

Design and Evaluation of Submersible 11/0.415kV Distribution Substation for Flood Prone Areas

M. D. M. Amir*, S. Ishak, A. Raj Gopal

TNB Research Sdn Bhd, Kawasan Institusi Penyelidikan, 43000 Kajang, Selangor, Malaysia +60389225000

*Corresponding author, e-mail: dzaki.amir@tnb.com.my

Abstract

Flood levels exceeding 2 metres above ground level has been observed causing electrical equipment in the 11/0.415kV substation to be fully submerged. This caused widespread supply disruption as the equipment need to be switched off due to safety reasons and prevention of further equipment damage. The use of submersible equipment and accessories has been identified as one of the mitigation methods to ensure continuous electrical supply during flood events. A research project was undertaken to develop the design criteria of the selection of submersible equipment and accessories as well as to develop the test method and evaluate the selected submersible equipment and accessories in a substation configuration. All the equipment could continuously operate in ON condition during the wet test. However, design improvements are suggested for the submersible switchgear and feeder pillar for better performance during and after flood events.

Keywords: high voltage testing, submersible substation, submersible electrical equipment, flood mitigation

Copyright © 2017 Universitas Ahmad Dahlan. All rights reserved.

1. Introduction

During the last major Malaysian flood events in 2014; the water level in several areas exceeded 2 metres above ground level. This caused electrical equipment in the 11/0.415kV distribution substation to be fully submerged. As the equipment is not rated for submersible operations, the equipment in the flood affected substation need to be switched off due to safety reasons and to prevent further damage to the equipment.

This does not only cause supply disruption to the local area served by the flood affected substation but also any substation downstream to the affected substation. This is especially critical in spur feeder configuration, normally used in rural areas, which is the most prone to flood events. This may cause a larger than necessary number of customers to be affected by the flood as the downstream substations might not be affected by the flood as shown in Figure 1.

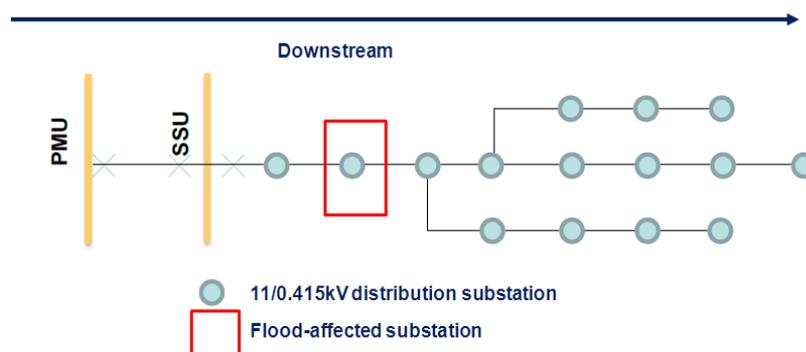


Figure 1. All the substations downstream of the affected substation will suffer from supply disruption even though they are not flooded themselves

During the flood events, Tenaga Nasional Berhad (TNB), which is the Malaysian national power utility company, will incur a large cost to replace and/or repair any equipment damaged by the flood as well the cost of providing temporary supply by using mobile gen-sets to areas downstream of the flood-affected substation. As the flood events can last up to one week, TNB suffered losses due to unserved energy during this period. Finally, TNB also suffered from intangible losses such as reputation loss in the eyes of the public and investors due to taking longer time in restoring the supply.

1.1. Current Utility Practice in Mitigating Flood Events

There are several major approaches used by utilities worldwide to mitigate flood events. Bogeos proposes the elevation of the substation as a mitigation for flooding. Distribution voltages are more convenient to elevate due to the availability of many substation designs that can be placed on stilts, platforms or slabs [1]. However, it is more tedious to elevate a transmission substation due to the large space needed for increased electrical clearances at high voltages. This will lead to increase in material cost for concrete and steel. This is practiced by TNB for flood-prone areas but its limitations are that this mitigation method caters only for low flood level. Figure 2(a) and 2(b) show example of raised substation for flood level above and below 3 metres respectively.

Succeeding suggestion of Joseph Baker is to elevate the substation that he defined as raising the substation utilizing existing structures [2]. The suggestion to elevate to existing structures makes the solution economical. The solution has an acceptable schedule criterion. However, the risk of service disruption time is relatively high with moderate increase in operation and maintenance risk.

