Black Start Exercise – Experience & Learning over past 7 years in Western Region, India

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***Abstract*—Resilience of the electricity grid, irrespective of its size, depends on the availability of a well-tested restoration procedure[1]. The Indian Electricity Grid Code (IEGC)[2] mandates periodic testing and validation of the grid recovery procedures at least twice a year. Black start drills are done to test & learn the behaviour of the power system elements under restorative state. These drills provide an opportunity for the system operators & field engineers to experience the challenges associated with a blackout scenario where-in the capabilities and response of each equipment as well as the operators are tested & validated. These drills involve physical isolation of a small part of the grid with a gas/hydro generator followed by creation of a blackout and restoration of that isolated part through bottom up approach. In India, several hydro and gas based generators are equipped with black start capability. This paper shares the experience & learning from the black start drills conducted under varying scenarios in Western Regional (WR) Grid of India over past 7 years (2011-2018). The learnings have been summarized from a system operator's perspective with an objective to ensure fastest grid recovery after blackouts & disturbances.**

Keywords— Black Start, Restoration, Islanding, Joint drill

I. INTRODUCTION

The Indian power system is one of the largest synchronized electricity grids in the world. The total installed capacity is more than 340 GW[3]. It caters a daily peak demand of the order of 160 GW with average energy consumption of 3.5 BUs/day[4]. With increase in network size and number of inter-regional & transnational inter-connections the reliability of the grid has increased manifold and so has the vulnerability to widespread blackouts. Thus, for system operators and all entities connected to the grid, preparedness for handling unfamiliar situations like grid disturbances & blackouts has become all the more important.

Two successive blackouts occurred in India in July 2012. Although major part of the grid could be restored within few hours on both the occasions, yet it was felt that the restoration could have been faster if more number of units could have contributed in black start. It was observed that the delay in extension of start-up supply to several thermal units could have been avoided if certain subsystems created by black start of units could have been prevented from subsequent collapse by better coordination among power stations, substations (s/s) and grid operators[5]. Similarly, many black-started units tripped due to paucity of loads commensurate with the generation build-up rate. One of the major reasons for delay in restoration was lack of preparedness among the substation engineers for handling this unfamiliar emergency. One crucial finding was longer than usual start-up time taken by certain gas generators during the restoration. Lack of dedicated communication links along the restoration path acted as a bottleneck in fast restoration of the grid. All these findings of the Grid Disturbance Enquiry Committee[5] were eye openers for the need of a well-tested grid restoration plan and its regular validation.

The Indian Power system follows a decentralized dispatch philosophy wherein the synchronous National Grid has been demarcated into 5 regional grids. The Western Regional (WR) grid of India has the highest installed capacity and it caters the second highest demand [4]. Large pit-head thermal stations are located in Chhattisgarh and North-eastern Maharashtra while major load centres as well as Atomic Power Stations are located in Southern Gujarat & Western Maharashtra. Madhya Pradesh (MP) has a fair geographical dispersal of hydro power stations across the state. Each of the 4 major states of WR have identified stations which are capable of black-start. The following table (I) gives a summary of black-start capability of WR States. Out of 29 black-start capable stations in WR, 21 are hydro stations and 8 are gas based power stations.

TABLE I. BLACK START STATIONS IN WESTERN REGION, INDIA

S.N.	Name of the State	Number of black-start sources (Total 29)	
		Hydro Stations	Gas Power stations
1	Gujarat	4	6
2	Maharashtra	7	2
3	Madhya Pradesh	9	0
4	Chhattisgarh	1	0
	WR-Total	21	8

Since 2011, more than 70 black start exercises have been conducted in WR with bottom-up approach where-in the above power stations (at Table-I) have demonstrated black-start capability. Although each black-start exercise is unique in terms of the island behavior, observations & learnings etc., still a general set of procedures are followed in each case. The following table (Table-II) summarizes the general steps involved in a black start drill. Over the years, these black start exercises have helped in developing familiarity with islanded operation of small sub-systems & each exercise has boosted confidence of system operators as well as field

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engineers to minimize the down time during the next trial. The following sections enumerate the gradual evolution of black-start exercises in WR. Learnings from smaller exercises have led to success in more extensive & complex exercises.

