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Multifunctional WAMPAC system concept for out-of-step protection based on synchrophasor measurements

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ABSTRACT

Transmission network control and protection system can be enhanced using synchrophasor measurement data. Wide Area Monitoring, Protection and Control (WAMPAC) systems incorporate three levels of protection functions. The first layer is the basic relay protection, the second layer is the central system protection with wide area protection functions (WAP) and the final layer is the power system control level. Centralized protection can use new methods based on synchrophasor data. The phasor data benefits protection functions of both the second and the third layer. Therefore, to investigate the operation of the different protection functions in a centralized system, a multifunctional Matlab simulation environment is developed and presented in this paper. The model is developed using the experience from the real-time operation and was additionally expanded with new function sets that are also described. Real-time operation measurements from various disturbances are used to validate the model. Validated model is then applied to perform a series of simulations of various events in different conditions in the transmission network, such as breaker operation, short circuit faults and power oscillations. Conducted simulations provide foundations and indicators for the development and definition of criteria needed to implement enhanced central protection system resilient to all disturbances.

1. Introduction

Data collected from a phasor measurement unit (PMU) in the transmission dispatch control centre can be used to create real-time system protection and control functions for wide area disturbance monitoring and detection [1,2]. Wide Area Monitoring, Protection and Control (WAMPAC) system can detect and react to complex system disturbances such as power swing and out-of-step conditions. WAMPAC systems must be tailor made and adapted for every particular transmission system [3]. In order to create a centralized protection system extensive transmission disturbance analysis is needed to be carried out. Therefore integrated models must be developed and numerous simulations need to be carried out [4,5]. All developed transmission network models and WAMPAC model functionalities and results must be validated with available real data [6].

Having available synchrophasor data from the entire transmission network in the control centre is a prerequisite for a Centralized out-of-step protection. Centralized out-of-step protection relies on angle values and angle derivatives to deliver reliable protection functions. These functions cover complete transmission network and are not dependant on impedance measurements which means the major setting values do not depend on system impedance or network topology. This is a significant feature of the proposed centralized concept. Traditional out-of-step protection incorporates just the line protection devices that use local measurement from one line end and act locally. Centralized out-of-step protection can react with more precision to both small and extreme active power oscillations. Centralized functionality can furthermore trace the disturbance origin.

Incorporating an out-of-step function in WAMPAC system enables the monitoring of angle stability and reaction and triggering of protection functions in real time based on that information [7–10]. These kind of enhanced protection functions help avoiding cascade disturbances and achieve adaptability in the transmission system [11]. Phasor data based out-of-step protection can cover more comprehensively angle instability issues in transmission network [12,13]. Model for that purpose can be found in [14] and was created to be able to define key characteristics of transmission network during such a complex disturbance.

This paper gives a description of a model of 400 kV Croatian transmission system and a model for protection and control

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functions as a part of WAMPAC system that were both developed in Matlab environment. Models were validated with the collected real operation data from various sources. Supervisory control and data acquisition (SCADA) and energy management system (EMS) system data were used to complement the phasor measurement data (relay protection disturbance recording) from Wide area monitoring (WAM) system. System protection functions, as part of WAMPAC, are challenging to verify because such disturbances happen rarely and archived data is scarce. Therefore, there is very important value of integrated models, like the one presented in this papers, to investigate system behavior in different scenarios. The main contributions of this paper are validated reference values for wide range of disturbances that can be used to design the proposed centralized WAMPAC system. Designing the protection functions is an initial part of the process in which it is very common to propose general setting recommendations for transmission protection functions. Basis for these decisions come from validated referenced values which are extracted after the key performance indices are determined for different protection functions.

2. Transmission control and protection layers

2.1. Hierarchical division of control and protection systems in transmission networks

As it can be seen from Fig. 1 line and transformer protection form the 1st layer of basic relay protection system in transmission network. Relay protection in 1st layer acts locally on element level (e.g. in substations) and usually covers just one element. Therefore, only a limited quantity of data is being exchanged between different protection devices.

Wide area protection (WAP) devices form the 2nd layer. Basic functionalities of WAP devices are synchronized measurement, local protection functions and input/output module. Power swing and out-of-step conditions in transmission network are very demanding for protection and control system to detect and properly react to. New protection functions for such cases can be incorporated in this 2nd layer of hierarchical power system control [15–17]. The 3rd layer is a complete power system control with wide range of manual and automatic protection features (e.g. SCADA functionalities). This layer is connected to other two subordinate layers and is used as a hub for central control visualization of all the available gathered data that will become increasingly important with large penetration of wind energy in the Croatian power system [18].

2.2. Transmission network element protection in central system protection

Transmission network element protection is a part of central system protection which is forms 2nd layer. Line and transformer protection are network element protection segments of the 1st layer. Out-of-step protection is incorporated in the line protection. Out-of-step protection function for wide area transmission network in 2nd layer should meet several key requirements like wide area transmission network observability, breaker switching operation detection, selectivity (successful distinguishing between regular operation condition and disturbances), and system disturbances detection (e.g. angle, voltage and frequency instability [19]). It is of utmost importance to have sensitive detection for active power oscillations for a whole range of oscillations. The detection must be sensitive enough to detect both the inter area oscillations and extreme oscillations during out-of-step conditions. Synchrophasor data is processed on the level of line protection with the goal of enabling system out-of-step protection and line back up protection.

2.3. Central transmission system protection

Central system protection is primarily designed to have only system protection functions which react and prevent the system disturbances. Central protection system for transmission network with out-of-step protection functionality is demanding for realization [20–22]. Out-of-step protection system receives processed data from line protection devices. The data includes angle values, angle speed and angle acceleration from all observed transmission lines with PMU devices. To achieve better selectivity remedial criteria must be set. A remedial criterion continuously tracks raw synchrophasor data (positive component of voltage and currant) and does the line protection data analysis (active and reactive power, impedance). With those values additional criteria are created for alarming and protection purposes. Main and remedial criteria run in parallel.

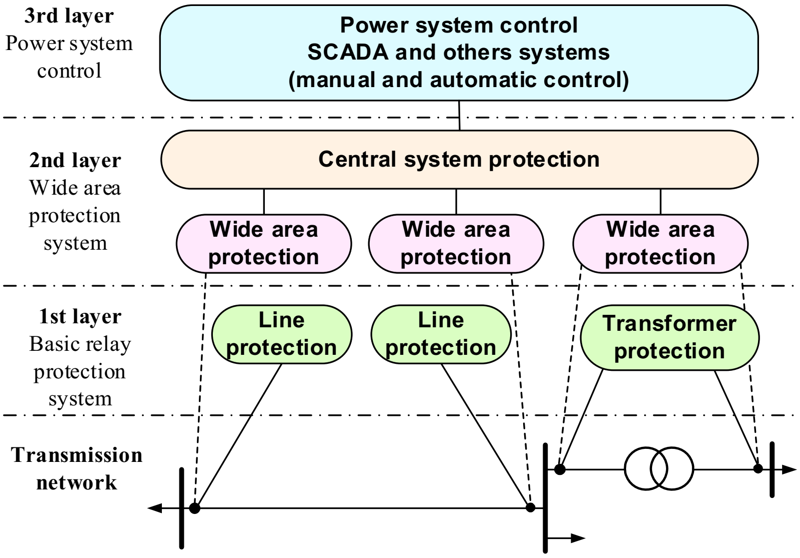


Fig. 1. Transmission control and protection layers.

3. Developing transmission system and WAMPAC system model in Matlab environment

3.1. Croatian 400 kV transmission network

Transmission network in Croatia is a part of EU continental transmission system, located in its southern-eastern part. It is well connected with neighbouring systems, with 10 lines on 400 kV level, 8 lines on 220 kV and 18 lines on 110 kV level. Power plants are dominantly coupled to transmission network on 220 and 110 kV levels with only one pumped storage hydro power plant connected to 400 kV level. The Croatian system is specific for its high shares of electricity import since local thermal power plants have high operational costs. Additionally, there are two dominant directions of power flows across Croatian power network towards Italian TSO. First direction goes from the north (Hungary) to the west (Slovenia) and the other is points from the east (Serbia) towards the west (Slovenia). Power peak demand is approximately 3200 MW and an average electricity import is around 20% of demand. Main characteristic of 400 kV and 220 kV transmission network is that the loop closing through neighbouring TSO and not inside national transmission system. Therefore the security issue of N-1 criterion is challenging task to fulfil especially along Adriatic costal line. All transmission lines are in category of short to medium length (from 60 to 230 km). Transmission network is meshed and there are no persistent oscillations. Inter-regional oscillations are known disturbances that occasionally appear with familiar characteristic oscillation directing from southern-eastern part of EU power system towards the central EU.

