Real-Time Detection of Distribution System Disruptions via Dynamic Power Quality Metrics

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***Abstract*— A complete characterization of transients is increasingly important, given the abundance of nonlinear loads and distributed generators in modern power systems. Effective control of power quality (PQ) can be achieved only when the contribution of imbalance and nonlinearities to non-active power is clearly understood and monitored. In this work, we customize our Dynamic Power Quality Metrics (DPQMs), which are developed from dynamic phasors and applied to utility data. The refresh rate of each dynamic phasor—and hence of each DPQM—is the same as the waveform sampling rate: an update occurs as soon as a new sample of each voltage and current waveform is acquired. Employing such a fast refresh rate facilitates accurate detection and tracking of short and long transients and provides a fast response, in the order of a few sampling intervals, to the onset of change. We also introduce a novel analysis tool: a normalized *N*-metric. Comparing its instantaneous value to a preset threshold enables accurate event detection and control actions. We illustrate the usefulness of the normalized *N*-metric and the other DPQMs as practical tools for analyzing a system's behavior during transients and steady-state operation.**

***Index Terms*—*N* Metric, Normalized *N* Metric, Power System Transients**

I. Introduction

The need for enhanced characterization of power quality during steady-state operation and transients is not only an analytical concern but also an urgent and practical necessity. The increasing number of power disturbances — such as RMS voltage deviations, frequency perturbations, harmonics, unbalances, flicker, voltage sags and swells, and temporary interruptions — is affecting the performance of end-user equipment, particularly for commercial and industrial customers [1]. This leads to added and unwanted operational costs. The increase in power disturbances in the past two decades has underscored the critical need for power quality analysis. Many electric utilities currently rely on CBEMA and ITIC curves to characterize voltage anomalies in the supply and distribution for the proper operation of end-user equipment [2]. It should be noted that these tools a) cannot provide a real-time indication of the onset and duration of each event, b) do not support instantaneous control response, and c) do not provide a detailed "signature" of each distinct event that may be used to classify it using modern pattern recognition tools. In contrast, DPQMs address all three of these challenges. Additionally, these curves sometimes prove too coarse as they define boundaries of safe operation without incorporating details of actual measurements or power quality metrics, and solely consider voltage levels without including harmonic distortion or the frequency content of transients [3]. Therefore, the use of PQ metrics that capture the characteristics of disturbances is not just necessary but highly practical for utilities to gain clear insight into events and system operations. To address this challenge, we demonstrate the efficacy of our developed metrics (DPQMs) as operational tools to capture the onset and behavior of disturbances. Applying the concept of dynamic phasors to transients, the scheme results in a novel, dynamic (time-varying) power decomposition for polyphase systems [4]-[6]. Unlike CBEMA and ITIC curves, the DPQMs consider all three-phase voltages and currents (six waveforms), providing a comprehensive view of the power system's behavior [3], [7]. In particular, we introduce in this paper the *normalized N-metric,* a novel analysis tool that uses a universal threshold (which is independent of the nominal level of power) to detect abrupt transients in any grid setting.

Our dynamic power decomposition captures transient behavior while reducing to the standard (constant phasor) characterization in the steady state. Thus, it relates to quantities that are part of utility regulations, such as harmonic distortion and power factor. We also propose a secondary decomposition of both the real power and the reactive power into their respective symmetrical sequence components. We demonstrate the value of our dynamic power decomposition by applying it to actual data recorded in the distribution sector of the electric power grid. Artificial Intelligence (AI) tools for automatic classification could benefit from the unique nature of our DPQMs, which can function as a front end to AI processing. In particular, the normalized N-metric captures most transients much more clearly than voltage or current waveforms, allowing the size of training data to be reduced. In other words, using DPQMs instead of raw waveforms may

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reduce the challenge of high-dimensional detection and classification.

