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Use of the DMAIC Approach to Identify Root Cause of Circuit Breaker Failure

Ivan Popov, David Jenner, Grazia Todeschini and Petar Igic
College of Engineering, Swansea University, Swansea UK
grazia.todeschini@swansea.ac.uk

Abstract—**The DMAIC (Define, Measure, Analyze, Implement and Control) approach is a well-established approach used to improve industrial processes and products. The DMAIC approach is mostly used as part of quality assurance processes, but this paper will show that it can be applied to investigation of root cause analysis of equipment failure. Specifically, the piece of equipment under investigation is a circuit breaker used in a distribution system. A second contribution of this paper is to provide suggestions on approaches to overcome modeling challenges related to lack of data, both in terms of measurements and in terms of system parameters.**

Keywords— DMAIC, distribution system, breaker, harmonics, power quality measurements

I. Introduction

This paper proposes a novel use of the DMAIC (Define, Measure, Analyze, Implement and Control) continuous quality assurance process [1] as a structured approach to identify root cause analysis of a breaker failure in an electrical distribution system. This approach consists in performing a series of defined steps which will be outlined in Section II.

The DMAIC process is a tool utilized in the Six Sigma Quality assurance scheme as a systematic method of refining continuous business processes [1]. It is a well-established method of continuous system improvement, implemented across a range of production lines in the manufacturing industry. The application of the DMAIC approach to eliminate defects in rubber glove production is discussed in [2]. Following the define, measure and analysis stages, adjustment to oven temperature and conveyer speed yielded a 50% reduction in defective units. The quality improvement process has also been implemented in aircraft coating procedures [3] to determine optimal process parameters resulting in a high quality finish, fast process and low waste. In this paper, the use of the DMAIC approach for root cause analysis in power system studies is exemplified by means of a Case study which will be outlined in Section III.

In real-life applications, it is not always possible to accurately perform each step of the DMAIC methodology, mostly due to the lack of data, both in terms of measurements and in terms of component parameters used to build the model. This paper will show that a systematic implementation of the DMAIC approach allows identifying the missing information and therefore suggesting where more data is required. It will be shown that, in the particular case studied, although the analysis leads to the identification of the cause of the undesired breaker operation and of a mitigating solution, more accurate data and component parameters are required to progress to the implementation.

II. DMAIC Process Overview

The DMAIC methodology consists in decomposing the analysis of a process or system into five manageable sections, thus resulting in a more focused approach to the problem and in the reduction of the likelihood of deviation or scope creep during each stage of the analysis. This simple yet structured approach makes it ideal for root cause analysis and fault mitigation, in addition to its intended field of continuous quality assurance. An overview of the DMAIC process is shown in Fig. 1, and each step is described below:

Define aims to improve the understanding of the system by identifying all relevant parameters, such as: metrics defining the desired operation, current performance and 'gap' (the deviation between actual and intended operation). Financial and business implications are also outlined covering potential costs incurred as a result of an inefficient system, the impact on product quality or likelihood of unplanned outage.

Measure aims to collate system data that can be used to identify areas of inefficiency and to quantify the system performance. The methods of data collection may include direct measurement from the system, recording of relevant dates corresponding to events, and identification of different system configurations. Mapping techniques may also be implemented to highlight the systematic flow of a process and providing full or partial traceability from output to input.

Using the datasets produced during the second stage of the process, an in depth Analysis of the system is performed to identify system attributes, potential points of failure and areas of inefficiency. Once identified, targeted mitigating solutions are outlined and implemented. The last step, called 'Control' consists in verifying the effectiveness of the proposed solution. Note that the process is likely to be iterative, as more refined mitigating solutions may be implemented depending on the results of the 'Analyze' stage.