National dispatch centre controls 400 kV transmission network which is completely covered by PMU devices. PMU devices are also placed on other transmission voltage levels, mostly at 220 kV level and rarely on 110 kV level. Block scheme for modelled 400 kV transmission network and WAMPAC system is shown in Fig. 2.

Line loading P can be presented with angle between two busbars and is defined as in (1), where X_{LINE} is line reactance, the sending end voltage is U_S and the receiving end voltage is U_R, and φ being angle between two phasors.

$$P = \frac{U_S \cdot U_R}{X_{LINE}} \cdot \sin\varphi \tag{1}$$

The loadability of each line in transmission system is calculated at the planning phase and being tracked during the real-time operation. The angle values enable insight into transmission line or corridor loading. These datasets also provide valuable basis for making estimations and predictions of transmission system stability in real time.

A security analysis (N – 1 criterion) is obtained for the following 24-h in each time period. From power flow calculations line loading and voltage angle difference can be extracted for each 400 kV line. These angle difference values can be imported to the Central system protection and the behavior of the transmission network is traced. Any values deviation is noticed and appropriate control action (manual or automatic) or protection action can be launched. Fig. 3 presents possible trajectory for angle difference obtained from calculations and in real time for a time span of a few hours (some planning processes run in 15 min time span). Time domains for small active power oscillations, large active power oscillations and out-of-step conditions are different. Fig. 3 illustratively shows different events that have a start a different moments (t_1, t_2 and t_3) and have different duration and are of different severance. The ranges are in minutes (event at moment t_1) for smaller disturbances to less than one minute (event at moment t_2) for power swing events. An out-of-step condition occurs within only a few seconds (event at moment t_3). Angle difference deviations are presented with dashed lines. It is presumed that during disturbances appropriate control or protection action have been activated. As a consequence angles values return to levels before disturbances.

External 400 kV transmission lines and neighbouring systems are modelled with their equivalents. This model is sufficiently detailed for protection system analyses purposes and design of new protection concepts. International lines are modelled with three-phase programmable voltage source with in series connected three-phase series RLC branch. Values of RLC branch are set accordingly to the short circuit current. Also each line has a model of circuit breaker and thus we can have many opportunities to simulate a normal operation and disturbance with setting a breaker sequence. Loads on 400 kV are also modelled on substation level. Model for testing protection function is a slightly different one from the power flow model. It operates in the time domain of less than a few second and there is no need to have wider model of

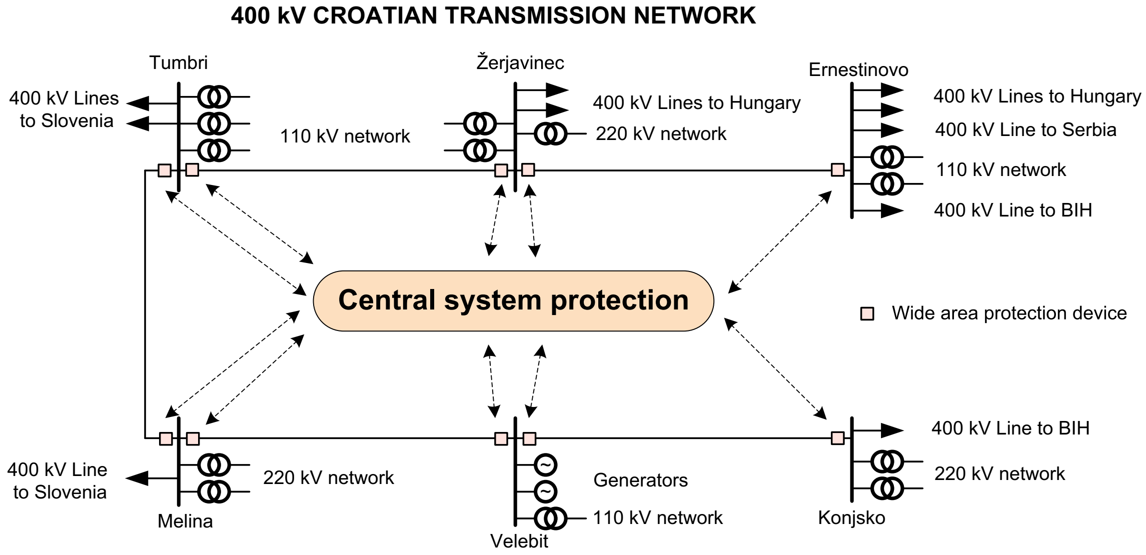


Fig. 2. Block scheme of 400 kV transmission network with central system protection and WAP devices.

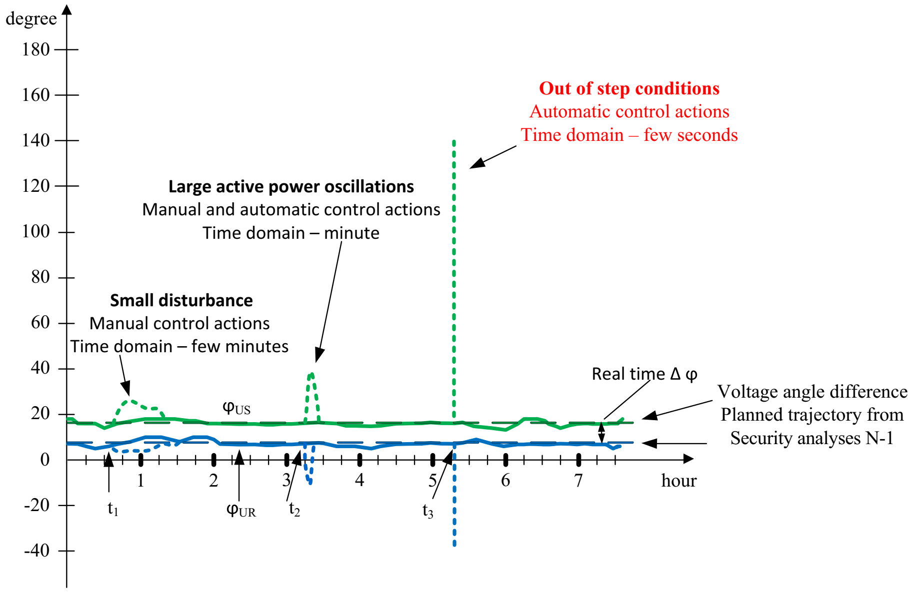


Fig. 3. Angle monitoring between two busbars (sending φ_{US} and receiving φ_{UR} bus voltage angle).

transmission network than one presented. Synchronising torques from neighbouring systems were also taken into consideration and accounted with corresponding short circuit currents in their equivalents. One of the main issues in the whole process is a lack of any well-established measurement of generation protection in power plants but the presented modelling process aims to use only measurements that are already at the disposal and these are only synchrophasor measurement from both 400 kV transmission line ends.

3.2. Transmission network Matlab model

Transmission network model includes five internal 400 kV lines and six substations as shown in Fig. 4. Model also contains equivalent connections towards neighbouring countries (three-phase programmable voltage source with in series connected three-phase series RLC branch), and a load model on 220 kV and 110 kV transmission levels. Two generators in hydro power plant Velebit, which are connected to the 400 kV transmission level, are also modelled.

All internal lines are modelled as three phase transmission line with distributed parameters. Line ends have three phase breaker model opening at zero crossing. To supervise conditions on line ends three phase measurement boxes which represent ideal instrument transformers are placed. Substations are created in subsystem with complete source and load equivalents, as shown in Fig. 4. Each transmission line is connected through its breaker to a 400 kV busbar. Breakers in the model give full flexibility to create various scenarios in order to simulate various disturbances for the design and tuning of the enhanced protection system.