TABLE II. GENERAL STEPS INVOLVED IN BLACK-START DRILLS

S.N.	Activity	Remarks
1	Preparation	Preparation & circulation of procedure, Public notice in News paper, Bus segregation, Subsystem identification, Configuration in RLDC/SLDC SCADA for monitoring, archival & reporting
2	Controlled Separation	Controlled separation of the subsystem (Black Start source + line + load) from grid,
3	Blackout in Island	Blackout of the sub-system by manual tripping
4	Black start & island build-up	Black Start and dead bus charging + line charging, load build up in islanded system, Frequency & voltage control by generator
5	Synchronization of Island with the grid	Chek-synchronization of island with the grid at an intermediate substation having this facility
6	Information dissemination, Gap identification	Compilation of report, dissemination of information, Identification of areas needing improvement

Section II summarizes black-start experience in WR using hydro units. Section III describes experience of a black-started hydro unit in WR extending power supply to feed auxiliaries of a nearby thermal power station. Section-IV covers black-start experience with gas units. Section V presents a unique case where joint black start & islanding operation involving two generating units are discussed. Section VI summarizes the lessons learnt during the black start drills over the years. Section VII concludes the paper with a brief on future scope.

II. BLACK START WITH HYDRO POWER STATIONS

Hydro power stations, due to their low auxiliary energy consumption & high inertia are conventionally one of the most reliable sources for black start. In WR, hydro units of different size & capacity (25 MW to 200 MW) have successfully tested for black-start & island mode operation in past 7 years. A few cases are given under to highlight the gradual improvement in the black start process & restoration strategy with learning and value addition from each exercise. Indira Sagar hydro power station (ISP), located in Khandwa district of Madhya Pradesh is a multipurpose project on river Narmada with installed generation capacity of 1000 MW (8 x 125 MW). These Francis turbine hydro units are connected with the grid at 400 kV level. Equipped with 2x1000 kVA black start DG sets, the 125 MW ISP units have successfully demonstrated black-start capability in 2011, 2014, 2016 & 2018.

The first black start drill at ISP on 22.05.2011[6] was partially successful. The island build-up process after black-start of one 125 MW unit at ISP was successful. However, the exercise witnessed several difficulties like island collapse within a few seconds of its separation from Grid; delay in energization of EHV transmission system during island build-up; wide variation of frequency due to manual control; slow response due to higher droop setting (10%); rough synchronization of a 400 kV bus-coupler leading to unit tripping with mild jerk during island integration with main grid etc. Despite the above glitches, the exercise familiarized the field engineers with the machine behavior & response in island mode of operation. The next black start drill at ISP was attempted on 30.05.14[8]. The schematic switching diagram is given at Fig. 2 where the dotted lines indicate the elements which were a part of the island during the exercise.

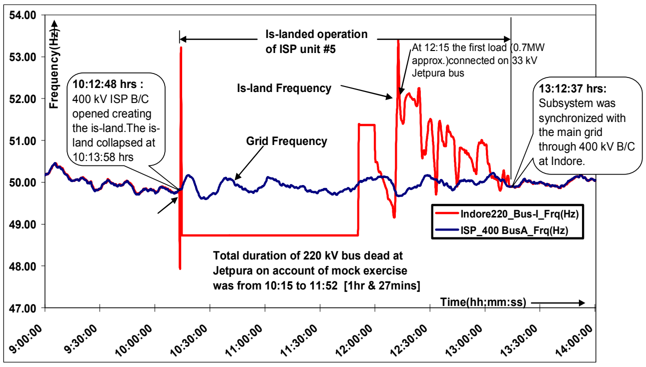

Fig. 1. Gird frequency vs Island frequency during Indira Sagar Black Start drill of 22nd May 2011

