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Transmission System Phase Angle Footprint Based on Synchrophasor Measurements

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***Abstract* — This paper analyzes the transmission system voltage angle footprint obtained from both the real-time synchrophasor data and the simulations. The simulations are performed on the 400 kV Croatian transmission system. The paper further elaborates the possibilities how to use this type of angle footprint information for both the planning and the real-time operation. In the end, we elaborate the value of knowing the voltage angle to describe system conditions and behavior for both the planning process and the real-time operation.**

Keywords—synchrophasor measurements; angle footprint; transmission system model; angle-guided real time operation

I. INTRODUCTION

Safety is the first priority in power system operation that needs to be maintained even in competitive electricity market environment. The development of electricity markets has had a significant impact on the power sector [1]. Power system operation nowadays is greatly driven by the integration of renewable energy sources (RES). As a result, planning and operation time-steps, i.e., 1 h or at best 15 min, are too long as compared to the intermittent nature of RES. Additionally, the single-directional power flows at the interface of transmission and distribution networks have changed to bi-directional power flows. This is caused by high amounts of renewables generation at the distribution and low voltage levels. On the other hand, the inevitable consumption growth also increases stress on the transmission network and causes congestions. All the above mentioned factors decrease operation safety margins. To avoid and solve some of these challenges, ENTSO-E organization has developed procedures for coordinated planning and operation of its system [2]. Regional initiatives in continental Europe, Transmission system operator Security Cooperation, TSC [3], [4] made the next step in increasing operation safety. Both of these organizations created obligatory rules for Transmission System Operators (TSO) with aim to enhance operation safety.

Commonly used power system control methodologies are constantly improved by the advancement of technology. Synchrophasor measurement technology has promising features for researching and finding new procedures for real-time operation of system power. Using accurate voltage angle data in transmission system provides a much better insight of the current state of the system. Nowadays, Wide Area Monitoring (WAM) system collects phasor data from the crucial transmission system busbars and forwards this data for further analysis and calculations. For this purpose, an internal Croatian 400 kV transmission grid has been modeled in Matlab (Fig.1). Model includes 400 kV lines towards neighboring countries and load to 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 modeled.

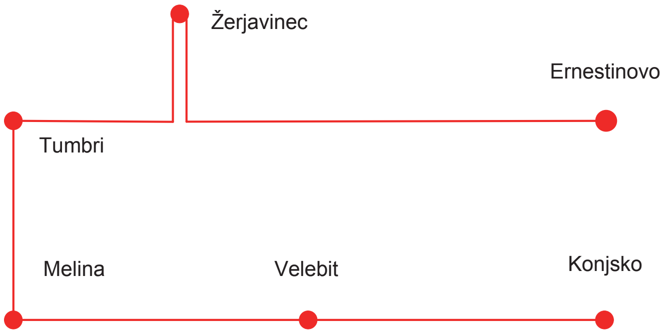


Figure 1, Single line diagram 400 kV transmission grid

This model is used in order to find voltage angle and rate of change of angle (ROCOA) across the transmission grid during normal operation times and during disturbances.

II. POWER FLOW PLANNING AND N-1 SECURITY

Rules of ancillary services and power system operating procedures [2, 3, 4] determined planning procedures for the next day in order to fulfill basic security criteria of N-1 operation. TSOs have intensified data and calculations results exchange in order to obtain power flows and loading of vital power system elements (lines and transformers) for the next day. Thus, for each element a load ability check in highly meshed grid is performed. Additionally, power flow calculations provide electrical values (commonly used values are active and reactive power, current and voltage) for the following day.

Reliable transmission grid is a prerequisite for safe electrical supply of all customers. Therefore, TSO has the obligation to keep a proper reliability and stability level. The following criteria must constantly be fulfilled:

- N-1 security;
- Short circuit safety;
- Transmission grid stability.

