A Wide Area Synchronized Frequency Measurement System using Network Time Protocol

Kunal A. Salunkhe and A. M. Kulkarni

***Abstract*—A power system is continually subject to disturbances in the form of load and generation changes, faults and equipment trippings. These disturbances give rise to electro-mechanical transients like inter-machine oscillations and system frequency changes. They can be observed in the frequency measurements at various locations in the grid. To study these transients, a wide area frequency measurement setup is implemented. The measurements are done at six different locations in the NEW grid and time synchronized using the internet based Network Time Protocol (NTP). The measured frequency is time stamped and send via the internet to a server in IITB. This system is low-cost, easy to implement and is a viable tool for tracking and studying system transients.**

***Index Terms*—Wide Area Frequency Measurement, Power System Oscillations, Network Time Protocol (NTP).**

I. Introduction

A power system is continually subjected to disturbances in the form of sudden load and generation changes or faults and tripping of equipment. The disturbances give rise to changes in the system frequency and/or oscillations in the relative frequency, which are observable at various locations in the grid. These are due to the electro-mechanical dynamics associated with synchronous machines which are interconnected by an ac network. The oscillation frequencies of these "swing modes" typically lie between 0.2-2 Hz. A centre-of-inertia mode which corresponds to overall (i.e. non-relative) frequency movement is observable throughout the grid whenever there is a load-generation imbalance.

Monitoring of these system wide transients is possible by the use of synchronized phasor measurements using a Wide Area Measurement System (WAMS) [1]. A typical WAMS consists of Phasor Measurement Units (PMU) which are time-synchronized using a Global Positioning System (GPS). A PMU is able to measure relative phase angles between the voltages at different buses. The requirement of measuring phase angular difference with a good accuracy (a $50\mu s$ error in synchronization roughly causes a 1^o error in the phase angle), makes GPS the most appropriate option for synchronization when phase angle has to be accurately measured.

It can be recognized that:

1) Voltage phase angles at the high voltage buses are of most significance for studying bulk power system phenomena. Therefore PMUs are generally placed in high voltage sub-stations.
2) The measurements from a WAMS can be used for emergency control and protection. These applications involve "closing the loop" and operation in a small time scale (0-1 s). Such schemes require a very robust design, along with a need for a very reliable communication system and hardware working in real time. However, at present, WAMS is used mainly for system monitoring and analysis. Its use for emergency control is being contemplated, but a significant application has not been reported so far.
3) The electro-mechanical phenomena are also observable in the measured frequency at a bus. Therefore if monitoring of system behaviour following disturbances is the main objective, then it can be carried out by synchronized measurement of frequency as well.
4) Frequency measured at a low voltage level (e.g the laboratory power supply at IIT Bombay), will practically mirror the frequency of the high voltage bus from which it is obtained. (The voltages at a lower level will, however, be prone to more distortion.)
5) Electromechanical phenomena have relatively low bandwidth, e.g. swings occur roughly between 0.2-1 Hz. High *synchronization* accuracy of the order of 1 μs is not required to get accurate frequency measurements. Moreover, synchronization errors, say, of the order of 10 ms, will not cause a significant error in the capture of the relatively slow electromechanical phenomena. Therefore, a synchronization source with less accuracy than GPS is also acceptable for these measurements. Network Time Protocol (NTP) [2] is an Internet based synchronization tool, which typically gives a synchronization accuracy of 1 - 15 ms, which can serve our purpose.
6) Frequency measurement is relatively easy. The simplest scheme measures the time between zero crossings of a sinusoidal voltage using a high resolution counter. This may be averaged over 2-3 cycles in order to reduce noise or distortion.
7) It is reasonable to communicate one measurement every 20 ms to a central server. The bandwidth requirements are therefore minimal. If monitoring and analysis are the main functions of such a system, then communication delays are not a critical concern, and the internet can be used for communicating the measured frequency.

