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PSSE-Based Dynamic Simulation of Western Regional Grid of India

Kamaljyoti Gogoi[1], Saibal Chatterjee[2]

[1]Department of Electrical Engineering, NERIST, Arunachal Pradesh, Nirjuli, India
[2]Department of Electrical and Electronics Engineering, NIT Mizoram, Aizawl, Mizoram, India

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ABSTRACT

Among the five regional grids of India, the Western Regional (WR) grid is the one consisting of voltage levels 765 kV, 400 kV, and 220 kV. The WR grid is considered as the spinal cord of the Indian grid as it delivers power to most of the heavy industrialized states, and hence is selected for analysis. In order to determine the weak area of the grid and perform stability studies, the L-Index algorithm is generally used. But for computation of maximum deviation of frequency, minimum time of voltage recovery, and critical clearing time (CCT) of the buses in a more detailed manner, the L-Index method is not infallible. Hence, for computing various parameters of the WR grid in a more detailed manner, dynamic simulation is performed. The WR grid has been modeled using 584 buses of voltage levels higher than 220 kV and transmission lines spread over the entire grid length of 86 220 km. In this work modeling, simulation and detailed analysis of the WR grid is accomplished. The L-Index algorithm clubbed with dynamic simulation provides the option of detailed analysis and computation of important parameters of the system, along with the prediction of weak area, which also acts as a parameter for designing various electrical protective equipment to be utilized in the grid.

***Index Terms*—**Dynamic simulation, L-Index, Critical clearing time

I. INTRODUCTION

The recent growth of industries in the country has led to increased electrical energy consumption. The importance of the transmission system of the country has increased exponentially with an increase in load in cities and crowded places as generation usually happens at remote places [1]. The evolution of generation and efficient transmission system at remote places takes place because of scarcely available natural resources at desired locations [2]. With the demand in load increasing every 4–5 years in major emerging economies like India, generation capacity of stations and the number of stations should proportionately increase [3, 6, 7]. Power flow study and analysis lead to innovation, expansion, and modernization of generation and transmission facilities [4]. After planning and designing the grid model, load flow studies is generally performed by electrical engineers before implementing the network. It ensures optimal and efficient performance besides maintaining standard safety measures and protocols [5, 6]. Power flowing in and out of each of the buses is the summation of the total power flowing in the terminals connected to the bus [6, 7]. Load flow also known by the name power flow is an analysis based on steady state that determines the power, voltage, and current flowing in the system in a predefined loading condition [8]. As the speed and processing power of modern day computers have evolved considerably, engineers can easily program various algorithms which help in determining the complex power flow network [5, 7].

Power grid failure is one such event which has been experienced by all major grids across the world in the past. Cascading failure of power in the Indian grid and the maximum transmission line loading capability of different regions is analyzed and presented in [9]. The Israel Electric Corporation power failure is analyzed and discussed in [10]. The North-Western American grid's simulation studies after disturbances and the collapse which followed are emphasized in [11,12]. The failure of 2003 Europe grid and North America grid, and its subsequent collapse,

Corresponding Author:
Kamaljyoti Gogoi

E-mail:
kamaljgogoi27@gmail.com

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are analyzed in [13–15], detailing the evaluation and its consequences during the collapse. The post grid failure analysis of the Athens grid is presented in [16, 17]. Wong et al. [18] presents a detailed analysis of Taiwan power grid failure. A detailed analysis of the European power grid blackout simulation studies are presented in [19]. Topological analysis and a detailed investigative study of the Indian-Eastern grid on the basis of graph theory is presented in [20].

Studies and analyses of different grids around the world [9-20] have facilitated the need to identify different constraints such as the maximum frequency deviation, minimum voltage recovery time, and the critical clearing time (CCT) after a small disturbance in the bus. Along with identification and computation of the weak area of the grid, severity of the effect on the respective weak buses and its parameters are also crucial for a more detailed analysis of the grid. A novel index named bus performance index is derived for identification of the area that's more prone to voltage collapse of the grid based on voltage sag and severity index in which bus performance can also be computed and is presented in [21]. Liao et al. [22] describes the impact of the Sag severity index using single-event indices constituting four numerical indices and a fuzzy voltage sag index for prediction of the weak area in the network. Voltage stability analysis based on the power voltage (PV) method to compute the margin index of voltage stability for determination of weak zones in bulk transmission in a grid is described in [23]. Artificial Neural Network (ANN) based weak zones or area determination of a system have been studied and analyzed along with voltage blackout investigation using the L-Index [24].

There are five regional grids in India having an installed generation capacity of 302 GW. In this paper, an analysis has been done on Western Regional (WR) grid which is operating synchronously from January 2014 with the Indian grid. The WR grid is considered as the mainstay of the Indian grid since it delivers power to most heavy industrialized states. The WR grid can also be modeled in line with the Eastern and North-Eastern Regional grids of India for detailed study and analysis [25-28]. Hence for detailed study and analysis, the WR grid has been selected and the weak location of the grid is identified. A detailed study and modeling of the Eastern Regional grid of India is presented in [28]. Dynamic simulation studies of the Eastern Regional grid is discussed and analyzed along with determination of the weak bus [29].