The fulfillment of these criteria present a barrier for cascade scenarios and spreading of disturbances that can lead to supply reduction and blackouts. Procedures for transmission stability maintenance are performed on three levels:

- Offline analysis through grid development and operation planning.
- Transmission grid real-time operation analysis with additional functionality like grid monitoring, stability maintenance and dispatcher support system.
- Predictive analysis for certain transmission parameters.

Real-time operation based on stability criteria is still a technological challenge. Especially demanding are short term instabilities such as angle instability and short-term voltage instability [6], [7].

During planning and real-time operation stages, angle values are still not fully utilized. Angle between busbars voltage phasors gives an accurate insight into current operation state of the system. Therefore, it can be used in all of the abovementioned phases since WAM system collects system state based on the synchrophasor measurement in real-time.

III. TRANSMISSION GRID OPERATION AND ANGLE TRACKING

A. *Line power flow*

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. System stability can be tracked in three ways.

- Static stability with small and slow changes caused by switching of small sources and loads. Establishing new stable working point and stability estimation of this new working point.
- Transient stability with large and intensive changes caused by switching of big sources and loads. Ability to establish new stable working point after such great disturbances. Estimation stability for new working point. Estimation of probability to reach generator out of step condition thus endangering the system with potential blackout situation.
- Angle stability of a line or a corridor can finally be estimated based on voltage angle.

Two machine model with phasor representation on both ends (sending and receiving) in transmission grid has been developed, as shown in Fig. 2. Line loading P is defined by equation (1), where X_{line} is line reactance, the sending end voltage is U_S and the receiving end voltage is U_R. Angle between two phasor is φ.

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

Loading in this two machine model depends on angle φ and voltage ends U_S and U_R. Theoretically maximum line load will be at angle δ=90°.

Advanced transmission operation control in real time can be realized by angle voltage monitoring. In that manner the angle stability in 400 kV transmission grid in real time is monitored. Processing of synchrophasor data and graphic representation and analysis of wide area monitoring system is done in real time in dispatcher control room. On that basis, all power system oscillations and swinging can be recognized beforehand and dispatcher crews can be alarmed.

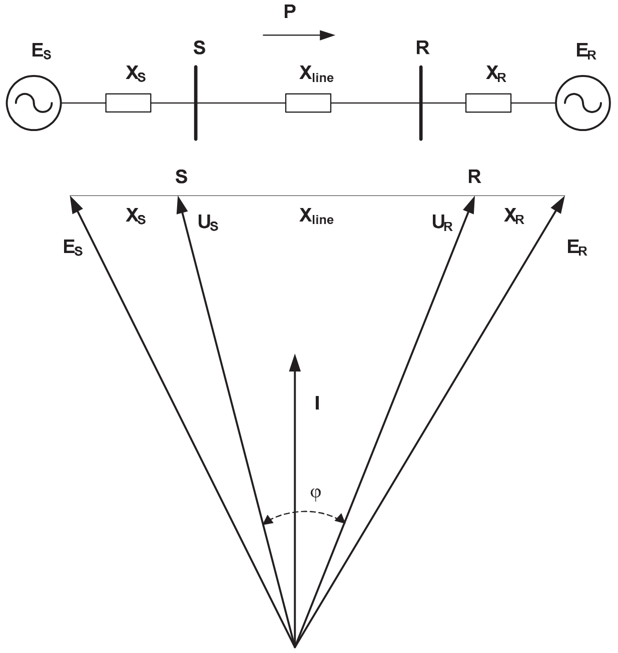


Figure 2, Two-machine model and corresponding phasors

Angle monitoring in real time enables reaching a satisfying system state and provides timely information. This enables initiation of the advanced control actions. During planning stage power flow calculation gives loading between busbar A and busbar B. This line loading can be presented with angle between these two busbars, Fig.3.

