Impact of delayed fault clearance on the load in Indian Power System

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Abstract — **Induction motor loads constitutes the major portion of the various types of the loads in any of the power grid across the world. Various control modes of induction motor along with its speed variability based on the slip provides its usage for versatile application. However, these induction motor based loads are affected by the voltage observed at their node during the constant torque mode due to their inherent characteristic. Such loads tend to stall/stop during voltage dip observed in the system. During any severe fault near to load centers with voltage suppression, a large amount of these load stall/stop as per their characteristic resulting in loss of a large amount of load from the grid. Further, they also recover quickly after the clearance of the fault by drawing large reactive power and current from the system causing delayed voltage recovery. Such phenomenon is also called as fault induced delayed voltage recovery in power system. These events are further accentuated under the condition of delayed fault clearance. This paper presents various such case studies on the impact of delayed fault clearance on the load in the Indian Grid.**

Keywords— Air-conditioning load, Fault Induced Delayed Voltage Recovery, Fault Induced Load Loss, Indian Power System Induction Motor, Load Loss, Synchrophasor.

I. INTRODUCTION

Nowadays power systems are more susceptible to voltage collapse than they were a few years ago. This is happening because of the grids are getting interconnected and synchronised resulting in increasing dependence on the generation sources which are remote to the load centers. In Indian power system, all the five regional grids are now synchronised. The cheaper generation is majorly available in the Western and Eastern grid which is catering to the major load centers in Northern and Southern region. The primary factor that encourages utilisation of the remote generation is the economics of purchasing bulk power at lower cost. However, this also poses a challenge to Power system operator in the Indian grid due to the transmission of power over long distances and requires adequate dynamic reactive power resource along the path. This has increased the dependency of the system on transmission system to deliver power directly near to the load centers. On the other hand, it also results in the huge stress on the transmission system as a whole. Any major tripping of these long-range path causes higher loading and voltage drop along the path which may become susceptible to voltage collapse in case adequate action are not taken within the time.

Another key factor that results in rapid voltage collapse in the power system is the nature of the loads that are being served by transmission and distribution system. The primary sources for demand nowadays consist of industrial motors and single-phase air conditioners (especially during summer seasons). These induction motors are prone to stall when subjected to a voltage dip since the supply voltage to the induction motor decreases, the motor speed decreases. This causes a decrease in power output of the motor. During the summers, air-conditioning load comprises a high percentage of the utility load especially in the Northern Region in Indian power system. While, in the large industrial areas of the Western region, the industrial motors constitute the large amount of load and are concentrated in certain pockets. Whenever there is a phase to phase or three phase type of fault near to these areas with delayed fault clearance, large load loss has been observed as a part of stalling of these motor based load [1]. This is observed as a sharp change in the power system frequency by the real-time system operator at the various control centers. Further, as the voltage starts recovering with the fault clearance, these induction motors restart and draws a large amount of reactive power as well as current causing prolonged voltage dip in the system. Such phenomenon is also called as Fault induced delayed voltage recovery (FIDVR) [2].

This paper discusses such cases of large load loss observed during power system faults on transmission system located near a load center. Section 2 of the paper discuss about the reasons for the loss of induction motor load during fault along with FIDVR followed by section 3 where various case studies on the load loss event and their classification whether they are FIDVR event or not. Section 4 showcases the challenges faced by the system operator during such event followed by section 5 where remedial actions have been discussed in detail.

II. LOAD LOSS DUE TO VOLTAGE DIP DURING FAULT AND FIDVR

Induction motor loads which constitute the major portion of the load in the grid and their operational characteristic is dependent on both voltages and frequency of the system through which they are connected. During any severe power system fault (phase to phase or three phase fault), the large voltage dip observed near to load center has significant impact on such kind of loads which is described below [3]:

1. Local Air conditioning load (Compressor of household A/C Units): Small single-phase induction motors found in A/C equipment have very low inertia and can stall within cycles during voltage dip under fault. Such loads trip on overcurrent protection or thermal protection.
2. Large High Voltage AC load: Large HVAC units in industries/complexes may also have the motor protection that will trip the unit offline before stalling occurs during voltage dip. These load comebacks in

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service after the voltage has recovered in the system. The absence of LVRT causes these loads to stall even though the fault is immediately cleared from the system.

