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VOLTAGE STABILITY ANALYSIS OF WIND ENERGY GENERATOR INTEGRATED IEEE 14 BUS SYSTEM USING HOPF BIFURCATION TECHNIQUES

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Abstract

Recently, analysis of some major blackouts and failures of power system shows that voltage instability problem has been one of the main reasons of these disturbances and networks collapse. In this paper, a systematic approach to voltage stability analysis using various techniques for the IEEE 14-bus case study is presented. Static analysis is used to analyze the voltage stability of the system under study, whilst the dynamic analysis is used to evaluate the performance of compensators. The static techniques used are Power Flow, V–P curve analysis, and Q–V modal analysis. In this study, Flexible Alternating Current Transmission system (FACTS) devices- namely, Static Synchronous Compensators (STATCOMs) and Static Var Compensators (SVCs) - are used as reactive power compensators, taking into account maintaining the violated voltage magnitudes of the weak buses within the acceptable limits defined in ANSI C84.1. Simulation results validate that both the STATCOMs and the SVCs can be effectively used to enhance the static voltage stability and increasing network load ability margin. Additionally, based on the dynamic analysis results, it has been shown that STATCOMs have superior performance, in dynamic voltage stability enhancement, compared to SVCs.

Keywords: *Dynamic analysis, FACTS, optimization, power flow, static analysis, voltage stability.*

Nomenclature

B_e	Suceptance of SVC
i_{ds}	Direct axis component of the stator current
i_{qs}	Quadrature axis component of the stator current
i_{dr}	Direct axis component of the rotor current
i_{qr}	Quadrature axis component of the rotor current
J	Jacobian matrix of the system
J_R	Reduced Jacobian matrix of the system
P	Real power
Q	Reactive power
r_s	Stator resistance
r_r	Rotor resistance
s	Slip
V_{ds}	Direct axis component of the stator voltage

V_{qs}	Quadrature axis component of the stator voltage
V_{dr}	Direct axis component of the rotor voltage
V_{qr}	Quadrature axis component of the rotor voltage
ω_m	Synchronous speed
X_s	Stator reactance
X_r	Rotor reactance
X_m	Magnetising reactance
ΔV	Change in the voltage matrix
ΔQ	Change in the reactive power
λ_i	The i*th* eigen value of J_R

I. INTRODUCTION

The depletion of fossil fuel resources and the growing concern for greenhouse gases are triggering many countries to invest in renewable energy resources such as energy production from wind and solar resources. Both wind and solar resources are free and once they are operating, they have almost no greenhouse gas emission associated with them [1]. However, the rapid growth in using renewable-based generation poses challenges for the system operators. In general, they experience intermittency, variability, partial controllability and location dependency. Some of the challenges introduced in [2] include system security, power quality and system stability. Among power system stability concerns, voltage stability, which is addressed in this paper, is one of the major concerns. Voltage stability of networks is still a major issue with major blackouts recently occurred, such as the massive blackout that took place on July 2012 in India affecting around 670 million people, or the partial blackout that took place on September 2014 in Egypt affecting around 20 million people. Typically, according to [3], voltage stability refers to the capability of power system to sustain constant voltage at all buses after being subjected to a disturbance from a given initial operating point. Moreover, voltage stability can be classified into two categories, according to the type of disturbance, or according to the time span over which instability may occur. Regarding to the type of disturbance, small–disturbance voltage stability can be seen as the ability of the power system to maintain voltage control after a small disturbance such as a load change, whilst large–disturbance voltage stability can be defined as the ability of the power system to maintain voltage control after a large disturbance such as big generation tripping. Regarding to time, short–term voltage stability considers the dynamics of the fast acting loads, whereas long–term voltage stability takes into consideration slower acting equipment. Generally, closeness to voltage collapse can be used to measure voltage stability of a power system. By definition, a voltage collapse is a sequence of events following voltage instability that leads to a blackout or severe low voltage condition in a network. Voltage collapse can be seen as a static phenomenon which is associated with reactive power imbalance [4]. In other words, transmission lines, transformers and loads are sinks of reactive power. Accordingly, if a sufficient reactive power compensator is not available in the power system, voltage instability may occur. Since voltage stability problem is seen as a static phenomenon, it can be addressed by off-line study through the initial design or during network improvement process. Additionally, issues such as the loadability limit of the network, fault ride through capability, reactive power reserve and time respond of these reserves, are all included in voltage stability studies. Furthermore, many distribution networks still operate in an open ring system. Power is restored during faults by moving open points. Hence, the power system network needs to be stable under these new operating conditions.

