Evaluating Rapid Voltage Changes and its Propagation Effect using Multipoint Measurement Technique

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***Abstract*- A multipoint measurement technique for detecting rapid voltage changes causing electromagnetic interference, and its propagation effect in a power distribution network, is presented. The main advantage of the proposed techniques lies in its capability to detect rapid voltage change disturbance and its correlation with other electromagnetic interference events simultaneously. This is achieved by combining a multipoint measurement technique and a coincidence ratio evaluation method. A multipoint measurement technique was applied by using four distributed power quality analyzers which record conducted electromagnetic interference events. The recorded data is evaluated using the coincidence ratio and the time gap analysis method. The results show that a rapid voltage change in a 440 V power distribution subsystem has a probability in between 70 % and 93.8 % of triggering a sag in an uninterrupted power supply, and thus electromagnetic interference towards other subsystems.**

Keywords—Rapid Voltage Changes, electromagnetic interference, coincidence ratio, propagation, multipoint, measurement

I. INTRODUCTION

There are many issues associated with power quality (PQ) degradation that occur due to electromagnetic interference (EMI), mainly consisting of conducted disturbances. The PQ issue refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system [1]. PQ issues due to EMI problems not only occur in a power distribution network with a physical connection to earth but also occur on islanded power networks such as a ship [2], [3].

Typical conducted EMI events are harmonic distortion, flicker, voltage surge, burst, voltage dip, voltage sag, voltage interruption, rapid voltage change (RVC) and swell. In a power distribution network, these could not only cause issues for the system that is directly connected to the interference source, but they could also propagate and interfere with other systems or subsystems that are located further away.

The problem of locating the EMI source, using the intercorrelation between each EMI in a power distribution network, is still a critical task [4]. Several methods based on a distributed multipoint measurement technique have been recently proposed to tackle the problem [4]–[10]. A method using a master-slave distributed measurement [4], [5] and a phasor measurement unit (PMU) [6] have been proposed for identifying and locating the EMI source. In [4], [5] the system measures continuously and the synchronization of all measurements can be obtained by synchronizing the clock of the slaves and master. However, these techniques are only used to find the source of harmonic EMI in the and cannot be used to determine the correlation between an EMI event with another EMI event. Whereas, evaluating the relationship between each EMI event is important because in the power distribution network, the equipment in the subsystem may be supplied by different parties.

On the other hand, to detect an RVC event with small voltage disturbance (bellow dips and swell threshold) as recommended by IEC 61000-4-30:2015 standard [11], a precise and accurate measurement system is required. However, if it is applied in a continuous multipoint measurement, it requires a very large storage memory. To solve this problem, this study proposes a method using a specific and simultaneously recording technique which was applied to the multipoint measurement system. This proposed method is important because, through synchronous recording, the correlation between an RVC event and related EMI events at different locations can be determined.

To validate the proposed method, a measurement has been applied to the power distribution network on a ship. The correlation between an RVC event from the 440 V power distribution system with other EMI disturbances in other subsystems has been investigated. Furthermore, the RVC propagation and its effect are considered by analyzing the coincidence ratio and the time gap. This analysis is needed to

