Evaluation of Power Grid Voltage Instability Point Using System Overloading Contingency in Real-Time Simulation

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June 10, 2024

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***Abstract*—In this research, we investigated the voltage stability collapse point (proximity to instability) by increasing the load demand. Before that, we carefully selected a power system network with all the parameters necessary for voltage stability studies. We modelled this network, ran all the initial load flow conditions using Newton's Raphson method on the software Real-time Computer-Aided Design (RSCAD), and then ran the simulations in real-time and looked at the actual system conditions before the disturbances were created. The method of simulations used in this study can be further used for other forms of power system stability studies.**

Keywords—Voltage stability, voltage collapse, contingency analysis.

I. Introduction

Electrical power grids are operating close to voltage stability limits (0.95 – 1.05 per unit) due to an increase in load demand [1]–[4]. Various methods have been proposed and (or) developed for overcoming the voltage stability challenges, such as the application of reactive power compensating devices, control of network voltage and generator reactive power output, coordination of protection or control devices, control of power transformer tap changers, and under-voltage load shedding schemes. These methods can only be effective up to certain limits, and their effect is global [5]–[7].

The main objective of the power system is the continuous supply of power to the end users. For this objective to be kept, methods like under-voltage load-shedding schemes must be the last resort [7]–[9].

Voltage stability challenges were once primarily associated with weak power grid systems and long transmission lines but are now associated with heavily stressed systems. The stress in power systems is often caused by violations such as the increase in load demand and transformer or line outages. These violations may cause sudden voltage rise or drop in other branches of the power system network [5].

The load demand from power grids keeps increasing and it has already been estimated that it will grow by a percentage of 56 starting from 2010 to 2040 [10]. This means that the existing power grids are still going to experience challenges in voltage stability and control if there is no further search for solutions [11], [12].

Since the power system voltage stability challenges have been addressed, more research studies have been conducted, with various methods in addition to those that are mentioned in [7], [5], [13] and [6], to solve power system voltage stability challenges. However, the approaches used at the stage of problem investigations are not substantial. The investigation of the problem is as important as finding the solutions to it. That being said, solving voltage stability challenges requires a significant look at the fundamental steps toward bringing solutions. One of the fundamental requirements is the investigation of voltage stability collapse points. According to the authors [1], [7], [12], [14] and [15], this is possible through contingency analysis. Let us first look at the definition of a word contingency analysis. It is defined as a power system function used in modern energy management systems (EMSs), intending to give full information about the static security of power systems to the system operator [15]. Examples of power system contingencies for voltage stability investigations are generator tripping, system overloading, switching off of the transmission lines, etc [5], [7], [12].

Our concern is on procedures or steps taken in various research to propose and (or) develop solutions to improve the voltage stability of power grids. However, we first review the existing work from various researchers. In there, we look at the steps taken by these researchers in proposing and (or) developing methods for solving voltage stability challenges of the power grid system.

A method of mitigating voltage collapse in the power system was developed in reference [16]. This method was proposed as a form of transient stability analysis based on machine learning techniques such as linear regression, neural networks, and decision trees. In their voltage mitigation method, they used three different mathematical voltage stability indices such as the fast voltage stability index (FVSI), line voltage stability index (L_{mn}), and novel line stability index (NLSI) to prepare datasets for training. Moreover, an early-warning system was built based on the voltage collapse predictor, which could be used to alert the power grid system operator about any potential voltage instability hazards. The early warning system was then used as a kernel to build the voltage stability automatic maneuver algorithm that can handle voltage instability issues.

It is a privilege to find a study by the authors in reference [17], who proposed a technique for improving the voltage stability of the power system by using the active and reactive power information of the transmission line based on the voltage stability index. In their study, they found out through simulations that the voltage stability of the power system can be improved by installing a battery storage system that supports the injection of the proper amount of active power and reactive power at the load substation. The authors did their study using the IEEE 5 Bus System.

The authors [18] used a static compensator (STATCOM) with a proportional-integral (PI) and fuzzy logic controller to restore voltage levels of the Egyptian power grid integrated with a wind power plant (WPP). The authors simulated and modelled their using Simulink.

It is also another privilege to find a study by the authors [19], in which the voltage stability improvement was done using the line voltage stability index (LVSI) based on the optimal power flow (OPF) in power systems. These authors made use of two conditions comprising load demand increase and line outage contingency to verify the performance of the method in the IEEE 30 Bus Power System.

However, the studies presented in the references [18] and [19] did not include any simulations. Simulations, especially in real-time, are an essential way of studying the power system problems before coming up with solutions, as disturbances can be created and monitored at the same time. In the existing literature, it is said that when conducting power system studies, the simplest representation of plant components with accurate and available data should be used. It is also said that there is no need to use complex items to model a system when the load and other data like transmission line data are known, up to a limited accuracy. Additionally, power system components like long transmission lines should only be used where it is necessary and this applies to synchronous generator models. For instance, power system stability studies require the use of sophisticated synchronous machines and special transformer models. The network size and its complexity provide more than sufficient academic motivation without unnecessary enhancement of the components. Often in high-voltage networks, resistance may be neglected with little loss of accuracy and a huge saving in computation time [12], [20].

