# Key Performance Indicies for Angle Stability Protection Function in WAMPAC System


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***Abstract*—Design process of the Wide area monitoring, protection and control system (WAMPAC) in control rooms consists of many project phases. Crucial part is to determine parameters for alarms triggering and setting parameters for control and protection modules. Integral segment is to define key performance indices (KPIs) through verified simulation models. Therefore, simulation scenarios were created to define key performance indices for both normal operation events and for various disturbances in the transmission network. Most significant results for setting of angle stability protection parameters are presented in this paper.**



***Index Terms*--Angle protection, Key performance indices, Transmission network, WAMPAC system.**


## I. Introduction

Angle stability protection function must operate in a complete range of possible angle instability events in a transmission network [1]. This range starts from disturbances that manifest in a small signal stability issues [2], progressing to disturbances occurring during active power oscillations or power swings in one or several transmission lines that can cause significant change in phase values across the whole transmission network. Finally, ending with out of step disturbances as final stage of severity for angle instability events. Angle stability protection functions have two main modules [3] which are used for the following cases:

- Monitoring and alarming purposes for each of the transmission lines with supervision of line conditions as first stage protection level where only alarm signals are generated.
- Protection purposes which is activated for medium and large disturbances on line resulting in both the alarm and command signals.

In order to adjust this multi modular protection functions [4] extensive study and simulation work is required to obtain key performance indices (KPIs) as a setting frame. With that aim, in this paper, simulation of disturbances were done using Matlab environment. Two network models [5] were developed, which were previously tuned and validate using real operation historic data. Part of the work was done using IEEE 9 bus model (IEEE9BUS) in order to get generalized data and reference results. More detailed simulation was done using developed Croatian transmission network model with 6 buses (CRO6BUS). Results of this network were compared with real operational data [6]. Furthermore, results generated with CRO6BUS model were used for WAMPAC [7] of the Croatian system operator which is operational and in in pre-production phase. This paper elaborates on obtained KPIs used for main and remedial criteria of angle stability protection functions.

## II. Simulation Platform for Angle Stability

Angle instability is a relatively rare event in transmission network and therefore an extensive set of simulations had to be done to obtain proper insights. As mentioned, two network models alike the Chilean case study in [8] were used (Table I).

TABLE I. GENERAL DATA COMPARISSON OF THE MODELS

| *No.* | *IEEE9BUS* | *CRO6BUS* |
|---|---|---|
| 1. | 6 HV buses [a] | 6 HV buses [b] |
| 2. | 6 HV lines | 5 HV lines |
| 3. | 3 generator buses | 1 generator bus |
| 4. | 3 generators | 2 generators |
| 5. | 3 loads | 5 loads |
| 6. | - | 5 HV network equivalents |

a. 230 kV high voltage bus; b. 400 kV high voltage bus

Basic scheme of the IEEE9BUS is depicted on Fig. 1.

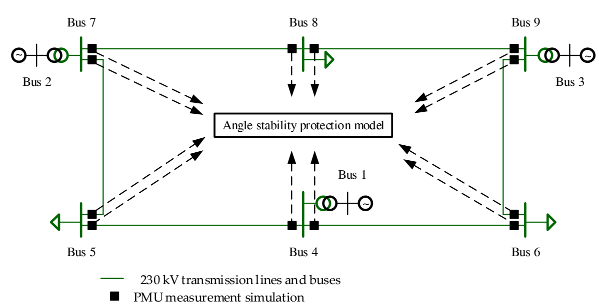


Figure 1. Basic scheme of the IEEE9BUS model


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In this paper, the focus was on transmission network behavior during angle instability events. Developed CRO6BUS model offers fully appropriate platform to perform simulation from relay protection engineer perspective. CRO6BUS model has high voltage network equivalents for surrounding transmission networks as shown on Fig. 2.

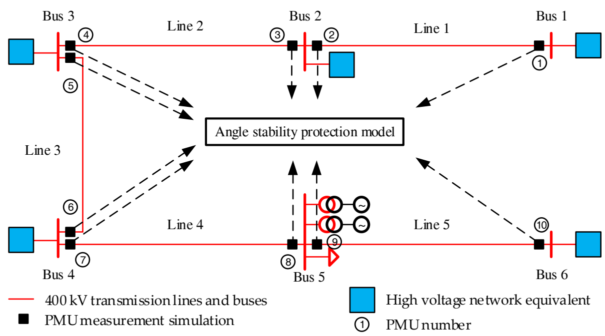


Figure 2. Basic scheme for CRO6BUS model

Angle stability function module was modeled in Matlab and incorporated into the basic network model Special protection schemes, out of step and transient stability function discussions can be found in [9] and [10]. Global design for the simulation platform was based on WAM system framework [11] and synchrophasor devices general approach [12].

