

Chapter 5

DETECTION AND CLASSIFICATION OF POWER QUALITY DISTURBANCE USING VARIATIONAL MODE DECOMPOSITION

This chapter extends the work on VMD-based PQD detection and classification. The assessment of power quality disturbance has a significant challenge due to the increase in electronic types of equipment usage. Since all these types of equipment are susceptible to voltage and frequency variation, these devices are highly sophisticated, and their performance depends on the quality of the power supply. This chapter proposes a Variational mode decomposition (VMD)-based classifier to effectively detect and classify power quality disturbances.

5.1 MATHEMATICAL MODELING POWER QUALITY DISTURBANCES

The PQ disturbances are primarily characterized by the system supply frequency and voltage throughout the circuit. Identifying these signals requires both information in time and frequency. PQ disturbances are majorly classified upon the voltage, frequency variations, magnitude variations, and transients. They mainly are divided into the following two categories:

1. Events/ Disturbances: These are measured when an abnormality from a regular parameter in the current or the voltage can be detected by analyzing values exceeding certain thresholds. (e.g., sag, swell, interruptions)

2. Steady-state variations: These are a measure of deviation from the nominal values of current and voltage or distortion/imbalance between the 3 phases. (e.g., RMS voltage variations, distortions, harmonics.)

Power quality is a crucial characteristic for real-world consumption and electrical utilities. There is an adverse effect on the consumer load if PQ disturbances continue for a prolonged period and degrade performance and efficiency. Thus inspection, monitoring, and analysis of electrical power quality become essential to determine the problem and further proper mitigation of these disturbances.

This chapter broadly discusses sag, swell, interruption, flicker, and harmonics-based PQ disturbances. Table 5-1 mentioned shows how PQ disturbances could be modeled effectively and efficiently in the MATLAB environment.

5.1.1 Sag

The voltage dip is the PQ disturbance that persists from 0.5 to 10 cycles on the user's end. These are short decrements in the magnitude of RMS voltage (0.1-0.9 pu) lasting for a duration of 0.5 cycles to 1min, as shown in Figure 5.1(a). The cause of sag is primarily linked with the short circuit faults like the line to ground (LG), double-line to the ground (LLG), and three-phase to ground (LLLG) faults.

5.1.2 Swell

A swell is defined as a rapid increase in the voltage and associated current in the electrical circuit. In an LG fault, the sag PQ disturbances are created in the fault's phase, while the swell PQ disturbances are produced in the non-fault phases. The swell PQ disturbances, as demonstrated in Figure 5.1(b), might also be created by energizing a large capacitor bank or switching off a heavy load. Other significant causes are lightning strikes, power

outages, tripped circuit breakers, or inductive spikes. If the swell sustains for over a minute, it is defined as ‘overvoltage.’

5.1.3 Interruption

Figure 5.1(c) has been demonstrated as a loss of the supply voltage for a period of time not overpassing 1 minute is known as an interruption. Most interruptions occur after a voltage sag, primarily due to loose connections, circuit breaker reclosing, or severe faults. The supply voltage is reduced to 10% of the nominal value, indicating no more supply available to the system. Interruptions, if left unchecked, cause severe faults and failure of equipment and control functions.

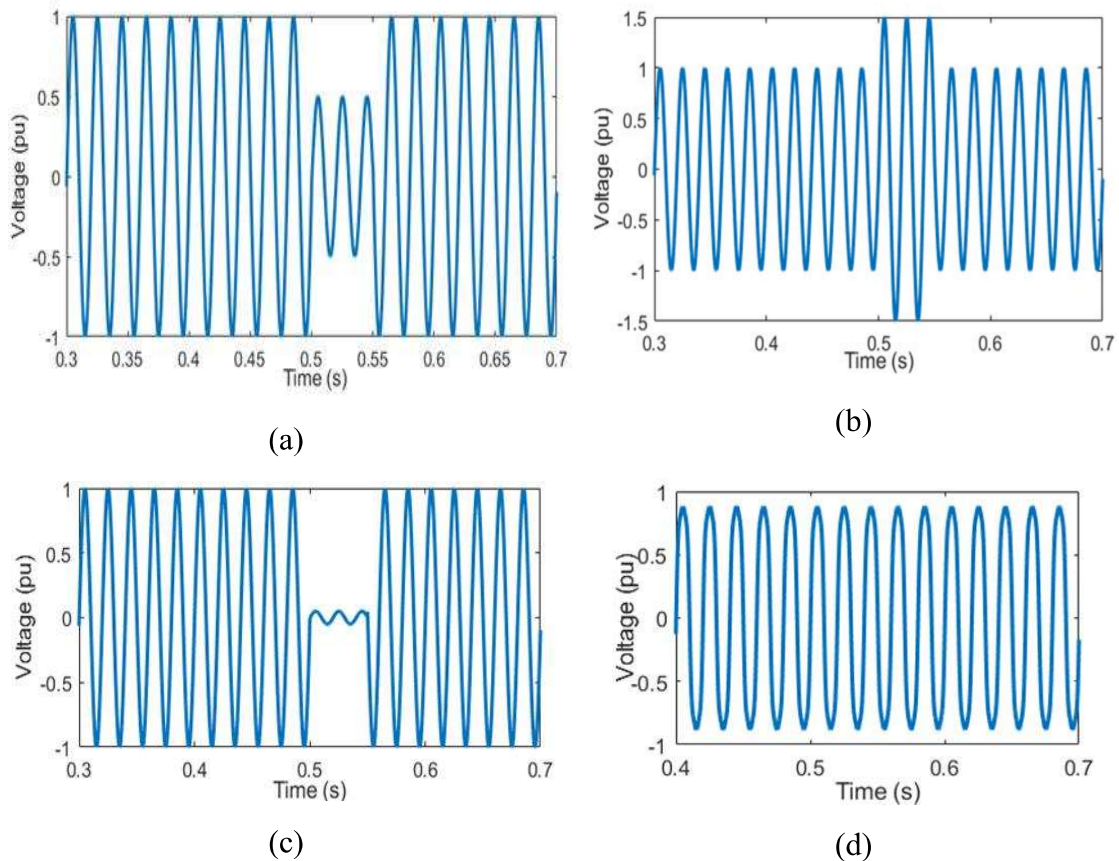


Figure 5.1 Power Quality disturbances (a) Sag (b) Swell (c) Interruption (d) Harmonics

5.1.4 Harmonic Distortion

Harmonic distortions are defined as distortions/variations in voltage/current due to frequent changes in the electrical power distribution system, as shown in Figure 5.1(d). Majorly, these are defined as deviations in the typical sinusoidal variations in system currents and voltages. Their primary cause is nonlinear loads such as PE converters with VFDs installed for fans and air-conditioners. They draw a non-sinusoidal current/voltage; nonlinear loads are introduced throughout the electrical distribution systems. The problems due to harmonic distortions are nowadays frequent since computers and other power electronic devices are being heavily utilized. In particular, power loss and overheating of the wires are several consequences of the harmonics PQ disturbances. A nonlinear load inputs harmonic currents, thereby resulting in harmonic voltages. A three-phase rectifier can be used as a nonlinear load.

5.1.5 Flicker

Flicker is defined as a low multi-frequency component content amplitude modulated sinusoid.

Table 5-1 PQD mathematical model

PQ Event	Mathematical Model	Parameters
Pure Sine	$V(t) = A \sin(\omega t)$	$A = 1$ (p.u.), $\omega = (2 * \pi * 50)$ rad/sec
Sag	$V(t) = A \left(1 - \alpha (u(t - t_1) - u(t - t_2)) \right) \sin(\omega t + \phi)$	$0.1 \leq \alpha \leq 0.9$, $T \leq (t_2 - t_1) \leq 9 * T$
Swell	$V(t) = A \left(1 + \beta (u(t - t_1) - u(t - t_2)) \right) \sin(\omega t + \phi)$	$0.1 \leq \beta \leq 0.8$, $T \leq (t_2 - t_1) \leq 9 * T$

Harmonics	$V(t) = a_1 \sin(\omega t) + a_3 \sin(3\omega t) + a_5 \sin(5\omega t) + a_7 \sin(7\omega t)$	$0.05 \leq a_3, a_5, a_7 \leq 0.15, \sum a_i^2 = 1$
Interruption	$V(t) = A \left(1 - \gamma (u(t - t_1) - u(t - t_2)) \right) \sin(\omega t + \phi)$	$0.1 \leq \gamma \leq 0.9, T \leq (t_2 - t_1) \leq 9 * T$
Flicker	$V(t) = (1 + a_f \sin(2\pi f_c t)) \sin(\omega t)$	$0.1 \leq a_f \leq 0.8, 0.5 * T \leq (t_2 - t_1) \leq 3.5 * T; 10 \leq f_c \leq 30$

5.2 CLASSIFICATION METHODOLOGY

The proposed VMD-based PQD detection has been implemented and tested in a three-stage process, as shown in Figure 5.2. In the first stage, the extensive synthetic data of PQD events have been created in MATLAB environment by changing the PQD parameters as given in Table 5-1, and different indices have been extracted. The threshold for different classes of PQD has been chosen for detection and classification. After that, a simulated test system in PSCAD/EMTDC was utilized to check the efficacy of the proposed method. Finally, it has been validated from provided practical PQD data by IEEE task force.