The contribution of this research is that it brings attention to the procedures to be followed when conducting a voltage stability study, as it carefully looks at the fundamental requirements to consider. It first looks at the power system network model and its fundamental requirements to use. It then looks at the validation of data pertinent to the network, and it is rare to find these considerations in the existing research regarding voltage stability studies. Moreover, the initial load conditions of the system before the actual investigation of the problem is done.

Following the introduction, Section II discusses the overview of contingency analysis. The system considered for this study is presented in Section III, whilst the normal load flow simulations and contingency in terms of system overloading are presented in Section IV. The results and their discussions are provided in Section V. Finally, conclusions are drawn in Section VI.

II. Overview of Contingency Analysis

Contingency analysis is mostly done for power system planning and operation. Usually, the load increase and transformer or line outages cause a sudden rise or drop in other branches of the power system, and such are called power system violations. Most often when performing power system voltage stability studies, the estimation of these violations is done using contingency analysis.

The term "contingency analysis" was defined earlier, and is further described below. Contingency analysis is putting the whole system under stress to observe power system violations and provide methods to prevent them, in case they happen in the future. From here, the word "security analysis" suits the study of contingencies well.

Security analysis can be done either in an online or offline mode. Online mode is mainly for indicating to the system operators about the effects future outages would have on the system, while offline mode looks at the analysis of the contingency events. There are several schemes used for any power system utility planning. Utilities perform these schemes to bring the system back to stability. Another term used for these schemes is special protection schemes (SPSs) or system integration schemes (SISs). In the case of SPSs, the power system protection used must guarantee security and must adapt to the conditions of power system changes like the direction of current flow when additional supplies are integrated into the system [15].

Remedial actions include shunt capacitor switching, generator re-dispatching, load shedding, under-load tap changing of the transformer, distributed generation, and islanding. Line and generator outages are common types of contingencies in the power system [15], [21]. However, generator tripping and system overloading are the most commonly applied contingencies in the existing literature. Moreover, in this study, we put our focus on system overloading contingency as it mostly enables the investigation of issues caused by the shortage of generated power in the power system network. System overloading contingency also forms part of the sudden disturbances that result in busbar voltage dips, and, therefore enables the precise estimation of the most convenient solutions to solve the issue of the system voltage stability issues.

III. Development of the System Used as the Fundamental Case in the Study

Planning studies are typically undertaken for both minimum and maximum load conditions. Under minimum load conditions, the possibility of high voltages is examined, while under maximum load conditions, the possibility of low voltages and instability is examined [7], [12], [22].

Load flow studies are concerned with the analysis of specific parameters in power system networks. Other types of research in power system engineering include circuit analysis and load or power flow analysis. The impedance parameters, voltage, and current source parameters are stated in the circuit analysis, and all nodal voltages and branch currents may be estimated using a simple expression in which the voltage and current relationship is linear.

Loads and sources in load or power flow analysis are described in terms of powers rather than impedances or ideal voltage or current generators. All power system network branches, transformers, and overhead or underground cables are specified in terms of impedance, with a nonlinear relationship between power, voltage, and impedance. When using these circuits, it is necessary to apply proper approaches [20], [23].

The power flow in complex power system networks is determined by the power system components, whose characteristics of operation differ. Stability studies require a strong analysis of power flow within the power system network before the resumption of any other investigations. Moreover, to perform a suitable simulation study with more accuracy, it is recommended in reference [24] and [23] to choose a system with all the necessary parameters. The IEEE 9 Bus Power System shown in Fig. 1 was used in this research, and it has all the parameters required for conducting a suitable voltage stability analysis study. The system, divided into two areas, was modelled using Real-time Computer-Aided Design (RSCAD) with its simulations carried out in real time using Real-Time Digital Simulator (RTDS) devices.

