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Recent Trends on Performance Analysis of Latency on Wide Area Technologies in Smart Grids

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Abstract— **Numerous researches and real time studies are being conducted on wide area technologies for emerging smart power grids. These technologies include measurements, control and protection. The backbone of wide area technologies is synchronized measurements using phasor measurement units (PMU). One of the major challenges faced in practical implementation of wide area technologies is time delay (latency) in communication. Various researches have highlighted that latency study is essential for effective wide area schemes under contingencies. Interdependence of smart grid technologies with power flow control and PMU communication constraints, challenges the performance of entire power grid. Time delays in communication within wide area monitoring system (WAMS) can substantially degrade the stability and quality of control actions. This paper investigates the effect of communication latency associated with wide area technologies on various smart grid operations.**

Keywords— Phasor measurement units (PMU), Latency, Wide area technologies, Power system Stability,

I. INTRODUCTION

National Smart Grid mission under Ministry of Power Govt. of India has initiated numerous research and development programmes for transforming national power sector into a secure, adaptive, sustainable and digitally enabled ecosystem. This integrates participation of all active stakeholders for delivering reliable and quality energy. Synchronous monitoring, self-healing, automated wide area control are a few on various expected features of India smart grid. The backbone of India smart grid is synchronized measurements collected across the nation with the aid of phasor measurement units (PMUs). Real-time synchronized phasors collected from various parts of the power grid deliver snapshot of the power system over a time span. Smaller this time span better the monitoring, control and protection system. Pilot projects are being conducted in the nation for efficient utilization of synchrophasor data from PMUs towards achieving aforementioned features. Interdependence of smart grid technologies with power flow control and PMU communication constraints challenges the performance of entire power grid. Time delays in communication within wide area monitoring system (WAMS) can substantially degrade the stability and quality of control actions. Numerous studies are being conducted globally towards the analysis of impact of time delay in the PMU measurements and communication on various wide area protection actions of the smart grid. This paper investigates recent trends in aforementioned researches and infer on qualitative outcomes. This can provide an insight to technologies for analyzing and vanquishing the latency based issues in smart grid.

II. EMERGENCE OF WIDE AREA TECHNOLOGIES

The traditional power infrastructure is being transformed into cloud-integrated cyber-physical system (CCPS) which significantly depends on sensors, computations, communications and controls. Such system provides significant advantages and challenges even at every micro stages of power grid operation [1]. Wide area monitoring system (WAM), wide area control system (WACS) and wide area protection system (WAPS) are new key players under CCPS. Importance of such CCPS in power grids was prominent after various power outages or blackouts occurred recently across the globe. Power grid blackout in WSCC on August 10, 1996, U.S.- Canada blackout on August 14, 2003, north Indian blackout on 30 July 2012 and several other major blackouts have exposed the necessity of smart and intelligent automated real time power grid monitoring, protection and control systems [1-3]. Power grid stability, which is of major concern behind all monitoring, control and protection schemes, was achieved traditionally through conventional power system stabilizer (CPSS) or flexible AC transmission system (FACTS) based supplementary controllers. These systems utilize locally available measurements as inputs and hence limited in their performance to limited regions of power grid. Many case studies presented in literature demonstrated that the aforementioned systems may not always effective to stabilize power grid with instability extending to a larger region [2-6]. While wide area monitoring, control and protection systems can effectively maintain power grid stability and integrity under such situations. The fundamental requirement of wide area technologies is synchrophasor measurement using PMUs. The later provide real time global positioning system (GPS) synchronized measurements from substations in phasor form [3-5]. Since all measurements are synchronized with time stamping, snapshot of power system voltage profile can be easily obtained. This is crucial for the aforementioned wide area technologies like wide area monitoring system (WAMS), wide area control systems (WACS), wide area protection system (WAPS) and combined methodologies like wide area monitoring and control systems (WAMCS) etc. Better understanding of inter area oscillations with the aid of synchrophasors paved the way for Wide Area Damping Controllers (WADC). WADC are known to provide improved performance than conventional damping controllers [6-10].