3. Small Induction motor load (Pumping load which is a major portion of the agricultural load as well as residential load): These induction motor stall during such low voltage situation like fault even though the fault is cleared immediately. The loads draw a large chunk of reactive power during such faults causing heavy losses and trip on thermal protection, which has an inverse time-current characteristic. Many of these load sometimes do not have any protection and depend on the main protection from where they are withdrawing power and more susceptible to stall.
4. Large Induction motor load (industries): Such loads have LVRT protection and go out if the low voltage duration persists for a large duration during delayed fault clearance however they reconnect immediately after voltage recovery.

Thus it can be observed that major portion of such loads either goes out of system permanently during voltage dip on overcurrent or overvoltage protection or temporarily stall due to the absence of LVRT protection. Under normal fault which is cleared within 100-200 ms, such load goes out of the system causing sudden load throw off in the grid. However, the stalled portion of the load recovers quickly drawing a large amount of reactive power and current from the system.

While under the delayed fault clearance condition all these four kinds of loads will become out if the fault is persisting for a time duration exceeding LVRT time. Under such condition, the load loss will be much more compared to the previous case. Further, when the load is recovering the amount of reactive power and current will be much higher which causes a unique phenomenon of fault induced delayed voltage recovery (FIDVR).

Fault-induced delayed voltage recovery (FIDVR) refers to the unexpected delay in the recovery of voltage to its nominal value following the clearing of a fault in the power system [2]. This phenomenon is caused by the load characteristic of the induction motor load in the grid. The stalled induction motor industrial load and the residential air-conditioning (AC) unit (powered by single-phase induction motors) causes this phenomenon.

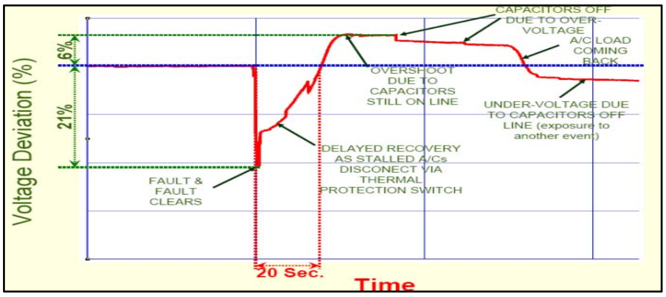

Fig. 1. Voltage variation during and after the fault in the case of FIDVR event in the power system [2].

Any induction motor in general runs under constant torque mode which depends on the node voltage where it is connected [4-6]. As soon as the voltage at that node is reduced, these loads try to slow down and if the voltage is low for the larger duration they may even stall/stop. However, as soon as the voltage starts recovering these stalled/stopped induction motor load restart which draws the large reactive power and current from the node causing the voltage dip to sustain for a larger duration and can result in tripping of additional load from the nearby node [7]. Figure 1 shows the fault induced delayed voltage recovery phenomenon in the system.

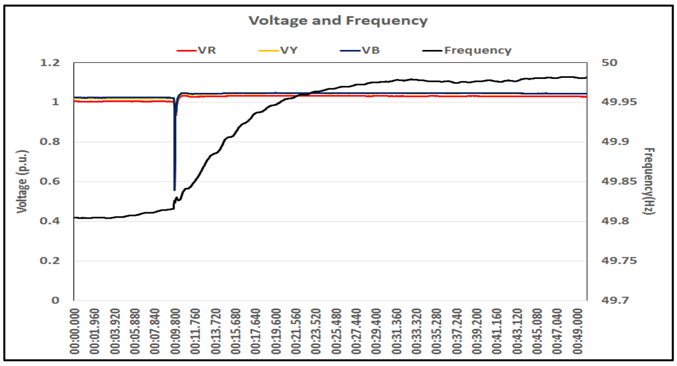

Fig. 2. Voltage and frequency during load throw off in the case of faults near to the load centers (Occurred at 400/220 kV Kalwa in the Western region of India).