In this work, the WR grid is modeled with the help of PSSE, Siemens's commercial software for load flow analysis [30-32]. It consists of 584 buses of voltage (AC) levels of 765 kV, 400 kV, and 220 kV. The total power generation of the WR grid is approximately 84 GW and the loading of the buses are at 80% of their capacity. The load flow solution is performed and the optimized values are computed using full Newton–Raphson method. The standard IEEE 30 bus network is used to validate the load flow solution performed using PSSE [28]. L-Index values are calculated based on steady state analyses which were derived from the load flow analysis outcome. Further, the L-Index data are organized in descending order of their magnitude which assist in determining the weak bus in the grid. Instead of predicting just the weak buses, detailed in-depth analysis is also required to be performed which facilitates the need of dynamic simulation. With the help of dynamic simulation, the minimum voltage recovery time and maximum frequency deviation after a disturbance can be computed. Furthermore, the CCT of buses more susceptible to voltage breakdown can also be determined. Finally the weak areas are determined, and hence the weak bus can be obtained with pin point accuracy from these detailed analyses along with its magnitude.

The remaining part of the work is organized as follows: Section 2 is an ephemeral synopsis of the breakdown of the voltage proximity indicator also known as the L-Index indicator; Section 3 presents an overview of the CCT computation and dynamic simulation; Section 4 depicts the validation process of the load flow analysis based on PSSE and 30 bus system of IEEE; Section 5 gives an overview of the Western grid where modeling and simulation studies are performed; Section 6 comprises the results and provides detailed analysis, and Section 7 draws the conclusion and the findings.

II. VOLTAGE COLLAPSE PROXIMITY INDICATOR

The indicator based on the L-Index for voltage collapse was first coined by Glavitch and Kessel [24] and was initially developed for the dual bus system which was latter generalized for multiple buses. Here a network with x buses, namely 1, 2, …, g (generator buses) and $(g+1)$, $(g+2)$, …, x (load buses) is taken into consideration and for the analysis of the base case and power flow calculation. The results obtained are utilized in computing the data as per the L-Index equation given by (1):

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \qquad (1)$$

where $j \in$ is the load bus set; $i \in$, is the generator bus set, and V_i and V_j are the bus voltages of the ith and jth buses, respectively. From Y-bus matrix F_{ij} in (1) is derived and is shown in (2):

$$F^{LG} = [Y^{LG}]\,[Y^{LL}]^{-1} \qquad (2)$$

where, $[Y^{LG}]$ and $[Y^{LL}]$ are the sub matrices of the original matrix.

III. DYNAMIC SIMULATION AND CCT

It is usually presumed in a dynamic simulation that the plant is in continuous state of alteration. Time is the variable for consideration in a dynamic based simulation. The assumption made here is that the load of the system is continuously fluctuating with regard to the variable time [33]. By introducing minute momentary disturbances to a bus in the plant and identifying how smoothly the controlling equipment's respond to such disturbances, dynamic simulation is conditioned to scrutinize the controlling techniques [34-36]. The transient stability simulation of the New England Power System consisting of 39 buses and 10 machines using Simulink having different large disturbances is presented in [37].

The maximum possible time for which any minute disturbance can be introduced without losing the stable nature of the network is called CCT [38]. The quality and quantity of the protection required for the system can easily be determined by it. From the CCT of three-phase fault parameter data, the transient stability boundary of the network can be computed [8]. The basis of the study is a dichotomic process, where the search is performed within a user-defined interval. An automated run of a simulation process is initiated by each step of the dichotomic process which generates numerous stable and unstable states [7]. As per the user-defined specification in a dynamic simulation, stability is determined based on the analysis of the last stable and first unstable states, which further helps in detailed analysis and computation of CCT [39].

The complete dynamic simulation flow chart and its methodology is presented in Fig. 1. WR grid's specification such as data of the bus, machine, transformer, and load are provided for modeling and simulation purposes. Entire transmission lines, generators, compensators, and the transformer are kept in operating state. Simulations are performed and power flow analysis is accomplished on PSSE-based the Western grid model and checked if convergence of the system is achieved with respect to the overloading specification and voltage limit. Steady state analysis is the basis on which dynamic simulation is done on the higher power flowing bus. Initially, the simulations are performed in the base case and are run for 1 s in the steady state condition. Subsequently, a minute disturbance is added in the selected buses chronologically for the duration of 0.1 s as shown in Table IV. After the elimination of the fault at 1.1 s, the network is further simulated or run till 100 s. Additionally, three more buses having a higher value of disturbance duration are sequentially amplified in steps of 10 ms and simulations are further repeated. When the frequency of the network becomes unstable even with a minute increase of time, that point of time is called CCT.

IV. VALIDATION OF LOAD FLOW ANALYSIS BASED ON PSS/E

The IEEE standard 30 bus network is taken and modeled using PSSE software. The model is simulated by means of various Gauss Seidel and Newton–Raphson methods (including the modified ones) for better and wider range of alternatives. The optimized simulation results are presented by implementing the full Newton–Raphson algorithm [28] with minimum number of iterations while running the power flow simulation with minimum root mean square error of 2.65% as presented in Table I. The root mean square error is computed and after detailed analysis it is found to be well within the accepted limits.

