A Grid Transaction Index for a Power System with Availability Based Tariff

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Abstract- The Indian power system is a large network with an installed capacity of 140GW. It is unique in that it is the only network which allows the operating frequency to vary over a band from 0.5 Hz to -1.0 Hz from the nominal 50 Hz. The pricing for power purchased is a function of the operating frequency following a commercial mechanism called availability based tariff. Since the network consists of several states which are each commercially independent, an elaborate metering system is required at the interconnecting 400 kV grid. Since 2004, 461 special energy meters with 0.2 class accuracy have been erected across the network. They provide online information about key network parameters in addition providing the data for commercial transactions. We show several examples of the utility of this measuring system with regard to scheduling plants in the network, planning and control studies. We propose a grid transaction index that would help assess the state of the network and the performance of various state's dispatchers. All discussions are based on the data of Tamil Nadu Electricity Board (TNEB), a utility in the Southern region.

I. Introduction

The Indian power System is demarcated into five regions – Northern, Southern, Western, Eastern and North_Eastern. Of these the Western, Eastern, North Eastern and Northern regions are synchronously tied (since 2003) while Southern region is on HVDC links. Figure 1 shows the Indian power network with the major tie lines and installed capacity. Each region has four or five states and most of the state generation is owned by the State Electricity Boards (SEBs) which are vertically integrated utilities. Apart from this, each state is entitled to a fixed percentage of power from Central government owned generation. The growth of Independent Power Producers (IPP) is also significant in the past two decades.

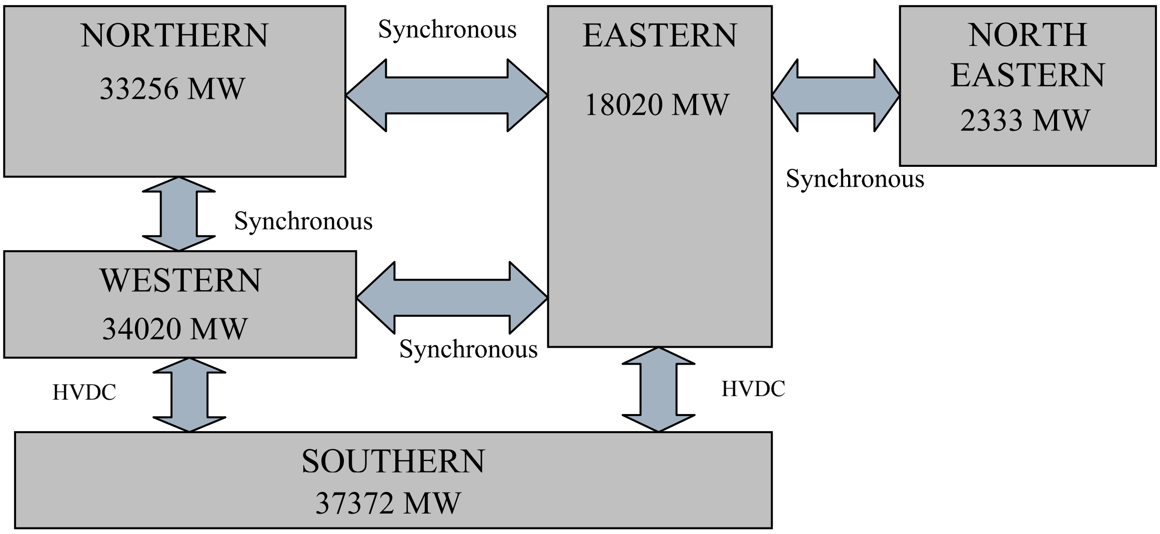

Figure 1. Schematic of the Indian power network.

Automatic generation control is not implemented for dispatch and most of the governors of the state generating stations are blocked. Instead generation is controlled once in 15 minutes in response to a price signal generated by the Availability based tariff (ABT) mechanism [1, 2]. This commercial mechanism was introduced in Indian Electricity Act 2003 by Central Electricity Regulatory Commission (CERC) and it defines the tariff structure for bulk power purchase by state utilities from Central Generating Stations(CGS). It was based on the recommendations of the study carried out by M/s ECC of USA sponsored by World

Bank/Asian Development Bank. The key concept of ABT was to ensure a frequency linked dispatch of generation.

