Dynamic Angle Instability Simulation Framework Based on Reference Model Platform

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*—For the developed dynamic angle instability simulation framework a reference IEEE 9 bus model was adapted and created in Matlab simulation environment. Model was validated and verified with available real operation historical data and fine tuning process was conducted. With the reference model, flexible platform for study work in the field of transmission network behavior during disturbances was created. Series of simulation scenarios were done analyzing dynamic angle instability: from a wide range of small active power oscillations to larger active power oscillations and out-of-step conditions occurrence. The paper is not oriented towards operations analyses of generators rather observes and enhances protection functions of the transmission lines in the transmission system. Simulation data that is generated is used to create setting parameter sets for protection functions in the proposed Wide Area Monitoring Protection and Control (WAMPAC) system, utilizing simulated synchrophasor measurements.**

Keywords—IEEE 9 bus reference model, WAMPAC system, Angle instability, Transmission network dynamics simulation

I. INTRODUCTION

Dynamic phenomena in transmission network are a challenging task for any kind of relay protection. Angle stability directly influences transmission line protection system and has various effects on the distance protection. Therefore the design of simulation environment for protection system simulation and improvement play an important role.

Angle stability analysis must be done in a dynamic simulation environment. Dynamic analysis of phenomena in transmission networks has many influencing factors, especially if the network considered has many buses and elements [1]. In those cases, reduction of transmission network can be required. In general, simulation model should have similar proportions like real transmission network being considered. Croatian Transmission System Operator (TSO) operates 400 kV backbone transmission network with six 400 kV buses and has many interconnections with neighboring TSOs and to lower voltage transmission networks (220 kV and 110 kV voltage levels). Therefore, as dynamic angle instability reference model in the first stage of analyses the most similar IEEE model, IEEE 9 bus model [2], was chosen as a reference model platform. It consists of 6 high voltage buses, similarly to real Croatian system. Some solid and useful conclusion can be acquired for the real Croatian transmission network using the reference model platform that was selected. Detailed comparison between the reference model and the real Croatian transmission system are given in Table I.

This work has been supported by Croatian Science Foundation, Croatian Transmission System Operator (HOPS) and HEP Generation under the project WINDLIPS – WIND Energy Integration in Low Inertia Power System, grant no. PAR-02-2017-03.

TABLE I. GENERAL DATA FOR BOTH MODELS

No.	*IEEE 9 BUS*	*Croatian TSO 400 kV network*
1.	6 HV buses [a]	6 HV buses [b]
2.	6 HV lines [a]	5 HV lines [b]
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

High voltage parts of the both models have the same number of buses and almost the same number of lines. Standard scheme for IEEE 9 bus system is depicted on Fig. 1.

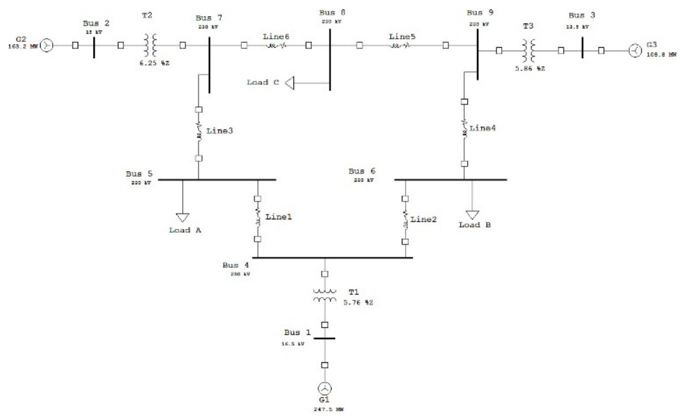

Fig. 1. Basic schemes for IEEE 9 bus model.

Model was designed with the goal of doing study and simulation process for the analyses of angle instabilities issues in transmission network. These kind of disturbances present rare events in network and additional knowledge for network response are collected and later used to define some key performance indices and setting parameters in WAMPAC system [3], [4].

II. Angle Instability Aspects

Angle instability of the transmission network can appear in the following ways:

- Small signal stability, with oscillations of active power in a range of less than 2 Hz. In that range the generators, area and interarea oscillations occur.
- Medium and large active power oscillations connected with larger disturbances can appear on transmission lines and will cause activation of line protection units.
- The largest oscillations of active power are out-of-step conditions, which endanger transmission network operations and require extensive protection operations.

