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Study of Different Methods of Voltage Stability Analysis

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ABSTRACT: In today's scenario, as the development is taking place simultaneously the demand for the electricity in the world is also increasing. Operation and planning of large interconnected power systems are becoming more and more complex. In power system, voltage stability plays a very important role. Voltage instability may cause blackouts and collapse of the power system. In last decade, many countries have experienced the problem of blackouts due to voltage instability. The problem of voltage stability is mainly caused due to stressed loading condition of the system. It is essential to analyse the voltage stability for improvement in the efficiency of power system. Various authors have conducted research on analysis of voltage stability and methods to improve it. This paper, presents a review on research and development in the voltage stability analysis and methods for improving the voltage stability.

KEYWORDS: Voltage Stability, Optimal Power Flow, Continuation Power Flow, Voltage Stability Index, Genetic Algorithm, Synchrophasor, FACTS devices, ANN.

I.INTRODUCTION

Voltage instability is caused due to heavily operated transmission lines and insufficient availability of reactive power. Voltage stability is defined as, "the ability of the power system to remain in equilibrium condition when subjected to the contingency" [1]. It depends on the ability of the power system to maintain or restore equilibrium between load demand and load supply. The instability results in progressive fall or rise of voltages of some buses which may result into voltage collapse of the system. Low voltage profile may results into the voltage collapse of the system which is responsible for causing blackouts. Therefore, it becomes essential to analyse the voltage stability. Main causes for the voltage instability, are listed below [2]:

1. Increased loading of transmission lines.
2. Reactive power constraints.
3. Load characteristic at low voltages.
4. Response of On Load TapChanging (OLTC) transformer.
5. Unexpected relay operations.

Voltage instability problem can be classified into large disturbance voltage stability and small disturbance voltage stability [3]. Analysis of voltage stability gives the proximity of the system towards voltage instability. The analysis of voltage stability is done by using different methods, different software and different systems. Methods for improving voltage stability include Generators AVR, under load tap changer, load shedding during contingencies and reactive power compensation [4].

II.ANALYSIS AND METHODS FOR VOLTAGE STABILITY

A*Optimal Power Flow*

An indicator termed as L –indicator which is derived from Kirchhoff law to determine voltage instability in [5]. This voltage stability indicator predicts the voltage stability margin of current operating point. The value of L-indicator lies in between 0 and 1. Lower the value of L - indicator greater is the stability margin. By using L-indicator it is used to find the impact of loads, area and power transaction. IEEE 9 bus system is used for the simulation. Optimal power flow by using Newton-Raphson method in PSAT is used. Indicator predicts the voltage stability problem accurately and properly.

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Load curtailment is one of the methods for voltage stability margin criteria of the power system [6]. For the computation of load curtailment an optimal power flow along with steady state voltage stability indicator is used. The effect of this algorithm is evaluated on the composite system. The Expected Energy Not Served (EENS) and downtime is calculated analytically and also by Monte Carlo simulation. A three bus system is taken to implement this algorithm. Load curtailment values are discussed with and without indicator. The EENS increases when system is operated with larger voltage stability margin. Down time has not much variation but in a larger system it will have a significance. Results obtained from the Monte Carlo Simulation matches closely.

B*Optimal Power Flow and Participation Factor for MW and MVAR Management*

Carolina [7] suggested a methodology to improve the voltage stability margin by economical dispatch. It is based on the methodology of active or reactive power re-dispatch for working of normal condition and also minimum load shedding during contingencies. It is to be determined by modal participation factor which is having impact on the voltage system margin and load shedding. Participation factor is obtained from the critical Eigen vector of Jacobian matrix. By using participation factor the critical area is easily found. Participation factor is obtained by optimal power flow. Modal participation factor indicates which generator should supply more or less active or reactive power for the voltage stability margin. This information is then included in the system dispatch problem and leads to final decision. Participation factor is also used for identifying most adequate buses in the system for the purpose of load scheduling. The test system studied is a Brazilian southeast system compounded by 810 buses, 96 generator and 1340 branches. Re-dispatch problem is utilized efficiently in the system for voltage stability by means of active-reactive re-scheduling and load shedding during contingencies. This system is found to be effective because of active reactive re-scheduling which maximizes the reactive resources.