The minute description of the iteration method used (Newton–Raphson) is analyzed and presented in [6].

V. DESCRIPTION OF THE STUDIED SYSTEM

The WR grid consists of five different states namely Madhya Pradesh, Gujrat, Chhattisgarh, Maharashtra, and Goa. For simulation of the model, voltage levels of 765 kV, 400 kV, and 220 kV are taken into consideration. Based on the voltage level, the WR grid is divided as presented in Table II.

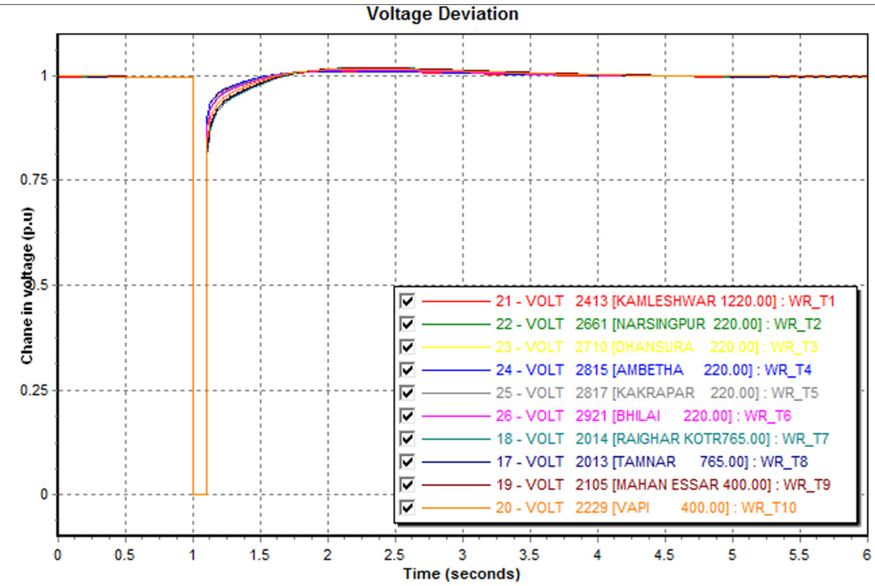

Fig. 1. Recovery Time After Voltage Deviation.

TABLE I. POWER FLOW SOLUTION METHOD [28]

S. No.	Methods Used for Solving Power Flow	No. of Iterations	% Error (RMSE)
1	Gauss Seidel	10	6.23
2	Modified Gauss Seidel	12	6.22
3	Fixed slope Decoupled Newton–Raphson	4	2.96
4	Full Newton–Raphson	2	2.65
5	Decoupled Newton–Raphson	7	3.68

TABLE II. BUS DETAILS

Voltage Level (kV)	No. of Buses	Length of Line (km)
765	17	3811
400	123	39 863
220	444	42 546

VI. RESULT AND ANALYSIS

The WR grid is modeled and simulated using a viable software from Siemens called PSSE. The optimized values are computed using the Newton–Raphson method with minimum iterations where solutions converge to a comparatively small value of tolerances (0.1 MVar and MW). At the very outset, analysis of steady state is done [40] utilizing the data of the power flow results of L-Index that are computed and arranged in decreasing order of magnitude and presented in Table III. It is observed

TABLE III. DYNAMIC SIMULATION

Sl. No.	Bus Name (Voltage in kV)	L-Index	Voltage Recovery Time (s)	Frequency Deviation (pu)
1	Raighar Kotr (765)	0.851	4.850012	0.009728
2	Tamnar (765)	0.844	4.791679	0.009101
3	Mahan Essar (400)	0.841	4.758347	0.008068
4	Narsingpur (220)	0.812	4.608349	0.006878
5	Vapi (220)	0.803	4.566683	0.006858
6	Bhilai (220)	0.786	4.500017	0.004239
7	Dhansura (220)	0.766	4.491684	0.003982
8	Kakrapar (220)	0.753	4.433352	0.003927
9	Kamleshwar (220)	0.747	4.416685	0.002989
10	Ambetha (220)	0.744	4.075024	0.002966

TABLE IV. SUMMARIZED CONCLUSION

Sl. No.	Bus Name (Voltage kV)	L-Index Bus Order	Dynamic Simulation Bus Order	Voltage Recovery Time (s)	Frequency Deviation (pu)	Critical Clearing Time (ms)
1	Raighar Kotr (765.00)	Raighar Kotr	Raighar Kotr	4.850012	0.009728	256
2	Tamnar (765.00)	Tamnar	Tamnar	4.791679	0.009101	264
3	Mahan Essar (400.00)	Mahan Essar	Mahan Essar	4.758347	0.008068	279