Now, it is known that during severe nature of fault which causes a large drop in node voltage can result in loss of induction motor load and sometimes event can further accentuate into FIDVR kind of event. Under both cases, large voltage dip will be followed by a sharp rise in frequency indicating fault induced load loss (FILL) as shown in figure 2. Further, such loads tend to recover within 5-10 minutes and thus frequency returns back to normal. This can be very troublesome for the system operator since this quick changes in load pattern can cause wide variation in power flow across the network.

Not all such load throw-off phenomena during stalling of induction motor results in FIDVR kind of event, however, they still result in large load loss event due to different kind of induction motor and their protection as discussed earlier in this section. Based on the observed experience such cases of load loss can be categorised as:

1. Power system fault causing load loss in the system due to stalling on Induction motor load due to severe voltage dip.
2. Delayed clearance of power system fault causing load loss in the system due to stalling on Induction motor load due to severe voltage dip.
3. Delayed clearance of Power system fault causing load loss and fault induced delayed voltage recovery (FIDVR).

It was further found that FIDVR event occurs only when the severe nature fault like phase to phase or three phase fault take place during the summer season when the AC load concentration are more in the system. In the next section, detailed case studies of such kind of events have been discussed in detail. These events will also present the challenges observed by system operators during such events.

III. CASE STUDIES IN NORTHERN REGION AND WESTERN REGION

Several instances have been observed in Indian Grid which depicts the phenomenon of fault induced load loss event. However, only a few cases of FIDVR events is observed among these events. Out of these, the faults during the summer peak season in Northern Region of Indian grid where load loss is observed is described in details in this section.

A. Padghe Event

On 1st October 2014 at 10:22 Hrs, 220 kV Y Phase CT (SCT make) of 3 X 200 MVA, 400/220kV ICT-4 burst and caught fire at 400/220 kV Padghe substation in Western Region. This subsequently damaged nearby R and B phase 220 kV CT causing a three phase fault at 220 kV Bus of Padghe substation. The voltage dip during the three phase fault was around 50 % at the 400 kV Padghe as well as nearby 400 kV Kalwa bus which is directly connected through a short line and is monitored through PMU. The Kalwa bus voltage can be observed in figure 3 indicating the severity of three phase fault.

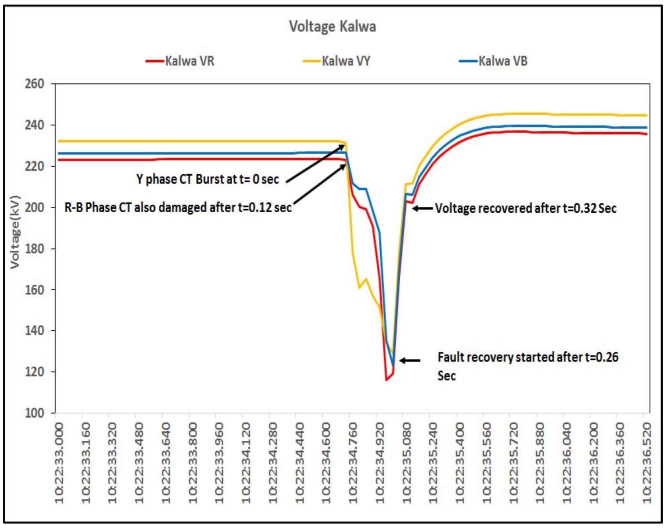

Fig. 3. Delayed fault clearance in of three phase fault in the system.