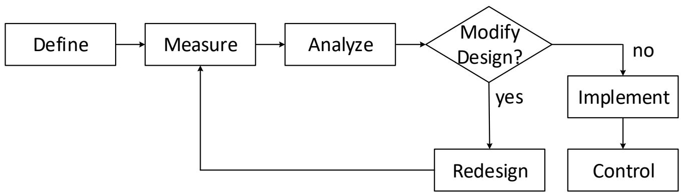

Figure 1: Flowchart for DMAIC process

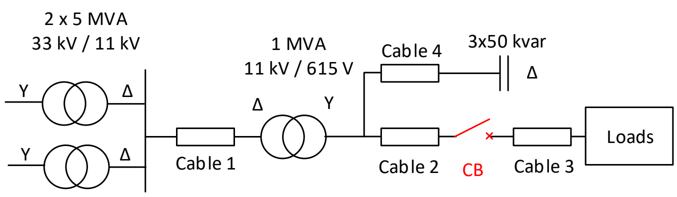

Figure 2: One line diagram of the system under consideration

III. Case Study

The DMAIC methodology is applied to establish the main cause of malfunction associated with a low voltage circuit breaker in a distribution system within the Swansea University Singleton Campus [4]. Several tripping events have been observed over approximately two years resulting in power loss to clean room filtration systems and scientific equipment. The circuit breaker is a solid state model rated at 400 A, with instantaneous overcurrent protection of 2000 A [5].

The one line diagram of the system is shown in Fig. 2. The distribution system is fed from an 11 kV substation, comprising of two parallel connected 33/11 kV 5 MVA transformers. The medium voltage connection is then branched to an 11 kV/415 V, 1 MVA transformer through an 11 kV cable approximately 0.5 km in length (Cable 1). The 415 V side of the transformer feeds several distribution boards located inside the Centre for Nano Health through parallel single-core cables (Cable 2). The faulty circuit breaker governs a distribution board housing individual breakers for each load. Three 50 kVA shunt capacitor banks are connected in parallel to 415 V bus by means of a single-core cable (Cable 4). Capacitor bank switching is determined by a power factor controller [6], and it is based on the instantaneous reactive power absorbed by the circuit.

IV. DMAIC Approach for the Case Study

A. Define

The intended operation of the system described in Section III is to supply power from the 11 kV source to the loads. The "gap" can thus be defined as the unavailability of power supply due to the opening of the circuit breaker. The loads comprise of expensive machinery used in the production of experimental semiconductor technologies. Unplanned, abrupt power outages can destroy samples being produced, waste resources and cause potential damage to the equipment. In the case of the clean room filtration systems, a long recovery period may be required to return the laboratory environment to appropriate working conditions. A prior mitigation attempt consisted in replacing the breaker under consideration with a spare unit. However, this proved ineffective as tripping events persisted. Therefore the attention has been shifted to the system rather than to the breaker.

B. Measure

A data logger was used to read voltage, current and harmonic measurements at the circuit breaker terminals over a week in the summer of 2016. During this period no tripping event took place, but high levels of harmonics have been recorded. For instance, Figure 3 shows a sudden increase in current harmonic distortion following what seems a switching event. The values recorded by the logger indicate current unbalance between the three phases: this has been observed consistently at any points of system operation, and seems to indicate that unbalance conditions exist in the system.