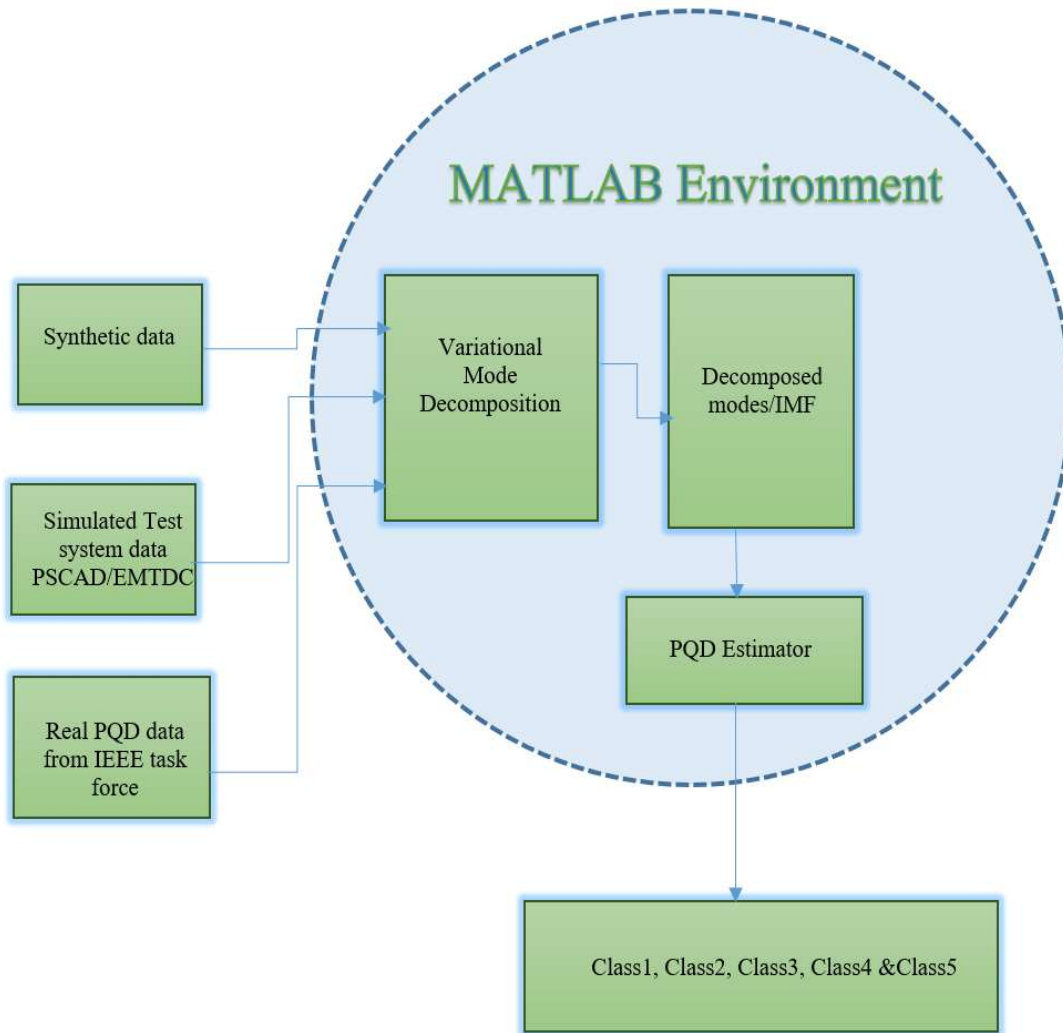


Figure 5.2 Offline simulation setup for implementing proposed VMD based PQD detection

5.2.1 VMD

A detailed discussion of the VMD method has already been described in chapter 3. This voltage waveform has been decomposed into four modes, and the reconstruction of a signal is the motive of decomposition. So the reconstruction fidelity factor is kept high in the range of 10000.

5.2.2 Power quality disturbance(PQD) index

The sliding window technique has been used to generate a classification index for PQD detection. A 64 sample window length has instances used as a source to detect the PQD. Four indexes have been derived from the decomposed voltage signal by VMD.

5.2.2.1 *Instantaneous Root mean square(RMS)*

The instantaneous RMS of IMF1/Mode1 has been calculated by (5.1). This index has easily detected the PQD, which depends on amplitude such as sag, swell, and interruption.

$$RMS(IMF1) = \sqrt{\frac{1}{N} \sum_n^N IMF(n)^2} \quad 5.1$$

5.2.2.2 *Standard deviation(SD)*

For a random variable vector A made up of N scalar observations, the standard deviation is defined as (5.2)

$$SD(A) = \sqrt{\frac{1}{N-1} \sum_n^N |A_n - \mu|^2} \quad 5.2$$

Where μ is the mean of A. here, A is the IMF vector obtained by decomposing voltage signal by VMD.

5.2.2.3 *Total harmonic distortion(THD)*

The THD is defined as the non-fundamental component present in the voltage and current signal. The excess harmonic pollution present in the system may cause the malfunctioning of relay, protection, and control. It is defined as

$$THD_v = \frac{\sqrt{\sum_{m=2}^{\infty} V_m^2}}{V_1} \times 100\% \quad 5.3$$

Where, V_1 is a fundamental component of voltage signal which is represented by IMF1 and V_m is a non-fundamental component of voltage signal which is represented by IMF2, IMF3 and IMF4.

5.2.2.4 Center frequency estimate

It is obtained from the VMD decomposition of a voltage signal by (3.5). This index is useful for the detection of flicker disturbance present in the system.

5.3 IMPLEMENTATION OF PROPOSED VMD BASED PQD ESTIMATOR

The implementation of the proposed algorithm is shown in Figure 5.3. After extensive simulation and testing PQD of synthetic signal, analysis has been carried out to set the classification threshold as given in Table 5-2 and Table 5-3.

Table 5-2 Threshold value for PQD indices

PQD	Th1(RMS(IMF1))	Th2(RMS(IMF1))	Th3(RMS(IMF1))	Th4(RMS(IMF1))
Sag	0.1	0.85	NA	NA
Swell	Na	Na	1.15	1.8
Interruption	0	NA	NA	NA

Table 5-3 Threshold value for Harmonic and flicker PQD index

Center frequency	f1	f2	f3	f4	THDv
Harmonic	≤50	nf1	nf1	nf1	≥ 5%
Flicker	≤50	≤30	≤30	≤30	NA

