

FREQUENCY RESPONSE CHARACTERISTICS OF AN INTERCONNECTED POWER SYSTEM - A CASE STUDY OF REGIONAL GRIDS IN INDIA

S.K. SOONEE AND S.C. SAXENA

Power Grid Corporation of India Ltd. India

Abstract control area's contribution to the frequency response comprises of two components, namely, load response and governor response of generators. Load response (rejection) is the reduction in the power consumption of motors in response to a decline in the frequency and occurs directly (or with a minimal time lag) as the frequency changes. Generator governor (primary) response occurs in the 3-10 second time frame. It is the natural frequency response of a control area, which provides the self-healing immediately after a loss of generation. The frequency response characteristic of any system varies depending upon various factors such as the time of day, season of the year and size of the interconnection. The paper studies the types of generation and the loads (agricultural, industrial, and domestic) in the country and discusses the 'frequency response characteristics' for the Regional Grids in India. Specific incidences of sudden loss of large generation and large loads are studied and the frequency response is calculated state-wise and for the entire region. Incidents of such loss of generation or loads in the Northern Region after synchronization with the Central Grid (Western, Eastern and North-Eastern Grids) have also been studied and presented.

Keywords Frequency response, primary response, stiffness constant, power number.

1. INTRODUCTION

Frequency response is defined as the automatic, sustained change in the power consumption by load or output of generators that occurs immediately after a change in the control area's load-generation balance and which is in a direction to oppose a change in the Interconnection's frequency. It is also known as the power number of the system, stiffness constant, system inertia and system resilience and is denoted by the constant 'k' in the Area Control Error (ACE) equation ($ACE = \Delta P + k \Delta f$). During a contingency, such as the tripping of a generator or a loss of load block, the frequency changes due to the mismatch in load and generation. The level to which the frequency drops depends on the starting point as well as the system inertia. It is the system inertia, which provides the initial ability of the power system to oppose change in the frequency. Physically, it may loosely be defined by the mass

of all the synchronous rotating generators and the motors connected to the system. If the system inertia is high, then the frequency will fall slowly and vice versa, during any system contingency. System inertia is *not* frequency control per se, but it does influence the time taken for frequency to change after a loss of generation or load. Higher system inertia provides more time to the generator governors to respond to a change in frequency and hence is desirable. The various resources that contribute to the response of a control area are shown in the resources pyramid (Fig. 1). It is the natural frequency response of a control area, which provides the self-healing immediately after occurrence of a contingency. The control area's contribution to the frequency response thus comprises of two components namely load response and governor response of generators.

Primary response is the generator governor response, which occurs in the 3-10 second time frame. The changes in the generator output (MW) are in response to the change in frequency and are independent of any commands. Primary response is responsible for the initial arrest of frequency variations, but does not restore the frequency or the tie-line flows to schedules. Under frequency and df/dt relay operation occurs in the millisecond time frame, even before the primary response comes into the play. Secondary response is slower and is activated by the control commands such as those issued by the AGC systems and tie line flow control systems. Tertiary response comprises all subsequent actions taken such as bringing in non-spinning reserves, manual load shedding, etc.

Load response (rejection) is the reduction in the power consumption of motors in response to a decline in the frequency and occurs directly (or with a minimal time lag) as the frequency changes.

Frequency response is actually a negative value i.e., the generator output should increase as frequency drops. The frequency response assumes greater significance in times of system restoration after a disturbance, islanding or black out since frequency control during restoration is extremely important.

