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Composite Load Model Validation through Event Analysis with Synchrophasor Measurements

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SUMMARY

The composite load model provides a possibility for improving representation of load behavior in power system voltage stability studies, especially when Fault-Induced Delayed Voltage Recovery (FIDVR) is the key phenomenon in the scope of analysis. Because composite load model parameter values affect the quality and trustworthiness of study results, it is necessary to validate or calibrate the composite load model parameter values with event records from the real system to ensure that the model represents the real system load performance. Synchrophasor measurements are the perfect event records to capture the system voltage response to an event exhibiting FIDVR. In this paper, a FIDVR event is presented as an example to demonstrate the synchrophasor measurement-based event analysis and load model validation approach. Lessons learned about composite load model performance and parameter sensitivities to voltage response from this analysis are also considered.

KEYWORDS

Synchrophasor, FIDVR, Composite Load Model, Load Model Validation, Event Analysis

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Introduction

The composite load model, which includes provisions for 3-phase motors, static loads, electronic loads, and single-phase air-condition motors, provides a possibility for improved representation of load behavior in power system voltage stability studies [1-3], especially when Fault-Induced Delayed Voltage Recovery (FIDVR) is the key phenomenon in the scope of analysis. The selection of composite load model parameter values, in particular the fraction of each type of motor and single-phase air conditioner motor constants, bears on the quality and trustworthiness of the study results, such as the magnitude and duration of the FIDVR effect. That result, in turn, may cause the estimated voltage constrained system operating limits to vary near or far from real system operating limits. Hence, it is necessary to validate the composite load model and calibrate model parameters with event records from the real system to ensure that the model represents the real system load performance [4].

A FIDVR event may persist for several seconds. The event analyzed in this paper lasted more than 15 seconds and a typical Digital Fault Recorder (DFR) could not provide event data for such a long period. At the same time, typical supervisory control and data acquisition system (SCADA) measurements do not provide enough resolution during the FIDVR period because SCADA sampling rates are not high enough to capture events of a transient nature. In this case, synchrophasor measurements are the perfect event records to capture the composite load model response to an event as it fulfills both event requirements, duration and visibility, at the same time.

In this paper, a late afternoon summer FIDVR event, which included Under Voltage Load Shedding (UVLS) relay actions in the American Electric Power (AEP) system, is presented as an example to demonstrate the event analysis and load model validation approach. Since voltage performance is one of a number of factors to determine system operating limits, proper load modeling is often the most sensitive variable affecting voltage performance and in determining the power importing levels of an area remote from the rest of an interconnection system.

The event analysis and load model validation process is composed of three steps: 1) pre-event system operating point replication, 2) event simulation, and 3) composite load model validation and model parameters calibration. In step one, historical state estimator power flow cases and SCADA measurements are used as the reference for the pre-event system operating point, which includes study area network topology, system load, and generator dispatch levels at a time just before the event. A current year planning dynamic case, which includes the dynamic model of the system, is adopted as the base case and adjusted accordingly to replicate the pre-event operating point. As PSS®E is used as the simulation software, the PSS®E CMLDZNU1 model is applied to the zonal loads in the study area. In step two, faults and relay actions are obtained from time-tagged DFR records in the relevant substations and then simulated. In step three, an iterative "trial and error" process is done to calibrate the model parameter values by comparing simulated voltage response of the composite load model to historical synchrophasor bus voltage data.

FIDVR and UVLS Event Description

The pre-fault and post-fault steady-state system operating points for one of two recent (2015) late afternoon summer FIDVR events are represented in Figure 1 and Figure 2, respectively.

Two load pockets are involved in this FIDVR event. The total loads in each pocket are 150 MW (load area 1) and 380 MW (load area 2), respectively. Load area 1 tied the rest of the system through four 138/69 kV transformers while Load area 2 tied the rest of the system through four 138 kV lines.

