

NOVEL APPROACH TO VARIABLE VOLTAGE SUBSTATION PROTECTION

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Abstract

Conventional electrical system protection of variable voltage substations (medium voltage rated) of using fuses and phase overcurrent and/or phase time overcurrent protection is not adequate. This was evident from the recent variable voltage substation (VVS) electrical fire at SLAC. Using information obtained from the fire investigation, ETAP simulations, and event reports of the faults which led to the fire, SLAC put into action a fast, feasible, and economical relay protection plan into adequately protecting VVS until long term plan of replacements is implemented. The plan utilizes the existing microprocessor protection relays on the upstream breakers and included the following adjustments: Adjusting the long-time overcurrent according to the derated cable ampacities, dual-fed arc flash fault protection, adding negative sequence settings and relay control logic to allow for two sets of settings for inrush mode and normal mode.

INTRODUCTION

The challenges we met were repetitive low fault currents in short durations not being protected by the fuses. At the same time, according to the protection coordination study results, the transformers' damage curves are positioned very close to the transformers' full load amps (FLA). It would not be possible to find a fuse fitting such configuration without creation of a significant risk of unintended tripping, as the transformers operated very close to the FLA. The ideal solution would be replacement of fuses by breakers controlled by protection relays equipped with differential protection elements and temperature monitoring. Use of the protection relays would also give us an opportunity to fine-tune the overcurrent time-current curve to fit it precisely between the full load amps point and the damage curve. This however would not be feasible in the short term due to restriction to capital resources and schedule impact to sciences.

An alternative solution presented in this document has been worked out and implemented instead. Thanks to the implemented protection system modification the transformers' protection at the low fault current range has been significantly improved in a very short period of time and at very low cost.

THE VARIABLE VOLTAGE SUBSTATIONS (VVS)

There are a total of 16 VVS in the SLAC linear accelerator. They are powered from breakers at the Master Substation with 3-500 MCM EPR insulated copper feeder cables. Each of the individual feeders can supply up to several (from 1 to 4) VVS substations, thus several

12.47/0.6 kV transformers may be powered by a single 12.47 kV breaker. The load break disconnect switches are deemed not operable due to their age and condition. The energizing of VVS is instead done at upstream breakers at Master Substation through the use of SEL 751A relays.

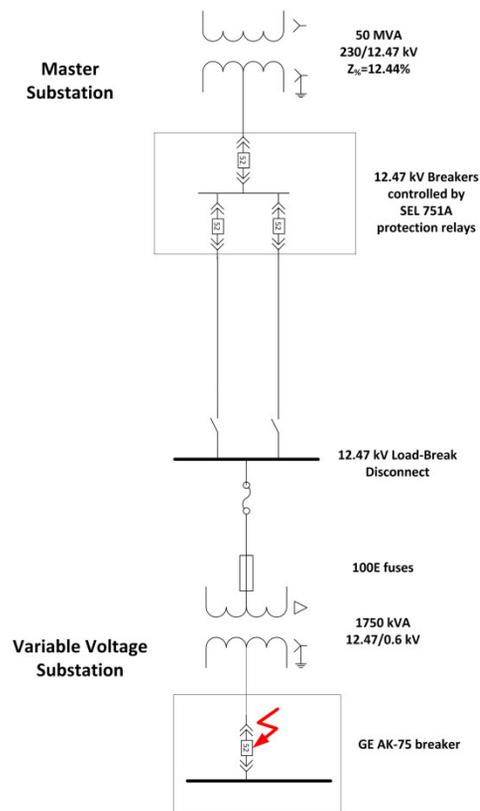


Figure 1: Simplified single line diagram of the VVS substation powering system.

VVS SUBSTATIONS PROTECTION SYSTEM AT THE TIME OF THE FIRE

The VVS substation protection system coordination plot is presented at Fig. 2. The 12.47/0.6 kV transformer damage curve has been shifted to reflect the overcurrent protection ability to see the fault current on the primary side of the transformer for secondary side faults. The plot shows that VVS 12.47 kV fuses do not ensure proper protection of the VVS 12.47/0.6 kV transformer for the range of currents below 220 A, which corresponds to time over 50 seconds on the 100E fuse time-current curve. The SEL 751A protection relay overcurrent settings were following.