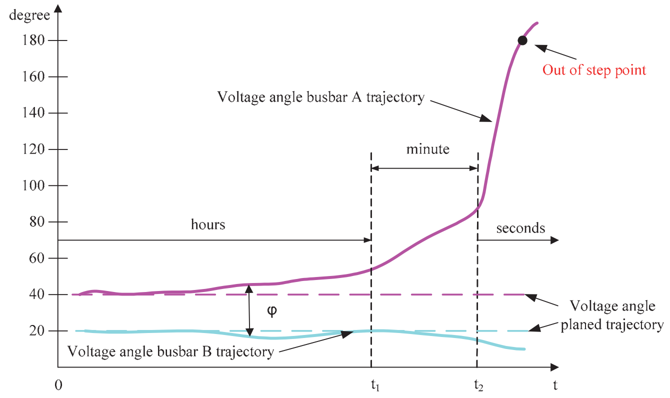


Figure 3, Example of angle monitoring between two busbars

During the first time span (0, t_1), the planned and realized angle values are almost the same. If small disturbances occur in transmission system, the angle difference starts to increase and φ changes in the second time span (t_1, t_2). There is no more matching between the planned and the real-time angle value. In case of inability to establish a new stable operating point or if there is no control action, φ increases even further and endangers the transient stability. During the third time span (time after t_2), there is a possibility of out-of-step condition. This is a stage when severe disturbances can occur, e.g., transmission system splitting, cascade outages or blackout.

Alarm activation can be derived from synchrophasor data. Fig. 3 shows an example of alarms which can be useful in control room to enhance the system operation:

- Slow or sudden voltage U change;
- Line active P and reactive power P change;
- Angle φ and rate of change of angle ω values change.

With these alarms some new control actions can be obtained in the control room. In slowly developing disturbances a manual dispatcher directed reaction is possible, but for fast developing disturbances only automatic protection and automatic control functions can be used. Only automatic respond is an adequate reaction in time domain of seconds to only few minutes.

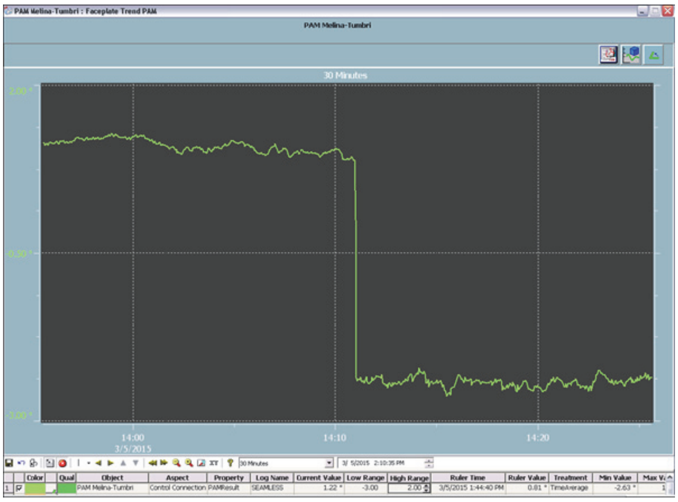
Power system operation in real time [8], [9], [10] with usage of synchrophasor data can fulfill all these technological requirements. Paper [11] described initial phase implementation of an advanced control system based on synchronized phasor measurements technology, and future use of system integrity protection schemes. The good quality synchrophasor data provide a platform for the realization of angle monitoring function between busbar voltages. The reason for that lays in a fact that the technology of synchrophasor measurement unit has established data flow with delay of only few dozens of millisecond, in comparison with SCADA data where inflow and calculation time reaches few seconds.

In order to obtain an angle transmission system footprint, it was necessary to analyze normal operation condition and some disturbances which can cause angle instability. Analyses include all sources and load on 400 kV transmission grid. Switching operation were performed at all six 400 kV transmission substation. Angle stability consideration must include certain heavy disturbances which can slide the operating point toward the out-of-step condition. Busbar faults are definitely a great challenge for operation crews and system protection schemes. Busbar switching off in transmission system has great impact on power flows and can create stability issues.