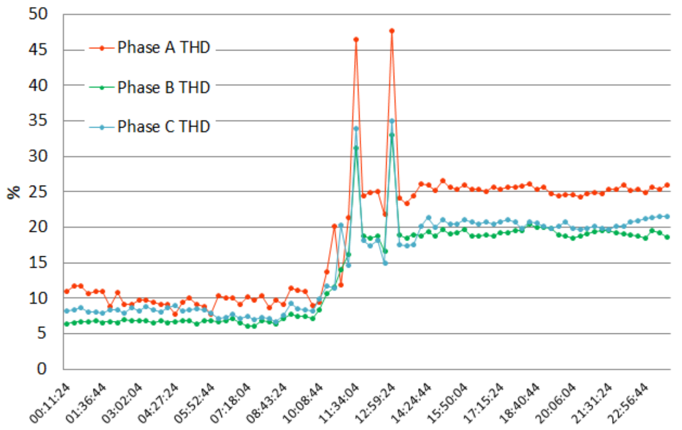

Figure 3: Current THD variation recorded by the meter

The data provided have the following limitations: the sampling rate is only 1 point per 17 minutes, and no tripping event took place during the recording period. In spite of this, the results shown in Fig. 3 indicate that, at least under certain operating conditions, high levels of harmonic are present in the system. High harmonic levels are often observed when a multiple-step capacitor bank is located in close proximity to a transformer, as discussed in details in the next section.

C. Analyze

C.1 - Theory

Shunt capacitor banks are used to improve power factor in a system, however they may have harmful effects on harmonic levels. In some cases, they create resonance conditions by interacting with the impedance of other components [7]. The resonant frequency of a system is the conditions where inductive and capacitive reactances are equal, and result in an amplification of harmonic currents at the same frequency. A first-approximation of the resonant frequency for a system including a transformer and shunt capacitor banks connected to the secondary winding is obtained as follows [7]:

$$h = \sqrt{\frac{kVA_T}{Z_T \times kvar_C}} \qquad (1)$$

where kVA_T is the transformer rating, Z_T is the transformer impedance and $kvar_C$ is the capacitor rating. For the system under consideration (kVA_T = 1 MVA, and Z_T = 6% and $kvar_C$ =50, 100 and 150 kvar), three different resonance frequencies are obtained by applying (1): 18.3rd, 12.9th and 10.5th for the case of one, two and three capacitor banks in service, respectively. These frequencies correspond to harmonics typically encountered in distribution systems, and therefore harmonic amplification is possible for the system under study. The circuit breaker specifications [5] indicate that high and continuous harmonic levels may result in breaker tripping, therefore further investigation is carried out to validate this hypothesis.

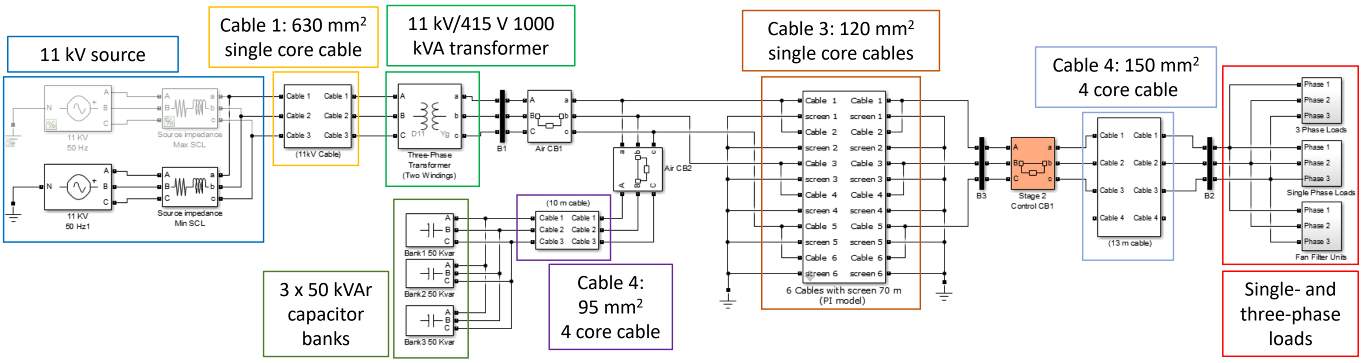

Figure 4: Simulink Model of the System shown in Figure 1

C-2 Model

A model of the system described in Section III was built using MATLAB/Simscape, in order to perform time- and frequency-domain analysis. A snapshot of the model is show in Fig. 4. To simulate maximum and minimum short circuit levels exhibited by the system, two separate models of the 11 kV source were built, using data provided by the local utility company [8] – this is indicated by the two parallel Thevenin branches in Fig. 4. Information on the short circuit level was provided by the local utility. Only one of the two sources is active at the time. Two main challenges were encountered when building the model, briefly described below.