ABT has a three part tariff-

1. Capacity charge – The capacity charge is meant to cover the fixed cost of the Central generating station. This is linked to plant availability and shared by states in proportion to their allocation from that generating station. This is independent of actual consumption.
2. Energy charge – The Energy charge is meant to cover the fuel cost of Central generating station and is in proportion to scheduled energy drawal. This is also independent of actual consumption.
3. Unscheduled Interchange rate (UI rate) – UI rates account for deviations in schedule and are priced as an inverse function of grid frequency. This means that every unit of energy, a Central station over generates or a utility overdraws will be priced as a function of grid frequency. The UI curve gives the UI rates as a function of grid frequency. The UI curve has been constantly revised since 2002. Figure 2 shows the current UI curve for the system.

The job of the dispatcher in a state is to estimate the load and committed generation 24 hours ahead. The regional load dispatch centre coordinates the exchange across all member states and finalizes the central schedule. Any drawal by the state in excess of committed value will be priced at UI rates. In view of the commercial importance, the regional load dispatch centre of the Southern region has installed special energy meters (SEM) that give the values of frequency and energy transactions for every 15 minutes. These are used to arrive at the operational UI curve and the price of energy. This data is also used to compute daily frequency variation index (*DFVI*) as a network performance indicator. In this work we initially illustrate the commercial aspects of ABT and the need for SEM meters in implementing ABT. Using the SEM data we propose a new performance index, called the Grid Transaction Index for the daily operation of the network. We also give several examples for the use of this index in scheduling and planning studies. An illustration on the pricing scheme of ABT is given in the next section.

II. Illustration of ABT

In order to understand the pricing made in ABT, a case of an utility entitled to 20 MW from a CGS, with a variable cost of 1Rs/kWh, for a period of one day is considered. Figure 3 gives the scheduled power from the CGS and the actual drawal by the utility from which deviations can be calculated. Figure 4 shows the assumed hourly frequency profile for the day. The UI rates corresponding to the frequency profile is shown in Figure 5 and are payable by the utility for overdrawal and receivable by the utility for under drawal. The UI charge and net variable charge for the consumed energy (cost of scheduled energy + cost of unscheduled energy) payable by the utility for the day is shown in Figure 6 and Figure 7 respectively. Fixed cost of the CGS is shared by the beneficiaries in proportion to their allocated capacity and is not shown here.

