Analysis of STATCOM Oscillations using Ambient Synchrophasor Data in Dominion Energy

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***Abstract*—In this paper, we provide a preliminary investigation of poorly damped oscillations from a STATCOM in Dominion Energy's system using ambient synchrophasor data-based methods. Synchrophasor data from multiple months are analyzed using parametric and non-parametric spectral analysis techniques as tools for understanding the oscillation phenomena. As a part of the analysis, relationships between estimated damping and system loading are drawn to arrive at a hypothesis.**

***Index Terms*—STATCOM, spectral analysis**

I. INTRODUCTION

With retirements of conventional power plants and the proliferation of renewable energy-based generation stations, power systems are facing unprecedented challenges [1]. To mitigate some of these, voltage source converter technology (VSC) has been utilized in the form of STATCOMS, HVDC, etc., by exploiting their flexibility. However, in a practical setting, the control design is often carried out using a model of the power grid that may not capture the dynamic behavior of the system completely. This results in control-related issues that are difficult to understand for the utilities due to not having full insight into these devices unlike conventional generators, their excitation systems, primary movers, and their controls.

In recent years, delta-connected modular multilevel converter (MMC)-based STATCOMs were widely adopted across the high voltage power system network due several advantages they offer such as modular expansion, independent inverter units, and fewer switching devices required at the same output level. Each submodule cell in the MMC-STATCOM is composed of a H-bridge converter and a dc capacitor. As the dc-link capacitor of each sub-module is separated and isolated, the voltage balancing of each sub-module becomes a critical issue for MMC-based STATCOM operations. To overcome this challenge, different modulation techniques [2] were proposed to balance each sub-module voltage and the current of each arm. However, it becomes more challenging when a STATCOM is operating at zero-current mode (stand-by mode) [3]. This is because balancing algorithm requires information about the power directly through the DC capacitor. Without the current flow information, voltage and current balancing cannot be achieved by IGBT switching alone. Since circulating current can flow inside the delta-connected converter, using circulating current for balancing purposes is considered a feasible solution. The circulating current can be adjusted through a designed circulating current control loop. It is also worth to mention some of the delta-connected MMC-STATCOM's negative sequence control can adjust circulating current among the delta-connected clusters [4], [5] or the so-called open-loop control approach [6]. In practice, this functionality is often challenging to realize in STATCOMs connected in areas with low system strength.

In a practical setting, the asset owner usually does not have a transparent model of the STATCOM and therefore, any issues with the control design cannot be captured in simulation studies. This situation leaves measurements as the only available source of data to derive insight into performance issues. Now, since a typical system stays in ambient conditions for much of the time where the response is strongly linear, spectral analysis techniques [7] have gained popularity for the dynamic analysis of the system. These techniques approach the problem from the frequency domain, where oscillations having distinct frequencies are separable. Furthermore, owing to the inherent decoupling between oscillatory modes, frequency domain analysis also enables the use of filters to focus on specific oscillation(s) of interest as opposed to analyzing the system in its entirety [8]. This becomes particularly helpful in large scale systems when analyzing local oscillations such as the one in this paper.

Some of the techniques [9] belonging to this family that are especially helpful in a practical setting are those from statistical signal processing. Welch's periodogram can be used to get an estimate of the power spectral density (a surrogate to the energy content, commonly referred to as "spectrum") in the signal at each frequency within a frequency range. The dominant oscillations as observed by the signal appear as peaks in a frequency range. Because the spectrum gives the distribution of the signal over frequency, when successively applying it to overlapped windows of data, a graph of the spectrum vs time can be constructed, known as the spectrogram. CSD (cross-spectral density) can be used to estimate the mode shape [10] and thus provides a good measure of relative observability of a mode across multiple signals. In this paper, we use spectral analysis tools to analyze poorly damped oscillations observed in voltage magnitude measurements from a STATCOM in the Dominion Energy system.