Taciana [8] proposes a methodology based on optimizing generator and synchronous condensor of reactive power injections in the system. Participation factor based on the optimal power flow is calculated which aims to provide the adequate reactive power to the system and prevent the instability of the system. New England test system of 39 buses and 10 generator is taken for this methodolgy. The active participation factor is sufficient for determinig the increase or decrease in the reactive power of generator and synchronous condensor for voltage stability margin. This method reserves reactive power and improves the voltage profile in the system.

Reactive power reserve management is a method for voltage stability margin, based on the optimal power flow [9]. Participation factor for each generator is calculated on the basis of Q-V curve methodology. The Bender's decomposition methodology is applied to the reactive reserve management problem. The reactivereserve management program based on the optimal power flow is used to manage the critical reactive power reserves. For the case study reducedwestern electric coordinating council (WECC) system representing United States is taken to test the reactive reserve management program. Complete analysis is done for the reactive power management for improving the voltage stability of the system. Both static and dynamic voltage stability is improved by this method.

C *Continuation Power Flow*

Voltage stability analysis is done by using Continuation power flow method [10]. It shows how much the system is close to voltage instability. Continuation power flow method is used to obtain the P-V curve of the system which gives maximum loading of the system. Power system analysis toolbox is used for the continuation power flow. Continuation power flow method is predictor, corrector scheme which finds the solution. IEEE 14 bus system is taken for the simulation. The system is run into 2 different conditions: with and without considering generator power limits. Continuation power flow is run up to bifurcationpoint and afterreaching the maximum loading point it will stops. Voltage stability margin is easily found by this method. On further calculation the weakest bus can be found out. Three-bus system and IEEE 14 bus system is used for the analysis of voltage stability by using continuation power flow, load flow and optimization technique to determine the static voltage stability [11]. Continuation power flow and optimization are the main analysis parameters which determine the voltage stability margin or loading margin of the system. CPF method computes the successive power flow solution to calculate the voltage profile up to the collapse point. Optimization technique gives more accurate solution but it gives the solution only at optimal point. Optimization toolbox is used for load flow in MATLAB.

D.VOLTAGE STABILITY INDICES

Voltage stability analysis is done on the basis of various indices [12]. This paper performs the comparison of various stability indices for the analysis of voltage stability system on IEEE 14 bus system. Analysis of this method is done by using indices like P-V curve and Q-V curve, L-index, V/V_0 index, modal analysis, line stability index L_{mn}, line stability index FVSI, line stability index LQP, line stability index VCPI are used for the analysis. It shows the comparative study along with the analysis of performance of some online static voltage collapse indices.

Estimating the load ability of the power system is very important and it is done by using voltage stability indices (VSI) [13]. It gives the distance from current operating point to collapse point. The comparisons and effectiveness of this method is studied on IEEE 14 bus system. The analysis of this method gives two parts: (1) Proximity of voltage instability (2) Weak bus and area in the system. The main purpose of these indices is to find out the point of voltage instability and weak bus in the system. The analysis and study of system is done by using line VSI and nodal VSI for detecting the weakest area and load ability of the system. Indices provide correct predictions which provide an alarm signal for the prevention from instability.

Four indices are used for the voltage stability in transmission line and system buses in [14].Two indices are used for the system buses termed as VPI_{bus} and VQI_{bus} for the study of dynamics of load and generator.The remaining two indices VPI_{line} and VQI_{line} are used for transmission line voltage stability for the study of transmission stress and outage. These indices are fast, accurate and provide the information about maximum active and reactive power transfer in the system. This analysis is done on the IEEE 14 bus system and IEEE 118 bus system. The analytical result obtained from the indices, helps to avoid voltage collapse and prevent the system from voltage instability.

E*Voltage Stability Index Method*

D. Thukaram[15] proposes the analysis of steady state voltage stability. It is based on new operational load flow and sensitivity of reactive control variable. It mainly deals with the analysis and enhancement of steady state voltage stability based on the L index method. Case study on Indian network of82 and 217 buses is studied with the L index method. It also gives the identification of critical OLTC transformer under peak load condition for the prevention of voltage collapse.