Major challenge in implementing wide area technologies is the latency associated with the communication network. Latency impacts both wide area measurement system as well as wide area control and protection systems [4-10]. Depending on various attributes of communication network like medium of communication, length of the network, bandwidth of channel, a typical communication could span over from tens to hundred milliseconds [5-11]. An in-depth analysis of delays associated with PMU based systems is presented in the following section.

III. LATENCY PROFILE OF PMU BASED WIDE AREA SCHEMES

Latency profile of PMU based wide area schemes includes delays associated with voltage/current transducers and actuators, processing delay and communication delay. Transducer delay and actuator delay together comes near to 10 ms while the last two adds up to 500 ms. Communication delay contains serial delays, “between packet” serial delays, routing delays, propagation delays. The serial delays occur in between each one bit sent. Between packet serial delays occur between two consecutive packets sent. In other words, serial delay can be defined as the time span over which bits of a communication data packet are coordinated at a specified transmission speed. The time span over which the data are sent/resent through a router is called routing delay. This delay includes the waiting and service time at a node. In general, routing delay can be ignored under light network traffic. The time span over which data are transmitted over a communication medium is called propagation delay. The type of communication media and the distance of communication have influence over propagation delay. While, it is independent of network bandwidth. An illustration of these delays in wide area system is shown in Fig. 1.

The delay associated with different communication links are discussed in [12]. The study presented infer that the optical fiber communication channel has smallest propagation delay and hence most suitable for wide area technologies. Case studies presented in literature show that the fiber optic digital communication has latency of about 80 ms which may rise to 175–350 ms under increase in the intermittent network traffic [7-10].

IV. MAJOR RESEARCHES ON LATENCY ANALYSIS AND ITS IMPACT ON WIDE AREA TECHNOLOGIES

Latency consideration in wide area technologies has been a very active research area in international perspective. The impact of time delays associated with wide-area monitoring and control systems (WAMCS) on smart power grid stability was addressed in [1]. The impact of delay was studied and validated under hardware-in-the-loop and software-in-the-loop schemes. Impact of communication time delay and its variation in an islanded microgrid system is studied in [2]. A frequency restoration methodology was proposed based on secondary control level assuming a single time delay communication network. Analysis of wide area controlled power system using a mathematical expectation model incorporating the effect of stochastic time delay was presented in [3]. The proposed modelling approach was verified in simulation studies conducted on a power grid modelled with eight generators and thirty-six nodes. Latency estimation methodology for measurements and control signals in a power system was presented in [4]. The case studies presented in the paper substantiate that latency associated with control signals can significantly degrade the performance wide area control system.

Reference [5] presented a latency compensation technique using Unified Smith Predictor (USP) based control strategy, which was utilized to design a synchrophasor powered wide area damping controller using a static VAR compensator. The reference [6] has proposed compensation of continuous variable latency of wide area system with the help of phasor Power Oscillating Damping (POD) controller. The concept of rotating coordinates was utilized in the paper. Reference [7] proposed a method to calculate latency based on comparison of clocks of GPS receiver and the time stamp of feedback signals. The latency data is then used to extrapolate trajectories of power systems, so that latency impacts on network can be compensated. Reference [8] provides extensive data regarding various communication delays associated with wide area technologies that can be considered in the analysis and simulation of WAMS. Various alternatives for communication systems for application in WAMS and latency profile for each type are presented. Reference [9] proposed a power system controller that can endure various delays associated with network, dropout of data packets and communication disorder of wide-area measurement systems [9]. The controller adopted a networked control system model, linear matrix inequality concepts and wide-area information as feedback signals to improve the power system performance. Reference [10] presented a latency based stability assessment of a power system equipped with a wide-area damping controller (WADC).