This paper is organized as follows. In Section II, a brief overview of the region of Dominion's grid understudy is given along with the specifications on the synchrophasor devices. Section III gives a brief overview of the analysis techniques implemented to carry out this work. Section IV gives details of our investigation of these undesirable local oscillations stemming from the STATCOM.

II. STUDY CASE

A. Sub-System under Analysis

This subsystem of the Dominion's system is a 115 kV, majorly radial network comprising of 4 substations denoted by A, B, C, and D as shown in Figure 1 with no nearby generation stations. It is connected to Dominion's 230 kV network at substation A and terminates at the distribution substation, i.e. substation D. This region has a history of voltage problems owing to generation retirements, which is why a 125 MVAR STATCOM was installed at substation B, the pilot bus of that part of the system. The STATCOM is designed to eliminate several potential voltage violations in that area and improve system recovery during the peak load condition. That being said, this region suffers from low system strength/ short circuit ratio due to a lack of a local fault current source making the STATCOM operation challenging.

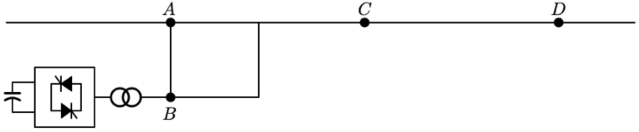


Figure 1. Study System One Line Diagram

B. STATCOM Specifications

The STATCOM installation under study has a rated reactive power output as +/- 125 MVAR. Its three-phase limbs are in delta connections. It can operate under voltage control mode (VCM), which provides reactive power to maintain voltage by referring to voltage setpoint, and Q control mode (QCM) which regulates the steady-state reactive power output based on reactive power set point. A stand-by function that blocks STATCOM operation when the voltage fluctuation is within a small range is also enabled. This function aims to reduce the losses caused by STATCOM IGBT switching. Zero-and-negative sequence current control are both implemented for adjusting DC voltage balance for each STATCOM sub-module. Finally, Auto Gain Control (AGC) is enabled to reduce gain settings when STATCOM output hunting is detected. This function is used to mitigate hunting and prevent instability.

C. Measurement Device

Synchrophasor measurements (i.e., PMU data) are available from the digital fault recorders (DFR) at substations A, B, and C. The DFR specs are as follows:

1. Sampling at a rate of 4800 Hz.
2. 4800 Hz signal down sampled to 960 Hz from which 60 Hz phasor component is reported.
3. Phasor reported at 60 Hz is down sampled to 30 Hz for long-term storage.

III. SPECTRAL ANALYSIS BACKGROUND

This section gives a brief overview of spectral analysis tools used in this work [9]. These tools are deployed in Python using Pyspectrum [11] and Scipy libraries.

A. Power Spectral Density (PSD)

PSD describes how the signal's power is distributed over frequency. Let $x(n)$ denote a stationary process with autocorrelation function,

$$r(k) = E_n(x^*(n)x(n+k)) \tag{1}$$

where, $E_n(\ )$ is the expectation operator over n. PSD value at frequency f, denoted by $S(f)$ can be defined as,

$$\begin{aligned} S(f) &= \sum_{k=-\infty}^{\infty} r(k)e^{-j2\pi fk} \\ &= \lim_{N\to\infty} E\left(\frac{1}{N}\left|\sum_{n=0}^{N-1} x(n)e^{\frac{-j2\pi fn}{N}}\right|^2\right) \end{aligned} \tag{2}$$

where N is a sampled data window of finite length To obtain a robust (low variance) spectrum estimate, Welch's method [12] is popularly used. It involves the following steps:

1. Divide the data window into N_b number of overlapping block intervals of length N_t
2. Each block is convolved with a window function $w(n)$ to obtain the new signal $w * x$.
3. PSD for each interval is estimated as,

$$\hat{S}(f,m) = \frac{1}{N_t}\left|\sum_{n=m}^{m+N_t-1} (w*x)(n)e^{-\frac{j2\pi fn}{N_t}}\right|^2 \tag{3}$$

4. The above PSD estimates are averaged to obtain the final estimate.

$$\hat{S}(f) = \frac{1}{N_b}\sum_{m=0}^{N_b-1} \hat{S}(f,m) \tag{4}$$

In the present work, for short-term analysis, typically of 20 min windows, each block is of 2 minutes duration with a 50 % overlap between successive blocks. The window function used is Hanning.