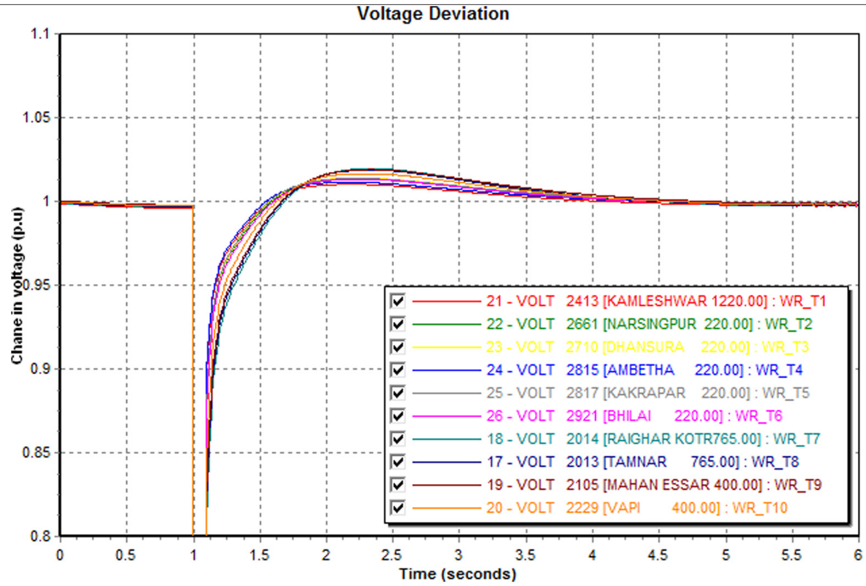

Fig. 2. Enlarged View of Voltage Deviation.

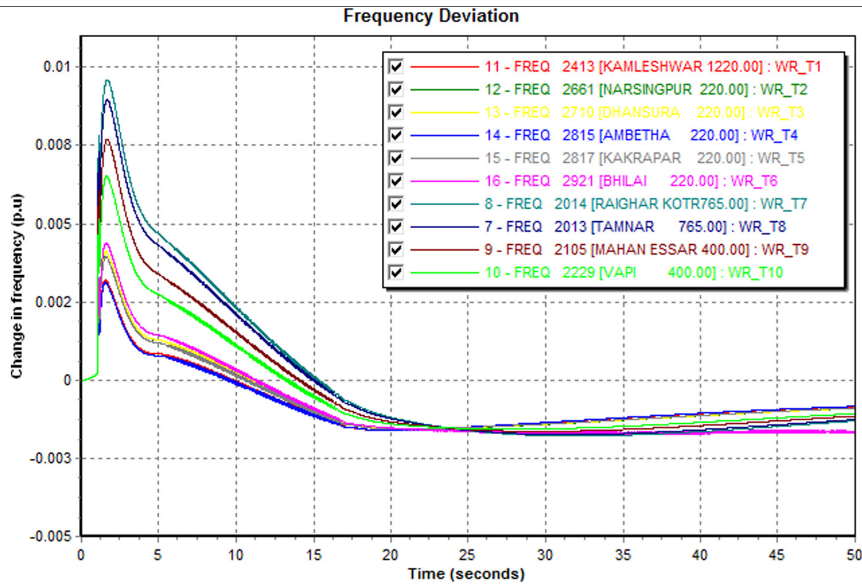

Fig. 3. Maximum Frequency Deviation.

in the results that the buses having a minimum recovery time of voltage and maximum deviation of frequency are similar in occurrence compared to the L-Index buses arrangement being in descending order.

Finally, buses with minimum time of recovery to obtain a voltage of steady state after the minute disturbance are presented in Fig. 2, and its enlarged views are given in Fig. 3. The buses with the highest deviation of frequency (pu) after a minute disturbance are shown in Fig. 4.

Deviation of frequency in the Raighar Kotr bus with minute upsurge of disturbance is presented in Fig. 5. Additionally, while computing the CCT minute disturbance incremental value as 10 ms, which is nearer to the expected result, for improved accurateness it is further reduced by 1 ms as presented in Fig. 6. Raighar Kotr Bus CCT is computed to be 256 ms from the results of the simulation data.

Deviation of frequency in the Tamnar bus with minute upsurge of disturbance is presented in Fig. 7. Additionally while

