Application of synchrophasor angular difference as a grid monitoring tool and for assessment of Real time voltage Stability-Case Study

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***Abstract*— This paper investigates about the application of Synchrophasor angular difference for detecting the various grid events which allows operators ease and advancement for grid monitoring. This paper explains the real time grid events and cases observed in eastern regional grid, where Phase angle difference has been used as a grid monitoring index for monitoring and sensitizing the grid stress. Synchrophasor angular difference used for predicting voltage collapse in collaboration with PV curve obtained from PMU, in real time which is very much effective and specially effective for weak nodes with low fault level and nodes with skewed/variable generation pattern. Monitoring Angular difference is of very much importance as system stress can be identified easily, under all set of different scenarios and contingencies. To enhance the situational awareness of grid operators, path flow monitoring along with the angular difference of the path is used for defining operating state of a particular corridor/area of the power system, whether operating in normal, Alert, or emergency state so that with corrective action system can be brought back to normal state. Path angular difference gives an upper hand and can predict about voltage collapse events beforehand and also margins to the knee point can be accessed in terms of angular difference of the path. In real time with the help of synchrophasor data, real time reserve monitoring for the identified path/area can be done so that sufficient margin can be maintained for contingency situations.**

Keywords—-Phasor Measurement Unit (PMU), Steady state Stability Limit (SSSL), Saddle Node Bifurcation (SNB) etc.

I. Introduction

A paradigm shift in real time system operation vis a vis post-dispatch forensic of mammoth Indian grid has been achieved through installation of PMU at strategic locations under the (URTDSM) Unified Real time Dynamic state measurement project, covering approximately 600 Nos. of substation including 3200 feeders across length and breadth of India . Huge amount of real time PMU data are now available with the control centers which can be utilized in different innovative ways for improved observability and monitoring of the grid. Phase Angular Difference between two judiciously chosen nodes, measured through PMU is one such salient data which can be revelation for detecting and analyzing the various grid events.

This paper investigates application of such Synchrophasor Angular Difference through real time grid events and cases observed in Eastern regional grid of India. Phase angle difference has been used as a grid monitoring index for quantification and ranking of grid stress. The paper even predicts voltage collapse in correlation to PV curve obtained from PMU. This is extremely effective for flagging grid instabilities at weak nodes having lesser fault level. With ingress of high volume intermittent renewable and peaking hydro, certain nodes are vulnerable with skewed generation pattern and variable fault level where PMU monitored Angular difference studies can identify the instability beforehand.

This paper also uses the knee point or voltage collapse point or SNB (Saddle node bifurcation) point in real time using PMU in terms of angular difference which has been been validated by real grid events. Phase Angle is indicative of state of the power system. Angular separation can be easily co related with voltage collapse and help to find the margin of allowable load ability before hitting the maximum angular separation which would call for violation of the knee point of PV curve. There will be no need to calculate other index such as SSS or maximum power transferred without hitting knee point or margin available under different set of contingencies and different operating condition etc, which requires full-fledged Dynamic Security Assessment tools for all these assessments. Angular separation itself contains all these dynamics of grid, and will vary according to different operating conditions and different set of contingencies.

In this paper we have calculated margin available in terms of angular difference before hitting the knee point , which can be monitored in real time through real time PV Curve plotted from available PMU measured Line flows and Bus Voltage. Angular difference along the path of the two distant nodes carrying power from source to sink is plotted against PV Curve.

Angular instability and voltage instability are both linked with each other. Voltage collapse or voltage instability is a slow phenomenon while angular instability happens fast specially for 400 kV and higher level. So angular instability hits first. For a load bus or weak nodes which are fed radially with weak sources, angular instability hits first this results into voltage collapse.

Thus, we have a clear track of the margin left in terms of angle correlated with PV curve obtained from PMU in real time. Angle corresponding to Knee point will be more or less fixed for a particular path or corridor which is derived

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here for a case and can be calculated for other different corridors.

II: Monitoring path flow vs Angular difference

Situational awareness of the grid operators can be increased by monitoring, Phase angle difference across a Path with the Path Flow. Path can be strategically chosen along which Phase angle monitoring will be most effective. Following points need to be considered for maximum observability:

Path should be monitored which is generally overloaded or congested or a Path which feeds to huge load centers or the nodes with low fault level. Problem with the low fault level nodes is that their voltage withstand capacity is very low so their voltage changes very much with the change in power flow.

If Such nodes lie in a generation rich pocket whose generation pattern is of variable nature, such as Hydro rich pocket or renewable rich pocket so due to varying nature of generation, some machines on bar and some out of bar, fault level of the nodes also varies and so the voltage.