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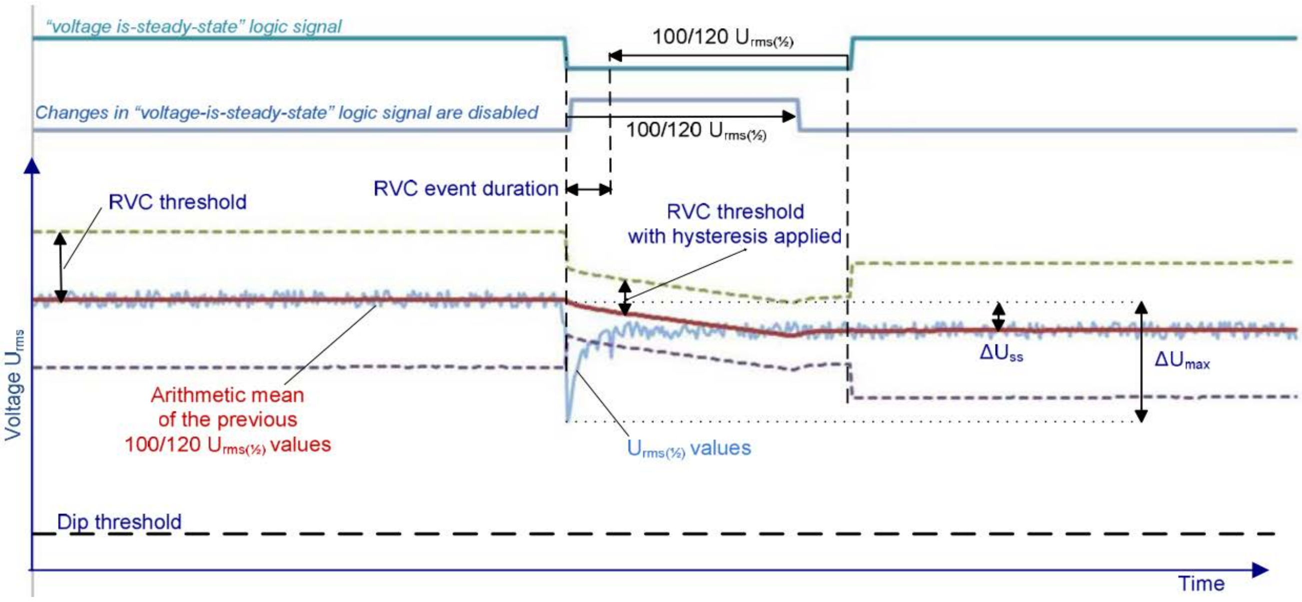

Fig. 1. The RVC event general consideration [16]

determine the correlation with other EMI events because, in a distributed measurement system, each event is recorded with a different timestamp even if it is triggered by the same source event. In other words, an event at one point does not trigger measurements at the other points.

This paper is organized as follows: Section II describes the general consideration of the RVC event based on IEC 61000-4-30:2015 standard. Section III describes the measurement method using a multipoint measurement and data analysis method. Section IV presents the measurement and analysis result of the RVC effect, and, finally, Section V gives the concluding remarks of the study.

II. RVC EVENT GENERAL CONSIDERATIONS

For many years, the RVC was known as a non-destructive EMI, and its main effect is light flicker [12]–[14]. Nowadays, several studies show that RVC will result in power quality disturbance. The non-flicker effects that have been reported are impairment of electronic equipment and malfunction of a control system [15], [16].

The RVC is introduced in the IEC standard 61000-4-30:2015 as a quick transition in root mean square (RMS) voltage between two steady-state conditions, during which the voltage does not exceed the dip or swell thresholds [11]. An RVC can be a voltage increase or voltage drop. If the deviation in voltage is more than the sag or swell thresholds, then the event is not recorded as RVC but becomes a sag or swell [11]. IEC 61000-4-30 standard does not specify the RVC threshold. The threshold should be defined by the user based on the application as a percentage of the declared input voltage U_{din}, a deviation between 1% and 6% from the declared input voltage is recommended [11], [17], [18]. This standard also defines the measurement and evaluation method of an RVC. Based on IEC 61000-4-30:2015, four parameters characterize an RVC event: [11], [14], [17]:

- Start time: the start time of an RVC event begins when the steady-state voltage logic signal converts from true to false [17].
- Duration: the RVC duration is 100/120 half-cycles shorter than the length of time that the steady-state voltage logic signal is false [17].
- ΔU_{max}: "ΔU_{max}: is the maximum absolute difference between any of the of the $U_{rms(1/2)}$ value during the RVC event, and the final arithmetic means 100/120 $U_{rms(1/2)}$" [17].
- ΔU_{ss}: "ΔU_{ss} is the absolute difference between the final arithmetic mean 100/120 $U_{rms(1/2)}$ value just prior to the RVC event"[17].

