

Static Priority Approach to Under-Frequency Based Load Shedding Scheme in Islanded Industrial Networks: Using the Case Study of Fatima Fertilizer Company Ltd - FFL

S. H. Kazmi, T. Ahmed, K. Javed, A. Ghani

Abstract—In this paper static scheme of under-frequency based load shedding is considered for chemical and petrochemical industries with islanded distribution networks relying heavily on the primary commodity to ensure minimum production loss, plant downtime or critical equipment shutdown. A simplistic methodology is proposed for in-house implementation of this scheme using under-frequency relays and a step by step guide is provided including the techniques to calculate maximum percentage overloads, frequency decay rates, time based frequency response and frequency based time response of the system. Case study of FFL electrical system is utilized, presenting the actual system parameters and employed load shedding settings following the similar series of steps. The arbitrary settings are then verified for worst overload conditions (loss of a generation source in this case) and comprehensive system response is then investigated.

Keywords—Islanding, under-frequency load shedding, frequency rate of change, static UFLS.

NOMENCLATURE

ΔP_{pu}	Per-Unit Overload
ΔF_{pu}	Per-Unit Frequency Decay
H_{net}	Net System Inertia Constant
J	Moment of Inertia in (kg – m ²)
ω	Angular speed (rad/sec)
$\frac{df_{pu}}{dt}$	Per-Unit Frequency Decay Rate (sec ⁻¹)
$\frac{df}{dt}$	Frequency Decay Rate (Hz/sec)
$F(t)$	Frequency as time function
$T(f)$	Time as frequency function
P_{load}	Demanded Load Power (kW)
P_{gen}	Available Generation Spin Reserves (kW)
GTG	Gas Turbine Generator
UFLS	Under-Frequency Load Shedding

I. INTRODUCTION

POWER generation using Island (or Isolated) method is a conventional technique of generating power in industrial

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plants all around the globe. At any given instant, these Islanded power systems either have a surplus of generation or load that exceeds the generation capacity of the system [1]. This excess in generation as well as load has the ability to disturb the operating frequency of the system [4]-[12]. The complications caused by excess of generation are easily dealt by Speed Governors by balancing the mechanical and electrical energies of the Generator. However, when the system is subjected to operate on a load greater than its generation capacity or if the governor fails to timely respond to an instantaneous increase in electrical demand (even within its generation capacity), a drop in system frequency is observed as a consequence. In case of small disturbances, the frequency decays at a low rate which gives the governor enough time to restore the frequency, provided the system has sufficient spinning reserves [6]. Hence frequency and frequency decay rate serve as the indicator for balance between supply and demand of electrical energy [2]-[15].

The frequency of the Islanded systems is severely disturbed due to continuous imbalance between generation and load demands [4]-[11]. This disturbance in frequency can lead to power collapse if not allowed to recover in time by shedding the appropriate amount of load [1], [2], [10], [11]. This decision is either static or dynamic in nature. Static algorithms employ under-frequency relays to shed predetermined quantities of load without considering the rate of frequency drop or governor response [11]-[14]. Hence because of its relative simplicity, isolated industrial networks commonly employ static method of frequency based load shedding.

Safety and downtime are the critical factors in petrochemical installations [9]. The complete load of an industrial complex especially for chemical and petro-chemical setups does not fall under same priority. It is prioritized on the basis of its effect on production of primary commodity and the total production loss resulted on its discard. The loss of primary product as the result of unplanned shutdowns on chemical and petrochemical plants is not prudent [3]. The research on UFLS schemes for prioritized loads (based on primary production loss) on islanded systems has shown that not much work has been conducted in this area [4].

