Send Orders for Reprints to reprints@benthamscience.ae

 The Open Electrical & Electronic Engineering Journal, 2014, *8*, 544-551

Transmitting Systems Dynamics in SCADA using Uneven Sampling/ Cubic Spline Interpolation based Data Compression

Sun Qiangqiang*, Qiu Huijun and Cai Meng

Shenzhen Power Supply Co., LTD, Information Department. Shenzhen, Guangdong, 518200, China

Abstract: Grasping power system dynamic information is helpful for dispatcher in the control center to take correct control action in time under emergency condition. Traditionally, Supervisory Control and Data Acquisition (SCADA) cannot transmit power system dynamics information since it updates system information once every several seconds. Based on the development of substation automation system, a data compression based approach is proposed in this paper to transmit power system dynamics information in existing SCADA. An uneven sampling is utilized to extract the feature points that determine the profile of system dynamics. Thereafter, these feature points contain dynamic information is transmitted from Remote Terminal Units to the control center. The system dynamics can thus be reconstructed with cubic spline interpolation. Numerical simulation on a 36 nodes system suggests that the system dynamics could be transmitted with high fidelity in existing SCADA using the proposed approach. Moreover, the proposed approach can be implemented in SCADA with limited software update.

Keywords: SCADA, data compression, substation automation.

1. INTRODUCTION

Since New York 1965 blackout, Supervisory Control and Data Acquisition (SCADA) have gotten extensive application in power systems. It facilitates dispatchers in control centers to monitor system state and take control action with system information updated in real time. Nevertheless, since the system information is restated once every several seconds, it cannot capture system dynamics. Therefore, low frequency oscillation can only be analyzed offline [1]. Furthermore, when a disturbance occurs, the dispatchers in the control center cannot determine whether the system is losing or regaining stability in time, this seriously impedes operators to take corrective and remedial control actions under emergency condition.

The technology of synchronized phasor measurements has provided an ideal system to monitor and control power systems, in particular during conditions of stress [2]. Based on phasors collected from Phasor Measurement Units (PMUs) in real time at 50 or 100Hz, it is feasible now for Wide Area Measurement System (WAMS) to implement fast and reliable state estimation [3, 4], evaluate stability margins [5], and take preventive and remedial control actions [6, 7].

WAMS has demanding requirement on communication systems. When several optical fibers fail, the communication load might not be redirected to the survived optical fibers. Therefore, WAMS might not be as reliable as expected when the failures of communication systems burst with extreme events present, such as ice storm and wild fire. Since SCADA has much lower demand upon communication system than WAMS, it is highly preferred to facilitate the existing SCADA with the capability to transmit system dynamics as an alternation to WAMS. When WAMS fails, dispatchers in control center can still notice dynamics easily and take action in time, although with a delay of a few seconds.

Polynomial fitting and even sampling based data compression is proposed in [8,9] to transmit power system dynamics in existing SCADA. However, performance of these approaches relies on the update interval of SCADA. An uneven sampling / spline interpolation based data compression is proposed in the article. The paper is organized as follows. State of the art of SCADA is given in Section 2. Uneven sampling / cubic spline interpolation is developed in Section 3. Performance of the proposed approach is simulated and analyzed in Section 4. Section 5 concludes the paper.

2. EVOLUTION OF SCADA

A SCADA is usually composed of three parts, on site Remote Terminal Units (RTUs), communication networks, and master station in the control center. The RTUs distributed in power plants and substations collect system information in real time. Data from RTUs are sent to the control center via communication networks, such as power line carrier, switched lines, microwave, and optic fiber.

