The Dependency of Bus Voltage and Frequency in Load Shedding

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***Abstract*—L**oad shedding schemes proposed in literature so far use voltage and frequency parameters separately. The individual consideration of these indices may not be reliable or effective, and may even lead to the over load shedding problems. Analysis of under-frequency load shedding is often done using the system frequency response models. The impact of voltage variation on the frequency deviation is not considered in these models. Furthermore, the under-voltage load shedding methods that are proposed for adjusting the under-voltage relays, do not consider the frequency behavior. This paper focuses on establishing the variation and the extent of dependence of these parameters on each other whenever a power system undergoes a disturbance due to loss of a transmission line.

Keywords- Voltage stability, Frequency stability, under frequency load shedding, under voltage load shedding.

I. Introduction

Most Load Shedding schemes proposed use voltage and frequency parameters, separately and also, the under-frequency and under-voltage relays work in the power system without any coordination. The individual use of these indices may not be reliable/effective, and may even lead to the over load shedding problems. These two parameters (voltage and frequency) are not independent and the coordination between UFLS and UVLS schemes is therefore crucial. The dependency between voltage and frequency will affect LS performance. The following paragraphs present several methods that consider these parameters separately.

One of the methods that consider only the voltage is suggested [1]. In this method, load shedding is carried out in two in conditions. One, where the load shedding occurs due to a post disturbance low voltage condition and secondly, where the load shedding results due to the inability of the system to achieve a stable operating condition during post disturbance. This method uses the load flow in order to decide the buses from which to shed load. The initial set of control actions are first carried out. These actions are capacitor switching, tap changing transformer and secondary voltage control.

Another method that considered voltage only was developed with risk indices in order to decide which buses should be targeted for load shedding to maintain voltage stability [2]. The buses with a high risk of voltage instability are considered first. This is estimated from the probability of a voltage collapse occurrence. The risk indices are the products of these probabilities and impact of voltage collapse.

In another method, a suggestion of offering economic incentives to customers for discontinuing the use of power during load control periods is presented [3]. This way the brunt of a sudden load shed is not borne by the customer alone. Also, systematic load control will lead to the stability of the system even when it is not faced with a disturbance.

A new method for planning the VAR allocation using the FACTS devices is suggested [4]. Here, the total economic cost for a voltage collapse along with its corrective control and load shedding are taken into account to come up with the optimum VAR planning scheme. Thus, the objective function is to minimize the cost while keeping in mind the voltage stability of the system.

A method that uses distributed controllers which are delegated with a transmission voltage and a group of loads to be controlled is presented [5]. Each controller acts in a closed loop, shedding loads that vary in magnitude based on the reference voltage. Each controller acts on a set of electrically close loads and monitors the voltage of the closest transmission bus in that area. The controller is rule based where the rules are simple if-then statements.

A method that considers the frequency separately is presented [6**]**. In this method, the System Frequency Response SFR and the Under Frequency Load Shedding UFLS are used together to get a closed form expression of the system frequency such that the UFLS effect can be included in it. The system and UFLS performance indicators can then be calculated. Thus these indicators can be used efficiently in any further optimization techniques of SFR – UFLS model. One such method has been discussed using the regression tree [7]. The regression tree is utilized to interpolate between recorded data to give an estimate of the frequency decline after a generator outage. It is a non-parametric method which can select the system parameters and their relations which are most relevant to the load imbalance (due to generator outage) and the frequency decline. The case considered here is only a generator outage but this method can be applied to other forms of disturbances as well.

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A Kalman filtering-based technique [8] estimates frequency and its rate of change which is beneficial for load shedding. The noisy voltage measurements are used to estimate the frequency and its rate of change. A three-state extended Kalman filter in series with a linear Kalman filter is used in a two stage load shedding algorithm. The output of the three stage Kalman filter acts as the input to the linear Kalman filter. It is the second filter which identifies linear components of the frequency and its rate of change. The amount of load to be shed is calculated using the linear component of the estimated frequency deviation.

The methods discussed above clearly consider both frequency and voltage parameters in the analysis of load shedding. However these parameters are considered separately. The dependency between these parameters in the proposed methods of load shedding is missing. These two parameters are not independent and the coordination between UFLS and UVLS schemes is therefore crucial. It is therefore important to establishing the extent of dependence of these parameters on each other whenever a power system undergoes a disturbance due to loss of a transmission line.