This paper defines a series of steps that are required for successful in-house implementation of Static UFLS scheme. These guidelines are common to both large and small systems [7]. The remainder of this paper is structured as follows:

Section II lays down a framework for proposed step-by-step methodology to employ the aforementioned scheme and defines the necessary system parameters required to make these settings which will enable the user to fulfill each criterion in an orderly manner. These parameters include maximum percentage overload, system inertia, permissible frequency set-points and load prioritization. The proposed scheme is then explained using the case study of FFL in Section III; which provides a detailed description of system and employed UFLS settings, calculates all the system parameters presented in Section II, verifies these settings for worst predictable overload condition (generation loss in this case) and finally presents the comprehensive system response. Conclusively, Section IV gives the closing remarks for this strategy.

II. SYSTEM EVALUATION AND PROPOSED METHODOLOGY

Implementation of static load shedding philosophy requires following a series of predefined steps. On an isolated system, first and foremost, the worst overload condition is determined. Then it has to be understood that the entire load cannot be shed in a single step; it is preferred to dispense the total load to be shed in a series of stages considering the df/dt of the system with each stage dissociating a particular portion subsequently depending upon the production priority, allowing the frequency decay to settle within the prescribed limits after each step [14]. Following on, the frequency set points of each stage are decided ensuring that the last set point lays in the permissible region of the short time frequency capability curves of the alternators. Finally the least priority load to be shed in each stage is determined.

A. Minimum Allowable Frequency

The entire power system is designed and constructed for nominal frequency. The auxiliaries of an industry are more vulnerable to frequencies below minimum allowable threshold [6]. The minimum allowed operating frequency usually specified by the manufacturer according to the type of turbine is 47.5 Hz [5]. Frequency below 47 Hz must be avoided at all costs. In fact, most commercial turbines can survive up to 10 contingencies at 47 Hz (for 1 Second) without complete failure [8].

The minimum allowable frequency is obtained from the short time frequency capability curve of the generator provided by the manufacturer.

B. Determination of worst possible case and Percentage Overload

Worst possible case determines the maximum overload that the system may go through. The possible events as a result of which system frequencies are severely disturbed include loss of generation (generator, importing HVDC link), instantaneous loss of load, variations in load and generator output. Usually the loss of one or more generation source is considered to cause extreme overload instances that may cause failure of remaining generation reserves, finally resulting in complete power failure [10], [11].

Per-Unit overloads (difference between demanded Load and available Generation spin reserves per unit Available Generation spin reserves) is found using (1):

$$\Delta P_{pu} = \frac{P_{load} - P_{gen}}{P_{gen}} \quad (1)$$

C. Frequency Decay, System Inertia and Net Accelerating Torque

Inertia is the stored rotational Kinetic energy of the system. The rate of frequency decay of a system depends upon the net Inertia (2) of its generating units. In case of generation loss, higher the inertia of the system the longer it takes for that system to reach a new steady state operating frequency. While islanded systems with smaller system inertia have quick variation of frequency [4].

The inertia of a generator is represented by Inertia Constant (H) which is given as the ratio between its stored kinetic energy ($1/2 J \omega^2$) and its rated apparent power.

$$H = \frac{1/2 J \omega^2}{VA} \quad (2)$$

With a system comprising of several generating units, its net Inertia constant is given as:

$$H_{net} = \frac{\sum_{k=1}^N H_k \times VA_k}{\sum_{k=1}^N VA_k} \quad (3)$$

where, H_k is inertia constant of k_{th} generator and VA_k is Rated Apparent power of k_{th} generator and N shows number of generators.

The rate of frequency decay in terms of Net System Inertia is determined using (4) and (5)

$$\frac{df_{pu}}{dt} = \frac{\Delta P_{pu}}{2 H_{net}} \quad (4)$$

$$\frac{d\omega_{pu}}{dt} = \frac{\Delta T_{pu}}{2 H_{net}} \quad (5)$$

where ΔT_{pu} is the per-unit accelerating Torque determined as the difference between Generated and demanded Load Torques with respect to Generated Torque at base frequency f_o .