Communication system determines performance of SCADA at large. Since large number of substations and power plants should be monitored in a SCADA, it can only update system information once every several seconds. It is too slow to catch system dynamics during disturbances. With extensive application of optic fiber during past years, most SCADA have migrated to communicate over broadband

1874-1290/14 2014 Bentham Open

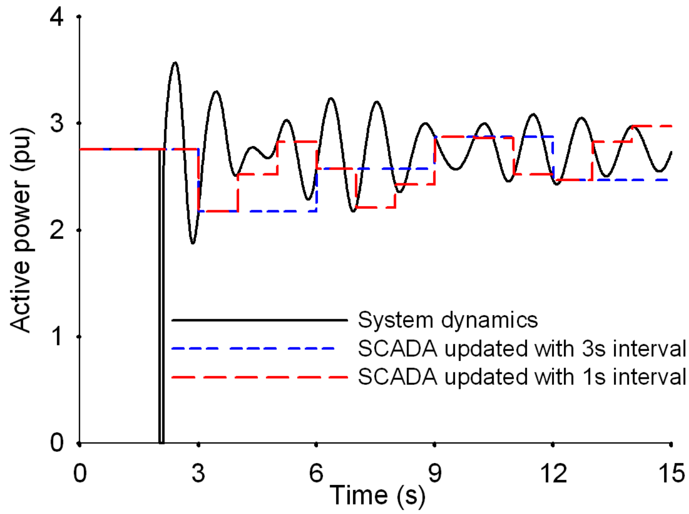

Fig. (1). Comparison of system disturbance and data observed in SCADA.

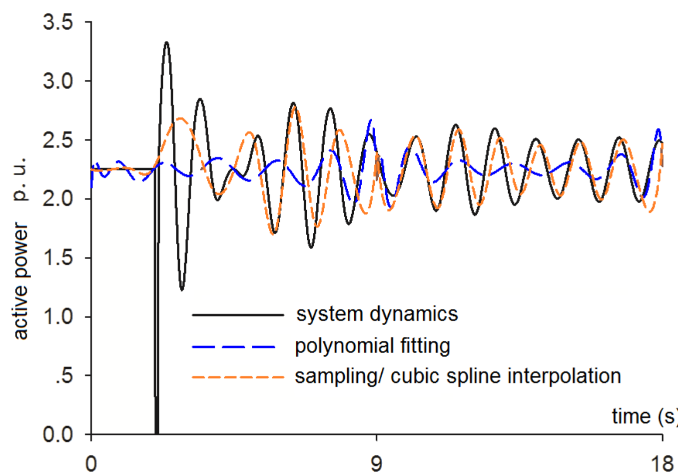

Fig. (2). Original & reconstructed dynamics with polynomial fitting & sampling/interpolation.

Wide Area Network [10-12]. The update interval reduced from tens to several seconds. H, it can be observed from Fig. (**1**) that it does not help much in grasping system dynamics even though the update interval is reduced from 3 second to 1 second.

With the advances in information technology, there are chances to transmit power system dynamics in existing SCADA. Firstly, with the emergence of substation automation system using Intelligent Electronic Devices (IEDs) [13], it is technically feasible for RTUs to collect phasors from Electronic Instrument Transducers (EITs) as protection system [14, 15] and digital fault recorders [16]. Thereafter, the RMS values of voltage, current, as well as power at any instant can be calculated at ease. The precision of SCADA is determined by EITs. Secondly, communication capability of SCADA has been improved substantially [10-12]. Therefore, if the data to be transmitted are confined within an acceptable constraint, system dynamics could be transmitted in existing SCADA. A possible approach to attain this is data compression.

Polynomial curve fitting based data compression is proposed in [8]. The system dynamics information is extracted by polynomial fitting and the polynomial coefficients are transmitted to reconstruct the dynamics in the control center. Sampling/interpolation based data compression is developed in [9]. Measurements are evenly sampled and the samples are transmitted to reconstruct the dynamics using cubic spline interpolation in the control center. Numerical simulation indicates 15 degrees polynomial fitting & 15 points sampling/ cubic spline interpolation can reconstruct system dynamics with high precision of a short update interval, such as 3 seconds [17, 18]. However, performance of these approaches deteriorates when update interval prolong to 9 seconds as showed in Fig. (**2**).