II. METHODOLOGY

The IEEE 14-bus system was selected for the study. The data for the system is readily available and this would ensure the validity of the results obtained. The power flow analysis was first carried out using the fast decoupled power flow technique to establish the loading levels of various transmission lines in the system. The main idea in this step is establish the heavily loaded line whose loss is likely to affect the performance of the entire system. This analysis was carried out using Power system Analysis Toolbox (PSAT). PSAT is a Matlab toolbox for static and dynamic analysis and control of electric power systems.

Equation 1 represents a linealized model of power system at an operating point

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_{11} & J_{12}\\ J_{21} & J_{22}\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \qquad (1)$$

By letting $\Delta P = 0$ in equation 1

$$\Delta P = 0 = J_{11}\Delta\theta + J_{12}\Delta V,\ \ \Delta\theta = -J_{11}{}^{-1}J_{12}\Delta V \qquad (2)$$

and

$$\Delta Q = J_{21}\Delta\theta + J_{22}\Delta V \qquad (3)$$

Substituting equation 2 into equation 3

$$\Delta Q = J_R\Delta V \qquad (4)$$

where

$$J_R = \left[J_{22} - J_{21}J_{11}{}^{-1}\ J_{12}\right]$$

J_R is the reduced Jacobian matrix of the system

Equation (4) can be written as

$$\Delta V = J_R{}^{-1}\Delta Q \qquad (5)$$

Eigenvalue analysis of J_R results in the following:

$$J_R = \Phi\Lambda\Gamma \qquad (6)$$

Where

Φ = right eigenvector matrix of J_R

Γ = left eigenvector matrix of J_R

Λ = diagonal eigenvalue matrix of J_R

Equation (5) can be written as

$$J_R{}^{-1} = \Phi\Lambda^{-1}\Gamma \qquad (7)$$

Equation (5) can be written as

$$\Delta V = \Phi\Lambda^{-1}\Delta Q \qquad (8)$$

or

$$\Delta V = \sum_i \frac{\Phi_i\Gamma_i}{\lambda_i}\Delta Q \qquad (9)$$

Where λ_i is the ith eigenvalue, Φ_i is the ith column right eigenvector and Γ_i is ith row left eigenvector of matrix J_R

The ith modal voltage variation is:

$$\Delta V_{mi} = \frac{1}{\lambda_i}\Delta Q_{mi} \qquad (10)$$

From equation (10) large values of λ_i suggests small changes the modal voltage for reactive poewer changes. As the system is stressed, the value of λ_i becomes smaller and the modal voltage becomes weaker. Once the minimum eigenvalues and the corresponding left and right eigenvectors have been calculated the participation factor can be used to identify the weakest node or bus in the system. The weakest mode and the buses parcipating in this mode was determined using PSAT.

A Matlab m-file was developed to compute the eigevalues,the parcipating factor of ith mode, and time domain simulation of the system.

```
% Initialize PSAT
initpsat;
 %Set data file testcase3.mdl
runpsat('testcase4_mdl','data');
 %Solve base case power flow
runpsat('pf');
 % Write current power flow solution
runpsat('pfrep');
 %Carry out time domain simulation
runpsat('td');
 %Invoke GUI for plotting results
fm_plotfig()
```

During the simulation a circuit breaker associated with the heavily loaded line activated at time $t = 10\ seconds$ The frequency and voltage at the buses was captured and ploted.

III. RESULTS AND ANALYSIS

Table I and table II shows the results obtained from power flow. Table II shows that line 11 connected between Bus 1 and Bus 2 was the most heavily loaded line and its loss would be significant to the performance and equilibrium of the system. It's for this reason that this line was chosen for investigation.

Table III represents the eigenvalues of reduced Jacobian matrix of the system. The eigenvalues gives the most critical mode to system voltage instability. The system has all eigenvalues real parts being positive indicating that the system is statically stable. The most critical mode was mode 9 whose eigenvalue had the smallest real part value of 1.0722

Table IV and figure 1 shows that the most associated bus was Bus 14 followed by Bus 10, Bus 12 and Bus 9. Bus 1 and Bus 2 were least associated with instability.

Figures 2, 3,4,5,6,7 and 8 represent the response of frequency and voltage on various buses when circuit breakers associated with line 11 are opened at time t= 10s. The system became unstable at t = 13.13 sec. Immediately the line was opened, the voltage in all the buses dropped significantly. A similar response of a drop was found with bus frequencies. However there was rise in frequency in most critical buses with Bus 14 frequency rising almost immediately followed by Bus 10 and the Bus 13. Both the frequency and voltage of the least critical buses 1 and 2 dropped when line 11 opened."