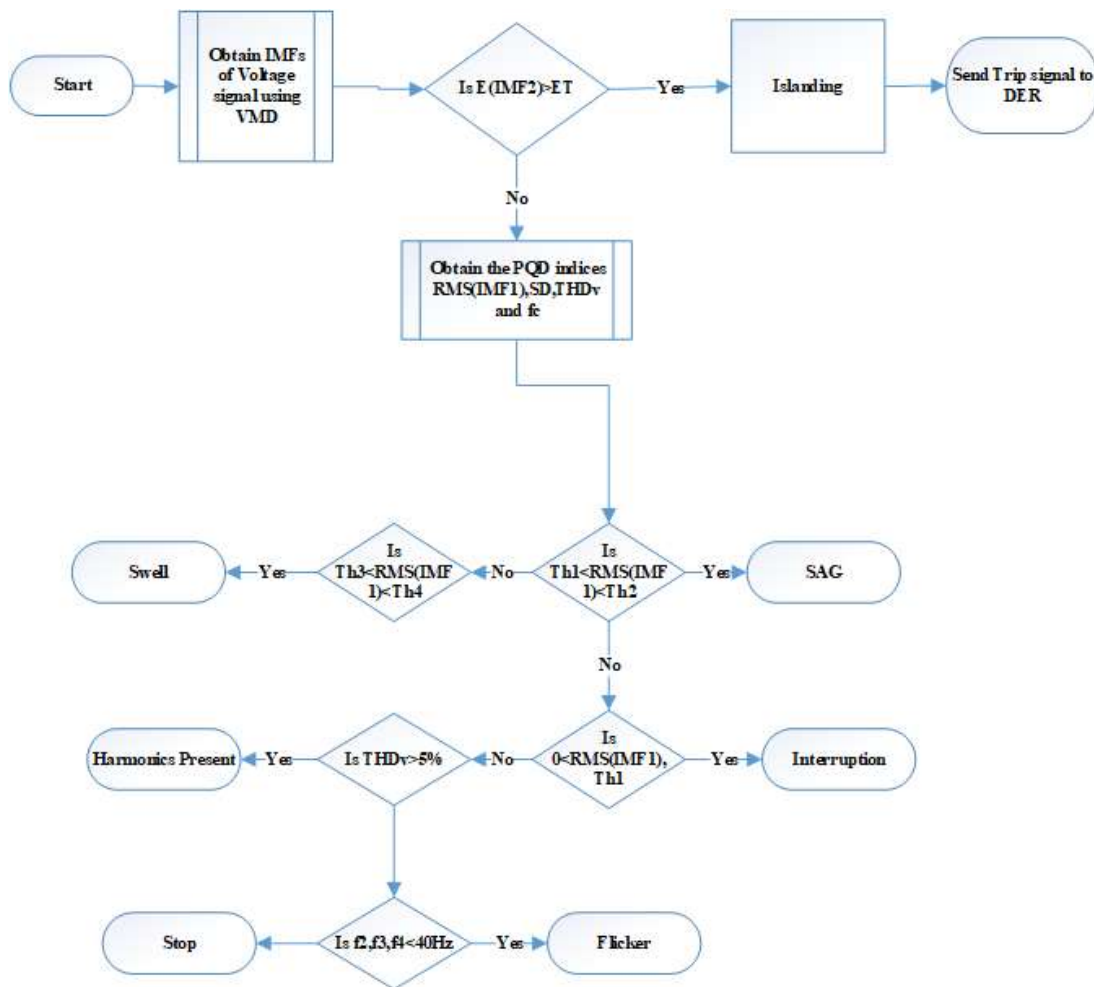


Figure 5.3 Flow chart of VMD based classification of Power quality disturbances

5.4 RESULT AND DISCUSSION

5.4.1 Test System

The test system consists of a 132 kV substation with a 132kV/33kV, 100 MVA step-down transformer, as shown in Figure 5.4. Loads are connected to Bus 5 and Bus 3. The circuit also consists of a DG. The DG is rated at 30 MVA, which is connected to Bus 5 along with a 33/0.69kV transformer. The test system has been modeled in EMTDC/PSCAD. Different types of disturbances have been created for dataset generation, and voltage waveform is stored for further analysis. The data set of the simulated test cases has been given in Table 5-4. Details implementation algorithm has been depicted in Figure 5.3.

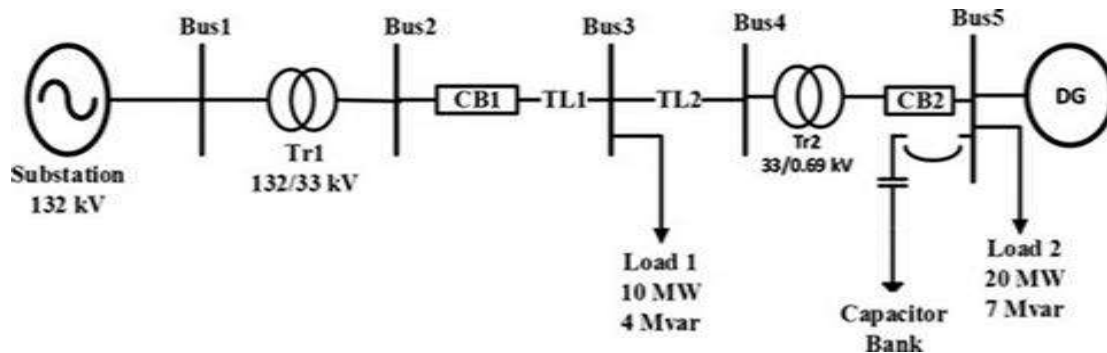
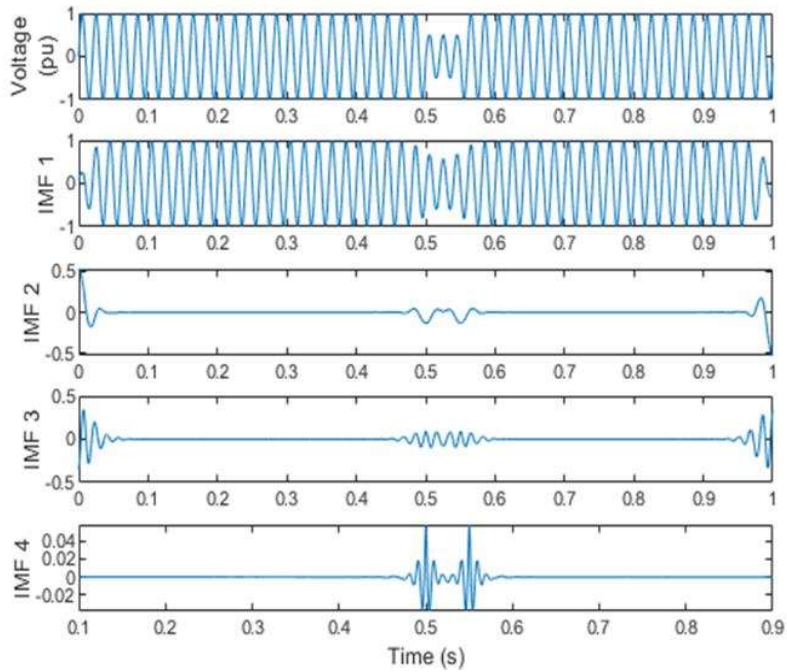


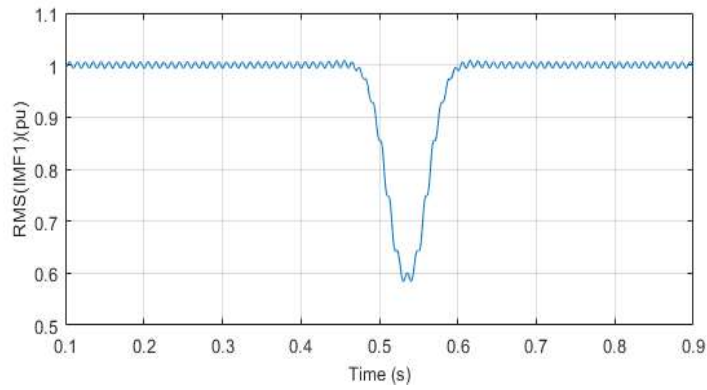
Figure 5.4 One-line diagram of the Test system

Table 5-4 Dataset generated for testing

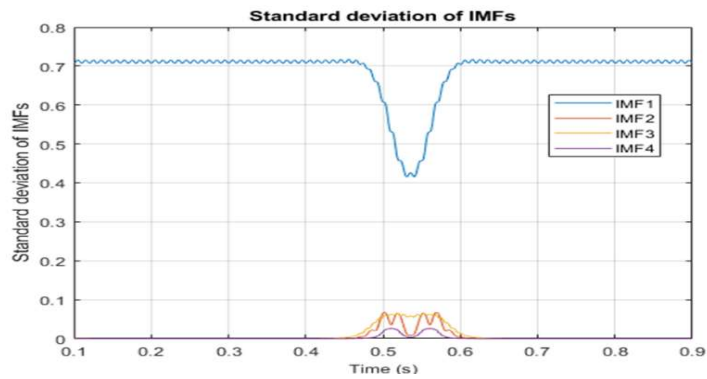
PQ disturbance	LG Fault	LL Fault	LLG Fault	LLLG Fault	Total
Sag	31	30	17	23	101
Swell	31	30	19	23	103
Interruption	40	34	34	38	146
Harmonics	40	40	40	40	160



(a)

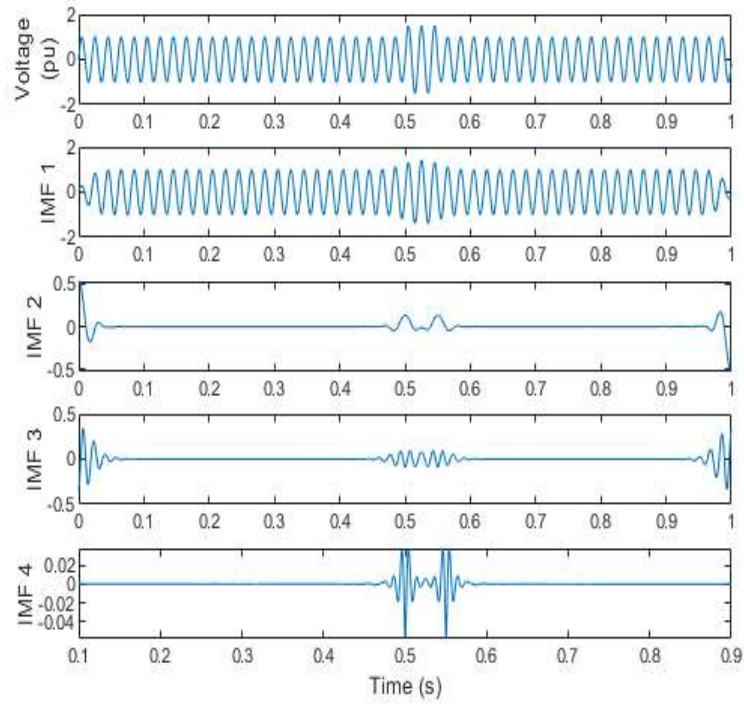


(b)