The shortcomings of existing approaches are as follows.

- Polynomial fitting based approach is sensitive to the variation of update interval. Its performance deteriorates notably with prolonged update interval. On one hand, low degree polynomial fitting cannot

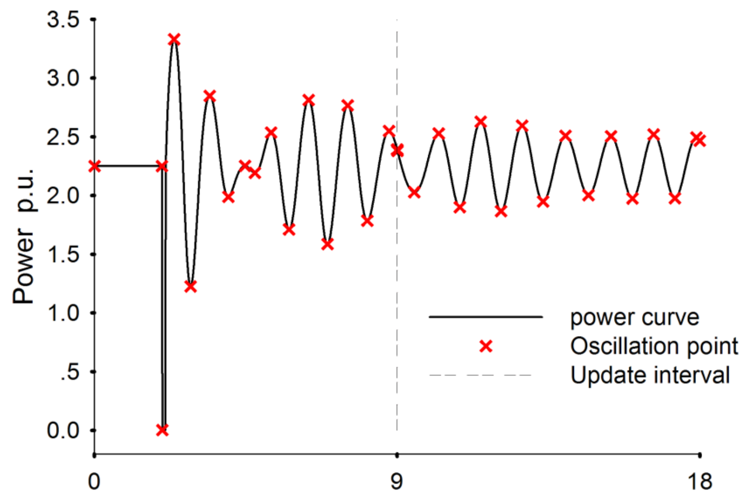

Fig. (3). Disturbance curve and extracted feature points.

reconstruct the dynamics with long interval precisely. On the other hand, higher degree polynomial fitting related Runger phenomena could introduce notable oscillatory artifacts at the end points [17, 18]. Moreover, it is not appropriate to solve high degree polynomial fitting related inverse matrix in latency critical application.

- The sampling/cubic spline interpolation based approach is sensitive to timing of inception of disturbance. Once the abrupt variation is not sampled, precision of the reconstructed data deteriorates notably.

3. UNEVEN SAMPLING BASED DATA COMPRESSION

- uneven sampling

According to the aforementioned analysis, the key to transmit dynamics in existing SCADA lies in precise capturing of data that can present characteristics of dynamics. Since the feature points that determine the profile of a curve are not necessarily evenly distributed, it is not strange that the even sampling cannot capture these feature points. On the contrary, uneven sampling that capturing feature point could be a promising way.

Since post-fault dynamics are characterized by oscillation, the peak and valley of oscillation could determine the profile of dynamics at large. The other feature points include start, end point of an interval, and inception of disturbance. It can be observed from Fig. (**3**) that once all these points (peak & valley, start & end, inception of disturbance) are captured, the dynamics reconstructed with the simplest linear interpolation could achieve a satisfying precision.

Rules to capture feature points are concluded as follows.

Rule 1: Only the data with big enough fluctuation require the sampling/spline interpolation to transmit dynamics. The data with accumulated variation less than 5% p.u. during an update interval could be transmitted as a constant data as in traditional SCADA.

Rule 2: The start and end point should be added to sampled point.

Rule 3: The peak and valley points should be added to sampled points.

Rule 4: The inception of a disturbance is usually accompanied by steep variation in measured voltage and current. The inception point could identify with the abrupt variation of the slope. Measurement variation (slope) at each instant i ($\Delta_i = x_{i+1} - x_i$) is calculated. Thereafter, the point whose summation of previous 3 consecutive point smaller than summation of following 3 consecutive point $((\Delta_{i-2} + \Delta_{i-1} + \Delta_i) < (\Delta_{i+1} + \Delta_{i+2} + \Delta_{i+3})/10)$ is selected as feature point (inception of disturbance) and added to sampled points.

- cubic spline interpolation based reconstruction

There are a number of ways, such as linear interpolation, spline interpolation, and spline interpolation, can be used to reconstruct the dynamics with sampled feature points. Linear interpolation is the simplest. However, it could yield substantial error for nonlinear curve fitting.