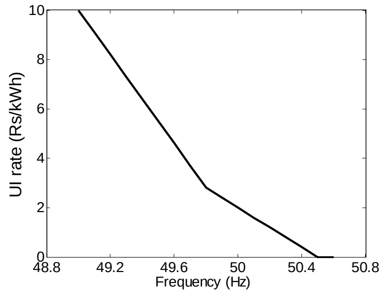

Figure 2. UI curve for frequency linked pricing

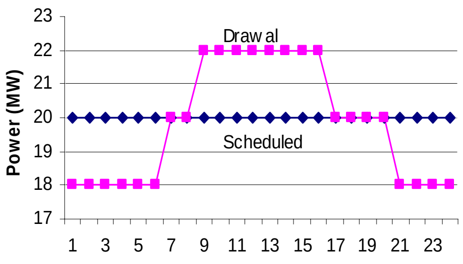

Figure 3. Scheduled/actual drawal of power

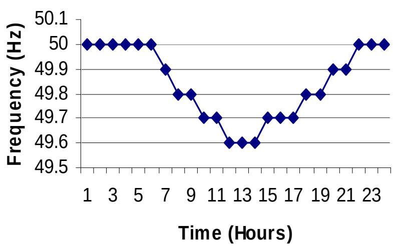

Figure 4. Assumed frequency profile for the day

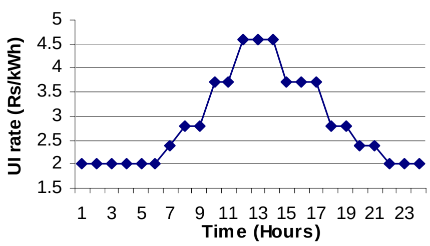

Figure 5. Unscheduled Interchange rate based on Figure. 4

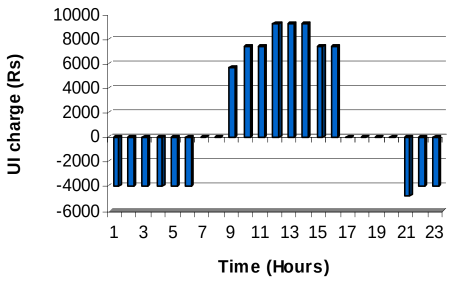

Figure 6. Unscheduled Interchange charge payable by the utility

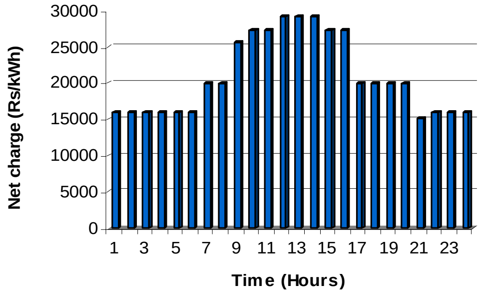

Figure 7. Net variable charge payable by the utility

The Southern region as a whole has a generation mix of 43% thermal, 30% hydro, 12.5% wind, 12.5% gas/diesel/naptha and 2% nuclear. Of these 85 hydro units, 12 thermal units, 10 gas/diesel/naptha units and 4 windmills are owned by the states. In addition there are 39 generating units held by IPPs and 9 generating units belong to the central sector. The SEM meters measure the unscheduled flows from CGS and intra state and inter regional flows for every 15 minute blocks. The salient features and the locations of these SEM meters are explained in the next section.

III. Special Energy Metering System for ABT

The SEM meters are of 0.2S accuracy class and are specially designed for frequency linked tariff metering scheme for inter utility exchanges at grid level [3]. They are totally electronic static meters capable of measuring active and reactive energy in all four quadrants.

The SEM meters are classified into three categories namely-

1. Main meters – These are the meters used for energy accounting and billing
2. Check meters – These meters are connected to the same CT/PT as the main meter. The readings of these meters are utilized in case of any discrepancy in the readings of the main meter.
3. Standby meters- These meters are used in case of discrepancy in the readings of the main and check meter. They are connected to other set of CT/PTs as that of the main meter.

The location of the SEM meters are as detailed in Table 1.

Table 1 Location of SEM meters

Sl No	Stages	Main Meter	Check Meter	Standby meter
1	Generating Stations	On all outgoing feeders	On all outgoing feeders	HV side of Generation transformers and all Station auxiliary transformers
2	Transmission and distribution system	At both ends of the line between substations.	Nil	There shall be no separate standby meter. Meter installed at other end of the line shall work as standby meter.
3	Inter connecting transformer (ICT)	High Voltage side of ICT	Nil	Low Voltage side of ICT

For every time block the SEM meters record the net active energy in 15 minute time blocks (Wh), average frequency in 15 minute time block and voltage failure flag (set if voltage in all three phases go below 70% of nominal value).This data is recorded for 96 time blocks a day and data for the previous 10 days is stored in memory. The data recorded once a day (at 00 hours) are the cumulative active power (Wh) and cumulative reactive power (VARh) sent out of the bus for the previous day. The instantaneous voltage and any of the other recorded readings can be observed on demand. The meter is provided with high security of data storage. At 00 hrs detailed report for the previous day operation is generated based on the recorded SEM data for 96 time blocks. From the data of unscheduled interchange with CGS and average frequency, the UI rate per unit per time block and UI charge to be paid/received by the utility for the previous day is established. Also as a performance parameter for that day, daily frequency variation index (*DFVI*) is computed. The present formulation of *DFVI*, its disadvantages and the proposed formulation of grid transaction index are detailed in the next section.