Motivated by these observations, a NTP based Wide Area Frequency Measurement System (WAFMeS) has been implemented in the synchronous (North-East-West) NEW grid of India with measurements located at 6 distant locations. Low cost Frequency Measurement Devices (FMDs) are connected to the 230 V distribution supply at these locations. A similar

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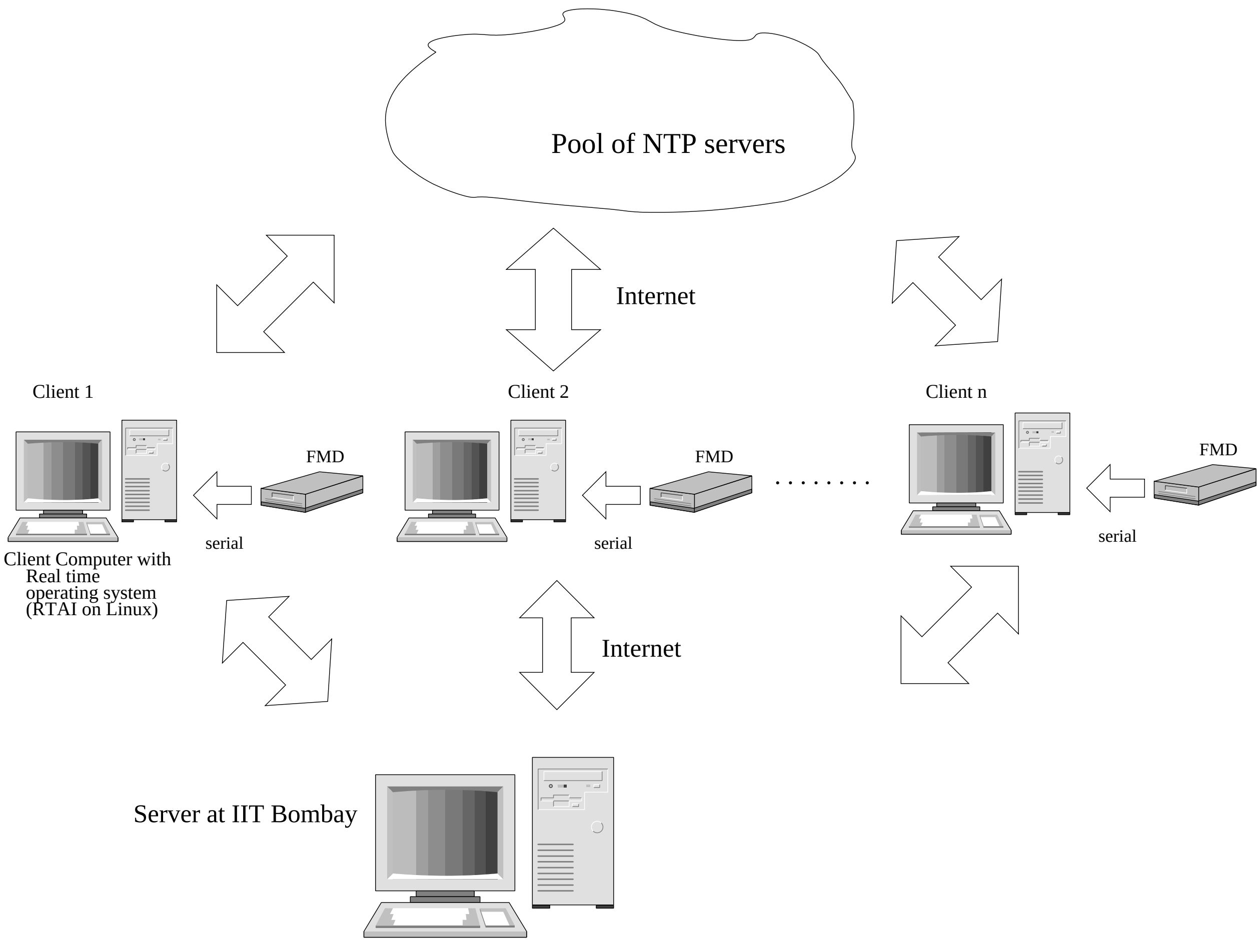

Fig. 1. Architecture of WAFMeS

large scale wide frequency measurement scheme known as Frequency Monitoring Network (FNET) is implemented at Virginia Polytechnic Institute and State University [3]. This uses GPS synchronization, although NTP was also considered for the same [4]. The use of NTP in our scheme makes it inexpensive and elegant, because the internet is used for both synchronization and data transfer. The system can be developed using open-source software and tools and is easy to deploy. The NTP synchronized measurements are sent via the internet to a server at IIT Bombay.