In this paper, we have briefly represented the modeling behind our DPQM metrics, as well as the newly introduced N-metric (Sec. II). The application of the metrics in real-world cases is shown in Sec. III.

II. Dynamic 3-Component Power Decomposition

The introduction of phasor representations also provides simple expressions for quantities defined in terms of temporal averages, such as RMS voltage and current, as well as real, apparent, and reactive power. Furthermore, it allows for the refinement of the power quality gap between real and apparent power. An explicit characterization of this gap is provided, in steady-state operation, by the 5-component decomposition of apparent power

$$S^2 = P^2 + Q^2 + \underbrace{N_g^2 + N_b^2 + S_\perp^2}_{N^2} \qquad (1)$$

where each quantity in this expression is evaluated from the polyphase voltage and current RMS phasors, $V_k = [V_k^{(1)}, V_k^{(2)}, V_k^{(3)}]$ and $I_k = [I_k^{(1)}, I_k^{(2)}, I_k^{(3)}]$, where k is the harmonic index. These are complex-valued row vectors, each consisting of three elements (in a 3-phase system), one for each phase of the corresponding polyphase waveform. A detailed discussion and derivation of this decomposition, as well as its $\frac{7}{11}$−component refinement is provided in [4, 5, 8]. In particular, the expressions for real and reactive power are $P = \sum_{k=0}^{\infty} \Re\{V_k I_k^H\}$ and $Q = \sum_{k=0}^{\infty} \Im\{V_k I_k^H\}$, where the superscript ^{H} denotes conjugate transposition. Similarly, the apparent power $S \overset{\text{def}}{=} V_{rms}\, I_{rms}$ is evaluated from the Euclidean norm of the same set of phasors, because $V_{rms}^2 = \sum_{k=0}^{\infty} ||V_k||^2$ and $I_{rms}^2 = \sum_{k=0}^{\infty} ||I_k||^2$.

The remaining three components – N_g, N_b and $S_\perp$ – represent the combined effect of unbalanced power flow, harmonic distortion, and frequency spreading. A detailed analysis of these components, as well as explicit expressions for their evaluation, can be found in [4, 8]. Notice that the non-negative aggregate power metric $N \overset{\text{def}}{=} \sqrt{N_g^2 + N_b^2 + S_\perp^2}$ can also be evaluated from the alternative expression $N = \sqrt{S^2 - (P^2 + Q^2)}$, which offers a significant reduction in computational cost.

The decomposition shown in (1) is still valid in the presence of transients, but with the traditional voltage and current phasors replaced by their *dynamic counterparts*: the dynamic (polyphase, RMS) voltage phasors associated with a 3-phase waveform $v(t) = [v_1(t)\; v_2(t)\; v_3(t)]$ are evaluated over a *sliding-window interval*, namely,

$$V_k(t) \overset{\text{def}}{=} \frac{\sqrt{2}}{T} \int_{t-T}^{t} v(s) e^{-jk\omega_0 s}\, ds, \quad k = 1, 2, 3, \ldots$$

and similarly for the dynamic polyphase current phasors $I_k(t)$. This means that every power component in (1) becomes time-dependent and thus needs to be re-evaluated at every new sampling instant t [12, 13]. The resulting dynamic N-metric – i.e., $N(t) = \sqrt{S^2(t) - (P^2(t) + Q^2(t)}$ – can be used to detect the onset of transients and determine their duration.

In order to facilitate the reliable detection of transients across a wide variety of scenarios, we propose to normalize the N- metric by its (time-dependent) steady-state value, viz.,

$$\overline{N(t)} \overset{\text{def}}{=} \frac{N(t)}{N_{ss}(t)} \qquad (2)$$

The resulting dimensionless metric $\overline{N(t)}$ equals unity in steady state, but increases noticeably above unity in the presence of a perturbation. The challenge lies in determining the continuously adjustable steady-state value $N_{ss}(t)$ during operation, including changes caused by the connection or disconnection of loads, and by occasional perturbations. For every time instant t, we define $N_{ss}(t) = \min\{\, N(s); t - T_1 \le s \le t\}$, i.e., the minimum of the non-negative waveform $N(\cdot)$ over a multi-cycle-long immediate past (of length T_1). In our experience, using the minimum – rather than the average – results in more accurate tracking of the steady-state value of $N(t)$, provided that the window used is longer than any transient event of interest. This is easy to implement in continuous operation, using a window of 10 seconds in our case, or even one minute.