3.3. Protection and monitoring Matlab model

The developed model uses line end positive sequence values for voltage, current, active power and reactive power [23,24]. Phasor data is also collected from PMU devices which are installed on line ends. From these basic measurements the model derives all necessary data for required basic set of monitoring and protection functions [25] including:

- Line differential protection;
- Line distance protection;
- Line overcurrent protection;
- Line over and under voltage protection.

The following expended set [26–30] of system protection functions was also created from basic data and line back up protection functions:

Line angle difference protection	$\Delta\varphi$
Line rate of change of angle protection (ROCOA)	$\omega = \frac{d\phi}{dt}$
Line angle acceleration protection	$\alpha = \frac{d^2\phi}{dt^2}$
Line protection to monitor the rate of change of line current, line voltage, active and reactive power flow and impedance, resistance, reactance of the line	$\frac{d}{dt}$

Each 400 kV line in the model has its own monitoring and protection three-phase voltage and current measurement module which is a source for other monitoring and protection functions as shown in the block diagram, Fig. 5.

These protection functions are designed to be sensitive and capable of alarming and issuing tripping commands in a case of a complex disturbance in transmission network. These disturbances are active power oscillations and out-of-step conditions. Also some of these functionalities will be used as an additional criterion in a decision process inside the protection model. Key protections functions for detection and proper reaction to power swing and out-of-step conditions are before mentioned angle difference ($\Delta\varphi$), ROCOA (ω), and angle acceleration (α).

Process of verifications and validation of the developed model and simulation environment was performed in several steps. First step included validations of normal operation of transmission network and regular breaker switching operations. For this stage there is a numerous archive data available. Next step included comparing the model with transmission line fault archive data. Last and most important step for power swing and out-of-step condition detection was to test the model with specific and unique recorded system disturbances that occur rarely and therefore the archived data is sparse.

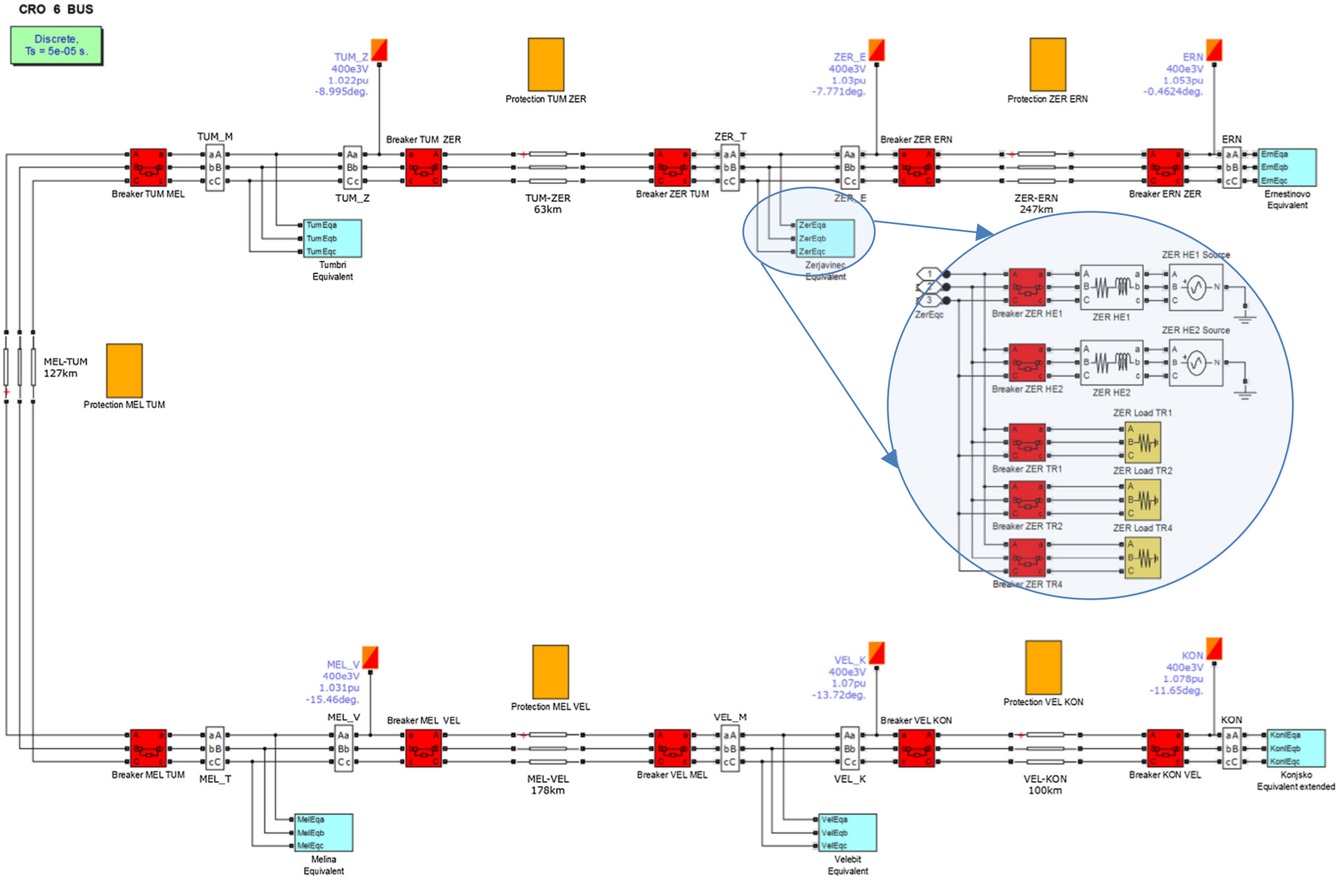


Fig. 4. Developed Matlab model of 400 kV Croatian transmission network.

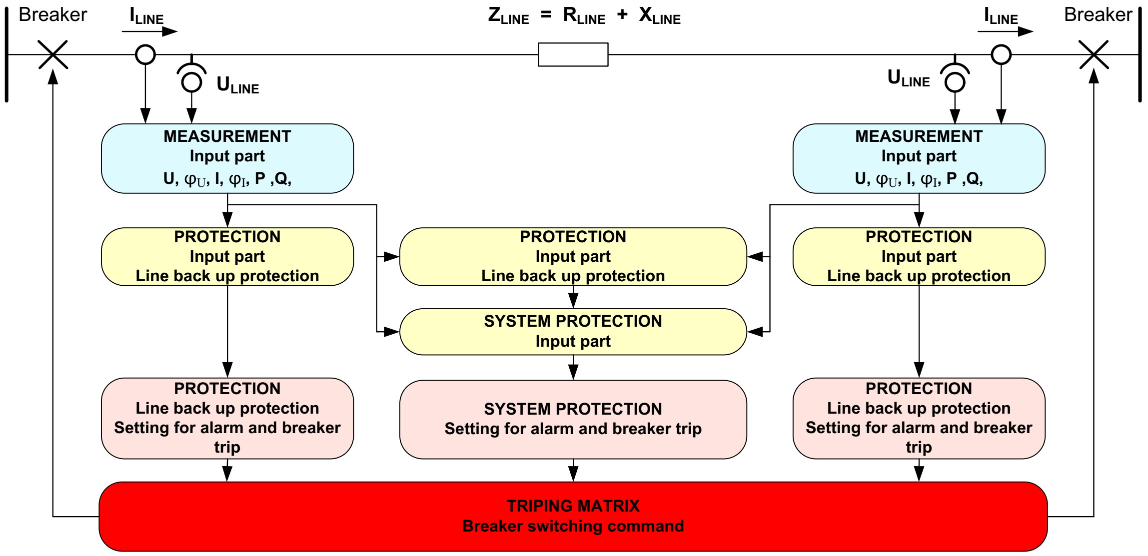


Fig. 5. Developed Matlab model block diagram for line protection and monitoring functions.