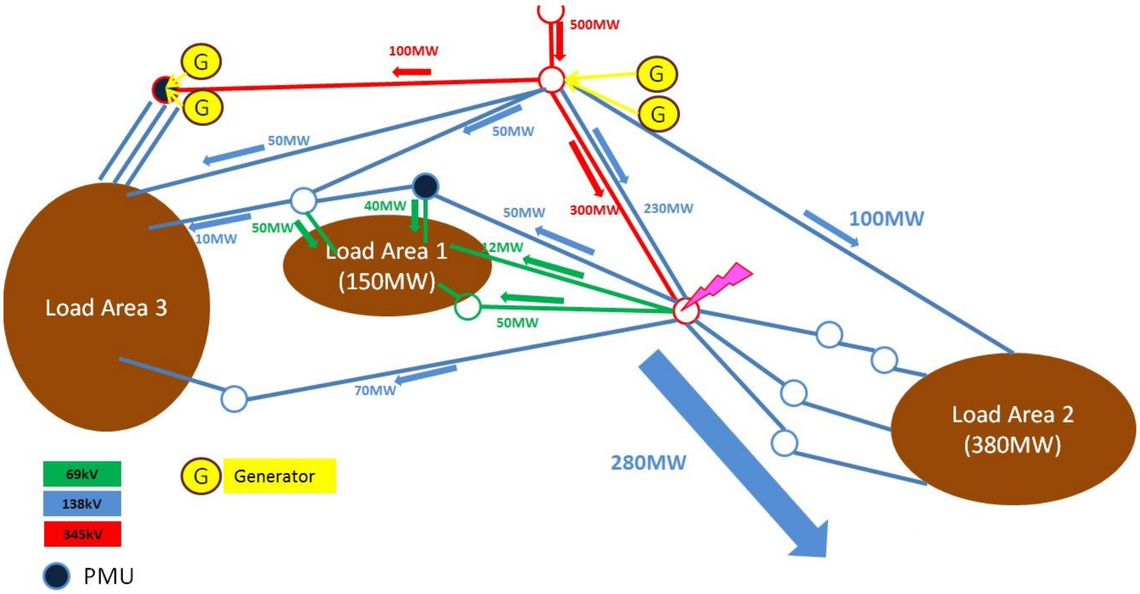

Figure 1. Pre-event Steady-State System Representation

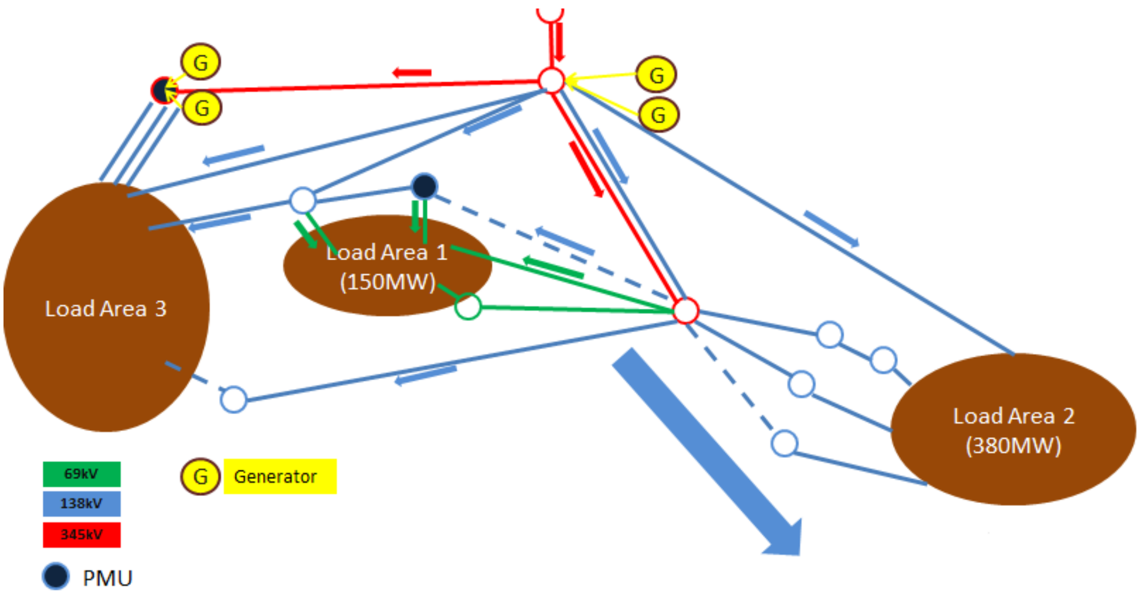

Figure 2. Post-event Steady-State System Representation

Since the early 2000s, AEP has had in place a system called the Substation Data Repository (SDR) to automatically retrieve Common format for Transient Data Exchange (COMTRADE) fault record files from relays, and then upload them to a central server for easy access as introduced in [5]. The SDR records give the exact relay timing and action throughout the events. Moreover, with the help of historical synchrophasor data, especially voltage measurements from PMUs at the nearby stations, e fault events, relay actions, and system responses may be arranged in a proper sequence.

The FIDVR event being considered here began as a permanent phase B and C to ground fault on a 138 kV line caused by horizontal post insulator failures at the purple flash station end in

Figure 1. After that breakers at the both ends of this line tripped, reclosed sequentially, and tripped again consequentially. The faulted line then contacted the station bus, causing a phase A to ground fault at the station nearest the initial fault. Next, all the 138kV lines connected to that bus tripped consequentially. A relay miss-trip on another 138kV station also occurred due to relay malfunctioning. The post-event steady-state representation is shown in Figure 2.

The sequence of all the events and system responses are identified in Figure 3 with the historical synchrophasor data plot. The PMU provided synchrophasor data records located at the far end of the faulted line. The remote end in Figure 3 is actually the faulted end of the line.