B. *Line fault on 400 kV Melina (HR) – Divača (SLO)*

Model of Croatian transmission system was made in Matlab. For power flow calculations the highest system loading was chosen (winter loading). In these conditions it is more complicated to maintain transmission stability. During the grid model tuning process, many historical scenarios from 400 kV transmission grid operations were used. Regular switching operations and failures (line fault, transformer fault, breaker fault, generator fault) recorded values were compared to the results of the model. One case will be presented as an example.

On the 400 kV line Melina (HR) – Divača (SLO) a fault occurred on March 5, 2015 at 14:11 h. The line was heavily loaded at 455 MW. A permanent fault occurred (broken grounding wire) and relay protection tripped the line for good. Croatian transmission system operator (HOPS) collects only their own synchrophasor measurement using the installed WAM system, while synchrophasor measurements from the neighboring countries are not available. Therefore, the angle comparison made on the date was collected from another Croatian 400 kV line Melina-Tumbri at the same substation. Angle values change between voltage phasor in two substations, Melina and Tumbri are shown on Fig.4. Data was collected from HOPS WAM system [12]. 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 $\Delta\varphi = 3.5^{\circ}$.



		Color		Qual	Object	Aspect	Property	Log Name	Current Value	Low Range	High Range	Ruler Time	Ruler Value	Treatment	Min Value	Max V
1	☑	🟩		🟩	PAM Melina-Tumbri	Control Connection	PAMResult	SEAMLESS	1.22 °	-3.00	2.00	3/5/2015 1:44:40 PM	0.81 °	TimeAverage	-2.63 °	1

Figure 4, Line angle Tumbri-Melina, during line tripping event on 400 kV line Melina-Divača, in WAM system

Fig.5 presents the line angle change of line Melina-Tumbri during the line tripping event at the neighboring line Melina-Divača in the same substation, simulated in Matlab model.

Angle difference in the model is $\Delta\varphi = 3.0^{\circ}$. The calculated result is almost the same as the recorded data of the WAM system. Reference angle values in WAM system and in the model are not the same and there are some differences presented in Fig. 4 and Fig. 5. Good similarity is shown between model result and real time transmission system data. Many similar comparisons done on the basis of other recorded failures or simple operators switching show the same thing. This case of tripping relatively highly loaded line is highlighted because of significant recorded angle shifting. This angle shifting propagates to more or less each 400 kV substation with damping effect.

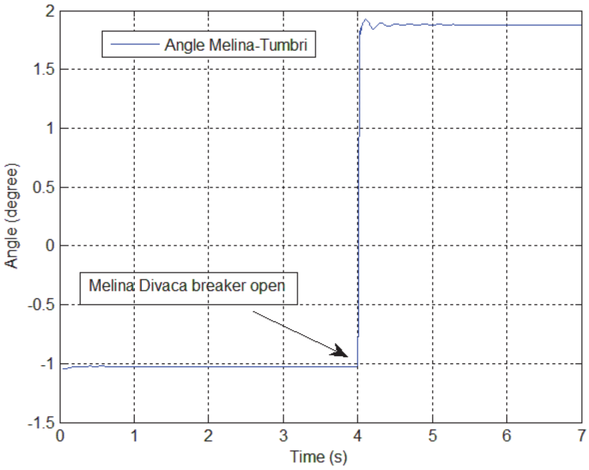


Figure 5, Line angle Tumbri-Melina, during line tripping event on 400 kV line Melina-Divača, in Matlab model

IV. CROATIAN TRANSMISSION SYSTEM ANGLE FOOTPRINT

After tuning and adjusting the model, simulation scenarios were run in order to obtain angle footprint for the 400 kV transmission systems. As already mentioned, a relatively high system loading was chosen. Three characteristic cases that cover regular breaker operation and serious faults (busbar fault) were analyzed. Busbar faults are categorized as hard disturbances with great risk of cascade spreading and possible impetus force towards out of step conditions. The following simulations were done.