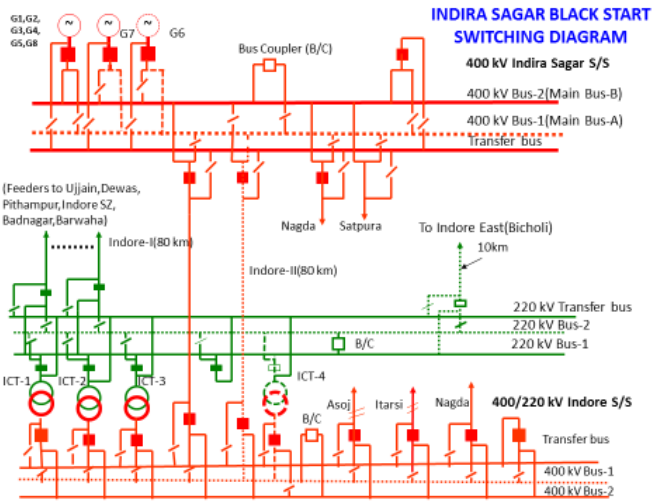

Fig. 2. Switching Diagram for ISP Black start exercise on 30.05.2014

As a learning from the previous exercise, the 125 MW ISP unit-6 was kept in free governor mode (i.e. speed control mode) which helped in smooth separation of the island from the grid. It operated as a islanded sub-system for a period of 35 minutes after which it was manually tripped. However, while building up the island with the unit, the 400 kV ISP-Indore line-2 (80 km) tripped twice on over voltage stage-II protection during energisation of transformers (i.e. 315 MVA 400/220 kV ICT-4 at Indore and the 100 MVA 220/33 kV ICT at Indore East). On analysis of the event it could be established that the tripping was attributable to transient over voltage caused by harmonic-rich inrush current (during transformer charging) by resonating with system impedance.

Based on the above experience, the next black-start drill was done on 10.06.2014 during which the existing over-voltage trip setting (120% & instantaneous) of the 400 kV ISP-Indore line was changed to 120% with 200 ms delay. Further, during island build-up the 400 kV line was charged from generator at a reduced bus voltage (0.6 pu) & the 400 kV line got charged at 227 kV. The voltage was gradually increased with AVR in manual mode to facilitate connection of load to the island. After load stabilisation, the AVR setting was changed from manual to auto mode which restored the voltage to nominal value. Speed droop was set at 4%. The island of 45 MW operated for 40 minutes before being check-synchronised with the grid. Similar black start drills were done with Indira Sagar (ISP) hydro units on 14th Oct 2016 & 10th Feb 2018. Table-III give a brief comparison of the 4 drills at ISP.

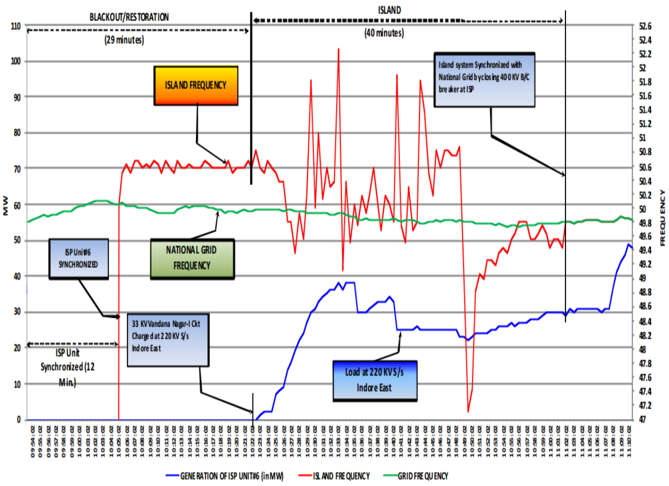

Fig. 3. Grid frequency vs. Island frequency & MW during the ISP black start (10.06.14)

TABLE III. COMPARISION OF KEY FACTORS (INDIRA SAGAR)

Key Time Indicators of 4 Black Start Exercises at Indira Sagar (ISP)				
Time in Minutes	**22-May-11**	**10-Jun-14**	**14-Oct-16**	**10-Feb-18**
Island operation before blackout	1.1	9	0	9
To start DG set after blackout	Instantaneous (Auto start on sensing zero voltage)			
To take the unit in service	66	8	18	8
To charge dead bus at ISP	66	12	23	9
To synchronise 400 kV line	80	15	27	13
Load interruption period	121	29	41 (U6) + 20 (U7)	24
Island operation after blackstart	57	40	17 (U6) + 12 (U7)	11
Other facts & observations				
ISP Unit No	U#5	U#6	U#6 & U#7	U#7
Max load catered by Island (MW)	12.6	44	49	50
400 kV path length (in Km)	80	80	80	80
Frequency variation (in hz)	49.2-53.4	48.3-51.3	47.7-52.6	46.8-53.5
Governor Status	Manual	FGMO	FGMO	FGMO
Governor Droop Setting	-	-	4%	4%
AVR Status	Manual	Manual	Auto	Auto
Other observations / tripping	Island collapsed after separation; Unit tripped during check-synchronisation with grid	Over Voltage stage-II trip setting changed (200 ms) to avoid tripping	400 kV line tripped on o/v during separattion; Unit-6 tripped on first synchronisation attempt; Next attempt with U#7 was successful	Over Voltage stage-II trip setting changed (200 ms) to avoid tripping