This paper describes the implementation of this WAFMeS project. Using the measurement obtained from this system, a few real-life power system disturbances in the NEW grid are analyzed.

II. Architecture of WAFMeS

The block diagram of the Architecture of WAFMeS is as shown in Fig. 1. It consists of following components.

- Frequency Measurement Devices (FMD)
- NTP synchronized client side computers with a Real Time Application Interface [5] on a Linux platform
- A server side computer at IIT Bombay with the Linux operating system.

A. Frequency Measurement Devices

A FMD consists of a MSP430 micro controller [6], a step down transformer, a RC filter and a Zero crossing Detector(ZCD). The circuit steps down the 230 V supply, passes it through a ZCD. The output of the ZCD is given to the MSP430, which calculates the count between the two positive zero crossings. The timer of MSP430 is configured in capture mode. A capture is a record of the timer count when a specific event occurs. The capture modules of the timers are tied to external pins of the MSP. The capture records the count in the timer when the pin in question makes a transition. The output of the ZCD is connected to this pin. The difference between counts of the two consecutive transitions from low to high is sent to computer serial port. Fig. 2 shows the block diagram of a FMD.

B. Client side computer

There are four tasks to be performed by the client side computer

1) Keep the computer synchronized with the others using NTP
2) Capture the measurement being sent at the serial port of the computer (real-time task).

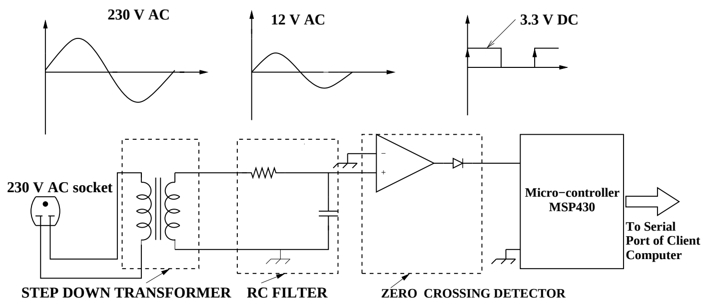

Fig. 2. Block diagram of Frequency Measurement Device

3) Time Stamp it using a NTP synchronized clock (real-time task)
4) Communicate the time-stamped measurement to the central IIT Bombay server.

The count obtained from the FMDs is transferred to the client computer. The client computer should take this data the moment it is on its serial port and get it time stamped at the same instant. The computer should accord a higher priority for reading and time stamping data. A tool like Real Time Application Interface (RTAI) satisfies this purpose.

1) RTAI: A real-time system can be defined as a system capable of guaranteeing timing requirements of the processes under its control. It must be fast and predictable. By fast we means that it has a low latency, i.e. it responds to external, asynchronous events in a short time. Lower the latency, better the system will respond to events which require immediate attention. By predictable we mean that it is able to determine completion time for the task with certainty. Linux is an open source operating system. However it does not guarantee response time for the processes. Real time applications require guaranteed response time for processes. Real time application interface (RTAI) is a patch on the Linux which makes Linux real time. RTAI allows running real time applications in Linux. This client side computer which does the reading and time stamping of data can also be used for other less resource demanding tasks like browsing the internet, office applications etc.