IV. Grid Transaction Index

From the data of average frequency obtained for 96 time blocks a day, the Regional Load Despatch centre computes a performance parameter called the daily frequency variation index, *DFVI*. The formulation of this index is,

$$FVI_t = 10 * (50 - f_t)^{\wedge}2$$
$$DFVI = \{\sum_t FVI_t\} / \sum t \qquad (1)$$

Where FVI_t is the frequency variation index for time block *t*. Some of the features of this index are-

- FVI_t will be the same for 49.9 Hz and 50.1 Hz.
- *DFVI* is not a weighted function of frequency deviation like the UI curve.
- The value of *DFVI* does not reflect the surplus/deficit conditions of the network or the worst frequency encountered by the network for the day.

For example three sample frequency profiles are shown in Figure 8, one reflecting a surplus condition, the second a deficit condition and the third a nearly steady frequency profile. (Of these the first two are real time profiles of the Southern region and the third is a generated one) The *DFVI* for the three profiles are almost the same and hence not indicative of these facts.

The unscheduled interchange curve is a weighted function of frequency deviation and the slope is defined for the permitted bands of frequency (Figure 2). Hence if the frequency variation indices could also be made as a weighted function of frequency deviation, the value of the index will directly indicate the upper and lower frequency bands for the day. This will be a better performance indicator. Also separate indices can be defined for a surplus and a deficient condition.

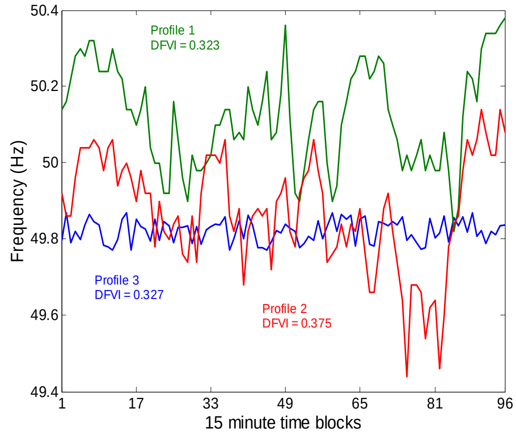

Figure 8. Daily frequency variation index

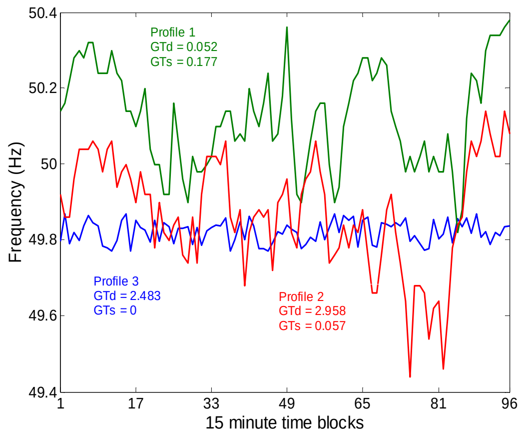

Figure 9. Grid transaction indices

Based on this we propose two daily frequency deviation indices for the network, called as the Grid Transaction index under surplus conditions (GT_s) and Grid Transaction index under deficit conditions (GT_d), which is defined as follows-

For $f_t \leq 50$ *Hz*

$$FVI_t = \{(50 - f_t)/50\} * \exp(\alpha) + 1 \qquad (2)$$
$$GT_d = \log\{(\sum_t FVI_t)/\sum t\} \qquad (3)$$

Where $\alpha = 4$ *for* $49.8 \text{ Hz} \leq ft \leq 50 \text{ Hz}$ *(first band)*
$\alpha = 9$ *for* $49 \text{ Hz} \leq ft < 49.8 \text{ Hz}$ *(second band)*
$\alpha = 14$ *for* $ft < 49 \text{ Hz}$ *(third band)*