B. Spectrogram

The goal of time-frequency analysis is to understand what frequencies are dominant at a given time. It is used to identify persisting dynamic behavior (modes) in the system. In the present work, we use Short Term Fourier Transform (STFT). Given a signal x, STFT yields the following time-frequency coefficients X,

$$X(f,m) = \sum_{n=0}^{N-1} x(n)w(n-m)e^{\frac{-j2\pi fn}{N}} \tag{5}$$

where, $w(n)$ is a window function with compact temporal support, i.e. non zero values in a finite range in time. Spectrogram gives a visual representation of time varying spectrum $S(f,m) = |X(f,m)|^2$ as shown in Figure 2. In the present work, window length is set to 5 minutes with 1/8th overlap between successive windows.

C. Yule-Walker Mode Estimation

In order to assess the dynamic stability of the system under small perturbations from output measurements, the mode characteristics (frequency and damping) need to be estimated from the measurement data. In this work, we use Yule-Walker method on measurement channel best observing the mode of interest, which is explained next.

An output $y(n)$ of a discrete time linear time invariant system driven by white noise $v(n) \sim N(0,\sigma)$ can be represented by a p^{th} order auto-regressive (AR) model,

$$y(n) = \sum_{k=1}^{p} a_k y(n-k) + e(n) \tag{6}$$

Where a_k are the AR model parameters. Since $e(n)$ is independent of $y(n-k)$, taking an autocorrelation eliminates that term, which enables estimating AR parameters a_k directly from output data,

$$\begin{aligned} E(y(n)y(n-i)) = r(i) = \sum_{k=1}^{p} a_k r(k-i) \\ = \sum_{k=1}^{p} a_k E\big(y(n-k)y(n-i)\big)\ \forall i > 0 \end{aligned} \tag{7}$$

where, r is the autocorrelation function as defined before. Finally, the mode frequency and damping can be estimated from a_k using Eigen analysis [13].

IV. RESULTS

A. Long Term Analysis of Ambient Data

The period of interest is 2019, when the oscillations emerging from the STATCOM were severe. However, back then, measurements were only available at Substations A and C and not the STATCOM itself at B. Out of these substations, the best signal to analyze for mode content was found to be the voltage magnitude measured at Line A-B. Thus, we have not included the results corresponding to the remaining signals.

Data from July-December 2019 was analyzed for this work. The original data at 30 Hz is passed through a 5th order Butterworth filter with a bandpass range of 0.1-3 Hz and down sampled to a sampling rate of 6 Hz to detrend and denoise. 24 hr. spectrograms of the filtered voltage magnitude data on the Line A-B, for a few chosen interesting dates are plotted in Figure 2. There are ~ 2 modes visible from 0.5-2.5 Hz. The energy content of the lower frequency 0.5-1.0 Hz mode is relatively high and therefore is the mode of interest. Furthermore, it can be seen that there is a strong dependence of energy and frequency of the higher frequency modes on this mode, which hints towards a harmonic association.

In a practical setting, it is fairly common that measurements from the device causing issues are unavailable or the device from where the problems are originating is unknown. Therefore, to detect the source, one needs to rely on the periods when different elements are taken offline based on operation and/or maintenance schedules and associate them to the changes in the spectrum.