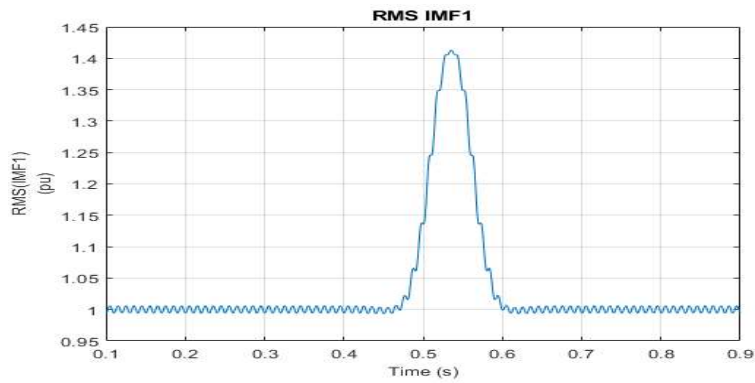


(c)

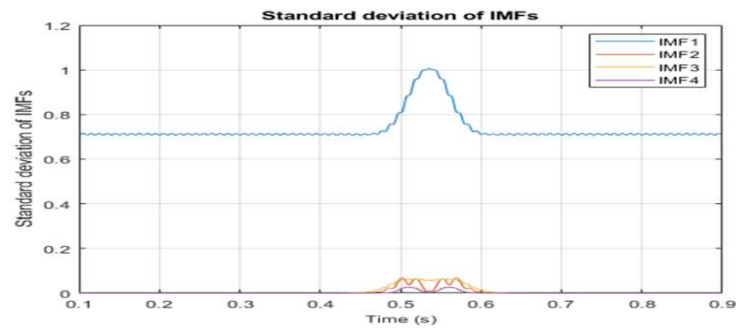
Figure 5.5 Power quality disturbance in case of Sag (a) Voltage and Decomposed IMFs (b) RMS index for classification of Sag (c) Standard deviation



(a)

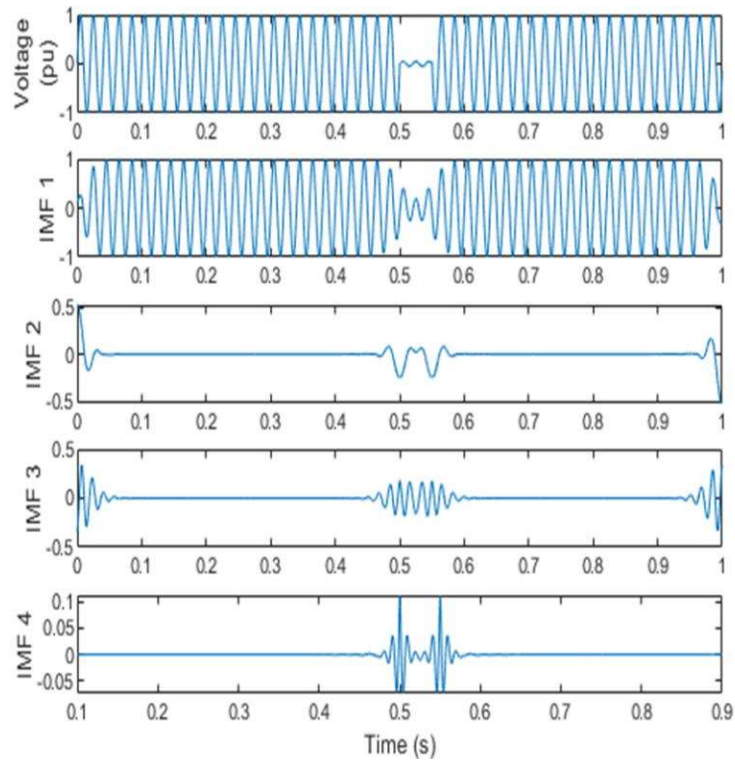


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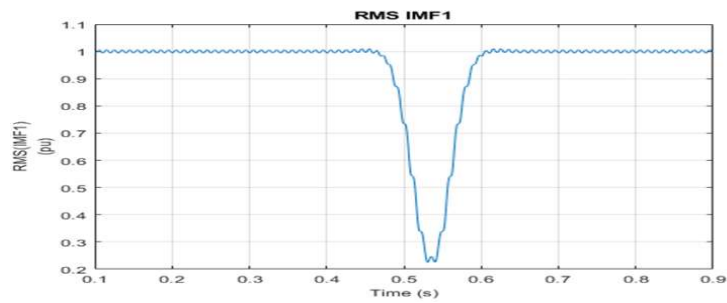


(c)

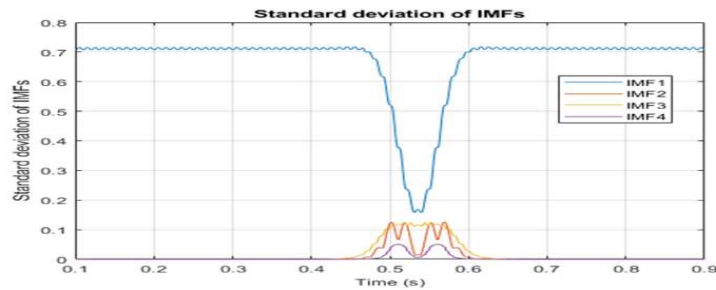
Figure 5.6 Power quality disturbance in case of Swell (a) Voltage and Decomposed IMFs (b) RMS index for classification of Swell (c) Standard deviation



(a)



(b)



(c)

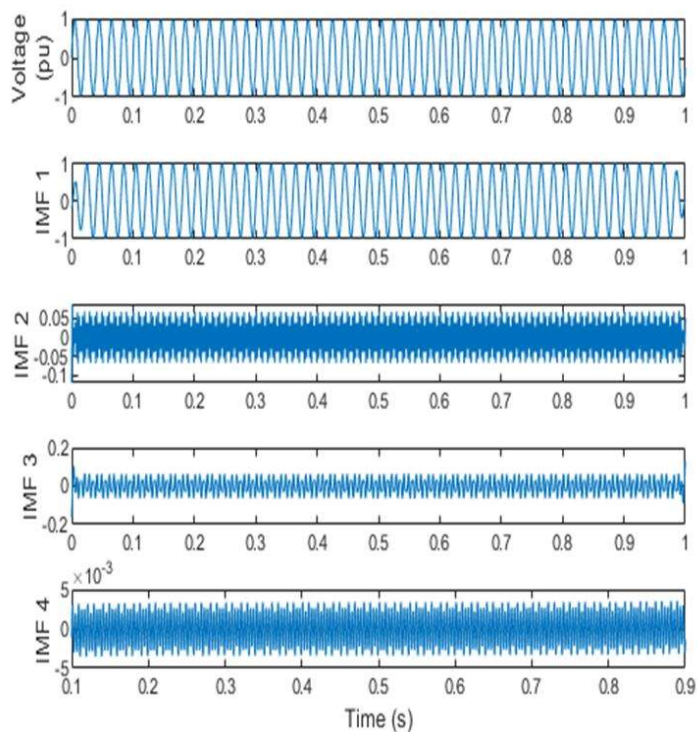
Figure 5.7 Power quality disturbance in case of Interruption (a) Voltage and Decomposed IMFs (b) RMS index for classification of PQ disturbance (c) Standard deviation

5.4.2 Voltage sag, swell, and interruption

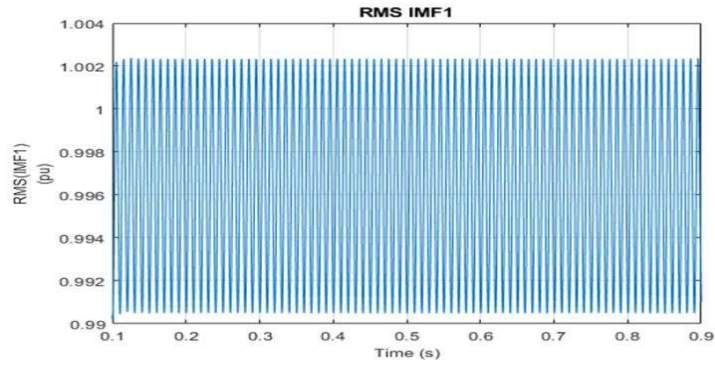
The PQD events of sag, swell, and interruption has been shown in Figure 5.5, Figure 5.6, and Figure 5.7. The sag, swell, and interruption PQD has been detected from the instantaneous RMS index as presented in Figures 5.5(b),5.6(b), and 5.7(b), respectively. The efficacy of the proposed automatic PQD detection has been exhibited in the results.