1) A total of approximately 14 single-phase and 6 three-phase loads are installed, for a total 231 kVA rated power. Detailed information on the power factor and harmonic characteristics were not available for all loads, therefore these parameters were modeled according to the values included in standards such as [9] and [10].
2) The system includes different cables, however, accurate lengths were not provided. This information was retrieved using the electrical drawings. A more challenging limitation was the lack of electrical parameters for the cables. Inductance and capacitance values for the 11 kV cables were found in [11] and this allowed developing an accurate model for Cable 1 (Fig 4). However, it was more difficult to find these values for the low voltage cables. As a result, to model Cable 3 and Cable 4 (Fig. 4), inductance and capacitance were calculated using the following equations [12]:

$$L = K + 0.2\ln\left(\frac{2S}{d}\right) \qquad \text{mH/km} \quad (2)$$

$$C = \varepsilon_r/18\ln\left(\frac{D}{d}\right) \qquad \mu\text{F/km} \quad (3)$$

In (2), K is a constant that relates the number of wire strands to each individual conductor, S is the axial spacing between conductors and d is the diameter of the individual conductor. In (3), ε_r is the relative permittivity of the insulating material, D is the diameter over the insulation for single core cables and d is the conductor diameter. Cable 2 is made of two parallel-connected cables which exhibit mutual inductance; the 'power_cableparam' tool in MATLAB [13] was utilized to calculate the parameters for this cable.

In spite of the above limitations, the model developed is still useful to perform a cursory analysis and help understanding if harmonics may be a root cause of the breaker malfunctioning.

Fig. 5 shows impedance scans measured at the low side of the 1 MVA transformer, with different number of capacitor banks in service. The waveforms show impedance peaks at 798 Hz, 548 Hz and 456 Hz for one, two and three capacitor banks in service, respectively. These frequencies correspond to the 16th, 11th and 9th harmonic orders. The values obtained from Fig. 5 are approximately two orders of magnitudes lower than the results obtained from (1). This result is explained by observing that there are reactive components in the system (such as the cables) which are not included in the simple formula (1), and which contribute to lowering the resonant frequency. The rest of the paper will focus on the study of the configuration with two capacitor banks in service, which shows a resonant frequency at the 11th harmonic, since this is one of the components most commonly encountered in distribution systems (also known as a 'characteristic harmonic').

Fig. 6 shows the sending end voltage and current, where the sending end is considered the low voltage side of the 11 kV/415 V transformer. The load level was set up to match the conditions for one of the circuit breaker tripping instances (117.4 kW).

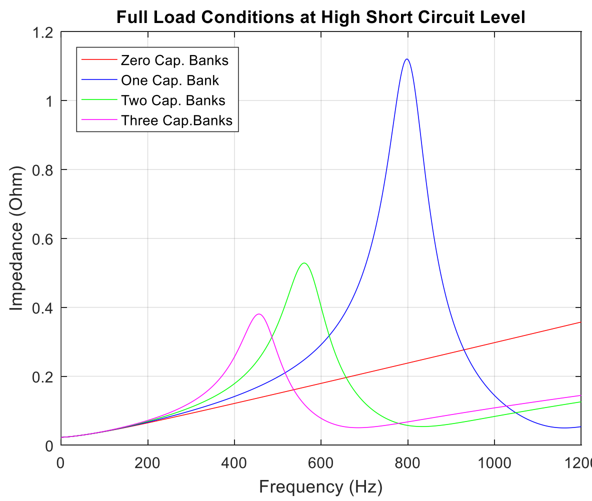

Figure 5: Impedance scan at the 415 V bus for different numbers of capacitor banks in service