The main characteristic of an RVC event based on these parameters are shown in Fig. 1 [18], [19]. Considering an RVC is a sudden event, "it can be modelled as a small step-like amplitude variation at time t^{*}" as is shown in (1) [20].

$$x(t) = \begin{cases} \sqrt{2}U\sin[2\pi f t + \varphi] & t < t^{*} \\ \sqrt{2}U\,(1+\delta_U)\sin\left[2\pi f t + \varphi + \delta_\varphi\right] & t \geq t^{*} \end{cases} \tag{1}$$

"where U is the RMS waveform amplitude in steady-state operating conditions, φ is the initial phase of RVC waveform, δ_φ is the phase shift during RVC event, δ_U is the relative amplitude variation in consequences of the RVC event, and $f = f_0(1+\delta_f)$ is the frequency of the waveform, which may differ from the nominal frequency value f_0 (e.g 50 Hz or 60 Hz) by a static fractional frequency offset δ_f" [20].

As a conducted electromagnetic wave, the propagation of RVC is influenced by several parameters, medium permittivity, medium permeability, impedance, length of the medium, and installed electrical component. The time delay of the electromagnetic wave propagation or T_D (s) depends on the total length of the conductor or L (m) and velocity of propagation or v (m/s) expressed in (2) [21].

$$T_D = \frac{L}{v} \tag{2}$$

In the case of a homogeneous medium, the velocity of propagation or v (m/s) of the voltage and current wave travel on the transmission line (two parallel-wire with insulation) is expressed in (3).

$$v = \frac{v_0}{\sqrt{\epsilon_r \mu_r}} \quad (3)$$

where the speed of light or $v_0 \cong 3 \times 10^8$ m/s, the unit ϵ_r is the relative permittivity of insulation between conductors and the unit μ_r is the relative permeability [21]. For a transmission line, that the conductor is copper and the insulation material is PVC ($\epsilon_r \cong 4$), with non-magnetic dielectrics ($\mu_r = 1$) the velocity of propagation or v (m/s) of the voltage and current waves that propagate along that transmission line will be $\cong 1.5 \times 10^8$ m/s. So, in this case of per 1 m conductors, the time delay approximately is 6,66 ns/m.

III. MULTIPOINT MEASUREMENT SETUP AND DATA ANALYSIS METHOD

In this study, PQ measurement was conducted on the islanded three-phase electricity network of a real ship with isolated terra (IT) configuration. The network consists of a 440 V distribution subsystem, a 440 V/115 V step-down transformer, a distribution panel that distributes voltage to three different lines. Each line consists of a reactor line, a low-pass filter, an uninterruptable power supply (UPS) and two loads.

In general, the characteristics of the PQ shipboard electrical network must comply with STANAG 1008 ed. 9 standard requirements [22]. To evaluate RVCs propagation effect, a distributed multipoint measurement technique was applied. The measurement consists of four power quality analyzers model PQube 3 manufactured by PSL-Power Standard Lab that are installed at four different measurement points:

1) *Point A: PQube A that is installed at the 440 V power distribution output*
2) *Point B: PQube B that is installed at UPS 1 input*
3) *Point C: PQube C that is installed at UPS 3 input*
4) *Point D: PQube D that is installed at UPS 1 output*

All PQubes are interconnected with a router, while a Raspberry pi-3 is used for time reference. Each PQube has a sampling rate of 512 samples per cycle at 50/60 Hz and an accuracy ±0.05 % rdg ±0.05 % FS. It has a voltage measurement range from 0 V_{AC} to 1300 V_{AC} (L-L). This PQube uses U_{rms} measurement method with true single-cycle RMS, and updates every ½ cycle based on IEC 61000-4-30:2015 standard [23]. Fig. 2 shows the measurement system configuration as was implemented in the ship power distribution network. The data was collected over 2 days during normal journey operation of the ship.