At the present time, in order to improve the voltage profile, power electronics based devices called Flexible AC Transmission Systems, or FACTS, are being used. FACTS is a family of power electronics devices that is involved in the control of bulk flow of both active and reactive powers [5]. FACTS devices can provide both series and shunt compensation to improve the system's voltage profile and increase load ability of the transmission systems. FACTS may also address other issues in the future, such as sub-synchronous oscillations or dynamic voltage control [6]. The most common devices that can provide shunt compensation are the Static Synchronous Compensators (STATCOMs) and the Static Var Compensators (SVCs).

In the literature, fault ride through capability has been checked in [7] using a fixed speed induction generator with STATCOM and SVC. Other works on dynamic analysis can be found in [8]. Induction generators need reactive power to operate, thus, they draw it from the grid unless fitted with local reactive power source. On the other hand, the doubly fed induction generator (DFIG) or the synchronous generator can regulate their own power factor from leading to lagging. Mathematical techniques are available to give an insight of the closeness of a system to voltage collapse. They can be classified either static or dynamic. In [4], static voltage analysis was performed using UWPFLOW for P-V curve analysis in order to identify voltage collapse using the Continuation Power Flow (CPF). STATCOM and SVC have been used to improve voltage stability. Tangent vector analysis was used to allocate compensators to the weakest buses. Related works have been done in [9-13].This paper demonstrates that a combination of both static and dynamic analyses should be used for voltage stability studies. One of the objectives is to devise a systematic approach for voltage stability analysis, which can be used by engineers during network planning. Specifically, load flow analysis, V – P curves and Q – V modal analysis, are used for the static voltage stability analysis. Dynamic analysis is used to re-evaluate the performance of the STATCOM and SVC during contingencies. Time domain simulation for differential algebraic equations for power systems are solved for the dynamic analysis.

II. VOLTAGE STABILITY ANALYSIS TECHNIQUES

Load flow is used to compute voltage magnitudes and phase angles at all buses. Hence, techniques such as V – P curves, V – Q Sensitivity Analysis, Q – V modal analysis, Q – V curves and minimum singular value method may be applied for voltage stability studies. Voltage stability analysis can be classified as static and dynamic analyses. In the static analysis, ‘snapshots’ of the system are taken from different time instances in the time domain trajectory, hence, useful information such as voltage stability and proximity to voltage collapse can be derived. Static techniques are sufficient to analyze the voltage stability of a system. In the dynamic one, a series of first order differential equations are derived and can be solved using any integration method such as Euler Method, Runge-Kutta Methods, numerical stability of explicit integration methods or the implicit integration method [19, 20]. In dynamic analysis, the sequence of events that leads to voltage instability can be analyzed. A complete study period would include the action of equipment with slow dynamics such as tap changers. Only the techniques used in this work are summarized below.

A. V – P curves Analysis

The V – P curve at a bus shows the voltage variation versus the real power. The nose point corresponds to the point of voltage collapse (PoVC), or the Saddle-node bifurcation point. The margin between the actual operating point and the PoVC corresponds to the voltage stability margin. Continuation power flow algorithms can be used to obtain the V – P curves.

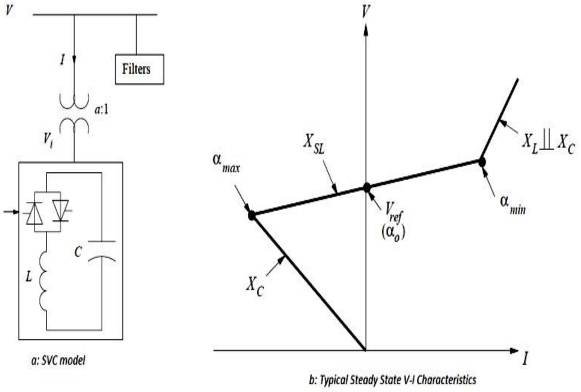
B. Bifurcation Analysis

Both qualitative and quantitative information about the behavior of nonlinear systems close to their ‘critical’ or bifurcation equilibrium point after variations of the system parameters can be analyzed using the bifurcation theory. In power systems, at least two types of bifurcation have to be discussed [18]:

- Saddle-node Bifurcation (SNB): This type of local bifurcation occurs as two equilibrium points, normally one unstable and one stable, merge and disappear. Mathematically, this corresponds to the singularity of the Jacobian matrix. In the V – P curve, this will correspond to the nose point.
- Hopf Bifurcation (HB): This occurs as a result of two conjugate pair of eigenvalues becoming pure imaginary. Consequently, more oscillatory becomes the system, hence, stability may be lost by increasing the amplitude of the oscillation [18].

III. FACTS AND PLACEMENT METHODS

The IEEE Working Group on FACTS defines the SVC as a generator that is capable of generating or absorbing reactive power (variable reactive current capability) when connected in parallel with a load, hence the desired parameters such as voltage can be controlled. The SVC and its V – I characteristic are shown in Figure (4). It consists of a thyristor-controlled reactor in an arm with a capacitor in the opposite arm. Varying the phase angle, a continuous range of reactive power variation can be achieved. The main drawbacks of this setting are the production of low-order harmonics and high losses while working in the inductive region. The FACTS models present in PSAT are described in [24].



a: SVC model

b: Typical Steady State V-I Characteristics

Figure 1. SVC model and its corresponding V – I characteristic [21]

IV. FORMULATION OF THE SEARCH ALGORITHM

A simple algorithm for the placement of the FACTS devices using static analysis is proposed. Figure (5) demonstrates a flowchart for the placement of these devices, STATCOM and the SVC. Q – V modal analysis is used to check the stability of the system, and the weakest buses are identified using the eigenvalues and the participation factors. The target voltage of the network is set according to the ANSI Standard C84.1 guidelines [29] given in Table 1. For voltage below 46 kV, Range A corresponds to the ideal or optimal voltage limits whereas Range B is acceptable but not desirable. For voltage above 46 kV, the two ranges, namely normal operating and emergency condition, are defined. Consequentially, the power flow is used to find the reactive power requirement so that the STATCOM and SVC can be sized. After compensation, all voltage limits in the network are re-checked. If the compensated voltage violates its permissible values, the above processes are repeated again. The IEEE 14- bus test system is used for case studies. The numerical data were primarily taken from [30]. The test network with its bus labels is shown in Figure (6).

The proposed algorithm is implemented by programming in MatLab and PSAT environments. PSAT can be run through the MatLab interface using command line technique. This enables solving large systems. On the other side, this method may present some computing and time challenges in a system comprising of thousands of buses. It becomes financially impractical to place a FACTS compensator at each bus to maintain voltage magnitude at its desired level. Generally, to overcome this challenge, a network is divided into different regions called pilot nodes. These pilot nodes represent the voltage in these regions. Hence, the presented flowchart can be applied to maintain voltage within tight tolerances at these nodes.

V. SIMULATIONS AND RESULT ANALYSIS

To analyze the impact of wind integration on voltage stability, the study has been performed in IEEE 14 bus system depicted in Fig.1.In the test system the DFIG generator is integrated at bus 1 .the introduction of DFIG in bus one leads to small signal stability problems. In the Small signal Stability analysis done on the given system shows the occurrence of Small signal instability problem that is the presence of Hops bifurcation as we can see presence of complex conjugate pairs of poles in the system. Also we can find existence of one pole with zero Eigen indicating that the system is almost unstable. With the introduction of SVC into the system we can identify that the small signal oscillations has been damped as the one of the Eigen value which had zero Eigen value has been removed thus increasing the stability of the system.