Tellegen’s theorem and adjoin network derive the new voltage stability index in [16]. This index provides different ways for curve fitting from two consecutive phasor measurements. The main purpose for the development of local method is that local phasor directly gives the voltage instability. It is tested on the Belgian-French 32 bus system. The proposed index requires voltage and current phasor to evaluate the system stability.

New online voltage stability index based on synchronized phasor measurement is proposed to find the voltage stability of the system [17]. Thisindex is mainly designed for the determination of maximum transferable power. For the application of this index to large power system it is converted into single source power system. The voltage stability index is applied on the two power system. If the value of the index tends to zero it represents the voltage collapse condition. The output obtained from the voltage stability indices is simple, accurate and reliable hence useful for the online application of the system.

F Synchrophasor Method

Early detection of voltage instability in the system is always preferable than the actual occurrence voltage instability state. The area detection of voltage instability is obtained from the synchronized phasor measurement method [18]. Initially, set of algebraic equations are solved and sensitivity is found for the identification of combination of load powers. Time domain simulation is done on Nordic 32 test system, with and without measurement of noise. The computation of voltage instability is found by the sensitivity of the system before low voltage occurs and the effect of noise is also taken into consideration. The effectiveness of the system is observed based on availability of Phasor Measurement Unit (PMU) configuration of the system to give the exact status of voltage instability. Finally impedance matching criteria is provided but it shows poor significance in case of large-disturbance scenario. It gives the early detection of impending voltage instability.

Heng-Yi Su [19] proposes an approach that secondary voltage control using synchronized phasor measurement as a control feedback in power system. The main purpose is to improve the voltage stability by proper management of reactive power against diverse load condition. This method is feasible where load disturbances are estimated on-line for computing and feasible control input for minimization of deviation of voltage under load variable condition. Extensive simulation based on IEEE 14 bus system and IEEE 30 bus system is carried out. Main concern is on the secondary side for maintaining the constant voltage by proper adjustment of reactive power. A new adaptive synchrophasor based SVC scheme is proposed having the application of PMU with time as a control signal. Simulation results obtained on the basis of adaptive secondary voltage control (ASVC) which shows it is better than robust secondary voltage control (RSVC) and maintains acceptable voltage on the systems studied.

G*Saddle Node Bifurcation*

Ian Dobson [20] gives a method for calculation of closet saddle node bifurcation point of the system. New iterative and direct method is used for the calculation of load power at which bifurcation occurs. The nature of the load cannot be estimated hence worst case load power margin is found out for the prevention from voltage collapse. It also gives the direction of load flow when the load increases. Simulation is studied on 2 bus and 5 bus system. Iterative method is simple and robust in nature but slower for calculation.

Jin Lu [21] proposes two methods for computing the saddle node bifurcation point. First method computes the saddle node bifurcation point along a given ray of power flow equation in the parameter space that can be calculated by optimization technique. Another method used for the computation of saddle node bifurcation point is locating closet saddle node bifurcation point with the current operating point. This method uses an iterative approach for the computation. Comparison of these methods on two test systems shows the efficiency and robustness for the calculation of saddle node bifurcation point.

The fast computation method is proposed to estimate the load power margin with respect to saddle node bifurcation point under the generator and branch contingencies for the evaluation of voltage stability in [22]. The method proposed is based on the linear sensitivity. Linear estimations are taken into account by considering the non linearities of power flow equations and fast search technique. Simulation on IEEE 14, 30 and 57 bus systems is analysed. Computation time for the contingency is calculated and the error is not more than 15% and 5% in case of branch and generator outage contingency respectively. This method can be reliably applied in contingency condition.

Magnus Perninge [23] proposed the risk estimation of critical time to voltage instability by saddle node-bifurcation with various loading condition. Stochastic method is used for predicting the voltage collapse. For the estimation of accuracy of the system Monte Carlo Simulation method is used. The difference between actual critical time and estimated critical time depends on the distance from current operating point to saddle-node bifurcation set. The uncertainties are modelled by linear combination with time which is changed by Brownian motions. The method employed is fast and reliable and can be used by daily operations.