Another option is to elevate to a new site to reduce service interruption time as discussed in [3]. This may prove to be costly and has a long lead time. Additional land is required to allow construction to allow continuation of supply. The recommended height raise is 1.2 m.



(a)



(b)

Figure 2. (a) Raised substation for flood level above 3 metres
(b) Raised substation for flood level below 3 metres

Another major approach is by using floodwalls. Floodwalls are defined as constructed barriers that provide more than 4 feet flood protection to buildings. Joseph Baker suggests in his paper that the floodwall around the substation will protect the substation and additions of pumps will remove entrapped water [2]. This method is economically viable and has minimum construction duration with minimal service disruption. However, the drawbacks may be additional monitoring of pump is needed and if the floodwall breaches complete operational failure may cause a devastating impact.

Mark Dunk in "Substation Flood Protection (2016)" agrees with flood protection for substations as a main highlight. This is due to the flooding events recorded across England and Wales. According to him the factors of flood are coastal (tidal), fluvial (river) or pluvial (surface water) [4].

His mitigation suggestions are using reinforced concrete retaining/flood walls around entire substation sites including using flood gates, raising equipment above level of flood, ensuring all ducts are sealed from water ingress using approved duct systems, sealing low level

air brick vents, installing non return valves on flood drainage systems, using temporary flood barriers and installing of pump system and pumping to external storage. Figure 3 below shows an example of a substation fitted with floodwall protection using concrete walls and removable panels.



Figure 3. Floodwall protection using concrete walls and removable panels [4]

The final approach to allow continuous operation of the electrical equipment in flood conditions is by using electrical equipment which has been rated for submersible operations. The standard IEEE C57.12.24-2016 defined submerged operation for transformers below 3750kVA as being capable of continuous unattended operation under 3m of water over the top of the tank [5]. IEC 62271-111:2012 similarly has a water head limit of not more than 3m over the base of the enclosure [6]. As part of their flood mitigation methods, Con Edison, which is the power utility in New York, has installed 52% of the underground transformers and switches in flood plains with submersible-capable equipment. Con Edison is planning to replace the remaining underground electrical equipment with submersible type in the 100-year floodplain [7].

1.2. Research Objectives

In Malaysia, submersible equipment has not yet been used in the distribution network among the three mitigation methods presented in the previous section. Hence, this method has been identified as one of the potential flood mitigation methods for further evaluation. The test methods in both IEEE and IEC standards only refer to individual testing of the electrical equipment. There is no method yet to test the equipment connected in a substation configuration. Hence, a research project was undertaken with the following objectives:

- a. Development of design criteria for the selection of submersible equipment and accessories to be used in a submersible substation
- b. Developing the testing method for the submersible equipment connected in a substation configuration as per actual flood condition.
- c. Evaluation of the performance of the submersible equipment using the method developed above.

2. Proposed Design Criteria

A typical 11/0.415kV distribution substation contains 11kV switchgears or ring main units, 11/0.415kV transformer and 415V feeder pillar as well as other substation accessories (DC supply, remote terminal units, remote control box etc.). For the purpose of laboratory testing and to ensure the substation are fully submersible, accessories are installed which are submersible 11kV and 415V cable termination as well as seals for the cable entry. Table 1 shows the design criteria of the submersible equipment and accessories. The design criteria are based on the standard operating procedure used by TNB during flood events.

Based on the design criteria, market survey was performed to determine suitable equipment which can withstand the flood conditions. There are many switchgear brands/models which can meet the design criteria. These switchgears can be grouped into two main technologies which are underground SF₆ gas insulated switchgears and solid insulated switchgears (SIS). SIS was chosen as the technology because of the lower price and to support

the nation's commitment in reducing greenhouse gas emission of which includes SF6 gas. While there are several submersible transformers available in the market, it was decided to partner with a local manufacturer to develop the submersible transformer to support the local transformer industry.