III. BLACK START OF HYDRO UNIT FOR EXTENSION OF START-UP POWER TO A THERMAL POWER STATION

Extending start-up power from a black-started generator to a nearby thermal power station is a priority task during grid restoration. A black start exercise was conducted on 20th December, 2015 with a 200 MW francis turbine hydro unit at Sardar Sarovar River Bed Power House (SSP-RBPH) in WR. SSP is located on down stream of Narmada river in the state of Gujarat. SSP is connected to the WR grid with 6 numbers of 400 kV lines (Fig. 5) connecting Asoj & Kasor substations (s/s) in Gujarat, Rajgarh s/s in Madhya Pradesh and Dhule s/s in Maharashtra. Because of its strategic connectivity to 3 states, success in SSP black-start can expedite simultaneous grid restoration during blackouts. The 200 MW units are equipped with 2x1000 kVA DG sets for black start purpose. SSP is a multipurpose hydro project co-owned by 3 states. Being a multi-purpose hydro project it primarily caters to the irrigation requirement, drinking water supply etc. in the beneficiary states. Sardar Sarovar Project has very limited water allocation for power generation which is a major constraint for planning black drills at SSP. Nevertheless, several black start drills have been conducted at SSP in recent past. A summary of key observations in 4 such drills at SSP has been given at Table-IV.

TABLE IV. BLACK START DRILLS AT SSP : KEY OBSERVATIONS

Key Time Indicators of 4 Black Start Exercises at SSP				
Time in Minutes	**08-Apr-12**	**26-Jun-14**	**20-Dec-15**	**14-Dec-16**
Island operation before blackout	15	22	48	N/A
To start DG set after blackout	5	2	5	8
To take the unit in service	19	28	27	33
To charge dead bus at ISP	19	28	27	33
To synchronise 400 kV line	44	29	29	n/a
Load interruption period	51	34	30	n/a
Island operation after blackstart	Not done	79	41	n/a
Other facts & observations				
Max load catered by Island (MW)	42	56	98	n/a
400 kV path length (in Km)	83	146	83	178
Frequency variation (in hz)	46.6-52.2	48.7-50.4	49.2-51.2	49.1-49.6
Governor Droop Setting	10%	6%	6%	5%
AVR Status	Manual throughout	Manual throughout	Manual during line charging	Manual during line charging
Other observations / tripping	Vibration due to operation in forbidden zone, 400 kV SSP-Asoj line tripped twice on o/v.	SSP-Kasor line tripped on first attempt during 400/220 kV ICT charging at Kasor	O/V stage -II trip setting changed(150 ms) to avoid tripping	SSP Unit-2 & Rajgarh line tripped during first charging attempt

The SSP black start drill of 20.12.2015 was unique in nature where an island of more than 100 MW was successfully created using a 200 MW unit at RBPH (U#2) and radial loads at 2 remote substations (220 kV Godhra and Waghodia s/s) and the island extended power supply to feed station auxiliaries of a nearby 210 MW thermal unit at Wanakbori Thermal Power Station. The frequency plots & schematic network diagram are given at Fig. 4 & 5 respectively. This exercise was successful with extensive planning & coordination backed by offline simulation studies carried out at WRLDC. Learnings from past exercises was a key factor behind the success of this first of its kind black start drill in WR. The most recent exercise (of 05.03.2017) which involved a joint black start drill of SSP with a nearby gas power station (i.e. CLPIPL) in south Gujarat is discussed in Section V.