Unlike linear interpolation, cubic spline interpolation uses low-degree polynomials in each interval, and chooses the polynomial pieces such that they fit smoothly together. The reconstructed data are continuous and derivable. The spline enjoys a high degree of popularity for its simplicity [17]. It could approximate nonlinear curve with higher precision as compared to linear interpolation. Cubic Spline interpolation is utilized to reconstruct system dynamics in the article.

- data compression index

Three indexes are used to evaluate performance of data compression based on data sampling and interpolation.

1(Mean-squared error, e_{MSE}

$$e_{MSE} = \left(\sqrt{\sum_{i=1}^{N} \left[d(i) - f(i) \right]^2} \Big/ \sqrt{\sum_{i=1}^{N} \left[d(i) \right]^2} \right) \times 100\% \quad (1)$$

where d denotes original data, f denotes reconstructed data.

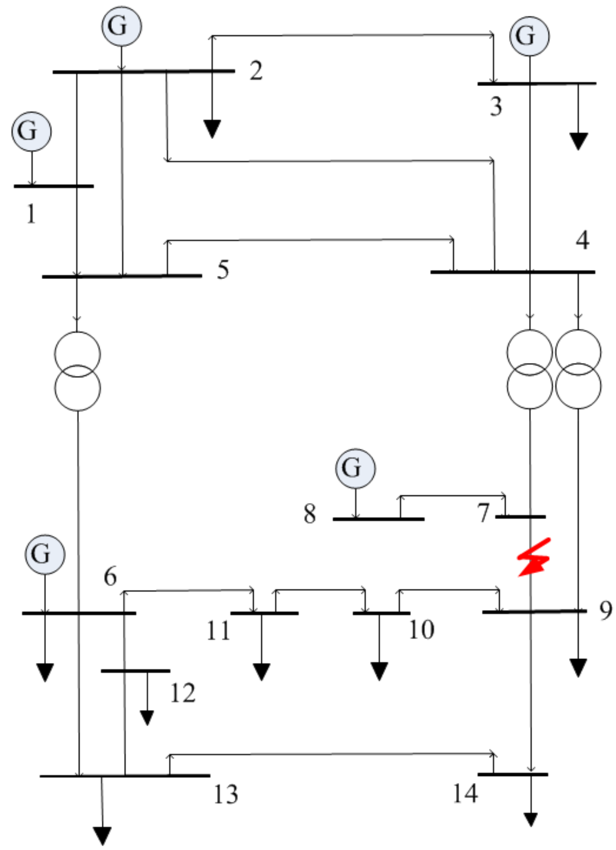

Fig. (4). 36 nodes system.

2) Signal to Noise Ratio, r_{SNR}

$$r_{SNR} = 10 \times \log\left(\sum_{i=1}^{N}\left[d(i)\right]^2\right) - 10 \times \log\left(\sum_{i=1}^{N}\left[d(i) - f(i)\right]^2\right) \tag{2}$$

SNR is the ratio of system dynamics curve to the approximation error. The unit is dB. The higher the SNR, the better the reconstructed data.

4. NUMERICAL SIMULATION

- Experimental configurations

A 36 nodes system with 33 busbars, 8 generators, and 10 transformers as plotted in Fig. (**4**) is used for numerical simulation. The Power System Analysis Software package is utilized to implement transient stability analysis for 18 seconds. A three-phase short circuit lasts for 0.1 seconds is configured at 2 second in the mid of transmission line between busbar 30 and 31. All branch power flow and busbar voltage is sent to an external file every 10 milliseconds. Based on the assumption that the SCADA updates with an interval of 9 seconds, the data of 18 seconds can be divided for 2 intervals, i.e., 900 data in each interval.