III. Detection of Perturbation Events

Two real-world events are analyzed to demonstrate the usefulness of DPQMs. Actual measurements collected by the local utility (Eversource Energy) were graciously shared with us and used to derive these metrics.

This is a case observed on the customer side. Voltage and current waveforms, as well as DPQM metrics, are shown in the following figures. The sampling rate of the data collection was 512 samples/cycle or, equivalently, 30,720 samples/sec. To visualize the case more clearly, a simplified Single-Line Diagram (SLD) representation of the event is shown in Fig. 1.

A. Case 1: Sporadic Transients Leading to Voltage Collapse

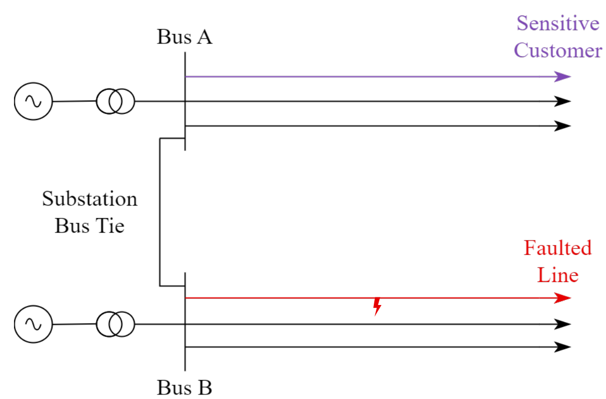

Fig. 1. Event Schematic for Case 1

The feeder is a mixed underground cable located in an urban environment with a 13.8 kV line-to-line RMS voltage rating. This disturbance case stems from a fault due to a cable splice failure on a separate feeder located on an adjacent substation bus. As shown in Fig. 3, no clear information can be obtained from the current waveforms except for harmonic distortion. The currents do not change much, even when the

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voltage of the phase B collapses. The phase B voltage, $v_B(t)$ shows intermittent shorts, which start at $0.52\ s$, and occurs again at $0.66\ s$ and continues (shown by arrows in Fig. 3). These momentary faults become severe at $0.81\ s$. The other two phases experience a transient voltage every time $v_B(t)$ shows a short. On the other hand, the power metrics indicate a severe problem more clearly than the voltage or current plots.

The N-metric peaks are apparent and substantially larger than the pre-event quantities (see Fig. 4). $P(t)$ and $Q(t)$ also show deviations from their respective values, although considerably smaller in their relative size. The N-metric recovers its steady state value after each of the first four peaks. However, once the short in $v_B(t)$ becomes severe, the N-metric becomes considerable. In the pre-event region, the N metric has a value of about $0.11\ MVA$, which is large for a system where the real power is about $0.95\ MW$. This implies that there is a severe imbalance before the onset of the first event. The (very) slow increase in $Q(t)$ within the same time interval suggests a minor crawling load change before the onset of the first fault.

Other useful metrics come from Symmetrical Sequence Decomposition (SSD). For instance, the negative sequence of real power, $P_{-}(t)$, is flat before the first disturbance, which facilitates the detection of the deviation almost immediately. Both $P_{-}(t)$ and $N(t)$ should be evaluated to detect the onset of a disturbance. However, in this case, $N(t)$ is a more sensitive indicator that easily achieves the sub-millisecond resolution of the event.