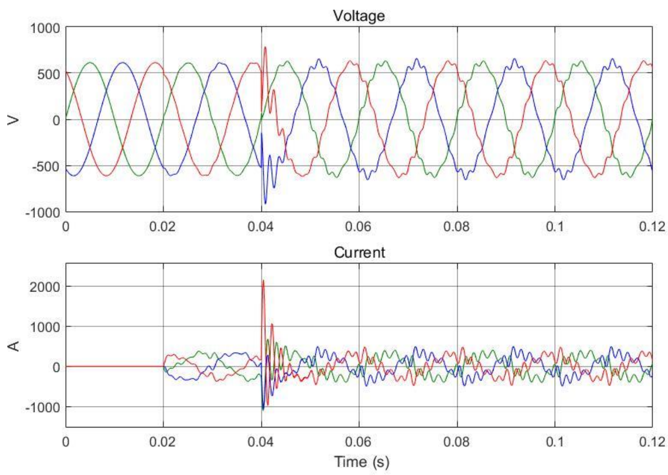

Figure 6: Voltage and current at the 415 V bus, two capacitor banks are switched in at t= 0.04 s.

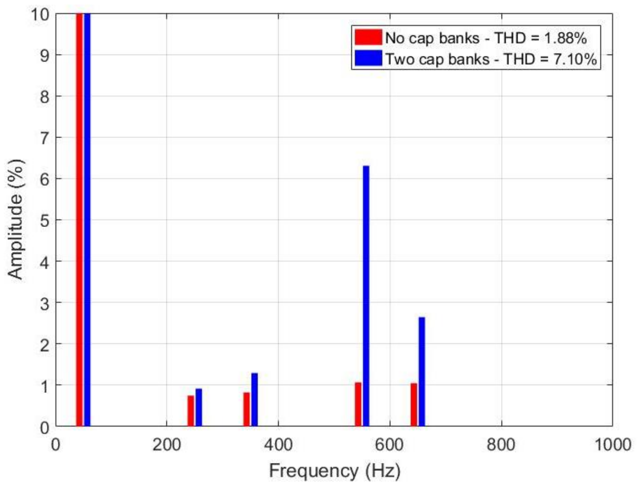

Figure 7: Voltage harmonic components for two different operating conditions

The loads are connected at t = 0.02 s and the capacitor banks are switched at t = 0.04 s. For the case when no capacitor banks are connected, the steady-state peak voltage is 613 V, while peak current is 376 A. When two capacitor banks are in service, the steady-state peak voltage and peak current increase to 669 V and 533 A, respectively. The transient behavior illustrated in the picture is not accurate as the model developed is valid only for low-frequency harmonic studies. Additionally, the reported breaker failure took place under steady-state conditions, typically with low-load and overnight, therefore, transient behavior is not considered as a possible root cause.

Fig. 7Figure 7 displays the voltage harmonic components for the two conditions shown in Fig. 6 – the red bars refer to the case with no capacitor banks in service, the blue bars refer to the case of two capacitor banks in service. The total voltage harmonic distortion increases from 1.88% to 7.10% for the configuration with two capacitor banks, and harmonic distortion is dominated by the 11^{th} harmonic frequency component (550 Hz). These results confirm the hypothesis stated in Section *C.1*: the harmonic currents injected by the loads are amplified due to the resonant condition when two capacitor banks are in service.

D. Implement

In spite of some limitations in the data, the analysis carried out in the previous section allows defining two sets of recommendations: one consists in suggesting a possible system modification to mitigate high harmonic levels. The second one consists in performing more accurate measurements.

D1: System modification

A solution to mitigate the amplification of harmonic components consists in adding a tuning reactor in series with the capacitor bank, with the purpose of de-tuning the resonant frequency of the system [14]. Tuning reactors are typically rated at 5 or 7%, where the rating is the percentage ratio of the inductive component of the reactor to the capacitive component of the capacitor bank.

