System Inertial Frequency Response Estimation and Impact of Renewable Resources in ERCOT Interconnection

Sandip Sharma, Shun-Hsien Huang and NDR Sarma

***Abstract*-- This paper presents observations and challenges related to integration of renewable resources with respect to frequency control with primary focus on Inertial Frequency Response in ERCOT Interconnection. Frequency Control, in general, can be categorized into Inertial, Primary and Secondary Frequency Responses based on the response time. In ERCOT Interconnection, currently, the primary and secondary frequency response can be achieved by employing adequate control settings and Ancillary Service procurement. The Inertial Frequency Response described in this paper refers to the total synchronous mass connected to the Grid which includes motor loads as well as synchronous generators. Maintaining minimum level of Inertial Frequency Response with unit commitments can be crucial to ensure reliable integration of renewable resources. A trend in decline of Inertial Frequency Response with respect to increasing renewable resources has been observed according to recorded frequency events in the past four years in ERCOT Interconnection. Since Inertial Frequency Response dictates the change in frequency due to supply demand mismatch, it is important to maintain adequate system inertia in real-time operations. Therefore, an on-line tool is developed for the purpose of providing an estimation of system wide Inertial Frequency Response to potentially assist System Operators to maintain adequate system inertia. The unit of the estimated Inertial Frequency Response is MW/0.1 Hz. This unit is recognized to be more practical for System Operator to evaluate the system condition.**

***Index Terms*- Frequency Response, Inertial Frequency Response, Balancing Authority, Intermittent Resources, Balancing Authority (BA).**

I. Introduction

Frequency response is defined as the automatic corrective response provided towards balancing demand and supply. Based on the different response time, Frequency Response can be classified into three different categories; Inertial Frequency Response, Primary Frequency Response and Secondary Frequency Response.

Inertial Frequency Response is inherent in the system due to rotating characteristic of typical Load (motor, pumps etc) and conventional generation (synchronous generators). The Inertial Frequency Response provides counter response within seconds to arrest the frequency deviation. Therefore, during low inertia period a lesser magnitude of imbalance can result in a larger deviation of frequency from nominal or scheduled frequency. In other words, less frequency deviation occurs at the same magnitude of imbalance when larger inertia is maintained in the system. Primary Frequency Response (PFR) can be defined as the instantaneous proportional increase or decrease in real power output provided by a Generation Resource in response to system frequency deviations. This response is in the direction that stabilizes frequency. Primary Frequency Response is attained due to Governor or Governor-like action to instantly act relative to the frequency deviation. The Primary Frequency Response is generally delivered completely within 12 seconds to 14 seconds. The Secondary Frequency Response is executed by Automatic Generation Controller (AGC) often referred to as Load Frequency Controller. The AGC system deploys regulating reserves to restore the frequency closer to scheduled frequency. Generally the AGC action can take anywhere from seconds to minutes. The Governor and AGC should work in tandem, after initial response from the governors (PFR), AGC should deploy regulating reserves so that frequency is recovered back to 60 HZ. [1-2]

As a Balancing Authority (BA), ERCOT has a primary role to continuously balance demand and supply to maintain scheduled frequency. Currently, ERCOT Interconnection is not synchronously connected with any of its neighboring Interconnections. The required Frequency Response has to come from the available resources within the Interconnection. Typically, smaller system inertia is observed during off-peak periods compared to peak periods because of less synchronously rotating mass online. The impact of higher penetration of renewable resources on frequency control can be extreme during light loads periods. In ERCOT Interconnection; frequency lower than 59.70 Hz will trigger under frequency relay and that would lead load resources to respond within 20 to 30 cycles [3]. Further frequency decay lower than 59.30 Hz would trigger the under frequency firm load shedding scheme. Therefore, it is important to maintain adequate Inertial Frequency Response in the Interconnection.