4. Verification and validation of WAMPAC model with real transmission phasor data measurements

4.1. Regular switching operations (400 kV substations Zerjavinec (HR)-Heviz 1 (HUN))

In order to obtain an angle transmission system footprint, it is necessary to analyze a wide range of normal operation conditions and disturbances which can cause angle instability. Therefore switching operations were performed at all six 400 kV transmission substations. Earlier studies indicate that a more loadable transmission network represents worse conditions for protection system. Therefore, winter loading conditions as a highest loading scenario for transmission network was chosen as a base scenario. Angle stability consideration must include certain severe disturbances which can slide the operating point towards the out-of-step condition. The switching off the busbar in transmission system has great impact on power flows and can create stability issues. Therefore, the following different disturbances simulations were done:

- Generation source switching off and then back on;
- Loads switching off and then back on;
- 400 kV busbar fault.

Impacts from RES integration and electricity market as a consequence have the need for a very dynamic transmission network operation response. Transmission operations must be able to follow the changes in a safe and reliable manner. One part of this process is adaptability of protection functions. Adaptability in proposed centralized protections system concept can be done in the following ways:

- Satisfactory hardware resources give opportunities to import data from planning stage for the next 24 h. As proposed in Fig. 3 it can be possible to trace a voltage angle differences on each transmission lines and compare in real time realized with planned data.
- Alarming and protection can be adjusted according to the current transmission network loading. This data can be automatically imported from planning applications after $N-1$ security analyses. In that sense it is important to establish bidirectional connectivity to the SCADA system in the control centre.

The model results show that switching operations and phase values change can be traced through whole system even in case of light disturbances a shown in Fig. 6. Simulation was done for breaker manipulation in 400 kV substation Zerjavinec on interconnection 400 kV line to substation Heviz 1. The interconnection line at that particular moment was acting as a source for the observed 400 kV Croatian system (import of approx. 300 MW).

The model needs to reach the steady state operating point. In first second it needs to stabilize after the generators in hydro power plant reach stabile operation point. Generators model have turbine and voltage regulation circuits implemented which is a reason for an aperiodic swing at the beginning of simulations.

Voltage fluctuations were caused by power flow changes in transmission grid in order to compensate for the loss of 300 MW import. In the first two seconds, the Matlab model manifested oscillations until reaching a steady stable point. Results depicted in Fig. 6 show moments when 400 kV line Zerjavinec-Heviz 1 is switched off and then back on.

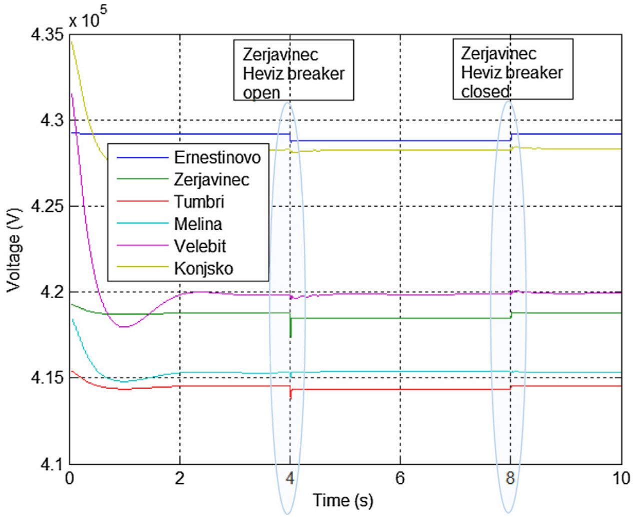


Fig. 6. Busbar voltage during source switching operation in 400 kV substation Zerjavinec.

Similarly to the case presented (400 kV substation Zerjavinec), breaker manipulations were carried out at all six 400 kV transmission substations in order to get utmost angle values. Results were compared with archived WAM system data and correlation was good.

In this step of model verification there is an opportunity to define key performance indicators (KPI) concerning the angle values in transmission network. Using earlier study work, operational experience and simulation results the proposal for angle KPI categorization is given in Table 1.

Currently, there are no recommendations directly concerning angle difference in electrical transmission networks and the differences are very case dependent. Presented KPIs can be used as benchmark values for protection setting in this particular part of transmission network. Synchro-check function settings can also be done using this KPI. Table 2 shortly presents simulation test result regarding suggested angle KPIs. Maximum angle shifting happens during busbar fault in Melina substation and is equal to $\Delta\varphi = 5.2^\circ$. In that particular case it can be concluded that a planning stage was properly done because there are no security issues caused by switching of 400 kV elements.

4.2. Single phase fault (400 kV line 400 kV Melina (HR)-Divaca (SLO))

This fault was chosen to verify developed model with a serious fault than could cause system wide problems. A permanent fault occurred on the 400 kV line Melina (HR)-Divaca (SLO) on March 5th 2015. The line was heavily loaded (455 MW). Croatian transmission system operator (HOPS) collects phasor data from internal lines [31] and therefore, the angle comparison (data collected from WAM system) made on the date was paired with the data from neighbouring 400 kV line Melina-Tumbri at the same substation. Phase angle monitoring (PAM) function was recorded and angle data for this particular 400 kV transmission line was collected. Line tripping caused an angle difference of $\Delta\varphi = 3.5^\circ$.

Angle difference in the model is approx. $\Delta\varphi = 3.0^\circ$ as shown in Fig. 7. The simulations results have good concurrence with the recorded data from the online WAM (Fig. 7). The calculated result is almost the same as the recorded data of the WAM system. Ref. angle values in WAM system are presented in Fig. 7(a) and (b). Good similarity is shown between model results and real time transmission system data. It is worth noting that reference directions are not the same in the model and WAM system.

4.3. Power oscillations on 400 kV transmission voltage level – hydro power plant generator unit disturbance

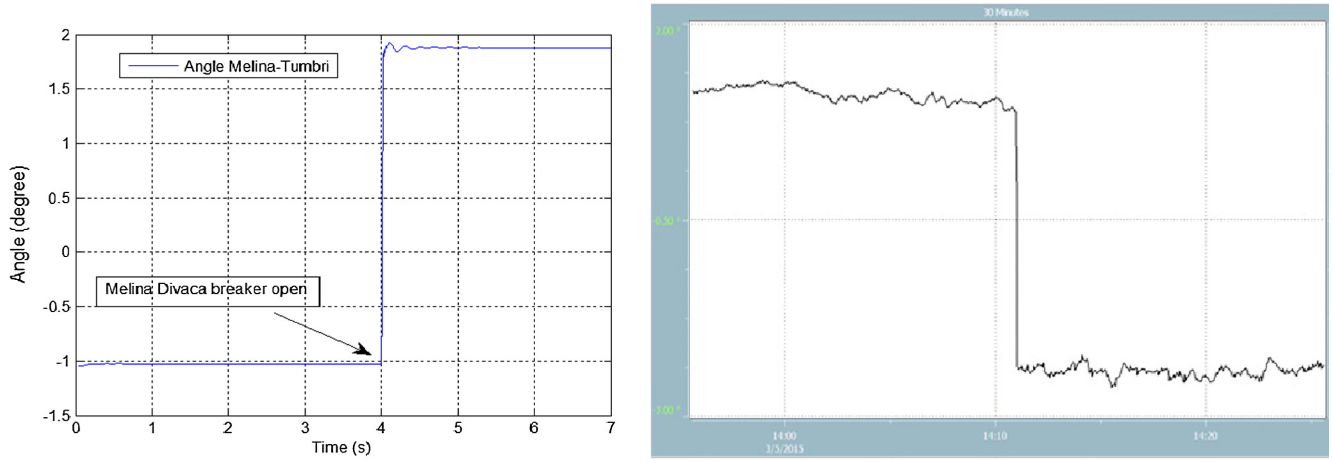
This specific disturbance with active power oscillations (Fig. 8) was used to evaluate the Matlab model and to analyze the impact of oscillations caused by generation unit on 400 kV line protection systems in 400 kV substation Konjsko. Line protection system must remain stable even during active power oscillations and trip the line only in very severe situations. 3 protection systems must operate in parallel and run coordinately to ensure this: (1) distance protection; (2) power swing protection; (3) out-of-step protection.

Table 1
Angle difference key performance indicators (KPI).