H*Genetic Algorithm*

Optimal reactive power dispatch problem is one of the difficult optimization problems in the power system. Reactive power dispatch problem include the maximum use of efficiency of existing generator bus voltage magnitude, transformer tap setting and output of reactive power sources to reduce the losses and maintain the voltage stability [24]. These parameters are taken as optimization variables. An improved genetic algorithm is used for the computation of this optimization problem. The effectiveness of this method is studied on IEEE 30 bus system. The application of genetic algorithm is made for the reactive power dispatch problem and stability assessment of the system is done on modal analysis. It is also found that Genetic algorithm is better than conventional methods.

Voltage stability assessment and control of core function of power system is determined by using improved genetic algorithm approach for the voltage stability enhancement [25]. Proposed technique is based on the minimization of the maximum L-index and optimization variables taken into consideration. The effectiveness of this method is done on IEEE 30 bus system and IEEE 57 bus system in MATLAB for voltage stability enhancement and contingency. The weak bus in the system is identified and subjected for reactive power injection.

M. Sedighizadeh [26] proposes optimal distributed generation allocation for the improvement in voltage stability and reduction of loss in the transmission line. The tool used for this method is genetic algorithm. Distributed generation helps in the improvement of voltage stability profile. MATPOWER package is used for load flow and it is analysed in MATLAB software along with ETAP for correctness of the system. The Khoda Bande Loo distribution test feeder in Tehran has been evaluated for voltage profile improvement by application genetic algorithm.

Superconducting magnetic energy storage (SMES) may help to improve the stability of power system. SMES consist of isolated transformer, voltage source convertor (VSC), DC convertor (DC/DC) and a superconducting magnetic coil [27]. It uses voltage stability index and genetic algorithm method for optimization of SMES location. The effectiveness of the system is simulated on IEEE14 bus system, where generating and regulated buses are ignored. Genetic algorithm is used to find the location for SMES which helps to improve voltage stability. Simulation is done under a three phase ground fault. Voltage profile with and without the optimally positioned SMES system are considered. Application of SMES system and genetic algorithm enhances the voltage stability of the system.

Load shedding is an efficient way for voltage stability. Puneet Chawla [28] proposes the continuation power flow analysis for the load shedding. Load bus at which load shedding is to be applied is obtained by voltage stability sensitivity computed from P-V curve at different buses. Genetic algorithm is used for the amount of load which is required to be reduced. The effectiveness of the system is studied on IEEE 30 bus system in Power World simulator. Genetic algorithm for optimal load shedding is used to enhance the voltage stability is used.

I*FACTS Devices*

Voltage instability is mainly caused due to the lack of reactive power in the system. NaotoYorino [29] proposes a formulation for reactive power management in the system including the flexible AC transmission (FACTS) devices. The problem is decomposed into multiple sub problems by using Benders decomposition technique. The master sub problem is solved by using genetic algorithm method. The effectiveness of the system is tested on AEP 14 bus system. The main goal of this method is to minimize the sum of installation cost and operating cost under normal and contingency stage. The numerical results obtained from theAEP 14 bus system reactive power management can be utilized for placing the TCSC and SVC in the system which ensures the voltage stability.

To increase the voltage stability margin and security of the system, FACTS devices are used which can regulate the active and reactive power of the system due to their flexibility and quick operation [30]. Introduction of FACTS devices in suitable position improves the voltage stability of the system. Genetic algorithm is used for the allocation of FACTS devices considering the cost of devices and power system losses. The effectiveness of the system is tested on IEEE 30 bus system. The enhancement in voltage stability is done by using three FACTS devices TCSC, SVC and UPFC. The application of genetic algorithm method and location of multi FACTS devices is applied for enhancement in voltage stability. The effect of SVC on IEEE 14 bus system is studied for investigating the effect ofvoltage stability in the system [31].

Position of FACTS devices in the system plays an important role in the system. The location of SVC and other FACTS devices are found by critical mode [32]. Critical modes are calculated by using the point of collapse of system mode. The effectiveness of the system is tested on the1380 bus model of BC hydro system. Modal analysis is used to find the point of collapse method. Power flow program and Eigen values are also used to find the point of collapse. It also gives location of FACTS devices.

FACTS controllers are intensively used in the system for improving transmission capability of the system. Prince Hooda [33] investigates the application of FACTS devices like STATCOM and TCSC for voltage stability in the system. The effectiveness of these devices is tested on IEEE 14 bus system. Application of these devices improves the magnitude of voltage profile.

