Transmission system phase angle footprint based on synchrophasor measurement

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***Abstract* — This paper presents a transmission system voltage angle footprint obtained both from a synchrophasor data collected in real-time operation and from simulations of the developed model. Transmission system (400 kV) is modeled to gather angle footprints for characteristic scenarios. The paper further elaborates on the possibilities how to use this kind of angle footprint information in planning stage and in real time operation. It is explained what value knowledge about voltage angle to describe a system conditions and behaviors can have in planning process and real time operation.**

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

I. Introduction

Safety is a number one priority in power system operation and also has to be maintained in competitive electricity market environment. Electricity market development had significant impact on power system sector [1]. Power system operation is greatly influenced by the integration of renewable energy sources (RES) and the fact that market planning and operation is done hourly or 15 minute time spans which can be problematic due to intermittent nature of RES. Additionally due to same cause, one directional power flow on transmission-distribution interface has changed to bi-directional flows. This happens mostly because renewables shares on the distribution and low voltage level have risen drastically. Inevitable consumption growth also increase transmission level load even further and causes congestions. All abovementioned factors decrease operation safety margins. To avoid and solve some of these challenges ENTSO-E organization constructed procedures for coordinated planning and operation [2]. Regional initiatives in continental Europe, Transmission system operator Security Cooperation, TSC [3], [4] made a further step to increase operation safety. Both of these organizations created obligatory rules for Transmission system operators (TSO) with aim to enhance operation safety.

Commonly used methodologies for power system control are always improved with the addition of new methods. Synchrophasor measurement technologies have promising features for researching and finding new procedures for power system real time operation. Using accurate voltage angle data in transmission system gives much better insight of the current state of the system. Nowadays Wide Area Monitoring (WAM) system collects phasor data from crucial transmission system busbars and relays 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 has included in each 440 kV substation lines towards neighboring countries and load to 220 kV and 110 kV transmission levels. Two generators in hydro power plant Velebit which are connected on 400 kV transmission level are also modeled.

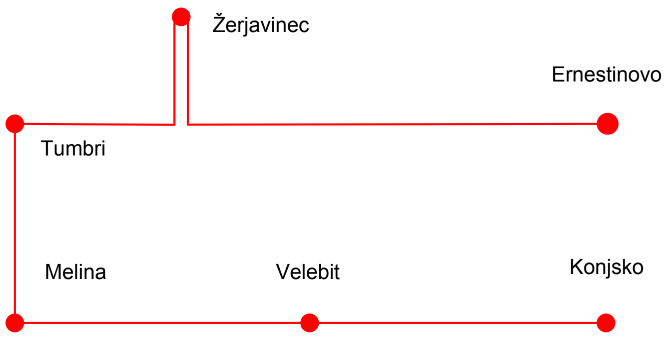

Figure 1, Simple line diagram 400 kV transmission grid

This model is used in order to find voltage angle and angle velocity across the transmission grid during normal operation times and during disturbances.

II. Power flow planning and N-1 security

These rules [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 loadability check in highly meshed grid is performed. Additionally, power flow calculations give electrical values (Commonly used values are active and reactive power, current and voltage) for next 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 acts as 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 gird 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 like angle instability and short-term voltage instability [6], [7].

Both during planning stage and real time operation angle values are still not used in a great deal. Angle between busbars voltage phasor gives accurate insight of the system current operation state. So it can be used in all of the abovementioned phases since WAM system collects in real time system state based on the synchrophasor measurement.

III. Transmission Grid Operation and Angle Tracking

A. *Line power flow*

In transmission system loadability of each line is calculated in planning phase and being tracked in real time operation. As stated before the angle values can give insight into transmission line or corridor loading. These data sets 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. Possibility to establish 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. Possibility 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 on line or 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, Fig.2. Line loading P is defined with equation (1) where X_{line} is line reactance, sending end voltage is U_S and receiving end voltage is U_R. Angle between two phasor is φ.

$$P = \frac{U_S \cdot U_R}{X_{line}} \cdot \sin\varphi \qquad (1)$$

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.