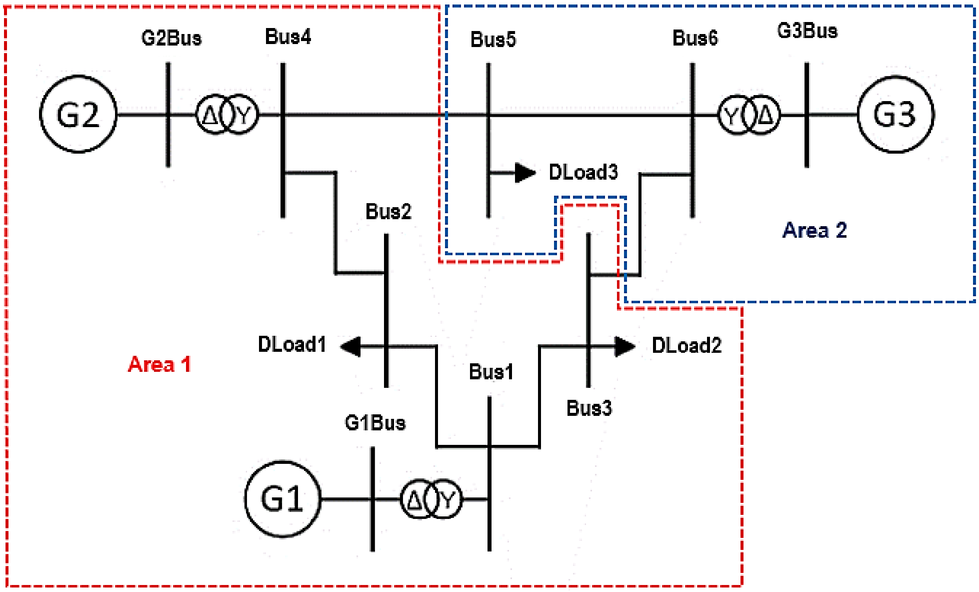

Fig. 1. Modified IEEE 9 Bus Power System (divided into two areas)

RSCAD has two modules, namely the draft and runtime module. In the draft, the modelling of the network is done, and the draft load flow simulation is performed, wherein the initial conditions of the network are confirmed in the form of iterations [12].

Therefore in this study, the RSCAD draft load flow simulation was performed, and the results during the simulation showed that the load flow converged on the sixth iteration. Table I shows the busbars' initial values due to the draft load flow simulation.

TABLE I. IEEE 9 BUS POWER SYSTEM BUSBAR INITIAL VOLTAGE VALUES AFTER DRAFT LOAD FLOW SIMULATION

Bus	**Bus type**	**Voltage (PU)**	**P_G (MW)**	**Q_G (MVAr)**	**P_L (MW)**	**Q_L (MVAr)**
G1Bus	Slack	1.040000∠0.000000°	71.779751	36.267457	-	-
G2Bus	PV	1.025000∠8.363888°	163.000000	11.230000	-	-
G3Bus	PV	1.025000∠4.022079°	85.000000	-3.720376	-	-
Bus1	PQ	1.020690∠27.767750°	-	-	-	-
Bus2	PQ	0.992780∠26.324740°	-	-	125.000000	50.000000
Bus3	PQ	1.006400∠26.565460°	-	-	90.0000000	30.000000
Bus4	PQ	1.022990∠32.788440°	-	-	-	-
Bus5	PQ	1.012840∠30.292890°	-	-	100.000000	35.000000

In the study, we made the system load dynamic so we can simulate the load increase contingency using a tuning logic. A logic shown in Fig. 2 was adopted from the study in reference [12], to enable the feature of tuning the loads. The logic in the figure is designed to apply tuning for both active power and reactive by keeping the power factor angle the same. For instance, in the figure, you will see the values 21.80089°, 18.43555°, and 19.28976°. These values are in degrees (°), which when the cos of each value is applied, the power factor (PF) of the load will be achieved. Furthermore, the explanation of the logic in Fig. 2. The angle values 21.80089°, 18.43555°, and 19.28976° are inputs to the component tan (deg) that goes to the multiplier component x whose output gives the value of the reactive power with the signal name *QDLoad1Set*. This signal gives the input reactive power setting to the load DLoad1. Another signal is *PDLoad1Set*, which gives the input active power setting to the load DLoad1. The output signals *QDLoad1Set* and *PDLoad1Set* are initiated when the switch DLoadSchedStartSW with output signal *DLoadsSchedStart* is pressed ON on the RSCAD real-time simulation. The same principle applies to the loads DLoad2 and DLoad3.

Following the power system stability study requirements mentioned in the references [24] and [23], before the overload contingency was simulated, the initial load flow conditions were simulated on run-time to ensure validation of the initial load conditions as calculated earlier using the RSCAD draft load flow simulation. The following section (IV) presents the normal load flow results from this simulation.

