Condition Monitoring and Fault Diagnosis of Generators in Power Networks

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***Abstract*—In this paper, a novel hierarchical signal processing methodology is proposed for generator condition monitoring and fault diagnosis based on raw electrical waveform data in power networks, which can often be measured by strategically-located waveform sensors. The impact of generator short circuit faults on strategically located electrical waveform sensors in power networks are firstly investigated and validated in Matlab Simulink. Based on the large set of electrical waveform data produced by Matlab Simulink, a hierarchical algorithm is then designed to locate fault site location and monitor the condition of generators in power networks. Finally, the proposed methodology is validated in 14-bus IEEE standard power network under different scenarios (e.g, one generator fault, two-generator-fault, various aging levels, etc). Our results show that we can locate fault site location and monitor the aging condition of generators in power networks. Compared to traditional condition monitoring and fault diagnosis based on generator sensors, our proposed methodology can monitor a large number of generators based on a limited number of waveform sensors, which promises to reduce the cost of the maintenance and improve the reliability of the power grid.**

***Index Terms*—Synchronous Generators, Power Networks, Condition Monitoring, Fault Diagnosis, Short Circuit Faults, Advanced Signal Processing**

I. Introduction

Generators are playing a vital role in electrical power generation. Synchronous generators have been major means to generate electric power over a century. In recent years, due to the increased penetration of wind energy, the number of asynchronous generators have risen rapidly. Condition monitoring and fault diagnosis of large generators in power networks are gaining more interest since generator faults can lead to a catastrophic failure and then outages if not detected in the early stage. Due to aging or severe operating conditions, generators are subject to many different types of faults including stator faults, rotor electrical faults and rotor mechanical faults. Among these faults, stator winding inter-turn short fault due to the aging of winding insulation is the most dominant, which account for over 25% of faults in generators. When the inter-turn short fault is progressing, the condition of stator windings deteriorates and it can lead to catastrophic failures (e.g., phase-to-ground short circuit).

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In the past decade, many condition monitoring and fault diagnosis methods for generators, including signal-based, model-based and data-driven, have been investigated [1]–[4]. Motor current signature analysis (MCSA) based on the frequency analysis of the stator currents has been one of the most popular noninvasive condition monitoring and diagnosis methods. MCSA technique is mostly used to identify both rotor faults (e.g., bearing damage, broken rotor bar, eccentricity, end ring breakage, etc) and stator faults (e.g., short circuit fault, etc) based on slots related harmonics [5], [6], third harmonic [7], the sideband frequency components [8], and the other [9]. The frequency analysis of stator voltages is also used to detect stator winding inter-turn short faults in some operating conditions [10], [11]. Symmetrical component analysis, which decomposes stator current or voltage to positive-sequence, negative-sequence, and zero-sequence components, is one of the alternative condition monitoring and fault diagnosis methods due to symmetry of stator windings under the healthy condition [12], [13]. Therefore, condition monitoring and fault diagnosis techniques based on generator sensors (e.g, voltage, current, vibration, etc) have been widely used and promise to reduce unscheduled downtime, and maintenance costs.

When generators are connected in power networks, current/voltage signature signals of faulty electric machines will propagate through the power networks [14]. The raw electrical waveform and signals (e.g., voltage, current, harmonics, power factor, etc) in power networks will likely change, which contain rich information about condition of generators. In [15], [16], some waveform information (magnitude or phase) were used to identify parameters of generators, however, they were not yet used to monitor the aging condition of the generators for scheduled maintenance. In addition, for condition monitoring and fault diagnosis of generators, raw electrical waveforms at higher sampling rate besides magnitude and phase mentioned above might be needed as fault/deteriorating condition of generators will produce unusual harmonics.

To the best of our knowledge, there are no existing works in condition monitoring/fault diagnosis of generators by analyzing raw electrical waveforms in power networks, which can be measured by strategically located electrical waveform sensors.

In this paper, we propose to develop advanced signal processing methodology for generator condition monitoring

and fault diagnosis based on strategically located waveform senors in power networks with the goal to reduce the cost of the maintenance and improve the reliability of the power grid. Firstly, we build the the equivalent model of synchronous generators under short circuit faults. Secondly, we analyze the impact of generator short circuit faults on strategically located electric waveform sensors in power networks. Thirdly, we build 14-bus IEEE standard power network model in Matlab Simulink and different scenarios (e.g, one generator fault, two-generator-fault, various aging levels, etc) to produce a large set of electric waveform data for condition monitoring and fault diagnosis. Finally, based on the electrical waveform data in power networks, we will develop data-driven signal analysis approach to locate fault sources and estimate the aging levels of generators in power networks.