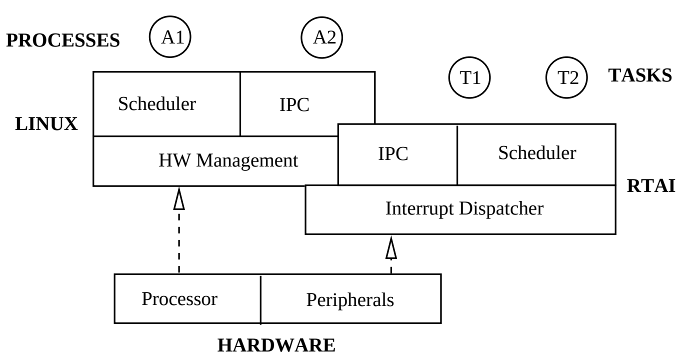

Fig. 3. Architecture of RTAI

Fig. 3 shows the basic architecture of RTAI [5]. The interrupts originate from processor and peripherals. Processor interrupts are still handled by a standard Linux kernel, but the interrupts originating from the peripherals (e.g. timer) are handled by RTAI's Interrupt Dispatcher. The scheduling units of RTAI are called as tasks. There is always at least one Task, namely the Linux kernel which is run as a low-priority task. When the real time tasks are added, the scheduler gives them priority over the standard Linux kernel Processes. RTAI forwards interrupts to the standard Linux kernel handler when a real-time task is not active. Fig. 3 also shows the inter process communication mechanisms and scheduler, which are implemented separately for Linux and for RTAI. There is a separate scheduler for Linux and RTAI.

2) Network Time Protocol: NTP [2] is used throughout the internet as a standard means of achieving and maintaining the synchronization of computers and network infrastructure. A NTP server is basically a device that receives precise time from an external hardware clock and provides a network with an accurate timing reference. Accurate time is maintained internally and passed to network time clients on demand. Any network device can contact a NTP server to request time and to synchronize its system clock. In this way networks of computers can synchronize time to an accurate reference. Fig. 4 shows NTP clock strata (clock sources) NTP is essentially a hierarchical protocol. It has a series of levels or 'stratums'. Each stratum is synchronized to the level above in the hierarchy. At the top level, a stratum 1 server obtains accurate time from an external hardware clock. It is the most accurate time reference, since it synchronizes directly to a external time reference. Lower stratum time servers synchronize to the stratum above and provide consistently less accuracy. There are a number of external reference clock time sources available, the most common being GPS. Each GPS satellite has an on board atomic clock that can provide extremely accurate timing information. National radio time and frequency broadcasts are also a good source of accurate

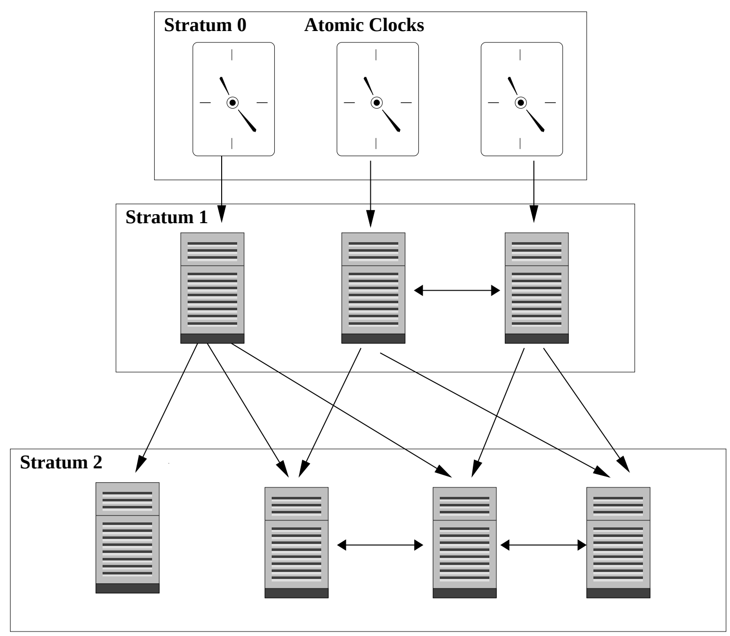

Fig. 4. Hierarchy showing various levels of NTP clock sources

time. Many time servers also contain precise crystal oscillators that can be used as backup timing references. A backup timing reference provides extended holdover while external references are unavailable.

Modern operating systems provide integrated NTP client software, which allow the system time synchronization to a time server. Linux and Unix operating systems have a freely available GNU public licence NTP client available. Microsoft incorporates the 'Windows Time' service in the latest Windows operating systems, which has NTP functionality. NTP client software uses User Datagram Protocol (UDP) to exchange packets between the client and the NTP server. NTP uses port 123 for UDP protocol. The time of this computer is synchronized with the pool of NTP servers using the NTPD client program. The client computer in IIT Bombay is synchronized to the NTP server in IIT Bombay (`ntp.iitb.ac.in`), while the other clients in the WAFMeS are synchronized to a pool of servers in India (`in.pool.ntp.org`).