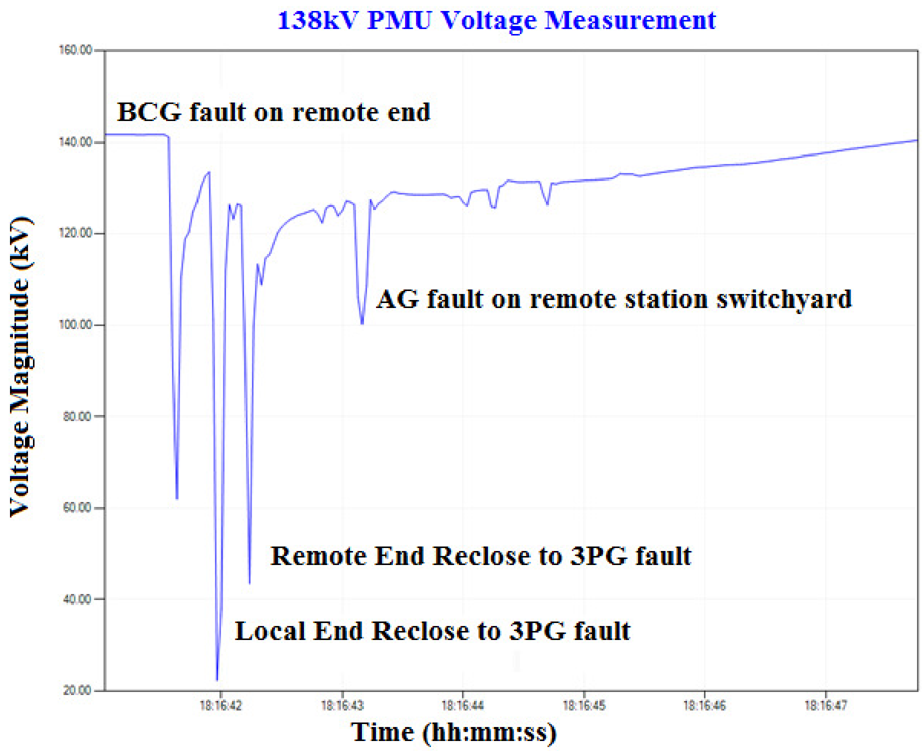

Figure 3. PMU Voltage Measurement on the 138 kV Bus during Event

Event Replication, Simulation, and Analysis Process

A. Replicate Pre-Event Power System Operating Point

There are two approaches to simulate the event. One is to use the state estimator saved power flow case at the time just prior to the event to form a pre-event power system operating point and then add the necessary dynamic modeling to the power flow case. This approach performs a dynamic simulation. The other approach is to use a dynamic base case built for planning studies and tune the study area power flow conditions to replicate the pre-event operating point. The second approach was used in this instance. Because the zonal composite load model data is to be validated, other quantities, such as tie line loadings and voltage profile around the study area, should be as close as possible to historical SCADA measurements or state estimator saved case as shown in Figure 4. Area loading, line load distribution factors for the tie lines, and load power factors are tuned to replicate the pre-event operating point as an initial steady-state condition for dynamic simulation.

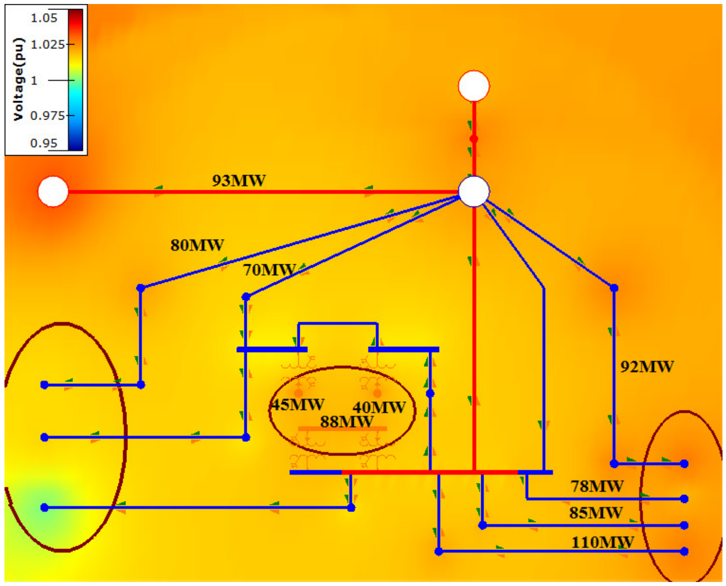

Figure 4. Pre-Event System on PSS®E Simulation

B. Event Simulation and Analysis

Single-line and double-line to ground fault simulations in PSS®E are represented by negative- and zero-sequence impedance network equivalents viewed at the fault location. The time sequence of the events was obtained from time-aligned relay records from AEP's SDR system as mentioned above. The simulation results were then aligned with the historical synchrophasor data to verify that the reference timing of each event in the simulation concurred with the reference timing in the event. The initial composite load model parameters used in the simulation were derived from EPRI's Load Component Export Tool (LCET) introduced in *Load Component Export Tool: Software Manual Version 1.0.* [6]. Figure 5 shows the comparison between the event PMU data and the composite load model response based on the initial set of parameter values produced by LCET. The composite load model parameter values were adjusted through a "trial and error" method to better match the PMU event record.