Complete range of above mentioned oscillations can be covered with modern WAMPAC systems [5]. Those dynamic aspects have a starting point from the interconnection between each of the generators connected to network and events (network topology changes) and disturbances (short circuit fault and others influences on regular network operations). Dynamics for a single generator is given with swing equitation, as in (1).

$$P_m - P_e = M \cdot \frac{d^2\delta}{dt^2} \tag{1}$$

Difference between power on the turbine shaft P_m and generator electrical output P_e gives resulting momentum M with an acceleration $d^2\varphi/dt^2$. Those values are only available on the generators level and processed in the power plant. Many generators are further connected to the transmission network and these specific data pieces (e.g. acceleration) are not available in the control center. Instead, synchrophasor data collected by the WAMPAC system can be utilized very well for angle instabilities detection and protection substituting absence of generator data. Voltage phasor angle value difference on one line is calculated by equation (2):

$$\Delta\varphi_{12} = \Delta\varphi_1 - \Delta\varphi_2 \tag{2}$$

Phasor on line end 1 and line end 2 can be synchronously processed in the control center in real time [6] and because of that it is suitable for protection and control functions. Angle speed on a single line can be defined as in equation (3) and angle acceleration is extracted as in equation (4).

$$\omega_{12} = \frac{d(\Delta\varphi_{12})}{dt} \tag{3}$$

$$\alpha_{12} = \frac{d^2(\Delta\varphi_{12})}{dt^2} \tag{4}$$

Lack of generator data and complex calculations for angle instability are handled by the WAMPAC system protection and control functions. Flexible simulations environment [7] and reference model knowledge described in this paper are used to improve detection and reaction to angle dynamics in transmission network.

III. Reference 9 Buses Model

Dynamic angle instability models can also be found in the literature [8], [9]. The common process is to have the generators in the reference model for all three high voltage buses (1, 2 and 3) substituted with equivalents of variable voltage source and equivalent RL branch for step-up transformer (Fig. 2.).

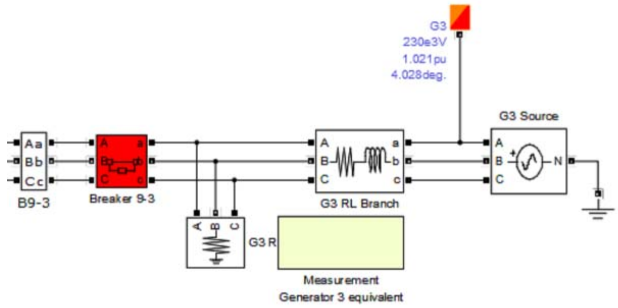

Fig. 2. Equivalent for generator and step-up transformer in the model of the IEEE 9 buses reference system.

Data for those equivalents are given in Table II, in a form of RLC values suitable for Matlab input.

TABLE II. RLC MODULE DATA FOR 230 KV EQUIVALENT

	Transformer (%)	Transformer (Ω)	Voltage (kV)	SC Power (MVA)
Bus 4 - 1	5,76	12,188	230,000	4,340
Bus 7 - 2	4,737	16,531	230,000	3,200
Bus 9 - 3	3,916	20,666	230,000	2,560

Important element for the creation of flexible simulation platform was design of high voltage breaker (red element on Fig. 2.) which operates in one and three phase sequences that were both modelled in details. Another important element was three phase measuring module (Fig. 3.). With that element simulation of the synchrophasor measurement was established.

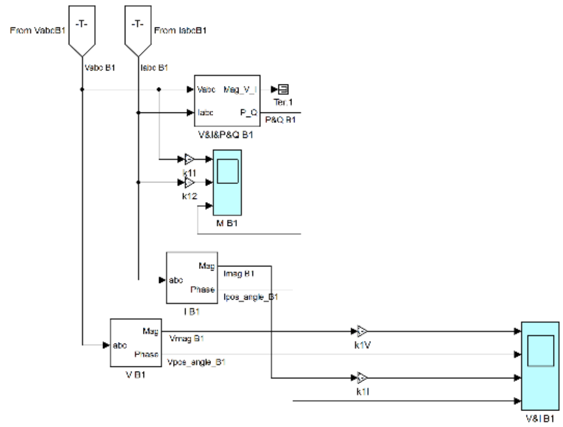

Fig. 3. Measurement module developed for synchrophasor measurements in the IEEE 9 buses reference model.