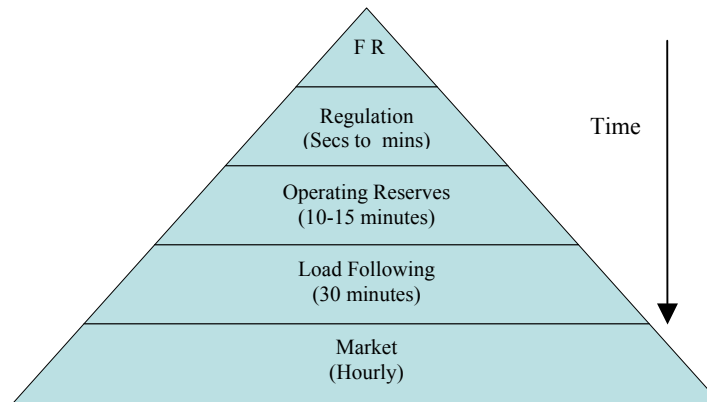


Fig. 1

FR: Frequency Response

2. THE INDIAN SCENARIO

India is divided into five regional grids namely the Northern, Southern, Eastern, Western and the Northeastern grids with a total All-India installed capacity of 127,673 MW. The fuel based breakup of the generation for the entire country is Hydro – 26.32%, Thermal – 65.78% (Coal – 54.20 %, Gas – 10.64%, Diesel – 0.94%), Nuclear – 3.05% and Renewable – 4.85% (as on 30-Nov-2006). Because of the uneven distribution of the fuel resources, the coal based thermal generation is mainly located in the Eastern part with Hydro generation concentrated in the North and the Northeast and some reservoir based hydro in the South. The load centers are mainly located in the North, West and South parts of the country with low load areas in the East and Northeast part. The North, West, East and the Northeast grids are operating synchronously and all the four regions are interconnected with AC as well as HVDC links. The Southern Region is connected to the East and West by HVDC links. Each regional grid is further divided into state grids, which form the respective control areas. Within a region, the various control areas are interconnected by AC links and it is these individual control areas and the regional boundaries that have been considered for calculating the frequency response.

From the frequency response perspective, the types of loads and their geographical distribution are important. Broadly speaking the loads can be classified as Industrial, Agricultural, Domestic and Commercial. At the end of 2004-2005 (Fig. 2), the industrial load constitutes about 44.5% of the total connected load, agriculture 19.8% and domestic and commercial together about 28.4%. The country's load has evolved over a period of time and as can be clearly seen from Fig. 2, there is a decline in the industrial load and a steady growth in the agriculture, domestic and commercial loads. Industrial loads comprise the high inertia heavy rotating loads which provide a good frequency response whereas; domestic and commercial loads use more efficient electronic load control devices, which, in general, reduce the frequency response.

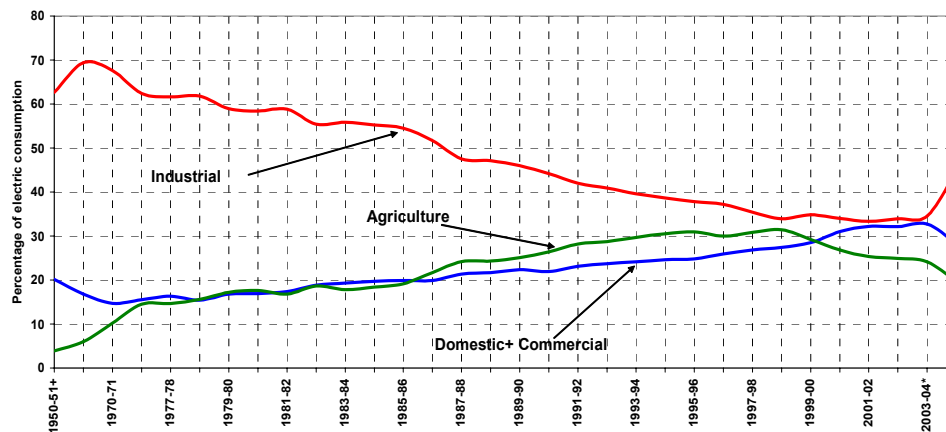


Fig. 2

3. CALCULATION OF FREQUENCY RESPONSE

3.1 Theoretical Background

The inertia constant ‘H’ for rotating machines is denoted by¹⁴,

$$H = (J \omega_{0m}^2) / 2VA_{base}$$

where, J = combined inertia of the generator and turbine

ω_{0m} = rated angular velocity in mechanical radians per second

The reduction in load following a decline in frequency is characterized by the load reduction factor “d”, which is defined as the percentage change in load for a percentage reduction in frequency^{1,6}. The general rule of the thumb is that a 1% change in frequency causes a 2% change in the load.

The simplest way to calculate the frequency response of a control area is to use the “1% of load” approach. However, this does not give very good results. A statistically rigorous approach is required to give better results.

3.2 NERC Methodology

The method used to calculate the frequency response in the Indian context has been adopted from the methodology suggested by the North American Electric Reliability Council (NERC)⁶.