Table I Power Flow Results

From Bus	To Bus	Line	P Flow (p.u)	Q Flow (p.u)	P Loss (p.u)	Q Loss (p.u)
Bus 2	Bus 5	1	0.57838	0.07	0.01785	0.01885
Bus 6	Bus 12	2	0.11407	0.04591	0.00162	0.00338
Bus 12	Bus 13	3	0.02704	0.02014	0.00023	0.00021
Bus 6	Bus 13	4	0.25989	0.14446	0.00511	0.01006
Bus 6	Bus 11	5	0.1186	0.12844	0.00254	0.00531
Bus 11	Bus 10	6	0.06706	0.09793	0.00108	0.00252
Bus 9	Bus 10	7	0.06013	-0.01389	0.00012	0.00031
Bus 9	Bus 14	8	0.12001	0.00518	0.00179	0.0038
Bus14	Bus 13	9	-0.09038	-0.06862	0.00221	0.00451
Bus 7	Bus 9	10	0.37857	0.22523	0	0.01989
Bus 1	Bus 2	11	**2.4172**	**-0.38062**	**0.10291**	**0.2557**
Bus 3	Bus 2	12	-1.0022	0.13952	0.04747	0.15375
Bus 3	Bus 4	13	-0.31661	0.19184	0.00947	-0.01071
Bus 1	Bus 5	14	1.1031	0.09865	0.05928	0.19231
Bus 5	Bus 4	15	0.84856	-0.13731	0.00978	0.01805
Bus2	Bus 4	16	0.7825	0.05026	0.03285	0.06063
Bus 5	Bus 6	17	0.64936	0.0724	0	0.09291
Bus 4	Bus 9	18	0.21456	0.04349	0	0.02514
Bus 4	Bus 7	19	0.33402	-0.06267	0	0.02958
Bus 8	Bus 7	20	0	0.33402	0	0.01654

Table II Line Flow Results

BUS	Voltage (p.u)	Phase (rad)	P Gen (p.u)	Q Gen (p.u)	P Load (p.u)	Q Load (p.u)
Bus 1	1.06	0	3.5203	-0.28197	0	0
Bus 2	1.045	-0.13568	0.4	0.9486	0.3038	0.1778
Bus 3	1.01	-0.33212	0	0.59736	1.3188	0.266
Bus 4	0.99782	-0.26441	0	0	0.6692	0.056
Bus 5	1.0029	-0.22695	0	0	0.1064	0.0224
Bus 6	1.07	-0.36956	0	0.44433	0.1568	0.105
Bus 7	1.036	-0.33938	0	0	0	0
Bus 8	1.09	-0.33938	0	0.33402	0	0
Bus 9	1.0129	-0.37908	0	0	0.413	0.2324
Bus 10	1.0122	-0.38446	0	0	0.126	0.0812
Bus 11	1.0357	-0.37984	0	0	0.049	0.0252
Bus 12	1.0462	-0.39059	0	0	0.0854	0.0224
Bus 13	1.0366	-0.39147	0	0	0.189	0.0812
Bus 14	0.99695	-0.41056	0	0	0.2086	0.07

Table III Eigenvalues of the Dynamic Power Jacobian Matrix

Eigen value	Most Associated Bus	Real Part	Imaginary Part
1	Bus 1	1601.9991	0
2	Bus 4	64.6693	0
3	Bus 2	49.3833	0
4	Bus 9	38.7603	0
5	Bus 6	31.9118	0
6	Bus 3	24.3448	0
7	Bus 7	21.8383	0
8	Bus 13	17.3558	0
9	Bus 14	**1.0722**	0
10	Bus 11	12.6507	0
11	Bus 4	10.9946	0
12	Bus 12	3.9803	0
13	Bus 8	7.3388	0
14	Bus 14	6.2626	0

Table IV Participation Factors of Buses in the Most Critical Mode 9

Bus	Participation Factor	Bus	Participation Factor
Bus 1	0	Bus 8	0.0239
Bus 2	0.00147	Bus 9	0.11274
Bus 3	0.00202	Bus 10	0.1358
Bus 4	0.01644	Bus 11	0.12725
Bus 5	0.01467	Bus 12	0.12901
Bus 6	0.07214	Bus 13	0.1248
Bus 7	0.06038	Bus 14	0.17939