Simulation scenarios are organized in five groups (Table II).

TABLE II. SIMULATIONS SCENARIOS

| ***No.*** | ***Scenarios*** | ***Remark*** |
|---|---|---|
| 1. | Breaker switching [b] | Opening and closing sequences |
| 2. | Line short circuit fault [c] | Three phase faults at line end |
| 3. | Busbar short circuit fault [c] | Three phase faults |
| 4. | Power swing [d] | Fault initiated in source or equivalent [a] |
| 5. | Out of step [d] | Fault initiated in source or equivalent [a] |

a. CRO6BUS model has network equivalents at international lines and lower voltage transmission network

b. Circuit breaker switched on for each line on both ends

c. Short circuit faults initiated on each line end and on each busbar

d. active power oscillations initiated in each network equivalent

KPIs definition is the focus of this research in order to prepare first iteration of protection devices settings that encompasses both normal operation and various disturbances in the transmission network.

## III. PROTECTION FUNCTION MODULES

Angle stability protection functions have basic angle protections modules as a fundamental part with addition of the line back up protection and system line protection. Angle stability protection must operate for a wide range of events and ensure stable and selective response. It has to be sensitive enough for small signal stability events such as minor disturbances and be precise and fast enough for out of step conditions occurrences in the transmission network.

### *A. Angle protection criteria*

In general, angle protection has three main criteria which use voltage angle values from PMU data collected by the WAMPAC system. Each of the transmission lines is equipped with measuring devices as can be seen from Fig. 1 and Fig. 2.

1) First criterion is voltage angle difference on one transmission line expressed as in (1):

$$\Delta\varphi_{ij} = \Delta\varphi_i - \Delta\varphi_j \tag{1}$$

Angle values are expressed in degrees (°).

2) Second criterion is angle speed as in (2):

$$\omega_{ij} = \frac{d(\Delta\varphi_{ij})}{dt} \tag{2}$$

Values are expressed in degrees per second (°/s).

3) Third criterion for angle protection is angle acceleration on one particular transmission line as in (3):

$$\alpha_{ij} = \frac{d^2(\Delta\varphi_{ij})}{dt^2} \tag{3}$$

Values for angle acceleration are degrees per second$^2$ (°/s$^2$). Complete angle surveillance of the network model is established with these three simple criteria listed as in (1), (2) and (3).

### *B. Remedial criteria*

In WAMPAC systems currently available PMU data allows the seamless creation and integration of remedial criteria functions [13]. These functions run in parallel with angle protection modules. Main operational issue for additional remedial criteria is detecting and distinguishing between the events and disturbances marked as scenarios no.1, no.2 and no.3 from the Table II. With the aim of achieving good response well proven current differential protection principle expressed as in (4) was used.

$$\Delta I_{ij} = \Delta I_i - \Delta I_j \tag{4}$$

Since line current values are available from both transmission line ends and whole modelled network is covered with PMU measurements it was possible to implement such remedial criteria functionality.

Availability of wide PMU data enables the creation of further complex criteria like for example online tracking of equivalent inertia of the transmission network [14]. Also, it enables the usage of other remedial criteria like complex under impedance criteria or simple current and voltage criteria [15]. If any of these criteria are to be used for monitoring purposes in WAMPAC systems KPIs calculation and definition needs to be done for them also.

### *C. Monitoring functionality*

WAMPAC systems are especially suitable for monitoring purposes since all of the required values are available through one unique system which has an additional benefit of running in parallel with protection function modules.