D. Time Function and Frequency Function

In order to determine Frequency and Time functions, (4) can be manipulated into (6) and (7)

$$F(t) = f_o \left(1 - \frac{\Delta P_{pu}}{2 H_{net}} t \right) \quad (6)$$

$$T(f) = \frac{\left(1 - \frac{f}{f_o} \right)}{\frac{\Delta P_{pu}}{2 H_{net}}} \quad (7)$$

Considering (5), the decayed frequency under any overload condition with respect to machine's permissible frequency-decay-duration "t" after disturbance can be determined. Similarly (6) helps in determining the time taken by the system in to reach the frequency set-point "F". Both the frequency set-points and permissible duration are obtained from the short time frequency capability curves of individual generation units.

E. Load Shedding Steps and Per-Unit Load to Be Shed:

An extremely important action in this conquest is to determine the total number of steps to shed the entire load and to decide the percentage load that is to be shed in each step. The frequency set-points and frequency decay rates are directly affected by the decided number of predefined steps; greater the number of steps lesser the time for the system to respond to frequency disturbances [13]. The frequency set-point for each step is selected to ensure safe operation of the generator within the permissive region of short-time-frequency capability curve even on reaching the last stage. According to PRC-006-1 UFLS criteria, there should be a minimum of three load shedding stages with the first set-point preferably lying on the threshold point of continuous allowable operation of the machine.

In the proposed scheme, the percentage load to be shed in each stage is chosen on the basis of priority. The load of entire facility is divided in to priority blocks with first step shedding the block having the least priority. The size of each block must be chosen to ensure complete recovery of system frequency by the end of final step in case of worst overload condition

F. Recommended Strategy

The scheme proposed in Fig. 1 gives a simplified approach for UFLS Implementation. This strategy utilizes the parameters already defined. Reference A in Fig. 1 utilizes (2), (3), (6) and (7); while verification of settings for worst overload conditions in Reference B are explained using FFL case study in Section III.

III. CASE STUDY OF FFL

A. System Description

The power system of Fatima Fertilizer Company Ltd (FFL) successfully employed this scheme in July 2011. The FFL system runs at 11kV consisting of two Gas Turbine Generation units with 26.25 MVA rated capacity each and one Emergency Diesel Generator (3.2 MVA) which is brought into service in case of total black out only. The complex itself comprises of 11 sub-complexes and the maximum load can mount up to 28.80 MW at pf 0.81, which is segregated into four priority blocks as shown in Fig. 2. Block 'X' holds the highest priority and is avoided from being shed at all costs.