The condition can be more complicated for the system with high integration of renewable energy. Greater penetration of intermittent resources can potentially displace conventional generation from economic perspective, and the grid operators would face more challenges in real-time operations with the increased integration of intermittent renewable resources. The

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latest wind turbine technologies can provide no Inertial Frequency Response to the system compared to conventional synchronous generators because of decoupling through power electronic devices. In this situation, larger frequency deviation can also possibly occur during mid or peak period with large wind penetration in the system. Under the common practice, System Operator would review the system inertia performance to adjust the frequency control scheme on seasonal or annual bases. It is not common to monitor and maintain adequate system inertia in the real time operations when the system generation was mainly provided by synchronized generators in past. However, with the increasing wind penetration in the system that can potentially result in decline of Inertial Frequency Response, the system inertia information becomes more important for System Operator to maintain the system reliability. Therefore, it is recognized that, to have an on-line tool to provide system inertia information to the real time operations can be very valuable. D.P. Chassin et al. [4] developed computer models to compute the inertial constant. Inoue et al. [5] developed a procedure to estimate the power system inertia constant based on measured frequency transient. Considering the difference between ERCOT and other regions, particularly in the wind generation penetration level, an on-line tool is developed to perform the estimation of system Inertial Frequency Response (MW/0.1Hz) that is suitable for ERCOT Interconnection. This paper presents the details of the development of such a tool in ERCOT.

Following is the structure of this paper. Section II will introduce the basic concept of Inertial Frequency Response. Section III shows the ERCOT historical Inertial Frequency Responses and observations. Section IV discusses the development of an Inertial Frequency Response Estimator Tool and its performance. A Conclusion is presented in Section V.

II. Inertial Frequency Response

Inertial Frequency Response is defined as "The power delivered by the Interconnection in response to any change in frequency due to the rotating mass of machines synchronously connected to the Bulk Power System (BPS), including both load and generation" [6].

System frequency drops whenever there is shortage of generation to supply demand and frequency increases whenever there is excess of energy. Frequency at its nominal value reflects balance in supply and demand. Sudden loss of supply or demand will result in frequency deviation from the nominal frequency. The rate of change in frequency due to imbalance depends on the system inertia. System inertia is directly proportional to synchronously rotating mass in the system (includes synchronous generation and motor load). The general equation for calculating rate of change of frequency using system inertia constant (H) is illustrated in (1) [1] below:

$$\frac{df}{dt} = \frac{\Delta P}{2H} \times f_0 + \frac{D}{2H} \times \Delta f \qquad (1)$$

Assuming load dampening D to be zero, (1) results in a simplified equation as below:

$$\frac{df}{dt} = \frac{\Delta P}{2H} \times f_0 \qquad (2)$$

Where;

H: System Inertia Constant on system base (seconds)
D: Power system Load Dampening Value in PU/HZ
f_0 : Frequency at the time of disturbance (Hz)
$\frac{df}{dt}$: Rate of change of frequency (Hz/Sec)
ΔP = (PL-PG)/PG, Power change (per unit in system load base)
PL = Load prior to generation Loss in MW
PG = System Generation after Loss in MW
Δf = Change in frequency

A typical frequency response during unit trip is shown in Fig. 1. [6]. In normal conditions, system frequency is controlled to be close to nominal frequency, which is 60 Hz in the ERCOT Interconnection. A generation unit outage results in the shortage of generation to supply load which results in frequency drop. As frequency starts to decay, Inertial Frequency Response including some portion of the Primary Frequency Response (i.e. Governor Response) will try to arrest the frequency decay. Full Primary Frequency Response and Secondary Frequency Response control (i.e. AGC) will eventually restore the frequency back to nominal value. Point A in Fig. 1 represents the Interconnection frequency immediately before the disturbance; point 'C' represents the Interconnection frequency at its maximum deviation due to loss of rotating kinetic energy from the Interconnection and point 'B' represents the Interconnection frequency at the point immediately after the frequency stabilizes due to governor action before the contingent control area takes corrective action [7]. The contingent control area stated above refers to the ERCOT ISO in context of this paper. The Inertial Frequency Response is the frequency response between point A and C, which is mainly dependent on the on-line available synchronous mass. The focus of this paper is on this Inertial Frequency Response.