Each control area has been considered to have its own internal generation and interconnections with the neighboring control areas. Any contingency, which occurs (a loss of generator or a load block), will manifest itself as a change in frequency and a change in the control area’s tie-line exchanges with its neighbors. The frequency response of the control area is calculated using the following.

$$\text{Actual net interchange immediately before the disturbance} = P_A$$

$$\text{Actual net interchange immediately after the disturbance} = P_B$$

$$\text{Change in net interchange} = P_B - P_A$$

$$\text{Load (+) or generator (-) loss causing the disturbance} = P_L$$

$$\text{Control area response } (\Delta p) = (P_B - P_A) - P_L$$

$$\text{Change in frequency } (\Delta f) = f_B - f_A$$

$$\text{Frequency response characteristic} = \Delta p / \Delta f$$

The data for the above calculations is taken from the real time telemetered data recorded by the SCADA systems installed at the Regional Load Dispatch Centers. Statistically speaking, about 30 observations are required to give a large enough sample to have confidence in the results. Both average and the median can be used to arrive at the frequency response, though the median is a better measure of the central tendency while analyzing a highly variable population like the frequency response events. The total frequency response of a region is the sum of all the control areas within the region.

4. CASE STUDY – FREQUENCY RESPONSE CHARACTERISTICS OF INDIAN GRIDS

System contingencies such as tripping of a large generating unit, tripping of HVDC back-to-back stations (or inter-regional HVDC links) and loss of a large block of load (tripping of ICTs) have been recorded and analyzed to arrive at the frequency response characteristics of the concerned region. Such incidents have been recorded both for Northern Regional Grid and the Southern Regional Grid over a period of time (December 2004 to September 2006 for Northern Region and March 2003 to May 2004 for Southern Region).

4.1 Northern Grid

The Northern Region comprises the states of Punjab, Haryana, Rajasthan, Delhi, Uttar Pradesh, Uttaranchal, UT Chandigarh, Himachal Pradesh and Jammu & Kashmir. Each state forms a control area. The load profile in the Northern Region is Industrial – 36.28%, Domestic – 26.70%, Commercial – 8.71%, Agriculture - 19.50% and others (including traction) – 8.81%. Contingencies resulting in a loss of generation varying from 500 MW to nearly 3300 MW and loss of load blocks from 400 MW to 600 MW have been recorded, data captured and analyzed to arrive at the frequency response characteristics of each control area and the region as a whole (Fig. 3).

Twenty-seven events have been captured (two not considered for analysis) and it is found that the frequency response characteristic of the Northern Region varies between 312 MW/Hz to 1075 MW/Hz. The average response is 678 MW/Hz and the median is 688 MW/Hz.

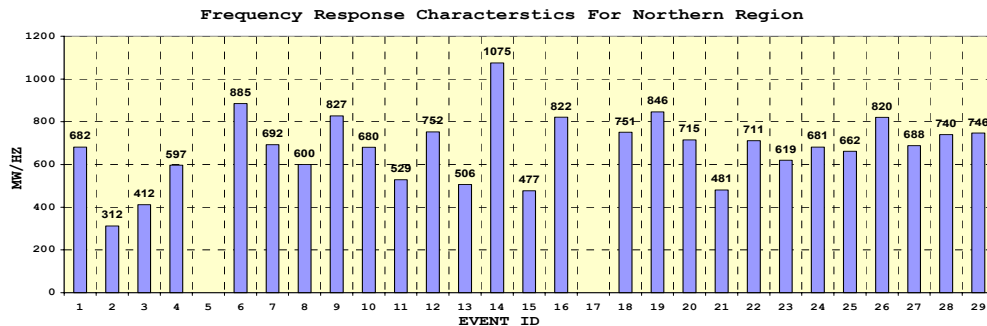


Fig. 3

A state like Delhi has a typically urban load, which is predominantly domestic and commercial (Domestic – 49.04%, Commercial – 27.88%, Industrial – 15.17%, Agriculture – 0.56% and others including traction – 7.35%). The frequency response characteristic for Delhi is found to vary from 16 MW/Hz to 328 MW/Hz. The average response is 96 MW/Hz and the median 82 MW/Hz (Table 1).

For a state like Punjab, which has predominantly industrial and agricultural load (Domestic – 21.86%, Commercial – 5.58%, Industrial – 40.39%, Agriculture – 27.92% and others including traction – 4.24%). The average frequency response is 100 MW/Hz and the median is 87 MW/Hz.

4.2 Southern Grid

The Southern Regional Grid comprises of the states of Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, Pondicherry and South Goa. The load profile in the Southern Region is Industrial – 38.17%, Domestic – 22.17%, Commercial – 6.97%, Agriculture - 26.13% and others (including traction) – 6.56%. Similar events of loss of generation & loads have been recorded and analyzed for each control area in the Southern Region and for the region as a whole. The frequency response for the Southern Region (Table 2) has been found to vary from 575 MW/Hz to 1515 MW/Hz with an average response of 1020 MW/Hz and a median of 1042 MW/Hz (Fig. 4).