- Elements switching off and back on. Elements are interconnection line, transformer 400/220 kV with massive production on 220 kV level and generators.
- Loads switching off and back on. Load are transformer 400/220 kV and 400/110 kV and interconnection tie line.
- Busbar fault. Switch off a nearly half feeder in substation (sources or loads).

Variation of voltage values *U*, angle differences $\Delta\varphi$ and rate of change of angle ω were in the focus of the simulations process. In the simulation, the breaker operation was scheduled as follows: the breaker opens in the fourth second and in the eighth second it closes. Switching sources and loads can represent regular dispatcher manipulation. Tripping caused by relay protection is a case of transmission element fault.

The most demanding disturbance is busbar fault. As there is no fast recovery in such case, the simulation is done only with breaker switching off in the fourth second.

Switching operations and phase values change can be traced through whole system even in case of light disturbances [13]. Fig.6 presents busbar voltages in all six 400 kV substation. Simulation was done in substation Žerjavinec with breaker manipulation on international tie line Heviz 1. This line acts as a source for the observed system (infeed of 300 MW).

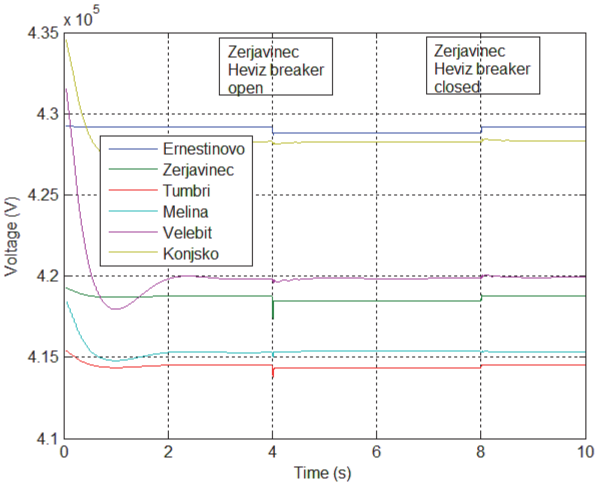


Figure 6, Busbar voltage during source switching operation in Žerjavinec

Voltage changes were caused by power flow changes in transmission grid in order to compensate for the loss of 300 MW from Hungary (import). Line Žerjavinec-Heviz 1 is switched off and back on. In the first two seconds, the Matlab model logged oscillations until reaching a steady stable point.

A. *Angles values during switching operations*

Breaker manipulations were carried out at all six 400 kV transmission substations in order to get utmost angle values. Results were matches with WAM system data. In table I. result are present which were obtained by the model during switching operations done by prepared scenarios for three major simulation groups.

TABLE I. ANGLE VALUES SHIFTING

Simulation type	Minimum angle value (degree)	Maximum angle value (degree)
Source switching	0.1	2.0
Load switching	0.1	2.4
Busbar failure	0.1	5.2

Marginal angle values in the 400 kV transmission grid for the chosen system load were obtained using simulation. It can be concluded that a planning stage was properly done because there are no security issues caused by switching of 400 kV elements. Maximum angle shifting happens during busbar fault in Melina substation and equals to is $\Delta\varphi = 5.2^o$.

Angle shifting is presented in Fig.7. This shifting was caused by switching of Divača line breaker in substation Melina and change was propagated on all five 400 kV internal lines which were modeled. Power export to Slovenia was during that period 500 MW. The highest angle shifting happens on two Melina lines, towards Tumbri and Velebit. On other lines angle shifting was smaller because of damping effect.

