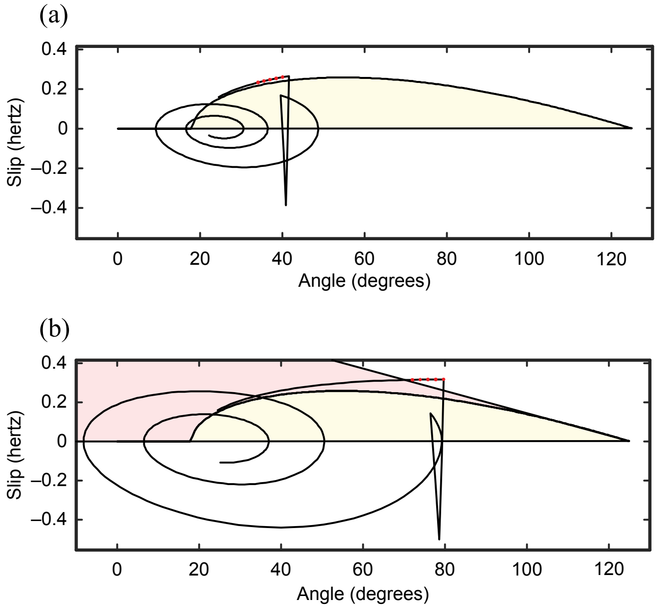

Figure 7. Angle-slip trajectory for new restraint region and response (a) and traditional restraint region and response (b).

C. *Traditional Out-of-Step Protection*

Applying a traditional, linear-blinder-based method to this transient, the protection system monitors the angle, slip, and acceleration to see if it lies outside the restraint region (shaded red in Fig. 7b). The linear blinder is set with an identical angle-intercept and similar slope to the adaptive region described above.

Once the angle-slip trajectory extends beyond the angle-slip restraint region, the same 5-sample pickup timer is applied (dots). At T = 15.67 seconds and an angle of 79.7 degrees, the system initiates remedial action with a load shed at Bus 3.

Fig. 6 shows the traditional trajectory of the system angle (dashed line) following a remedial action. Fig. 7b shows the trajectory on the angle-slip plane.

Of note in these trajectories is the increased deviation in both angle and slip experienced when employing the traditional method. The deviation in slip is directly relatable to system frequency deviations, which can lead to over- or underfrequency tripping of equipment as well as increased mechanical stresses to rotating equipment.

D. *Calculating Remedial Action*

In both the traditional and new protection methods described above, the remedial action consists of a load shed at Bus 3. The amount of this load shed is determined by comparing the measured acceleration (340 mHz/s) to the critical acceleration (220 mHz/s), as shown in Fig. 8. This difference is then divided by J to provide the required path unloading consistent with (2). Fig. 8 shows this process graphically on the slip-acceleration plane for the new method.

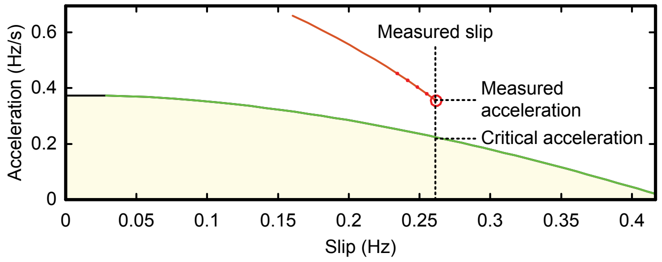

Figure 8. Slip-acceleration trajectory.

V. CONCLUSIONS

This paper proposed a new out-of-step protective remedial engine for identifying and mitigating out-of-step transients based on the equal area criterion and energy balance. We have shown that this method provides earlier detection of transients and provides parameters by which the minimally disruptive remedial action can be determined. Both of these capabilities result in improved system stability, minimized customer disruption, and reduced stress on power system apparatus.

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