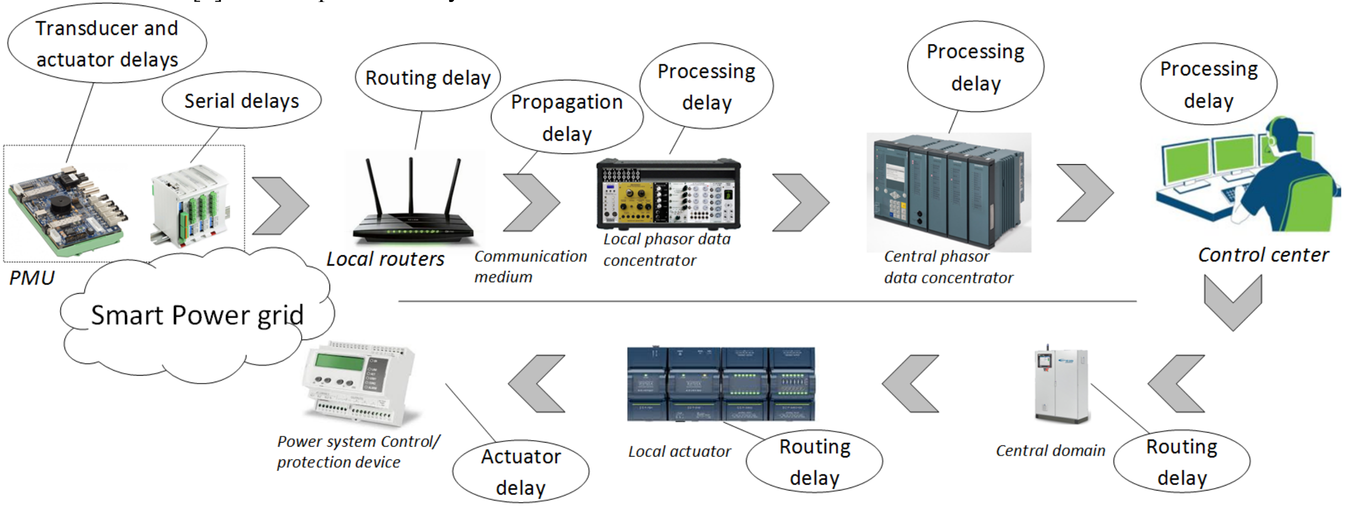

Fig. 1. Illustration of various delays associated with PMU based wide area systems

Lyapunov theory based time delay dependent criterion and model reduction technique were employed in this paper. The maximal delay within which the closed-loop power system can retain stability was termed as delay margin. The calculation of delay margin of a power system was illustrated based on reduced order model and linear matrix inequality (LMI) technique. A fuzzy logic based wide area damping controller (FLWADC) was proposed in [11] for compensating the continuous latency and to damp inter area oscillations effectively. The proposed controller was validated for its robustness against input signal variations through case studies.

Reference [12] proposed a wide area centralized damping controller to improve the stability of a power system under variable latency and packet dropout in the communication network. Reference [13] assessed the quality of service of communication infrastructure implemented in smart grid environment for load frequency control application. To reduce the mean square error of states variable estimation of the power system under topological changes, a decentralized controller and linear matrix inequality-based linear quadratic regulator were proposed. Reference [14] proposed a modified extended Kalman filter (MEKF) to compensate for the network latency synchrophasor assisted wide area monitoring and control systems.

V. IMPACT OF LATENCY ON WIDE AREA CONTROL TECHNIQUES

When decoupled power flow principles are applied to large scale power grids, the voltage magnitude and reactive power flow can be related as follows.

$$\begin{bmatrix} \Delta Q_c(t) \\ \Delta Q_u(t) \end{bmatrix} = -\begin{bmatrix} B_{cc} & B_{cu} \\ B_{uc} & B_{uu} \end{bmatrix} \begin{bmatrix} \Delta |V_c(t)| \\ \Delta |V_u(t)| \end{bmatrix} \quad (1)$$