In general, a protection functionality continuously tracking changes in voltage, current and power values is very important for implementation of the angle stability functions. Voltage changes are traced as expressed in (5):

$$dV_i = \frac{dV_i}{dt} \quad (5)$$

Current changes are traced according to (6):

$$dI_i = \frac{dI_i}{dt} \quad (6)$$

Power changes were traced for active (7) and reactive (8) part:

$$dP_i = \frac{dP_i}{dt} \quad (7)$$

$$dQ_i = \frac{dQ_i}{dt} \quad (8)$$

Impedance changes were traced in accordance with (9):

$$dZ_i = \frac{dZ_i}{dt} \quad (9)$$

## IV. KEY PERFORMANCE INDICIES (KPIS)

Simulations result analyses determines the KPIs for various values of protection and monitoring settings parameters. In angle protection modules angle difference values ranges relevant for function setting can be defined as depicted on Fig. 3.

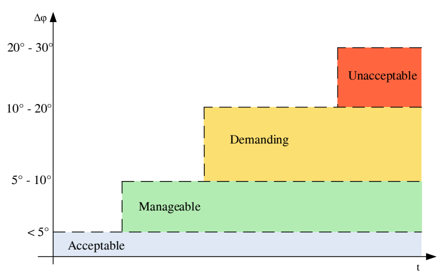


Figure 3. Example of four category for voltage angle difference KPIs

The values (Fig. 3) are based on previous study works [14] for dynamic assessment issues of the transmission network.

### A. *KPI for breaker switching during normal operations*

Simulations scenarios no.1 (Table II) gives angle values during opening of circuit breaker on lines equipped with PMU devices. Number of switched breakers is the same as the PMU number (Fig. 2). Angle difference values (equation (1)) obtained from each line breaker are depicted on Fig. 4.

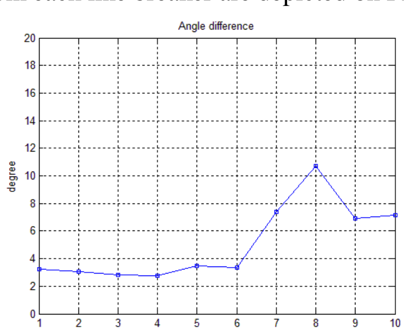


Figure 4. Δφ KPI range for breaker switching in normal operations

Angle speed values (equation (2)) for circuit breaker operations (Fig. 5) show that network around substations no. 5 and no. 6 is relatively week.

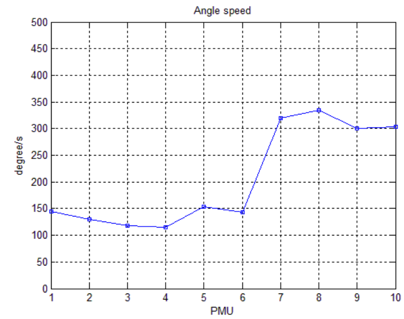


Figure 5. ω KPI range for breaker switching in normal operations

Angle acceleration values (equation (3)) obtained from the same simulations process (scenario no.1) are shown on Fig. 6.

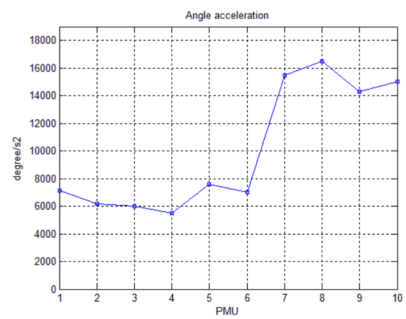


Figure 6. α KPI range for breaker switching in normal operations

Maximum values for these KPIs determines settings parameters for some protection actions, Table III.

TABLE III. KPIS FOR BREAKER SWITCHING IN NORMAL OPERATIONS

| ***No.*** | ***KPI*** | ***Maximum values*** |
|---|---|---|
| 1. | Angle difference Δφ | 10.7 [°] |
| 2. | Angle speed ω | 335 [°/s] |
| 3. | Angle acceleration α | 16500 [°/s$^2$] |

Values from Table III give characteristic footprint for this kind of switching operations in the network and the general settings similar to ones depicted on Fig. 3 can be defined.

### B. *KPI for lines and busbar short circuits*

Short circuit disturbances KPIs values are generated from simulations scenarios no.2 and no.3. Values for angle difference (equation (1)) have the following values in a case of short circuit on one of the transmission line ends (Fig .7).

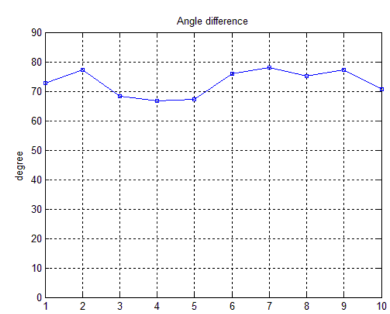


Figure 7. Δφ KPI range for short ciruit disturbance

Values of angle speed (2) and angle acceleration (3) are presented on Fig. 8 and Fig. 9 respectively.