Classification	Indicator	Angle difference (degrees)
Acceptable	🟦	$\Delta\varphi \leqslant 3^\circ$
Manageable	🟩	$3^\circ < \Delta\varphi \leqslant 10^\circ$
Over-demanding	🟨	$10^\circ < \Delta\varphi \leqslant 20^\circ$
Unacceptable	🟥	$\Delta\varphi > 20^\circ$

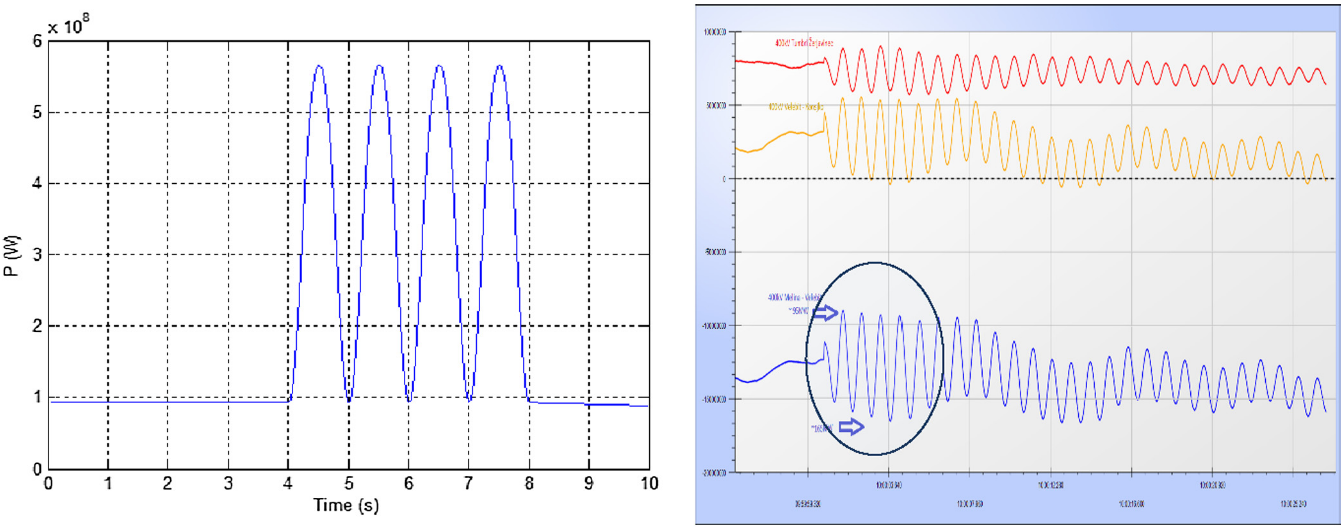
Table 2
Angle values changes depending on observed disturbance type.

Simulation type	Minimum angle value (degrees)	Maximum angle value (degrees)	KPI	
Source switching	0.1	2.0	🟦	Acceptable
Load switching	0.1	2.4	🟦	Acceptable
Busbar failure	0.1	5.2	🟩	Manageable



(a) (b)

Fig. 7. Line angle on 400 kV line Tumbri-Melina during line tripping event on (a) results obtained from the model (b) measured data from the WAM system.



(a) (b)

Fig. 8. Active power oscillations response curve on 400 kV line Velebit-Melina (a) simulated results (b) as measured by the WAM system.

Their design is tested and evaluated through conducted simulations.

The oscillations originated from the hydro power plant Zakucac connected to 110 kV voltage level and propagated to 400 kV transmission network. WAM system recorded the oscillations generated by the generation units on the 400 kV transmission lines as shown in Fig. 8b. Highest oscillations were detected on the lines which are closest to the source of the oscillations, in this case the 400 kV lines Konjsko-Velebit (yellow[1] line Fig. 8) and Melina-Velebit (blue line Fig. 8). Ref. angle values in WAM system and in the model are not the same and there are some differences presented in Fig. 8 (a) and (b) but the difference is reasonably small. It is worth noting that reference directions are not the same in the model and WAM system. Oscillations from 50 to 70 MW were detected on the 400 kV transmission line with oscillation frequency around 1 Hz (result from Prony analyses reveals frequency $f_o = 0.96$ Hz and damping factor $\xi = 0.057$). The damping factor has a positive value which indicates existence of an undamped oscillation.

The model was tuned to be able to simulate this particular disturbance which started in the power plant mentioned above (HPP Zakucac). The goal was to check if the impedance trajectory during

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[1] For interpretation of color in Figs. 8 and 23, the reader is referred to the web version of this article.

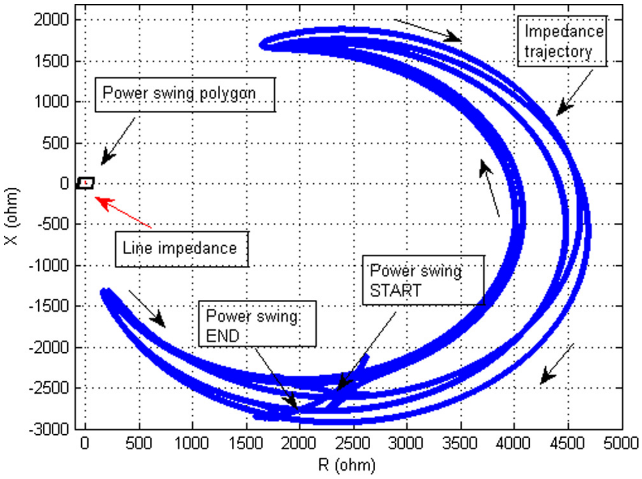

Fig. 9. Impedance trajectory trace during simulation.

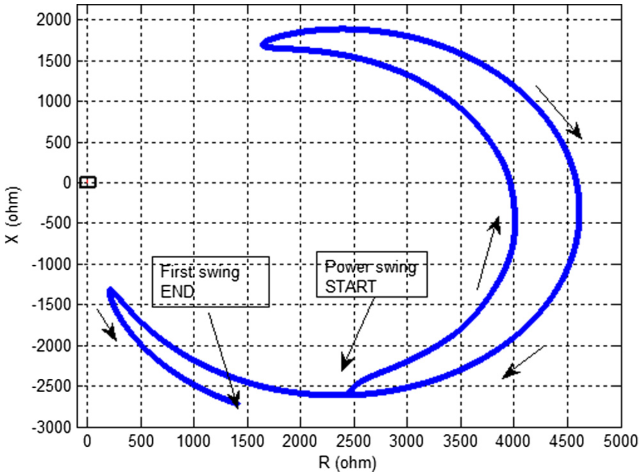

Fig. 10. Impedance trajectory swing during one non-critical event.

this disturbance enters into any of the relay protection distance zones and power swing polygon (Fig. 9). The results of these analyses in the R/X plane are presented in Fig. 10. The impedance characteristic with the highest impedance setting is used for the power swing function. This particular polygon is the first one which is expected to be reached by the impedance trajectory.

Power swing polygon depicted in Fig. 10 has the following setting in R/X plane: R = 65 O; X = 65 O (black line). Line impedance is presented with the red line. During oscillations, the impedance trajectory swings on a safe distance from the polygon (the trajectory of just one swing is shown as in Fig. 10).

These swings (Fig. 10) were stable and did not start any of the protection functions inside 400 kV line protection devices. The transmission lines were not heavily loaded and the additionally power swing did not push impedance inside any of the relay protection activation regions. Electromechanical oscillations produced by generation unit on the 110 voltage level propagated to the highest transmission level but in this case did not endanger the normal power system operation as the results of the simulations have shown.

Simulation case with large active power deviations on highly loaded 400 kV lines has a significant impedance trajectory moving towards line relay characteristic. Oscillations enter into the power swing characteristic (Fig. 11) and will raise an alarm for power swing but since impedance trajectory did not enter into any of the three distance protection zones and there will be no issuing of breaker tripping command.

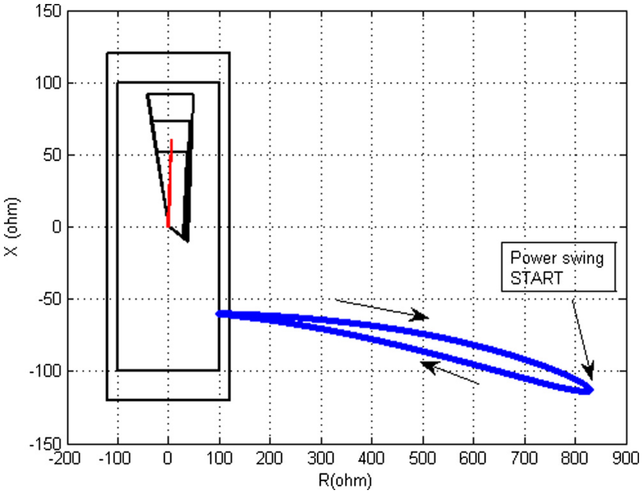

Fig. 11. Impedance trajectory swing during one large power oscillations. Impedance trajectory touches power swing characteristic in line relay protection.