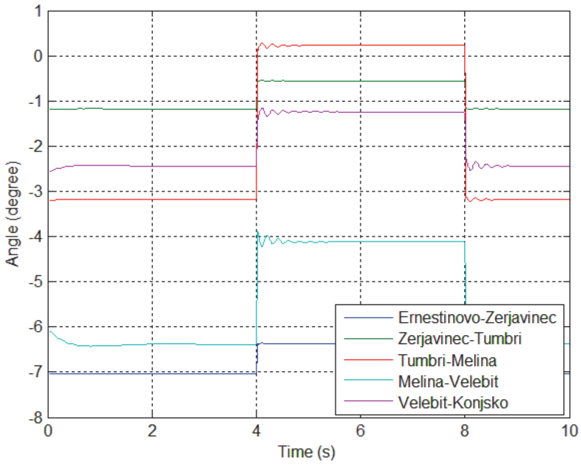


Figure 7, Angle shifting on 400 kV lines during load switching operations in Melina

B. *Angle velocoty during switching operations*

Besides angle shifting indices, others valuable data can be calculated in real time. Rate of change of angle can provide additional system state indications. These kind of data can be used in automatic system operation, protection and control or even in creation of central system protection. Marginal values for the rate of change of angle calculated in the model are presented in Table II. This index also pinpoints serious disturbances in transmission system, since a busbar fault causes the highest rate of change of the angle value.

TABLE II. ANGLE RATE OF CHANGE OF ANGLE VALUES

Simulation type	Minimum rate of change of angle value (degree/second)	Maximum rate of change of angle value (degree/second)
Source switching	2	71
Load switching	1	140
Busbar failure	0	205

A detailed graph with rate of change of angle is presented on Fig. 8. The switching operation started in the fourth second and three 400 kV breakers were forced to open caused by the busbar fault. This means that in substation Melina three breakers are open and the remaining two breakers stay closed.

The maximum rate of change of angle reaches more than 200 degrees in second. Also two highest peaks, Tumbri-Melina and Melina-Velebit give indices where disturbance origin is. Therefore, this is also a valuable information for the real-time operation and post fault analysis [14] and can be an input for an intelligent alarm processing system as a smart grid application [14] in modern control centers.

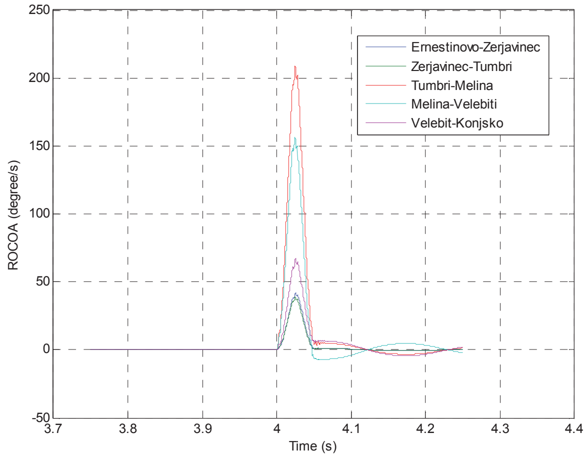


Figure 8, Rate of change of angle during busbar fault simulations in Melina

V. CONCLUSION

This paper presents an opportunity to intensify utilization of voltage angle data at the planning phase and at the real-time operation of transmission system. Synchrophasor measurement data collected in WAM application provide sharp and useful angle footprints of real time operation to control centers. Operational data was analyzed and compared to the developed Matlab model of 400 kV transmission systems. Except for the usage of voltage angle for determining a transmission system status and behavior others derivatives can also be used. Rate of change of angle is one of the values which can be incorporated in some system protection schemes in controls centers. In developed Matlab model different scenarios were simulated to investigate transmission system angle footprint in different circumstances. The simulation data and the real-time operation data form WAM system show that every breaker switching operation can be detected through angle monitoring. Voltage, voltage angle and rate of change of angle were analyzed for various switching breaker operations. In further work, protection functions based on the angle data can be developed primarily designed for system application in control centers.

VI. ACKNOWLEDGEMENT

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