II. ANALYSIS OF THREE-PHASE SHORT FAULT

When the short circuit faults happens in synchronous generators, the current could be multiple times of the rating current of the generator, which could bring catastrophic damages to the power grid. In this section, the short-circuit fault of synchronous generators is analyzed.

Assume the generator operates at speed ω, then the flux linkage will be: $\psi = \Psi_0 \cos(\alpha_0 + \omega t)$. And the fault happens at $t = 0$, the induced current will produce $\Delta\psi$ to maintain the initial flux linkage ψ_0, so $\Delta\psi = \psi_0 - \Psi_0 \cos(\alpha_0 + \omega t)$.

According to the flux linkage analysis above, stator current includes two parts: one is the DC component i_{ap} generating the initial flux linkage ψ_0; the other one is the AC component i'at the synchronous frequency ($f = \frac{\omega}{2\pi}$), which generates the rotating field to offset the rotor exciting field.

For the salient pole machine, to compensate the difference in magnetic resistance of d- and q- axis, there will be one additional AC component, the frequency of which is twice the synchronous frequency of the stator current. Therefore, three types of magnetic field will be induced by the stator. And these three magnetic fields will then change the flux linkage in the rotor winding. Therefore, to maintain its flux linkage in the rotor, the rotor will have similar armature reaction and induce three types of currents. Since the rotor is rotating at angular speed ω, frequencies of these currents will be: ω, 0 and $-\omega$. It should be noted that $-\omega$ means the field rotates in the opposite direction.

The current components which will attenuate are refereed to as free current Δi, while others are refereed to as forced current i_∞. The classification is shown in Table I.

TABLE I: Short Current Classification.

	forced current i_∞	free current Δi	
stator	i_∞	$\Delta i' = i' - i_\infty$	i_{ap}, $i_{2\omega}$
rotor	$i_{f[0]}$	Δi_{fa}	$\Delta i_{f\omega}$

According to the synchronous generator model and constant-linkage theorem, the short circuit current of generators with damping windings could be deducted by:

$$\begin{aligned} i_a = & -\frac{E_{q[0]}}{x_d}\cos(\omega t + \alpha_0) \\ & - (\frac{E''_{q0}}{x''_d} - \frac{E_{q[0]}}{x_d})\exp(-\frac{t}{T''_d})\cos(\omega t + \alpha_0) \\ & - (\frac{E'_{q[0]}}{x'_d} - \frac{E_{q[0]}}{x_d})\exp(-\frac{t}{T'_d})\cos(\omega t + \alpha_0) \\ & - \frac{E''_{d0}}{x''_q}\exp(-\frac{t}{T''_q})\sin(\omega t + \alpha_0) \\ & + \frac{U_{[0]}}{2}(\frac{1}{x''_d} + \frac{1}{x''_q})\exp(-\frac{t}{T_a})\cos(\alpha_0 - \delta_0) \\ & + \frac{U_{[0]}}{2}(\frac{1}{x''_d} - \frac{1}{x''_q})\exp(-\frac{t}{T_a})\cos(2\omega t + \alpha_0 + \delta_0) \end{aligned} \tag{1}$$

Similarly, the rotor current can be obtained by:

$$\begin{aligned} i_f = & \, i_{f[0]} \\ & + [\frac{x_{ad}x_{\sigma D}U_{[0]}\cos\delta_0}{(x_f x_D - x_{ad}^2)x''_d} - \frac{(x_d - x'_d)U_{[0]}\cos\delta_0}{x_{ad}x'_d}]\exp(-\frac{t}{T''_d}) \\ & + \frac{(x_d - x'_d)U_{[0]}\cos\delta_0}{x_{ad}x'_d}\exp(-\frac{t}{T'_d}) \\ & - \frac{x_{ad}x_{\sigma D}U_{[0]}}{(x_f x_D - x_{ad}^2)x''_d}\exp(-\frac{t}{T_a})\cos(\omega t + \delta_0) \end{aligned} \tag{2}$$