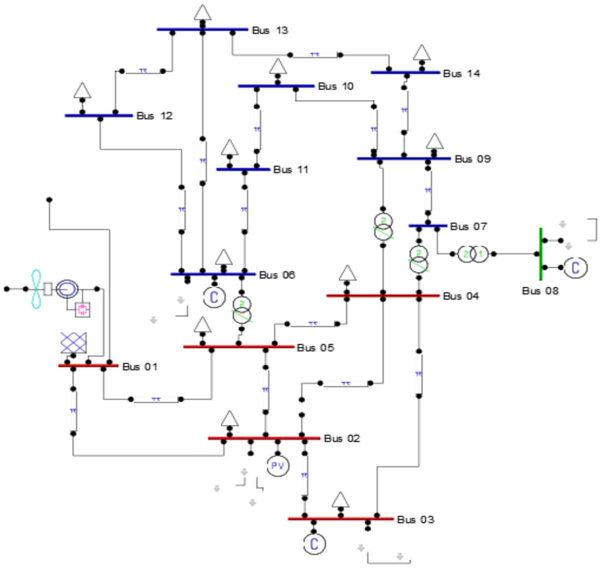
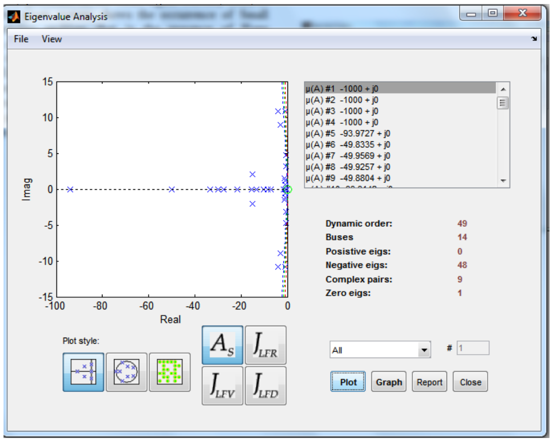


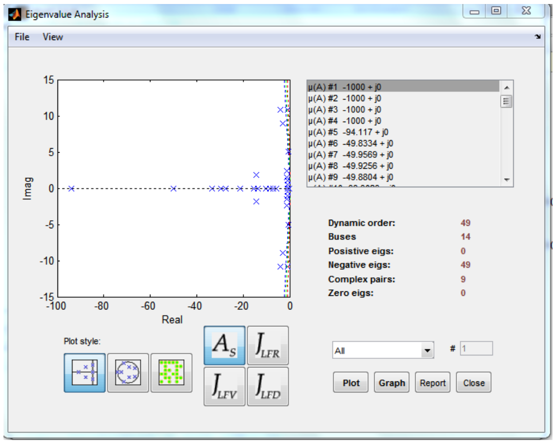
Fig 3. DFIG Connected to IEEE14 bus system



μ(A) #1 -1000 + j0
μ(A) #2 -1000 + j0
μ(A) #3 -1000 + j0
μ(A) #4 -1000 + j0
μ(A) #5 -93.9727 + j0
μ(A) #6 -49.8335 + j0
μ(A) #7 -49.9569 + j0
μ(A) #8 -49.9257 + j0
μ(A) #9 -49.8804 + j0

Dynamic order:	49
Buses	14
Posistive eigs:	0
Negative eigs:	48
Complex pairs:	9
Zero eigs:	1

Fig 4. S domain analysis graphical representation of IEEE14 bus system without SVC



```
μ(A) #1  -1000 + j0
μ(A) #2  -1000 + j0
μ(A) #3  -1000 + j0
μ(A) #4  -1000 + j0
μ(A) #5  -94.117 + j0
μ(A) #6  -49.8334 + j0
μ(A) #7  -49.9569 + j0
μ(A) #8  -49.9256 + j0
μ(A) #9  -49.8804 + j0
```

```
Dynamic order:      49
Buses               14
Posistive eigs:     0
Negative eigs:      49
Complex pairs:      9
Zero eigs:          0
```

\# 1

Fig . S domain analysis graphical representation of IEEE14 bus system without SVC

VI. CONCLUSION

This paper investigates the dynamic voltage stability of a DFIG connected IEEE14 test bus system. The simulation e carried out using Eigen value analysis reveals the presence of complex conjugate pairs of Eigen values along with the presence of one Eigen value with zero, which is a clear indication about the existence of Hops bifurcation that results in on set of small signal oscillations. The analysis also shows that the introduction of SVC in the appropriate bus, the small signal oscillations can be damped.

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