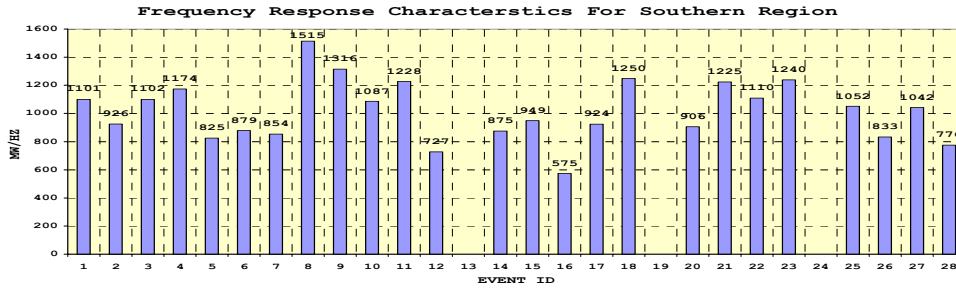


Fig. 4

Table 1 Frequency response characteristics for northern region

| Event ID | Date | Time | Occurrence | Frequency Response Characteristics (MW/Hz) | | | | | | | | | | | |
|----------------|----------|-------|-----------------------------|--|-----------|------------|------------|------------|-----------|--------------|-----------|----------|-------------|-----------------|--|
| | | | | Loss | Punjab | Haryana | Rajas than | Delhi | UP | Uttar anchal | HP | JK | Chandi garh | Northern Region | |
| 1 | 16-12-04 | 23:27 | Ropar #3,4,5 | 600 | 62 | 64 | 161 | 111 | 216 | 10 | 13 | 19 | 7 | 682 | |
| 2 | 17-12-04 | 8:10 | Tanda #1,2,4 | 282 | 113 | 46 | 61 | 36 | -12 | 8 | 10 | -13 | 6 | 312 | |
| 3 | 27-12-04 | 13:35 | Dadri(T) ICT #1,2 | -400 | 12 | 215 | 15 | 19 | 323 | 46 | 15 | 23 | 4 | 412 | |
| 4 | 02-01-05 | 22:27 | Panipat #2,4,5,6 | 635 | -23 | 3 | 174 | 35 | 184 | 29 | 6 | 16 | 10 | 597 | |
| 5 | 03-01-05 | 18:25 | Panipat #4,6,7 | Not Considered | | | | | | | | | | | |
| 6 | 20-01-05 | 9:52 | Dadri(T) ICT #1,2 | 795 | 87 | 56 | 136 | 69 | 41 | 0 | 3 | 0 | 0 | 885 | |
| 7 | 05-02-05 | 23:33 | Suratgarh Stn | 1038 | 71 | 67 | 455 | 26 | 25 | -8 | 10 | 16 | 0 | 692 | |
| 8 | 24-02-05 | 20:01 | Suratgarh Stn | 800 | 48 | 43 | 70 | 16 | 307 | -2 | -4 | 0 | 1 | 600 | |
| 9 | 21-03-05 | 16:03 | Singrauli #7 | 488 | 40 | 75 | 145 | 156 | 236 | 15 | 20 | 34 | 0 | 827 | |
| 10 | 14-04-05 | 11:36 | Suratgarh, Kota Stn | 2110 | 65 | 49 | 205 | 75 | 239 | 1 | 14 | 4 | 0 | 680 | |
| 11 | 21-04-05 | 20:40 | Anpara Stn | 567 | 97 | 73 | 79 | 129 | 285 | 12 | 10 | 6 | 1 | 529 | |
| 12 | 13-05-05 | 17:24 | Singrauli #7 | 471 | 46 | 4 | 65 | 117 | 172 | 3 | 2 | 2 | 0 | 752 | |