Voltage instability in the power system is easily preventable when the identification of critical bus line in the system is done [34]. Identification of critical line and buses is analysed by the fast voltage stability index (FVSI) and then by application of FACTS controller in the system to avoid instability in the system. The identification of weak bus in the system can also find by voltage collapse proximity index (VCPI), along with the application of FACTS devices [35].

SVC and TCS are also used for enhancement of voltage stability [36].The effectiveness of the system is studied on IEEE 14 bus system in PSAT. The value of FVSI gives the critical bus in the system and by installing the FACTS devices in a particular line voltage stability margin can be achieved and make system stable.

The comparison of FACTS devices is done on the basis of P-V curves, voltage profile and power losses under normal and contingency conditions. Sode-Yome [37] proposes placement and sizing techniques for series FACTS device and UPFC, based on reactive power loss sensitivity of the system. The effectiveness of the system is tested on IEEE 14-bus system. UPFC enhances the voltage stability under maximum loading condition also. The worst condition is also analyzed by this method.

J*Artificial Neural Network*

Artificial neural network is used for online voltage stability of the system in [38]. In this system, the most vulnerable load bus system is determined by the modal analysis method. For the vulnerable load bus system a separate feed forward type of ANN is trained. The ANN's are trained for the different loading condition of the system, which computes the active and reactive power of the system. This method is implemented on IEEE 30 bus system. ANN is used for the real time monitoring of the voltage stability of the system.

Analysis of voltage stability in the multi-bus power system is done by using artificial neural network and linear voltage stability indicator in [39]. Linear voltage stability indicator is used for the prediction of voltage collapse of the system while its combination with the ANN gives an estimation of voltage security of the system. ANN is used for the online monitoring of voltage stability of the system.

K *Fuzzy Logic*

S. Senthil Kumar [40] deals with the estimation of steady state of voltage stability. The analysis is done on the basis of L-index method modelled in terms of fuzzy set by using triangular membership function. The applicability of this method is studied on the basis of sample 5 bus system and IEEE 14 bus system.This method gives proximity of voltage collapse before system become unstable.

L.*Hybrid Method*

Hybrid system

Yoshihiko Susuki [41] proposes reachability analysis of hybrid system for estimation of voltage instability. Reachability analysis is obtained by using the backward reachable sets for unsafe set of hybrid automata. Automata represent discrete operation of relay as well as continuous voltage dynamic. The voltage instability in single machine load bus system is estimated by using reachability analysis. This gives the identification of voltage instability before collapse of the system.

Controllability

Voltage stability problem is affected by the unsolvability and controllability loss in voltage stability probabilistic assessment. Anselmo Barbosa Rodrigues [41] introduces the computation of voltage instability risk by the combination of Monte Carlo Simulation Method, non-linear optimal power flow and D'matrix method. DMM or model analysis is used to identify the controllability loss problem. OPF or continuation power flow is used to assess the solvability of power flow equations. An unstable state is identified when difference between maximum and current (i.e., present) system loading is negative. These indices are evaluated on the Brazilian interconnected system and modified version of IEEE 24 bus system. The evaluation is done on parameters like topological processing, load/generation dispatch, data complication, and solvability restoration with nonlinear OPF along with voltage stability analysis with DMM. It indicates that load forecasting has greater impact on the system. This method also gives the weak bus and voltage unstable area.

Operation of relays

Relays are used for the protection purpose in the system, but its undesirable zone 3 distance relay operation leads to the collapse of the system [43]. An adaptive algorithm is proposed which helps to avoid the undesirable distance of therelays. The paper implements a self-designed 15 bus system and Nordic 32 bus system. This algorithm prevents undesirable relayoperation and mal tripping of relay. It helps to maintain voltage stability of the system and prevents it from voltage collapse.

III.CONCLUSION

Voltage stability is plays an important role in the security of the power system. In this paper, different analysis and methods for improving voltage stability is studied. Different bus systems are taken into consideration for the analysis of voltage stability. Analysis of the system helps to prevent the voltage collapse and blackouts in the system. The voltage instability buses in the system are easily recognized by various methods. Voltage stability analysis helps us to take the preventive measures before system shuts down.

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