- Simulation Analysis

Uneven sampling/cubic spline interpolation are utilized to compress all branch power and busbar voltage. The detailed performance of the phasors undergo largest disturbance, including power flow from busbar 3 to 4 and voltage of busbar 9, are plotted as Fig. (**5**), Fig. (**6**), and Fig. (**7**). The blue crosses denote captured feature points and the red dashed lines denote the reconstructed dynamics. It can be observed that either busbar voltage or branch power vary drastically with short circuit present. When the fault is cleared, they fluctuate to regain stable.

It can be noted from Fig. (**5**) and Fig. (**6**) that the performance of reconstructed branch power and reactive power is perfect. Since all feature points have been precisely captured, there seems no observable error between active and reactive power and the reconstructed dynamics.

It can be noted from Fig. (**7**) that there is a defect in the reconstructed voltage dynamics. The reconstructed data during the first oscillation deviate notably from system dynamics. The deviation might be brought about by the turning point between the third and the fourth feature points. Since there is notable variation in the slope before and after the turning point, the turning point can also be identified as feature point using rule 4 developed in Section 3.1. Since performance of reconstructed data in the other part is satisfying and the envelop of curve profile could be reconstructed with high fidelity at large, it is also acceptable without any modification.

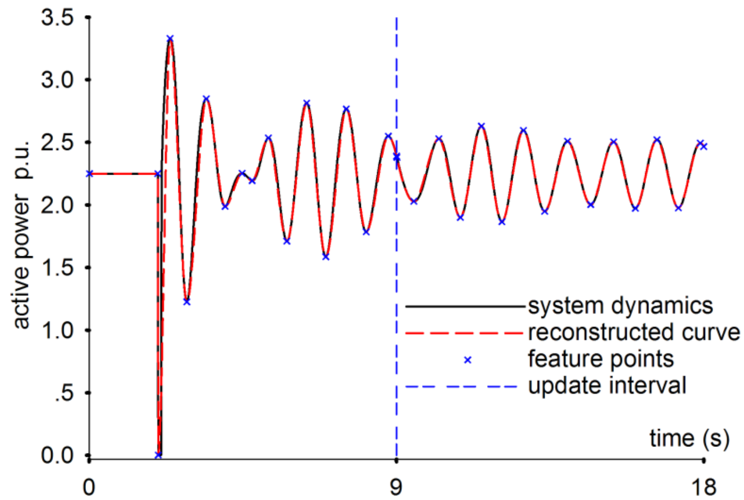

Fig. (5). uneven sampling/cubic spline interpolation & branch active power.

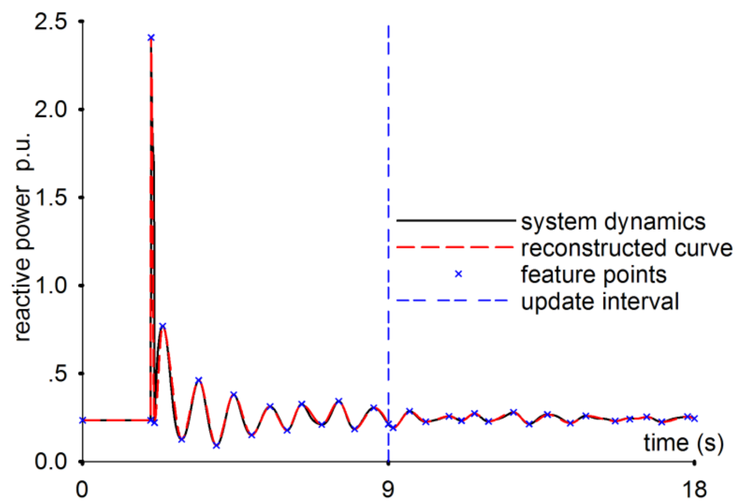

Fig. (6). Uneven sampling/cubic spline interpolation & branch reactive power.