| 13 | 17-05-05 | 12:53 | NJPC, Baspa, Suratgarh Stns | 3276 | 87 | 114 | 212 | 194 | 388 | 1 | 171 | 55 | 0 | 506 | |
| 14 | 17-06-05 | 22:36 | Anpara #2,5 Obra #10 to 13 | 1188 | 86 | 48 | 205 | 137 | 404 | 0 | -46 | 103 | 1 | 1075 | |
| 15 | 30-06-05 | 12:06 | HVDC Pusauli B/B | 500 | 178 | 87 | 148 | 114 | 275 | 5 | 13 | 110 | 0 | 477 | |
| 16 | 06-07-05 | 1:23 | Dadri Stn | 1100 | 101 | -87 | 43 | 55 | 249 | 20 | 11 | 37 | 2 | 822 | |
| 17 | 25-08-05 | | Anpara | Not Considered | | | | | | | | | | | |
| 18 | 09-09-05 | 9:40 | Ropar Stn | 950 | 198 | 104 | 53 | 53 | 124 | 0 | 2 | 1 | 0 | 751 | |
| 19 | 11-09-05 | 12:48 | Dadri Th Stn | 730 | 162 | 111 | 78 | 52 | 117 | 1 | 0 | 0 | 1 | 846 | |
| 20 | 14-09-05 | 6:02 | Singrauli #6 | 500 | 64 | 61 | 132 | 89 | 298 | 11 | 12 | 18 | 1 | 715 | |
| 21 | 06-10-05 | 14:39 | Singrauli #7 | 500 | 100 | 77 | 150 | 30 | 189 | 0 | 9 | 15 | 0 | 481 | |
| 22 | 14-10-05 | 12:29 | Rihand #3 | 500 | 146 | 72 | 144 | 100 | 143 | 1 | 7 | 15 | 0 | 711 | |
| 23 | 16-11-05 | 11:51 | HVDC Pusauli B/B | 500 | 54 | 109 | 105 | 20 | 122 | 3 | 8 | 11 | 0 | 619 | |
| 24 | 03-01-06 | 2:22 | Ropar Stn | 600 | 62 | 99 | 238 | 89 | 221 | 27 | 8 | 17 | 1 | 681 | |
| 25 | 19-01-06 | 5:04 | Suratgarh Stn | 1150 | 106 | 177 | 144 | 115 | 174 | 22 | 3 | 0 | 3 | 662 | |
| 26 | 27-02-06 | 2:55 | Rihand Stn | 935 | 77 | 51 | 216 | 11 | 261 | 0 | -4 | -24 | 0 | 820 | |
| 27 | 21-04-06 | 9:53 | Anpara #5 | 480 | 63 | 260 | 38 | 127 | 367 | 71 | 63 | 163 | 0 | 688 | |
| 28 | 23-05-06 | 13:49 | Singrauli Stn | 969 | 74 | 25 | 95 | 71 | 191 | 9 | 14 | 10 | 3 | 740 | |
| 29 | 16-08-06 | 11:59 | Ropar Stn | 1240 | 128 | 166 | 290 | -8 | 165 | -15 | 23 | -3 | 6 | 746 | |
| Median | | | | 77 | 72 | 144 | 71 | 216 | 3 | 10 | 15 | 1 | 688 | | |
| Average | | | | 85 | 80 | 143 | 76 | 211 | 10 | 15 | 24 | 2 | 678 | | |

