Algorithm for Out-of-Step Condition Detection and Early Warning Using Phasor Measurement Unit Data

Igor Ivanković
Croatian transmission system operator – HOPS
Zagreb, Croatia
igor.ivankovic@hops.hr

Igor Kuzle
University of Zagreb, Faculty of electrical engineering and computing
Zagreb, Croatia
igor.kuzle@fer.hr

Ninoslav Holjevac
University of Zagreb, Faculty of electrical engineering and computing
Zagreb, Croatia
ninoslav.holjevac@fer.hr

***Abstract*—In wide area monitoring, protection and control systems (WAMPAC), angle stability of transmission network is monitored using data from phasor measurement units (PMU) placed on transmission lines. Based on PMU data stream measurements advanced algorithm in order to detect and issue an early warning for out-of-step conditions is developed. That research hypothesis and algorithm is described in this paper. Data and results from corresponding simulations done in Matlab environment are elaborated and explained to provide the insights of the potential benefits. This algorithm will be adjusted for implementation in protection segments of WAMPAC systems in the transmission system operator central control centers.**

Keywords—transmission network protection; out-of-step condition; WAMPAC system; PMU data

I. INTRODUCTION

Transmission network control center uses large number of applications for control and protection of transmission power system. Wide area monitoring, protection and control (WAMPAC) system utilizes phasor data from phasor measurement units (PMU). Wide spread deployment of PMU devices has enabled development of a range of advanced protection functions [1]-[2].

Usage of such data streams from PMU for development of the WAMPAC system with advanced angle instability protection functionalities is in more details elaborated in [3]. The prerequisite for such angle instability protection algorithms are PMUs installed across the important nodes in the transmission system. This way good insight into conditions in transmission corridors is obtained. In order to have a proper detection and reaction on different angle instability events it is necessary to have an algorithm which can detect the instability and react swiftly [4]. These algorithms are to be implemented into future WAMPAC systems and will give good observability and protection for transmission power system in general and for each line equipped with PMU devices individually [5].

The suggested algorithm completely relies on synchronized phasor data stream from PMU devices. Modern PMU devices [6] and phasor data concentrators (PDC) normally operate with sampling time equal to one electricity sine period (20 milliseconds) which enables all actions of the algorithm, both in detection and operation, to be completed.

II. ANGLE INSTABILITY

Angle instability conditions in transmission power network are undesirable events. They can seriously jeopardize normal operation in the transmission network with great risk of energy supply reduction. Out-of-step disturbance is an extreme manifestation of angle instability. Huge oscillations in voltage (Fig. 1) and current (Fig. 2) values followed the occurrence of out-of-step condition (simulations done for real 400 kV Croatian transmission network).

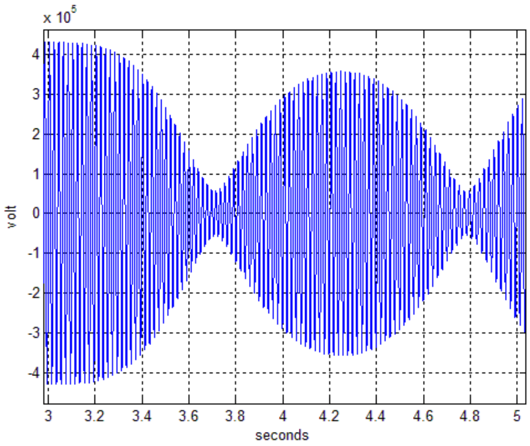

Fig. 1. Details for starting point of voltage oscillations on 400 kV transmission line during out-of-step condition during simulation scenario.

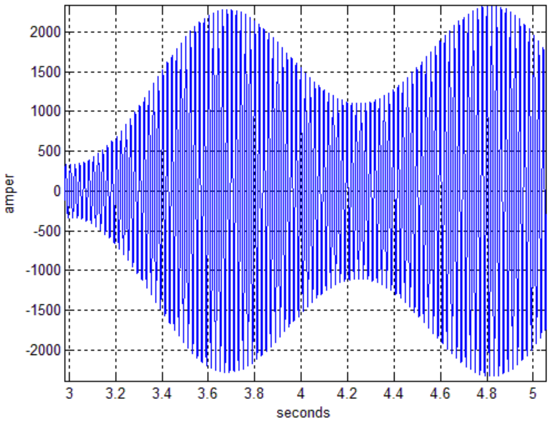

Fig. 2. Details for starting point of voltage oscillations on 400 kV transmission line during out-of-step condition during simulation scenario.