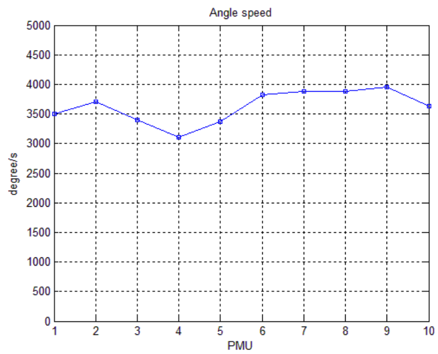


Figure 8. ω KPI range for short ciruit disturbance

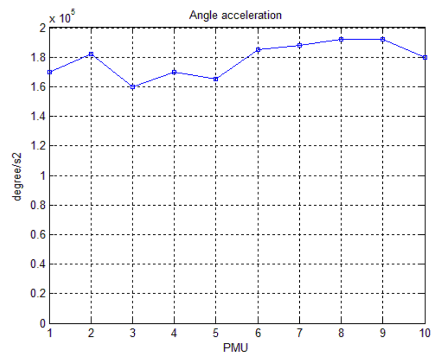


Figure 9. α KPI range for short ciruit disturbance

Range for KPIs during short circuit on lines and busbars also has a characteristic footprint (Table IV) and these KPIs are then used for protection and alarming functions settings.

TABLE IV. KPIs FOR SHORT CIRCUIT DISTURBANCES

| *Scenario no.* | *KPI values* | *Δφ* [°] | *ω* [°/s] | *α* [°/s$^2$] |
|---|---|---|---|---|
| 1. | Minimum | 66 | 3100 | 190000 |
| 2. | Maximum | 78 | 3900 | 190000 |

It is important to note that those events and disturbances have significant discontinuities (jumps) in measured values trajectory. Trajectory manifests major changes in values during the events and the angle characteristics retains these values until the circuit breaker is opened when new value levels are reached.

## C. *KPIs for power swing and out of step*

Different trajectory is measured during power swing conditions. It changes smoothly without jumps until out of step condition is reached. In Table V limit of 30° is defined for power swing condition serious disturbances which can jeopardize normal operations. Footprint of angle values expressed with equations (1), (2) and (3) manifests different amplitudes (Table V) compared to those of other normal operations (Table IV).

TABLE V. KPIs FOR POWER SWING AND OUT OF STEP

| *Scenario No.* | *KPI values* | *Δφ* [°] | *ω* [°/s] | *α* [°/s$^2$] |
|---|---|---|---|---|
| 1. | Minimum | < 30 | 380 | 3000 |
| 2. | Maximum | 180 | 17000 | 850000 |

Out of step disturbance has highest maximum values (even greater than the short circuit) of angle difference, angle speed and angle acceleration and Table V summarizes the results of the simulations.

Values of frequency aberrations (disturbance frequency and frequency change) for a set of simulation scenarios for power swing condition on lines 5 and 6 is shown in Table VI.

TABLE VI. SIMULATIONS SCENARIOUS FOR POWER SWING CONDITION

| *Scenario no.* | *KPIs values* |
|---|---|
| 1. [a] | Small disturbance: f=1,0Hz, Δf=0,03 Hz [a] |
| 2. [a] | Medium disturbance: f=0,6Hz, Δf=0,20 Hz [a] |
| 3. [a] | Large disturbance: f=0,6Hz, Δf=0,50 Hz [a] |
| 4. [a] | Medium disturbance: f=0,8Hz, Δf=0,20 Hz [a] |
| 5. [a] | Large disturbance: f=0,8Hz, Δf=0,50 Hz [a] |
| 6. [b] | Medium disturbance: f=0,6Hz, Δf=0,20 Hz [b] |
| 7. [b] | Large disturbance: f=0,6Hz, Δf=0,50 Hz [b] |
| 8. [b] | Medium disturbance: f=0,8Hz, Δf=0,20 Hz [b] |
| 9. [b] | Large disturbance: f=0,8Hz, Δf=0,50 Hz [b] |

a. Source f oscillations is in network equivalent connected to bus 6

b. Source of oscillations is in network equivalent connected to bus 4

Simulations results for angle indicators for oscillations on the line 5 are given in the Table VII.