Table 2 Frequency response characteristics for southern region

| EVENT NO | DATE | TIME | OCCURRENCE | LOSS | Frequency Response Characteristic MW/HZ | | | | | |
|----------------|----------|-------|------------------------------------|------|---|------------|------------|------------|----------|-----------------|
| | | | | | ANDHRA PRADESH | KARNATAKA | KERALA | TAMILNADU | PONDY | SOUTHERN REGION |
| 1 | 04-03-03 | 13:54 | VTS 2,3,6 TRIP | 630 | 292 | 416 | 114 | 260 | 6 | 1101 |
| 2 | 06-03-03 | 18:40 | SIMH U2 TRIP | 500 | 319 | 169 | 228 | 257 | 9 | 926 |
| 3 | 16-03-03 | 13:34 | KOLAR TRIP | 672 | 187 | 300 | 133 | 484 | 8 | 1102 |
| 4 | 28-03-03 | 16:31 | KOLAR TRIP | 775 | 314 | 286 | 109 | 320 | 0 | 1174 |
| 5 | 12-04-03 | 15:38 | KOLAR TRIP | 850 | 236 | 157 | 119 | 309 | 1 | 825 |
| 6 | 20-04-03 | 16:38 | KOLAR TRIP | 620 | 218 | 161 | 127 | 342 | 3 | 879 |
| 7 | 21-04-03 | 9:35 | KOLAR TRIP | 555 | 222 | 212 | 129 | 245 | 3 | 854 |
| 8 | 03-05-03 | 17:08 | SIMH UNIT TRIP | 500 | 455 | 579 | 158 | 306 | 12 | 1515 |
| 9 | 05-05-03 | 14:43 | SIMH UNIT TRIP | 500 | 345 | 450 | 205 | 295 | 11 | 1316 |
| 10 | 06-05-03 | 9:36 | SIMH UNIT TRIP | 500 | 222 | 426 | 91 | 298 | 7 | 1087 |
| 11 | 10-05-03 | 3:42 | SIMH UNIT TRIP | 1000 | 300 | 628 | 200 | 211 | 0 | 1228 |
| 12 | 18-05-03 | 22:45 | KTPS UNITS TRIP | 550 | 235 | 255 | 149 | 190 | 5 | 727 |
| 13 | 19-05-03 | 12:00 | VTPS6 UNITS+SIMH1 UNIT + GAS UNITS | 1100 | NOT CONSIDERED | | | | | |
| 14 | 20-06-03 | 1:50 | KOLAR TRIP | 490 | 179 | 270 | 152 | 370 | 0 | 875 |
| 15 | 28-06-03 | 12:49 | KOLAR TRIP | 750 | 200 | 278 | 57 | 437 | 1 | 949 |
| 16 | 29-06-03 | 13:00 | KOLAR TRIP | 630 | 203 | 93 | 120 | 195 | 0 | 575 |
| 17 | 01-08-03 | 12:27 | KOLAR TRIP | 427 | 314 | 180 | 143 | 307 | 6 | 924 |
| 18 | 05-09-03 | 11:35 | RTPS UNITS TRIPPED | 1000 | 383 | 658 | 58 | 202 | 8 | 1250 |
| 19 | 29-09-03 | 14:20 | KOLAR TRIP | 750 | NOT CONSIDERED | | | | | |
| 20 | 08-10-03 | 13:10 | KOLAR TRIP | 1060 | 220 | 280 | 111 | 294 | 2 | 906 |
| 21 | 17-11-03 | 22:46 | SIMH UNIT TRIP | 1000 | 167 | 245 | 171 | 187 | 0 | 1225 |
| 22 | 21-12-03 | 14:10 | MTPS UNIT TRIP | 855 | 209 | 488 | 75 | 323 | 0 | 1110 |
| 23 | 15-01-04 | 4:33 | TTPS UNIT TRIP | 682 | 380 | 318 | 53 | 480 | 0 | 1240 |
| 24 | 04-02-04 | 15:51 | KOLAR TRIP | 1428 | NOT CONSIDERED | | | | | |
| 25 | 05-03-04 | 14:45 | KOLAR TRIP | 1188 | 335 | 380 | 172 | 176 | 6 | 1052 |
| 26 | 13-05-04 | 4:21 | VTPS TRIP | 1000 | 192 | 266 | 47 | 278 | 9 | 833 |
| 27 | 15-05-04 | 17:30 | KTPS UNITS TRIP | 750 | 385 | 301 | 75 | 132 | 3 | 1042 |
| 28 | 21-05-04 | 13:30 | SIMH+GAZK TRIP | 776 | 322 | 166 | 79 | 167 | 0 | 776 |
| Average | | | | | 273 | 318 | 123 | 283 | 4 | 1020 |
| Median | | | | | 236 | 280 | 120 | 294 | 3 | 1042 |

4.3 Combined Northern Grid and Central Grid

On 26th August 2006, the Northern Grid was synchronized with the Central Grid (Western, Eastern and North Eastern Grids). Post synchronization, three events occurred which have been captured to calculate the frequency response characteristics of the combined grid. The

frequency response has been found to vary from 1550 MW/Hz to 1664 MW/Hz with an average of 1611 MW/Hz and a median value of 1620 MW/Hz. The number of events captured so far is not adequate to give a figure with higher confidence level and more events need to be captured. Theoretical simulation studies carried out prior to the synchronization of the two large grids (North and Central) suggest that the frequency response of the combined system should be of the order of 1800 MW/Hz.

5. DISCUSSION

From the results obtained, it is evident that the frequency response characteristic of a control area is a highly variable parameter and it is difficult to accurately quantify the system's natural response. The factors affecting the FRC are the system size, frequency at the start of the incident, generator loading, losses, distance of generators from the point of loss, load composition, number of generators in service at the time of the incident, type of generation, governor action, time of day, season and interconnections with the neighbors. For instance in summers, systems tend to have a larger proportion of motor load. An area serving heavy industrial load or agricultural pumping load would have a better frequency response than an area serving predominantly domestic and commercial load. There is an increasing trend in the all silicon load (electronic devices) component not only in the domestic and commercial segments but also in the industry. These electronic loads do not provide the desired frequency response. The industry also uses variable speed drives/solid state drives, which do not provide the traditional response to frequency variations.