5.4.3 Harmonic

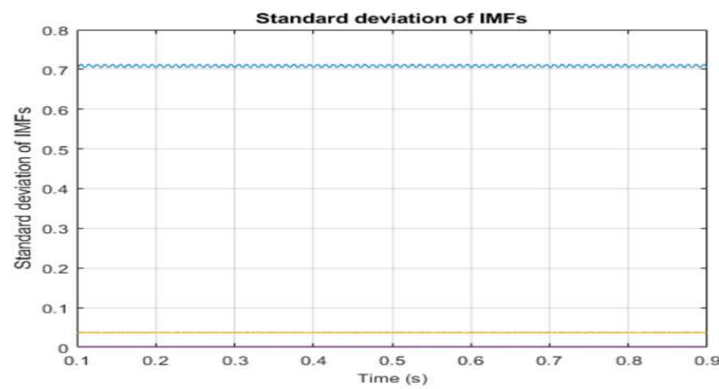
The PQD events of the Harmonic voltage waveform have been decomposed by VMD, as depicted in Figure 5.8 (a). From the decomposed IMF, PQD indices have been derived. It is clearly shown from results depicted in Figure 5.8(b) and (c) that instantaneous RMS and Standard deviation fail to classify the PQD event. However, from the $THDv$ index, it clearly classify as harmonic PQD as shown in Figure 5.9(a) and (b)



(a)

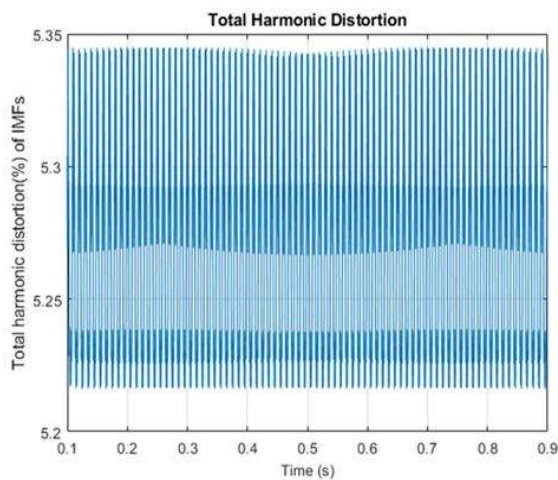


(b)

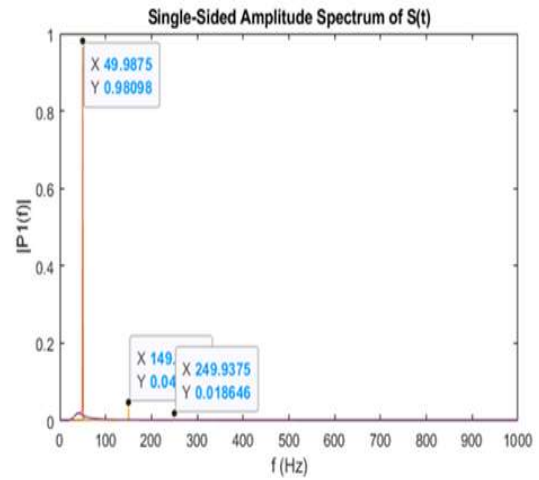


(c)

Figure 5.8 Power quality disturbance in case of Harmonics (a) Voltage and Decomposed IMFs (b) RMS index for classification of PQ disturbance (c) Standard deviation



(a)

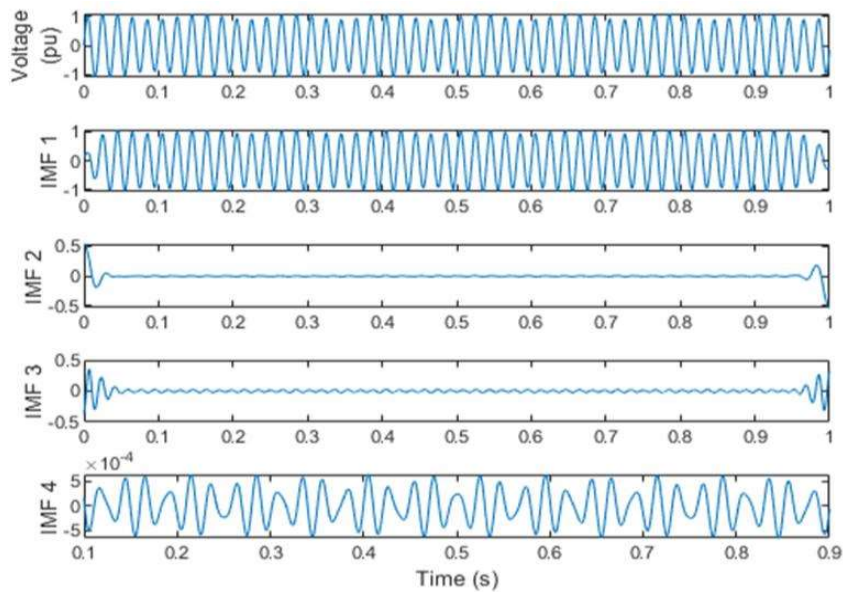


(b)

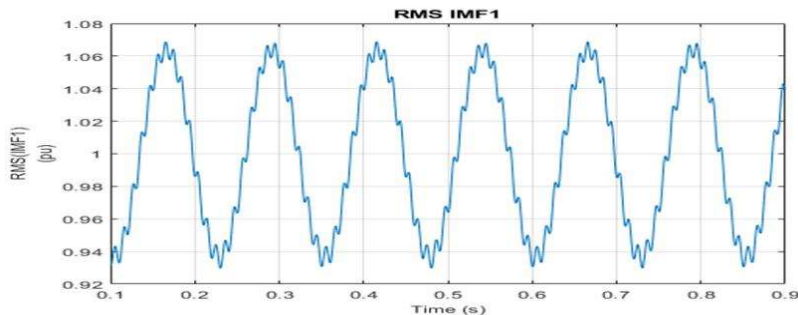
Figure 5.9 Power quality disturbance in case of Harmonics (a) THD (b) Estimated center frequency

5.4.4 Flicker

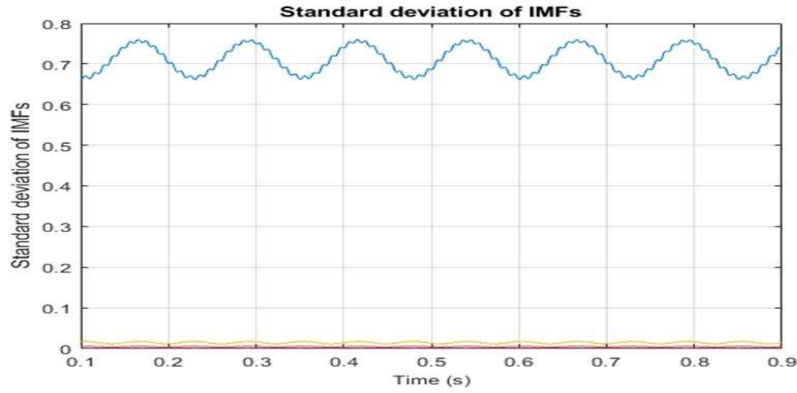
The low-frequency signal present in the voltage signal characterizes the flicker. Therefore, flicker detection is complex apart from other PQD. The PQD index of center frequency has been an important feature to detect low-frequency presence in the input voltage signal. The decomposed voltage waveform and other PQD indexes have been plotted in Figure 5.10 and Figure 5.11. The result shows that the RMS, SD, and THDv indices have not been classified as PQD. The center frequency estimate is shown in Figure 5.11(b) confirms that the low frequency(40Hz) component is present in the signal, classifying it as flicker PQD.