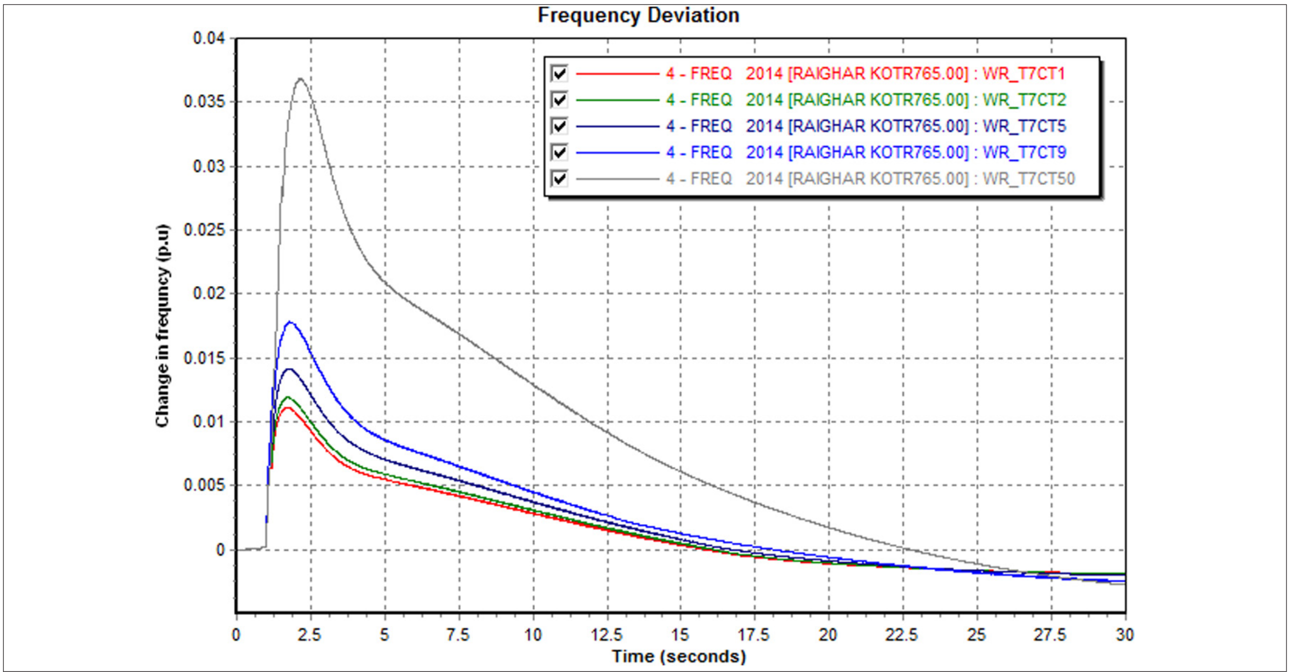

Fig. 4. Frequency Deviation in Raigarh Kotr Bus.

computing the CCT minute disturbance incremental value as 10 ms, which is nearer to the expected result, for improved accurateness it is further reduced by 1 ms as presented in Fig. 8. Tamnar Bus CCT is computed to be 264 ms from the results of the simulation data.

Deviation of frequency in the Mahan Essar bus with minute upsurge disturbance is presented in Fig. 9. Additionally while computing CCT the minute disturbance incremental value as 10 ms, which is nearer to the expected result, for improved accurateness it is further reduced by 1 ms as presented in

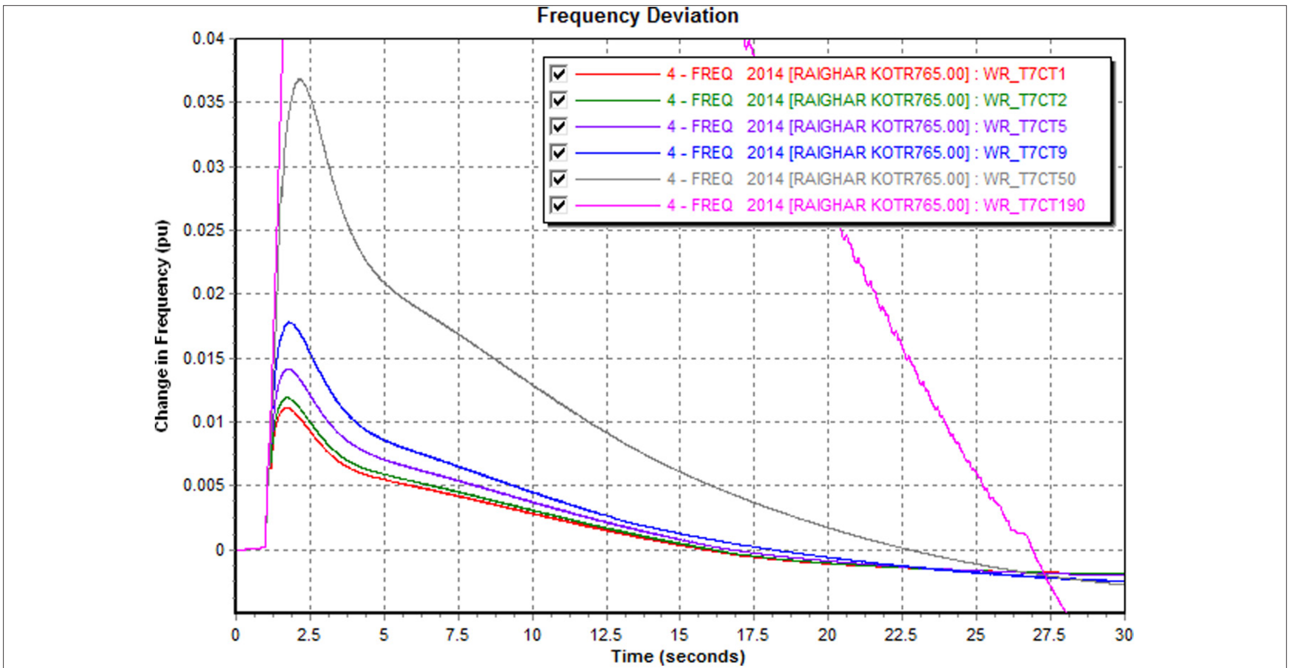

Fig. 5. Critical Clearing Time in Raigarh Kotr Bus.