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Voltage magnitude decreased almost to zero kV for a transmission line where the out-of-step condition manifested (Fig. 1) and current values surpassed nominal values by a large margin (Fig. 2). In parallel, intense power oscillations are also present (Fig. 3).

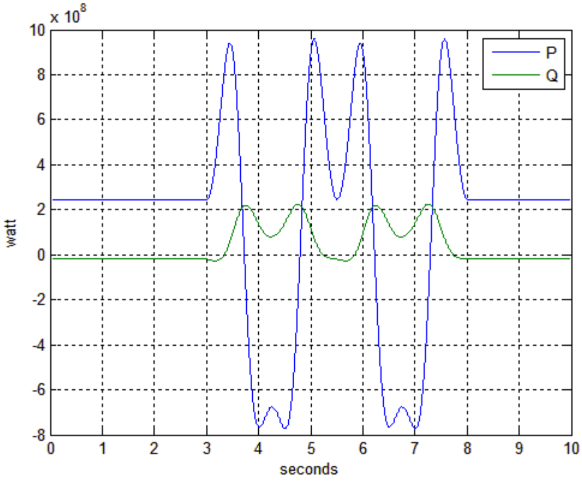


Fig. 3. Active and reactive power oscillations on 400 kV transmission line during out-of-step condition.

These power oscillations are far above the nominal values of transmission lines which can cause damage to other parts in electrical power system, especially generators units that can be seriously damaged [7]. Furthermore, circuit breakers on transmission lines can also be endangered due to increased voltage stress caused by even doubled voltage amplitudes.

III. METHOD FOR QUICK DETECTION OF ANGLE INSTABILITIES IN TRANSMISSION POWER NETWORK

Transmission lines equipped with PMU devices inside a transmission network can be also presented as isolated connections between two machine equivalents (shaded equivalent generator behind busbar on Fig. 4).

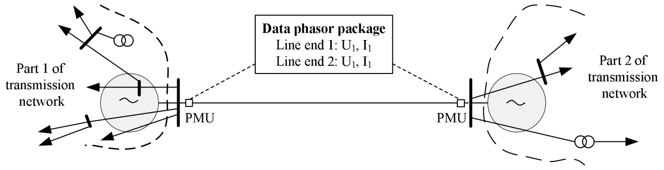


Fig. 4. Two machine equivalent on one line in transmission network eqiupped with PMU devices.

Despite that simplification clear picture for analyses and action is still obtained. From relay protection perspective full protection and monitoring functions can be implemented. These include protection algorithms for active power oscillations, with focus on adequate reaction during out-of-step conditions and tracing energy oscillations on observed line and indirectly in wider transmission area. Main goal is to detect various types of active power oscillations in transmission system in order to issue appropriate protective alarms and actions.

Clear differentiation between power oscillations and ramping characteristics should be assured. Usually, trajectory during oscillating conditions manifests smoothly changed electrical values (voltages, currents, active and reactive power). Ramping changes happen when sudden actions such as short circuit or breaker switching operations occur as shown on Fig. 5.

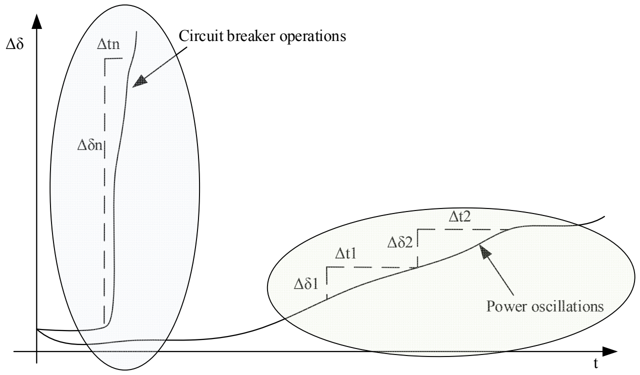


Fig. 5. Trajectory paths for circuit breaker switching operations and active power oscilations

All trajectories during oscillations are change following two main principles:

- Uniformity – values received from PMU devices each sample period (20 ms) change proportionally below preset thresholds without significant steps or jumps.
- Continuity – two subsequent values have consistently small differences. Trajectories have no discontinuities or disruptions in their path. Breaker switching operations manifest as leaps from one value to other without further changes of trajectory for the duration of fault.