In (1), the subscripts ‘t’ stands for wide area protection time instant, ‘u’ for voltage-uncontrolled busses, and ‘c’ for voltage-controlled buses (with the help of FACTS devices or similar devices [1]). The voltage of uncontrolled bus at upcoming time step can be formulated from the above expression as,

$$\left(\Delta |V_u(t+1)|\right) = -(B_{uu})^{-1}\left(\left(B_{uc}\left(\Delta |V_c|(t+1)\right)\right) + \left(\Delta Q_u(t)\right)\right) \quad (2)$$

The voltage at uncontrolled bus are estimated through PMU measurements and that of controlled buses are collected from respective local controllers. For system stability, the voltage deviation of the uncontrolled bus $\Delta |V_u(t)|$ should be kept minimum. This can be ensured by optimizing the function

$$\min \left| -(B_{uu})^{-1}\left(\left(B_{uc}\left(\Delta |V_c|(t+1)\right)\right) + \left(\Delta Q_u(t)\right)\right)\right|$$

Subjected to

$$\begin{cases} |V|_c^{\min}(t+1) \le |V|_c(t+1) \le |V|_c^{\max}(t+1) \\ Q_c^{\min}(t+1) \le Q_c(t+1) \le Q_c^{\max}(t+1) \end{cases} \quad (3)$$

The online optimization system presented by equation (3) need to be solved with minimum time as possible for maintaining stability. Usually for attaining the same, optimality is compromised. Many algorithms are being reported in the literature to achieve this goal. One of the approaches that received unique attention is interior point algorithm (IPA). Many researches have shown that IPA algorithm could provide the solutions of convex programming problems much better simplex method. IPA reaches the optimal solution by traversing the interior of the feasible region through iterations, which is in contradiction to simplex methods [35]. Another approach received many research attention is genetic algorithm. Genetic algorithm is a heuristic approach in which set of possible solutions are generated in the form of random chromosomes and evaluated. With the aid of crossover and mutation, the best solutions are determined among different generations.

The optimization problem discussed above can be represented as follows when latency is present [1].

$$\left(\Delta |V_u(t+1)|\right) = -(B_{uu})^{-1}\left(\left(B_{uc}\left(\Delta |V_c|(t+1)\right)\right) + \left(\Delta Q_u(t-\tau_d)\right)\right)$$

$$\min \left| -(B_{uu})^{-1}\left(\left(B_{uc}\left(\Delta |V_c|(t+1)\right)\right) + \left(\Delta Q_u(t-\tau_d)\right)\right)\right|$$

Subjected to

$$\begin{cases} |V|_c^{\min}(t+1) \le |V|_c(t+1) \le |V|_c^{\max}(t+1) \\ Q_c^{\min}(t+1) \le Q_c(t+1) \le Q_c^{\max}(t+1) \end{cases} \quad (4)$$

The above expression illustrates the impact of latency on voltage estimation and voltage control. Hence the latency should be as minimum as possible to maintain stable operation of the power grid. A feasible method to reduce time delay is to find an optimized route for the signals to travel from transmitter to receiver.

VI. OPTIMIZED ROUTING ESTIMATION

One of the major research challenges in latency analysis is to find shortest route between PMU and control center (where PDC is deployed). Optimized routing estimation is achieved by combining router processing delays and data propagation delays. By employing Dijkstra’s algorithm, optimized channeling period from each PMU to the control center is estimated. E.W. Dijkstra in 1959 developed Dijkstra’s algorithm for estimating the optimal travelling distance between any two nodes in a grid [10]. For the purpose of optimized routing estimation problem, the length can be replaced by time delay between two nodes in a network. Recent years have witnessed wide adoption of this method in various network routing protocols.