The event was followed by a sudden rise in frequency and unloading of the various transformer in the system serving the load near the Padghe area indicating load loss in tune of 1000 MW. This can be observed from figure 4. Although this event does not lead to FIDVR as the load concentration in the area is majorly of Industrial load yet it has significantly highlighted the issue of impact of delayed fault near to load centers under severe nature fault.

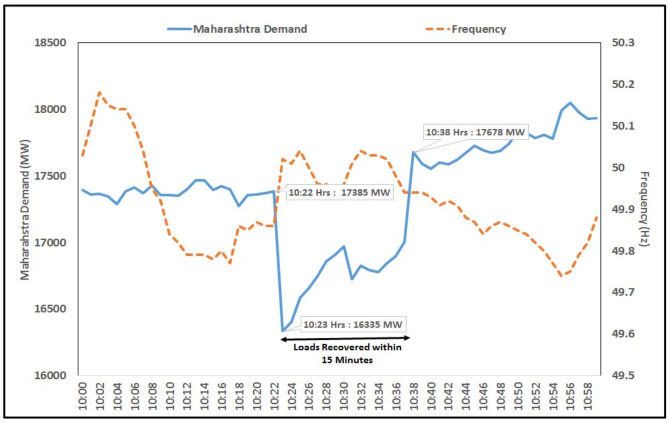

Fig. 4. The revival of load in the Maharshtra after the fault clearance and thus frequency resturning to nominal value.

The next event is unique in the sense that even though the fault has cleared within 100 ms, it has resulted in the loss of a large amount of load in the Western Region. The event this time has occurred at Kalwa which majorly is an industrial load center as well as house load catering to Mumbai area.

B. Kalwa Event

On 29th November 2014, a three phase fault occurred on 220 kV circuit from 400/220 kV Kalwa substation in Maharashtra in the Western region. The frequency and voltage plot during this event is shown in figure 2 where it can be observed that voltage has reduced by 40 % however fault has cleared immediately. Yet the system has observed a load loss in tune of 740 MW during this fault as observed from figure 5. This event has showcased the severity of a three phase fault near the load centers as it can result in stalling/tripping of loads on under voltage protection.

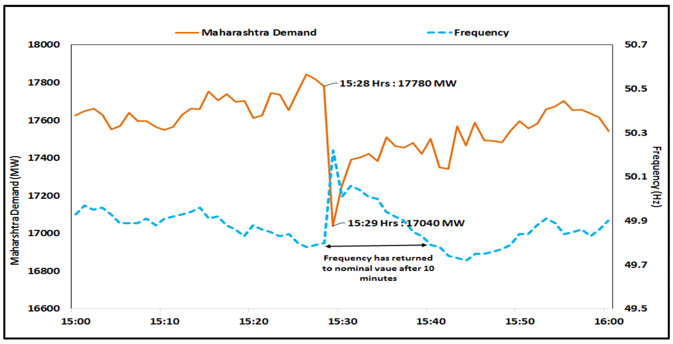

Fig. 5. The revival of the load in the Maharashtra after the fault clearance and thus frequency returning to the nominal value.

The third event discussed in next section is of a delayed three phase in the Northern Region during early morning hour in the month of summer.

C. Greater Noida Event

On 31st May 2015 at 0119 hrs, 400 kV Dadri-Greater Noida and 400 kV Greater Noida-Nawada circuit have tripped due to damage in disc insulator of Y Phase Jack Bus of 400 kV bus coupler bay at 400/220 kV Greater Noida substation. The fault clearing time was observed to be around 440 ms. The fault inception and clearing time from 400 kV Dadri substation bus voltage (located in nearness to the Noida substation) measured from PMU is shown in figure 6. Immediately after this fault, the frequency has shot up to 50.33 Hz from 49.97 Hz indicating large load loss in the Indian grid. This rise in frequency can be observed in figure 7 indicating load loss due to stalling or tripping of induction motor load. The Noida area constitutes mainly of the HVAC or the Industrial load which may have tripped during the delayed fault in the system on O/C or U/V or LVRT and recovered after the fault.

