Power quality diagnosis using time frequency analysis and rule based techniques

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ABSTRACT

Diagnosing a power quality disturbance means identifying the type and cause of the disturbance. Fast diagnosis of power quality disturbances is important so as to assist network operators in performing counter measures and implementing suitable power quality mitigation actions. In this study a novel method for performing power quality diagnosis is presented by using the S-transform and rule based classification techniques. The proposed power quality diagnosis method was evaluated for its functionality in detecting the type of short duration voltage disturbances and identifying the cause of the disturbances which may be due to permanent or non permanent faults. Based on the results, this new method has the potential to be used in the existing real time power quality monitoring system in Malaysia to expedite the diagnosis on the recorded voltage disturbances.

1. Introduction

It is widely believed that power quality problems can only be traced to the incoming power from the utility. However, it is not always true because the source of such problems can be traced either to the customer facility or even up to the equipment inside a facility. Power quality problems that originate from the utility often have the greatest impact on a facility's operation. Typical utility-generated events are such as breaker clearing which can produce voltage sag and arcing contactors which may generate impulses (Yalcinkaya, Bollen, & Crossley, 1998). The power quality problems arise within the customer's own installation may be due to loose connections, overloaded circuits and transformers, ground loops and wiring errors. In addition, some automated and computer-based equipments produce harmonics which may propagate into the network and affect other customers.

The initial step taken to solve power quality problems is by installing permanent power quality recorders (PQR) in the power supply networks either at the main substations or the point of common coupling (PCC) between the customers and the power utility. A power quality monitoring system (PQMS) as shown in Fig. 1 is usually required to connect all the PQR via a communication network to transmit the real-time measured power quality data to the power utility engineers. The PQMS server immediately sends a summary of the power quality disturbance data through short message system to the utility engineers. However, the existing PQMS does not diagnose power quality disturbances in which the sources and causes of the disturbances are not known. The sources of disturbance may originate from distribution feeder 1 (DF1), transmission feeder 2 (TF2) and other distribution feeders. Usually, the sources and causes of the disturbances are known only after conducting site inspections which is a time consuming process.

Many research works focus on automated detection and classification of power quality disturbances but not on diagnosis of disturbances. Some studies on power quality diagnosis consider event identification, stochastic diagnosis, and power quality indexing and cause identification (Azam, Fang, Pattipati, & Rajaiah Karanam, 2004; Il-Yop et al., 2003; Il-Yop, Dong-Jun, Joong-Moon, Seon-Ju, & Seung-II, 2007; Kezunovic, 2001). For event identification, three functions are considered which include event location, cause identification and solution suggestion. An automated software approach for the analysis of voltage sags, their causes and impacts has been developed using the Fourier and wavelet-transform signal processing techniques and fuzzy expert system (Kezunovic, 2001). Another method for identifying the types and causes of disturbances is by using the model based approach and decision fusion (Azam et al., 2004). A network based power quality diagnostic system (PQDS) that incorporates a graphical user interface of an existing PQMS has also been developed (Il-Yop et al., 2003, 2007). This PQDS has the functions for event detection, power quality trend analysis, event cause identification and event location. However, in this PQDS, the source of voltage sag can only be determined by analyzing the actual power system topology and this presents a disadvantage to the system.

In this paper a novel approach to perform automatic power quality diagnosis for identifying the cause of short duration voltage disturbances is presented. The proposed method is developed by using the S-transform and rule based techniques. The excellent
time-frequency resolution characteristic of the S-transform makes it an attractive candidate for the analysis of power quality disturbances under noisy condition and has the ability to detect the single and multiple disturbances correctly. Features extracted by the S-transform are applied to a modular rule based classifier for automatic diagnosis of the disturbances as shown in Fig. 2. The process starts with the recording of disturbance data using the on-line PQMS. These data are then processed using the S-transform to extract the features that characterize the disturbances. These features are then applied to three rule based classifiers (RBC). The first RBC detects the type of short duration voltage disturbances which are either voltage sag or swell, while the second RBC diagnoses the cause of sag or swell as either due to permanent or non permanent faults. The third RBC than further classifies the non permanent fault as either transient or incipient fault. In this way, the cause of voltage sag or swell can be determined as to whether it is due to a permanent fault, transient fault or incipient fault.

2. Categories of network faults and causes of short duration voltage disturbances

Faults that occur in a power network may be categorized as either permanent or non permanent faults as shown in Fig. 3. Faults in a power network generally cause large increase in short circuit current to flow in the network which in turn gives rise to large voltage drops across the impedances of the supply system. These short circuits are caused by external interferences termed as permanent faults. Examples of causes of permanent fault are due to underground cable faults and flashover at medium voltage circuit breakers. Permanent faults that occur in a power network tend to produce short duration voltage disturbances such as voltage sag and swell as specified in IEC/TR 61000-2-8.