In this study, each PQube monitors the current and voltage continuously, and stores the data based on event triggers and record the data automatically only if any EMI event occurs within the threshold value. It specifically records EMI events like RVC, dip, sag, interruption, impulse, and swell events in accordance with IEC 61000-4-30:2015 and programmed using a higher level to measure voltage deviation based on STANAG-1008 ed. 9. Table I show the measurement threshold setting and its comparison with STANAG 1008 ed.9 [24]

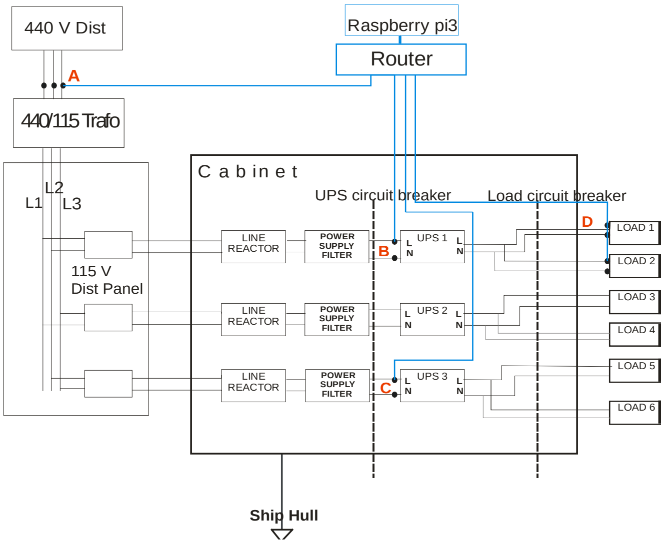

Fig. 2. System under test indicating the measurement points at which the PQubes are connected.

In the IEC 61000-4-30:2015, a voltage dip is also referred to as sag [11]. However, in this study, sag is used as a voltage drop with the threshold value of -5 % U_{rms} and with duration less then dip duration threshold. The purpose of this sag setting is to record voltages drop event that has a duration shorter than the dip duration.

The stored data is analyzed by the folder timeline structure of each PQube. The folder names contain information about the specific event and at which time it occurred. The time format is hh.mm.ss:mmm. In a total of 15.2 GB of data was gathered in 2 days.

TABLE I. MEASUREMENT THRESHOLD SETTING COMPARED WITH STANAG 1008 ED.9.

Parameters	**STANAG 1008 ed.9**	**Measurement threshold setting**
Dip	-16 % (2 s)	-6 % (2 s) -10 % (1 s) -14 % (0.05 s)
Sag	-	-5 % (< dip duration)
Interruption	-	>90 %
RVC	-	-5 up to +5 %
Impulse / spike	2.5 kV, 440 V 1 kV, 115 V 0.6 kV, 24 Vdc	200 V (except PQ A, 1000 V)
Swell	+16 % (2 s)	+5 %

To calculate the event percentage correlation with RVC event at 440 V distribution subsystem, a coincidence ratio method is used. The coincidence ratio is calculated using the Venn intersection compared with the total sum (union) approach. An intersection is an event that occurs simultaneously in the time window duration on reference measurement point, for example, PQube A with another specific event occurring in any other PQubes. Total sum (union) is the total numbers of two specific events in the two PQubes.

In the ideal situation, the time window can be determined from the total time delay (T_D) from wire path, connector path and microstrip path on PCB and also transient time response from each subsystem component. But to simplify the measurement in this case, 1-second windowing is taken because the total connector wire length between point A to point B or point A to point C or point A to point D is approximately 15 – 20 m and the path inside PCB is unknown. Meaning that every EMI event within this time window will be counted as a coincidence event.

Then the total number of the coincident events will be rationalized with the total sum (union) of the specific data events. The coincidence ratio (β) is proposed in [7]:

$$\beta = \frac{\sum(PQ_{1,\text{event x}} \cap PQ_{2,\text{event y}})}{\sum(PQ_{1,\text{event x}} \cup PQ_{2,\text{event y}})} \tag{4}$$

The $PQ_{1,\text{event x}}$ being reference event, in this case, are RVC events at point A, and PQ_2 being second measurement point (B, C, D). While the event y can be a dip, sag, interruption, RVC, impulse or swell event on that point.

IV. INVESTIGATION AND RESULT

In this section, we describe the investigation of an RVC example event that occurs in point A, RVC effects or coincidence ratio, and also time gap between RVC events recorded at point A are compared with other EMI event timing.