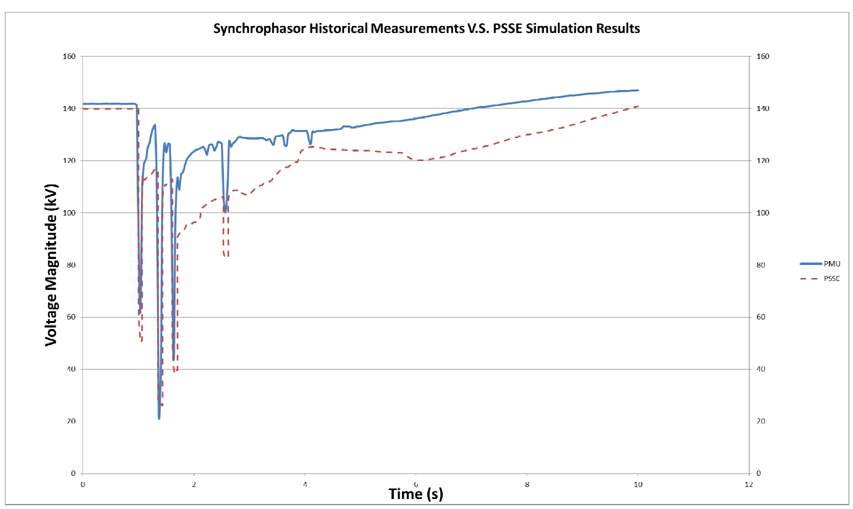

Figure 5. Event Simulation Using Typical Composite Load Model

Composite Load Model Validation and System Reliability Studies

The PSS®E implementation of the composite load model has 132 different parameter values that need to be specified as input data. Figure 6 below summarizes the categories of required input data. The four items identified as "M" in Figure 6 represent four different induction motor loads (otherwise identified as the A, B, C, and D components), the first three being analytical models of three-phase induction motors to represent compressors, pumps, and fans, and the fourth being an empirical model of single-phase air conditioning load. Fortunately, there are tools available to assist the transmission planner in determining reasonable sets of parameter values.

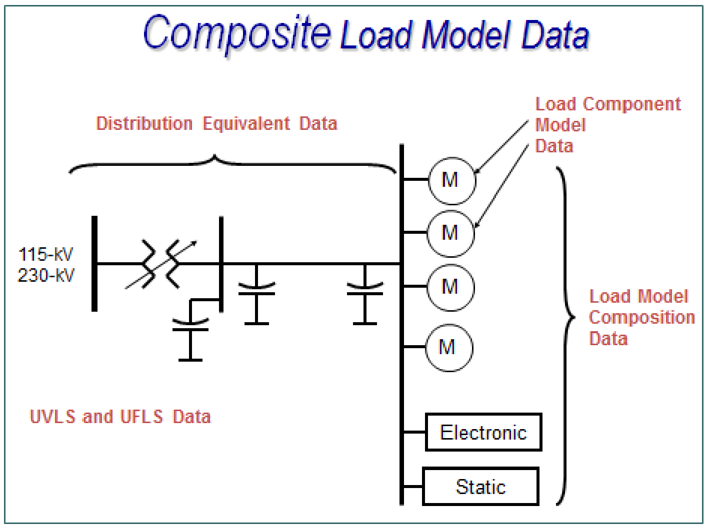

Figure 6: Composite Load Model Data Categories (Source: WECC)

As mentioned above, the EPRI LCET tool was used in the present case to supply the initial set of composite load model parameter values. This tool accepts load class (industrial, commercial, and residential) percentages applicable to the study area and combines that data with load composition data available from a DOE report on various North American climate zones. Having determined composite load model parameter values, a trial and error process of aligning the composite load model response with the PMU voltage recording of the FIDVR event may begin. Again, fortunately, most of the parameter values do not need to be adjusted. The specific parameters that needed to be adjusted were found to be limited to the A, B, C, D, E, and static component percentages and the thermal protection parameters of the D component. Adjustments from the EPRI LCET initial values in the present case were as follows:

A, B, C, D, E fractions from **.179, .09, .171, .245,** and **.122** to **.10, .10, .10, .08,** and **.10**
D-component heating time constant, Tth, from **20.** to **9.**
D-component temperature points, Th1t and Th2t, from **.7** and **1.3** to **.5** and **2.5**
D-component fraction of restartable from **.50** to **zero**
D-component Tstall = .033 and contactor drop out deactivated

The D component percentage was found to be the best way to adjust the initial post-fault voltage depression. The D component thermal protection function time constant and beginning and ending temperature points were the chief variables to control the time frame and rate of load tripping and thus to adjust the time frame and rate of voltage recovery. The D component restartable fraction was not helpful and was set to zero. Similarly, the contactor dropout and under voltage protection functions were not helpful and set to zero. Other D component parameters were either not significant in adjusting the load model response, or considered undesirable to depart from their empirical basis, the laboratory tests of various a/c units on which the values were determined.