3) Communication to the Central Server: The time stamped data is given to a client program which sends it to a server in IITB using the UDP [7]. UDP provides communication without the overhead of handshaking signals. An alternative protocol, Transport Control Protocol (TCP) is a connection oriented protocol, thus requires handshaking to be set up for end-to-end communication. TCP requires three packets to set up a socket connection, before any user data can be sent.

In our application, a small amount of data is to be sent continuously from various locations to the central server. Since no emergency control actions using this data are being contemplated, an occasional lost packet is not of much consequence. TCP favors the reliability of a single data packet over connection reliability. UDP favors overall reliability of the connection, keeping data flowing at the cost of occasional lost packets. Therefore, UDP is a better option for this application.

The data sent contains the location name, time stamp and the measured frequency. The UDP header is of 8 bytes. The IPv4 header adds about 20 bytes. The time stamp and frequency require about 40 bytes. Thus the total size of the packet is about 68 bytes. This data is conveyed to the central server every 20 ms. Therefore the required bandwidth is very modest (less than 4 KB/s).

C. Tasks of the Server-side computer

The central server computer is located at IITB. The measured frequency from all the clients is sent to this server using UDP protocol as described above. The data is stored in a database which is analyzed for any kind of disturbances in the grid. The tasks to be carried out on the server side are:

1) Insert data received from clients into a database which is arranged according to time stamp and location.
2) Make the data available to the web server. Real time visual display of the data which can be accessible via the internet.
3) Flag any transients in the frequency by appropriate event triggered storage.

Some of these functions are under development.

III. Analysis of Recorded Disturbances

In this section, few disturbances which were captured by the WAFMeS are described. Fig. 5 Shows locations of FMDs. They are placed in Ahmedabad, Pune, Sangli, Surat, Mumbai and Bhubaneswar. The recordings were not available from all locations for all the disturbances which are described here.

Fig. 5. Locations of Frequency Measurement devices

A. Generator Trippings on 8th Oct 2009

On 8/10/2009 two major generating stations Anpara and Obra of about 1800 MW capacity tripped. The time resolution of the SCADA data available with NRLDC is insufficient to see the sequence and a detailed view of the frequency transients [8]. However, since we measure frequency at an interval of 20 ms, we have obtained a better resolution. Fig. 6 shows plot of frequency plots at Mumbai, Sangli and Surat. An expanded view is shown in Fig. 7 which captures the nuances of the transient :

1) A generation trip first took place at 10:29:15 hrs while another one took place at 10:29:30 hrs.
2) While the frequency decay is a predictable consequence of the generator trippings, the disturbance also triggered a small and fast-decaying oscillation swing. This is seen superimposed on the general decline in frequencies - see Fig. 7. The oscillation, with a period greater than 2.5 s, probably corresponds to an inter-area swing mode in which the western machines swing together. Note that the frequencies were observed at Sangli, Surat and Mumbai, i.e., locations in the Western Region. These locations are far away from the tripped generators (which are in UP). Therefore it is not surprising that the frequencies "move together" at these locations, with practically no relative motion among themselves.
3) A set of under-frequency relays in the system are set to operate at 49.2 Hz if df/dt exceeds 0.2 Hz/s and

provides a load relief of about 1500 MW [9]. The sudden reduction in the rate of frequency decay at 49.2 Hz indicates that some load relief was obtained due to the operation of these relays.

4) The operation of load tripping relays at 49.2 was inadequate to arrest the decline in frequencies although the rate of decay is reduced. Therefore the frequencies declined to 48.8 Hz at which point additional load relief was obtained. This indicates the operation of another set of under-frequency relays. There is indeed such a set of relays which are set at 48.8 Hz and give a load relief of 750 MW [9]. Consequent to these actions, the frequency of the system settled to an acceptable value