Another type of network fault is termed as a non permanent fault which occurs at random moments for a finite period of time. The non permanent faults can be further categorized as either transient or incipient faults. A transient fault is defined as a fault that is
no longer present if power is disconnected for a short time (White,
Transient faults, & IEEE Aerospace Conference, 2004). Typical
examples of causes of transient faults are due to momentarily
tree contact, bird or other animal contact, lightning strike and conduc-
tor clash.
Incipient faults are on the other hand are considered as non per-
manent faults caused by partial damage or contamination that pro-
gressively weakens the integrity of the network components over
time and leads to insulation failure (Weeks & Steiner, 1982). Such
faults are intermittent in nature and are considered as self-clearing
arching faults which occur very frequently prior to failing perma-
nently. These events typically last for one half-cycle and extinguish
at the first natural zero crossing of the current. The magnitude of
the half-cycle event is primarily dependent on the location of the
fault on the feeder. But it is also dependent on the point on the volt-
age waveform where the fault starts. Operational experience sug-
gests that it is beneficial to isolate a feeder suspicious of
incipient cable faults very early after detecting the first symptom
of an incipient fault. Isolating the feeder can limit the overall en-
ergy at the point of fault and it also limits the often-repeated volt-
age transient seen by the system. However, due to short duration
of an incipient fault and the inability to achieve selectivity via time
coordination, designing an incipient fault protection function be-
comes challenging. Incipient faults are predictable and avoidable
if the degradation processes are known. Therefore, the detection
and isolation of incipient faults in the power supply system is
essential for guaranteeing safe, reliable, and efficient operation of
customers’ installations.

3. S-transform and its application for extracting disturbance
features

Short duration voltage disturbances can be easily detected by
using advanced signal processing technique such as the S-trans-
form which give time frequency representation of a signal (Pinne-
gar & Mansinha, 2003). The S-transform of a function $h(t)$ can be
defined as a continuous wavelet transform (CWT) multiplied by a
phase factor $e^{-2i\pi ft}$ and it is given by,

$$ S(f, t) = e^{-2i\pi ft} W(f, d) $$

where $W(f, d)$ is the CWT, $f$ is time, and the dilation factor, $d$ is the
inverse of frequency, $f$.

The CWT is a series of correlations of the time series with a
function called as wavelet which is defined as,

$$ W(f, d) = \int_{-\infty}^{\infty} h(t) \omega(t - \tau, d) dt $$

where $\omega(t - \tau, d)$ is the mother wavelet, $t$ and $\tau$ are both time.

The mother wavelet is then given as,

$$ \omega(t, f) = \frac{|f|}{\sqrt{2\pi}} e^{\frac{-2i\pi ft}{C_0}} e^{-2i\pi ft} $$

Substituting (2) and (3) into (1), the new S-transform equation
is derived as,

$$ S(f, t) = \frac{|f|}{\sqrt{2\pi}} \int_{-\infty}^{\infty} h(t) e^{\frac{-2i\pi ft}{C_0}} e^{-2i\pi ft} dt $$

The phase factor in (4) is a phase correction of the definition of
the CWT. It eliminates the concept of wavelet analysis by separat-
ing the mother wavelet into two parts, the slowly varying envelope
(Gaussian function) which localizes in time, and the oscillatory
exponential kernel $e^{-2i\pi ft}$ which selects the frequency being local-
ized (Pinnegar & Mansinha 2003). It is the time localizing Gaussian
that is translated while the oscillatory exponential kernel remains
stationary. By not translating the oscillatory exponential kernel,
the S-transform localizes the real and the imaginary components
of the spectrum independently, localizing the phase spectrum as
well as the amplitude spectrum, and is thus directly invertible into
the Fourier Transform Spectrum (H). This characteristic of the
phase is referred to as absolutely referenced phase information
which is given by,

$$ \int_{-\infty}^{\infty} S(f, t) dt = H(f) $$

The output of the S-transform is an $N \times M$ matrix called the S-
matrix whose rows pertain to the frequency and columns to time.
Each element of the S-matrix is complex number and can be used
as features to classify the non stationary multiple disturbances.
The information in the S-matrix can be plotted as time-frequency
contours which can be used to identify the existence of power
quality disturbances.