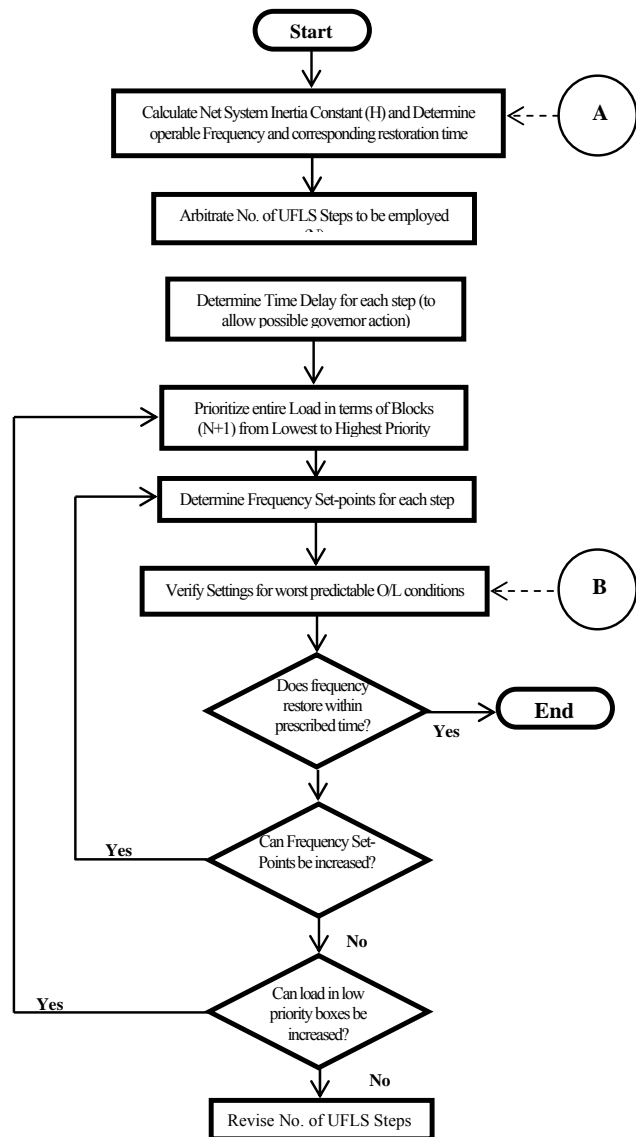


Fig. 1 Flowchart of recommended strategy for employment of proposed UFLS scheme

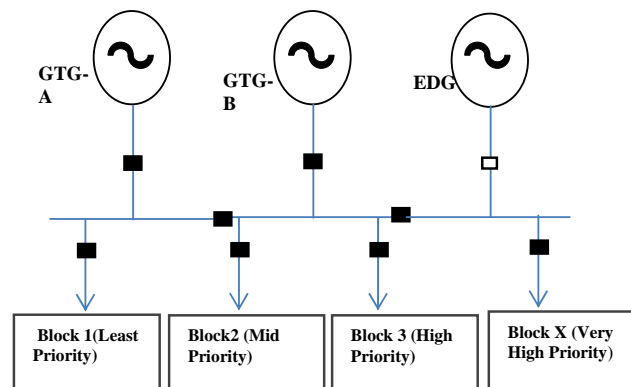


Fig. 2 Description of FFL Electrical Distribution System

B. Frequency Set Point, Load Priority and System Parameters

The UFLS Scheme at FFL is divided into 3 steps. Fig. 3 gives the short time frequency capability curve for each GTG.

The effectiveness of the employed scheme depends considerably upon the extent to which the permissive region of this curve is followed. According to the manufacturer, the alternator is invulnerable to operate within $\Delta F_{pu} = 1 \pm 0.02$ pu (49 to 50 Hz) range. But if $\Delta F_{pu} = 1 \pm 0.05$ pu (47.5 to 52.5 Hz) zone is reached the frequency must be allowed to recover in 10 seconds, and must cease to stop within 3 seconds if 50 \pm 3.75 Hz region arrives.

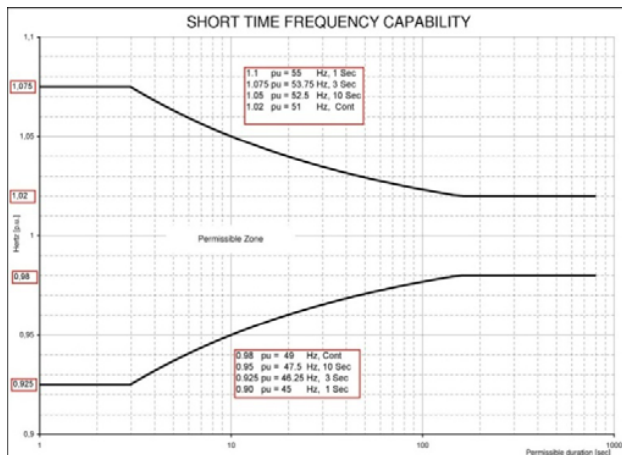


Fig. 3 Short Time Frequency Capability Curve for GTGs at FFL (provided by manufacturer)

System net Inertia is found using (2) and summarized in Table I. Tables II and III classify the load based on priority and present the scheme's necessary parameter settings for each step along with corresponding frequency set-points.