For $f_t > 50$ *Hz*

$$FVI_t = \{(f_t - 50)/50\} * \exp(\alpha) + 1 \qquad (4)$$
$$GT_s = \log\{(\sum_t FVI_t)/\sum t\} \qquad (5)$$

Where $\alpha = 4$ *for* $50 \text{ Hz} < ft \leq 50.5 \text{ Hz}$ *(first band)*
$\alpha = 14$ *for* $ft > 50.5 \text{ Hz}$ *(zero band)*

Table 2 gives the range of *GT* for the different bands of frequency. For instance, any value of GT_d greater than 5.08 indicates the presence of at least one frequency in the third band and a value of GT_d greater than 0.2 and less than 5.08 indicate the presence of at least one frequency in the second band.

Table **2** Range of Grid Transaction indices

Band Number	Frequency Range	GT range
0	$f_t > 50.5$ Hz	$GT_s > 0.44$
1	50 Hz < $f_t \leq 50.5$ Hz	$0 < GT_s \leq 0.44$
1	49.8 Hz $\leq f_t \leq$ 50 Hz	$0.2 \geq GT_d \geq 0$
2	49 Hz $\leq f_t <$ 49.8 Hz	$5.08 \geq GT_d > 0.2$
3	$f_t < 49$ *Hz*	$5.08 < GT_d$

Table 3 illustrates some sample cases to validate the proposed index. This table indicates that the proposed *GT* indices can identify the worst frequency in the day profile (under surplus and deficit conditions) even if it occurs for only one time block. Extreme cases of frequency profiles are taken as samples to prove this point.

Table 3 Sample frequency profiles to validate the proposed Grid Transaction indices

Frequency Profile	*DFVI*	Grid Transition Index (surplus) GT_s	Grid Transition index (deficit) GT_d	Remarks
50 Hz in 95 time blocks and 49.81 Hz in 1 time block	0.0038	0	0.0022	All frequencies in first band
50 Hz in 95 time blocks and 49.79 Hz in 1 time block	0.0046	0	0.3034	One frequency in second band
49.79 Hz in 95 time blocks and 49.01 Hz in 1 time block	0.5385	0	3.5932	All frequencies in second band
49.79 Hz in 95 time blocks and 48.99 Hz in 1 time block	0.5427	0	5.6620	One frequency in third band
50 Hz in 95 time blocks and 48.99 Hz in 1 time block	0.1063	0	5.5375	One frequency in third band
50 Hz in 95 time blocks and 50.51 Hz in one time block	0.0271	4.8581	0	One frequency in zero band

The sample profiles discussed in Figure 8 are shown in Figure 9 with the proposed *GT* values. The value of *GT* is directly indicative of the upper and lower limits of frequency for the day. GT_d for the first frequency profile indicates that the lowest frequency is in the first band and that for the second and third indicates that the lowest frequency is in the second band. The value of GT_s for the first two profiles shows presence of frequency above 50 Hz but below 50.5 Hz. We show some examples below for the beneficial usage of grid transaction indices.