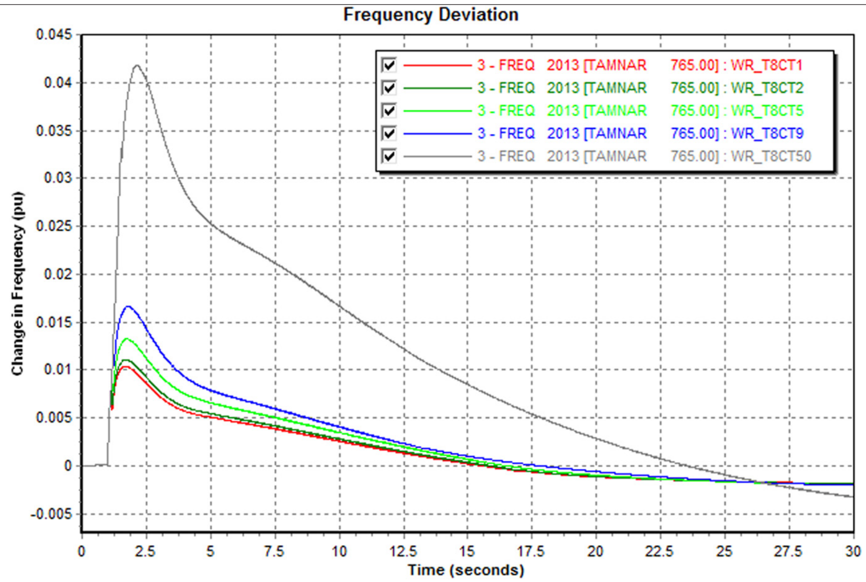

Fig. 6. Frequency Deviation in Tamnar Bus.

Fig. 10. The Mahan Essar Bus CCT is computed to be 279 ms from the results of the simulation data.

VII. CONCLUSION

This work depicts an in-depth study and analysis of the WR Power grid. Load flow simulation and detailed analysis are undertaken after using PSSE to model the WR grid. Further, using the power flow data and clubbing it with the L-Index algorithm, it can be concluded that Raighar Kotr has the maximum value of L-Index (0.764) making it more susceptible to voltage breakdown. Raighar Kotr with the maximum L-Index value ultimately becomes the utmost vulnerable to voltage collapse followed by Tamnar and Mahan Essar. Additionally, a dynamic simulation process is carried out at these buses which aids in computing the minimum recovery time of voltage and maximum deviation of frequency. Further, the CCT of buses more susceptible to voltage breakdown is also computed and found out as 256 ms for Raighar Kotr bus. So from these

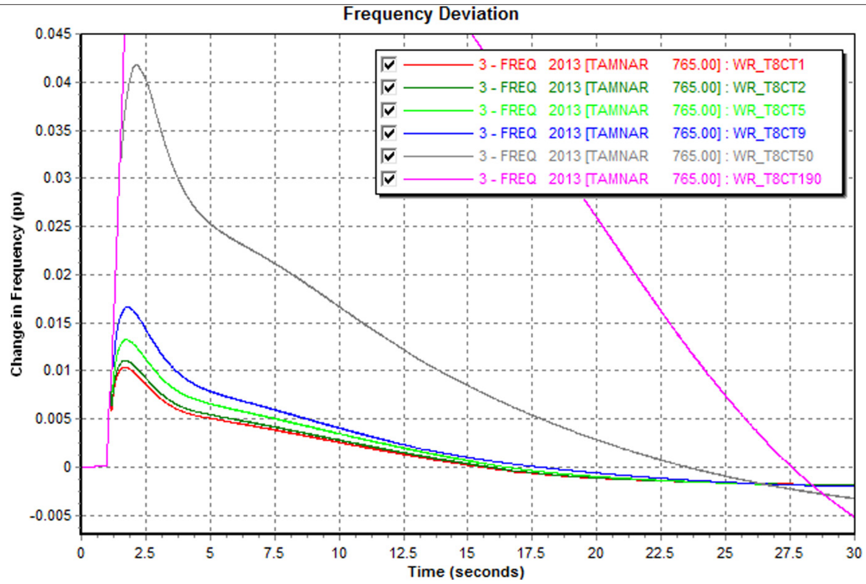

Fig. 7. Critical Clearing Time in Tamnar Bus.