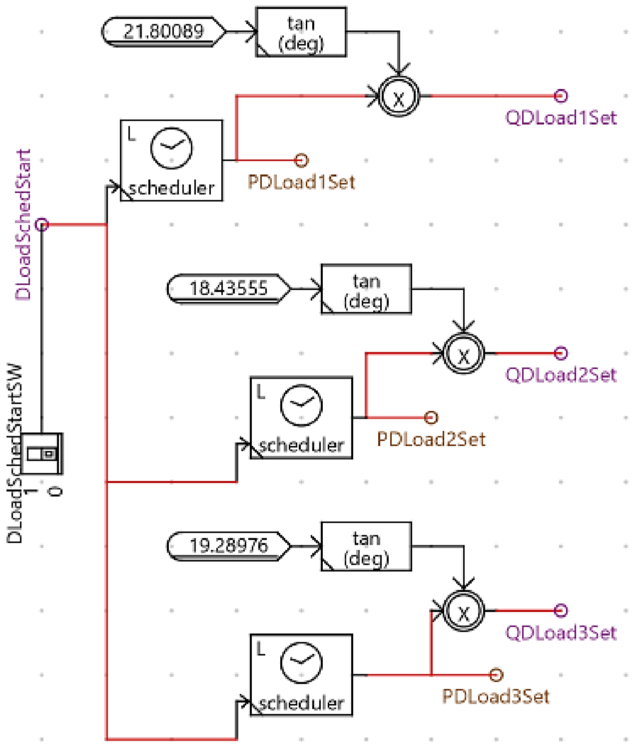

Fig. 2. Logic for power demand scheduling of DLoad1, DLoad2, and DLoad3 from the system

IV. Validation of Normal Load Flow Conditions and Simulation of the System Overloading Contingency

These results are used as the validation that the system has been successfully modelled and that the initial conditions are within the acceptable operational standards of power systems. In the same section, we provide the results obtained during the simulation of the system overloading contingency. Table II and Table III show the results.

TABLE II. Busbar Voltages Under Normal and Load Increase Disturbance Conditions

Busbars	Voltage (PU)	
	Normal conditions	*Overload contingency*
Bus1	1.0210	0.9929
Bus2	0.9928	0.9487
Bus3	1.0060	0.9624
Bus4	1.0230	0.9884
Bus5	1.0130	0.9704
Bus6	1.0280	0.9938

TABLE III. Apparent Power on Load Busbars and their Loads Under Normal and Load Increase Disturbance Conditions

Load Busbars and Loads	Apparent Power (MVA)	
	Normal conditions	*Overload contingency*
Bus2 and DLoad1	134.6 and 134.6	172.8 and 172.8
Bus3 and DLoad2	94.87 and 94.87	132 and 132
Bus5 and DLoad3	105.9 and 105.9	143.3 and 143.3

V. Results and Discussion

The load increase contingency simulation was run for the IEEE 9 Bus Power System to detect the voltage stability collapse point, which according to power system rules could be any voltages that are not within the range of 0.95 and 1.05 per unit. After the implementation of the system overloading contingency, it was discovered that the Bus2 voltage did not recover. The results showing these voltage results are shown in Table IV. In the same table of results, the apparent power in MVAs is also shown and is viewed from the load and the busbar from which the mentioned load is drawing power.

The initial load demand at Bus2 was 134.629120 MVA, and the voltage was 0.992800 per unit. The load demand was increased by 5.321361 MVA every 0.1 seconds while the behaviour of the voltage at the busbar was monitored.

TABLE IV. Bus2 and DLoad1 quantities during the load increase contingency simulation

Duration (seconds)	SDLoad1 (MVA)	PFDLoad1	SBus2 (MVA)	PFBus2	VBus2 (PU)
20.1	134.629120	0.928477	134.629120	0.928477	0.9928
20.2	139.950481	0.928900	139.950481	0.928900	0.984
20.3	145.291877	0.929164	145.291877	0.929164	0.974
20.4	150.832583	0.928181	150.832583	0.928181	0.964
20.5	156.173773	0.928453	156.173773	0.928453	0.950
21.1	172.297000	0.928627	172.297000	0.928627	0.903
42.1	172.297000	0.928627	172.297000	0.928627	0.948

The purpose of this simulation was to determine the exact amount of load demand that would cause the voltage to fall out of the stability margin. In this case, Bus2 voltage fell to 0.903 per unit which is out of the acceptable voltage operating range, and still, after the overall disturbance, settled at 0.948 per unit at the power demand of 172.297000 MVA. At this point, we knew that the load demand increase of 5.321361 MVA causes the voltage collapse at Bus2 when the demand reaches 172.297000 MVA.

VI. Conclusions

In our previous work, we explored the existing work on the control methods for modern power grids integrated with wind power plants (WPPs), wherein there we discussed the existing integration challenges regarding voltage stability and control methods for improving the voltage stability of modern power grids.

The fundamental requirements for conducting a voltage stability study have been presented in this paper. The IEEE 9 Bus Power System was selected based on its parameters which meet the requirements of a system for conducting such a study. Simulations were done, and disturbances such as the increased load demand contingency were created to find the voltage stability collapse point. The results obtained in this study show that a load demand increase contingency simulation can be used for determining the load demand at which the voltage at the substation or busbar can start to collapse. This study can be used by other researchers as a guide on how to estimate the voltage collapse point and find solutions to compensate for it.

Future work will focus on the protection system required at the busbar identified with a voltage collapse.

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