B. *Case 2: Evolutionary Voltage Sag*

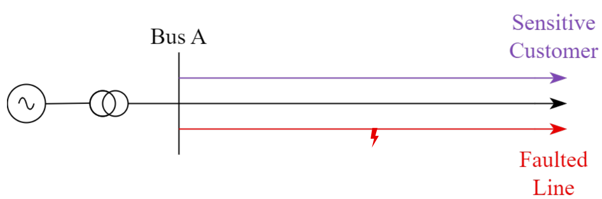

Fig. 2. Event Schematic for Case 2

This case is another example of a disturbance observed from the customer's side of the system. The DPQMs and SSD metrics are evaluated on data collected by the customer (see Fig. 5 and Fig. 6). The data collection sampling rate was 512 samples/cycle or, equivalently, 30,720 samples/sec. The feeder is a $13.8\ kV$ (line-to-line) mixed underground cable located in an urban setting. This disturbance event was triggered by an evolving fault that occurred on a neighboring feeder supplied by the same substation bus. To visualize the case more clearly, a simplified SLD illustrating the event is shown in Fig. 2.

Case 2 is an example of a Single Line-to-Ground (SLG) event that eventually becomes a Line-to-Line (LL) disruption. The voltage waveforms capture the events, but not as clearly as the current waveforms, in which the changes are more noticeable. The signatures of the events are not explicitly captured by the phase voltage $v_A(t)$ and $v_B(t)$. Therefore, relying on voltage waveforms as PQ metrics does not fully capture the system's behavior. However, the disruptions are well captured by DPQMs and the SSD metrics at $0.53\ s$ and $0.69\ s$, as shown in Fig. 6. Similar to Case 1, the use of these metrics detects the disturbances almost instantly and provides insight into the duration and nature of the events. The N-metric becomes considerable once the first disturbance starts, while $P_{-}(t)$ and $Q_{-}(t)$, would detect the onset of the events. However, the dynamic N- metric again seems more precise.

A difference between Case 1 and Case 2 is that the provided data for Case 2 included line-to-line voltages and line currents. The measurement of line-to-line voltages is due to the installation and configuration of sensors that capture data. When only line-to-line voltages are available, the phase-to-neutral voltages depend on the (unknown) neutral line voltage with respect to a voltage reference point. The following conversions, shown in (3), are used to calculate the phase-to-neutral voltages:

$$\begin{aligned} v_A(t) &= \tfrac{1}{3}[v_{AB}(t) - v_{CA}(t)] \\ v_B(t) &= \tfrac{1}{3}[v_{BC}(t) - v_{AB}(t)] \\ v_C(t) &= \tfrac{1}{3}[v_{CA}(t) - v_{BC}(t)] \end{aligned} \tag{3}$$

As explained in [10], the above conversion uses the virtual star point as a voltage reference and results in a vanishing zero-sequence voltage. This leads to the disappearance of $P_0(t)$ and $Q_0(t)$, hence its exclusion from Fig. 6.

C. *Threshold Determination*

Fig. 7 displays the normalized N- metric for Cases 1 and 2. In both examples, this metric increases at the onset of a perturbation to a value within the range $1 \leq \overline{N(t)} \leq 5$ (approximately 2 for Case 1 and 4 for Case 2). Thus, setting a universal threshold value such as 1.5 would result in the successful detection of the transient onset in both cases. A careful study of a large number of perturbation scenarios may suggest a further adjustment of this universal threshold, so that it can be used to program relays and other control actions. Notice that the normalized N-metric can be evaluated causally, in real-time. This means that a perturbation onset can be detected with minimum delay: typically, within a single sampling interval. A similar observation applies, of course, to each of the power quality metrics in the decomposition (1). However, our cumulative past experience suggests that the N-metric is a remarkably accurate and reliable indicator of perturbation occurrence.