A. *The RVC event example*

During two days of measurements, PQube A recorded a total of 80 RVC events. All of the recorded RVC events in point A are voltage drops. To simplify the discussion, we take an example from the measurement result that shows the characteristic of an RVC event in 440 V distribution subsystem. The graph in Fig. 3 is an RVC event example that occurs at point A on the first day of measurement at 09.09.37:810. Fig. 3 shows that the voltage decreases as much as 22 V compared with first U_{rms} ($\Delta U_{\max}$ = 4.5 %), and final RMS decreases 1 V compared with first U_{rms} (ΔU_{ss}= 0.2 %) and duration of this RVC is 807 ms.

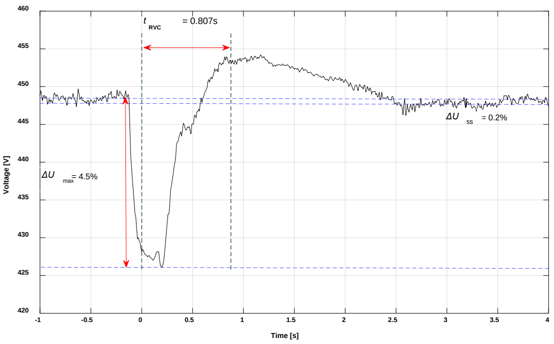

Fig. 3. An RVC event at 440V distribution subsystem, recorded by PQube A on the first-day measurement at 09.09.37:810.

B. *RVC Coincidence ratio and effect*

An analysis approach using the coincidence ratio was applied to assess the effect of the RVC. By applying (4) and time windowing for 1 second after RVC events at the 440 V distribution subsystem, we can calculate the relationship between RVC events with other events in other subsystems. The higher the percentage of coincidence ratio, the greater their relationship. Table II presents the coincident ratio of each event with the RVC event at point A.

TABLE II. COINCIDENCE RATIO (%) OF RVC EVENT AT POINT A AND OTHER EMI EVENT AT EACH MEASUREMENT POINT.

Event occurrence and PQ location	**A** **440 V distribution output**	**B** **UPS 1 input**	**C** **UPS 3 input**	**D** **UPS 1 output**
Sag		70 %	93.8 %	0
Dip		0	0	0
Interruption		0	0	0
RVC	100 %	1.3 %	0	0
Impulse		0	0	0
Swell		0	0	0

As can be seen from Table II, not all of the EMI disturbances have a correlation with an RVC event. The RVC effect only appears at point B (70 %) and point C (93.8 %) as sag form.

Every time an RVC event happens, it propagates through a 440/115 V step down transformer, a 115 V distribution panel, an impedance line reactor, a power supply filter and ends up being a sag at UPS input in most of the case. These because all the recorded RVC events during two days measurement only form as voltage drop, if in other cases the RVC occur in the form of a voltage increase then the effect might be different.

At point D no EMI event that recorded has a correlation with RVC event. That means the RVC disturbance is eliminated by the UPS subsystem.

C. *RVC Propagation*

An RVC waveform and RMS value from 440 V power distribution subsystem can change according to the component characteristic in its path. So it can be detected as a different type of disturbance in the next subsystem even though it comes from the same EMI source. The RVC propagation is considered by analyzing the percentage value of the coincidence ratio, the propagation path, and the time gap.

The time gap (Δt) is the time difference between an RVC event recorded by PQube A and an EMI event which recorded by another PQube. The duration of this time gap is influenced by the total time delay and characteristics of each component in the subsystem. The standard deviation (σ) represents the amount of data dispersion. The time gap average and the standard deviation (σ) is presented in Table III. However, in this case, the value displayed does not take into account if there is a wave reflection or re-reflection due to imbalance impedance.

TABLE III THE TIME GAP BETWEEN RVC EVENT AT 440 V DISTRIBUTION AND OTHER EMI EVENT.