TABLE I
CALCULATION OF FFL SYSTEM NET INERTIA

GTG	Rated MVA	H in seconds (Manufacturer Data)	Hnet (s)
A	26.25	7.74	7.74
B	26.25	7.74	

TABLE II
PRIORITIZED LOAD BLOCKS WITH MINIMUM AND MAXIMUM RUNNING LOADS AT FFL

Priority Block Shed	Max Shed Load (MW)	Min Shed Load (MW)
Block 1	6.0	5.55
Block 2	4.8	4.5
Block 3	2.1	1.8

TABLE III
STEPWISE UFLS SETTING ATTRIBUTES AT FFL (CURRENTLY EMPLOYED)

Step	Frequency Pickup Setting (Hz)	Time Delay (ms)	Priority Block Shed	Min Shed Load (MW)	Percentage of Total Load (%)
1	49	120	Block 1	5.55	19.27
2	48.7	160	Block 2	4.5	15.62
3	48.4	180	Block 3	1.8	6.25

C. Worst Case Scenario

The system is designed for the worst overload condition which will be resulted in case of failure and tripping of one of the generation units. At extremely poor pf of 0.70, the remaining generation capacity of the system will be 18.375 MW (rounded off to 18 MW).

D. Verification of Worst Case Settings

In order to verify the effectiveness of this scheme, FFL system is considered to operate at its maximum load of 28.80 MW at instant $t=0$ and sways on to the worst predicted case. This triggers the enunciation of each step until the system frequency is restored to its permissible region of 50 ± 1 Hz.

1) Step 1

This step is initiated as soon as the first frequency set point is traversed for its set time delay. Table IV gives inclusive explanation of the first step's mechanism. At worst, the system will be overloaded by 60 % ($\Delta P_{pu} = 0.6$). The frequency drops at the rate of 1.94 Hz/s and reaches the first set-point of 49 Hz in 0.516 s. The set time delay allows the frequency to drop further to 48.767 Hz at which point Block-1 is shed.

TABLE IV
SYSTEM RESPONSE BEFORE INITIATION OF UFLS STEP1 IN CASE OF WORST OVERLOAD CONDITIONS AT FFL (CALCULATED)

Quantity	Symbol	Equation	Value
Per-Unit Overload	ΔP_{pu}	(1)	0.6
Per-unit frequency decay rate	$\frac{df_{pu}}{dt}$	(4)	0.0388 s^{-1}
Frequency Decay rate	$\frac{df}{dt}$	$\frac{df_{pu}}{dt} \times f_o$	1.94 Hz/s
Time to reach first frequency set-point	T (49)	(7)	0.516 s
Total time to shed Block-1	T _{step1}	T (49) + 0.120	0.636 s
Frequency at $t = T_{\text{step1}}$	F(0.686)	(6)	48.767 Hz

2) Step 2 and Step 3

Following the shed of Block-1, the rate of frequency-decay decreases, which is perceivable in Fig. 4. Tables V and VI summarize the mechanisms of Step 2 and 3 respectively.

TABLE V
SYSTEM RESPONSE BEFORE INITIATION OF UFLS STEP2 IN CASE OF WORST OVERLOAD CONDITIONS AT FFL (AFTER COMMENCEMENT OF STEP1)

Quantity	Symbol	Equation	Value
Per-Unit Overload	ΔP_{pu}	(1)	0.2917
Per-unit frequency decay rate	$\frac{df_{pu}}{dt}$	(4)	0.0188 s^{-1}
Frequency Decay rate	$\frac{df}{dt}$	$\frac{df_{pu}}{dt} \times f_o$	0.94 Hz/s
Time to reach first frequency set-point	T (48.7)	(7)	0.073 s
Total time to shed Block-2	T _{step2}	T (48.7) + 0.160	0.233s
Frequency at $t = T_{\text{step2}}$	F(0.233)	(6)	48.553 Hz

TABLE VI
SYSTEM RESPONSE BEFORE INITIATION OF UFLS STEP3 IN CASE OF WORST OVERLOAD CONDITIONS AT FFL (AFTER COMMENCEMENT OF STEP2)