With the PMU reporting rate given with 50 fps (frames/seconds) smooth trajectory characteristics can be obtained.

A. Main detection and protection criteria

Voltage phase angle can be deployed as new values for protection purposes. Basic values of voltage phase angle difference Δφ is shown in Eq. (1).

$$\Delta\varphi = \varphi_1 - \varphi_2 \tag{1}$$

This value is available on all PMU observed transmission line. Other two values and indicators of conditions on transmission lines are angle speed (Eq. (2)) and angle acceleration (Eq. (3)).

$$\omega = \frac{d(\Delta\varphi)}{dt} \tag{2}$$

$$\alpha = \frac{d^2(\Delta\varphi)}{dt^2} \tag{3}$$

Algorithm has to react before $\Delta\varphi$ reaches 180^0. It should differentiate active power oscillations in transmission network from out-of-step conditions. Reaction time is very limited because out-of-step conditions in transmission network develop extremely fast. In each phasor cycle, every 20 ms window, angle difference, angle speed and angle acceleration are constantly monitored. Trigger values for α and $\Delta\varphi$ are used. With active power changes on transmission lines accelerations ($\alpha \neq 0$) the most significant change is observed:

$$|\alpha_{i+1}| > |\alpha_i| \tag{4}$$

In a case of out-of-step condition angle acceleration will have high values. For a stable active power swing it passes through zero in first few hundred milliseconds. Therefore values of α equal 0 in first $i+n$ cycles, is a first indices that a stable swing will occurs in that power swing period. During that time angle speed ω (Eq. (6)) and angle difference (Eq. (7)) follow their own trajectory. Values of angle speed will have zero crossing in first $(i+n)+m$ cycles. Angle difference $\Delta\varphi$ will have zero crossing in $(i+n+m)+k$ cycles. Where n, m and k represent limited number of cycles after consecutive zero crossing of corresponding phase angle value.

$$|\omega_{i+1}| > |\omega_i| \tag{6}$$

$$|\varphi_{i+1}| > |\varphi_i| \tag{7}$$

If those conditions are realized in described particular sequence (α than ω and than φ) that power swing will remain stable and will not develop in out-of-step condition. Simulation scenarios indicate that signal for stable power swing flag is possible to be generated in time before angle difference reaches its maximum value. Different values and trajectories are measured for occurrence of unstable swing which leads to out-of-step conditions. Angle difference threshold is set as maximal allowed value for operations of transmission network in alert conditions. Those values ($\Delta\varphi_{\text{MONITOR START}}$) are used for setting of the synchrocheck functions on transmission lines. Empirically these values are in range from 20° to 30°. If the following sequence accomplishes (Eq. (8)) for each observed cycle and the trajectory has a monotony increasing trend alarm for unstable swing will be generated before out-of-step condition occurs ($\Delta\varphi$=180°).

$$\begin{cases} |\varphi_{i+1}| > |\varphi_i| \\ |\omega_{i+1}| > |\omega_i| \\ |\alpha_{i+1}| > |\alpha_i| \end{cases} \tag{8}$$

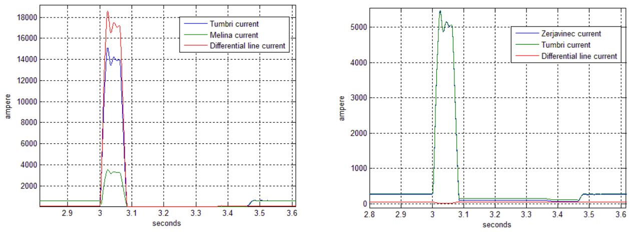
Alarm will be generated few hundreds of milliseconds before out-of-step condition occurs. These values can be indirectly defined through with preset values ($\Delta\varphi_{\text{TRIP COMMAND}}$) that are in range from 30° to 50° which will assure enough time to send a trip command to dedicated line circuit breaker.