III. IMPACT OF GENERATOR FAULTS ON ELECTRIC WAVEFORMS IN POWER NETWORKS

To simplify the analysis of short circuit fault, the method of symmetrical components is used in this section to analyze the impact of generator short circuit faults on the power networks. A according to symmetrical components, any types of asymmetrical three-phase phasor could be decomposed to three symmetrical three-phase phasors. Take current for example, (3) shows the relationship between currents in two coordinates. Phase b and phase c currents could be derived by similar equations.

$$\begin{bmatrix} \dot{I}_{a(1)} \\ \dot{I}_{a(2)} \\ \dot{I}_{a(0)} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} \tag{3}$$

where $a = e^{j120^\circ}$, $a^2 = e^{j240^\circ}$; $\dot{I}_{a(1)}$, $\dot{I}_{a(2)}$, $\dot{I}_{a(0)}$ are the positive, negative and zero sequence of phase currents, respectively. Then sequence impedance is introduced to describe relationship between voltage and current in symmetrical components coordinate. Thevenin's equivalent circuit for sequence impedance is shown in figure1. It should be noted that the asymmetrical components in sequence impedance are eliminated by adopting the asymmetrical voltage source and the transmission line reactances are modeled in Z_{ff}. For generality, the equivalent circuit equation could be derived by:

$$\begin{aligned} \dot{E}_{eq} - Z_{ff(1)}\dot{I}_{fa(1)} &= \dot{U}_{fa(1)} \\ 0 - Z_{ff(2)}\dot{I}_{fa(2)} &= \dot{U}_{fa(2)} \\ 0 - Z_{ff(0)}\dot{I}_{fa(0)} &= \dot{U}_{fa(0)} \end{aligned} \tag{4}$$

Three more equations are needed to solve the equations with 6 unknown variables, which are derived from the fault conditions. And common faults in power system include two

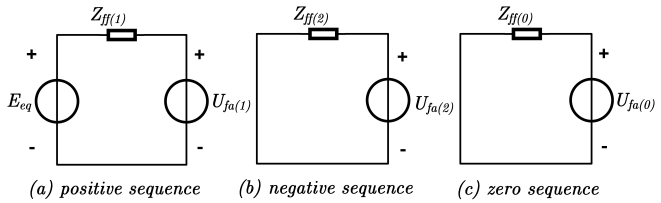

Fig. 1: Equivalent circuit of each phase sequence

TABLE II: Common Fault Condition in Power System.

fault category	fault condition		
single phase short	$\dot{U}_{fa}=0$	$\dot{I}_{fb}=0$	$\dot{I}_{fc}=0$
two phases short	$\dot{I}_{fa}=0$	$\dot{I}_{fb}+\dot{I}_{fc}=0$	$\dot{U}_{fb}=\dot{U}_{fc}$
two phases grounded	$\dot{I}_{fa}=0$	$\dot{U}_{fb}=0$	$\dot{U}_{fc}=0$

phase short fault, two phase grounded short fault, etc. The related fault conditions are listed in Table II.

Therefore, common asymmetric short faults could be solved by (4) and the related fault equations listed in Table II. Other bus voltage and branch current in the normal condition could also be solved similarly. However, this method requires the detailed grid topology information and the accurate fault location, which may not be easy to acquire. In addition, to simulate multiple fault cases, this method is based on a strong assumption that the whole system is linear, which is hardly applicable in the real power system. Therefore, in the following section, an advanced signal processing technique will be proposed to locate the fault source for condition monitoring and fault diagnosis.

IV. Fault Identification and Location

In this section, we use the measured waveform data to identify and locate generator faults. Algorithm 1 shows how the whole process works. The waveforms of voltage and current signals $\mathbf{V}=[V_1,V_2,\ldots,V_N]^T$, $\mathbf{I}=[I_1,I_2,\ldots,I_N]^T$ are measured from a network with size N the nodal, where depending on the number of phases at node i, V_i and I_i can be row vectors of size 1, 2 or 3. In order to characterize the waveform properties, we adopt instantaneous properties from:

$$s_c(t)=s(t)+j\mathcal{H}\{s(t)\}=A(t)e^{j\psi(t)}, \tag{5}$$

where $s(t)$ is the real signal, $s_c(t)$ is the complex expression, $A(t)$ is the instantaneous amplitude (IA) (envelope), $\psi(t)$ is the instantaneous phase(IP), $\mathcal{H}$ is the Hilbert transform as:

$$\mathcal{H}\{s(t)\}=\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{s(\tau)}{t-\tau}\mathrm{d}\tau. \tag{6}$$

Thus, for a three phase current $I_n=[I_{nA},I_{nB},I_{nC}]^T$, where $I_{nA}=A_{I_{nA}}e^{j\psi_{I_{nA}}(t)}$. ($V_n$ can be expressed in the same way.)