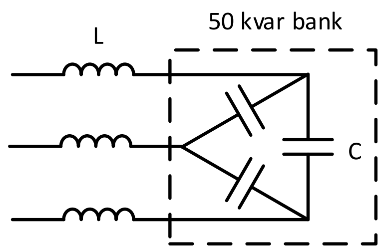

Figure 8: Modification of one of the capacitor bank configuration to include a tuning reactor

To test the effectiveness of this solution, the model of the distribution system was modified by adding a 7% tuning reactor in series to each individual capacitor bank, as shown in Fig. 8. Each 50 kvar capacitor yields a capacitance of 0.9240 μF, therefore, to match 7% rating value, the inductance value is 0.0647 μH.

The mitigating solution was tested for the condition with two capacitor banks in service at first. Fig. 9 displays the impedance frequency scans of the system for the original configuration (blue) and for the case with the tuning reactor included (green). The use of tuning reactors has the effect of shifting the resonance frequency from 548 Hz to 450 Hz, or from the 11^{th} to 9^{th} harmonic order. Since triplen harmonic currents are rare in three-phase systems, this frequency can be assumed to be safe.

The benefit of detuning the resonant frequency is confirmed by the voltage and current plots shown in Fig. 10. In comparison to Fig. 6, the peak voltage is reduced to 620 V and the peak current to 400 A. Fig. 11 shows that the total voltage harmonic distortion is reduced to 1.91%, and the 11^{th} harmonic component is reduced from 6% to 1%.

The proposed mitigating solution was tested for other operating conditions, including different number of capacitor banks in service, load levels and short-circuit levels, to ensure sure that harmonic issues were not introduced under different operating conditions.

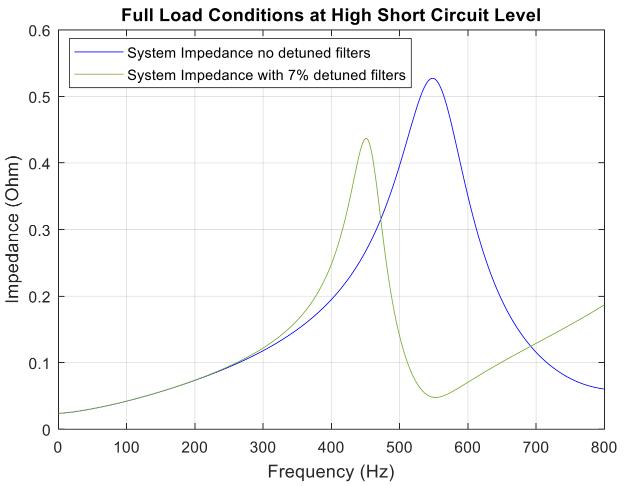

Figure 9: Frequency scan: original configuration (blue) and with tuning reactor (green)