B. Remedial protection criteria

Protection systems should always assure correct detection of disturbances in the transmission network. Additional conditions need to be used for this demanding task. The main criteria will be evaluated through additional remedial criteria. Two criteria are chosen in the algorithm described in this paper. In a case of line fault appearance, first criteria is line current difference that can help determine the exact fault locations. This criterion relies on well proven technology of line differential current (Eq. (9)), which compares currents from sending (I_1) and receiving (I_2) end of the transmission line.

$$\Delta I = |\overline{I}_1 - \overline{I}_2| \tag{9}$$

Values I_1 and I_2 are phasor values from both line ends and comparison is done for values with the same time tag. This criterion will detect every kind of line fault (short circuit, high resistance fault, earth fault). Three phase short circuit line fault on Tumbri-Melina 400 kV line was simulated and line current and differential current conditions are presented on Fig. 6. Neighboring line, Tumbri-Zerjavinec with current conditions is presented on the left part of Fig. 6.



a) b)

Fig. 6. a) Short circuit fault on Tumbri-Melina line with currents from both side of line with differential current ΔI. b) Tumbri-Zerjavinec line with trough fault current and differentila curent ΔI.

Swing equitation with some simplification can be adapted for usage as the second additional remedial criteria. Values for transmission line equivalent inertia on H_{eq} has very different trajectories and patterns for stable active power oscillations and out-of-step conditions. On this basis one remedial criterion for early recognitions of out-of-step was created. As shown on Fig. 4 it covers a two machine case and can be phrased as in Eq. (10).

$$P_m - P_e = M \cdot \frac{d^2\delta}{dt^2} \tag{10}$$

Mechanical power from turbine P_m and electrical generator output P_e are in balance during steady state conditions. Cumulative momentum M that is monitored on a transmission line:

$$M = \frac{2H}{\omega_s} = \frac{H}{\pi \cdot f} \; [p.u] \tag{11}$$

Unbalance power ΔP is:

$$\Delta P = P_a = M \cdot \alpha \tag{12}$$

Equivalent transmission system inertia H_{eq} on the particular phasor monitored line can be expressed as in Eq. (13).

$$H_{eq} = \frac{\Delta P_{line}}{\alpha_{line}} \cdot \pi \cdot f \tag{13}$$

C. Two level criteria protection schems

Main criteria for detecting active power oscillations and differentiation between stable and unstable power swing was designed and explained in previous section. It conforms to be implemented into WAMPAC system. Detection of out-of-step conditions in transmission network is a complex process in comparison to short circuit detection. Additionally, checks need to be carried out in a case of real line fault because in that case line relay protection has to be activated. This checking process runs in parallel with main criteria and it is divided into two level protection schemes (Fig. 7). A line differential criterion provides additional confirmation of the location of the faulted line. Equivalent transmission system inertia H_{eq} criterion additionally differentiates between stable and unstable swing development on transmission line.

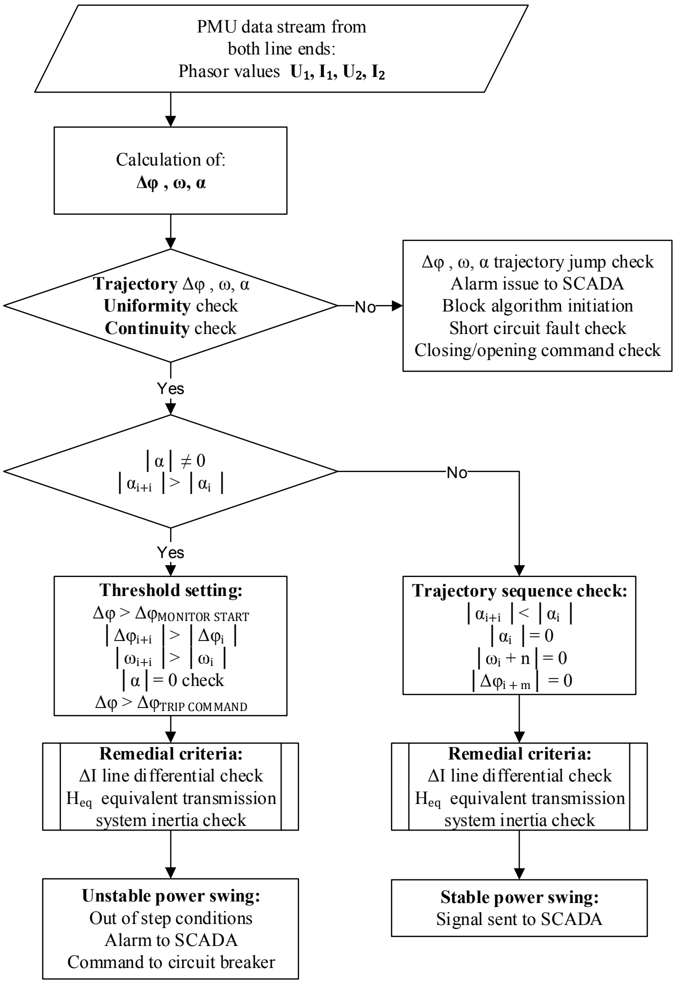


Fig. 7. Flow chart of algorithm for active power oscilaltions and out-of-step condition detection and early warning.