3.1. STMV and STFV Indices

Two indices called as S-transform magnitude-time voltage
(STMV) and S-transform frequency–time voltage (STFV) are
derived from the S-matrices. The STMV indices for all the three phase
voltages are given as follows:

STMV for the red phase voltage is derived from,

$$ S_{\text{STMV}} = \max(S_{\text{STMV}}) $$

Similarly, the STMV for the yellow and the blue phase voltages are,

$$ S_{\text{STMV}} = \max(S_{\text{STMV}}) $$

The STFV indices for all the three phase voltages are next given
as follows: STFV for the red phase voltage is derived from,

$$ S_{\text{STFV}} = \max(S_{\text{STFV}}) $$

The STFV for the red phase voltage is the maximum value for all
the columns in the S-matrix which is given by.

$$ \max(S_{\text{STFV}}) $$
Similarly, the STFV for the yellow and the blue phase voltages are,
\[ V_{\text{STFVY}} = \max(V_Y) \]  
\[ V_{\text{STFVB}} = \max(V_B) \]

The STMV and STFV are used as input features to the rule based system for identifying the network faults. Examples of STMV and STFV plots for a non-permanent fault, permanent fault, and incipient fault can be visualized as shown in Figs. 4–6, respectively. In the first row of Fig. 4, the per unit (pu) values of the STMV are shown. The STMV plots are almost similar to that of the root mean
square plots in which the plots show the existence of voltage sags in the red and blue phases. The STFV plots shown in the second row of Fig. 4 are the variations in the system frequency before, during and after a voltage disturbance. Referring to the STFV plots, the frequency oscillations are seen more severe for the phases which experience the voltage disturbances.

The main difference between the plots shown in Figs. 4 and 5 is in the oscillations of the system frequency. The permanent fault gives a more severe frequency oscillation and inflicted more severe variations in the system frequency during the initiation and ending of the faults as compared to a non permanent fault. The STMV plot in Fig. 6 shows short duration increase in the yellow phase voltage values which signifies the existence of high frequency current in one of the cable cores and hence indicates the existence of an incipient fault which is usually initiated by a partial discharge. This high frequency current will partially bridge the gap between phase insulation to ground or phase-to-phase insulation. Normally, when partial discharge is initiated, high frequency transient current pulses will appear and persist for nano-seconds to a milli-second, then disappear and reappear repeatedly (Weeks & Steiner 1982). The event may be detected as a very small change in the current drawn by the sample under test. A significant increase either in the PD level or in the developing rate of PD activity can provide an early indication of an incipient fault condition.

3.2. Features for detecting short duration voltage disturbances

From the STMV and the STFV indices, several features are extracted and used for detecting the short duration voltage disturbances as depicted in Table 1.

3.3. Features for diagnosing the causes of the short duration voltage disturbances

To perform automatic diagnosis of the causes of the voltage disturbances, four features (F1, F2, F3 and F4) are chosen from Table 2 and two new features, F10 and F11 are selected from the STFV index. The overall features shown in Table 2 are used to identify the cause of voltage disturbances which may be due to permanent and non permanent faults. The respective feature values for classifying permanent and non permanent faults are given as depicted in Table 3.

The feature values for classifying transient and incipient faults are explained in Table 4. If all these features meet the specific data ranges for incipient fault, then it is considered as an incipient fault.

Table 1
Features selected for detecting short duration voltage disturbances.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Max</td>
<td>Max values of STMV in per unit</td>
</tr>
<tr>
<td>F2</td>
<td>Min</td>
<td>Min values of STMV in per unit</td>
</tr>
<tr>
<td>F3</td>
<td>Dmax</td>
<td>Duration of max values of STMV above 1.10 per unit</td>
</tr>
<tr>
<td>F4</td>
<td>Dmin</td>
<td>Duration of min values of STMV below 0.90 per unit</td>
</tr>
<tr>
<td>F5</td>
<td>FR7</td>
<td>Values of frequency resolution from 0.0061 to 0.022</td>
</tr>
<tr>
<td>F6</td>
<td>FR4</td>
<td>Values of frequency resolution from 0.022 to 0.04</td>
</tr>
<tr>
<td>F7</td>
<td>FR5</td>
<td>Values of frequency resolution from 0.04 to 0.08</td>
</tr>
<tr>
<td>F8</td>
<td>FR6</td>
<td>Values of frequency resolution from 0.08 to 0.40</td>
</tr>
<tr>
<td>F9</td>
<td>FR9</td>
<td>Values of frequency resolution from 0.40 to 0.50</td>
</tr>
</tbody>
</table>

Table 2
Features selected for performing power quality diagnosis.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Max</td>
<td>Max values of STMV in per unit</td>
</tr>
<tr>
<td>F2</td>
<td>Min</td>
<td>Min values of STMV in per unit</td>
</tr>
<tr>
<td>F3</td>
<td>Dmax</td>
<td>Duration of max values of STMV above 1.10 per unit</td>
</tr>
<tr>
<td>F4</td>
<td>Dmin</td>
<td>Duration of min values of STMV below 0.90 per unit</td>
</tr>
<tr>
<td>F10</td>
<td>STDST</td>
<td>Standard deviation of STFV</td>
</tr>
<tr>
<td>F11</td>
<td>DFST</td>
<td>Difference of max and min of STFV in per unit</td>
</tr>
</tbody>
</table>
If the data range does not meet the limits of incipient fault, then the fault is categorized as a transient fault.