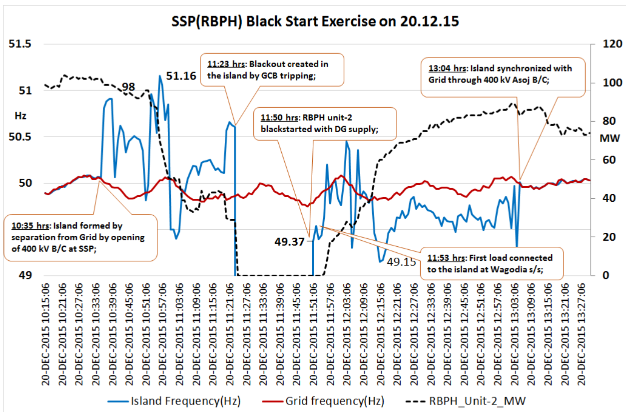

Fig. 4. SSP Island frequency vs Grid frequency (20.12.15)

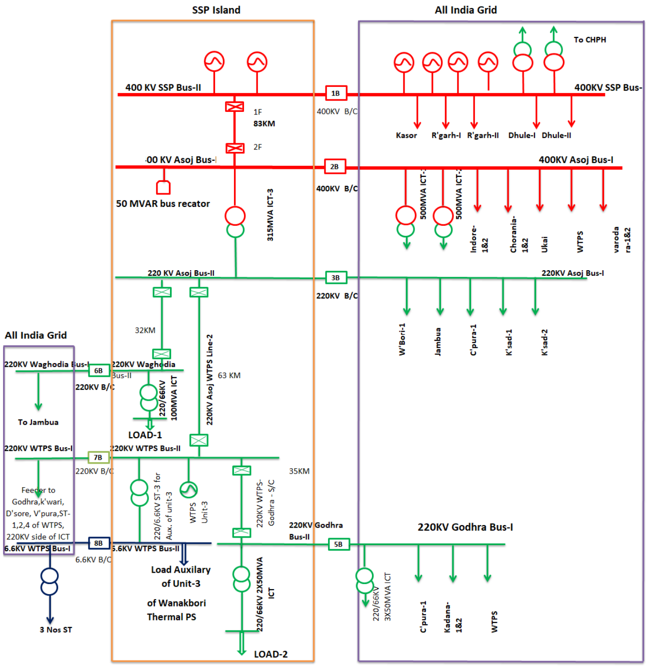

Fig. 5. SSP black start & suplpy extension to Wanakbori TPS (20.12.15)

IV. Black Start with Gas Power Stations

Similar to hydro power stations the gas power stations too have lower auxiliary consumption (typically 1.5-3% of installed capacity) [9]. Hence a gas unit can be self-started with a DG set to build an island during restoration. In WR several gas power stations viz. Kawas (NTPC), Jhanor (NTPC), CLPIPL, GIPCL-I in south Gujarat and Uran power station in Maharashtra have successfully conducted black start drills. Kawas & Jhanor gas power stations are connected to grid at 220 kV level. They have contributed in grid restoration after blackout of WR grid in July 2002 during which issues like hunting of DG set, unit tripping for lack of commensurate load etc. were observed.

A black start drill was conducted on 15.10.2013 using one 106 MW gas turbine unit of Kawas Gas power station of NTPC Ltd. It is equipped with a 2850 kW DG set for black start. This was a unique exercise where-in 3 stages of islanding operation were tested viz. one controlled separations of the subsystem from grid at an intermediate substation (220 kV Vav) followed by manual black-out and then island build-up with black-start of one gas unit at Kawas with load at 220 kV Ichhapur s/s. Synchronization of this 45 MW island with the grid was done at Vav s/s. Again a controlled separation was carried out at Vav s/s followed by re-synchronization with the grid at another 220 kV s/s (Essar). After the planned blackout it took around 32 minutes to start the 106 MW gas turbine unit in open cycle and extend supply to the load substation at Ichhapur. The schematic diagram and frequency plots are given at Fig. 6 & Fig. 7 respectively.