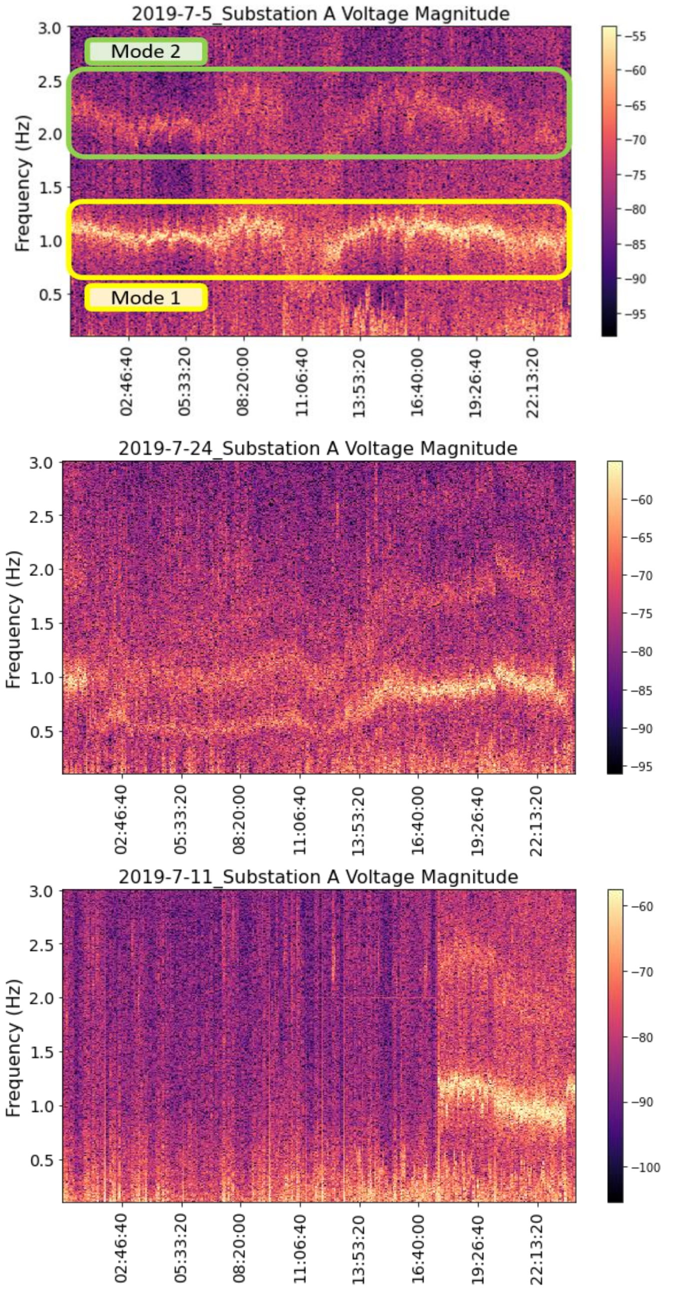


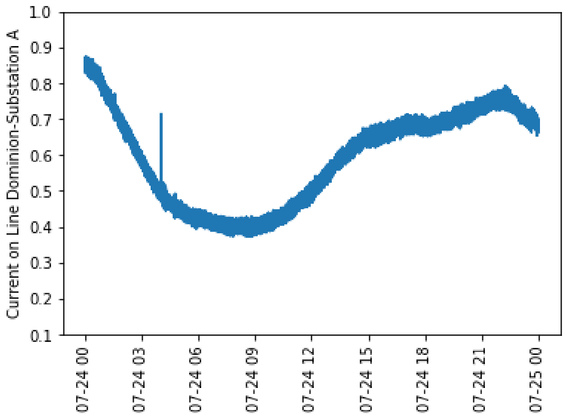
Figure 2. Substation A Spectrograms

To illustrate, note that there are no measurements available at Substation B, where the STATCOM is connected and hence, we analyzed the measurements at Substation A. On July 11th, the mode of interest wasn’t observable until 5 PM. This period coincided with the time when STATCOM was taken offline, and therefore, this gave a clear indication towards the STATCOM at Substation B being the source.