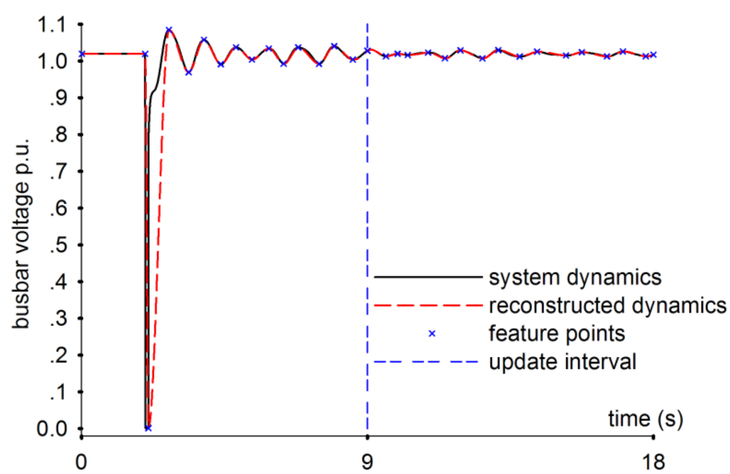

Fig. (7). uneven sampling/cubic spline interpolation & busbar voltage.

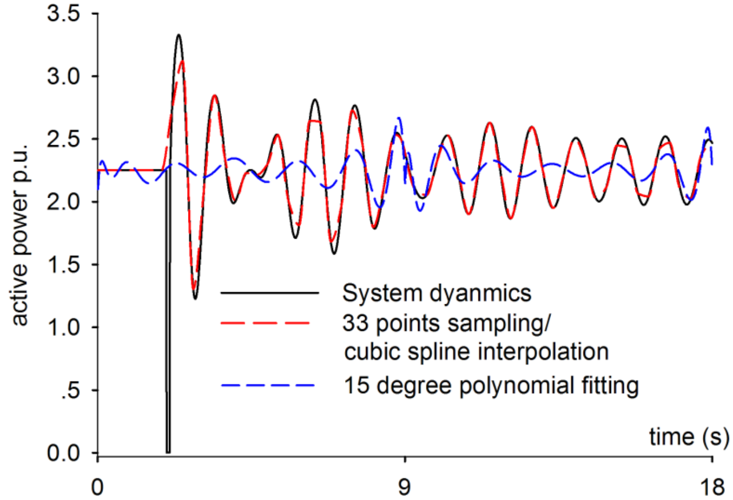

Fig. (8). Even sampling/cubic spline interpolation and polynomial fitting & branch power.

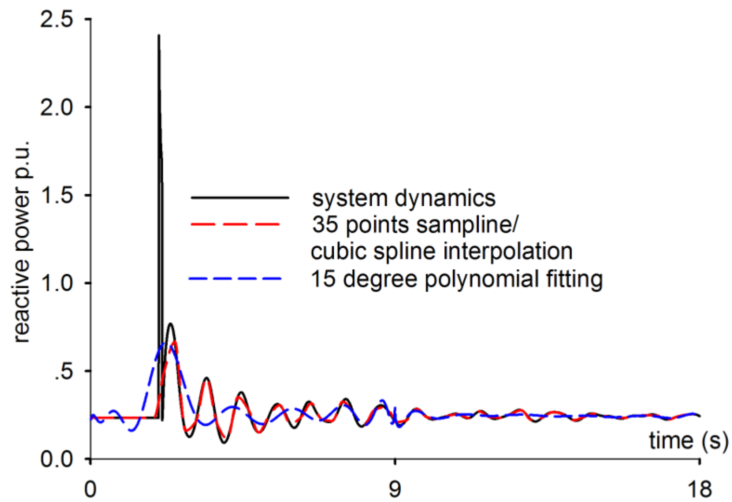

Fig. (9). Even sampling/cubic spline interpolation and polynomial fitting & reactive power.