4. Application of the rule based classifiers for implementing power quality diagnosis

Three rule based classifiers (RBC) have been developed for implementing power quality diagnosis in a structured manner in which the first level RBC is used to detect the short duration voltage disturbances. The overall procedure for implementing power quality diagnosis using the three rule based classifiers is as shown in Table 1, Table 3 (permanent and non-permanent faults) and Table 4 (incipient and transient faults). The details of the rules for the first, second and third RBC are described as in Tables 5–7, respectively.

5. Results and discussion

The performance of the proposed power quality diagnosis using the S-transform and the rule based classifiers was evaluated by testing the RBC with 342 sets of voltage disturbance data obtained from the existing PQMS in Malaysia. The power quality monitoring was performed at the 33 kV network before the first step down transformer as shown in Fig. 1. The voltage waveforms recorded underwent two transformations before being recorded by the power quality recorder.

From the 342 sets of data shown in Table 8, the type and cause of short duration voltage disturbances are known. The causes of the disturbances were validated by referring to the existing database from 2001 to 2008 provided by the national power utility.
Tenaga Nasional Berhad. The data comprises of 121 sets of voltage disturbances caused by permanent faults and 221 sets of voltage disturbances caused by non permanent faults which are either transient or incipient fault. The source of the permanent and non permanent faults originates from either the transmission, distribution or customers own internal networks. By using the 342 sets of data, the RBC are evaluated in which the results for detecting the short duration voltage disturbances are as shown in Table 9. The results for diagnosing the cause of voltage disturbances as to whether the disturbance is caused by a permanent fault, non permanent fault which is either incipient or transient fault are as shown in Table 10.

Table 8
Description of the power quality data to be diagnosed.

<table>
<thead>
<tr>
<th>Type of short duration voltage disturbance</th>
<th>Cause of voltage disturbance</th>
<th>Number of data sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage sag and swell</td>
<td>Permanent fault</td>
<td>121</td>
</tr>
<tr>
<td>Voltage sag</td>
<td>Non permanent fault (transient fault)</td>
<td>111</td>
</tr>
<tr>
<td>Voltage swell</td>
<td>Non permanent fault (incipient fault)</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 9
Results of first level RBC for detecting short duration voltage disturbances.

<table>
<thead>
<tr>
<th>Type of short duration voltage disturbance</th>
<th>Number of data sets</th>
<th>Correct detection</th>
<th>Wrong detection</th>
<th>% Accuracy in detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage sag and swell</td>
<td>121</td>
<td>121</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>Voltage sag</td>
<td>111</td>
<td>111</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>Voltage swell</td>
<td>110</td>
<td>110</td>
<td>0</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 10
Results of the second and third level RBCs for diagnosing the cause of voltage disturbance.

<table>
<thead>
<tr>
<th>Type of network fault</th>
<th>Number of data sets</th>
<th>Correct diagnosis</th>
<th>Wrong diagnosis</th>
<th>% Accuracy in diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent fault</td>
<td>121</td>
<td>115</td>
<td>6</td>
<td>95.0%</td>
</tr>
<tr>
<td>Non permanent fault (transient fault)</td>
<td>111</td>
<td>104</td>
<td>7</td>
<td>93.7%</td>
</tr>
<tr>
<td>Non permanent fault (incipient fault)</td>
<td>110</td>
<td>103</td>
<td>7</td>
<td>93.6%</td>
</tr>
</tbody>
</table>

The new power quality diagnosis method provides diagnostic functions that can give sufficient information for power utility engineers to identify the cause of short duration voltage disturbances. The main advantage offered by the new method is the use of the S-transform to decompose the power line signals into a set of time-frequency components and evaluate the changes in the system frequency in which simple feature extraction can be performed. The features extracted from the S-transform are then used by the three rule based classifiers to diagnose the type and causes of the short duration voltage disturbances. The numerical results obtained with actual power quality data recorded in a power distribution system indicated that the new method is effective in diagnosing the type and causes of the disturbances which may be due to permanent faults and non permanent faults categorized as either incipient or transient faults.

6. Conclusion

The new power quality diagnosis method provides diagnostic functions that can give sufficient information for power utility engineers to identify the cause of short duration voltage disturbances. The main advantage offered by the new method is the use of the S-transform to decompose the power line signals into a set of time-frequency components and evaluate the changes in the system frequency in which simple feature extraction can be performed. The features extracted from the S-transform are then used by the three rule based classifiers to diagnose the type and causes of the short duration voltage disturbances. The numerical results obtained with actual power quality data recorded in a power distribution system indicated that the new method is effective in diagnosing the type and causes of the disturbances which may be due to permanent faults and non permanent faults categorized as either incipient or transient faults.

References