Similarly, another black start drill was conducted with one 144 MW gas unit & 2.95 MW DG set at NTPC Jhanor gas power station on 07.12.2014 which catered a radial load of 29 MW at 220 kV Haldarwa substation. Frequency plot is given at Fig. 8. These two black start drills at two major gas stations in WR tested the grid restoration capabilities of gas units viz. surviving controlled separation, charging of dead bus, charging of EHV line from self-started unit, controlling island frequency & voltage with a single gas generator running in open cycle and the capability to check-synchronize the island with a larger grid at different intermediate substations.

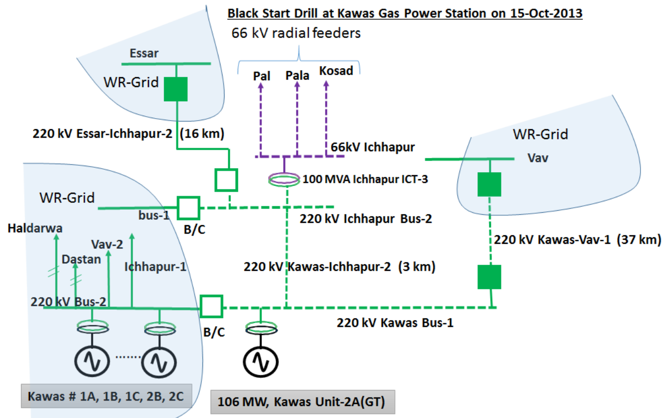

Fig. 6. Schematic Network for Kawas (Gas) Black Start Drill on 15.10.13

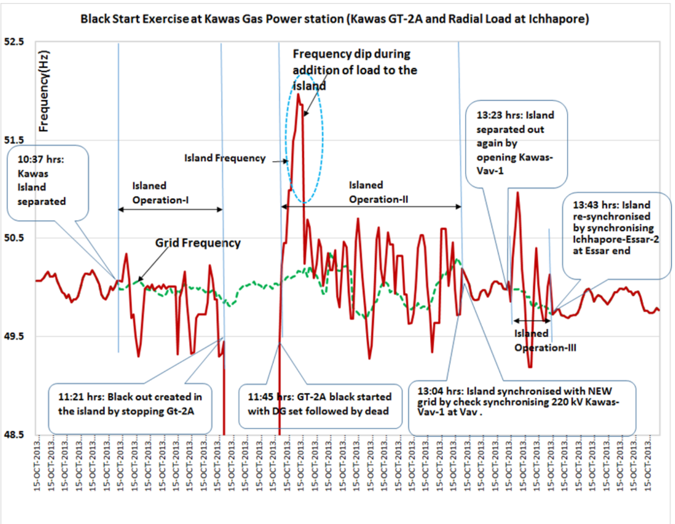

Fig. 7. Grid freq. vs Island freq. in Kawas Black Start Drill on 15.10.2013

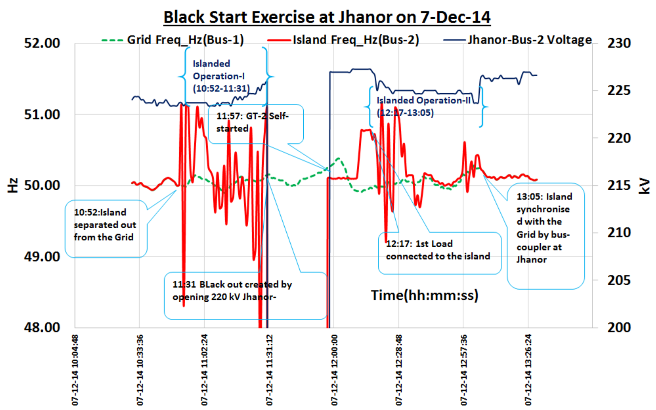

Fig. 8. Frequency plot during Black start drill at NTPC Jhanor (7.12.2014)