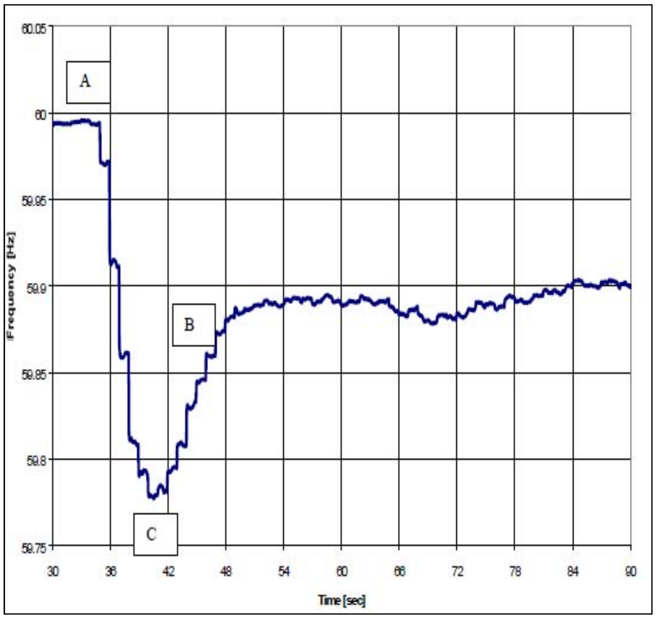

Fig. 1. Showing NERC defined A, C and B points

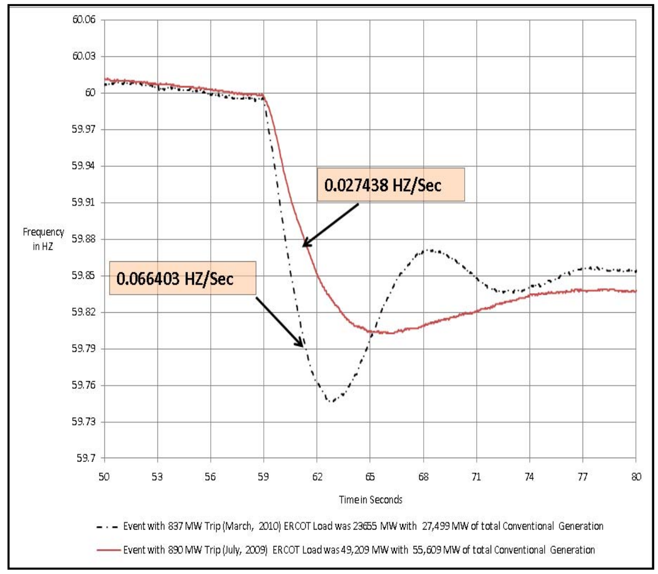

Fig.2. Depiction of Inertial Frequency Response

III. Inertial Frequency Response in ERCOT Interconnection

The impact of Inertial Frequency Response in ERCOT region shall be demonstrated with some case studies. Two recorded frequency disturbance events at high load and low load periods due to a generator trip are shown in Fig. 2 to demonstrate the impact of inertia on the frequency response and point 'C' discussed in the previous section. The frequency plots in Fig. 2 were recorded using a high speed frequency recorder, sampled at 8.33 milliseconds rate.

The solid line in Fig. 2 represents the frequency response for an event that occurred in July2009 due to the loss of a unit generating at 890 MW. Total system load was 49,209 MW with 675 MW wind generation in service. The dash line represents the frequency response for an event that occurred in March 2010 due to the loss of a unit generating at 837 MW. Total system load was 23,655 MW with 4,300 MW wind generation in service.

As indicated in Fig. 2, the $\frac{df}{dt}$ in Hz per seconds for the event in March 2010 was significantly higher than the event in July 2009. The higher value of $\frac{df}{dt}$ leads the system frequency to its nadir more quickly as compared to lower magnitude of $\frac{df}{dt}$. Two main reasons contribute to this significant Inertial Frequency Response difference between these two events. First, there were fewer generators online to supply the off-peak load. Second, higher wind generation in service did displace the conventional units and resulted in even less system inertia in the system.

A. Historical Inertial Frequency response review and observation

Fig. 3 shows the wind generation installation history in ERCOT Interconnection. ERCOT has experienced a significant increase in wind generation in 2008 and 2009 that resulted in almost 9,000 MW in the system by the end of 2009.