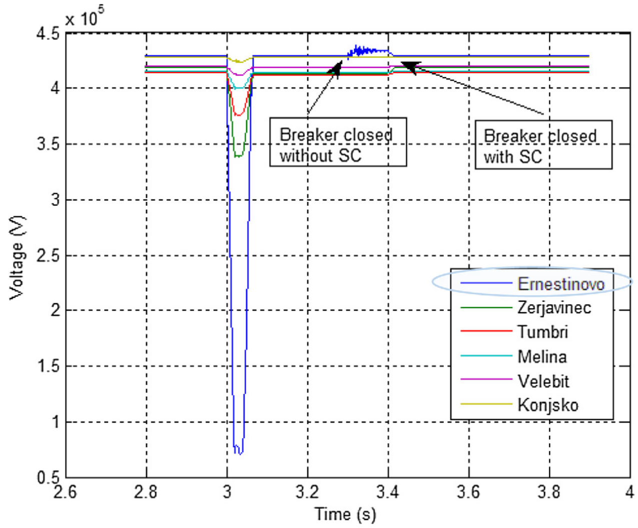

Fig. 12. Voltage drop pattern for line fault near 400 kV substation Ernestinovo.

5. Disturbance simulations in transmission network

5.1. Line and busbar short circuit simulations

For the simulation of both busbar and line short circuit after successful auto reclose attempt and clearing of the fault all voltage values recovered to normal operation levels. One line end was closed in autorecloser sequence without synchrocheck (SC) function and the other line end closed with SC permission. Monitoring the voltage level on busbar or transmission lines manifests the characteristic behavior of voltage drop (Fig. 12). Therefore, with this series of simulations it is possible to obtain parameters and benchmarks for transmission network in perspective to angle behavior during power swing and out-of-step conditions.

For transient fault performed auto reclose sequence in model. The evidenced voltage drop pattern in transmission network is a typical one and is almost the same for line ends failures on other transmission lines and busbars.

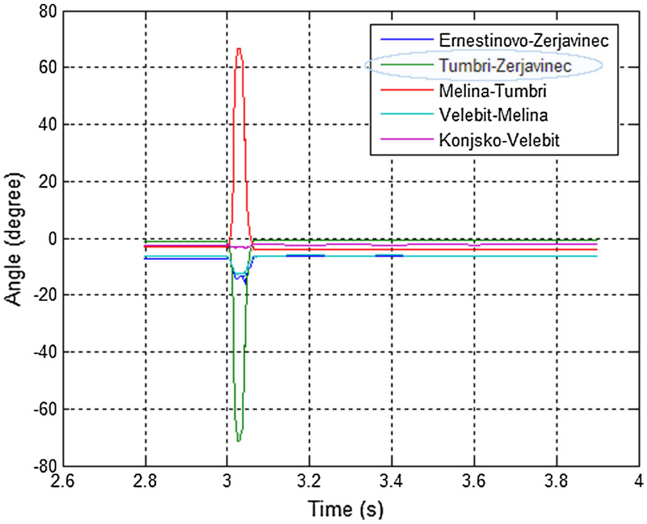

Fig. 13. Angle dynamics pattern for busbar fault in 400 kV substation Tumbri.

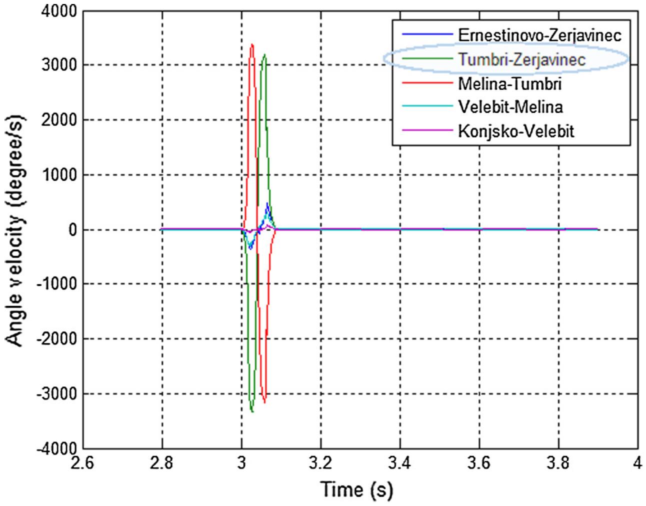

Fig. 14. ROCOA pattern for busbar fault in 400 kV substation Tumbri.

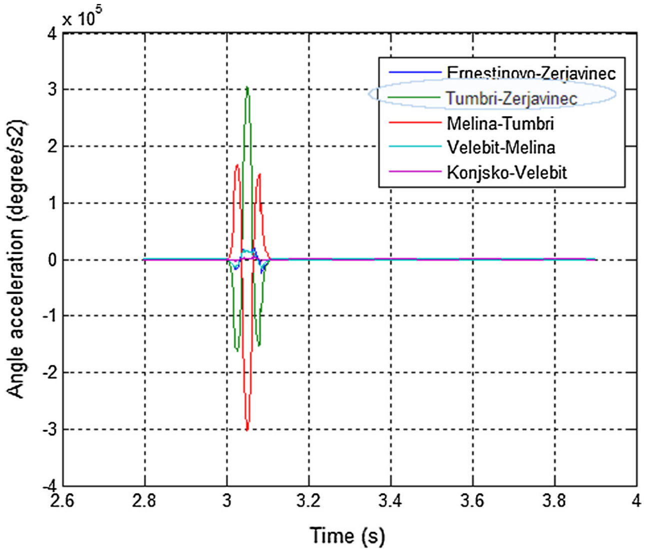

Fig. 15. Angle acceleration pattern for busbar fault in 400 kV substation Tumbri.

Angle dynamic Δφ (Fig. 13), ROCOA (Fig. 14), and angle acceleration (Fig. 15) were in focus of the simulations process. Simulations were performed on all line ends and busbars of the modelled 400 kV network. The characteristic shape for observed values is presented in each of the diagrams (Figs. 13–15). Simultaneous monitoring of voltage phasor angle in whole transmission system gives quick and exact indication about the failure position. That information is validated end supported by ROCOA measurement at two connected lines in substation and by angle dynamics Δφ measurement that can both give precise information where the fault occurred.

The simulation model shows that angle acceleration has a characteristic diagram of change. Only lines connected to busbar that is in fault have significant deviations in angle. There is also no significant angle dynamics on other transmission lines that are not faulted. Only on the two connected lines there is noticeable angle acceleration (Fig. 15). This information can pinpoint the fault location.

Transmission network pattern for power swing and out-of-step consideration in a case of short circuit is characteristic. The observed changes of indices (Δφ, ROCOA and angle acceleration) happen in parallel and in a very short period of time (less than 100 ms). This is the reason why correct detection of the indices at a beginning of disturbances and at its fast termination is important. The proposed simulation environment can provide that response. These indicators can be very useful as inputs in one of many criteria needed for wide area out-of-step protection (2nd layer in Fig. 1). Benchmark suggestions derived from the performed simulations are shown in Table 3.

5.2. System disturbance simulations

The main group of simulated system disturbance is power swing situations. In the example presented oscillation occur in 400 kV substation Melina on Divaca-Melina transmission line (Fig. 16). Voltage pattern propagates through the whole network but is damped to a certain amount (Fig. 16).

Angle dynamic pattern as one shown in Fig. 17 indicates that an oscillation source is in 400 kV Melina substation. Two highest oscillations peaks happened on transmission lines coming from the Melina substation.

Similar pattern is visible for ROCOA (Fig. 18). Angle acceleration pattern is shown in Fig. 19. Monitoring these values can reliably help point to elements in transmission network where the disturbance source occurred.