- Function 50: $I = 4.8$ kA, time delay: 0.02 s.
- Function 51: extremely inverse U4 time-current curve, $I = 451$ A, time dial: 5.3 s

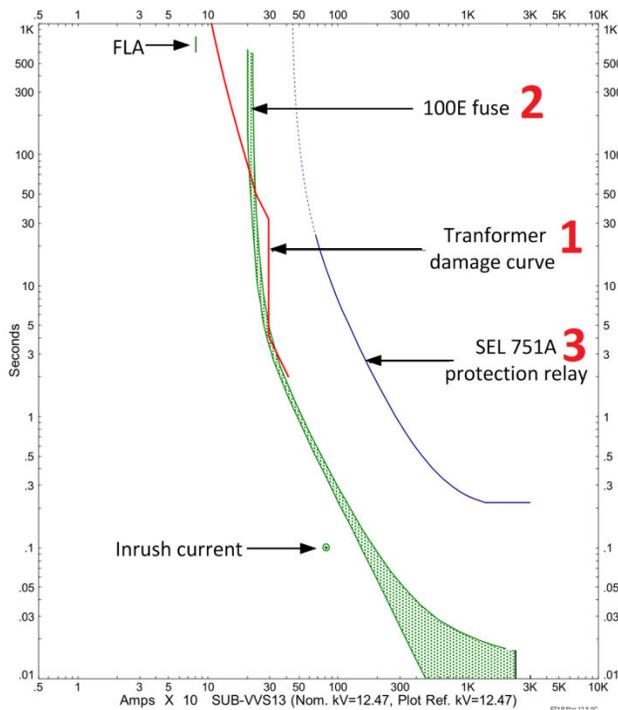


Figure 2: The VVS substation protection coordination graph at the time of the fire. 1 – 12.47 kV transformer damage curve, 2 – 100E fuse, 3 – SEL 751A protection relay overcurrent settings.

RESPONSE OF THE PROTECTION SYSTEM TO THE FAULT CONDITIONS

Based on the archived data it can be said that the fault current values during the fire ranged approximately between 140 A and 550 A at 12.47 kV, and sometimes spiking near 800 A. All faults were for very short periods of time. Reference the exemplary current plot samples shown in Fig 3 and 4. The current plot samples were retrieved from the upstream SEL 751A protection relay.

The main properties of the fault current can be summarized as follows:

- The fault current was asymmetrical in many samples (see relatively low value of the phase A current in Fig. 4)
- Very quick changes of the current values (change from about 800 A to about 200 A within duration of one cycle in the Fig. 3)
- There are periods of relatively low current value that follows very big current periods. An evident proof that arcing current was very unstable.

Apart from VVS-13, there are two other VVS substations powered by the same 12.47 kV breaker, consuming about 70 A each. That means, 140 A can be considered as an offset value, giving 0 A to 360 A of real fault current flowing through the arcing point inside the VVS13 switchgear.

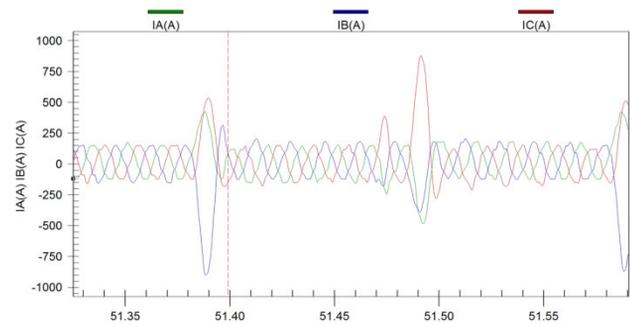


Figure 3: An exemplary fault current plot (time 22:01:00).

The upstream 12.47 kV breaker did not trip, indicating that fault current never reached the instantaneous protection threshold of 4.8 kA. Moreover, the fault current did not withstand long enough levels and high enough levels to activate the long-time protection setting of 450 A.

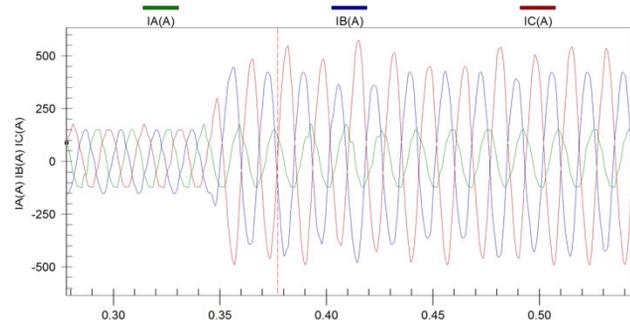


Figure 4: An exemplary fault current plot (time 22:02:09).

PROTECTION SYSTEM MODIFICATION

In order to address the protection system deficiencies the following action had been applied at the upstream 12.47kV protection relays.

- The relay's long-time overcurrent settings had been decreased from 451 A due to derating (as a function of the cable grouping factor value) of cables. This allows for better protect against overloading of cables. Settings ranged from 278 A to 321 A from breaker to breaker.
- The negative sequence (I₂) overcurrent setting protection had been enabled to better protect the 12.47/0.6 kV transformer from faults. Negative sequence currents ranged starting at approximately 130 A. Negative sequence, along with positive (I₁), and zero sequence (I₀) are symmetrical components of three phase system. Symmetrical components are beyond the scope of this paper, but it should be noted, negative sequence is a consequence of unbalance conditions.
- The instantaneous overcurrent settings had been lowered from the 4.8 kA to 3.0 kA in order to be able to detect and clear dual-fed faults.