The described two level criterion enables fast reaction for line protection purposes during angle instabilities.

IV. ANALYSIS OF THE SIMULATIONS RESULTS AND BASIC CHARACTERISTICS OF ANGLE INSTABILITIES IN TRANSMISSION POWER NETWORK

Simulations model was developed in Matlab and afterwards ran through the extensive process of verification and validation against real operation archived data [8], [9]. The modelled 400 kV network is a multi-machine network of the real 400 kV Croatian transmission system.

For the test of the proposed algorithm simulations duration was set to 10 seconds and oscillations were initiated in 3rd second and lasted till 8th second. Segments of the simulation results are presented. Model was designed for developing protection functions. That was priority task how to have proper protection respond. Model actually has built for high voltage transmission network.

Using synchronized phasor measurement data in daily operation gives the TSO a broad range of advanced and powerful possibilities such as monitoring of angle stability. That means, every oscillation in transmission network will be observed and noted thus alarm can be issued or even automated reaction can be generated. Described protection algorithm, as was mentioned before, is developed with aim to help the detection and provide basis for fast reaction. Simulations results for high active power oscillations on two lines are presented on Fig. 8. 400 kV transmission line Konjsko-Velebit is exposed to unstable swing which develops to out-of-step condition. Neighboring 400 kV line Velebit-Melina, manifests the stable power swing only (Fig. 8).

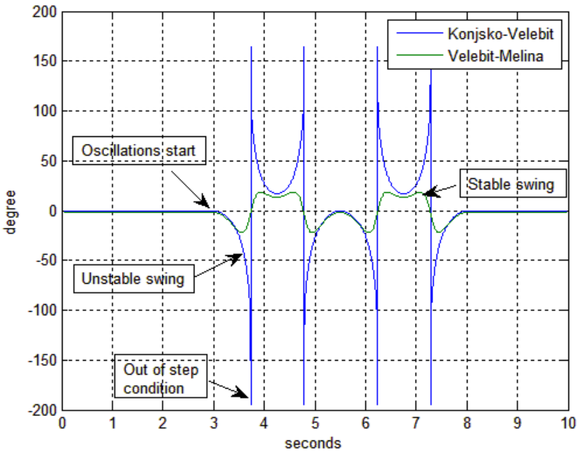


Fig. 8. Active and reactive power oscillations on two 400 kV transmission line during high activepower oscillations.

Angle difference, Δ*φ* presents how power oscillations behave using the data of voltage angle from both sides of the transmission lines. Simulated disturbances in Matlab environment follow the characteristic pattern [10]. The representative disturbance for out-of-step condition occurrence on 400 kV transmission line (Konjsko-Velebit) was chosen. Neighboring 400 kV lines (e.g. Velebit-Melina) manifested strong active power oscillations. Through simulation it was shown that besides angle difference other angle values should be traced and monitored in order to correctly detect the disturbance. Those values are angle speed and angle acceleration. Line with out of step conditions (blue line Konjsko-Velebit) has significantly higher angle speed ω then other lines where only power swings manifest (green line Velebit-Melina) Fig. 9.

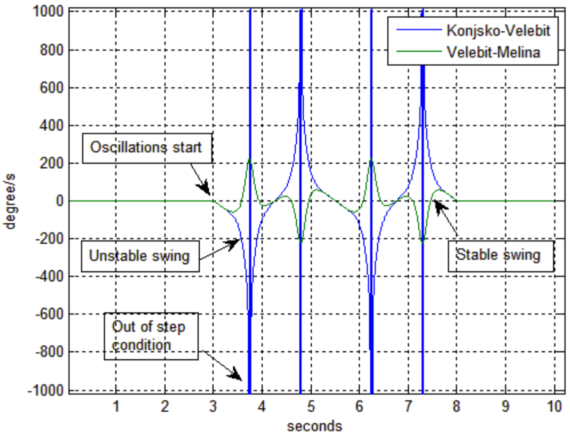


Fig. 9. Angle speed ω, for two 400 kV transmission lines during out-of-step conditions occurrence.