Further analyses were done for two different, hypothetical cases. The first one is a heavy power swing with origin on the 400 kV level (Fig. 20) and the second one is out-of-step disturbance also originating from 400 kV level (Fig. 21).

The simulations were carried out with the focus on the southern part of the Croatian transmission network (bottom part of system in Fig. 2).

The first disturbance was simulated on the 400 kV interconnection line Konjsko-Mostar and the protection performance was monitored on the 400 kV line Konjsko-Velebit. The results of this simulation show that the impedance trajectory reaches the vicinity of the power swing polygon (Fig. 20) which is very important for the design of the out-of-step protection.

This particular simulation scenario shows how close to the power swing polygon the impedance trajectory can approach. If the power swing conditions persist in the transmission network,

Table 3
Angle benchmark for short circuit.

Simulation type	Angle shift (degree)	ROCOA (degree/s)	Angle acceleration (degree/s^2)	Fault duration (second)
Line fault	65	3500	170,000	0.1
Busbar fault	70	3400	300,000	0.1

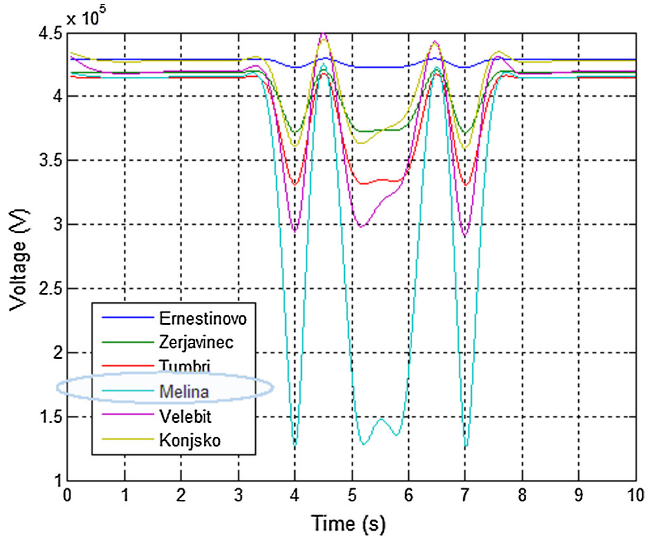

Fig. 16. Voltage drop pattern for oscillation sourcing in Melina substation.

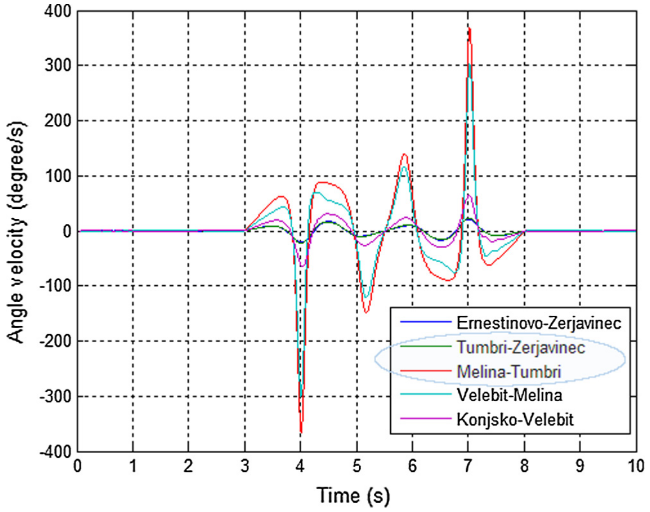

Fig. 18. ROCOA pattern for oscillation source in Melina substation.

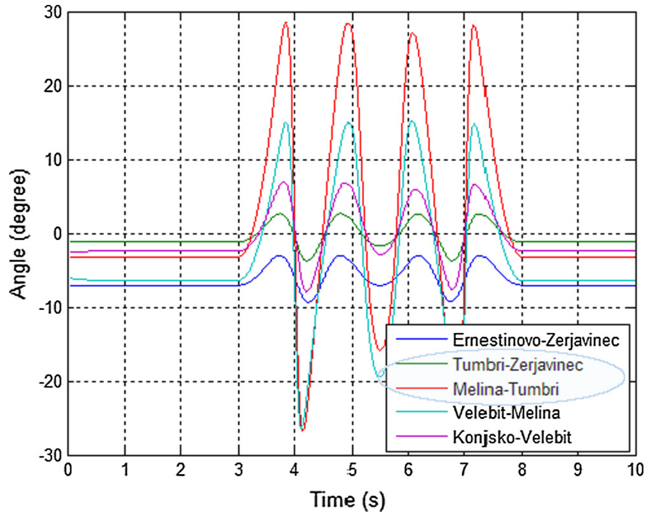

Fig. 17. Angle dynamics pattern for oscillation source in Melina substation.

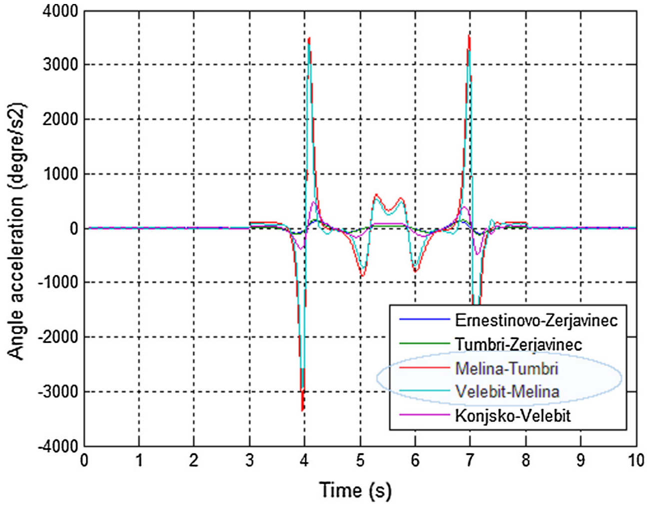

Fig. 19. Angle acceleration pattern for oscillation source in Melina substation.

they can easily develop out-of-step disturbance which is a serious threat to power supply and generator operation and therefore the information obtained from the simulation of the bordering scenario is very valuable.

The second simulation series were out-of-step simulations induced in 400 kV substation Konjsko. This substation is in a relatively weak part of Croatia transmission network and a smaller misbalance is needed to provoke out-of-step conditions as one shown in Fig. 21. It can be seen that at substation Konjsko voltage decreased to critical values (almost to zero) for this particular case.

Angle dynamics shown in Fig. 22 clearly present development of this out-of-step conditions and the moment when angle difference between 400 kV substations Konjsko and Velebit reached critical difference of $\Delta\varphi = 180°$ is visible. This severe disturbance was primarily manifested on Konjsko-Velebit 400 kV transmission line, but also propagated throughout the transmission system with certain damping factor and was manifested as power swing in other parts of the system. The moment of out-of-step in disturbance happened three times (approximately every 2 s). Simulations lasted 10 s without protection actions in order to present angle difference behavior. In real time operation the protection device would activate and stop the further oscillations, like it is presented in Fig. 24.

The time frame between the start of the disturbance and the slip occurrence is only few seconds and therefore reaction time is extremely short. Angle out-of-step benchmarks are very similar to short circuit disturbance benchmarks. Main difference is

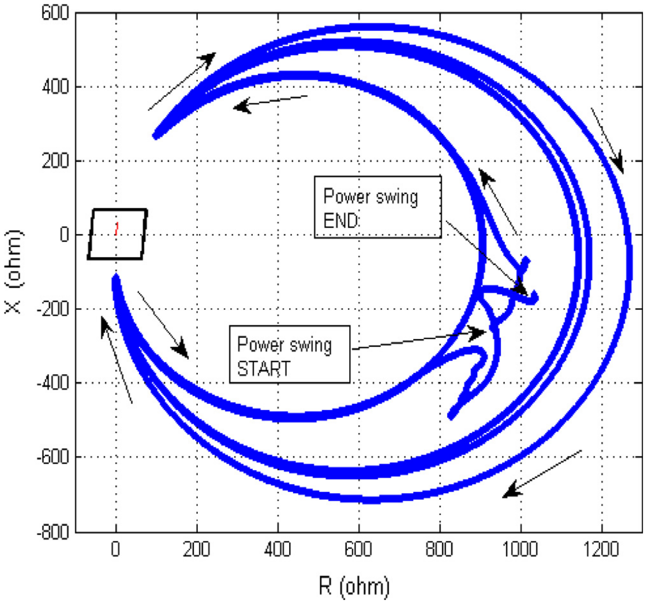

Fig. 20. Impedance trajectory during power swing on 400 kV transmission line Konjsko-Velebit.