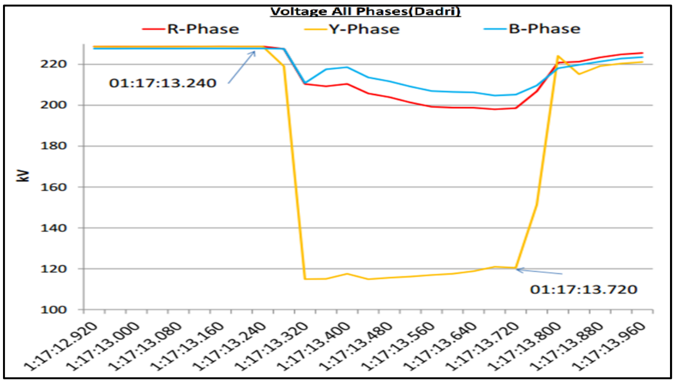

Fig. 6. Delayed fault clearance in Y phase.

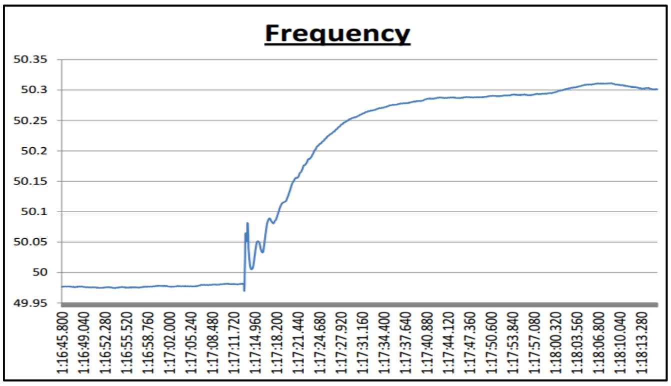

Fig. 7. Indian grid frequency during the fault indicating large load loss in the system.

In this event, the frequency has returned to the nominal frequency within seven minutes indicating the quick revival of the stalled air conditioning loads and industrial load. However, in this case, the FIDVR was not observed in the system.

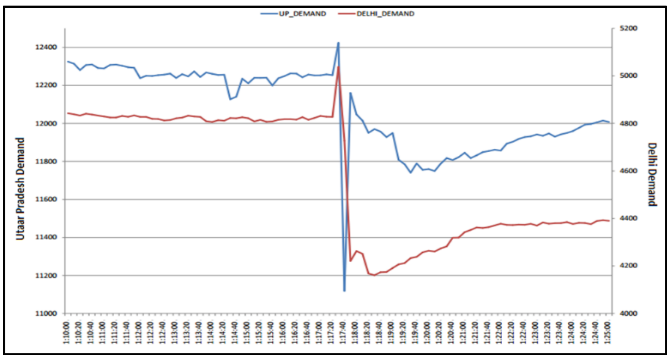

Fig. 8. The revival of the load in the Uttar Pradesh and Delhi after the fault.

This change in frequency corresponds to a sudden rejection of loads of approximately 1700 MW in Northern Region with 1000 MW in Delhi and rest 700 MW in Uttar Pradesh. The load throw-off and its quick recovery can be seen from figure 8.

The next two events presented after this are the cases of FIDVR event where the fault followed by stalling of induction motor load and their quick recovery has resulted in the delayed recovery of the voltage.

D. 400 kV Bawana-Mundka-II tripping event

On 18th May 2016 at 17:31 hrs, due to Y-B phase to phase fault occurred on the 400 kV Bawana–Mundka circuit 2 which is near to the Delhi and Noida area constituting residential load comprising of A/C and pumping load and Industrial load with HVAC and large induction motor loads. During this event, the fault clearing time as observed from the 400 kV Dadri bus voltage measured from PMU was 400 msec. shown in figure 9.

The fault has occurred in the peak hours of summer season followed by its very nearness to the load centers which constitute majorly of air-conditioning loads. So immediately after the fault, frequency rose up to 0.36 Hz as shown in figure 10 indicating a loss of 3700 MW load in the northern region.