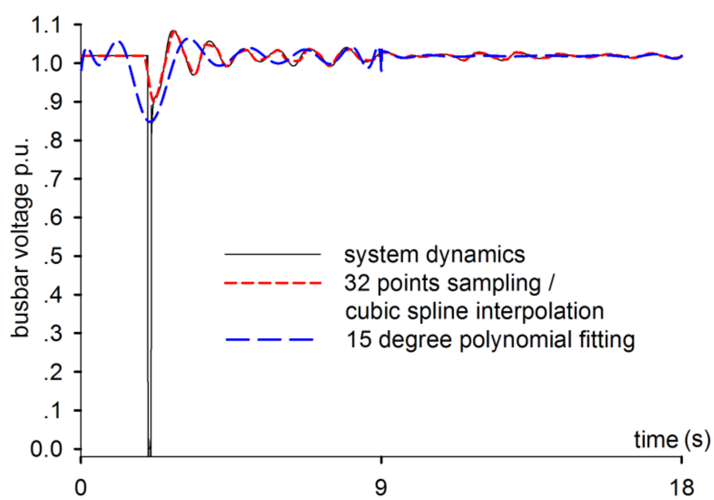

Fig. (10). Even sampling/cubic spline interpolation and polynomial fitting & voltage.

Table 1. Performance of compressed/reconstructed system dynamics.

Approach		Active Power	Reactive Power	Busbar Voltage
uneven sampling / cubic spline interpolation	e_{MSE}	0.0520	0.1913	0.1066
	r_{SNR}	59.1309	33.0816	44.7819
Even sampling/cubic spline interpolation	e_{MSE}	0.0863	0.2350	0.0695
	r_{SNR}	49.0012	19.0894	53.3388
Polynomial fitting	e_{MSE}	0.1433	0.4015	0.0692
	r_{SNR}	38.8530	18.2496	53.4237

Since there are 33, 35, and 32 feature points in power, reactive power, and voltage dynamics of uneven sampling/spline interpolation based approach, the 33, 35, and 32 points even sampling/cubic spline interpolation are simulated for comparative study. Since the high degree polynomial could either be unsolvable or induce Runger phenomena, only 15 degree polynomial fitting are simulated for comparative study. The system dyanmics and reconstructed data are plotted in Fig. (**8**), Fig. (**9**), and Fig. (**10**). The mean square error and signal to noise ratio of all these approaches are calculated and listed in Table **1**.

It can be observed from Table **1** that uneven sampling/cubic spline interpolation based approach outperform the other two approaches in both mean square error & signal to noise ratio for power & reactive power without turning point, which is consistent with the comparison of Fig. (**5**), Fig. (**6**) and Fig. (**8**), Fig. (**9**).

Since a turning point is not captured, the mean square error & signal to noise ratio of reconstructed busbar voltage is not so good as that of the other two approaches as shown in Fig. (**10**). However, its overall visual performance is better for the reason as follows.

- The magnitude of first fluctuation is precisely captured in the proposed approach as shown in Fig. (**7**). On the contrary, the magnitudes of first fluctuation reconstructed with polynomial fitting and even sampling/cubic spline interpolation are misleading and dispatcher in control center cannot determine severity of the fault at all.
- The error induced by the turning point of the first fluctuation does not affect the precision of the following fluctuation. There is no detectable visual difference in the following fluctuation as showed in Fig. (**7**).

CONCLUSION

An uneven sampling/cubic spline interpolation based data compression technique is developed in this article to transmit power system dynamics by existing SCADA. Numerical simulation result suggests that for a SCADA update interval of 9 seconds, about 30 points sampling/interpolation can provide with precise system dynamics. The proposed approach can be implemented on existing substation automation system with software update while no hardware investment is required. Moreover, it can transmit system dynamics without demanding request on communication systems. The computation cost of RTU is trivial and the computation cost of SCADA server is controllable.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

The authors would like to thank the funding support of the GuangDong electric power corporation and Shen Zhen Electric Power Corporation for providing the resources and facilities.

REFERENCES

[1] X. Xie, J. Xiao, C. Lu, Y. Han. “Wide-area stability control for damping interarea oscillations of interconnected power systems”, IEE Proc. Generation, Transmission & Distribution, vol.153, no.5, Sep. 2006, pp: 507 – 514.