TABLE VII. SIMULATIONS RESULTS FOR LINE 5

| *Scenario no.* | *Δφ* [°] | *ω* [°/s] | *Enters into relay characteristic* |
|---|---|---|---|
| 1. | 0.8 | 2.4 | No |
| 2. | 8.5 | 16 | No |
| 3. | 27 | 52 | Yes [a] |
| 4. | 6 | 16 | No |
| 5. | 18 | 44 | No |
| 6. | 2.5 | 5.0 | No |
| 7. | 5.4 | 11 | No |
| 8. | 2 | 5.0 | No |
| 9. | 4 | 12 | No |

a. Impedance trajectory reaches power swing reaction polygon of the protection relay

## D. *Additional KPIs for short circuits disturbances*

Additional KPIs sets are used for remedial protection module and for detection of the location of the disturbance. Results from these simulations are presented through one example scenario of a short circuit on line 3 (near bus 4). Voltage changes (Fig. 10) were traced on line 3 and line 4 (both are connected to bus 4).

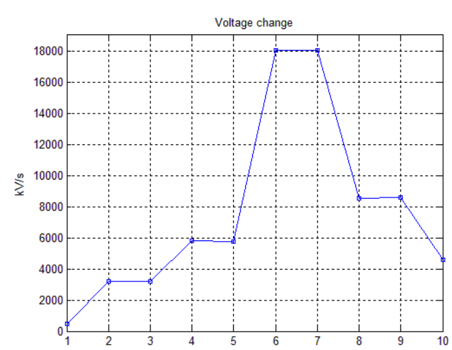


Figure 10. V/s KPI range for short ciruit disturbance

Changes in current and active power undoubtedly indicate the location of the fault (Fig. 11 and Fig. 12). Similar footprints were generated for all short circuits simulations.

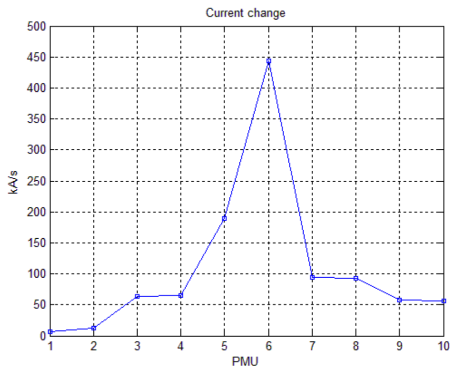


Figure 11. A/s KPI range for short ciruit disturbance

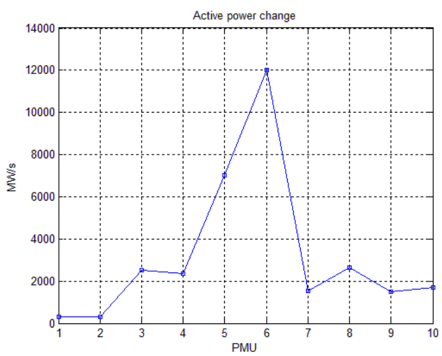


Figure 12. MW/s KPI range for short ciruit disturbance

Under impedance KPI can also be used for tracing of the disturbance events in network since it can point directly to the fault location (Fig. 13).

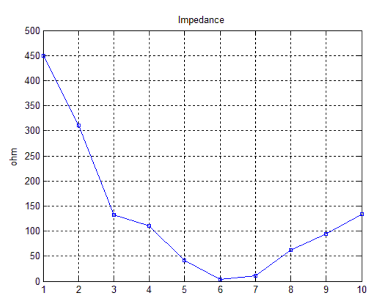


Figure 13. Impedance KPI range for short ciruit disturbance

Footprints for power swing have different patterns but locating the source of disturbance is done following the same trend as with current and active power changes.

## V. Conclusion

In order to have right settings parameters for angle stability protection it is necessary to perform detailed simulations, primarily analyzing and calculating KPIs sets which will be used for setting of the parameters. Angle stability KPIs were in focus of this article. Furthermore, KPIs generated for remedial protection criteria were elaborated.

KPIs sets provide a way to timely detect important disturbances in transmission network. Additionally, using KPIs sets breaker switching operations can be traced and source of the disturbance can be extrapolated for both PMU observed and unobserved network. Therefore, definition of KPIs is an important segment of WAMPAC system design.