V. Black Start Exercise with Multiple Generators

After a series of success in black start drills with a single hydro/gas generator & pre-identified radial loads, it was attempted to conduct joint exercises in WR involving parallel black start operation of two generators. During such exercises the following steps were followed: (a) Two black-start capable generators are simultaneously allowed to separate out from the main grid along with pre-identified loads & operate in island mode; (b) This island comprising of two generators is then split into two separate islands by proper coordination & circuit breaker switching; (c) These two separate islands are allowed to operate independently for some time; (d) Creation of blackout in the two subsystems by tripping the respective generators; (e) Black start of the two generators independently & gradual building-up of two separate islands around each generator; (f) Check-synchronization of these two separate islands at a pre-identified EHV substations to form a larger island; (g) This combined two-generator island is then allowed to check-synchronize with rest of the grid. A joint black-start exercise involving one 106 MW gas turbine generator (GT-2B) at Kawas and one 144 MW gas turbine generator (GT-2) at Jhanor was conducted successfully on 27.08.2016[10]. This drill, which involved multiple stages of islanding operation, was first of its kind in WR grid and was executed with detailed planning & coordination between engineers at RLDC/SLDC, generating stations, transmission & distribution s/s. The plots showing major events during the joint exercise is given at Fig. 9. Schematic network is shown at Fig. 10. The joint island catered a load of around 90 MW during the exercise. This 5-stage islanding operation was analyzed in detail using archived SCADA data (at WRLDC) for parameters like island frequency, voltage, MW & MVAR flows across different elements. The island response, generator reactive capability etc. were studied. The joint drill was successful as per the plan except for step (b) mentioned above. The joint sub-system survived the controlled separation from grid in step (a) & operated for 17 minutes. In the next step (b) while splitting the Kawas+Jhanor joint island into two separate islands, Kawas island survived with 44 MW load but Jhanor island collapsed on unit under frequency operation & the unit went on house load before being manually tripped.

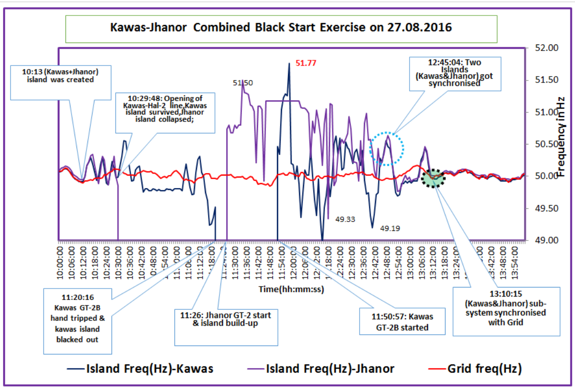

Fig. 9. Gird freq. vs Island freq. during joint black start drill on 27.08.16

Based on the learnings from this exercise a similar joint exercise was conducted using one 200 MW hydro unit (RBPH U#3 at SSP) and a 138 MW gas unit (GT-1 at CLPIPL gas station) in Gujarat on 05.03.2017. The combined island catered a load of around 100 MW. The initial separation of the two machine island (SSP+CLPIPL) from the grid was smooth. Then splitting of the individual islands around SSP unit-3 & CLPIPL GT-1 was done & the two islands operated independently. During build-up phase post manual blackout, the SSP unit-3 tripped twice on under-