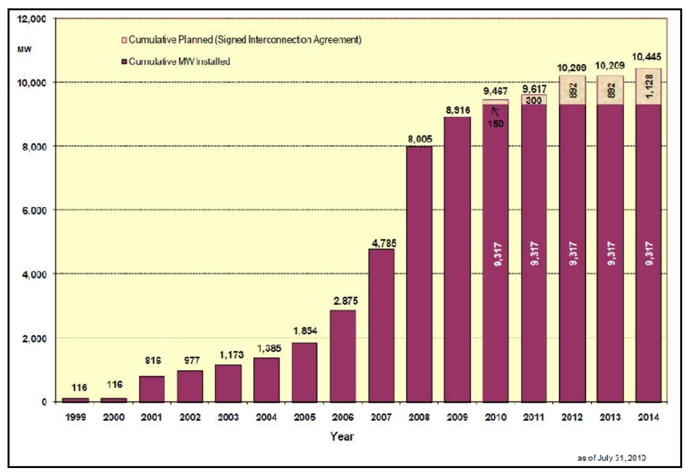

Fig.3. Wind Installations in ERCOT Interconnection.

To study the impact of Inertia in ERCOT Interconnection, approximately four years worth of recorded frequency disturbance events data for off-peak seasons beginning from 2006 were collected. Furthermore, in order to demonstrate the impact of system inertia on the frequency response during disturbances based on wind penetration, the data is categorized into two data sets.

The Data Set I consists of 43 events with average wind generation of 1157 MW and an average 557 MW size of unit trip. Data Set I consisted of frequency disturbance events during January to May and October to December of 2006 & 2007 as well as January to May of 2008. The Data Set II consists of 44 events with average wind generation of 2490 MW and an average 595 MW size of unit trip. Data Set II consists of frequency disturbance events during October to December of 2008, January to May and October to December of 2009 as well as January to April of 2010.

Frequency events during fall and the spring, when ERCOT's system demand is typically low, were analyzed to accurately quantify the effect of penetration of intermittent resources. The coefficient of correlation (R) between system load and Inertial Frequency Response was found to be closer to 1, which implies that the relationship between loss of MWs and change in frequency was highly correlated and varied linearly with system inertia. The correlation coefficient was closer to 90% for both the Data-sets shown in the Fig. 4 and Fig. 5.