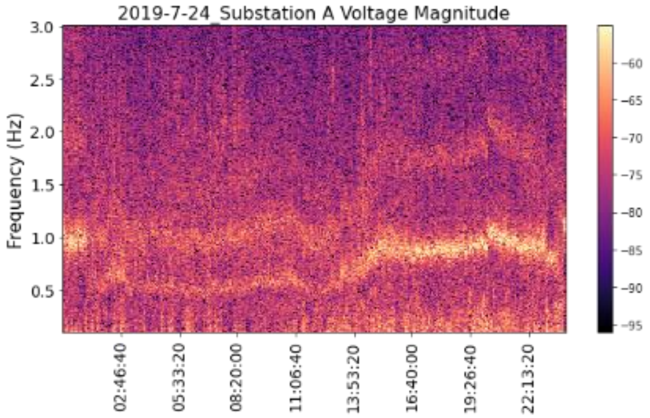
B. Mode Trends and Characteristics

From Figure 2, it is evident that the evolution of the modes throughout the day follow a familiar pattern. One of the spectrograms is shown alongside the current magnitude on Line from the rest of the Dominion network to this region (connecting to Substation A) in

Figure 3. It can be seen that there is a dependence of mode characteristics on the system loading. It can also be seen that the energy of the mode frequency component decreases significantly when there is a reduction in subsystem consumption.



(a) Current in p.u. in Line A-B



(b) Spectrogram of the voltage magnitude at Line A-B

Figure 3 Similarities in Load Curve and Mode Frequency Trajectory

This phenomenon is investigated further by estimating the dominant mode’s damping ratio and plotting it against the sub-system loading on 20 min windows picked randomly from the peak load month of August. The damping is estimated from the voltage magnitude signal, first bandpass filtering is applied to the data for the 0.1-3 Hz range and then using the Yule-Walker method is applied using an AR model of 6th order, as presented in the previous section. Figure 4 shows the high sensitivity of the damping of the mode of interest to load changes where higher loading operating conditions are associated with extremely low damping of as low as 1%. This raises concerns about the adequacy of the control system at the STATCOM.

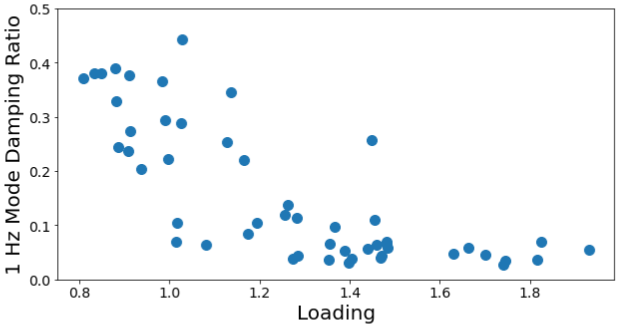


Figure 4. Damping vs Loading

C. Hypothesis of the Underlying Phenomenon

From the analysis of observational data from the transmission system, it is difficult to understand the underlying phenomenon/component behavior inside the STATCOM that is responsible for such oscillations. Based on our experiences with other STATCOMs in the system, it is hypothesized that the negative sequence control functionality is the culprit for these oscillations. This can be explained as follows. Dominion’s STATCOMs are typically operating at standby mode (zero-current injection mode) with reference reactive power set to zero. When exchanging current flows in each submodule cell is zero, each DC-link voltage control cannot take the correct insertion decision to adequately balance the DC capacitor’s voltage, especially when both measurement and process noise is also imposed on the measured signal. Thus, the STATCOM’s internal circulating current control is used for submodule DC voltage balancing. If the imbalance is too large, the negative sequence control injects more circulating current. This explains the reason for the given mode worsening with an increase in loading, which naturally increases the 3-phase imbalance in the network. However, confirming this hypothesis requires field tests to be performed on the equipment, such tests have been scheduled and will be conducted in the near future.

V. DISCUSSION AND FUTURE WORK

In this work, an investigation of poorly damped oscillations emerging from a STATCOM installed in Dominion Energy’s transmission system is presented. Analysis of historical ambient data using spectral analysis techniques is done to characterize the dynamic behavior of the STATCOM. The relationship of the oscillations to the subsystem loading is derived which helps form an initial hypothesis regarding the cause of these oscillations. Further investigation is needed to confirm the proposed hypothesis, to this end, field tests have been scheduled and will be conducted in the near future.

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