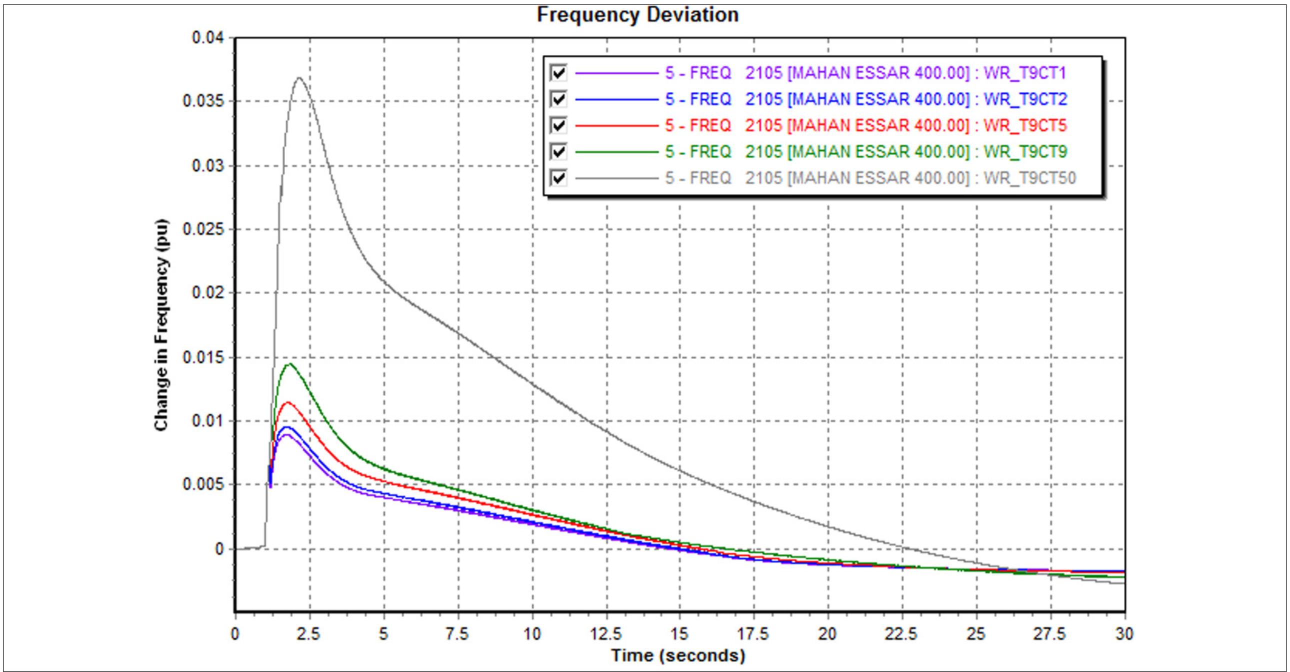

Fig. 8. Frequency Deviation in Mahan Essar Bus.

interpretations, the inference can be drawn that the weakest bus is Raighar Kotr, and eventually area adjacent to it is further susceptible to breakdown due to voltage. A complete presentation of this is given in Table IV. Henceforth, precautionary steps necessary to avoid cascading collapse in the grid should be taken. The minimum recovery time of voltage, maximum deviation of frequency, and time required for critically clearing the fault which is computed in this process ultimately becomes very helpful and in the long run can be used as the basis of designing numerous protective equipment which are to be utilized in the system.

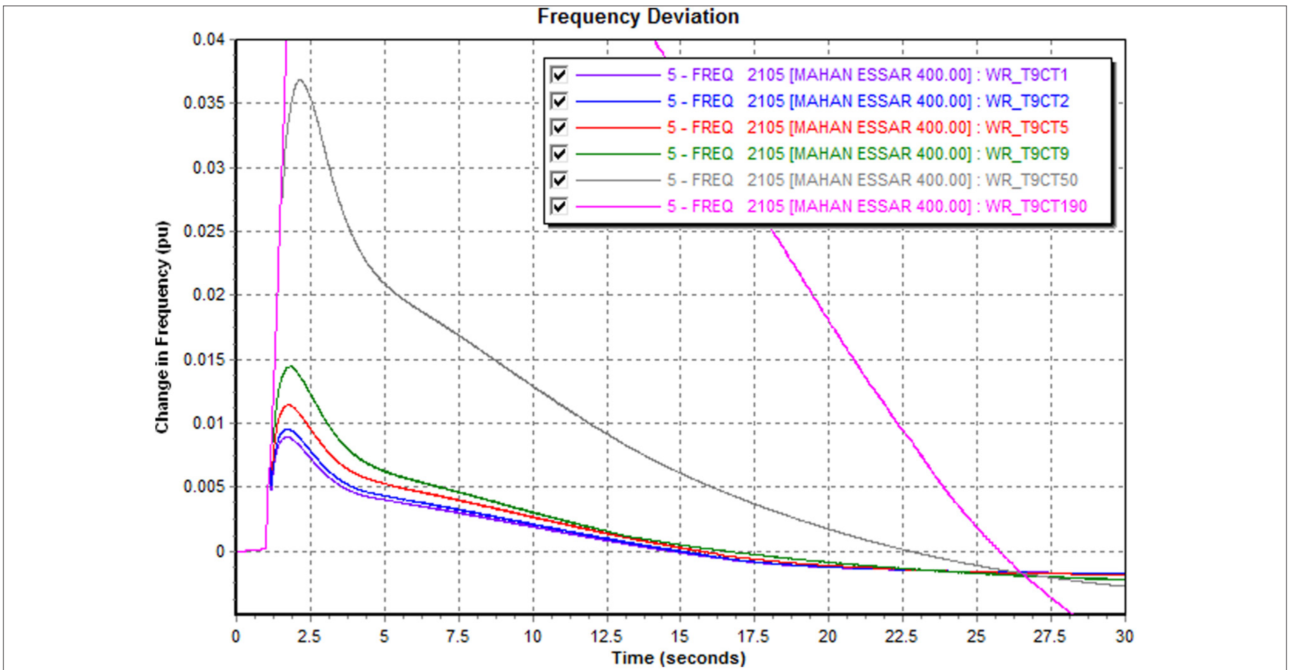

Fig. 9. Critical Clearing Time in Mahan Essar Bus.