The designed modules are part of Wide Area Monitoring Protection and Control (WAMPAC) system that was implemented for detection and prevention of angle instability (Fig. 4). Proposed WAMPAC system has additional protection functions implemented similar to [10]. Line parameters are recalculated and adjusted as shown in Table III. Line data is checked accordingly (Equation (5)):

$$v_{line} = \frac{1}{\sqrt{L \cdot C}} < v_0 \tag{5}$$

Where v_{line} values were calculated for positive and zero line components and compered with speed of light (v_0).

TABLE III. DATA FOR POSITIVE AND ZERO SEQUENCE LINE PARAMETERS

Line parameter [a]	4 - 5	4 - 6	5 - 7	6 – 9	7 - 8	8 - 9
r1 (Ω/km)	0.0529	0.08993	0.16928	0.20631	0.044965	0.062951
r0 (Ω /km)	0.13225	0.224825	0.4232	0.5157	0.11241	0.15737
l1 (H/km)	1.192×10^{-3}	1.290×10^{-3}	2.259×10^{-3}	2.380×10^{-3}	1.010×10^{-3}	1.414×10^{-3}
l0 (H/km)	2.380×10^{-3}	3.220×10^{-3}	5.640×10^{-3}	6.090×10^{-3}	2.020×10^{-3}	3.530×10^{-3}
c1 (F/km)	9.322×10^{-9} [a]	8.614×10^{-9} [a]	1.534×10^{-8}	1.795×10^{-8}	7.471×10^{-8}	1.047×10^{-8}
c0 (F/km)	5.188×10^{-9}	4.740×10^{-9}	9.025×10^{-9}	1.055×10^{-9}	5.50060×10^{-9} [a]	6.15×10^{-9}
Length (km)	100	100	100	100	100	100

a. Line parameter check and modification is done according to equation (5)

Dynamic simulations in described reference model platform contribute to gaining detailed insights into transmission network behavior when angle instability conditions occur [11]. This kind of disturbance is rare, as was mentioned, in European continental high voltage transmission network and historical real operation data is scarce. Therefore, valuable conclusions can be obtained using the suggested simulation framework. Main idea is to maximally utilize available synchrophasor measurement data stream of the WAMPAC system to react to network instabilities. WAMPAC part in model was used for simulations of phasor data stream of phasor data concentrators [12]. The reference simulation platform was put through validation and verification process with the available data to finely tune the model. This step was done with utmost care in order to have results as good as possible for dynamic simulations. This process was done in the static domain for power flows in equivalent sources shown in Table IV for cases available in literature [13], [14].

TABLE IV. POWER FLOWS FOR EQUIVALENTS ON GENERATOR BUSES

	IJSRP (MW)	MANITOBA (MW)	Matlab model (MW)
Bus 4 - 1	71,6	71,6	73,4
Bus 7 - 2	163	163	161
Bus 9 - 3	85	85	83,9

Referenced power flow models can be found in literature [13] and [15]. Further checks and validation were done for the transmission line power flows shown in Table V.

TABLE V. POWER FLOW THROUGH TRANSMISSION LINES

	IJSRP (MW)	MANITOBA (MW)	Matlab model (MW)
Line 4 - 5	40,9	43,3	42,4
Line 4 - 6	30,7	28,3	31
Line 5 - 7	86,6	84,2	82,8
Line 6 - 9	60,9	63,3	59,2
Line 7 - 8	76,4	78,8	76,2
Line 8 -9	24,1	21,7	24,4

Next step in validation process was focused on voltage angle values on which new protection functions in WAMPAC system are based. Necessary additional checks were done for voltage amplitude on each of the high voltage buses (Table VI).

TABLE VI. VOLTAGE ON BUSES

	IJSRP (pu)	IJSRP (kV)	Matlab model (kV)	Matlab model (pu)
Bus 4	1,0258	235,934	236	1,0261
Bus 5	0,9956	228,988	228	0,9913
Bus 6	1,0127	232,921	234	1,0174
Bus 7	1,0258	235,934	234	1,0174
Bus 8	1,0159	235,657	232	1,0087
Bus 9	1,0324	235,452	235	1,0217

Final check and comparison was done for voltage angle difference on all transmission lines, Table VII.