IV. CONCLUDING REMARKS

As a step towards developing possible corrective actions, we have analyzed the waveforms of the transient events reported either by customers or utilities. DPQMs and SSDs are valuable tools that provide clear information about the onset and characteristics of the disturbances, such as a sudden increase in harmonics or a sudden deviation from phase balance. In this work, we propose two additional metrics: the N-metric and its normalized form. These single metrics effectively capture system perturbations. By evaluating the normalized N-metric across numerous datasets, a common threshold value can be identified for operational use, making it a universal indicator.

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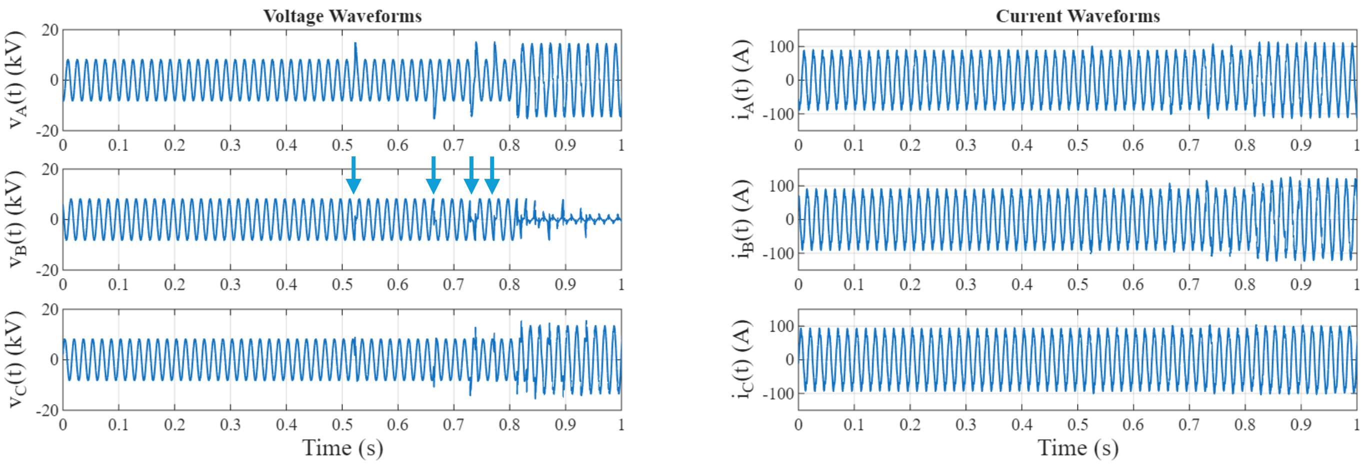