Quantity	Symbol	Equation	Value
Per-Unit Overload	ΔP_{pu}	(1)	0.0417
Per-unit frequency decay rate	$\frac{df_{pu}}{dt}$	(4)	0.0027 s ⁻¹
Frequency Decay rate	$\frac{df}{dt}$	$\frac{df_{pu}}{dt} \times f_o$	0.134 Hz/s
Time to reach first frequency set-point	T (48.4)	(7)	1.170 s
Total time to shed Block-3	T _{step3}	T (48.4) + 0.180	1.35 s
Frequency at t = T _{step3}	F(1.35)	(6)	48.376 Hz
			@ f _o = 48.553 Hz

3) Frequency Restoration

Once all the steps are prompted, the direction of frequency decay slope is shifted which restores the frequency back to its permissible region of 49 Hz in 3.425 seconds which is shown in Table VII.

TABLE VII
SYSTEM RESPONSE AFTER IN CASE OF WORST OVERLOAD CONDITIONS AT FFL (AFTER COMMENCEMENT OF ALL UFLS STEPS)

Quantity	Symbol	Equation	Value
Per-Unit Overload	ΔP_{pu}	(1)	-0.0583
Per-unit frequency Rise rate	$\frac{df_{pu}}{dt}$	(4)	-0.0038 s ⁻¹
Frequency Rise rate	$\frac{df}{dt}$	$\frac{df_{pu}}{dt} \times f_o$	-0.188 Hz/s
Time to reach permissible frequency zone	T (49)	(7)	3.425 s
			@ f _o = 48.376 Hz

4) Comprehensive System Response

By virtue of this priority based static UFLS scheme, when FFL system is allowed to undergo the worst predicted overload condition it takes a total of 5.644 seconds for the system frequency to drop down to the minimal value of 48.376 Hz and return to its allowable region of 49 - 51 Hz. Table VIII explains this expedition and its results are plotted in Fig. 4.

TABLE VIII
COMPREHENSIVE SYSTEM RESPONSE IN CASE OF WORST OVERLOAD CONDITIONS AT FFL

Accumulated Time (s)	Interval	Interval Time (s)	Frequency (Hz)
0.000	Interval 1 (Initiation of Step-1)	0.000	50.000
0.516		0.516	49.000
0.636		0.636	48.767
0.709	Interval 2 (Initiation of Step-2)	0.073	48.699
0.869		0.233	48.553
2.039	Interval 3 (Initiation of Step-3)	1.170	48.400
2.219		1.350	48.376
5.644	Interval 4 (Frequency Restoration)	3.425	49.000

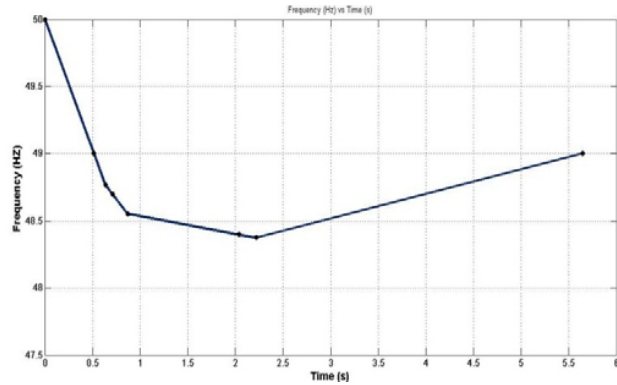


Fig. 4 Graphical Comprehensive System Response in case of worst overload conditions at FFL (Frequency versus Time)

IV. CONCLUSION

This paper has drafted a simplified strategy for employing UFLS scheme using under-frequency relays. The static approach presented in this paper can be utilized by islanded industrial systems using distributed generation techniques, especially chemical and petrochemical plants looking to prevent shutdown of critical plant equipment or minimize the primary commodity's production loss in case of generation failure or other overload conditions.

The case study of FFL discussed in this paper uses this scheme and theoretical calculations conclude that, on a comprehensive note, FFL system restores system frequency within the permissible operable range in less than 6 seconds in case of worst overload conditions.

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