Sending time delay (Tsend) defined in optimized route estimate is the time span of sending the data from the sensor device to the control center. This time span comprises of individual router processing delays and the propagation delay between the routers. Similarly, the new data propagation delay as follows:

$$T^{i}_{l_j new} = \begin{cases} T^{i}_{l_j}, i = 1 \\ T^{i}_{l_j} + T_{router}, i = 2, 3 \ldots N_{l_j} \end{cases} \tag{5}$$

Where, $T^{i}_{l_j new}$ is the combined propagation time of the ith link in lj. 'l' stands for the shortest communication time link between PMUs and PDC. Nlj is the total number of links and 'Trouter' stands for the data processing time in a router. Hence the total sending time can be represented as,

$$T_{send} = \max_{l_1, l_2 \ldots l_n \in l} \left\{ \sum_{i=1}^{N_{l_1}} T^{i}_{l_1 new}, \sum_{i=1}^{N_{l_2}} T^{i}_{l_2 new} \cdots \sum_{i=1}^{N_{l_n}} T^{i}_{l_n new} \right\} \tag{6}$$

The Dijkstra's algorithm for finding shortest communication link can be designed as given in Fig. 2.

VII. RECENT TRENDS ON PERFORMANCE EVALUATION OF LATENCY ON WIDE AREA CONTROL

Reference [1] addressed impact of time delay in wide area monitoring and control on power system stability under contingencies. Wide area control was achieved with the help of flexible AC transmission system by controlling through wide area controller. The whole study was conducted on a testbed developed within RTDS with software in loop (SIL). The performance of wide area controller was assessed based on voltage profile index and voltage settling time. It was shown that an error of 0.078% occurred to overall power grid voltage profile index under a delay of 0.2 second. The same increased to 0.23% when the delay increased to 0.5second. While voltage settling time has shown an increase of 60% under the delay of 0.2 second. The same witnessed an increase of 340% under a time delay of 0.5 second.

Impact of latency on wide area damping controllers employed in large power grids for preventing small signal oscillations is studied in reference [15]. The case studies conducted on power system model depicts that a latency of 1 second resulted in oscillating response of power system stabilized with a peak overshoot of about 75%. A robust type-2 Fuzzy controller was proposed to condense the impact of latency. Impact of latency on power damping controller was studied in reference [16]. Power flow oscillation are reported in tie-line when damping controllers are operated under measurement latency. A method of adjusting the position of rotating vector used for phasor extraction is proposed to tackle the issue of latency. Reference [4] analyzed the impact of measurement latency on wide area control actions in a power grid. The latency was modelled as stochastic process and the impact was studied based on damping ratio on inter-area mode. The case studies demonstrated that damping ratio has sharp descent with time delay.

Reference [17] proposed adaptive quality of service scheme (AQoS) and adaptive guaranteed time slot (AGTS) for preventing excessive delays of critical data. Based on probabilistic operating conditions of wide area measurement systems, guaranteed time slots are modified by AQoS. The case studies presented demonstrated that nearly 50% reduction in average end to end time delay.