TABLE VII. VOLTAGE ANGLE DIFFERENCE ON TRANSMISSION LINES

	Mathworks (∘)	Matlab model (∘)
Line 4 - 5	1.776	1.974
Line 4 - 6	1.475	1.681
Line 5 - 7	-7.622	-7.642
Line 6 - 9	-5.568	-5.594
Line 7 - 8	2.987	3.047
Line 8 -9	-1.234	-1.292

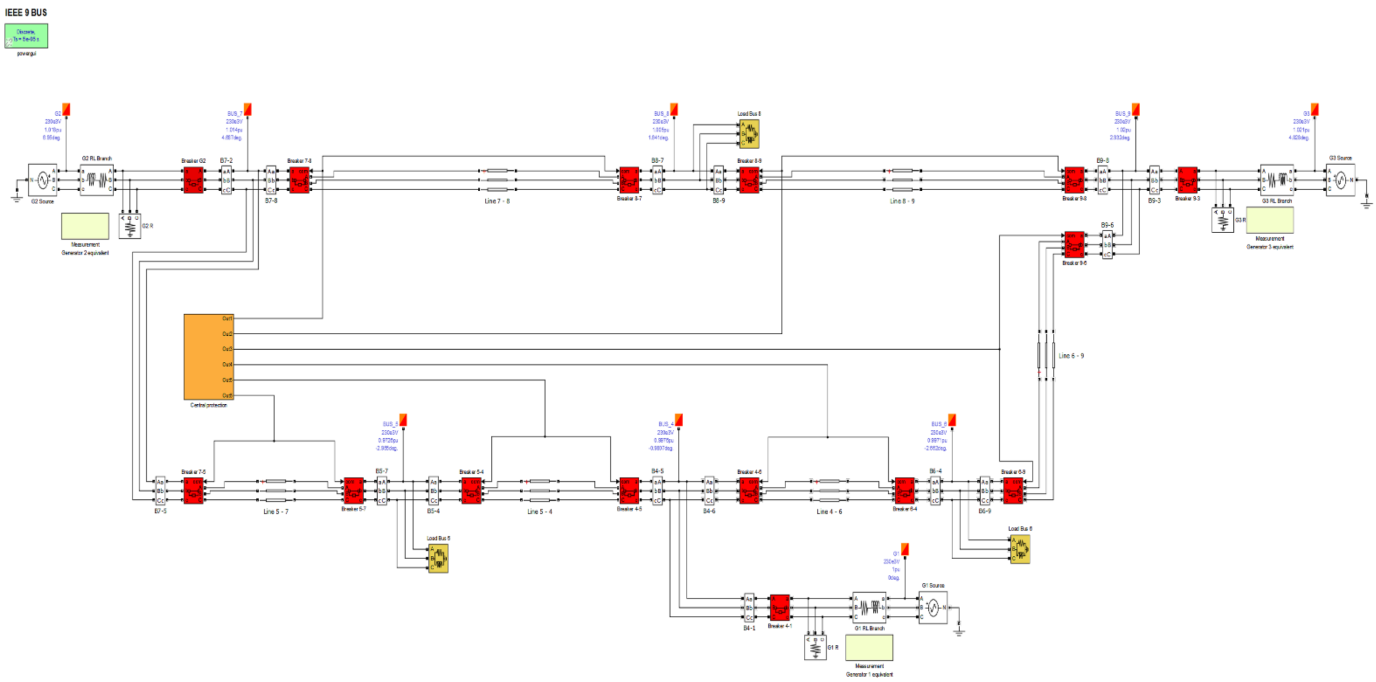

Fig. 4. Matlab model of reference 9 buses network with incorporated WAMPAC system protection

Above mentioned and presented data from validation and verification process shows that the proposed reference model platform was tuned well with available data and further study work in dynamic angle instability conditions can be obtained.

In the verification process, the model was checked for the following indicators:

- Active power flow of generators;
- Active power flow on transmission lines;
- Voltage angle on buses;
- Voltage angle difference on transmission lines;
- Reactive power flow for generators;
- Reactive power flow for transmission lines.