Table 1. The Design Criteria for the Submersible Equipment and Accessories During and After Flooding

Equipment / Accessories	During Flooding	After Flooding
11kV switchgear	<ol style="list-style-type: none"> 1. No water ingress into the live parts of the switchgear (busbar, vacuum interrupters) 2. Switchgear can continue to be in ON condition. 3. Switchgear protection system should be able to continue function. 4. Switchgear status can be partially be monitored. 5. Trip operation is possible once. 	<ol style="list-style-type: none"> 1. Switchgear can continue to be in ON condition. 2. Trip operation is possible once prior to retesting & inspection 3. Normal operation can only be allowed after retesting & inspection.
11/0.415kV transformer	<ol style="list-style-type: none"> 1. No water ingress into the internal parts of the transformer 2. Transformer can continue to be in ON condition. 	<ol style="list-style-type: none"> 1. Transformer can continue to be in ON condition. 2. Normal operation can only be allowed after retesting & inspection.
415V feeder pillar	<ol style="list-style-type: none"> 1. No water ingress into the live parts of the feeder pillar (busbar) 2. Feeder pillar can continue to be in ON condition. 	<ol style="list-style-type: none"> 3. Transformer can continue to be in ON condition. 4. Normal operation can only be allowed after retesting & inspection.
11kV and 415V cable termination	<ol style="list-style-type: none"> 1. No water ingress into the live elements of the connection. 2. No damage to the cable termination insulation material. 	<ol style="list-style-type: none"> 1. Cable termination can be reused after flooding.
Seals for cable entry	<ol style="list-style-type: none"> 1. No water ingress into the cable compartments. 2. No physical damage to the seals. 	<ol style="list-style-type: none"> 1. Seals can be reused after flooding.

There is currently, no commercially available submersible feeder pillar. This is most probably due to the technical difficulty in balancing ventilation needs as well as preventing water ingress during the flooding. Another likely cause is the lack of demand for submersible feeder pillars compared to submersible switchgears and transformers. A local manufacturer was contracted to design and develop the submersible feeder pillar. The selected equipment is as detailed in Table 2 below.

Table 2. The Description of Submersible Equipment Evaluated in the Submersible Test

Equipment	Description
11kV switchgear	<ol style="list-style-type: none"> 1. Solid insulated switchgear technology 2. Live parts encapsulated in solid resin insulation with IP67 protection 3. Other switchgear parts (e.g. motor, LV components, trip coils) are housed in a IP4X rated panel
11/0.415kV transformer	<ol style="list-style-type: none"> 1. Almost identical to a normal 11/0.415kV transformer design. 2. The main difference with non-submersible transformer is in the use of bushing which is specifically made for submersible conditions. 3. This bushing is rated IP67.
415V feeder pillar	<ol style="list-style-type: none"> 1. Equipped with valve to allow air flow (ventilation) during normal conditions 2. Valves are opened during normal conditions 3. Sensors are installed to detect water level 4. During flood, the valves will be closed automatically if the pre-determined water level are exceeded to prevent water ingress 5. After flood receded, the valves are opened again automatically

3. Research Method

Each of the submersible equipment and accessory are placed in a specially designed water tank for the purpose of testing. The cables from the high voltage sources are inserted into the tank through designated cable entry holes which are then closed off by using the cable entry seal as shown in Figure 4. The test-setup for the submersible equipment and accessories

during the test is shown in Figure 5. Table 3 shows each phase for the submersible substation testing with the tests performed during each phase. Figure 6(a) and 6(b) show the condition of the submersible equipment and accessories during and after the wet test.



Figure 4. Use of seal for the cable entry hole

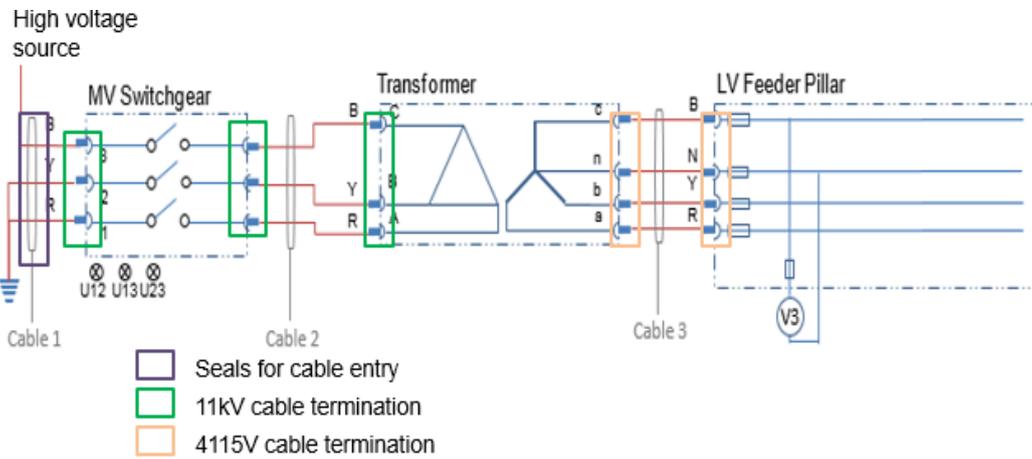


Figure 5. Test set-up for the submersible equipment and accessories in a substation configuration