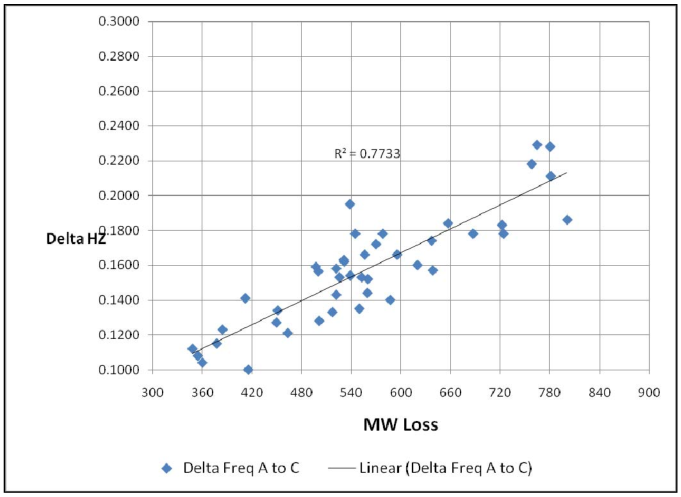

Fig. 4. Change in System Frequency and MW loss relationship for Data-Set I

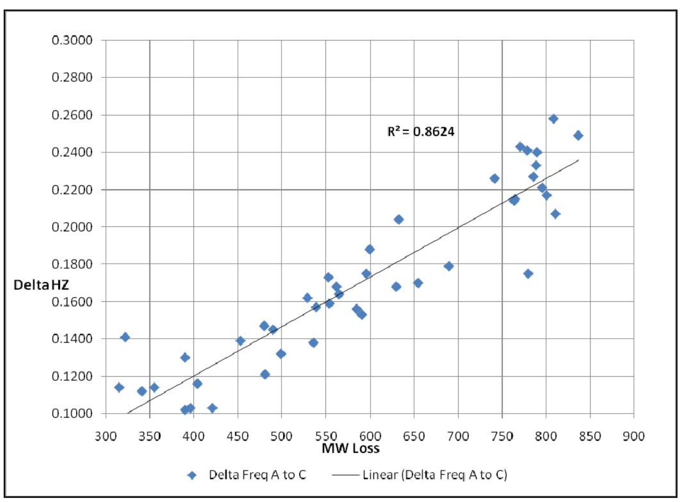

Fig. 5. Change in System Frequency and MW loss relationship for Data-Set II

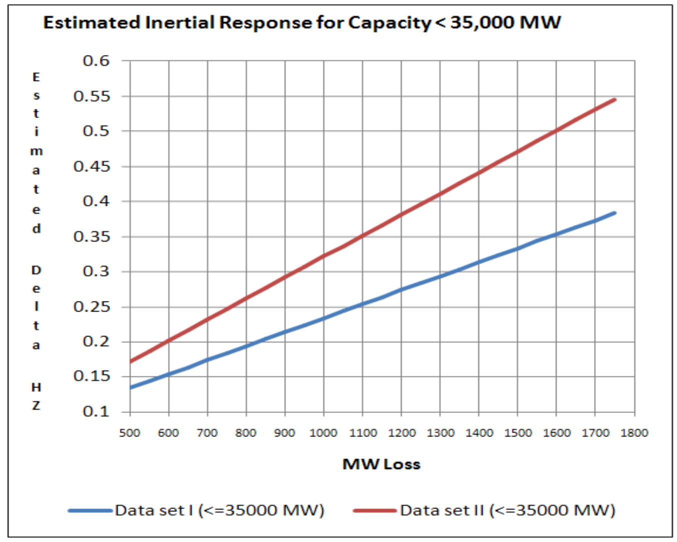

Fig. 6. Interpolated Inertial Frequency Response based on the relationship obtained from Data-Set I and Data-Set II

Using the linear relationship from Data-set I and Data-set II, linear equations were developed to estimate the corresponding change in frequency for different sizes of MW loss as shown in Fig. 6 below. The decline in inertia for Data-set II is clearly illustrated in Fig. 6 in comparison to Data-set I. For same level of MW loss the change in magnitude of the system frequency is greater in Data-set II thus illustrating the decline in inertia due to the increase of wind generation.

IV. Inertial Frequency Response Estimator Tool Development and Applications

A. IFRET development and performance

The motivation for this work is a result of awareness regarding increasing penetration of renewable resources and its impact on the frequency control in ERCOT Interconnection. As a member of ERCOT ISO's Performance Disturbance Compliance Working Group, ERCOT is primarily responsible for analyzing frequency disturbance events and measuring the primary frequency response. Furthermore, the Federal Energy Regulatory Commission's Order on May 13, 2009 to perform a study entitled, "Using Frequency Response to Assess Reliable Integration of Wind and Other Renewable Resources" [8] further emphasizes the concern of system inertia due to increasing penetration of renewable energy. The Study was to be performed by Lawrence Berkeley National Laboratory with three main goals stated as below:

- "*determine if frequency response is an appropriate metric to assess the reliability impacts of integrating renewable;*
- *use the resulting metric to assess the reliability impact of various levels of renewables on the grid; and*
- *Identify what further work and studies are necessary to quantify and mitigate any reliability impacts associated with the integration of renewable."*[8]

As illustrated in the Figures 4-6, the analysis of system frequency disturbances categorized based on system load in ERCOT interconnection resulted in highly correlated sets of linear equations for each category. Based on the system characteristic of ERCOT Interconnection and study of four years of frequency disturbance events triggered by instantaneous loss of generation beginning from 2006, the impact of the penetration of wind generation would be considered if total wind generation was greater than 10% of the system load. In other words, empirically, Inertia Frequency Response will be affected if wind generation is more than 10% of the system load.

The highly correlated nature of Inertial Frequency Response with system load, total on-line conventional generation capacity, spinning reserves and ratio of wind generation to total generation among others, are key inputs to develop the on-line Inertial Frequency Response Estimator Tool (IFRET) to estimate ERCOT system Inertial Frequency Response in terms of MW/0.1 Hz. To test the performance of the Inertial Frequency Response Estimator Tool (IFRET), 137 historical frequency disturbance events were used as an input to back-cast the Inertial Frequency Response.

The estimated Inertial Frequency Responses for the historical frequency disturbances were compared to the actual recorded data; and the average error for estimated Inertial Frequency Response was 5.92% with 3.5% standard deviation of error. The IFRET can with fair accuracy provide the Inertial Frequency Response in terms of MW/0.1 HZ to estimate the nadir for a predetermined supply/demand side contingency. The results of back-cast showed that within 2.5 times standard deviation the accuracy of estimated Inertial Frequency Response was estimated correctly 136 times out of 137 events used in the back-cast analysis. The results are very encouraging and very promising.