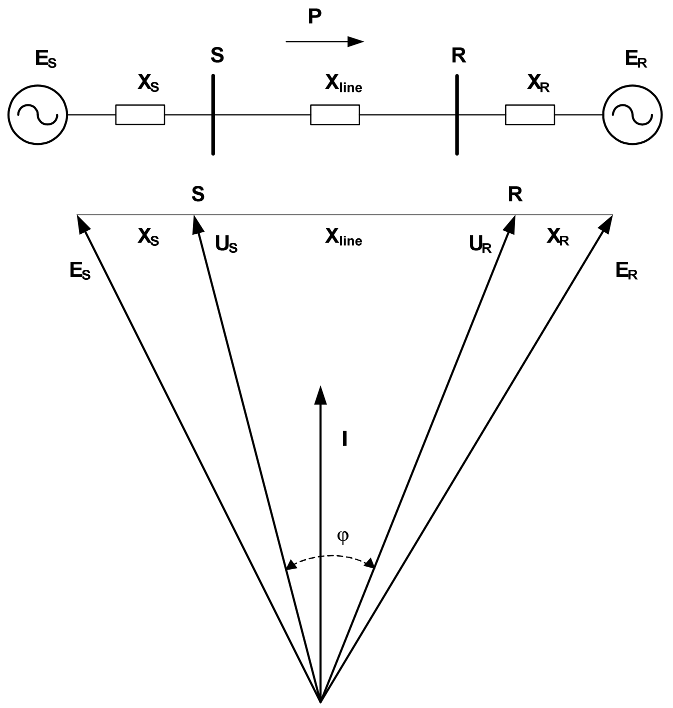

Figure 2, Two machine model and corresponding phasors

Angle monitoring in real time enables reaching of a good system state and provides timed information after which can lead to initiation of 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.

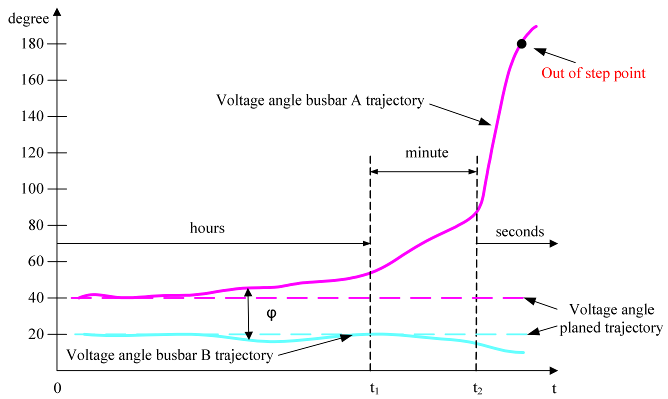

Figure 3, Example of angle monitoring between two busbars

In first time span (0, t_1) planed and realized angle values are almost equal. If small disturbances occur in transmission system an angle difference starts to increase and φ changes in second time span (t_1, t_2). There is no more matching between planed and real time realized angle value. In case of inability to establish new stable working point or if there is no control action, φ increases even further and endangers a transient stability. Third time span (time after t_2) present a possibility of out of step condition. This is a stage when sever disturbances can occur, like 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 system operation:

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

With these alarms some new control actions can be obtained in the control room. In slowly developing disturbances some manual (dispatcher) reaction is possible, but for fast developing disturbances only automatic protection and automatic control functions can be used. Only automatic respond is a right and 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. The quality data synchrophasor provide are platform for the realization of angle monitoring function between busbar voltages. The reason for that lays in a fact that 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 get 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 done in all six 400 kV transmission substation. Angle stability consideration must include certain heavy disturbances which can slide working point toward final point, out of step condition. Busbar faults are definitely great challenge for operation crews and system protection schemes. Busbar switching off in transmission system has great impact on power flow and can create stability issue.

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 most complicated to maintain transmission stability. During grid model tuning process many recorded 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 with model result. One case will be presented as an example.

On line 400 kV Melina (HR) – Divača (SLO) line fault occurred on 5^{th} of March 2015 at 14.11 hours. Line was heavily loaded with 455 MW. Permanent fault occurred (broken grounding wire) and relay protection triped the line definitely. Croatian transmission system operator (HOPS) is collecting only their own synchrophasor measurement in installed WAM system. Synchrophasor measurements from neighboring countries are not available and connected. So angle comparison made on date collected from another internal 400 kV line Melina-Tumbri in 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 [11]. 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 $\Delta\varphi = 3.5^o$.