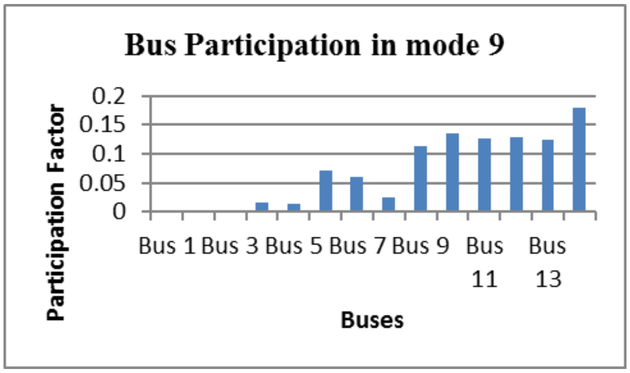

Fig 1: Bus participation in mode 9

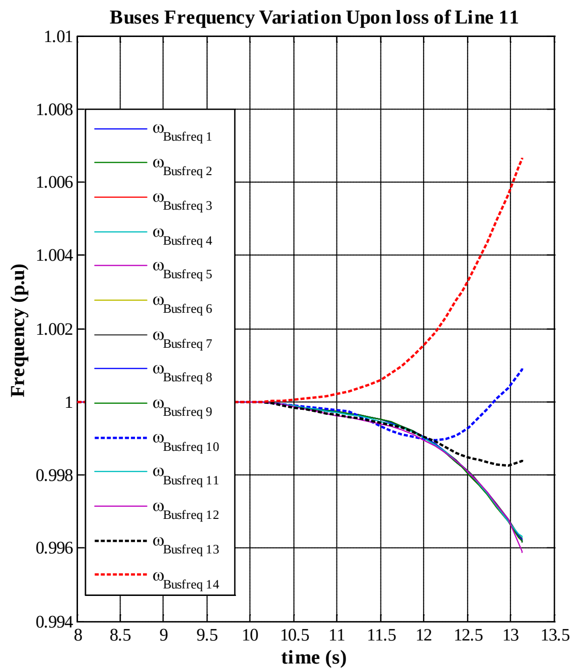

Fig 2: Bus Frequency Variation Upon Loss of Line 11

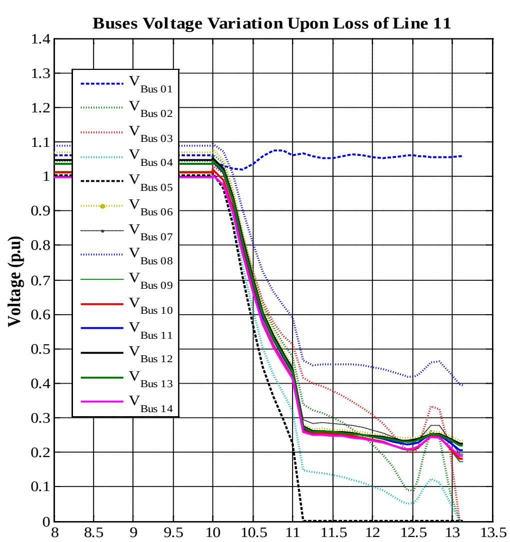

Fig 3: Bus Voltage Variation Upon Loss of Line 11

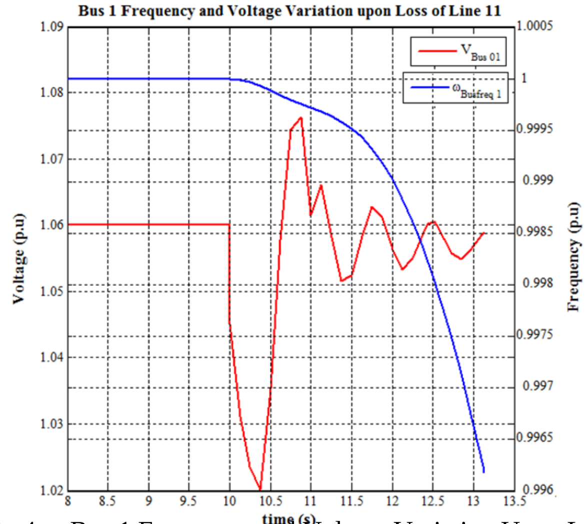

Fig 4: Bus 1 Frequency and Voltage Variation Upon Loss of Line 11

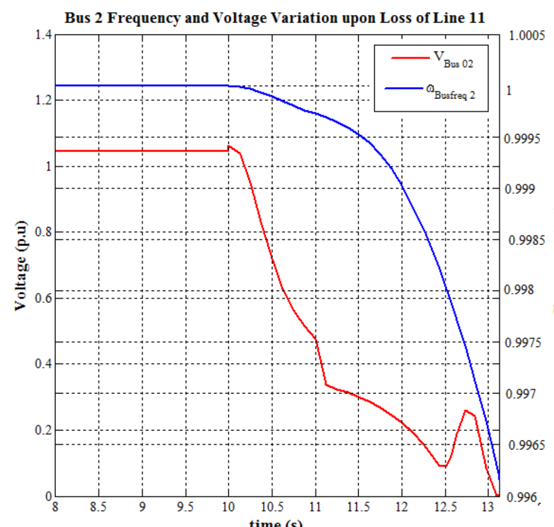

Fig 5: Bus 2 Frequency and Voltage Variation Upon Loss of Line 11

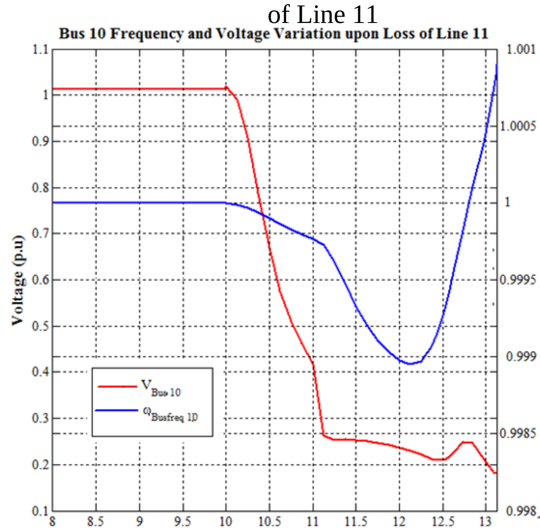

Fig 6: Bus 10 Frequency and Voltage Variation Upon Loss of Line 11

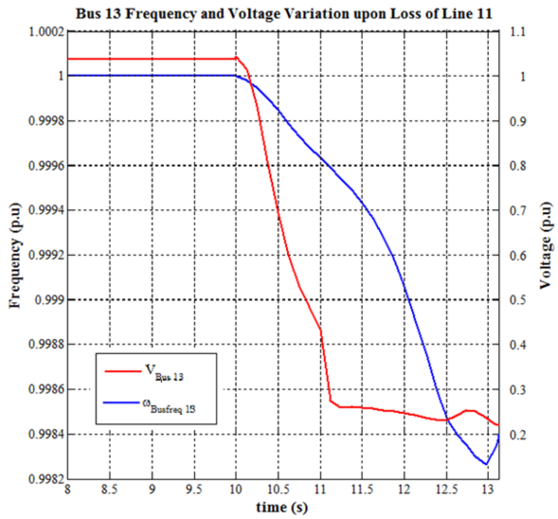

Figure 7: Bus 13 Frequency and Voltage Variation Upon Loss of Line 11