(a)

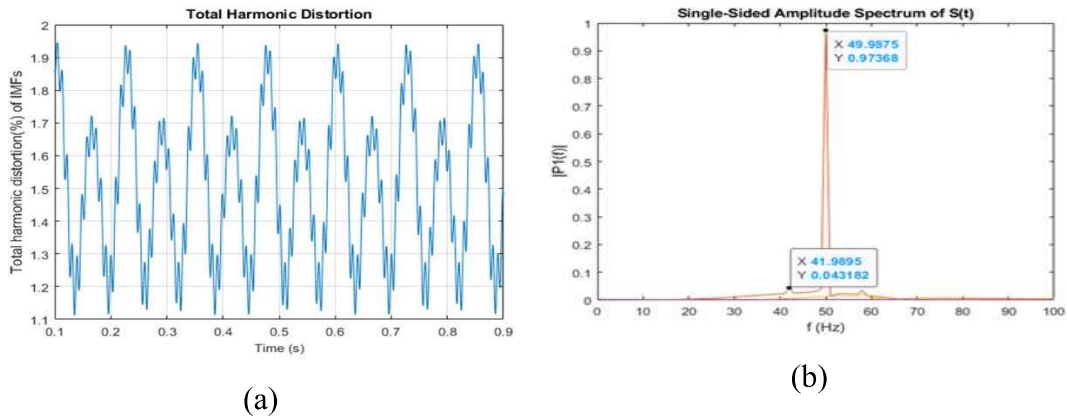


(b)



(c)

Figure 5.10 Power quality disturbance in case of Flicker (a) Voltage and Decomposed IMFs (b) RMS index for classification of PQ disturbance (c) Standard deviation



(a)

(b)

Figure 5.11 Power quality disturbance in case of Flicker (a) THD (b) Estimated center frequency

5.5 VALIDATION OF PROPOSED VMD BASED METHOD ON PRACTICAL RECORDED DATA

The dataset has been preprocessed by normalizing using their respective base kV rating. The normalized voltage waveform has been processed from VMD, and PQD indices have been estimated to classify the PQD events. The results have shown that the proposed method is suitable for online PQD monitoring.

Table 5-5 Harmonic data taken from IEEE task force database [113]

Sl.No.	Data Tyes	Types of PQD	No of Events
1.	Aluminum Sheet Facility 88 kV	Sag & Swell	6
2.	Arc Furnace Facility 138 kV	Flicker, Interruption, Harmonic & Sag	11
3.	Cement Facility 138 kV	Interruption, Harmonic, Sag & Swell	17
4.	Cement Facility 138 kV	Unknown disturbances	
5.	FIFA World Cup 2006 – City #1 – 138 kV	Flicker, Interruption, Harmonic, Sag & Unknown disturbances	7
6.	FIFA World Cup 2006 – City #2 – 138 kV	Sag	7
7.	FIFA World Cup 2006 – City #3 – 138 kV	Harmonic & Sag	7
8.	Iron Mineration Facility – 13.8KV	Interruption, Harmonic, Sag & Swell	1
9.	LAPTEL voltage (Signal Processing and Telecommunications Laboratory/UFJF)		1
10.	Medicine Facility 88 kV #1	Interruption, Harmonic & Sag	8
11.	Medicine Facility 88 kV #2	Sag	8
12.	Milk Pasteurization Facility 13-8 kV	Harmonic, Sag & Swell	17
13.	Soybean oil facility 13-8kV	Harmonic & Sag	11
14.	TV Broadcast Building 13-8 kV	Interruption, Harmonic, Swell & Sag	17
15.	SUBSTATION 1 (69kV,138kV &230kV)	Harmonic, Sag & Swell	9
16.	SUBSTATION 2 (69kV,138kV &230kV)	Harmonic, Sag & Swell	9
17.	SUBSTATION 3 (69kV,138kV &230kV)	Interruption, Harmonic, Sag & Swell	9

5.5.1 Result and Discussion

The proposed method has been validated on all the recorded PQD data shown in Table 5-5. Some of the representative results of mixed types of PQD events are shown in Figures 5.12, 5.13, and 5.14. It can be apprehended from these figures that the proposed method accurately detects and classify the PQD events. Some of the cases have been discussed here:

i) Aluminum Sheet Facility:

This recorded voltage waveform presents two types of PQD disturbances (sag and swell). The instantaneous RMS plot is depicted in Figure 5.12. The proposed method has correctly classified the events.

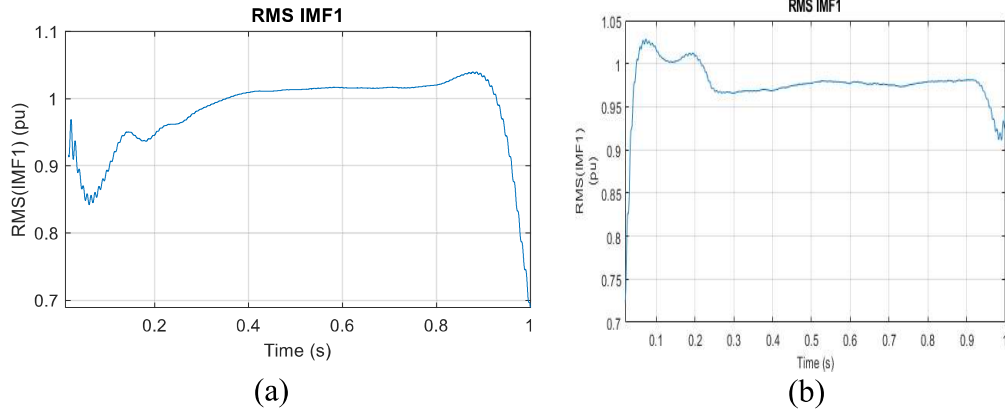


Figure 5.12 PQD disturbance in Aluminium sheet Facility (a) sag, (b) swell.

ii) Arc Furnace Facility:

In this case, four types of PQD have been presented in the captured waveform.

The PQD indices have been plotted in mixed PQD events such as interruption and harmonic, as shown in Figures 5.13 (a) and (b).

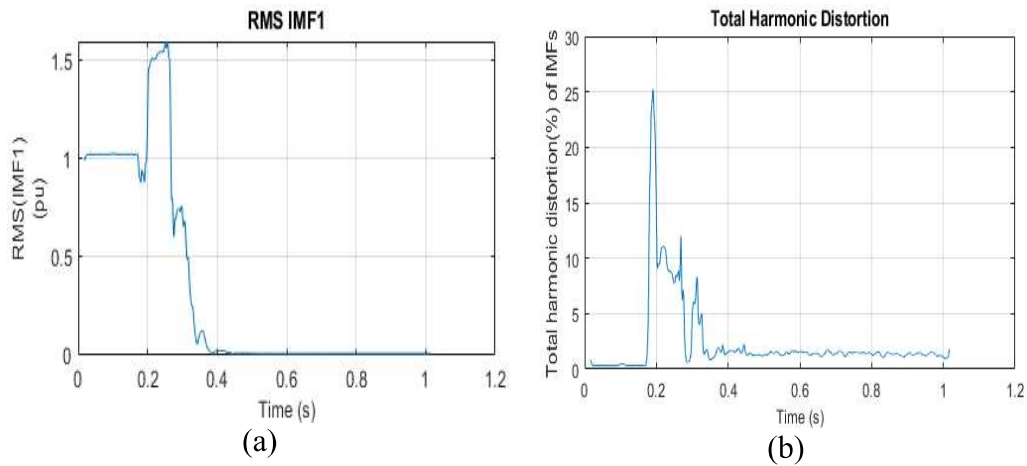


Figure 5.13 Arc furnace Facility in case of interruption and harmonic (a) RMS (b) THDv

iii) Substations:

In this case, Mixed types of PQD have been present in the voltage waveform.

Some of the representative results of substation-1 have been depicted in Figure 5.14 (a) and (b).

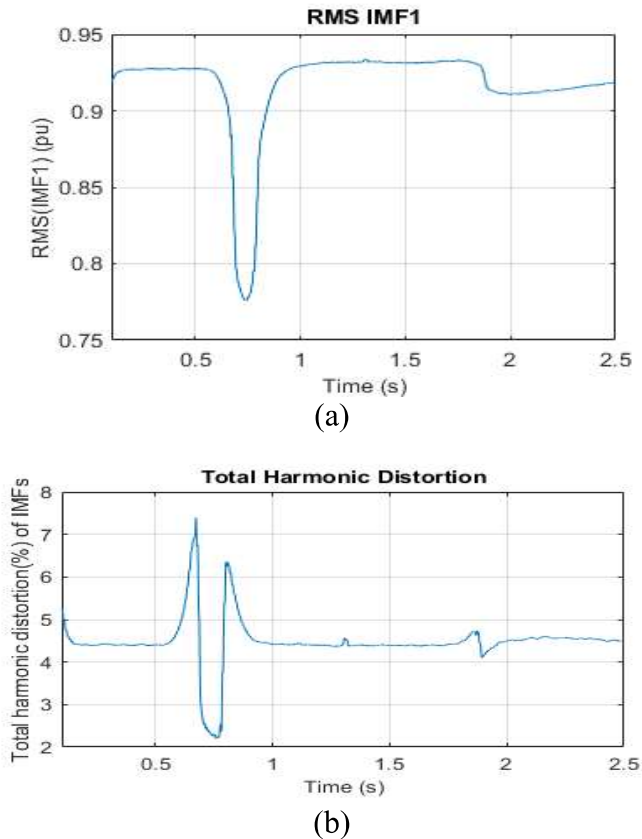


Figure 5.14 Substation 1 mixed types of PQD (a) RMS(IMF1) (b) THDv

From the above result and discussion, it is obvious that the proposed VMD-based PQD detection method is suitable for the practical application of monitoring PQD.