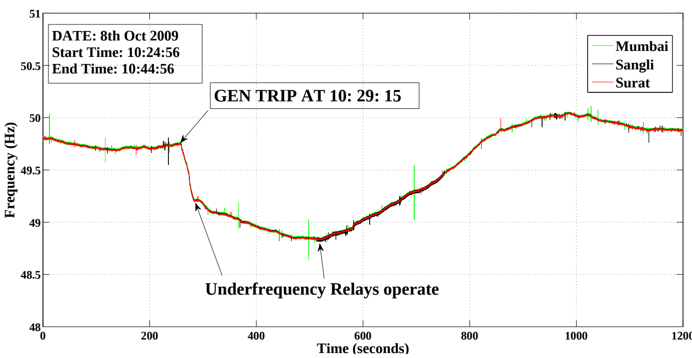

Fig. 6. Response to generator trippings at Anpara and Obra

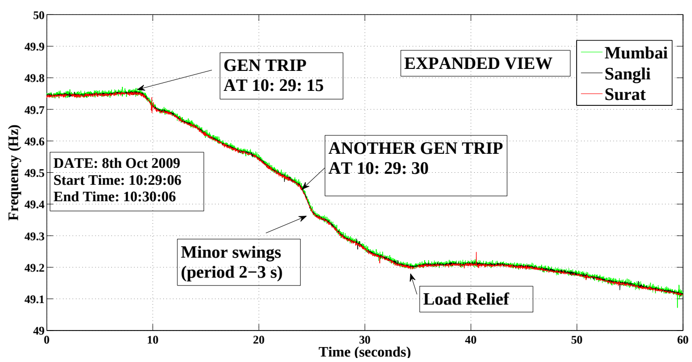

Fig. 7. Response to generator trippings at Anpara and Obra [Expanded]

B. Operation of Busbar Protection at Padgha

On 1/11/2009 Busbar protection operated on the Padgha bus which is near Mumbai. This is a major bus, with several lines incident on it. This event occurred at about 22:36:45 hrs. Just after the operation of Busbar protection the lines connected to this bus were tripped [10].

Fig. 8 shows the plots of the measured frequencies during this time which indicate the following:

1) Three major stages of the disturbance were observed a few seconds apart from each other. The frequency transients in Mumbai maximum due to their close proximity to this bus.
2) Local mode swings of about 1 Hz are seen initially. These involve relative frequency oscillations in which frequencies at Mumbai and Sangli swing together against those at Ahmedabad and Surat - see the expanded view in Fig. 9.

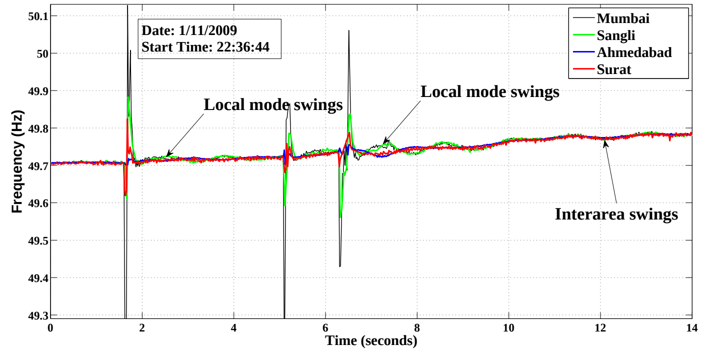

Fig. 8. Response to operation of Busbar protection at Padgha

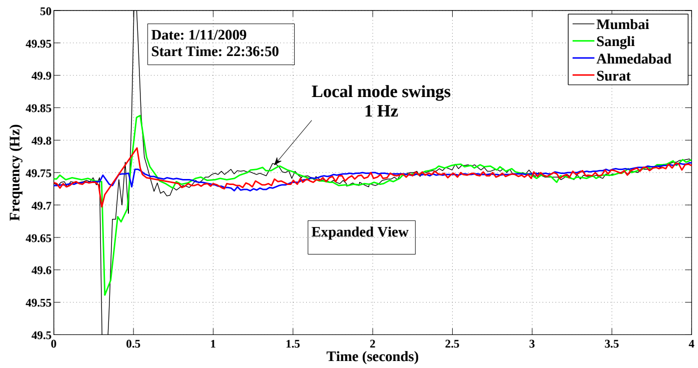

Fig. 9. Response to operation of Busbar protection at Padgha [Expanded]

3) The local mode (i.e., local to the Western Region of the NEW grid) oscillations decay quickly, revealing a low frequency inter-area mode, wherein the frequencies at these locations swing together at less than 0.5 Hz (presumably against the frequencies of the rest of the system.)
4) There is little movement in the overall (non-relative) frequency since there is no significant change in the load or generation.