The simulation platform model was intensively used for acquiring detailed insights of the transmission network behavior during active power oscillations and more specifically for out- of-step condition occurrences. The goal was to induce out-of-step conditions and then try to accurately define the marginal conditions for every source equivalent through series of simulations. The simulations conducted provide valuable data for such conditions understanding and will be used in further process of preparing the setting parameters for protection functions in WAMPAC system.

Others conclusion, such as new key performance indices for various monitoring and protection conditions for transmission network could also be defined based on the simulation data.

IV. Angle Stability Simulations Results

The goal of the simulation scenarios were to find initial starting conditions and values when angle stability is lost and out-of-step conditions occurs.

A. Simulation scenarios

Reference model has three source equivalents (at buses 4, 7 and 9 on Fig. 4). In those equivalents, oscillations were induced in order to create angle instability conditions. Oscillations of active power (power swings) range from small stability to large oscillations but the paper concentrated on large active oscillations that can jeopardize the normal operation of the transmission network. Particular focus was on large power swing oscillations that can influence line angle instability protection function that has two main roles.

1) Detection and recognitions of power swing.
The goal is to detect variation of the power angle and correctly detect potential threats.

2) Protection from out-of-step condition occurrence.
The goal is to find marginal values for the initiation of oscillations which lead to angle instability in the final stage of the simulation. Those values are found for all source equivalents even though the reference network model is relatively small in an electrical sense so the oscillations in one equivalent source always induce power swings in all other adjacent ones.

When the part of transmission system loses angle stability that means the critical and ultimate operations conditions are present and swift protective reaction is required. For that purpose in the developed reference model the similar conditions were setup to simulate the occurrence of out-of-step. These conditions are presented in the Table VIII.

TABLE VIII. Active Power Oscillations in Sources

No.	Bus	Source equival.	Remark
1.	4	1	Range of active power oscillations in source, 2 - 3 P_{Source}[a]
2.	7	2	Range of active power oscillations in source, < 9 P_{Source}[a]
3.	9	3	Range of active power oscillations in source, < 3 P_{Source}[a]

a. Range of oscillations according to nominal values in the model

For each source equivalent the following parameters (Table IX) were defined during the analyses and implemented in the model setting phase with the purposes of provoking and creating an out-of-step condition.

TABLE IX. Detail Data for Simulations Scenarios

No.	Source active power	Oscillations	Source frequency parameters	Lines with OOS[a]
1.	334 MW	Source 1	Δf=0,4 Hz[b], f=0,2 Hz[c]	4-5, 4-6, 5-7, 6-9
2.	163 MW	Source 2	Δf=0,35 Hz[b], f=0,2 Hz[c]	7-5, 7-8, 8-9
3.	85 MW	Source 3	Δf=0,35 Hz[b], f=0,2 Hz[c]	9-6, 9-8

a. Out-of-step condition occurrence, b. change of nominal frequency, c. frequency of oscillations

One of the findings of the simulation process is that the reference nine buses model is relatively sensitive to angle instability disturbances. During the large oscillations in many simulation scenarios, the out-of-step conditions appears in two or three lines simultaneously. For the case when investigation about the influence these conditions have on the power system operation it can even mean more insights could be obtained. In the case, for example, of Croatian system, which is very well interconnected, the conditions required for out-of-step condition occurrence are rare.

B. Simulation results

The analyses were done for all six transmission lines without and with line protection operations present. Simulation duration is set to last ten seconds. Results from all three sets of simulations scenarios were similar enough for the proposed reference model simulation framework therefore in the following chapter only results for the simulations scenario No. 1 (out-of-step condition on line 5-7) will be presented.

The Fig. 5 presents the situation on particular line with power swing oscillations and out-of-step condition without angle instability detection and protection activity on any of the transmission lines in the modelled system. It can be seen how the out-of-step condition is developed on line 5-7 while the strong power oscillation is present on neighboring line 4-5.

On the other hand, from Fig. 6 it can be seen that activation of line protection (red line depicts protection signal) after third second has prevented the complete developing of out-of-step condition on line 4-5. This is manifested in a distinction between degree difference measurements for the cases with and without protective actions (y-axis on Fig. 5 and Fig. 6) for which values on Fig. 6 reach only 50% of maximum value compared to the case without protective actions.