Hence these corridors needs to be monitored as any single line contingency (N-1) may be very vital and catastrophic.

Selection of pair of Nodes for angular difference monitoring should be selected strategically so that with change in Path flow change in angular difference between two nodes should be maximum and if any contingency arises in the path the line with maximum flow transfer should be in the path so that maximum change in angular difference between the two selected distant nodes can be observed with path flow.

These paths and nodes, can be selected strategically as mentioned above with the help of Offline simulation and Operators experience with the past data analysis for angle and path flow monitoring .

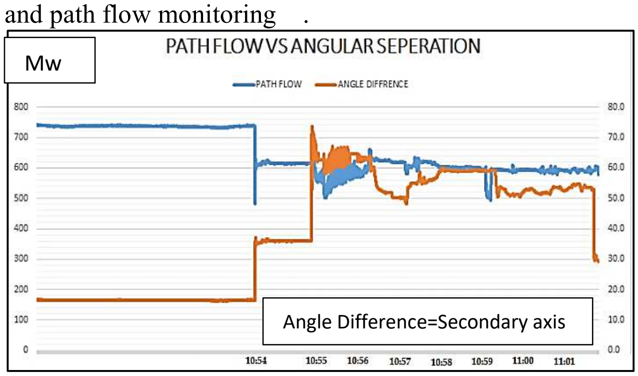


Figure (1) Path Flow vs Angular separation

As can be seen from above Figure where Path flow (Blue line) of a corridor is being plotted against Angular separation (Red line). Following are the inferences of plotting Path flow vs angle.

I. If Path flow increases and angle separation between the path also increases, hence stress of the path is also increasing. It can be anticipated by Angular separation through correlating them with the safe operating angular separation limit as it contains all dynamics included in itself, rather than using SSSL(Steady state stability limit) as SSSL will vary depending upon the real time network configuration.

II. In normal steady state condition If the Path flow Decreases angular difference should also decrease.

III. If the Path flow decreases or remains more or less same but Angular separation has increased between the path then it shows any one or more lines have tripped in the path as path impedance has increased hence angular separation so the stress of the path .

IV. If Path flow is increasing but angular separation is still decreasing that means it has encroached towards instability region.

Above inferences can be used for monitoring the grid and different path stress.

State of a power system based on the angular difference, can be determined and limit for angular difference needs to be set for each state ,Normal state , Alert state , Emergency state based on past incidents , operator experience in collaboration with offline study for each path and this limit will be different for different path/area.. Angular variation captures all dynamics rapidly which is occurring in a power system.

As seen in Figure(1) at 10:54 Hrs Path flow reduced by some amount from 700 Mw to 600 Mw but angular difference increased from 17 degree to 36 degree it shows one of the line between the path has tripped.

At 10:55 Hrs although path flow was almost same but angular separation increased to 60 degrees from 36 degree as one more line in the path tripped. With such huge angular difference further any contingency in the system may hamper its stability as system has gone to emergency state.

Corrective actions must be taken to bring back the system to normal state by bringing back the angular separation to the identified limit in normal state by reducing power flow or by restoring one of the line on priority basis .

Based on pre-Identified Angular separation limit, Normal Alert, emergency state can be obtained and system stability, voltage collapse etc can be predicted as shown in next section of case study.

III. Case study of voltage Collapse

Case study of voltage collapse for a weak 400 kV node lying in eastern region has been analyzed with the help of PMU Data.

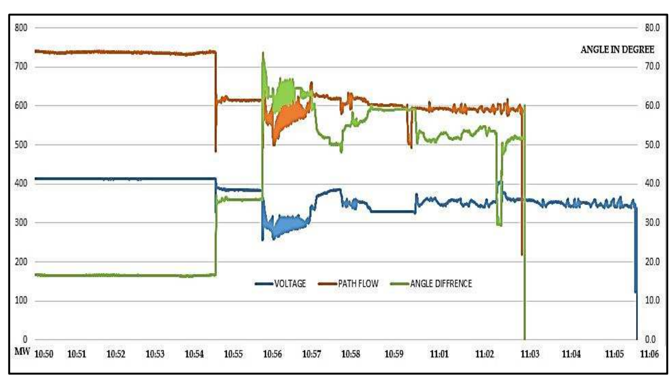


Figure (2) Path flow vs Angular Separation vs Voltage collapse plot.