Table 3. The phases during the testing method for the submersible equipment connected in a substation configuration as per actual flood condition.

Phase	Tests Performed
Pre-testing for submersible equipment	<ol style="list-style-type: none"> 1. Functional test for switchgear 2. Dielectric withstand test for switchgear 3. Insulation resistance (IR) test for transformer and switchgear 4. Test on secondary circuits 5. Contact resistance (CR) for switchgear
Dry test (240V supply – single phase)	<ol style="list-style-type: none"> 6. Check relay output 7. Check supply output from feeder pillar
Dry test (6.5kV supply – single phase)	<ol style="list-style-type: none"> 8. Check outgoing voltage at feeder pillar 9. Remote tripping test
Wet test (Circuit not energized)	<ol style="list-style-type: none"> 10. Fill the tank with water at various levels (0.5m, 1m, 1.5m, 2m) 11. IR test at various levels
Wet test (Circuit energized at 6.5kV supply single phase for 48 hours)	<ol style="list-style-type: none"> 12. Current leakage tests throughout the wet test 13. Current leakage tests throughout the wet test 14. Switchgear remote tripping test after 48 hours
Post-testing for submersible equipment	<ol style="list-style-type: none"> 15. Visual inspection of all equipment and accessories 16. Functional test for switchgear 17. Dielectric withstand test for switchgear 18. Insulation resistance (IR) test for transformer and switchgear 19. Contact resistance (CR) for switchgear

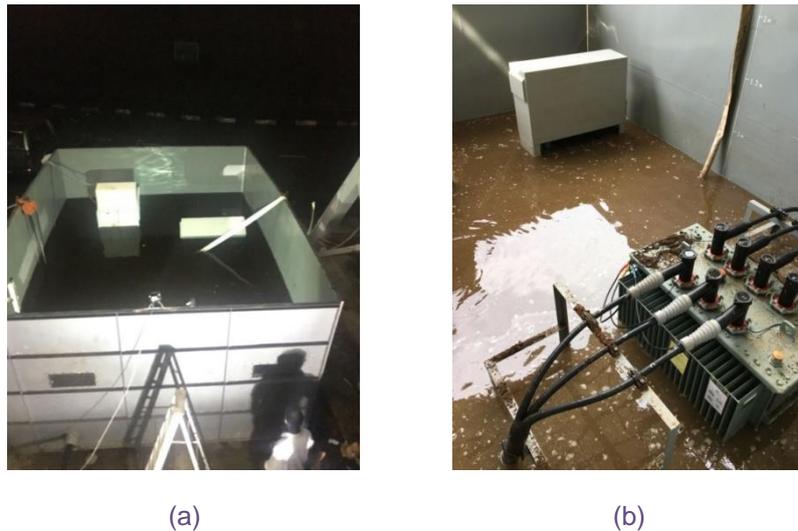


Figure 6. (a) Submersible test at 2 metre water level (b) Conditions of the submersible substation after water level receded. Note that the both sets of 11kV and 415V cable termination installed on the transformer are still in good condition

4. Results and Analysis

Table 4 summarises the results of the performance of the submersible equipment and accessories during the submersible test. The main pass criterion is that each of the equipment is able to continuously operate in ON condition while the circuit is energized at 6.5kV for 48 hours without tripping the main circuit.