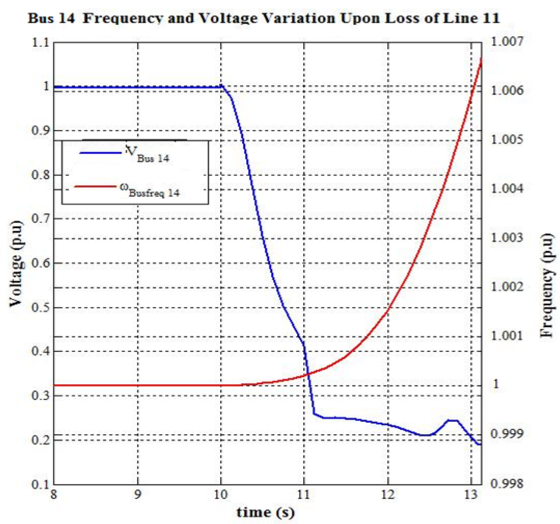

Figure 8: Bus 14 Frequency and Voltage Variation Upon Loss of Line 11

IV. Conclusion

The Loss of a High Voltage transmission line affects both bus voltage and bus frequency. Immediately the line is lost voltage drops significantly in all the buses. However the frequency on critical buses immediately rises while that on least critical buses drops. In this research only one disturbance was considered. There is therefore need for further research on the effects of other disturbances like load loss on the system buses voltage and frequency.

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