As shown in figure (2) case of voltage collapse is depicted with the PMU plot, where path flow (which contains the summation of power flow of all lines which are acting as a source for feeding the load), and angular difference between the nodes of path have been plotted with voltage of the node.

- It is clear by the plot that between 10:54 and 10:55 as the path flow reduced from 720 to 600 Mw Angular separation increased from 15 to 36 degree that means one of the lines between the path feeding to the load tripped. With the tripping of one line power flow in remaining lines of the path increased which caused voltage reduction at node ,although Path flow will be more or less same.
- At 10:56 Hrs angular separation increased suddenly beyond 60 degrees, which indicates of one more contingency in the path and voltage of the node further reduced. After few minutes' voltage collapsed and bus became dead.
- Important point to be noticed here is after 10:56 Hrs when angle increased beyond 60 degrees, the power flow and voltage of the node are not following the relation as the power flow is reducing voltage of the node also decreased and as the power flow increased voltage also increased.
- This indicates that the point at 10:56 Hrs was the SNB(saddle node bifurcation) point or the knee point of PV curve .Same thing can be clearly observed by the real time PV plot obtained from PMU for the event .
- With the contingency in the path maximum power that it can transmit without losing voltage stability is approx. 650 Mw, so under contingency situation knee point is corresponding to 650 Mw as also observed from Figure(3).

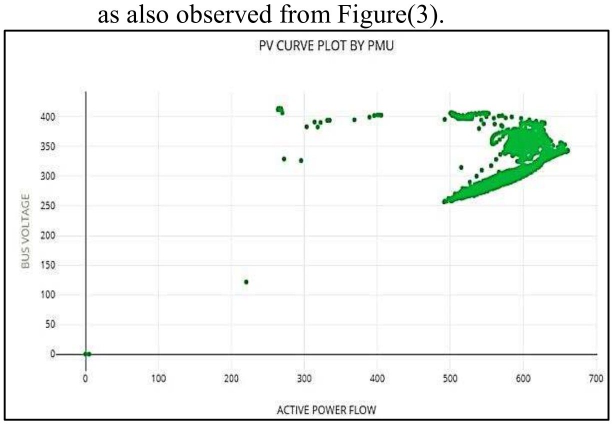


Figure (3) PV curve from PMU for the event .

IV. Angular separation Monitoring for identification of Operating state of a corridor and for Assessing Voltage stability:

Angular instability and voltage instability are both linked with each other, voltage collapse or voltage instability is a slow phenomenon while angular instability is fast and for 400 kV level generally Angular instability hits first. For a load bus or weak nodes which are fed radially with weak sources angular instability hits first which as a outcome causes voltage collapse. Remedial measures and restorative actions may be taken within proper time to avoid voltage collapse.

Margin available under different set of contingencies and different operating condition can be supplemented with angular separation itself which contains all these dynamics. Generally, it is the practice to monitor angular difference between two distant nodes which should not exceed 90 degrees to maintain angular stability of the system, which is true for well-connected system and strong grid.

Extra precaution should be taken for some corridors which are having radial feeding, or with low fault level nodes and highly variable power infeed there is high possibility that before angular difference is reaching 90 degrees between the two distant nodes, angular difference between two adjacent nodes are crossing 30 degree and the node loses its stability and may lead to voltage collapse.

Corridor identification and strategic path and node selection is very important to monitor angular difference and stability as PMUs are limited in number, else for those nodes adjacent angular separation monitoring will be much fruitful.

Operating State of the particular area can be defined by monitoring angular difference. Limits for identifying the operating state are set based on the past incidence in collaboration with offline studies which can be utilized in real time. Below mentioned limits and inferences are for the specific case study mentioned here. Figure (4) shows the angular separation trajectory during the event along with the operating state limits.

- As shown in figure (4) When angular separation between two identified nodes of the path is less than 30 degree it is in normal state.
- When Angular separation is more than 30 degree and less than 50 Degree it is in Alert State. Corrective actions such and line restoration or load reduction, generation and load re-dispatch, reactive compensation can be utilized to bring back in normal state.
- When Angular separation is more than 50 Degree and less than 60 degree it is in emergency state corrective actions must be taken to bring back it from emergency to either in alert or if possible, to normal state.
- When Angular separation is More than 60 degree it is entering into restorative state, due to angular instability which in turn after few seconds or minute causing voltage collapse.

For the above corridor for each event it was verified, whenever angular separation between the two identified nodes of the path is more than 60 it is observed that the angular difference between two adjacent nodes in the path is becoming more than 30 degree which is leading to angular instability.