A. Event Detection

Before identifying the location of an event, we must first become aware of the occurrence of such event. Thanks to the data-driven time series anomaly detection techniques, the presence of the event can be detected continuously. The changes of the nodal voltages and branch currents can be expressed as:

$$\Delta V_n=V_n(t)-V_n(t-w),\quad \Delta I_{np}=I_{np}(t)-I_{np}(t-w), \tag{7}$$

Algorithm 1 Waveform based Generator Fault Identification and Location Algorithm

1: **Input**: Waveforms of voltage and current.
2: **Output**: Fault properties and location.
3: Event detection based on time series anomaly detection techniques;
4: Unbalance detection to distinguish single phase, double phase or three phase fault;
5: Event source region determination based on measurement changes;

where, w is the analysis window size, n and p denote two arbitrary neighboring nodes. If abnormal changes happen to ΔV_n and ΔI_{np}, which indicate the difference between the pre- and post-event, an event can be detected. Once the occurrence of an event is detected, the next step is to identify the types of the event and location of the root cause of the event.

B. Phase Unbalance Characterization

Simulating the generator aging faults, we could meet single, two or even three phase issues, which means the short circuit as shown in Figure 2. The waveforms of Phases A,B, and C allow a relatively straightforward phase unbalance characterization based on direct comparisons of phase signal attributes.

Based on the IA, we define the current unbalance characterization functions I_α, I_β, and I_γ as:

$$I_{n\alpha}=\frac{1}{3}\sum_{i\neq j}^{i,j\in\{A,B,C\}}(A_{I_{ni}}-A_{I_{nj}})^2. \tag{8}$$

$$I_{n\beta}=\frac{I_{max}-I_{min}}{I_{max}}\times 100\%, \tag{9}$$

$$I_{n\gamma}=\sum_{i\neq j}^{i,j\in\{A,B,C\}}\Gamma(A_{I_{ni}},A_{I_{nj}}), \tag{10}$$

where, $I_{n,max}=\max\{A_{I_{nA}},A_{I_{nB}},A_{I_{nC}}\}$ and $I_{n,min}=\min\{A_{I_{nA}},A_{I_{nB}},A_{I_{nC}}\}$, Γ denotes a thresholding function to measure the difference. Similarly, we can also get V_α, V_β and V_γ. If I_β and V_β is not zero, there exists unbalance among the three phases. Then we use I_γ and V_γ to determine the how many phases are affected. In addition, I_α and V_α are used to measure the absolute changes.

C. Identifying the Event Source Region

Assuming there are two waveform sets from two nodes, if it happens, an event may occur in three regions: upstream of node n, downstream of node p, and between nodes n and p. The measurements can be expressed as M_n and M_p. Since we not only have the voltage and current, but also the unbalance measurements, M_n can be defined as

$$M_n=[I_{nA},I_{nB},I_{nC},V_{nA},V_{nB},V_{nC},I_\alpha,I_\beta,I_\gamma,V_\alpha,V_\beta,V_\gamma]^T. \tag{11}$$

Then, event location can determined by the comparison between ΔM_n and ΔM_p. For example, if the change patterns of ΔM_n and ΔM_p are the same, the event happens either on the upstream or downstream, but if those are different, the event happens between nodes n and p.