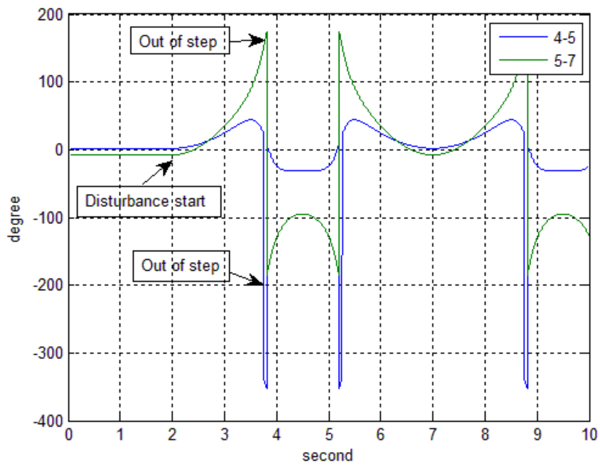

Fig. 5. Voltage angle difference for line 4-5 and 5-7 during out-of-step conditions in the reference model without protection operation.

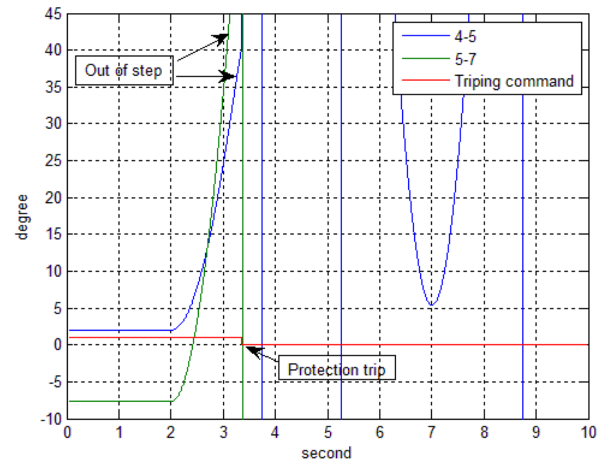

Fig. 6. Voltage angle difference for line 4-5 and 5-7 during out-of-step conditions in the reference model with protection operation.

In addition, as can be seen on Fig. 6 spreading of the disturbance through network was stopped with proper protection operations. This is of utmost importance for the system reaction to instability disturbances and cannot be done without phasor measurement system. On line 4-5 the circuit breakers were opened effectively reducing the voltage to zero, but the measurement modules that are oriented towards busbars were still active and measured the voltages on buses which were still on the network voltage and that manifested as angle difference oscillations. But these oscillations do not tangent the observed line 5-7.

Confirmations that circuits breaker action and protection on line 4-5 operated properly can be seen from the trends of currents and line differential currents depicted on Fig. 8 that contrast the trends depicted on Fig. 7 for a case without protection actions. As can be seen the proposed detection and protection algorithm efficiently reduced the impact of the angle instability event.

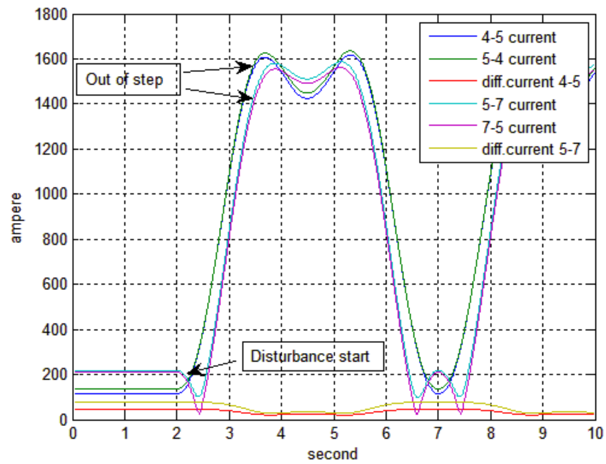

Fig. 7. Transmission line currents and line differential currents for lines 4-5 and 5-7 without protection operations.