Generally angular difference between two adjacent node is very low (5 to 10 degrees) maximum of the order of 15 degree but in case of very low fault level nodes it is very important to monitor angular difference of adjacent nodes as with any contingency and with long haulage of power it increases more and can cross 30 degrees, which causes angular instability which in turn causes voltage collapse, refer to section V this has been explained and validated through simulation.

As shown in Figure (2) at 10:56 Hrs Angular separation becomes more than 60 degree and at this point SNB (Knee Point of PV curve) also coincides as shown in Figure (5).

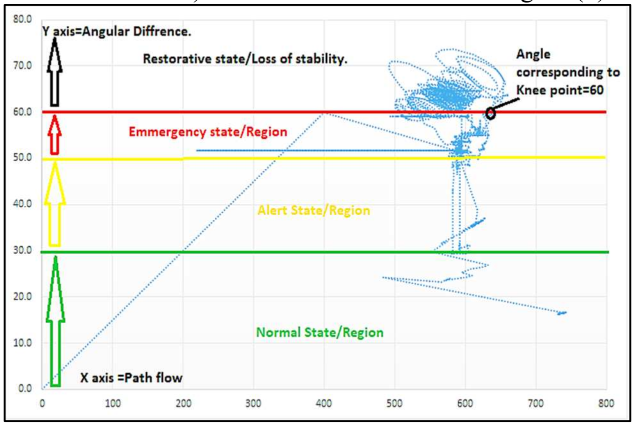
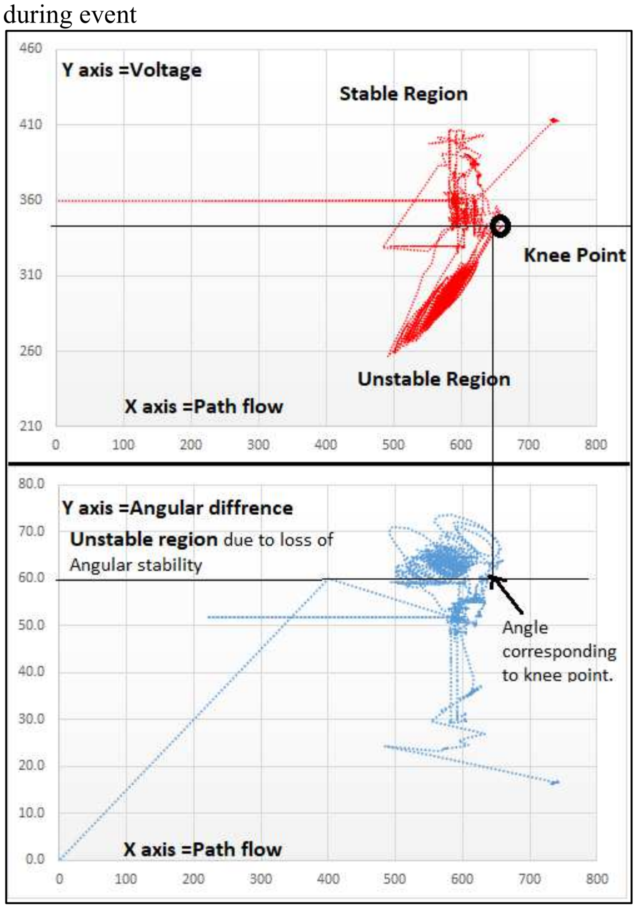


Figure (4) Angular separation trajectory for the path during event



Figure(5) PV Curve trajectory Vs Angular separation trajectory for the event.

It can be observed from Figure (5) that Knee point of PV curve is coinciding corresponding to the point when angular separation is reaching 60 Degrees in angular separation trajectory.

Below the Knee point of PV curve, system is entering into unstable region and above the 60 degrees in angle trajectory system is entering into unstable region.

So monitoring Angular difference can give a clear indication how far we are operating from the voltage instability region or knee point, Margin left to Knee point or SNB point in all operating conditions and Power system states can also be determined based on which corrective actions can be taken to bring it in Normal state if it is moving towards alert state or emergency state.

Knee point of PV curve can be related with angular difference in terms of degree as mentioned in above case, point at which angular separation becomes 60 degree is the knee point for our case study system.

Hence current operating state of the corridor can be identified and margin left to the knee point in terms of angle (degree) will be known to the operator in real time and accordingly steps can to taken to avoid touching knee point to have extra cushion for contingencies to avoid voltage collapse.