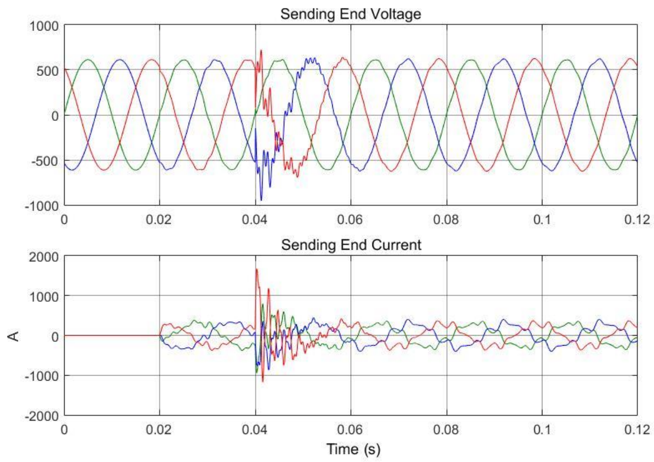

Figure 10: Voltage and current with tuning reactor and two capacitor banks

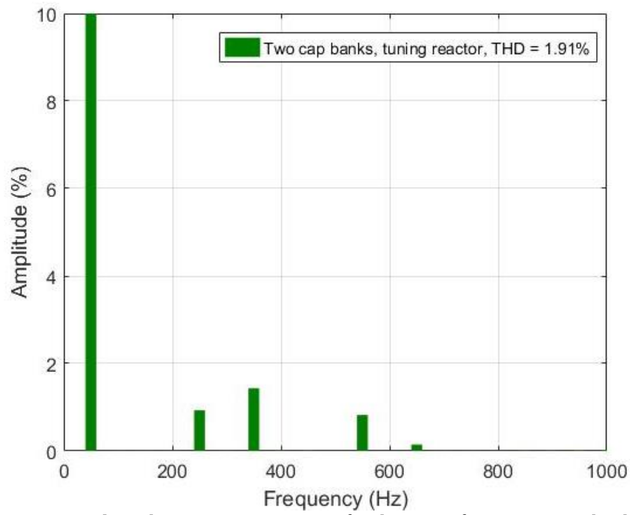

Figure 11: Voltage harmonic components for the case of two capacitor banks in service, with tuning reactor

D2: Perform new harmonic measurements

As discussed in Section IV.B, the short period of installation and the poor data resolution severely limited the insights that could be drawn from the data collected. Therefore, a second recommendation is to implement more systematic and detailed harmonic measurement. This would allow further validation of the model. Two possibilities are shortly described in this section.

The Diris A20 [15] meter is currently installed at the breaker terminals and at other locations in the distribution system, but it is not fully utilized. This unit has the ability to record voltage, current and harmonic components with a sampling rate of 1 second, providing a much improved resolution compared to the available one. This resolution is sufficient for continuous monitoring of the system. To access the recordings, the A20 requires an additional logger and a gateway module. The main drawback of this method is that data would be continuously recorded and the cache would have to be regularly cleared to free up memory space. It would however be a cheap solution to implement.

A second possibility is to use an advanced power quality meter such as the Dranetz PX5 [16] or the Fluke 435 [17]. These are stand alone and portable power quality units that offer a high sampling rate (up to 500 samples per cycle). These meters also have an inbuilt trigger commands, allowing to increase the rate of data collection, under events such as the THD levels exceeding a pre-determined threshold. This solution will be more expensive, however, high resolution data would be provided, and the triggering function would allow for a better analysis of the transients caused by breaker tripping.

E. Control

The last stage of the DMAIC approach consists monitoring the improved process. For the system under study, at the moment the analysis performed requires further validation, and therefore the proposed mitigating solution has not been implemented yet.

It is instead recommended to repeat the 'measure' step using the previous recommendations and to gather more accurate data for the loads and the cables, thus allowing to develop a more accurate model and to size more precisely the tuning reactors.

V. CONCLUSIONS

This paper presented the application of the DMAIC approach to the root cause analysis of breaker failure in a distribution system. Based on the data provided by the define and measure stage, the analysis focused on performing a harmonic analysis of the system. The harmonic analysis seems to confirm the hypothesis that under certain operating conditions, high harmonic levels are encountered in the system. It has been also shown that introducing series reactors may be a simple yet effective solution to mitigate the problem.

Due to the lack of accurate measurement and component data, it is understood that at this stage the conclusions are only preliminary. Therefore, recommendations have been provided on gathering more accurate measurement data that would allow developing a more effective model.

The paper also showed how to mitigate common limitations encountered when building models of distribution systems. When manufacturer data are not available, typical data can be used, or values included in the standards can be applied, however, in these cases, the less conservative approach should be always used. Clearly, the availability of accurate system data would allow not only performing a more effective analysis, but also reducing the time required to build models.

VI. ACKNOWLEDGEMENTS

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