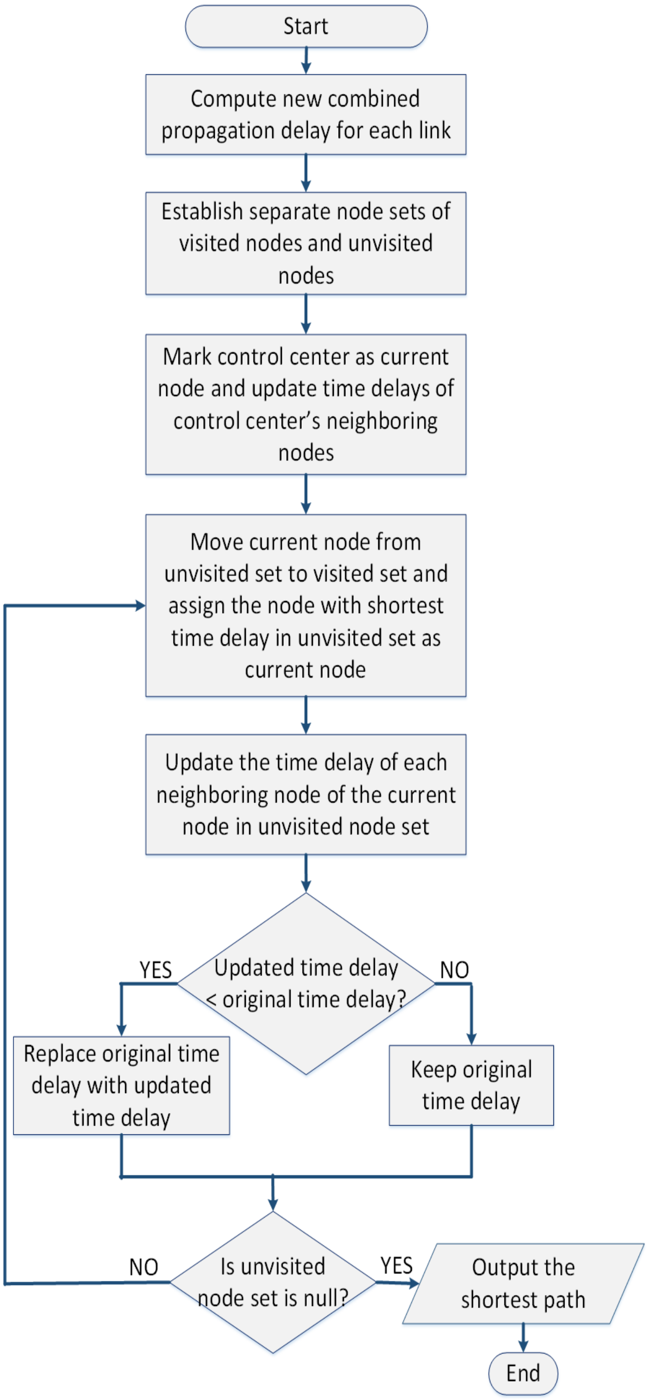

Fig. 2. Flowchart for optimized route estimation

Impact of communication latency on power system state estimation is discussed in reference [18]. A delay aware synchrophasor recovery and prediction framework is proposed to address the problem. The recovery and prediction framework are based on iteration using existing incomplete synchrophasor data. A more detailed comparative study of recent trends in aforementioned area is given in Table 1.

TABLE 1: RECENT RESEARCH STUDIES ON IMPACT OF LATENCY OVER WIDE AREA TECHNOLOGIES

Sl.	Reference No.	Wide area technology adopted in the research	Latency Considered	Performance Analysis Considered in the research	Methodology proposed in the research to overcome latency issue
1	[1]	Wide area controlled FACTS	0.2s to 0.5s	Performance of FACTS to maintain voltage stability under contingencies	--
2	[4]	Wide area control for inter-area mode damping	0.1s to 0.5s	Damping ratio of inter area mode oscillation	--
3	[15]	Wide area damping controller	1s	Dynamics of tie-line power flow	Fuzzy Type-2 Controller
4	[16]	Wide-area phasor power oscillation damping controller	1s	Damping of power through TCSC	Continuous compensation for time-varying delay
5	[17]	Wireless sensor networks	0.42	Delay critical application	Adaptive QoS scheme (AQoS) and adaptive guaranteed time slot (AGTS) allocation
6	[18]	Wide area PMUs	0.05s to 0.1s	Real time state estimation	Synchrophasor recovery and prediction framework
7	[19]	Wide area damping controller	0.2s	Variable loop gain controller to ensure stability	Excessive Regeneration Detector (ERD)
8	[20]	Wide area PMUs	30ms to 60ms	Voltage magnitude and angle measurements	Shortest path routing
9	[21]	Wide area damping controller	0.1s	Frequency and voltage angle deviation	Time-delayed Control (TDC)
10	[22]	Wide-Area Power System Stabilizers	Up to 1s	Damping factor, frequency deviation	--
11	[23]	Wide area damping controller	Up to 0.2s	Oscillations in active power	Expectation model based method

VIII. CONCLUSION

This paper investigates recent trends in latency analysis and its impact on wide area technologies of a smart power grid. Various researches have highlighted that latency study is essential for effective wide area schemes under contingencies. Interdependence of smart grid technologies with power flow control and PMU communication constraints, challenges the performance of entire power grid. Many researches have demonstrated that the stability of power grid and quality of control actions can be degraded due to latency.

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