Readings from Fig. 9 give value of ω=16,000 degree/s (value out of range for selected axis range) for line with out-of-step condition and for line with only power swing value ω=700 (degree/s). Very similar ratio but with much bigger absolute values happened with angle acceleration α as shown on Fig. 10. Angle acceleration α, for out-of-step conditions maxed at α=900,000 (degree/s^2) and the neighboring line had value of only α=9,250 (degree/s^2). Values on Fig. 10 show only a limited range to present in more details most important parameters of the characteristics.

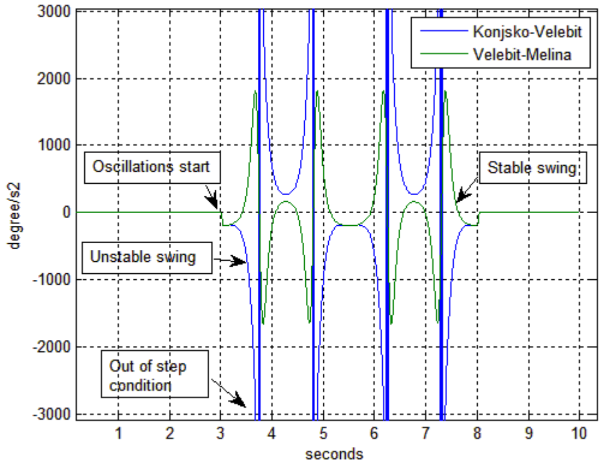


Fig. 10. Angle acceleration α, for two 400 kV transmission lines during out of step condition occurrence.

After series of conducted simulations of angle instability it is clear that focus must be on relationship between values of ω and α. It is well known that reaction time for any action during angle instability is extremely short. Control action must be generated and propagated to circuit breaker in a less than one second. Protection algorithms can be based on the interdependent behavior of the three angle values, $\Delta\varphi$, ω and α [11], [12]. The described algorithm in this paper uses characteristic behavior of observed values (Fig. 11) for power swing and out-of-step condition detection and early warning issue.

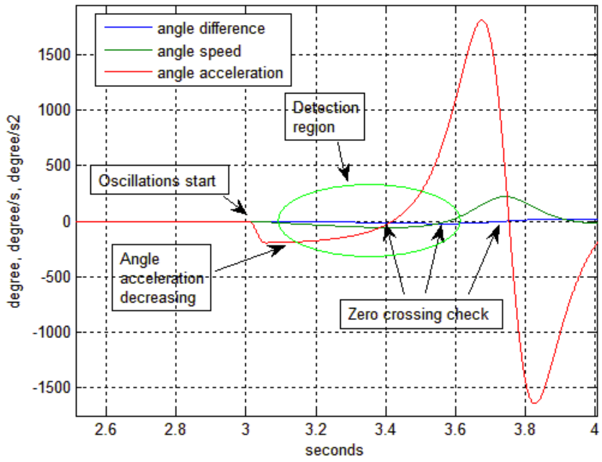


Fig. 11. Details of the voltage angle difference $\Delta\varphi$, angle speed ω and angle acceleration α, on 400 kV transmission line with stable swing.

Angle acceleration α, has zero crossing (at t<3.4s) before angle difference $\Delta\varphi$. Additionally angle speed ω, has zero crossing (at t~3.6s) before $\Delta\varphi$ crosses the x-axis. This is a characteristic footprint for power swing. Line affected with out-of-step condition has very different pattern (Fig. 12) compared to power swing pattern (Fig. 11). Line affected with out-of-step condition has different pattern for all three angle values, $\Delta\varphi$, ω and α. All of these values will not have zero crossing before reaching the 180 degrees point and all values continue increasing until slip finally occurs.