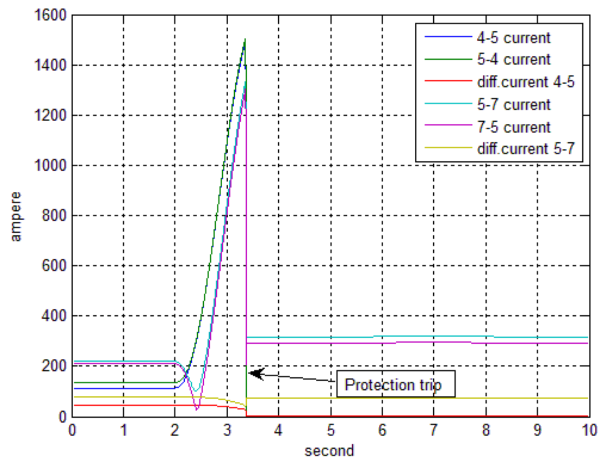

Fig. 8. Transmission line currents and line differential currents for lines 4-5 and 5-7 with protection operations.

The focus of this paper, as was mentioned in the introduction, is on the analyses of transmission lines protection operations and therefore generator units are not considered and it is assumed they have protection modules that are properly coordinated with transmission network protection. The reasoning for that lies in the fact that proposed WAMPAC system has phasor measurements from transmission lines only and to a certain extent needs to compensate unavailability of the generator exact data as was mentioned already.

Through developed WAMPAC system based on knowledge partially gained through simulations on reference framework complete monitoring of all relevant values of the network model were established (similar to real Croatian TSO system). For each line measurements of line currents from both line ends are present and the line differential current protection (alike in [16]) based on synchrophasor measurement was designed as a part of the proposed WAMPAC system. During heavy loading of lines caused by out-of-step conditions, which is characterized by high current and significant voltage decrease, the differential current decreases only slightly Fig. 7. When line protection is activated and line 4-5 is disconnected Fig. 8, all current values drop to zero which is a desirable behavior in case of such angle instability event.

According to equations (3) and (4) the model can very accurately trace those values (angle speed ω and angle acceleration α) and key performance indices could be defined. Angle speed for out-of-step disturbance for two lines is depicted on Fig. 9 and angle acceleration is depicted on Fig.10. The difference between out-of-step and power oscillation conditions is noticeable.

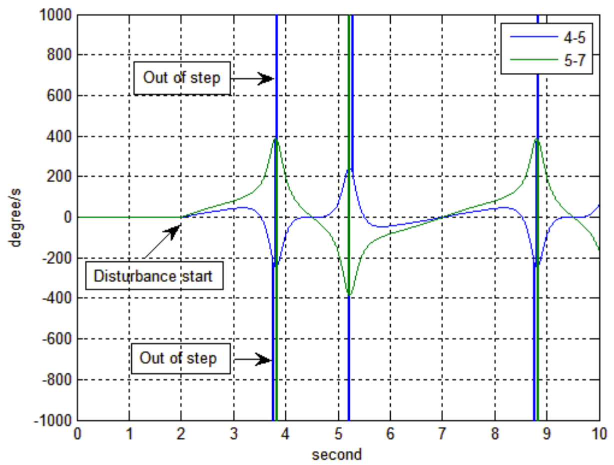

Fig. 9. Details for angle speed for line 4-5 and 5-7 during out-of-step condition occurrance without protection operation.

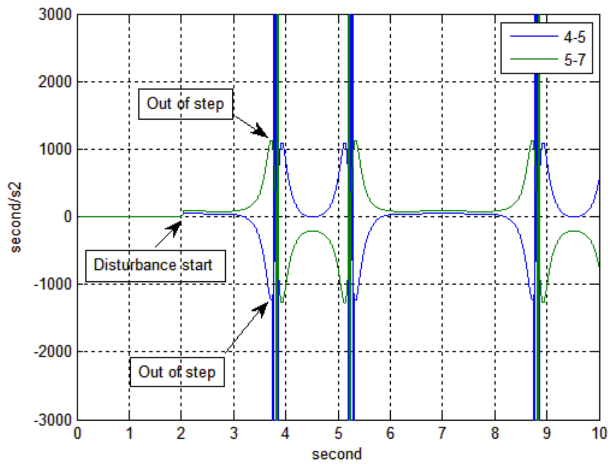

Fig. 10. Details for angle acceleration for line 4-5 and 5-7 during out-of-step conditions occurrance without protection operation.

CONCLUSION

Dynamic angle instability simulation framework based on reference model platform was created to analyze the transmission network disturbances. It includes developed WAMPAC system model.

Simulation data obtained from reference model based framework can help to improve transmission network protection of the real transmission systems by means of acquiring the parameters for fine tuning of classical transmission relay and WAMPAC protection systems.