5.6 REAL-TIME VALIDATION FOR MICROGRID TEST SYSTEM ON REAL TIME DIGITAL SIMULATOR

A co-simulation platform has been developed to validate VMD-based PQD detection in real-time, as shown in Figure 5.15. This co-simulation platform consists of two computer systems. The one computer system is interfaced with RTDS/RSCAD GUI. Other computer hosted the MATLAB script for the proposed VMD-based PQD index estimator. The Personal Computer (PC) I hosted the RSCAD draft model and runtime application, as shown in Figure 5.16 and Figure 5.17. The data of the Microgrid system has been taken from [114].

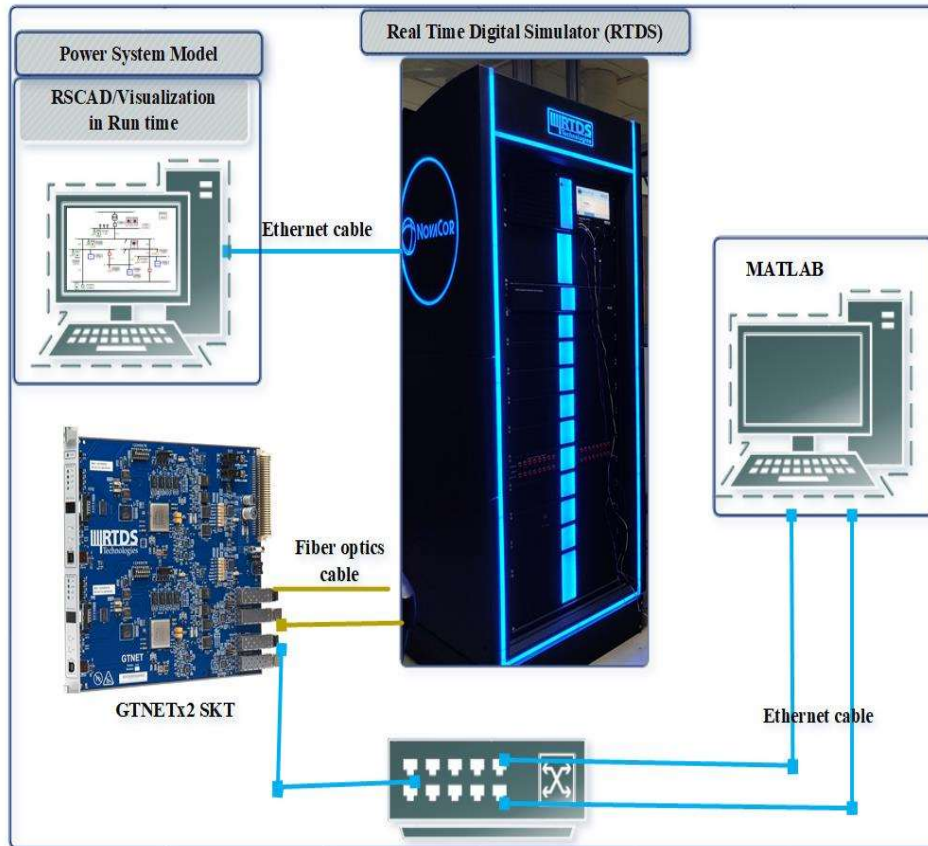


Figure 5.15 Real-Time Co-simulation Platform

The stepwise implementation of the proposed method has been given as follows:

Step 1: Three-phase voltage data from various locations of the Microgrid system in runtime has been sent via the GTNETx2 block included in the draft model to facilitate data exchange between MATLAB and RSCAD.

Step 2: The MATLAB, RSCAD-RTDS co-simulation platform is established through the logical and physical ports of GTNETx2 card mounted in RTDS Novacor chassis, including four core licenses. GTNETx2 card has many communication protocols available. In this, we use TCP/IP Socket protocol (SKT) to enable bidirectional communication between MATLAB and RSCAD/RTDS.

Step 4: Upon successfully compiling the Draft model, the voltages are monitored through RSCAD runtime using separate meters. Note that RSCAD Draft and RSCAD runtime applications are loaded in Novacore chassis.

Step 5: As soon as the RSCAD model starts to run in real-time, three-phase voltage has been sampled @2kHz sampling frequency and sent to computer II, where the proposed VMD-based PQD algorithm is implemented in a MATLAB script. The RTDS conducts simulation in power system mode with 75 μ s time-step.

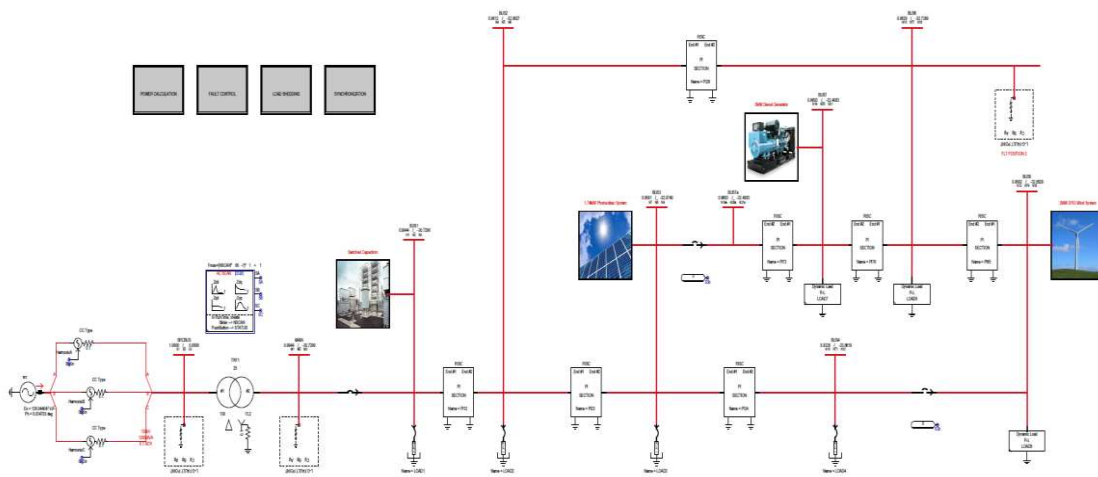


Figure 5.16 Draft Microgrid model in RSCAD

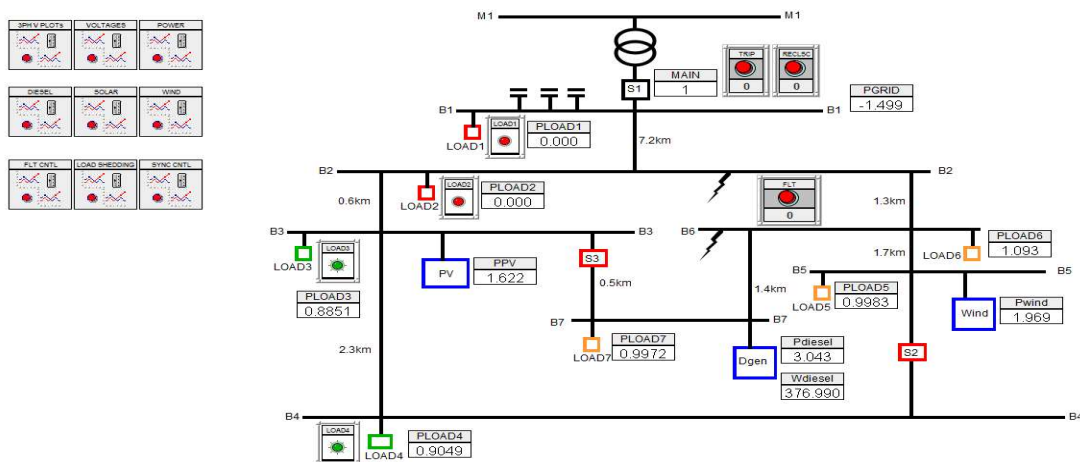
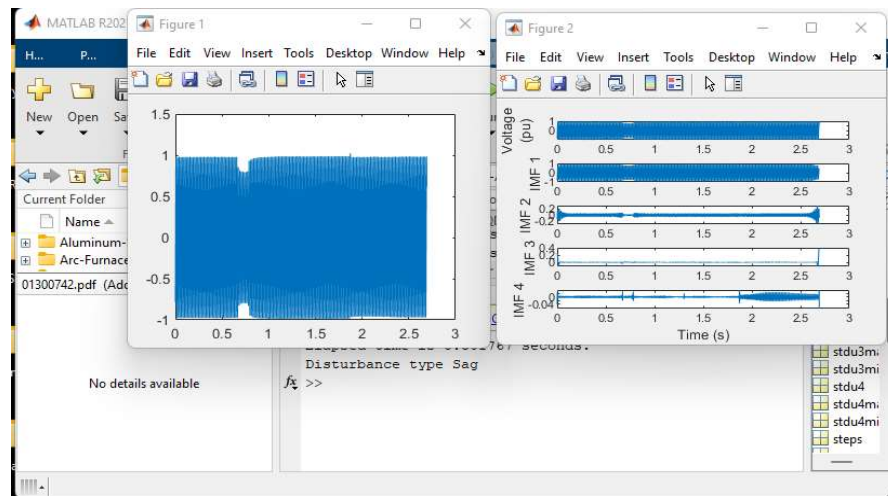