Fig. 3. Case 1 Waveforms

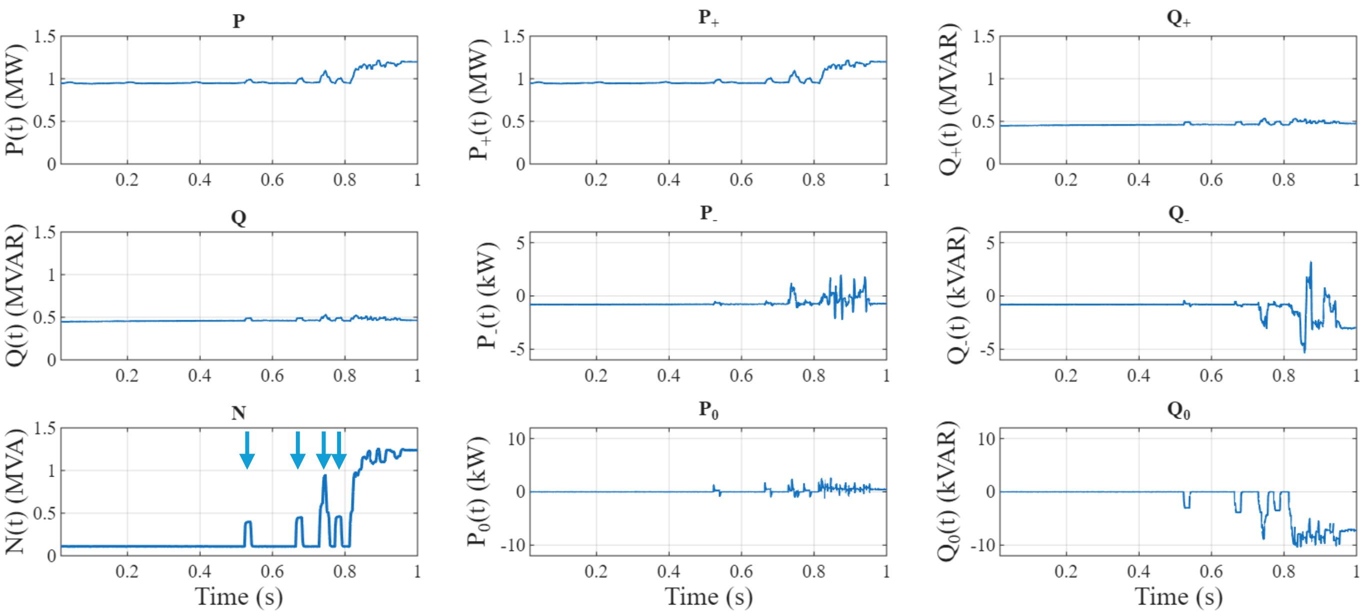

Fig. 4. Case 1 Power Components

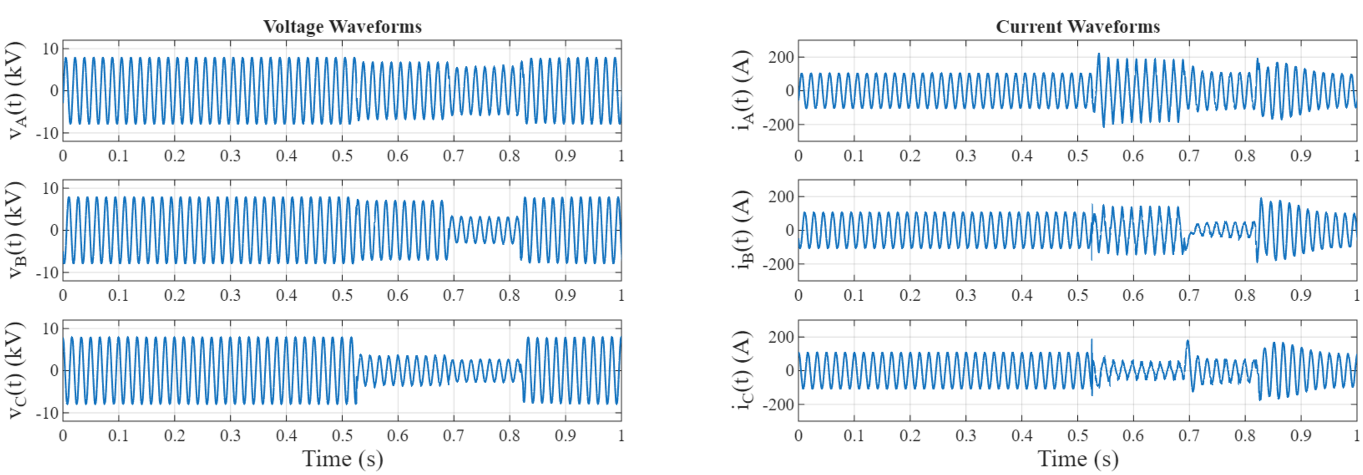

Fig. 5. Case 2 Waveforms

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