Further, it can be observed from the voltage plot of nearby Dadri Bus measured from PMU that, after initial recovery of voltage up to 193 kV with the clearance of fault, the voltage recovery is slow. Later the voltage has exceeded the nominal voltage which was before the incident indicating a FIDVR event.

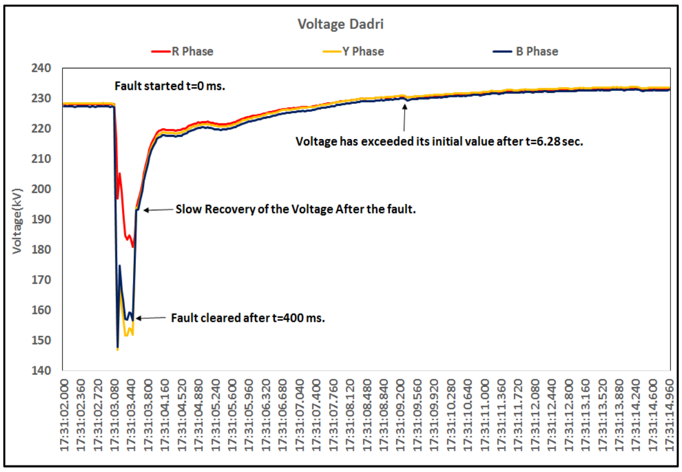

Fig. 9. Fault in Y & B phase as captured by Dadri PMU

This event has posed as a challenge to real time operator as prior to the event, the major 765 kV Sholapur-Raichur D/C tie lines connecting the Southern Region with rest of grid were out and operators were in the process to take these lines in service. In order to achieve the same, system operators were reducing the angular separation in the grid by increasing generation in the Southern region and pushing of more power from rest of grid to the Southern grid through interconnecting HVDC links. This was done in order to change the reverse the flow on the additional 400 kV AC tie lines connecting the Southern grid with the rest of the system from Sothern region to Western region. However, in between the event of load throw-off occurred in the Northern region which has negated the effect of action taken by system operator so far. This has led to a large angular separation across the 765 kV Sholapur-Raichur circuit as shown in figure 10. The figure depicts the frequency rise due to very large loss of induction motor load due to delayed three phase fault clearance near to load centers. This was a surprise to both field operators who were in process of synchronising the line as well as grid operator. Further, it can be seen that the load has recovered quickly bringing the frequency and angular separation within the limit immediately after 6 minutes of the event along with the governor response of generators. Figure 11 depicts the pattern of load behaviour after the tripping and it can be seen that load has immediately started recovering after the event.

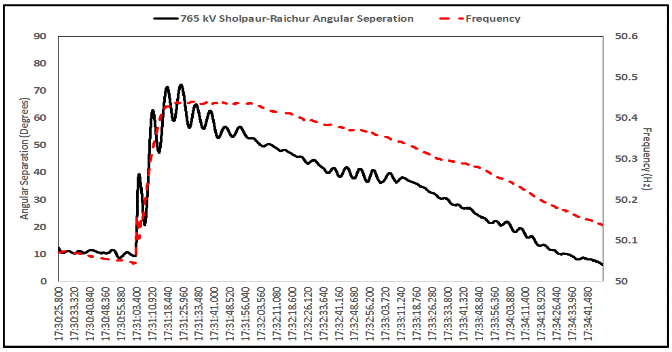

Fig. 10. The sharp rise in frequency after the incident due to loss of load.