During periods of high loads, the frequency response is available mainly from the load since the generating units are operating near their full capacities. During light load periods, units are operating at less than their full capacities and governor response is available. No spinning reserves are available in the Indian system.

The type of generation too has an important role to play in the frequency response. Combined Cycle Gas based generation exhibits a positive frequency response, which means that the generation actually reduces with a decline in the frequency. This is because of the slow down of the auxiliaries. In India, the nuclear generation is totally inflexible as governors are blocked for various reasons. Most of the governors on the hydro and thermal generating units are blocked or have a delay configured thereby inhibiting the response. In the prevailing shortage scenario in the country, the generating units are almost always operated near the full capacity and even if governors are free, these units are not capable of picking up further generation. Moreover, no attempt is made to utilize the short-term overload capability of the machines. In the past, free governor mode of operation was used as suggested by JG Siroux¹. The report also suggested maintenance of reserves equal to the single largest generating unit in each region. However, because of a huge demand – supply gap, these could not be maintained.

5.1 Under-Frequency and df/dt Relays

Under frequency relays (UFR) and df/dt relays are installed in all the regions to arrest a fast fall in frequency and below a per-designated level (e.g., 48.80 Hz in Northern Region). The UFRs and df/dt relays act in the millisecond timeframe and are the first to provide relief by way of load shedding. A unique use of the under frequency relays has been made by the state

of Tamil Nadu at Aliyar HPS where the machines are running in the synchronous condenser mode and generation is picked up by the units using a signal from the UFR.

5.2 Limiting Factors

The factors affecting the accuracy of the calculation of the FRC are:

- (a) A large number of events must be captured and subjected to statistical treatment before a reasonably accurate figure can be obtained. This is also necessary to rule out the impact of high variability of the load.
- (b) Small excursions, which are significantly smaller than the maximum governor deadband, should not be included.
- (c) Both load and generation are continuously changing naturally.
- (d) Identification of the exact point of disturbance and interpretation of the time window to be measured. "Immediately before" and "immediately after" are subject to interpretation.
- (e) Limitation of the sampling rate of the data recorded by the SCADA system (normally 10 second samples are available in the SCADA). At times, there is also a loss in part of the telemetered data due to various reasons and this causes inaccuracies.

5.3 Interdependencies of P, Q, V & f

In the study undertaken, it is assumed that active power-frequency (P-f) and reactive power-voltage (Q-V) dependencies are decoupled. With the reduction in frequency the active power drawn by the motor load reduces. However, as the motor load is primarily inductive, the reactive power drawn increases (negative correlation). This leads to a reduction in the voltage, which in turn further decreases the active power⁵. Thus, in addition to the P-f and Q-V relation, the P-V and Q-f relations cannot be ignored. This becomes all the more important in systems where frequency and voltage vary widely. The Transmission Planning Criterion of CEA adopts the following load model⁷:

$$P = P_0 (f/f_0) \quad \dots(1)$$

$$Q = Q_0 (V/V_0)^2 \quad \dots(2)$$

This model considers the reactive demand of load to be frequency independent. For composite load model as per the IEEE Committee Report [17], the following must be considered:

$$P (v, f) = (a_1 v^{n_1} f^{m_1} + a_2 v^{n_2} f^{m_2} + a_3 v^{n_3} f^{m_3}) P_0 \quad \dots(3)$$

$$Q (v, f) = (a_4 v^{n_4} f^{m_4} + a_5 v^{n_5} f^{m_5} + a_6 v^{n_6} f^{m_6}) Q_0 \quad \dots(4)$$

The coefficients a_1 to a_6 are normally associated with load categories such as general residential load, industrial load and agricultural load. However, the coefficients are fractions with sum to unity i.e.,

$$a_1 + a_2 + a_3 = 1.0 \quad \dots(5)$$

$$a_4 + a_5 + a_6 = 1.0 \quad \dots(6)$$

In the Northern Region, studies carried out revealed that there is a change of 2% in the voltage with a change of 1% in the frequency.