Figure 5.17 Run time Microgrid model

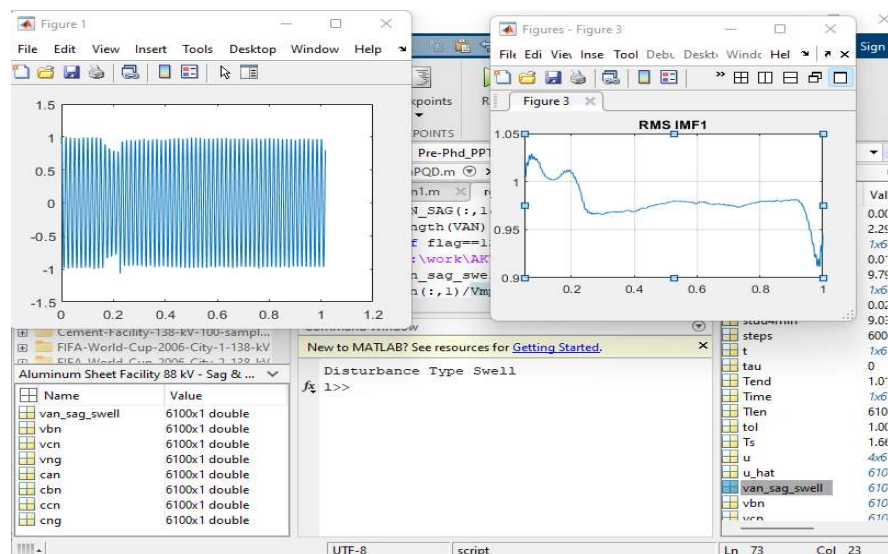
5.6.1 Result and discussion

i) Sag and Swell

The sag and swell events are created in the Microgrid test system, and the voltage waveform is sent to MATLAB, which monitors the PQD event. The results are shown in Figure 5.18. The figure shows the MATLAB command window for the classification of PQD events.



(a)



(b)

Figure 5.18 Real-time Generation and categorization (a) Voltage sag(b) Voltage swell

ii) *Harmonics and swell*

The harmonic injection block is developed to injection harmonics in the Microgrid system in the draft module. In the run time, this block was enabled to inject higher-order harmonics. The voltage waveform has been sent to MATLAB for decomposition, shown in Figure 5.19.

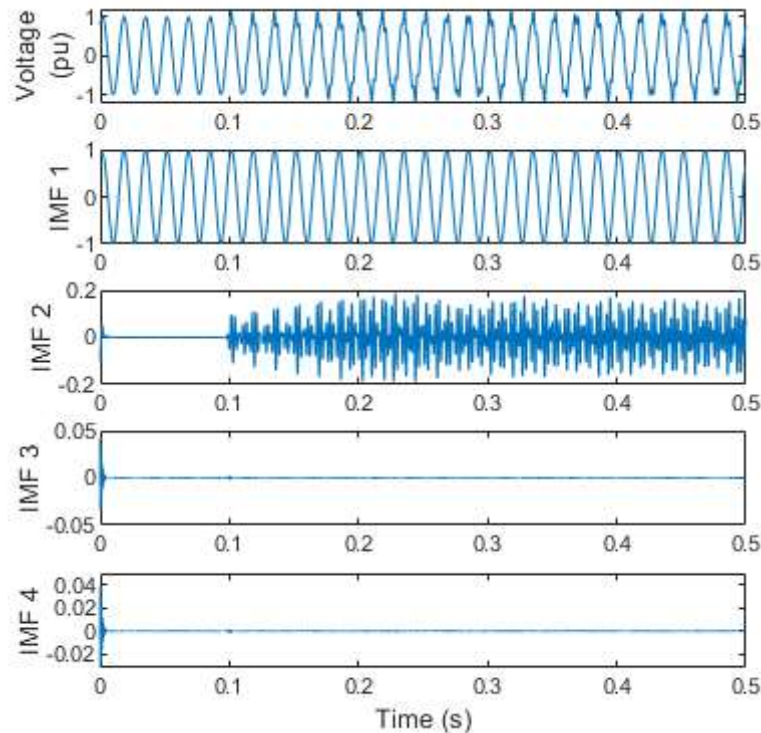
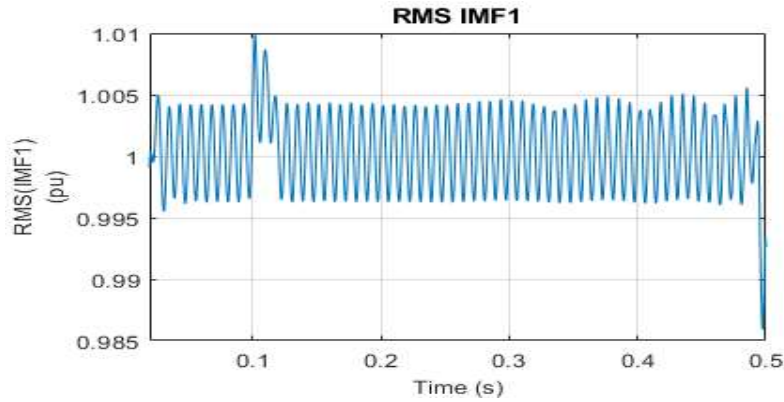
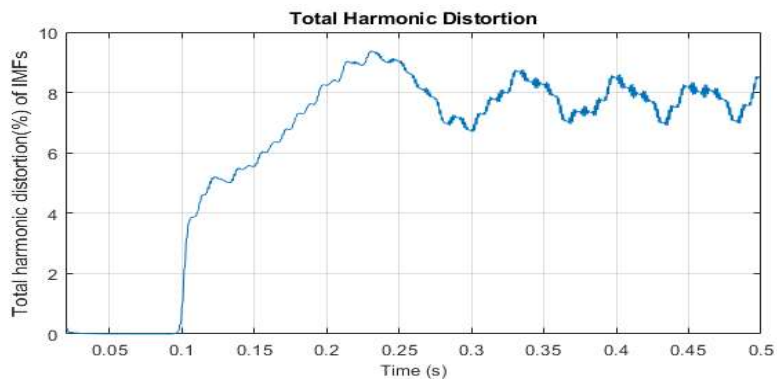


Figure 5.19 Voltage waveform decomposition by VMD in case of swell and harmonics

The decomposition results clearly show that the VMD has separated the harmonic component from the fundamental voltage signal. The PQD index instantaneous RMS and THDv have been depicted in Figure 5.20(a) and (b). The results validate that the proposed method is suitable for single PQD and mixed PQD problems.



(a)



(b)

Figure 5.20 PQD index (a) Instantaneous RMS (b) THDv

This section presents a new automated method using variational mode decomposition and PQD indices to detect and classify single and mixed PQ disturbances in grid-connected DG systems. The accuracy and robustness of the method are tested and validated with four stages under various system operating scenarios. Validation with several synthetic and real-time generated signals and simulations on a microgrid testbed on the RTDS platform shows the potential ability of the VMD technique to estimate amplitudes, frequencies accurately, and phases of the fundamental, harmonic and inter harmonic, and flicker components under a mixture of other non-sinusoidal PQ disturbances, in both noise-free and noisy scenarios. Various studies show that the proposed VMD with four PQD indices has been effectively and efficiently used to detect and classify single and mixed PQ disturbances under noise-free and noisy environments.

5.7 SUMMARY

A new approach for the classification of power quality disturbances has been proposed. In this approach original signal is analyzed by VMD, and the voltage signal has been decomposed into four modes. The classification index was extracted from these modes. The simulation results show the efficacy of the proposed method. The central frequency estimated by VMD is close to the frequency present in harmonics components in the original signal.