REFERENCES

[1] F. G. Velez, V. A. Centano, A. G. Phadke, "Multiple swing transient stabillty assessment with phasor measurements," PowerTech, 2017 IEEE Manchester, 18-22 June 2017, United Kingdom, doi:10.1109/PTC.2017.7981173.

[2] Data for model IEEE 9 bus, official web page (accessed 15th January, 2018), https://www.mathworks.com/matlabcentral/fileexchange/45936-ieee-9-bus.

[3] I. Ivankovic, I. Kuzle, and N. Holjevac, "Wide Area Information-Based Transmission System Centralized Out-of-Step Protection Scheme," Energies, vol. 10, no. 5, 2017. doi:10.3390/en10050633

[4] B. Mallikarjuna, P.V. Vardhan Varma, S. D. Samir, M. J. B. Reddy, D. K. Mohanta, "An adaptive supervised wide-area backup protection scheme for transmission lines protection", Protection and Control of Modern Power Systems, vol 2, no. 22, 2017, doi: 10.1186/s41601-017-0053-1.

[5] I. Ivankovic, I. Kuzle, and N. Holjevac, "Multifunctional WAMPAC system concept for out-of-step protection based on synchrophasor measurements," Int. J. Electr. Power Energy Syst., vol. 87, pp. 77–88, 2017.

[6] I. Ivankovic, I. Kuzle, and N. Holjevac, "Algorithm for Fast and Efficient Detection and Reaction to Angle Instability Conditions Using Phasor Measurement Unit Data," Energies, vol. 11, no. 3, 2018. doi:10.3390/en11030681

[7] R. Patel, T. S. Bhatti, D. P. Kothari, "MATLAB/Simulink-based transient stability analyses of a multimachine power system", International Journal of Electrical Engineering Education, vol 34, no. 5, pp. 320-336, 2002.

[8] G. Aggarwal, A. Mittal, L. Mathew, "MATLAB/Simulink Model of Multi-machine (3-machine, 9-bus) WSCC System Incorporated with Hybrid Power Flow Controller", 2015 Fifth International Conference on Advanced Computing & Communication Technologies, , Washington, DC, USA, pp. 194-201, 21-22 February 2015, doi 10.1109/ACCT.2015.71.

[9] D.Asija, P. Choudekar, K. M. Soni, S. K. Sinha, "Power Flow Study and Contingency status of WSCC 9 Bus Test System using MATLAB", 2015 International Conference on Recent Developments in Control, Automation and Power Engineering (RDCAPE), Noida, India , pp. 338-342, 12-13 March 2015. doi: 10.1109/RDCAPE.2015.7281420.

[10] I H. Elghazaly, A. Emam, A. Saber, "A Backup Wide-Area Protection Technique for Power Transmission Network," IEEJ Transaction on electrical and electronic engineering, vol. 12., pp. 702-709, 2017.

[11] D. R. Gurusinghe, A. D. Rajapakse, "Post-disturbance transient stability status prediction using synchrophasor measurements," IEEE Transactions on Power systems, vol. 31, no. 05, pp. 3656-3664, 2016.

[12] I. Ivankovic, R. Rubesa, and I. Kuzle, "Modeling 400 kV transmission grid with system protection and disturbance analysis," in 2016 IEEE International Energy Conference (ENERGYCON), pp. 1–7, 2016.

[13] R. Terzioğlu, T. F. Çavuş, "Probabilistic Load Flow Analysis of the 9 Bus WSCC System", International Journal of Scientific and Research Publications, Volume 3, Issue 9, September 2013, ISSN 2250-3153.

[14] N. Fnaiech, A. Jendoubi, M. Zoghlami, F. Bacha, "Continuation Power Flow of Voltage Stability Limits and a Three Dimensional Visualization Approach", 16th international conference on Sciences and Techniques of Automatic control & computer engineering - STA'2015, Monastir, Tunisia, , pp 163-168, December 21-23, 2015.

[15] "PSCAD, IEEE 9 Bus System", Manitoba HVDC Research Centre, Rev:0.00, December 30th 2014.

[16] R. Dubey, S. R. Samantaray, B. K. Panigrahi, "An spatiotemporal information system based wide-area protection fault identification scheme," International Journal of Electrical Power and Energy System, vol. 89, pp. 136-145, 2017.