5.4 Introduction of Competition in the Electricity Sector in India

Power utilities are being unbundled to bring in competition in India. Availability based tariff and open access in transmission at the inter-state level have been implemented successfully. Market mechanisms are being developed further and establishment of a Power Exchange is envisaged in the year 2007. The balancing market is provided by the UI mechanism. Implementation of intra-state ABT is being taken up. These factors are responsible for an ever-increasing pressure to bring about economy and efficiency. Market mechanisms have stressed the existing transmission systems more than ever before. All these have a direct bearing on the security of the grids and good frequency response of the system is necessary.

6. TRENDS WORLDWIDE

Extensive work has been done by the NERC in the USA on the frequency response. Frequency response is one of the important services that the utilities have to provide. NERC has also proposed a Frequency Response Standard. It is mandatory to calculate and report the frequency response characteristics for each control area using the methodology provided by NERC.

Calculations of the frequency response characteristics by the Eastern Interconnection and the Western Interconnection in the USA show that there is a declining trend in the frequency response obtained. The period considered is ten years (1993 to 2003) for the Eastern Interconnection and five years (1998 to 2002 both inclusive) for the Western Interconnection⁴. Theoretically speaking, there should be an increase in the frequency response since load levels are increasing and new generation is added. Evidence, however, suggests otherwise. Many reasons are contributing to this decline in the frequency response in the United States:

- (a) Steam turbine generators operating on “sliding pressure” or “boiler follower” control and/or with “valves wide open operation”.
- (b) Blocked governors on nuclear units.
- (c) Less heavy manufacturing in the North America.
- (d) Variable speed drives that do not provide the traditional load rejection.
- (e) Increasing percentage of combined cycle gas based generation, which actually gives a positive frequency response. This phenomenon reportedly contributed to a blackout in Malaysia in 1996.
- (f) Deregulation and market pressures have resulted in a reduction in the reserves maintained by the utilities. There is an increase in the number of reserve sharing groups as compared to the past when utilities maintained full reserves for their individual largest contingency.
- (g) New generator designs having less inertia i.e., less mass per MW of output.

NERC suggests that though some decline in the frequency response is not a problem for large interconnections, it is difficult to arrive at the cut off point below which it could become a serious issue. Primary frequency response becomes a major consideration in islanding/disturbance situations. Initiating black start in an area with poor frequency control is not desirable.

There is also an ongoing debate as to whether frequency response capability should be a mandatory requirement of all generators or it could be a commercial product (ancillary service). As a matter of fact, in the prevailing deregulated environment with ever-increasing pressures for economy and efficiency, it is a costly proposition to maintain a part of generation as idle capacity just to provide support during contingent situations. Some suggest that all generators should have operating governors, respond to frequency deviations equitably and this should be a mandatory requirement for connection to the grid. Others argue that the market can better determine the best use of resources.

7. CONCLUSION

There is an increase in the sizes of the generating units, the present maximum size is 500 MW and very soon there would be units of 1000 MW size. The tripping of a single generating unit of such a large size would create a far more severe contingency and tripping of the entire station is another credible contingency. There is also an increasing trend in the share of combined cycle gas and nuclear-based generation. Load profiles are changing and there is a reduction in the percentage of the load providing the self-healing in case of contingencies. Power systems will be faced with increasingly silicon-intensive loads. As a result, the mechanical inertia of the system will be less than with today's motor-intensive loads. Because such inertia helps the system "ride through" momentary disruptions, the coming of predominantly silicon-based loads could contribute to dynamic instability¹⁵. In these circumstances, there is a need for having a good frequency response characteristic for each control area. Free governor mode of operation and provision of reserves by each utility is required. Though the Indian Electricity Grid Code (IEGC)¹⁶ has mandated these, much needs to be done on the implementation front. Ancillary services are absent in the Indian Electricity Market and there is a need to develop these.

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BIOGRAPHICAL DETAILS OF THE AUTHORS

Sushil Kumar Soonee graduated in Electrical Engineering from the Indian Institute of Technology (IIT), Kharagpur in 1977. He has been actively involved in the evolution and development of regional power grids and entire gamut of integrated system operation in the country. He has been responsible for the successful implementation of ABT mechanism, Short Term Open Access at the inter-state level. He has worked in ERLDC, SRLDC and is presently Executive Director (System Operation & NRLDC).

Samir Chandra Saxena graduated in Electrical Engineering from the Aligarh Muslim University in 1992. He joined Power Grid Corporation of India Ltd as an Engineering Executive Trainee in 1994. From January 1996, he has been working with the Northern Regional Load Dispatch Center (NRLDC), New Delhi. He has been associated with the real time operation of the Northern Regional Grid and SCADA-IT Group at NRLDC.