V. Simulation and Evaluation

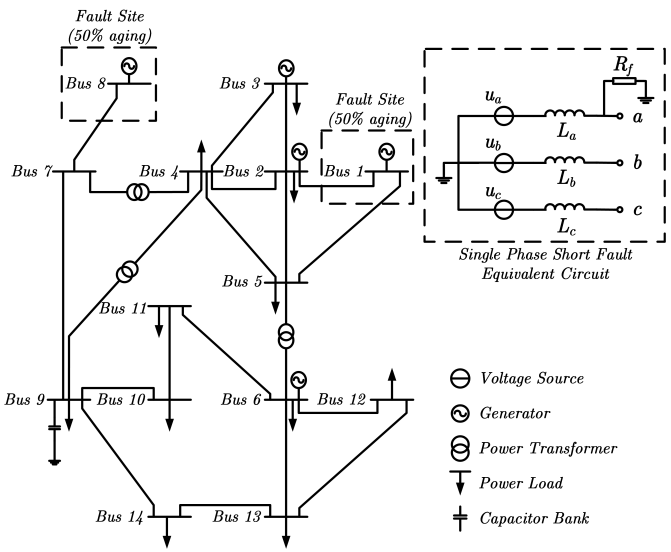

Fig. 2: IEEE 14 Bus Power Network

For evaluation, a 14-bus IEEE standard power network (Figure 2) is built to investigate the impact of the generator faults on electrical waveforms in power networks, which is also used to generate a large set of waveform data needed in the proposed algorithms. In the simulation model, generators are simplified as non-ideal three-phase voltage sources, and the loads are modeled as constant power loads. Meanwhile, the transmission line reactances are modeled by Simulink block 'Three-Phase PI Section Line'. And the parameters are calculated from the IEEE standard 14-bus testbed datasheet. Specifically, the level of the short fault or the aging degree is modeled as a short circuit resistance, R_f, as shown in figure 2 (only depict the single phase grounded short fault for example). R_f is modeled as $R_f = 10^{(5-10*\kappa_{\text{aging}})}$, where κ_{aging} denotes the generator condition aging level.

When two generators highlighted in Figure 2 have aging stator windings both at 50% level, their voltage and current signature will change and will likely impact raw electrical waveforms and signals (e.g.,voltage, current, harmonics, power factor) in power networks (e.g, voltage, current, etc) due to waveform and signal propagation. As a result, the voltage and current waveforms in bus 6 generator and bus from 6 to 11 are significantly impacted as shown in Figure 3. The traditional approaches based on machine sensors, for instance, sensors in bus 6 generator, cannot distinguish whether bus 6 generator is faulty or not. To address this challenges, we developed an advanced signal processing approach based on strategically located waveform senors. The proposed data-driven approach utilizes waveforms as well as derived signal attributes to characterize the dynamic relationships among limited sensors to deduce the actual fault locations, which may not be monitored.

Based on the model shown in Figure 2, two generator faults are simulated, which are located at G1 and G8 with 50% aging. There are 14 nodes in the grid, and typically all generators (5) and transformers (3) should have built-in sensors, so there

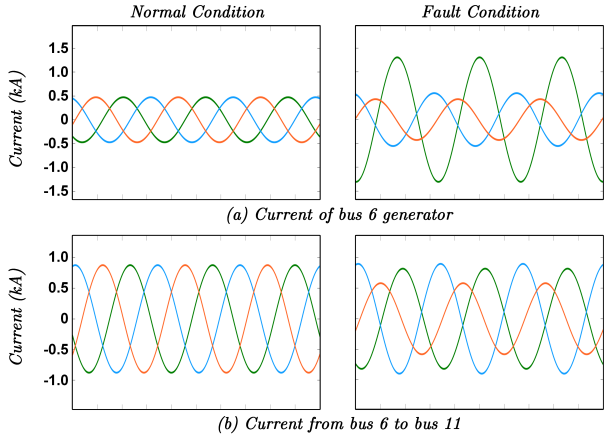

Fig. 3: Single Phase Short Fault Simulation Results.

could be 8 sensors in the traditional power networks. In our experiment, we only use 4 sensors from Nodes 1, 6, 7, and 14, to simulate the limited sensor situation.

Figure 4 shows the voltages and IAs from the 4 sensors. Based on the V_γ function, we can know only Phase A has the short circuit event. Although observations from Nodes 7 and 14 indicate differences between Phases B and C, the small deviations should be caused be the unbalanced Phase A current rather than more than one phase short circuit.

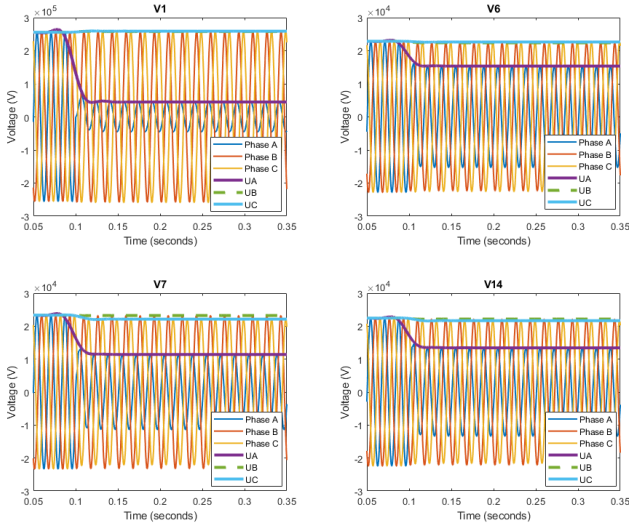

Fig. 4: Voltage waveforms and corresponding instantaneous amplitudes at Nodes 1, 6, 7 and 14.