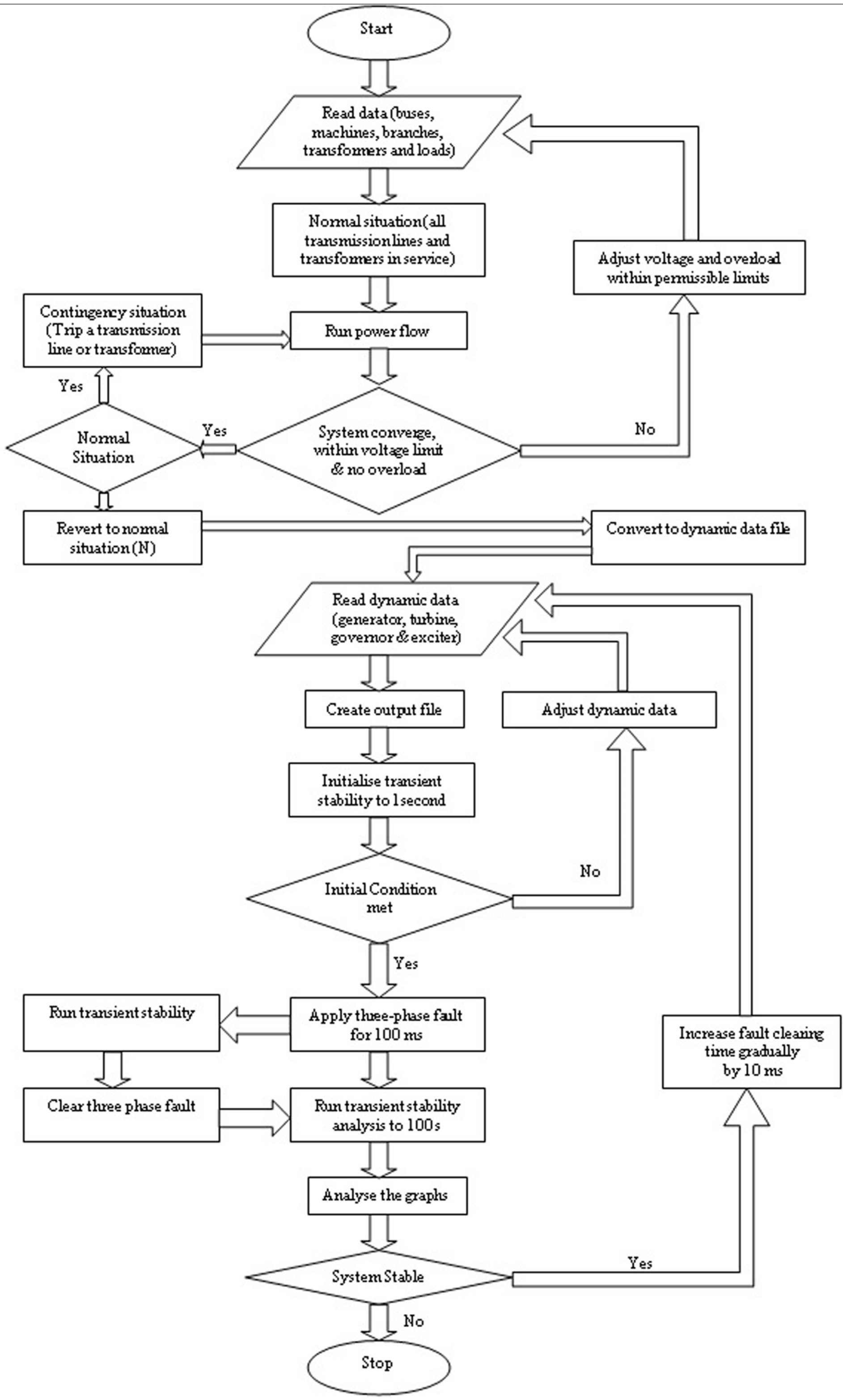

Fig. 10. Flowchart of Dynamic Simulation Performed.

Thus, the detailed analytical report proves that dynamic simulation is important in the prediction of the buses which are weak in a system using PSSE.

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Saibal Chatterjee (M'2007, SM'13) was born in West Bengal, India, on January 12, 1969. He did his graduation from NIT Durgapur. He did his post-graduation and PhD from Jadavpur University. He did his PGDIM from IGNOU. His employment experience includes Sales Engineer in ORG Limited, Howrah, for 12 months. He also worked as Shop Floor Engineer and Design Engineer in Marson's Limited, Kolkata, for 3 years. He also worked as Lecturer, Assistant Professor, Associate Professor, and Professor for 21 years in NERIST. He is now working as Professor at NIT Mizoram.

Kamaljyoti Gogoi (M'2014) was born in Bishwanath Chariali, Assam, on March 29, 1986. He did his graduation and post-graduation from NERIST (Deemed University) and is currently pursuing PhD. He did his MBA from SHIATS. His employment experience includes Site Engineer. in BCPL and NEECON for 18 months.