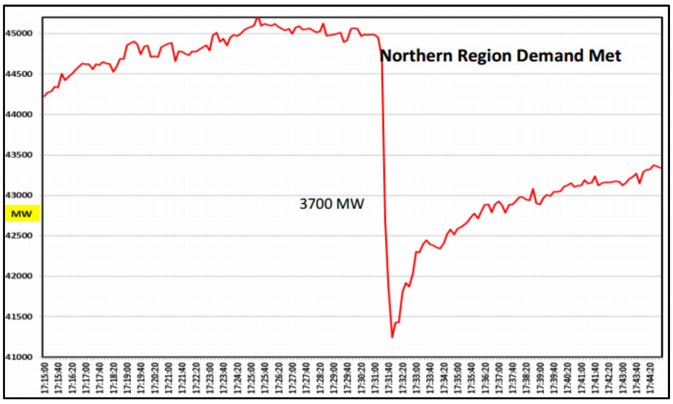

Fig. 11. Large Load throw-off in Northern region during the fault and its quick recovery.

E. Samaypur (BBMB) Multiple Tripping incident

The last incident which occurred in the northern grid indicating the FIDVR occurred on 9th June 2016. At 14:27 hrs, there was a Y Phase Current transformer burst event at the 220 kV Bus at Samaypur on the 220 kV Samaypur-Palwal circuit 1. This fault was cleared by line protection, however, the event later turned into causing a three phase fault on the 220 kV Samaypur substation. Since bus bar protection at Samaypur substation was out of service, therefore, all lines from this substation tripped from remote ends including all four 400/220 kV ICTs of Ballabhgarh (PG). Thus, due to non-availability of bus bar protection, the subsequently developed fault clearance time was nearly 1300 milliseconds (Figure 12). The FIDVR phenomenon explained earlier in the paper can be observed in the 3-Phase voltage plot. The delayed voltage recovery from 210 kV to 225 kV can be observed on account of large drawal of reactive power and current from the system by stalled induction motor loads.

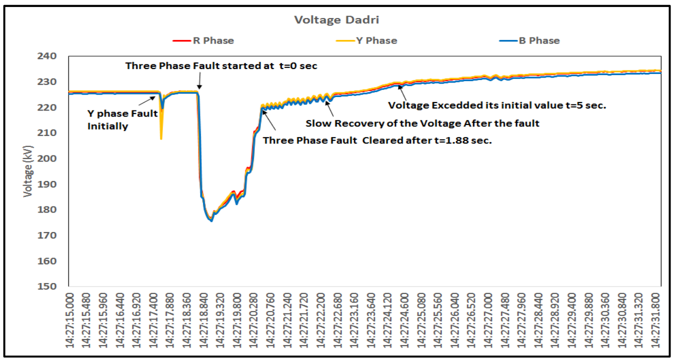

Fig. 12. Dadri station PMU Voltage plot indicating Delayed Fault clearance in Y-Phase and later 3-Phase fault

From the SCADA data, the load loss estimated was around 3890 MW in the Northern Region has been observed and consequently, the system frequency shot up from 49.89 Hz to 50.37 Hz as observed in figure 10.

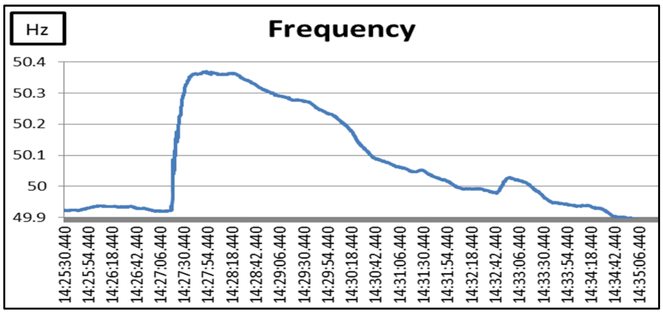

Fig. 13. Sharp rise and recovery in system frequency indctaing large load loss and its quick recovery.

The major states where load throw off was observed were Delhi (1450 MW), Haryana (1515 MW) and Uttar Pradesh (1050 MW). Figure 11 indicates the sudden reduction in demand and quantum of load loss. Again it was observed that all loads (except Haryana) recovered with 10 minutes and the frequency has also reached nominal value within this time. In the case of Haryana, the load could not recover since complete outage of Samaypur station caused loss of feeders.