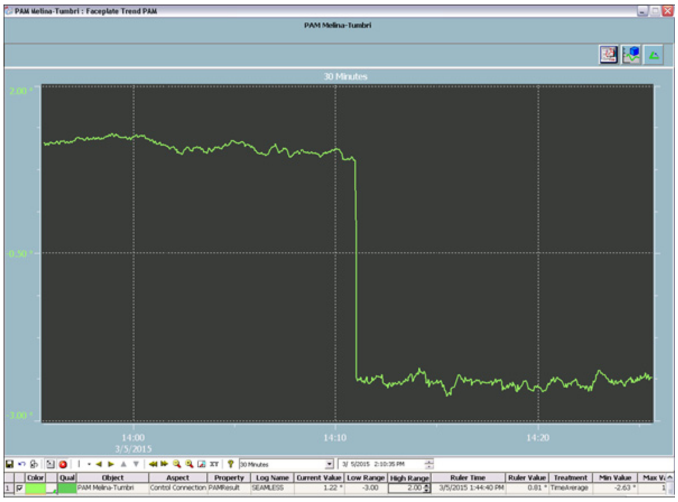

Figure 4, Line angle Tumbri-Melina, during line triping event on 400 kV line Melina-Divača, in WAM system

Fig.5 presents line angle change for Melina-Tumbri during line triping event on neighboring line Melina-Divača in the same substation, simulated in Matlab model.

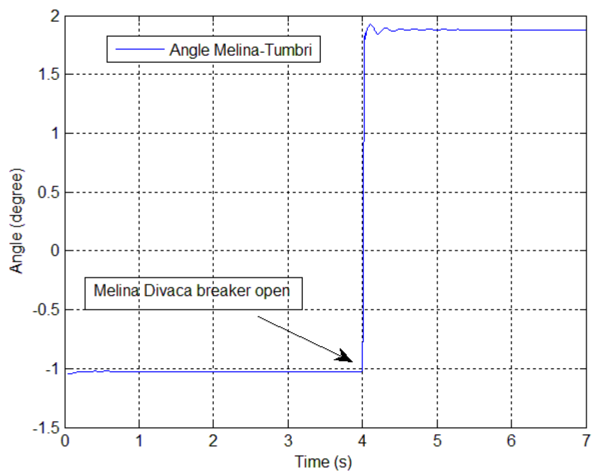

Figure 5, Line angle Tumbri-Melina, during line triping event on 400 kV line Melina-Divača, in Matlab model

Angle difference process in model is Δφ = 3.0°. Calculated result is almost the same like recordings in WAM system. Reference angle values in WAM system and in the model are not the same and there are some differences presented on 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 triping 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.

IV. Croatian Transmission System Angle Footprint

After model tuning and adjustments were made case simulation scenarios were done in order to get angle footprint for 400 kV transmission systems. As mentioned before, relatively high system loading was chosen. Three characteristic cases were analyzed and they cover regular breaker operation and serious faults (busbar fault). 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 on. Elements are interconnection line, transformer 400/220 kV with massive production on 220 kV level and generators.
- Loads switching off and 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 Δφ and angle velocity ω were in the focus of the simulations process. In the simulation breaker operation was scheduled as following: breaker open in second 4 and in the second 8 the same breaker is closed. Switching sources and loads can represent regular dispatcher manipulation. Triping caused by relay protection is a case of transmission element fault.

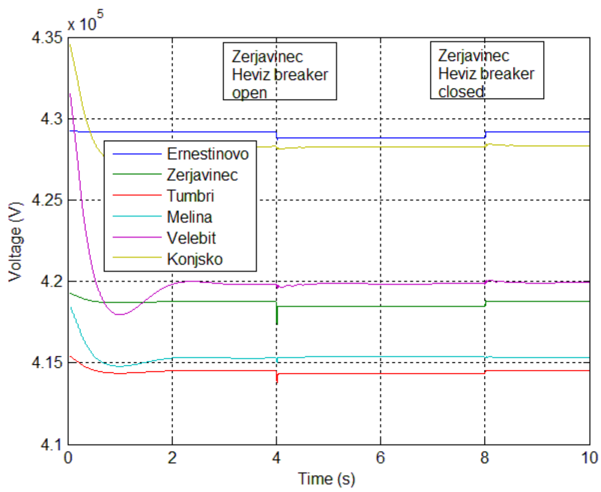

Figure 6, Busbar voltage during source switching operation in Žerjavinec

Most demanding disturbance is busbar fault and there is no fast recovery in such case so the simulation is done only with breaker switching off in fourth second.