Simulations of the adjusted composite load model responses with and without addition of the UVLS operations that occurred during the actual event are shown in Figure 7.

By comparing Figures 5 and 7, it should be apparent that the successful replication of the FIDVR event in Figure 7 favors the combined component-measurement approach to load modeling over the component approach alone as represented by LCET. As seen in Figure 5, the original LCET data overestimates the initial voltage depression and voltage recovery time. Although the LCET determined parameter values appeared quite reasonable, the associated composite load model response was clearly erroneous. The remaining deviation in Figure 7 of the validated load mode (with UVLS operations simulated) after approximately 6 seconds is attributed to additional non-UVLS load tripping. The fortuitous recording by PMU of a significant FIDVR event facilitated a substantially improved the load model.

As in this case, the study area included under-voltage load shedding (UVLS), because it was desirable that UVLS not operate for normally cleared faults, since it is reserved for the more extreme event scenarios. So, the amount of FIDVR effect that is introduced into the load model has a critical bearing on the analysis of UVLS settings. Moreover, as the area in which this FIDVR event occurred has been stability limited in the past, the overlapping of a FIDVR effect in the immediate post-fault time frame with the voltage dip associated with first swing stability is of central importance to the calculation of system operating limits. The greater the FIDVR effect, the more negative is its impact on stability system operating limits.

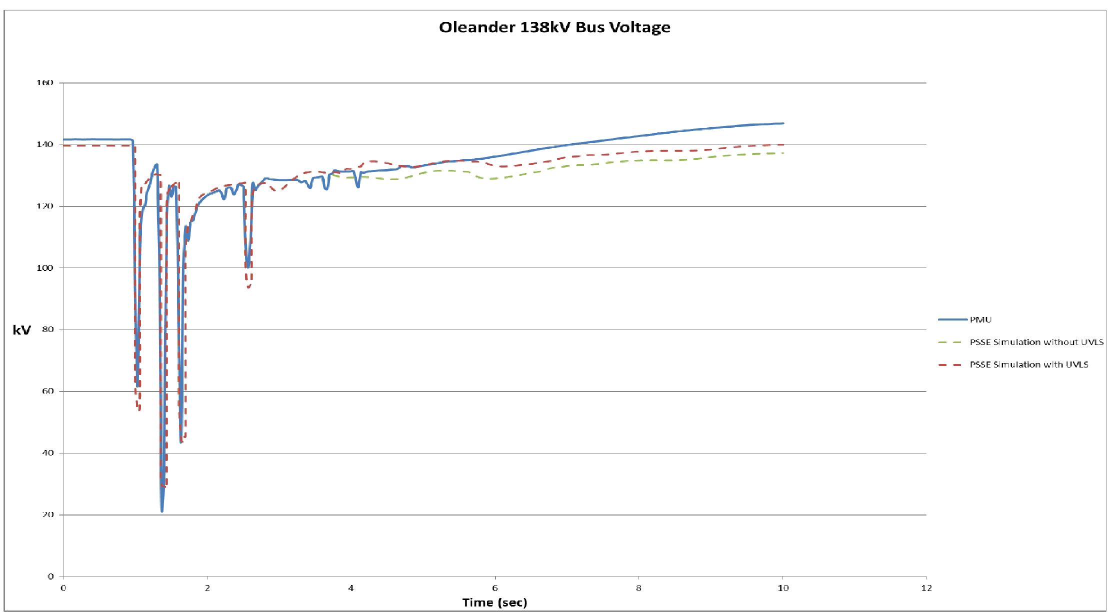

Figure 7: Composite Load Model Response Following Adjustment of Selected Parameter Values

Conclusions

A composite load model parameter adjustment achieved through comparison with a PMU-based FIDVR event record shows how a more representative load model of a study area may be validated for reliability analysis. The superiority of a combined component-measurement approach for load modeling as opposed to relying solely on a component approach becomes evident. The event described in this paper was one of two recent FIDVR events in the study area recorded during a late afternoon summer load condition. The study shows a liberal PMU deployment plan is advantageous in capturing data on such events wherever they occur.

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