C. Bus fault on 14th Oct 2009

On 14th Oct 2009, there was a R-ph to ground fault on the Mundra-Sami -II line [11]. Evidence of this fault was seen at 17:37:55 hrs in the frequency plots - Fig. 10. The following can be observed:

1) During the fault the frequency near Ahmedabad increases
2) After clearing of the fault, a local mode swing of about 1 Hz is seen in the Ahmedabad frequency.
3) After the decay of this mode, all the three frequencies swing together, at around 0.33 Hz.

D. Other Minor Disturbances

Fig. 11 shows the plot of frequencies subsequent to what appears to be a sudden load trip. A significant swing is also

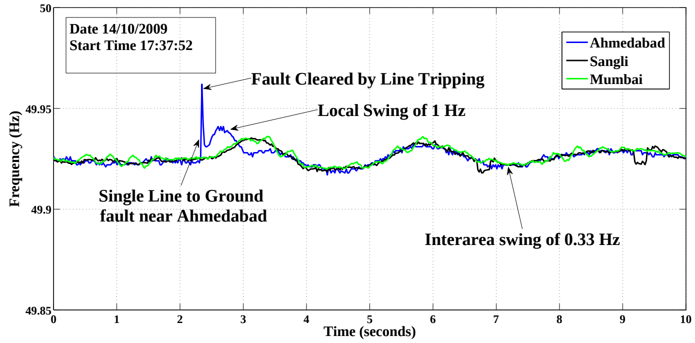

Fig. 10. Response to R-phase to ground fault on the Mundra-Sami -II

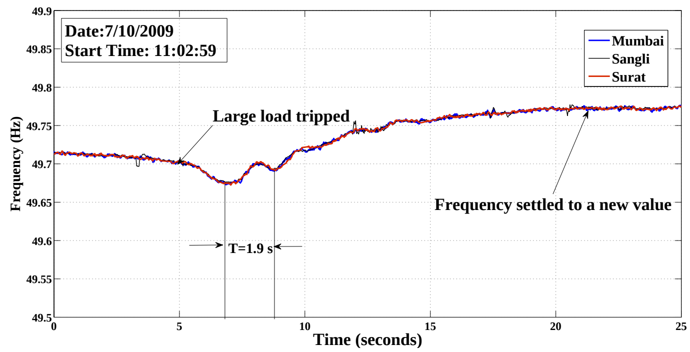

Fig. 11. Plot of frequencies due to a sudden load Trip

observed. This could not be co-related to available disturbance reports. However a well damped swing is also evident in addition to the overall frequency change. Fig. 12 shows the

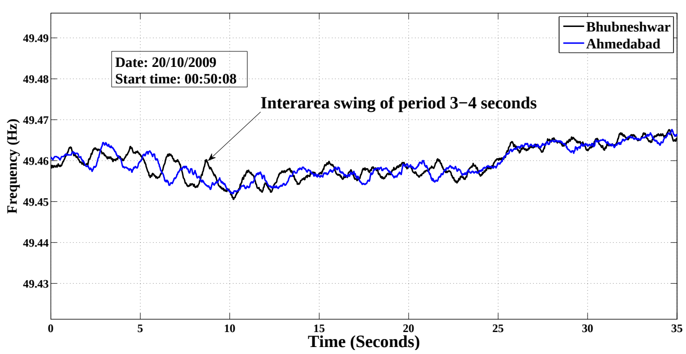

Fig. 12. Plot of frequencies showing inter-area oscillations

plot of frequencies of Bhubaneshwar and Ahmedabad which was recorded on 20/10/2009 at 00:50:08 hrs. A very low amplitude and low frequency (< 0.33 Hz), but persistent swing is observed. It can be seen that the frequencies are swinging against each other.

IV. Conclusion

The implementation of a wide area synchronized frequency monitoring system based on Network Time Protocol synchronization is described in this paper. While the synchronization accuracy of a GPS based system is much better than that obtained by using NTP, the accuracy is adequate to capture slow transients which are observable in the frequency. The system can therefore monitor electro-mechanical transients which are excited due to disturbances in the grid. A few disturbances which took place in the NEW grid and were captured by this system. These were analyzed to bring out the utility of this system as a good monitoring and post-disturbance analysis tool.

V. Acknowledgments

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