A. GT indices for scheduling pumped storage

It is intuitively apparent that pumped storage schemes could help maintain better frequency profiles[4]. The proposed index can be used for scheduling of storage. A definite GT_d value implies storage can be scheduled in generating mode and a definite GT_s value indicates scheduling of storage in pump mode. Figure 9 gives the *GT* indices for the sample profiles considered. Profile 1 indicates a GT_d value in band 1 and a definite GT_s value which means frequencies in the range of 49.8 Hz to 50.5 Hz. With this profile UI rates will be very less and storage can be planned for a pumping mode for the entire day. With the idea of indices over months/year, storage could be based on weekly or seasonal mode. Profile 2 indicates presence of frequencies in band 2 as well as a definite GT_s value. For such a day storage can be operated on daily cycle mode as there is a significant difference between off-load and peak load prices. Profile 3 has a GT_d value in band 2 and a GT_s value of zero. Here the operation of storage will not be profitable since there will be no significant difference between off load price and peak load price. The economics in storage operation can be taken as the deciding criteria as far as frequency is in the permitted band that is in band 1 (49.8 Hz $\leq f_t \leq$ 50.5 Hz) and band 2 (49 Hz $\leq f_t <$ 49.8 Hz). If the GT_d index goes above 5.08 ($f_t < 49$ *Hz*) it means presence of frequencies in band 3, in which case storage should be scheduled in generating mode in peak hours irrespective of the economics. In this case the storage operation will be profitable if there are time blocks with frequencies in band 2 and band 1.Thus having two indices, one for surplus and other for deficit network conditions and having them as a function of slopes of the UI curve is more meaningful in planning studies than the present index. The preferred mode of operation for the sample profiles are indicated in Table 4.

Table 4 The GT index as a guide to schedule pumped storage operation

Profile	*DFVI*	*GT*		Cycle of operation	Mode of operation
		GT_d	GT_s		
1	0.323	0.052	0.177	Weekly/Seasonal	Pumping
2	0.376	2.958	0.057	Daily	Pumping/Generating
3	0.327	2.483	0	Nil	Nil

B. GT indices for assessing frequency collapse

A particularly dramatic change in frequency profile occurs within days when wind speeds change their direction by the end of October in the Southern region. This normally results in a steep decrease in wind power. In 2007, this occurred in early October and was not predicted in time. This resulted in enormous load curtailment and low frequency operation for about 10 days in the Southern region. Figure 10 shows the fall in frequency from 50 Hz to below 49 Hz within a week during this period. The *DFVI* for these profiles (Figure 11) are steadily increasing indicating a fall in frequency profile. But the values are not indicative of the bands of frequency operation. There is no idea whether the frequency has entered the un-permitted band (ft<49 Hz) in any time slot. Figure 12 gives the *GT* values for these profiles. The GT_s values indicate the surplus conditions (ft>50 Hz) and it can be seen that on 9th Oct the frequency has never crossed 50 Hz. The GT_d values indicate that on 2nd Oct the worst band has been band 1 whereas on the remaining three days the worst band has been band 2. Also the value of GT_d on 9th Oct is close to the lower limit of band 2 which is indicative that the network is operating on 49 Hz and is likely to enter into the un-permitted band.

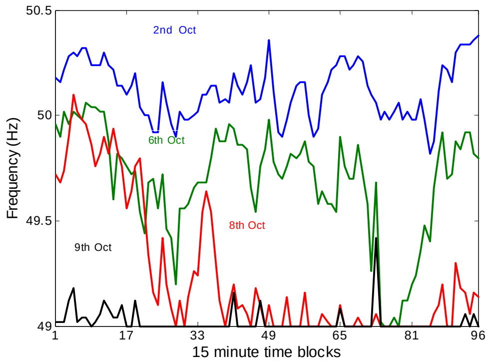

Figure 10. Sample frequency profiles of Southern region in 2007

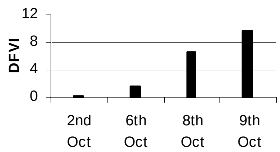

Figure 11. *DFVI* for the sample profiles

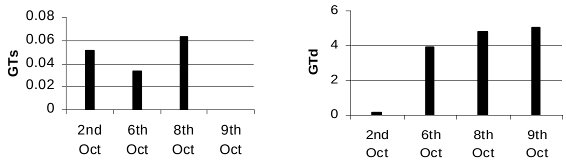

Figure 12. *GT* for the sample profiles

V. Conclusion

The technical and commercial implications of the present tariff scheme in India are illustrated. The use of SEM meters to account for the unscheduled power flows are highlighted. The disadvantages of the currently computed grid performance index parameter are listed. A grid transaction index is proposed to assess the network performance and its usefulness in scheduling the units in the network and planning studies are discussed with suitable real time examples.

VI. References

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