Switching operations and phase values change can be traced through whole system even in case of light disturbances [12]. 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 is acting like a source for the observed system (infeed of 300MW). 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 switched off and on. In first two second Matlab model logged oscillations until reaching steady stable point.

A. *Angles values during switching operations*

Breaker manipulations were carried out in 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

Through simulation marginal angle values in 400 kV transmission grids for chosen system load were obtained. It can be concluded that a planning stage was properly done because there is no security issue caused by switching of 400 kV elements. Maximum angle shifting happens during busbar fault in Melina substation and equals to is Δφ = 5.2°.

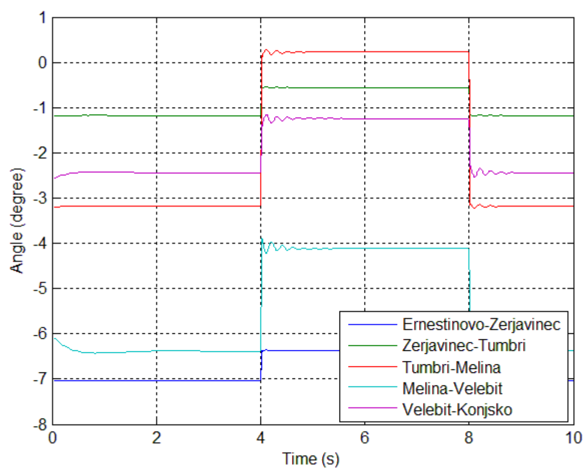

Figure 7, Angle shifting on 400 kV lines during load switching operations in Melina

Angle shifting is presented in Fig.7. This shifting was caused by switching of Divaca 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.

B. *Angle velocoty during switching operations*

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

TABLE II. ANGLE VELOCITY VALUES

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

Detailed graph with angle velocity is presented on Fig.8. Switching operation started in fourth second and three 400 kV breakers were forced to open caused by busbar fault. That means in substation Melina three breakers are open and remaining two breakers stay closed.

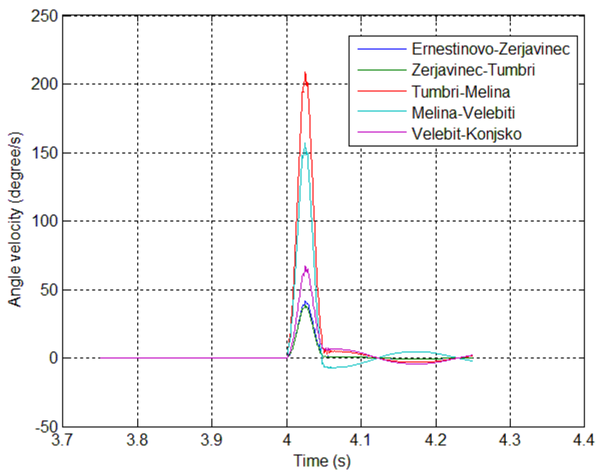

Figure 8, Angle velocity during busbar fault simulations in Melina

Maximum velocity 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 valuable information for real time operation and post fault analysis [13] and can be input for intelligent alarm processing system as a smart grid application [14] in nowadays control center.

V. Conclusion

This paper proposes an opportunity to intensive usage of voltage angle data in planning phase and real time operation of transmission system. Synchrophasor measurement data collected in WAM application for control centers gives sharp and useful angle footprints of real time operation. Operational data was analyzed and compared to 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. Angle velocity 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. Simulation data and real time operation data form WAM system show that every breaker switching operations can be detected through angle monitoring. Voltage, voltage angle and angle velocity 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.

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