Table 4. Results of the Performance of the Submersible Equipment using the Testing Method for the Submersible Equipment Connected in a Substation Configuration as per Actual Flood Condition

Equipment / Accessories	Pass Criteria	Results
11kV solid insulated switchgear	Pass the wet test at 6.5kV for 48 hours Able to trip during the flood	Passed
11/0.415kV custom-made transformer	Pass the wet test at 6.5kV for 48 hours. Pass IR test before & after the wet test.	Passed
415V custom-made feeder pillar	Pass the wet test at 6.5kV for 48 hours. Pass IR test before & after the wet test.	Partially Passed (Water droplets were observed inside the feeder pillar after the wet test)
11kV submersible cable termination	Pass the wet test at 6.5kV for 48 hours. Pass IR test before & after the wet test.	Passed
415V submersible cable termination	Pass the wet test at 6.5kV for 48 hours.	Passed
Seals for cable entry	No leaks during the wet test.	Passed

All the equipment could continuously operate in ON condition during the wet test. The submersible transformer, cable termination and seals for cable entry performed as per design criteria and can be reused immediately after flood with only requiring minor external cleaning. It proved to be robust enough to withstand the flood while resuming operation as usual afterwards.

For the submersible feeder pillar, a little amount of water droplets was observed in the feeder pillar after the submersible testing. Investigations determined that the root cause is due to water seeping through the valve. This was caused by the weakness in the ball valve design. Despite that, the main circuit was not tripped throughout the wet test indicating that the feeder pillar was still able to continuously operate in ON condition.

Even though the submersible switchgear could pass the test, several components need to be replaced after the wet test. These components, which include the motor, trip and close coil as well as the operation counter, are not situated inside the IP67 solid insulated tank, but rather within the IP4X panel. This means that after flooding, maintenance will need to be performed prior to restoring the switchgear to full service. This has the implication of extra expenditure for the utility due to maintenance works and component replacement costs.

5. Conclusion

The design criteria for the selection of submersible equipment and accessories to be used in a submersible substation have been developed based on the prevailing TNB standard operating procedure during flood conditions. The equipment and accessories were then selected partly based on commercially available products in the market and partly developed in collaboration with local manufacturers.

The test method for the submersible equipment connected in a substation configuration as per flood condition has been developed. The test method is separated into 6 different phases designed to test the performance of the submersible equipment in different conditions. The facilities for the submersible substation test were constructed and can be used for testing of other types of electrical equipment under submerged conditions.

All the equipment could continuously operate in ON condition during the wet test. The submersible transformer, cable termination and seals for cable entry performed as per design criteria and can be reused immediately after flood with only requiring minor external cleaning. The submersible switchgear requires maintenance works and component replacement after flood events. It is recommended for the manufacturer to improve the design and durability of the components to minimize the replacement works.

Water droplets were found in the feeder pillar caused by the weakness in the ball valve design. The corrective measure will be to redesign and retest the feeder pillar. A potential improvement is by replacing the ball valve using a latching solenoid valve. By doing so, the solenoid valve will be useful to prevent water seeping through due to its better mechanical design capability.

In summary, the use of submersible equipment and accessories is technically feasible as a mitigation method for flood conditions. However, several design improvements need to be made in the evaluated submersible switchgear and feeder pillar before being implemented in the field.

References

- [1] Boggess JM, Becker GW, Mitchell MK. *Storm & flood hardening of electrical substations*. IEEE PES T&D Conference and Exposition. Chicago. 2014: 1 - 5.
- [2] Baker JW. *Eliminating hurricane-induced storm surge damage to electric utilities via in-place elevation of substation structures and equipment*. IEEE PES T&D Conference and Exposition. Chicago. 2014: 1 - 5.
- [3] Matos SM, Joao PC. Flood Adaptation Measures Applicable in the Design of Urban Public Spaces: Proposal for a Conceptual Framework. *Water*. 2016; 8(7): 284.
- [4] Dunk M. *Substation Flood Protection: Engineering Design Standard*. UK Power Networks. EDS 07-0106. 2016.
- [5] IEEE Standards Association. C57.12.24-2016, *IEEE Standard for Submersible, Three-Phase Transformers, 3750kVA and Smaller: High Voltage, 34 500 GRDY/19 920 Volts and Below; Low Voltage, 600 Volts and Below*. IEEE Press. 2016.
- [6] International Electrotechnical Commission. 62271-111:2012, *High Voltage Switchgear and Controlgear – Part 111: Automatic Circuit Reclosers and Fault Interrupters for Alternating Current Systems up to 38kV*. IEC. 2012.
- [7] A Stronger, More Resilient New York. New York: City of New York. 2013: 107 – 129.