Next, let us locate the root source region. Figure 5 shows the current waveforms measured at Node 6. From Table III, I_β is the largest for IG6, which means the major unbalance source for Node 6 is from the Node 5 direction. (If Node 6 is the fault source, the current unbalance metrics between 6 and 11, 12, 13 would be similar.) So the fault source could be Nodes 1, 2 or 3. However, if Node 2 or 3 is the fault source, the current measured at Node 7 about Bus 4 would display more obvious unbalances. While, Node 1 could be the source, as both its voltage and current are not balanced.

Furthermore, we need to check whether Node 1 is one only fault source. If yes, the unbalanced current metrics from Table III should show largest value from Bus 4 instead of current between Nodes 7 and 8. Thus, for Node 7, the major fault source is from Node 8, which is also a generator. So, we decide Nodes 1 and 8 are two fault sources. Considering the space limit, more discussions are omitted.

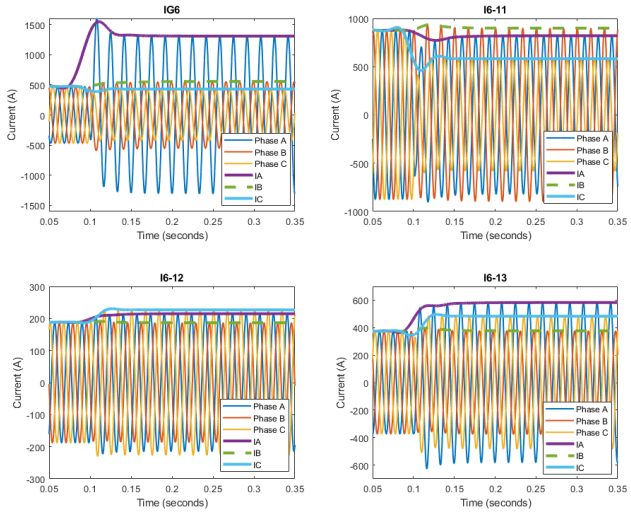

Fig. 5: Current waveforms and corresponding instantaneous amplitudes at Node 6.

In addition, based on the current and voltage changes, we estimate the $\hat{R}_{f_1} = 9.17\Omega$ and $\hat{R}_{f_8} = 1.35\Omega$. According to the relation between R_f and κ_{aging} in Section V, $\kappa_{\text{aging}}^{G1} = 40.3\%$ and $\kappa_{\text{aging}}^{G8} = 48.7\%$. The aging percentage estimation for Node 8 is close to the ground truth 50%, while there is still space for improvement as $\kappa_{\text{aging}}^{G1}$ is not accurate.

Note that the measurements from Node 14 are not useful in our experiment, so we actually only use 3 nodes to locate the event source. There are two remarks: (1) limited measurements can be used to monitor the whole network; (2) the observation selection (sensor location) should be considered carefully to get the maximum information using minimum sensors and avoid recording useless information.

TABLE III: Unbalance metrics of Nodes 1, 6, 7, 14.

Node #	1	6	7	14
V_β	0.832	0.328	0.511	0.383
I_β	(1-2) 0.922	(G6) 0.6865	(B4) 0.269	(B14) 0.390
	(1-5) 0.825	(6-11) 0.359	(7-8) 0.887	N/A
	N/A	(6-12) 0.181	(7-9) 0.627	N/A
	N/A	(6-13) 0.366	N/A	N/A

VI. Conclusion

In this paper, an advanced signal processing methodology for generator condition monitoring and fault diagnosis has been developed based on strategically located waveform sensors in power networks. The impact of the generator short circuit fault caused by winding aging and other severe operation conditions are discussed, and then analyzed in a great detail. Meanwhile, an IEEE 14-bus power network is built in the MATLAB Simulink to produce a large set of waveform data in different scenarios. A hierarchal signal processing technique has been developed, which shows promise in locating fault location and monitoring the condition, or more specifically identifying the aging level. With the reduced number of strategically located waveform sensors, the proposed methodology will bring the advantages of reducing the cost of the maintenance and improving the reliability of the power grid.

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