Event occurrence and PQ location	**A** **440 V distribution output**	**B** **UPS 1 input**		**C** **UPS 3 input**		**D** **UPS 1 output**	
	$\overline{\Delta t}$ (ms)	$\overline{\Delta t}$ (ms)	σ	$\overline{\Delta t}$ (ms)	σ	$\overline{\Delta t}$ (ms)	σ
Sag		171	40	86	46.6	-	-
RVC	0	222	0	-	-	-	-

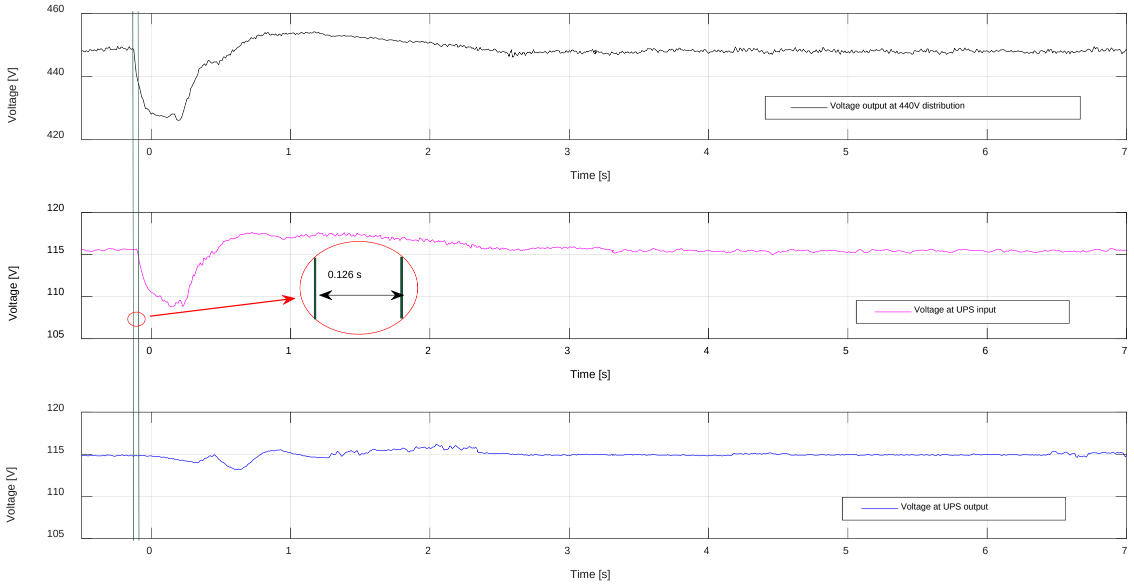

Fig. 4. Comparison between an RVC event at 440 V distribution subsystem, sag event at UPS input and the response at UPS output.

To explain the propagation mechanism, an example of an RVC event at point A with a sag event at point B and point D is shown in Fig. 4. This example is taken from the first-day measurement at 09.09.37. In this case, as soon as the RVC occurs and recorded by PQube A, a sag occur in UPS input around 126 ms after. By comparing the envelope of this RVC event and sag event, it showed similarity in their pattern. It starts from the steady-state phase and then the voltage drop. When the voltage starts to recover, it followed by a voltage increase exceed the $U_{\mathrm{rms},}$ then the voltage ramps down and reach the final steady-state value. At this example, an RVC event with 4.5 % ($\Delta U_{\max}$) could have strong correlation cause-effect with the 5.43 % ($\Delta U_{\max}$) voltage decrease (sag event) at point B. This result confirms the relationship between RVC event at 440 V distribution subsystem and sag event at UPS input. At the same time reference, at UPS output, the voltage fluctuates but only 0.8 %. That means, the RVC event does not have much effect on the voltage at UPS output, and it is also in line with the result that was shown in Table II and Table III. The voltage drop greater than 5 % which is recorded at PQube B and PQube C as a sag might be caused due to voltage loss or non-ideal characteristic of a step-down transformer, cable or other components in the pathway.

V. CONCLUSION

The objective of this research is to find a method to understand the propagation effect of an RVC from the 440 V distribution subsystem on a ship's power network using a multipoint measurement technique. The proposed method has proven to be useful in determining the correlation between RVC events and other EMI events. The investigation has also revealed that a small voltage disturbance like an RVC in the ship can trigger other voltage disturbances, e.g. voltage sags, in other subsystems. A non-ideal transformer or a voltage loss on components might make the voltage drop bigger. This finding enhances our understanding that any other non-light-flicker effects occur as a result of the RVC event on the ship's 440 V distribution subsystem. The observations from this study also suggest that to maintain a high PQ, a small disturbance such as an RVC must still be considered and not taken lightly.

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