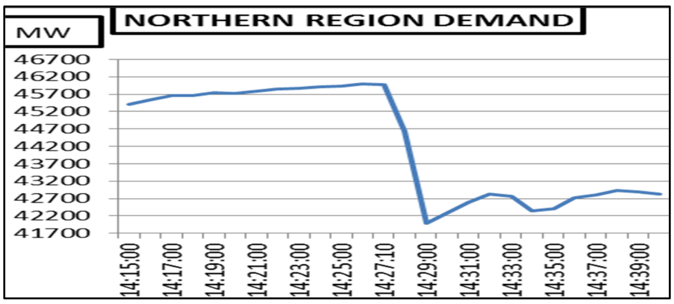

Fig. 14. Demand Plot of Northern Region during the event.

IV. SUMMARY OF THE CASE STUDIES

So, the five case studies of load loss during severe fault near to load centers has been discussed in the previous section. Out of the five cases, the last two cases have shown the FIDVR event while first three has shown the fault induced load loss event. In one of the case studies, where major tie lines synchronization was affected by such events has been shown and it has described the challenges faced by the system operator during such kind of events.

Overall, such kind of events of Fault induced load loss (FILL) and Fault induced delayed voltage recovery (FIDVR) can be summarised with following key points:

1. Any phase to phase or three phase of fault at 220 kV and above level near to load centers is of severe nature and can cause load loss due to tripping of induction motor load on overcurrent/under voltage protection.
2. Any delayed fault at 220 kV and above level near to load center is severe in view that it will result in significant amount of load loss due to tripping as well as stalling of induction motor loads.
3. FIDVR event occurs during the summer season when load centers share majorly of single phase AC units' load.
4. FIDVR event mainly occurs during severe fault near to the load centers along with its delayed clearance from the system.
5. These events are followed by a sharp rise in frequency due to load loss and quick recovery with 5-20 minutes.

Such events are further characterised by large loading pattern variation within a span of 5-10 minutes and poses as a challenge for real time operator. These large changeovers and system recovering so quickly significantly impact the real-time operation and also affects the ability of system operator to take any decision under such scenario.

V. REMEDIAL ACTION

So, it was seen in the previous section that the FILL and FIDVR have significant impact on the real time operation and also it significantly impacts the safety of the consumer load. In order to lessen the impact of these events, several remedial actions are desired which can be summarised as following:

1. Utilization of LVRT protection for induction motor load at the lower voltage level.
2. Requirement of review of the standards for the protection of single phase air-conditioning system in view of FILL and FIDVR.
3. Installation of adequate dynamic reactive compensation like STATCOM/SVC at distribution and transmission level near to load centers.
4. Bus Sectionalization of large substations to reduce the fault level.
5. Fault current limiter installation to reduce the fault levels of load catering substations.
6. Protection system at 132 kV and above system should be proper and adequate in order to clear the fault within least possible time.

These are among the few remedial actions which can help in reducing the impact of FILL and FIDVR on the load as well power system.

CONCLUSION

Fault induced load loss and fault induced delayed voltage recovery phenomenon are now increasing day by day in the Indian grid as showcased in the paper. Such phenomena can be observed presently with the fast measuring devices like Synchrophasor and can be monitored in real time. Generally, it was observed that such incidents are occurring when the fault is multi-phase in nature and has delayed recovery i.e. more than 100 msec for 400 kV & 160 msec for 220 kV system faults. However, cases have been observed where load loss during fault recovery within 100 ms also has been observed. However, decision making process for system operator is becoming challenging during such condition [8-9] due to large changeover in line loading as well as tie line flow which can also impact the voltage and angular stability of the system. The large changeover in frequency followed by quick recovery in addition to large change in line flow and voltage dip can result in difficulty in making any decision to bring the system back within reliability margin. If the problem compounds further, then the system may undergo – separation/islanding and eventual collapse. The paper also discusses few of remedial actions.

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