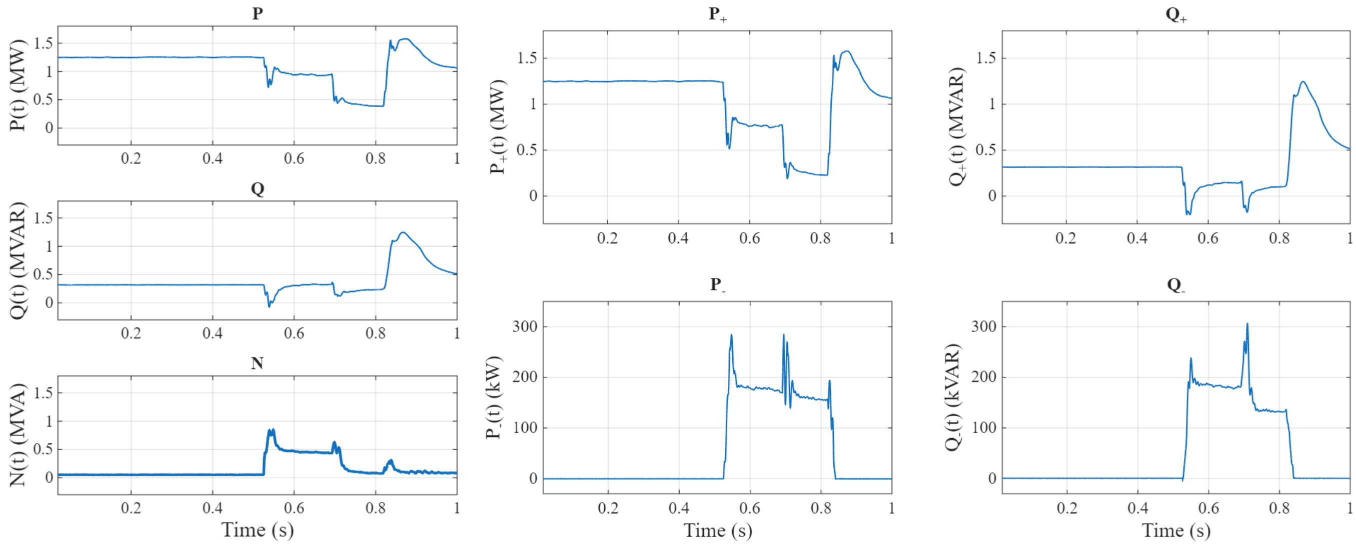

Fig. 6. Case 2 Power Components

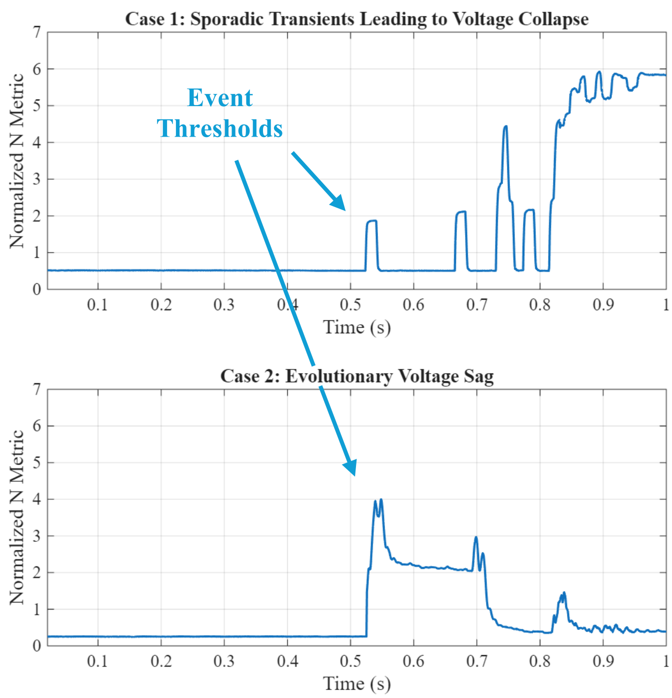

Fig. 7. Normalized *N* Metric Ratio for Cases 1 and 2

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