- d) Two operation modes: “start-up” and “normal” had been implemented to avoid tripping by the 12.47/0.6 kV transformer inrush current.

NEGATIVE SEQUENCE SHORT-TIME OVERCURRENT PROTECTION

Normal Operation

The analysis done on multiple available samples indicates that during normal operation of the negative sequence current value corresponds roughly up to 10-20% of the phase current, and varies between 5 and 35 A for a feeder powering three VVS substations (210A - 220A of the phase current). The typical sample of the Master Substation breaker No. 61 phase current and negative sequence current value is presented in the Fig. 5.

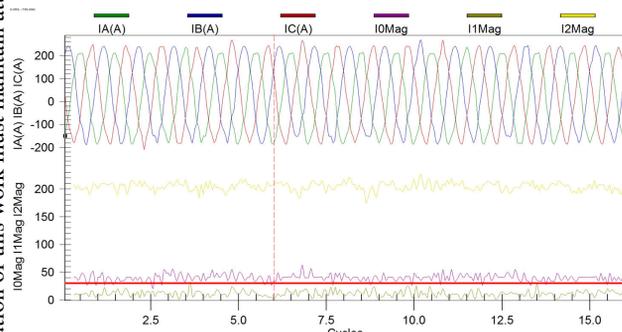


Figure 5: The normal operating phase currents and negative sequence current at breaker No. 61 sample. The negative sequence current maximum level is marked by the red line.

Start-Up of Transformer

According to data collected on several samples, the transformer inrush negative current value may correspond to about 30-50% of the phase current. One example of is presented in the Fig. 6.

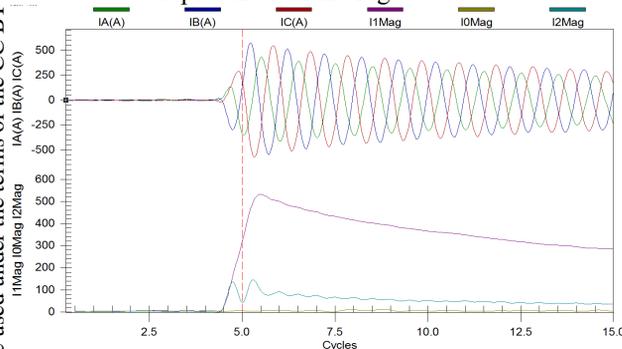


Figure 6: The inrush current recorded at the Master Substation breaker 61 (startup of four 1750 kVA transformers). The negative sequence current corresponds to about 20% of the phase current.

Fault Conditions

The negative sequence current value during electrical fire in June 25, 2014 exceeded 50% of the phase current

in many samples. Figure 7 presents a current sample showing negative sequence current value in approximate range of 280-400 A for phase current value equal to approximately 500A.

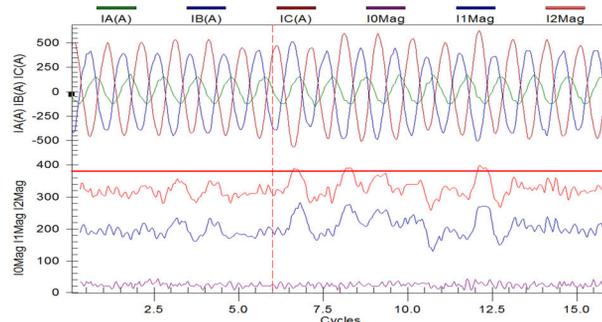


Figure 7: The VVS13 fire phase current and negative sequence current breaker No. 61 sample. The negative sequence current maximum level is marked by the red line.

Negative Sequence Overcurrent Settings

The following negative sequence overcurrent protection settings have been applied:

- Negative sequence overcurrent trip pickup (ANSI 50Q): 65 A
- Time delay 100 ms.

This setting will ensure protection for phase currents exceeding 130 A in unbalanced fault conditions. This is important to keep in mind that such high negative sequence component will not exist in the case of symmetrical 3-phase faults, and such type of fault will not be detected by the negative sequence overcurrent protection.

CONCLUSIONS

The negative sequence instantaneous overcurrent protection may be used to complement the phase overcurrent protection. The main advantage of such solution is better sensitivity to the unsymmetrical faults in symmetrical systems (when compared to the phase overcurrent protection). There are also some drawbacks of this solution. Such protection will not detect the 3-phase fully symmetrical fault. This is not a problem in a majority of cases, because as studies show [1] only two to three percent of distribution faults are three phase faults. Application of negative sequence overcurrent protection may lead to necessity of a separate start-up settings mode into protection relay program to avoid unintended tripping by the inrush current. Nevertheless, even taking into account all mentioned disadvantages, the negative sequence overcurrent protection is worth consideration as a temporary low-cost and quick alternative to the protection equipment upgrade or as a complement of the phase overcurrent protection system.

REFERENCE

- [1] R. Moxley, Distribution Single-Phase Tripping and Reclosing, Protection, Automation, and Control World, Spring 2009.