[2] M. Begovic, D. Nivose, Daniel Karlsson, Charlie Henville, Gary Michel. “Wide-area protection and emergency control”, Proc. of the IEEE, 2005, vol.93, no5, pp: 876-891.

[3] A. G. Phadke, J.S. Thorp, K. J. Karimi. “State estimation with phasor measurements”. IEEE Transactions on Power Systems, vol.1, no.1, Feb. 1986, pp: 233 – 238.

[4] Liang Zhao, A. Abur. “Multi area state estimation using synchronized phasor measurements”, IEEE Transactions on Power Syst., vol.20, no.2, May 2005, pp: 611–617.

[5] Weiqing Jiang, V. Vittal, G.T. Heydt. “A distributed state estimator utilizing synchronized phasor measurements”, IEEE Transactions Power Systems, vol. 22, no.2, May 2007, pp: 563 – 571.

[6] C.-W. Liu, J.S. Thorp. “Application of synchronized phasor measurements to real-time transient stability prediction”, IEE Proc. Generation, Transmission & Distribution, vol.142, no. 4, July 1995, pp: 355 – 360.

[7] H. Liu, Y. Sun, L. Cheng, P. Wang, F. Xiao. “Online short-term reliability evaluation using a fast sorting technique”, IET Proc. Generation, Transmission & Distribution, vol.2, no.1, Jan. 2008, pp: 139-141.

[8] Duan Xianzhong, Su Sheng, Mei Nian. “Transmitting Electric Power System Dynamics using Polynomial Fitting”, Science in China Series. E, vol.52, no.2, Feb. 2009, pp: 1-7.

[9] Su Sheng, Hong Feng, Shi Dongyuan, Duan Xianzhong. Transmitting power system dynamics in existing SCADA Using sampling/interpolation based data compression. 2010 IEEE Industry Applications Society Annual Meeting, pp. 1-7.

[10] Bin Qiu, Hoay Beng Gooi, Yilu Liu, Eng Kiat Chan. "Internet based SCADA display system", IEEE Computer Applications in Power, vol. 15, no. 1, pp. 14-19, 2002.

[11] Robert J. Landman, Belvin Louie. "Fiber optic SCADA system safeguards underground distribution network". IEEE Computer Applications in Power, vol. 5, no. 2, pp. 39-44, 1992.

[12] Shyh-Jier Huang, Chih-Chieh Lin. "Application of ATM-based network for an integrated distribution SCADA-GIS system". IEEE Transactions on Power Syst., vol. 17, no. 1, pp: 80-86, 2002.

[13] Su Sheng, K.K. Li, W.L. Chan, Zeng Xiangjun, Duan Xianzhong. "Agent based Self Healing Protection System", IEEE Transactions on Power Delivery, vol. 21, no 2, Apr. 2006, pp: 610–618.

[14] A. Apostolov. "Distributed protection, control and recording in IEC 61850 based substation automation systems", IEE International Conference on Developments in Power System Protection, Apr. 2004, pp: 647–651.

[15] R. Cagil, Ozansoy, Aladin Zayegh, Akhtar Kalam. "The Real-Time Publisher/Subscriber Communication Model for Distributed Substation Systems", IEEE Transactions on Power Delivery, vol. 22, no. 3, July 2007, pp: 1411-1423.

[16] A. Apostolov. "Disturbance Recording in IEC 61850 Substation Automation Systems", IEEE PES TD Meeting, May, 2006, pp: 921–926.

[17] S.A. Dyer, J.S. Dyer. "Cubic spline interpolation. 1", IEEE Instrumentation & Measurement Magazine, Mar 2001, Vol. 4, No.1, pp: 44-46.

[18] Richard L. Burden, J. Douglas Faires. Numerical analysis. Thomson Learning Inc. 2001

Received: October 16, 2014 Revised: December 23, 2014 Accepted: December 31, 2014