V. Verification through simulation plot

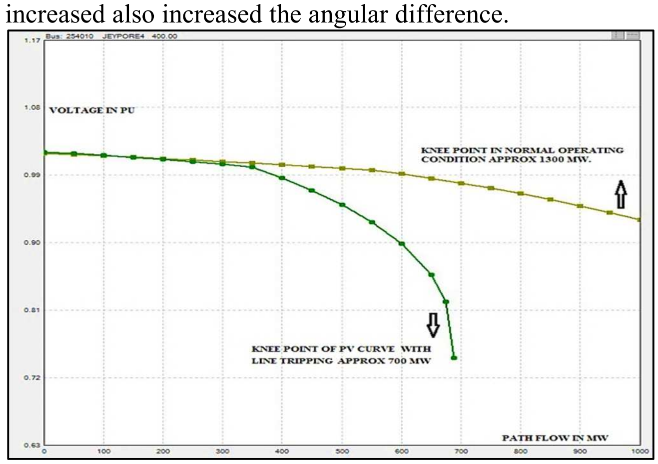
Same event has been analyzed and simulated through the help of PSS/E dynamic simulation for observing path flow with angular difference.

The identified node where voltage collapse occurred with the one single contingency (Line tripping) for the same case PV plot is generated for normal operating condition and for the contingency case. Curve below the knee point cannot be plotted through simulation as below the knee point simulation does not converges.

Figure(6) shows that Knee point of the PV curve for normal operating condition which is more than 1000 Mw approx. 1300 Mw, where in the case of contingency, it is observed Knee point obtained at a very early stage for a path flow of 670 Mw.

Knee point value reduced drastically as with tripping of line fault level further reduced and existing power flow along the path shifted to other lines and reactive power absorption by the lines increased due to high line loading which resulted to reduction of the node voltage.

High loading along the path whose path impedance has increased also increased the angular difference.



Figure(6) PV curve for the node obtained through simulation.

Angular difference increased along the path with the line tripping as shown in Figure(7) through simulation path flow with angular difference of the path.

As the fault occurred in one of the line along the path and it tripped suddenly angular difference along the path (shown by red color) increased up to 40 degree while the

path flow (shown by blue color) did not reduced significantly along the path as it was feeding the load which was fixed.
With another contingency in the system angle difference increased more than 60 degrees as shown in figure (7) at the same time angle difference between two adjacent nodes (shown in green color) also crossed 30 degree which is causing angular instability which is resulting into voltage collapse.
In the Grid code also, it is mandated to have angular difference less than 30 degree between two adjacent nodes for maintaining stability.
Same stability criteria between the two adjacent node was violated during this case due to long haulage of power from a weak path resulting into angular instability resulting to collapse.
As shown in previous section through PMU plot same thing is verified here as the line tripping occurred path angular difference crossed 60 Degree and at the same instance angle difference between two adjacent nodes also crossed 30 degree which is causing angular instability.

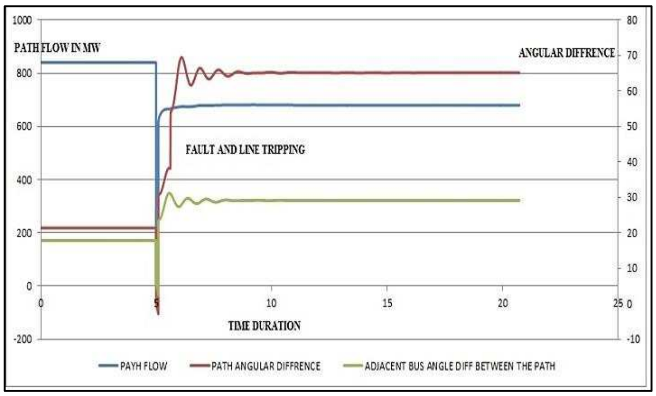


Figure (7) Simulated Path flow with angular difference.

VI. CONCLUSION

Synchro phasor angular difference can be applied in various ways for sensitizing grid operators in real time as explained in above sections such as identifying grid stress, for determining the operating state of a particular corridor which are cause of concern for grid operators. Remedial measures can be taken based on the angular difference to bring back the system to normal state from alert or emergency condition.
Angular difference along the path of the two distant nodes carrying power from source to sink can be plotted against PV Curve in real time using PMU data. Angular difference corresponding to Knee point is calculated for the worst set of contingencies based on the past experience and offline simulations which will act as a security reference line.
Thus, we have calculated margin available in terms of angular difference before hitting the knee point in real time through corroboration of PV curve. Phase angle gives an upper hand and can predict about voltage collapse event so that corrective actions can be taken to avoid the system being unstable or encroaching towards voltage collapse point by monitoring angular separation.

VII. REFERENCES

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