## References

[1] A. G. Phadke, P. Wall, L. Deng, V. Terzija, “Improving the performance of power system protection using wide area monitoring systems,” Journal of Modern Power System Clean Energy, (2016), 4(3):319-331, DOI:10.1007/s40565-016-0211-x

[2] M. Larsson, L. F. Santos, A. Suranyi, W. Sattinger, R. Notter, “Monitoring of oscillations in the continental European transmission grid,” IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, pp. 4774-4778, November 2013.

[3] H. F. Albinali, A. P. Meliopoulos, C. Vournas, “Dynamic state estimation-based centralized protection scheme,” 2017 IEEE Manchester PowerTech, pp. 1-6, June 2017.

[4] N. Liu, P. A. Crossley, “Assessing the Risk of Implementing System Integrity Protection Schemes in a Power System with Significant Wind Integration,” IEEE Transactions on Power Delivery, Vol. PP No. 99, pp. 1-11, October 2017, DOI: 10.1109/TPWRD.2017.2759181.

[5] M. A. Khorsand, V. Vittal, “Modeling Protection Systems in Time-Domain Simulations: A New Method to Detect Mis-Operating Relays for Unstable Power Swings,” IEEE Transactions on Power Systems, Vol. 32, No. 4, pp. 2790-2798, July 2017.

[6] I. Ivanković, I. Kuzle, N. Holjevac, “Multifunctional WAMPAC system concept for out-of-step protection based on synchrophasor measurements,“ International Journal of Electrical Power & Energy Systems (0142-0615), Vol. 87, pp. 77-88, May 2017.

[7] V. Salehi, A. Mazloomzadeh, J. F. Fernandez, O. A. Mohammed, “Real-time power system analysis and security monitoring by WAMPAC systems,” 2012 IEEE PES Innovative Smart Grid Technologies (ISGT), pp. 1-8, January 2012.

[8] F. Valencia, R. Palma-Behnke, D. Ortiz-Villalba, A. De La Quintana, C. Rahmann, R. Cifuentes, "Special Protection Systems: Challenges in the Chilean Market in the Face of the Massive Integration of Solar Energy," IEEE Transaction Power Delivery, Vol. 32, No. 1, pp. 575-584, February 2017.

[9] M. A. M. Ariff, B. C. Pal, “Adaptive Protection and Control in the Power System for Wide-Area Blackout Prevention,” IEEE Transactions on Power Delivery, Vol. 31, No. 4, pp. 1815-1825, August 2016.

[10] H. Iwaki, Y. Inoue, A. Ishibashi, M. Kimura, K. Omata, Y. Ishihara, “System integrity protection scheme based on on-line transient stability calculation using protection relay device hardware,” 13th International Conference on Development in Power System Protection 2016 (DPSP), pp. 1-6, March 2016.

[11] Z. Hu, J. V. Milanovic, “The Effectiveness of WAM Based Adaptive Supervisory Controller for Global Stabilization of Power Systems,” 2007 IEEE Lausanne Power Tech, pp. 1652-1659, July 2007.

[12] K. Bhuyan, S. Chatterjee, “Vulnerability analysis and PMUs as next generation protection system in Smart Grid,” 2014 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), pp. 1-5, 2014. December 2014.

[13] N.A. Samaan, J.E. Dagle, Y.V. Makarov, R. Diao, M.R. Vallem, T.B. Nguyen, L.E. Miller, B.G. Vyakaranam, F.K. Tuffner, M. A. Pai, J. Conto, S. W. Kang, “Modeling of protection in dynamic simulation using generic relay models and settings,” 2016 IEEE Power and Energy Society General Meeting (PESGM), pp. 1-5, July 2016.

[14] I. Ivanković, I. Kuzle, N. Holjevac, “Algorithm for Out-of-Step Condition Detection and Early Warning Using Phasor Measurement Unit Data,“ 17th IEEE International Conference on Environment and Electrical Engineering – EEEIC 2017, pp. 1-6, June 2017.

[15] Z. Jiao, X. Wang, H. Gong, “Wide area measurement/wide area information-based control strategy to fast relieve overloads in a self-healing power grid,” IET Generation, Transmission & Distribution, Vol. 8, No. 6, pp. 1168-1176, June 2014.