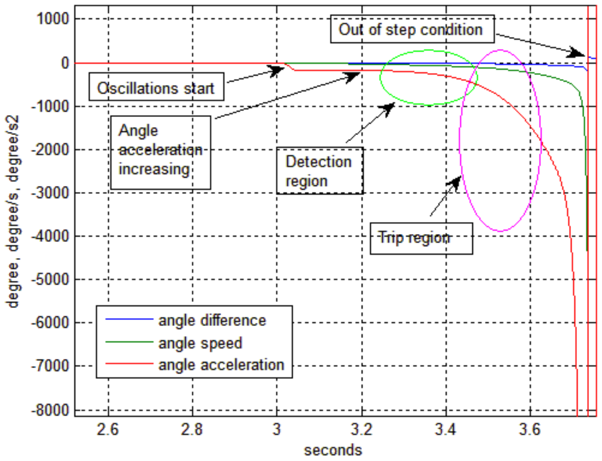


Fig. 12. Details for voltage angle difference Δφ, angle speed ω and angle acceleration α, on 400 kV transmission line with out of step conditions.

Remedial criteria ΔI, clearly points only power oscillations developed on both lines without any short circuit faults as shown on Fig. 13. Values of ΔI have small values caused by line charging current. Other remedial criteria, equivalent transmission system inertia H_{eq} for both lines also has a characteristic pattern shown on Fig. 14.

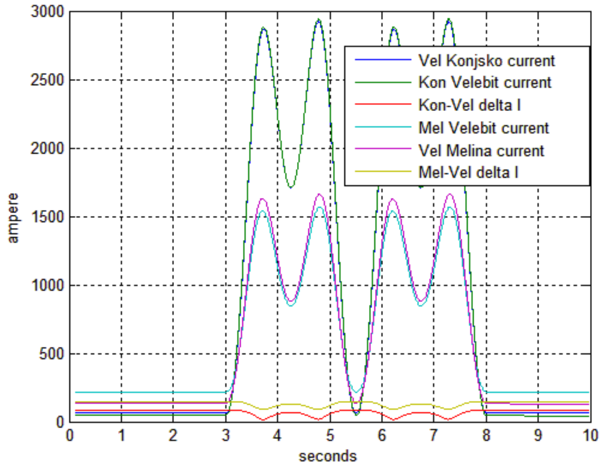


Fig. 13. Konjsko-Velebit and Melina-Velebit currents from both line ends with differential current protection (ΔI). Out-of-step has developed on Konjsko-Velebit line and only stable power swing was present on Melina-Velebit line.

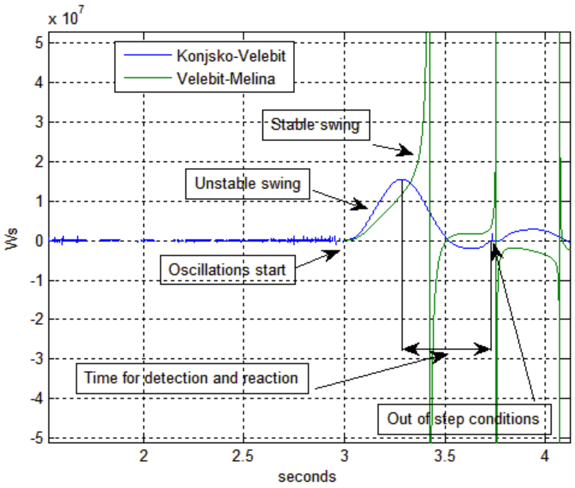


Fig. 14. Konjsko-Velebit and Melina-Velebit lines with equivalent transmission system inertia H_{eq} measurements. Out-of-step developed on Konjsko-Melina line and only stable swing was present on Melina-Velebit line.

Line affected by unstable swing has significantly lower H_{eq} with trajectory which decreases few hundred ms before out-of-step is developed. Line with stable swing has higher values of H_{eq} and zero crossing exists.

V. CONCLUSION

Developing algorithm for fast and efficient detection and reaction to angle instability is important for transmission network operations. It acts as an important segment of WAMPAC applications in control center. The paper presented simulation results that provide guidelines for the design of such protection algorithm and finally gives an algorithm design suggestion. Algorithm was described in analytical way with flow diagram based on simulation results and conclusions.

Proposed protection algorithm based on PMU data has advantages compared to the traditional relay protection logic. This method is not dependable on network configuration and enables good observability and detection of different disturbances including power swing and out-of-step conditions. Algorithms is robust and simple to implement (short processing time) on transmission line equipped with PMU devices. It operates on transmission line independently from other elements (any number of generators, lines, transformers or FACTS devices) that are also connected to the busbar.

The proposed algorithm will be unifying transmission phasor measurement in WAMPAC system which will allow the creations of new protection functions in control center. Future work will be focused on implementation of described algorithm in transmission system control center and extensive testing in real operation conditions.

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