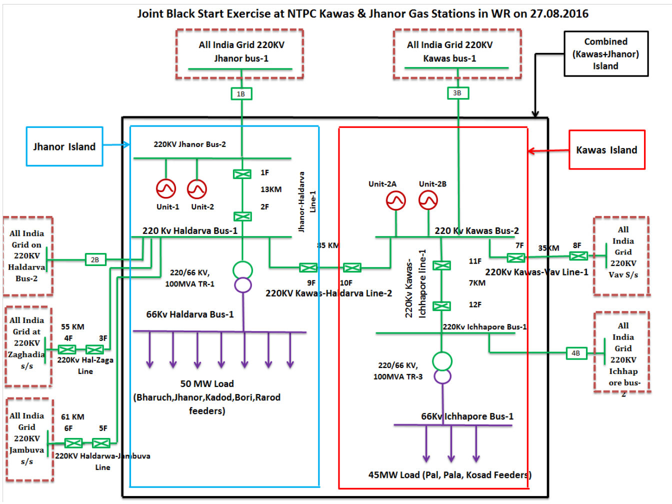

Fig. 10. Schematic network:Joint Black start Drill (Kawas&Jhanor) 27.8.16

frequency protection during load addition. The SSP island collapsed once again due to tripping of 400 kV SSP-Kasor line. In the fourth attempt with anther unit at SSP (unit-2) it could successfully black-start & build an island of 40 MW. No major issues were faced in building up the island (35 MW) around the CLPIPL gas unit & subsequent synchronization of the two islands (around SSP & CLPIPL) to form a larger island followed by its synchronisation with the main grid. This was another unique exercise involving joint islanding of a gas & a hydro unit. After success of these two joint drills in Gujarat, another joint black start exercise was carried out in Madhya Pradesh on 11.04.2018. This exercise involved creation of two separate islands around two hydro units (an 80 MW unit at Pench and a 45 MW unit at Bargi) followed by synchronization to form a larger island. This 2-machine island was then synchronized with the main grid. Joint black start drill of Kawas & Gandhar could be planned in future for extending supply to the nearby nuclear power station at Kakrapar, Gujarat, since the extension of start-up power supply to a nuclear power station within 15-30 minutes of station black-out is considered as one of the high priority tasks during grid restoration.

VI. Key Learnings

The key learnings from the black start exercises conducted over the past 7 years in WR grid are summarized under.

(1) Black start drills involve extensive coordination with generation, transmission & distribution utilities and load despatch centres (RLDC/SLDC). (2) Granularity of load & its characteristics play a vital role in island build-up & its stability. (3) Dead bus charging is a critical activity during black start and must be properly coordinated. Similarly, circuit breaker (CB) switching sequence must be known to the coordinating engineers. (4) The under-frequency tripping of units (during controlled separation) could be avoided by operating the units under isochronous mode (i.e. speed control mode with 0% droop). (5) Due to low inertia the island frequency is sensitive to load variations & transients. Lower droop (0-2%) ensures lesser frequency fluctuation

during transients like dead bus charging, load addition etc. (6) During controlled separation the last breaker opening should be attempted at zero power flow or at an instant when the power flow is from island to main grid i.e. when the island generation is slightly higher than its load. (7) No load charging of long line is a challenge due to switching over voltage. This should be done at a reduced generator voltage (0.7-0.8 pu) during black start. Temporary change in time delay setting of over voltage relays (with generator AVR in manual mode) is advisable during network energization. (8) Gas units take longer time (~15 minutes) than hydro units to come to rated speed from stand still & vice versa. Similarly, other limitations viz. response time of DG sets etc. need to be factored while devising restoration plans. (9) Availability of dedicated voice & data communication between control centres & power stations is vital for faster restoration. Dedicated wide-band communication is advisable for remote hydro stations. (10) In view of wide variation in voltage & frequency there is high probability of magnetic core saturation of machines on over-fluxing. Thus, under-frequency relays must be kept in service. The load identification for conducting black start drills needs to be done keeping view of the expected variation in system parameters (i.e. voltage, frequency) and usage of sensitive loads should be avoided. (11) Having auto-synchronization facility in substations helps in smooth integration of island with the grid. Further, during black start, the stations need adequate flexibility for synchronization through line CB/bus coupler. Non-availability of this feature may lead to delay and loss of resources. (12) All temporary changes in settings in generator control system (AVR, Governor etc.), and protection relays must be restored after completion of the black start drill.

VII. Conclusion and Way Ahead

Black start drills immensely help in assessing grid resilience and crisis preparedness thereby identifying & plugging the gaps to ensure faster grid recovery in restorative phase. The capabilities of specific power system elements (such as a generating unit) could also be evaluated with the help of a Digital Simulator that mimics the grid conditions similar to the restorative state[11] & creates an artificial reality in order to evoke player/equipment reactions similar to real restoration situations[11]. A similar test was conducted on pilot basis with a hydro power station (180 MW Chamrea unit-3) in Northen Grid of India in October 2014 using a simulator equipment (SSPS) developed by M/s. Solvina International[12] for evaluation of the island operation capability of power turbines. It gives simulated frequency signal and a system load (corresponding to island conditions) as input to the generator & records the response. Thus, in a sumulated environment, the capability of running in island mode can be tested while the turbine is still synchronized to a large grid. Similar tests can be replicated else where in future. With increasing renewable penetration in India there has been growing emphasis on promoting flexible generation viz. hydro & gas which are capable of providing black start service in addition to several other flexibility services. Presently, testing the black start capability is a mandated activity under the grid code (IEGC) in India. However, the regulators are envisaging incentives for black start service under ancillary services in future.

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