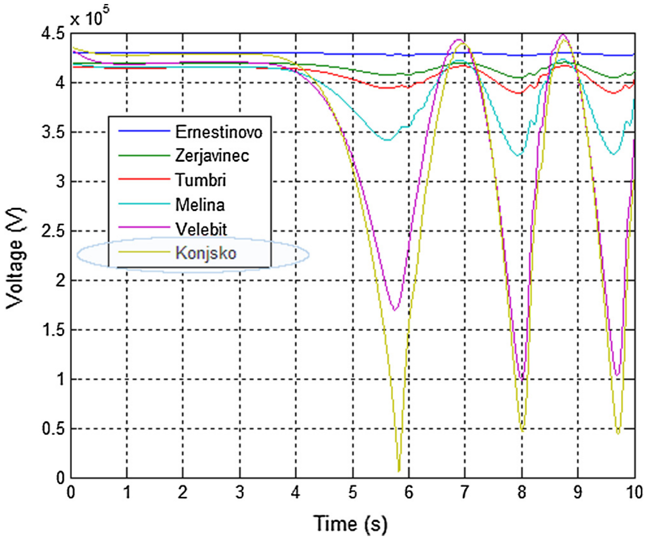

Fig. 21. Voltage drop pattern for out-of-step source in 400 kV substation Konjsko.

represented by the failure duration. Line relay protection systems have a fault clearing time of only a few periods (<80 ms). System disturbance can last more than few periods if proper protection reaction failed.

Impedance trajectory for performed simulations on the 400 kV line Konjsko-Velebit (Fig. 23) shows that for this serious disturbance the impedance trajectory passes several times through the power swing polygon and intersects with the line impedance (red line).

Like in the previous case (line and busbar short circuit simulations) the angle benchmarks are presented both for power swing and out-of-step disturbances (Table 4).

Fault duration for power swing can last for longer period of time from power system protection perspective (sometimes even minutes). But out-of-step first slip reach happens within seconds range which means WAMPAC out-of-step function should detect the problem and initialize breaker trip before first slip occurs.

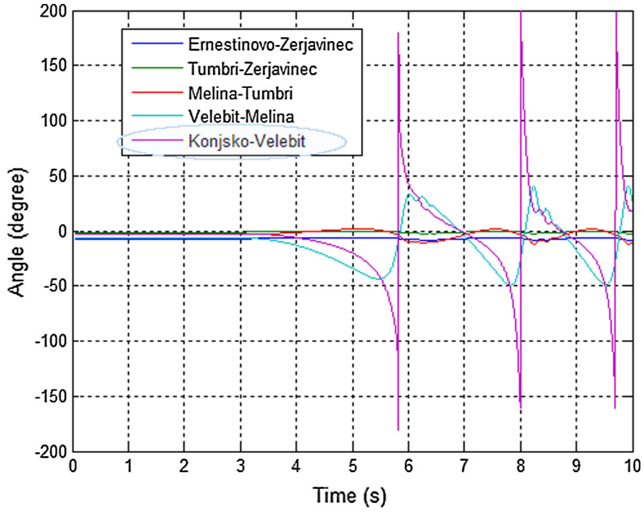

Fig. 22. Angle dynamics pattern for out-of-step source in 400 kV substation Konjsko.

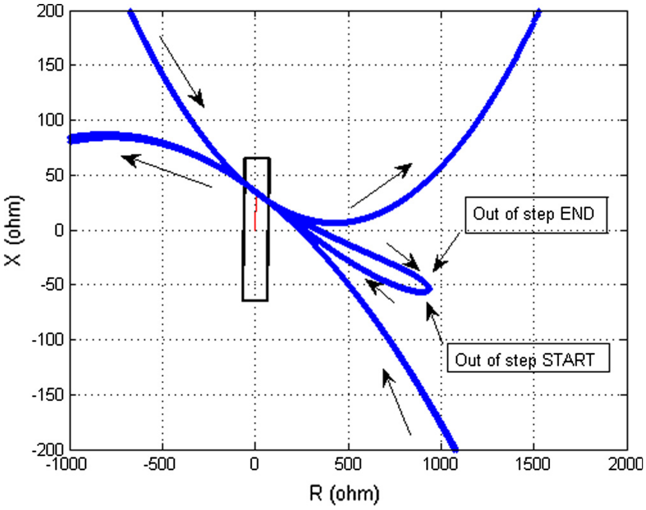

Fig. 23. Multiple impedance trajectory pass through relay characteristic during out-of-step disturbance.

Table 4
Angle benchmark for system disturbance.

Simulation type	Angle shift (degree)	ROCOA (degree/s)	Angle acceleration (degree/s^2)	Fault duration (second)
Power swing	<30	380	3000	<60
Out-of-step	180	17,000	850,000	2–4

Fig. 24 shows a simulation case when fault was cleared before first slip occurred. Disturbance started at $t = 3.0$ s and approached first slip at $t = 5.83$ s. WAMPAC had a very limited time to react. At time $t = 5.8$ s simulated WAMPAC system initiated breaker trip on the faulty 400 kV transmission line towards Mostar in substation Konjsko. After the isolation of failure all monitored values recover to normal operating level (Fig. 24). The observed behavior of the modelled protection system was satisfying.

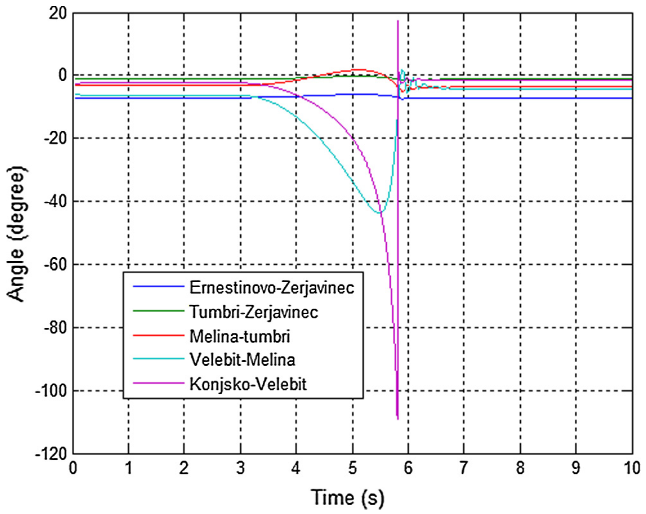

Fig. 24. Angle acceleration pattern detail for out-of-step source in 400 kV substation Konjsko.

6. Conclusion

Multifunctional WAMPAC system concept for centralized out-of-step protection in control centre was proposed in this paper. It is based on synchrophasor data stream from the 400 kV transmission network measurements. The proposed concept needed to be evaluated and tested and therefore the Matlab simulation environment was used. Modelling of 400 kV transmission network and system protection in Matlab gives a powerful simulation environment to investigate the transmission system behavior during disturbances. Simulation results and performed analyses can be used in the further work to reach a parameter setting and other required benchmark values needed to design a WAMPAC system. In developed Matlab model different scenarios were simulated to investigate transmission system angle footprint under different circumstances. Archived data was used to verify and validate a developed Matlab model. The simulation data and the real-time operation data from presently installed WAM system show that every breaker switching operation can be detected through angle monitoring. Different disturbances can be observed through different key performance indicators, angle dynamic $\Delta\varphi$, ROCOA, and angle acceleration. Based on conducted simulations this paper proposes benchmark values for key performance indicators that can be implemented into protection system. With the simulation environment validated on an available (archived) set of disturbance the wide range of all possible disturbances was simulated. In future work, protection functions based on the angle data that was obtained can be developed for system application in control centres. The model presented in the paper will have a key role in creating such WAMPAC system on a national 400 kV network level.

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