After obtaining these successful results based on an historical event, the Inertial Frequency Response Estimator was brought on-line in February 2010 to synch with real-time system data and to monitor and estimate the system inertia frequency response on an around the clock basis running every minute and recording its results. The Inertial Frequency Response estimated in real-time was compared with some of the captured actual events as shown in the Table I below.

The results from IFRET as observed have been noticeably more accurate for frequency disturbance events due to sudden loss of generation. The error has been higher for multiple generation resource outages as well as run-back type outages. A typical run-back outage is a rapid drop of a unit's output following a possible unit trip. It has also been observed during the analysis that Inertial Frequency Response is not the same across the frequency spectrum, especially when the pre-disturbance frequency (Point A) is higher than nominal frequency.

Table 1 Comparison of actual and IFRET estimated Inertial Frequency Response

DATE	TIME	MW loss	NERC A Point	NERC C Point	Actual IR	Estimated IR	Error
2/12/2010	10:21	640	59.99	59.849	454	437	3.72%
2/13/2010	1:22	612	59.986	59.824	378	360	4.71%
2/19/2010	16:34	757	60.028	59.802	335	347	3.60%
3/1/2010	18:26	651	60.002	59.84	402	386	3.94%
3/18/2010	16:04	561	59.987	59.819	334	331	0.88%
6/15/2010	16:54	527	59.980	59.875	502	503	0.22%
06/23/2010	15:19	1214	59.980	59.708	446	478	7.16 %
07/10/2010	04:10	627	59.998	59.837	389	404	3.72 %
07/12/2010	01:17	665	59.974	59.836	482	500	3.80 %
07/12/2010	01:54	696	59.970	59.823	474	506	6.86 %
07/27/2010	15:55	696	59.970	59.829	432	469	8.55 %
07/30/2010	14:31	747	59.984	59.834	498	502	0.88 %
09/07/2010	18:60	760	60.014	59.83	413	435	5.56%
09/22/2010	23:33	534	59.994	59.853	378.72	370.82	2.08%
11/10/2010	10:21	596	60.017	59.819	301.01	323.43	7.44%

B. Applications

The Inertial Frequency Response Estimator Tool gives the best approximation of MW and Frequency relationship in real-time, which is supported by the comparison with real-time disturbance as shown in the Table 1. From an application prospective, IFRET can be further used for several applications as discussed below:

1. As a situation awareness tool, IFRET provides the estimated Inertial Frequency Response, based on which the System Operator would have a better awareness of the potential frequency deviation especially due to loss of unit.

2. As a decision support tool, the System Operator can commit additional units to provide adequate Inertia support in normal operations based on IFRET result. System Operators, during a system outage condition, can also determine required response, such as the amount of additional units to be committed, based on IFRET result to recover from high frequency excursions, especially after the exhaustion of regulation services.

3. IFRET can also be used as an off-line study tool which could provide the estimated Inertial Frequency

Response for simulated cases. The Inertial Frequency Response estimated during the simulation will closely approximate the size of unit trip that will be required to trip the Load Resources controlled by under frequency relays (UFRs).

C. *Future Works*

Although this tool has provided some very promising results, efforts have to be under-taken continuously to improve the tool to provide more accurate results for certain conditions, such as high pre-disturbance system frequency condition. Besides, in order to be able to apply this tool in real time operations, the most important task is to determine the criteria and procedure for System Operators which will require more testing and studies.

IV. Conclusions

Estimating Inertial Frequency Response is particularly important for single area interconnection like ERCOT because all of the Frequency Response (Inertial and Primary) has to come from within the Interconnection. A decline of Inertial Frequency Response has been observed based on past four years of frequency event records due to increasing wind generation penetration that not only replaces the conventional units but also provides limited inertia response compared to conventional units. Therefore, it is also important for the Grid Operator to know relatively accurate amount of Inertial Frequency Response to commit resources to increase spinning mass. With the developed on-line Inertial Frequency Response Estimation Tool (IFRET), the Grid Operator will be able to know approximately the Frequency nadir or point 'C' for any pre-defined magnitude of supply/demand side loss.

VI. Acknowledgment

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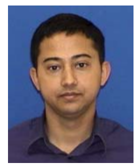
VIII. Biographies



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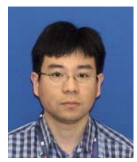

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